LISA

Gerhard Heinzel
Rencontres de Moriond, La Thuile, 28.3.2017
LISA Sources
LISA: LIGO Event Predicted 10 Years in Advance!

Accurate to seconds and within 0.1 square-degree!

GW150914

Sesana 2016
10^5 M_☉ BH binary merger at z=5
In Red: Pathfinder instrumental noise

Black Hole Merger far above Noise

A. Petiteau 2016
LISA history

• Long history going back to the 1990’s
• Original plans for a 50/50 ESA/NASA mission
• Now an ESA mission with significant contributions from ESA member states and the US
• LISA answers the L3 theme „The gravitational Universe“
• Call for Mission Concepts was issued by ESA end of 2016
• Consortium proposal submitted in January 2017
• Formal acceptance expected this summer
• ESA has already started CDF study based on our proposal
• Decision on Implementation 2020
• Launch of L2 foreseen in 2028
• Launch of L3 foreseen in 2034
• Technically LISA is ready for an earlier launch!
LISA Mission Concept Document

Submitted on
January 13th, 2017

The LISA Consortium:
12 EU Member States
plus the US!

https://www.lisamission.org/proposal/LISA.pdf
LISA

- 3 identical spacecraft
- Armlength ca. 2-3 Mio km
- 50 Mio km from the Earth
- Triangle rotates and changes by ±1.5°, ±20 000 km, ±10 m/s
- Drag-free mode with test masses verified in Lisa Pathfinder
- Heterodyne laser interferometry in transponder mode
- 1…2 W laser with 20…30 cm telescopes gives ≈ 100 pW at receiver
- 1 year cruise, 4+ years operation
“Split interferometry”: test mass to test mass in 3 pieces

\[ L_{12} = d_1 + d_{12} + d_2 \]

Optical Bench

nm motion

“Optical Readout” (ORO)

“Science Interferometry” (Long Arm Interferometry)

PM

OB

EADS Astrium

Max-Planck

Albert Einstein Institut
LISA noise budget

- Shot + ifo noise
  \( \approx 10\text{pm} / \sqrt{\text{Hz}} \)

- GRS + acc. Noise
  LPF levels

- Armlength
  (2.5 mio km)

- MR1.1 Galactic Binaries
- MR2.1 Light, seed black holes at high redshift
- MR2.2 Blackhole growth over cosmic history
- MR2.3a Mergers of Milky-way type galaxies
- MR2.4a Detection of Intermediate Mass Black Holes
- MR2.4b High mass ratio Intermediate Mass Black Holes
- MR3.1 EMRI around massive black holes
- MR4.1 LIGO-type black holes
- MR5.1 Tests of GR with high SNR ring-down signals
- MR7.1 Astrophysical stochastic background
- MR7.2 Cosmological stochastic background

- Observatory Strain Sensitivity
- Galactic Background
- Total

- Frequency (Hz)
- Strain Sensitivity \( \left( \frac{1}{\sqrt{\text{Hz}}} \right) \)
New features compared to LPF

- Armlength 2..3 Mio km  
  → use of telescopes, ≈100 pW received power
- Velocity $\pm 10$ m/s → Doppler $\pm 10$ MHz  
  → heterodyne interferometry at 5...25 MHz
- Armlength variation $\pm 1\% = 20000...30000$ km,  
  → Time Delay Interferometry to cancel frequency noise
- Need for very stable sampling clocks, passively synchronized between 3 spacecraft  
  → clock noise transfer with GHz sidebands on laser beams
- Angle variations $\pm 1.5\degree$  
  → Pointing mechanism, two options
- Point-Ahead Angle $\pm 6$ μrad  
  → Point Ahead Angle Actuator Mechanism (PAAM)
- Absolute ranging of armlengths and data transfer between the arms  
  → additional weak spread spectrum code modulation on laser beams
Architecture question #1: breathing angle

2 separate optical benches with one test mass each:
+ narrow field of view sufficient
+ actuator errors not in optical path measurement
— backlink fiber necessary

Alternative: single optical bench with wide-range pointer:
+ can be smaller, lighter
+ would allow single test mass
+ no backlink fiber
— telescope needs wide field of view
— actuator with several degrees range in optical path

Under study by AEI (backlink) / Airbus (in-field-pointing) with DLR funding
Using ultrastable baseplates and hydroxy-catalysis bonding as demonstrated in LISA Pathfinder Optical Bench (Glasgow)
\[ \delta \phi = \frac{2\pi}{c} \Delta L \delta v \]

• Armlength difference \( \Delta L \) up to 20000 km
• Would be totally overwhelming noise source if not mitigated
• Three possible methods, two of which would be sufficient

• Ongoing trade-off studies:
  o Use arm locking? (probably no)
  o Prestabilization by cavity or unequal armlength Mach-Zehnder?
Time delay Interferometry

\[ X(t) = s_1(t) - s_2(t) - [s_1(t - 2\tau_2) - s_2(t - 2\tau_1)] \]
\[ = [s_1(t) - s_1(t - 2\tau_2)] - [s_2(t) - s_2(t - 2\tau_1)] \]

\( s_i(t) = \text{laser phase in arm } i \)
\( \tau_i = \text{one way light travel time down arm } i \)
TDI for LISA

- TDI is essential to remove frequency noise in postprocessing
- Based on pioneering work at JPL (Tinto et al 1999...)
- 2nd generation necessary for moving spacecraft
- Complicated transfer function for GW signal
LISA Pathfinder heritage

- We understand the local interferometer at the $30 \text{ fm/sqrt(} \text{Hz}) / 100 \text{ prad/sqrt(} \text{Hz})$ level.
- We have learned many details, e.g. about:
  - tilt-to-length coupling and its subtraction,
  - RIN at twice the heterodyne frequency,
  - the impact of operating unsynchronized instruments.
LISA Phasemeter

- D/DK development (ESA contract) has full performance and all functions, including clock distribution, absolute ranging, clock transfer, data transfer (*).
- Next step: thermal management and development into flight hardware.
- NASA/JPL has similar developments, with flight heritage for simpler version, but ITAR problems.

* Delgado et al 2009
GRACE: Satellite-to-satellite tracking

- Observation of Earth gravity field by low-low satellite tracking
- US-German collaboration
- Launched 2002, still working
- μ-wave ranging
GRACE signals

- Changes of order $\mu$m ... mm
- No absolute measurement of separation (GPS is enough)
- Rather complicated data analysis to recover Earth gravity field and remove effects of ocean tides, atmosphere etc.
Some GRACE results


Horwath and Dietrich, Geophys.J.Int 2009

GRACE Follow-On

- GRACE mission nearing the end of its on-orbit life (long past design life)
- Follow-On mission for continued data with minimal gap:
  - near rebuild of GRACE using microwave ranging, launch 2017/18.
  - New: **laser interferometer** as experimental demonstrator, **first laser interferometer between satellites**.
- LRI is a US-German joint project, in a collaborative partnership resulting from earlier LISA work:
  - US: phasemeter, cavity, laser (lead: JPL)
  - Germany: optics (design lead: AEI)
- Spacecraft are completed, now in testing, launch early 2018
Transponder configuration

Offset phase locked transponder
Similar to one LISA arm
Doppler shift is $\pm 3$ MHz, operate with offset of 10 MHz to escape 0-2 MHz band
Distance variations lead to phase changes which are continuously tracked
Offset phase lock on transponder S/C, zero signal if perfect
Range variations appear accumulated in beatnote signal on master S/C

$$|f_D| = \frac{|v_{rel}|}{\lambda}$$
GRACE rebuild

- Nearly identical rebuild, but many detailed improvements:
  - 3 star cameras (not 2), improved AOCS pointing accuracy
  - Improved thermal insulation
  - Many small changes in subsystems and electronic units
- Same team and operations concept
- Except, of course the **new Laser Ranging Instrument**
- Status: LRI is integrated on spacecraft, now testing.

Max-Planck Institut für Gravitationsphysik
Albert Einstein Institut
LRI Laser ranging noise sources

Laser frequency noise (requirement 30 Hz/√Hz, like LISA)
  Reference cavity on one spacecraft, offset phase lock on second spacecraft
Pointing jitter
  Beam steering mechanism and special properties of triple mirror
Thermally driven effects
  Mitigate with appropriate material choice, thermal shielding and control
Readout noise (important for acquisition):
  USO noise
  Shot noise
  Laser power noise
  Photodetector electronic noise
  Parasitic signals (e.g. scattered light and electronic cross-talk)
  ADC quantization noise
  Spurious electronic phase shifts
Laser frequency stabilisation

Frequency noise coupling proportional to arm-length mismatch:

$$\delta x = \Delta L \frac{\delta \nu}{\nu}$$

Stabilisation is required

LISA tricks (armlocking, TDI) not applicable, since there is only one link ("arm")

Space qualified reference cavity developed by Ball Aerospace and tested at JPL

Even with stabilisation laser frequency noise will be a significant component of error budget

Performance significantly better than 30 Hz/√(Hz), sufficient for LISA

Similar efforts ongoing in Europe

Laser Ranging Interferometer

Elegant and efficient beam steering that aligns both TX and RX with a single steering mirror that is outside of the sensitive path
Measurement is exactly the round-trip distance, insensitive to paths on optical bench

Many details we learned in the LRI development are useful for LISA:

- Acquisition algorithm development and test
- Optical simulations
- Precise measurement of near-Gaussian beams
- Generation of flat-top beams
- Precise control of hexapods and steering mirrors for ground test equipment
Interferometry summary

<table>
<thead>
<tr>
<th></th>
<th>LTP</th>
<th>GRACE Follow-On LRI</th>
<th>LISA test mass</th>
<th>LISA long arm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Separation</td>
<td>40cm</td>
<td>270km</td>
<td>&lt;1m</td>
<td>Mio km</td>
</tr>
<tr>
<td>Meas. beam</td>
<td>1 mW Gaussian</td>
<td>100 pW flat-top</td>
<td>1 mW Gaussian</td>
<td>100 pW flat-top</td>
</tr>
<tr>
<td>Meas. band</td>
<td>mHz-Hz</td>
<td>mHz-Hz</td>
<td>mHz-Hz</td>
<td></td>
</tr>
<tr>
<td>Het. Frequency</td>
<td>1 kHz, fixed</td>
<td>4-16 MHz, variable</td>
<td>3-20 MHz, variable</td>
<td></td>
</tr>
<tr>
<td>Interferometer principle</td>
<td>Heterodyne Mach-Zehnder with local Reference ifo</td>
<td>Offset phase-locked transponder</td>
<td>Heterodyne Mach-Zehnder with local Reference ifo</td>
<td>Offset phase-locked transponder</td>
</tr>
<tr>
<td>Phasometer</td>
<td>SBDFT</td>
<td>DPLL</td>
<td>DPLL</td>
<td>DPLL with extra functions</td>
</tr>
<tr>
<td>Modulators</td>
<td>AOM @ 80 MHz</td>
<td>EOM for cavity</td>
<td>—</td>
<td>EOM @ 2 GHz</td>
</tr>
<tr>
<td>Frequency stability req.</td>
<td>&gt; kHz/sqrt(Hz)</td>
<td>30 Hz/sqrt(Hz)</td>
<td>&gt; kHz/sqrt(Hz)</td>
<td>30 Hz/sqrt(Hz)</td>
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<tr>
<td>Laser</td>
<td>30 mW Nd:YAG</td>
<td>30 mW Nd:YAG</td>
<td>Few mW, part of TX laser</td>
<td>few W</td>
</tr>
<tr>
<td>Photoreceiver</td>
<td>5mm InGaAs QPD, kHz operation, no special noise req.</td>
<td>1mm InGaAs QPD, MHz operation, 3...4 pA/sqrt(Hz)</td>
<td>1mm InGaAs QPD, MHz operation, no special noise req.</td>
<td>1mm InGaAs QPD, MHz operation, 2 pA/sqrt(Hz)</td>
</tr>
<tr>
<td>Optical Bench</td>
<td>Complex, ultra-stable</td>
<td>Simple, metal</td>
<td>Complex, ultra-stable</td>
<td></td>
</tr>
<tr>
<td>Imaging Systems</td>
<td>—</td>
<td>2-lens</td>
<td>None / 2...4-lens</td>
<td>2...4-lens</td>
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<tr>
<td>Telescope</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>20...25cm</td>
</tr>
<tr>
<td>Ifo noise</td>
<td>35 fm/sqrt(Hz)</td>
<td>80 nm/sqrt(Hz)</td>
<td></td>
<td>some pm/sqrt(Hz)</td>
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<tr>
<td>Ifo pointing control</td>
<td>DFACS of test mass</td>
<td>Steering mirror (not in sensitive path)</td>
<td>DFACS of test mass</td>
<td>DFACS of S/C and backlink or in-field pointing</td>
</tr>
<tr>
<td>Data processing</td>
<td>In DMU/OBC for DFACS on ground (LTPDA)</td>
<td>on ground</td>
<td>In OBC for DFACS, on ground for science (TDI)</td>
<td></td>
</tr>
<tr>
<td>Link acquisition</td>
<td>One TM after the other</td>
<td>5 DOF simultaneously</td>
<td>One TM after the other</td>
<td>5 DOF simultaneously</td>
</tr>
</tbody>
</table>