Orientation based on ESA LISA proposal

David Shoemaker, MIT
L3 Study Group Chair
31 January 2017
• This afternoon
  o Overall Status (dhs)
  o Technology (John Conklin)
  o Astrophysics (Shane Larson)
  o NASA Vision (Ira Thorpe)
  o How can newcomers to LISA get involved?
  o (any remaining) Q&A

• Objectives:
  o Offer overview to non-L3ST folk
  o Elicit topics for further discussion, questions and ideas from all – most discussion may be deferred to later/tomorrow
  o PLEASE ask questions along the way

• First:
  o A walk through of the proposal recently submitted to ESA
    • Written by the LISA Consortium
    • Both EU and US contributions
  o I’ll assume all know the basic principles, and just speak to the realization proposed
Process for response to the Call from ESA

- ESA was prescriptive in the call
  - Chapters, with questions to be answered for each
  - Lengths of chapters suggested, total mandated
  - Technical supplement dictating orbit, launcher
- Group had one in-person meeting in Hannover, good L3ST presence
  - Group conversations led by Karsten Danzmann
  - Chapter-by-chapter status assessment with all present; several key issues resolved (e.g., sensitivity curve to adopt, Consortium structure, format of Science section)
- Remaining work done through Google Doc open to editing to all, two telecon meetings of a large group
- Executive Board (Danzmann, Vitale, Binetruy, Shoemaker) active
  - Telecons every ~2 weeks
  - Discussions of authorship, composition of Consortium bodies, low-frequency limit, strategy for e.g., requirements, goals, degradation
  - (group now will add two members: Ward (UK) and Domenico (Switz))
- Overall: constructive environment, welcoming also to US/NASA people, concerns, interests, desires
Science Requirements

- Requirements were 'reverse engineered'
  - Lisa Pathfinder (LPF) sensitivity for low-frequency acceleration-dominated regime assumed, no extrapolations etc.
  - Interferometry limits from detailed models; elements tested in LPF, others from ‘reasonable constraints’ and ESA Addendum

- This gave the sensitivity curve
- Mission duration chosen at 4 years (10 years consumables)
- Astro folk determined what science could be done
- Good logical connections from science to sensitivity recorded
- Credible scientifically, and the curve is technically feasible

- Some exploration and documentation of consequences of degradation/descope and potential improvements undertaken; not detailed in the proposal
2.1 SO1: Study the formation and evolution of compact binary stars in the Milky Way Galaxy.

2.2 SO2: Trace the origin, growth and merger history of massive black holes across cosmic ages

2.3 SO3: Probe the dynamics of dense nuclear clusters using EMRIs

2.4 SO4: Understand the astrophysics of stellar origin black holes

2.5 SO5: Explore the fundamental nature of gravity and black holes

2.6 SO6: Probe the rate of expansion of the Universe

2.7 SO7: Understand stochastic GW backgrounds and their implications for the early Universe and TeV-scale particle physics

2.8 SO8: Search for GW bursts and unforeseen sources

Will hear about this in detail from Shane in a bit
LISA Astrophysics

Credit: LISA L3 Mission Concept Proposal
Science analysis

• Not much discussion on the Science/Data processing centers
  o French have concept, looks reasonable
  o NASA is called out as equal science partner throughout
  o NASA should duplicate the ground-based data processing and computational infrastructure
  o L3ST needs to do more work in this domain to form a community conceptual approach and 'negotiate' with French
• Is there some proportionality of access established by ESA/NASA?
  o Not really feasible with this kind of data
  o Planck as example of a successful joint (US junior) endeavor
  o Should the US strive for a named, key, role in the process?
Science Operations/Archiving

- Joint effort between ESA, NASA, and the LISA Consortium
- France as lead
- Multiple DPC (incl. US)

- Some ‘observing’ dynamics – protected times for specific events

- Data release to follow ESA/NASA rules; transients in near real-time, public release after proprietary period

Figure 12: A schematic of data and information flows between the different mission elements.
Science-imposed mission performance; 4-year mission

Credit: LISA L3 Mission Concept Proposal
ESA Addendum to Call

- ESA Addendum to Call was specific about key issues:
  - Launcher: Ariane 6.4, which has large lift capabilities.
    - 7000 kg for most launch scenarios
    - LISA 3-satellite mass currently estimated at 6000 kg
  - 3-4 year nominal lifetime (we chose 4); orbit evolution supplied for 10 years (suggesting the ‘consumables’ lifetime of 10 years)
  - 2.5 mKm-long arms
  - Triangular constellation
  - Standard ‘LISA’ orbit recommended
Technical Addendum
from ESA

- Table of contents to give sense of the document
- General Guidelines 5
- Launcher 5
- Space segment constraints 6
- Mission operations. 6
- MISSION AND SYSTEM CONSIDERATIONS 7
- General Remarks for Mission Options 7
- Launch and Transfer Scenarios. 8
- Transfer durations, data rates and power considerations 10
- Power, Data transmission and link budget considerations. 11
- Ground station characteristics. 12
- Space debris regulations. 13
- APPENDIX A - TRL DEFINITION (ISO SCALE). 15
- APPENDIX B – C3 DEFINITION. 17
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- APPENDIX D – TECHNOLOGY DEVELOPMENTS IN THE FRAME OF L3. 21
- APPENDIX E – OVERVIEW OF MISSION ANALYSIS. 2
Mission Profile

- Much of this dictated by the Technical Addendum to be consistent with the GOAT report
  - The Proposal adopts all the ‘targets’ in the addendum

- 3.1 Orbit
  - Target to be the standard LISA L1 Lagrange point
  - Target to be 2.5 mKm arm length, full triangle

- 3.2 Launcher
  - Dictated to be Ariane 6.2 or 6.4
  - Mass requires Ariane 6.4, but then margin for mass and volume

- 3.3 Concept of Operations
  - Describes the initial insertion, alignment, and startup
  - Describes the basic measurement of GWs via changes in optical path

- 3.4 Mission Lifetime
  - 4 years planned
  - 10 years possible for consumables etc. (Cold gas thrusters not ideal!)

- 3.5 Communication requirements and strategy
  - Entire constellation is expected to produce about 35 kbit/s of data
  - 7.2 hours to one ground station calculated to suffice for 1 day of data; 8 hours of calculated visibility (sounds marginal now that I read it)
Instrument requirements

- Key requirements adopted in the Proposal:
  - Frequency range 0.1 mHz to 0.1 Hz;
    - Goal: 20 microHz to 1 Hz
    - LPF showed the Goal LF sensitivity to be feasible
  - 2.5 mKm arms (per addendum)
  - 30 cm telescope (much discussion, and may yet be tuned; export easier from US to Europe at this diameter)
  - 2 W (end of fiber) laser (again much discussion, but more sounded risky)
  - 4 year lifetime
- All sensible technically, excellent science enabled, and should not shock ESA (or NASA)
- Strongly motivated to present a feasible, affordable project
  - Do not want to waste time and money iterating on descopes!
Model Payload

4.1 Description of the measurement technique

- Interferometry between 3 spacecraft
  - Send out ~2W of Nd:YAG 1 micron laser light
  - Receive about 100 pW (due to beam spreading)
- Interferometry is between ‘free-falling’ test masses
  - Inside drag-free spacecraft ‘shells’ protecting masses from external forces, temperature fluctuations
  - All 6 links – send/receive between S/C – used, allowing multiple interferometers to be synthesized
- Not ‘locked’ (not formation flying) -- ~5 m/sec relative velocities
  - Different time scales for celestially-induced and GW-induce arm length changes allows them to be separated
  - Constant servo adjustment of S/C to follow masses using ‘micro thrusters’
  - Periodic adjustments of the constellation to maintain orbits
Model Payload

- **4.2 Key measurement performance requirement**
- Frequency range:
  \[
  100 \, \mu \text{Hz} \leq f \leq 0.1 \, \text{Hz} \quad \text{req.}
  \]
  \[
  20 \, \mu \text{Hz} \leq f \leq 1 \, \text{Hz} \quad \text{goal}
  \]
- Accelerations: (LPF performance)
  \[
  S_a^{1/2} \leq 3 \cdot 10^{-15} \, \frac{\text{m s}^{-2}}{\sqrt{\text{Hz}}} \cdot \sqrt{1 + \left( \frac{0.4 \, \text{mHz}}{f} \right)^2} \cdot \sqrt{1 + \left( \frac{f}{8 \, \text{mHz}} \right)^4}
  \]
- Displacement noise: (Modeled, and consistent with elements of LPF where tested)
  \[
  S_{\text{IFO}}^{1/2} \leq 10 \cdot 10^{-12} \, \frac{\text{m}}{\sqrt{\text{Hz}}} \cdot \sqrt{1 + \left( \frac{2 \, \text{mHz}}{f} \right)^4}
  \]
- Above approximately 30 mHz strain noise increases with frequency as the Gravitational Wave period becomes shorter than the round trip light time, resulting in a partial cancellation of the signal.
Model Payload

4.3 Payload conceptual design and key characteristics

- Three identical S/C
- Telescope 30 cm; thermally stable (optical truss if needed, hope not)
- Low scatter (do not want 2W outgoing beam to mix with incoming 100 pW)
- Articulation (~1 deg) of two telescopes, or movable intermediate optic (in-field guiding)
- Telescope was not tested in LPF
Model Payload

- **4.4 Interferometry Measurement System (IMS)**
- Optical bench is Zerodur with contacted optical components
- LPF unit tested all basic notions, but much simpler and one-off
Model Payload

4.4 Interferometry Measurement System (IMS)

- Photoreceivers InGaAs 2mm dia
  - LPF photoreceivers electrically not directly relevant to LISA application
- One laser is locked to a reference cavity
  - Other lasers phase-locked to it
  - Specific LPF laser is not directly relevant to LISA laser (higher power needed, lifetime requirements)
- Modulation for inter-S/C communication added to outgoing light
- Phasemeter converts Interferometer signals to length information
  - A-D conversion, and Phase-Locked Loop generates data on frequency and phase
  - Auxiliary information (lengths, clocks, etc.) also extracted
  - Phasemeters well tested in LPF and on the ground; LISA requires many more channels
4.5 Gravitational Reference Sensor
GRS is composed of the test mass and the hardware that surrounds it
Position sensing, minor forces and torques on Test Mass, and shielding
Reflectivity for local laser beam
GRS core is the TM itself, a 46 mm, roughly 2 kg, Au-coated cube of Au/Pt
Demonstration on LPF perfectly relevant
Performance of LPF units established LISA Performance Curve
Electrostatic discharge on LPF by Hg lamp; wish to move to LEDs
  - Development needed
4.6 Performance assessment with respect to science objectives

- Proposed LISA acceleration performance based on observed LPF performance
- The interferometry displacement noise requirement is based on a detailed noise budget that includes shot noise, path-length variations, laser frequency and amplitude noise, clock noise, stray light, phasemeter electronics noise and tilt-to-length coupling.

Figure 9: Average TM acceleration noise measured with LISA Pathfinder, compared against the LISA single TM acceleration requirement.
Model Payload

• **4.7 Resources:** mass, volume, power, on board data processing, data handling and telemetry
  - Resources discussed in System Requirements
  - No clear separation of spacecraft and payload is possible

• **4.8 Payload control, operations and calibration requirements**
  - Again, the S/C and payload work as a single entity
  - The telescopes must be pointed to the two distant spacecraft
  - The remaining S/C degree of freedom, orthogonal to the constellation plane, is drag-free controlled
  - Calibration is based on the laser wavelength
  - All clocks locked to a master Ultra-Stable Oscillator (USO)
  - Interruptions to observing due to phase-lock resets, antenna repointing, and test-mass discharge; seconds-to-minutes duration
System Requirements

- **5 System Requirements & Spacecraft Key Factors**
  - Pointing is self-referenced, based on the inter-S/C interferometry
    - Requires Micro-Thrusters: Cold Gas (baseline) or
    - Colloid (NASA) - mass saving of ~100 kg per S/C
      - (Ariane 6.4 can lift the extra Cold Gas)
  - Gravitational Balance (unchanging Newtonian attraction)
    - Cold gas may be a challenge esp. for a 10-year mission
  - EM environment: stable, quiet
  - Temperature: extraordinarily stable; e.g., electronics should stay permanently ‘on’, orientation of S/C w.r.t. Sun critical, etc.
  - Scattered light challenging, leading to contamination requirements; this is a domain that needs significant work
  - Interplanetary magnetic fields and charged particles: LPF gives good data, but in a quiet time. Modeling needed.
System Requirements

- **5.3 S/C Concept**
- Structure based on NGO (ESA L1 proposal)
- Assume Ariane 6.4 fairing
- Proposed S/C 3.4 height (each), 2.9M diameter
- Total of 3 S/C makes 12.2 m by 3.5 m; fits in Ariane fairing

*Figure 11: (Left) cut away showing the modified upper bay with larger cold gas tanks sized to hold sufficient propellant for a 10 year total mission duration. (Right) concept S/C design from the outside, showing the 2.9 m diameter flat solar array. The array is sized to ensure the S/C remains in shade at all times.*
System Requirements

5.4 Budgets
Mass:
Unit margins of 5-20% have been applied, depending on the technical maturity
A total system margin of 20% has been applied.
Data:
0.5 m antenna with a 50 W transmit power in the X-Band.
Microthrusters:
Cold gas LPF experience, plus deterministic nature (solar radiation pressure) leads to 90 kg Cold Gas for 10-year mission and 20% margin
Some requirements, specs
From the LISA L3 Mission Concept Proposal

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Nominal mission duration</td>
<td>4 years</td>
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<tr>
<td>Extended mission duration</td>
<td>10 years</td>
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<tr>
<td>Orbits</td>
<td>3 heliocentric orbits</td>
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<tr>
<td>Transfer time</td>
<td>&lt; 18 months</td>
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<tr>
<td>Range to Earth</td>
<td>50-65 Gm</td>
</tr>
<tr>
<td>Arm length</td>
<td>2.5 Gm</td>
</tr>
<tr>
<td>Number of Links</td>
<td>6 links/3 arms</td>
</tr>
<tr>
<td>Measurement Bandwidth</td>
<td>Req: 100 μHz ≤ f ≤ 0.1 Hz</td>
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<tr>
<td></td>
<td>Goal: 20 μHz ≤ f ≤ 1 Hz</td>
</tr>
<tr>
<td>S/C Power Requirements</td>
<td>≤ 760 W</td>
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<tr>
<td>Laser Power</td>
<td>2 W (out of the fiber)</td>
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<tr>
<td>Telescope Diameter</td>
<td>30 cm</td>
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<tr>
<td>System wavefront quality</td>
<td>λ/20 RMS</td>
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<tr>
<td>Data latency</td>
<td>&lt; 1 day</td>
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<tr>
<td>Communication Needs</td>
<td>334 MB/day</td>
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</table>

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass [kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ariane 6.4 Launch Capacity</td>
<td>7000.0</td>
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<tr>
<td><strong>Total Launch Mass</strong></td>
<td><strong>6076.3</strong></td>
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<tr>
<td>Stack and Launch Adapter</td>
<td>500.0</td>
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<tr>
<td>Wet Stack Mass</td>
<td>5576.3</td>
</tr>
<tr>
<td>Total Propellant</td>
<td>2050.0</td>
</tr>
</tbody>
</table>
Technology Development

- Relatively high readiness for pre-project phase, due to LPF, Gaia, Grace-follow on, and a long history of LISA development
- TRL listing in proposal; some solid, many guesses
- TRL 4 or so:
  - UV Source: LEDs
  - (Colloidal Thrusters (JPL) 7/5)
  - Laser and amplifier (GSFC)
  - Optical table fabrication
  - Photoreceivers
  - Most Telescope technologies
    - Phasemeter ‘Complete functionality’
  - Diagnostics for LISA-scale S/C
- Pretty good agreement with the L3ST prioritization

Table 8: Technology readiness levels of primary mission items.
Technology readiness

- List of TRLs in proposal:
  - broadly distributed
  - LPF-tested elements are appropriately high TRL
  - lower TRLs were guessed, and values are not well documented
- No disconnects with the L3ST Technology Roadmap assessments
- Separately, the ITTs from ESA have been shared via the Consortium with the L3ST and Study Office
  - We will be invited (at least by Germans) to observe reviews
Proposal recommendations for ESA/NASA roles

- Proposal recommends that ESA appoint a single prime contractor to take responsibility for the payload as well as the S/C.
- **Recommends ESA to set up a System Engineering Office for the entire mission** including the core scientific instrumentation, providing top-level overview of all mission aspects including the payload.
  - “NASA will also contribute to the Systems Engineering.“
- “The Consortium is proposing that NASA provide directly to ESA further parts of the payload and the spacecraft. There may also be NASA contributions to the Consortium.”
- “The total NASA contribution is expected to be at a level of 20% of the total mission cost.”
US roles in LISA Consortium

- Consortium:
  - Executive Board: 1 US member (Shoemaker) of ~6 persons
  - Consortium Board: 4 US members (Shoemaker, Cornish, Mueller, Larson) of 21 persons
  - Need to ensure that leadership continues into subsystems and Science working groups as appropriate
- “Core Team” is 82 persons
  - Union of LISA astrophysicists, instrument scientists, and LPF folk
  - Uneven level of contribution; certainly will evolve
- All of NASA’s L3ST and TAG are currently included (21 persons)
Figure 13: LISA Organisation in Phase A/B. OMS: Optical Measurement System, PM: Phasemeter, CMU: Charge Management Unit; DDS: Payload Computer and Diagnostics.
NASA Contributions

• Quoting from the proposal:
  “The specific items identified so far comprise the following potential contributions to the LISA payload directly supplied by NASA to ESA:
  o Space-qualified laser systems
  o Frequency reference cavity for laser stabilisation
  o Send/receive telescopes
• Potential contributions to the S/C that could be made by NASA to ESA:
  o Propulsion modules
  o Solar panels
  o Micropropulsion systems
• NASA may also contribute elements of the LISA instrument to the European member states, such as:
  o Charge management system
  o Optical bench photoreceivers and front-end electronics
  o Contributions to phasemeter hardware and software”

• More on this from John Conklin
Schedule, Cost, Risks

• Schedule: Presents the ‘technically possible timeline’ with a launch in 2029
  o “possible without financial or programmatic constraints”
• Costs: Scaled from NGO
  o 6 instead of 4 links → 250M€ instead of 175 M€ for the member states
  o ESA cost at completion (CaC) for the NGO 1200 M€; hope to have NASA contributions to bring ESA down to 1050 M€ cap
  o (total NASA contribution assumed to be ~350M$)
• Total estimated cost can be inferred to be 250+1050+350 = 1650 M€
  o Last NASA estimate was $2.1B
• Risks: many high risks mitigated or retired due to LPF.
L3ST comments

1) L3ST wishes to have leadership, authority, and responsibility that is commensurate with NASA’s contribution and the US team skills
2) L3ST strongly supports the vision of System Engineering at ESA rather than in an industrial firm
3) L3ST wishes that ESA include US persons in the Science Team
4) L3ST wishes to be full players in the scientific exploitation of the LISA data

The Interim Report Technology Matrix is updated with ‘subassemblies’ – parts of major subsystems that NASA could contribute to EU Member States