Precision Measurement Sensing for Spaceborne Gravitational Wave Detectors

Christian Killow for the LISA Team

Image credit: ESO
Gravitational Wave Detection

- What and Why

  - Space observatory: eLISA
    - Gigametres and picometres

  - LISA Pathfinder
    - Technology demonstration

- Optical sensing for spaceborne precision measurement missions
Gravitational waves are a prediction of Einstein’s theory of relativity

They are *ripples in spacetime*
- Not EM radiation
- Akin to *listening* to the Universe

When we observe them they will provide a new observational window on the universe

They are the only known way of observing some of the most exotic processes that take place in the universe, e.g.
- Super Massive Black Hole collisions
- Extreme mass-ratio inspirals
The best way we have to build gravitational wave detectors is to isolate ‘test masses’ from local disturbances and measure their separation as gravitational waves pass through the system.

- We use laser interferometry as the ‘ruler’ as high precision is needed.

\[ h = \frac{\Delta L}{L} \sim 10^{-20} \]

- LIGO extends one ten thousandth of the way around the earth!
- You could use \( \sim 530 \) calories if you ran it.

The 4 km arm length LIGO gravitational wave observatory in Louisiana, part of the world-wide effort to detect gravitational waves.
A problem and a solution

- Changes in local mass distribution – even clouds passing – cause a variation of the forces acting on the test masses
  - This is a problem if the mass distribution changes in the band you want to measure
- We need to go to a gravitationally quiet environment: space
  - Added benefit that we can have very long armlengths
- eLISA is a proposed spaceborne gravitational wave detector

Similar detection principles as ground-based detectors: monitor separation of inertially free masses using interferometry

With gigametre armlengths and requiring picometre test mass monitoring at milliHertz
  - A demonstrator mission – LISA Pathfinder – is being flown to retire technological risks
● We can verify many aspects of eLISA on ground, but not all

● The aim of LISA Pathfinder is to verify technology for future spaceborne gravitational wave detectors
  – It will effectively demonstrate the ‘short-arm’ interferometry for eLISA

● Fly two test masses and measure the purity of their freefall
  – Experiment in micro-gravity at L1

● European Space Agency mission due for launch in 2015
LISA Pathfinder in two graphs

**Differential acceleration noise:**  
Can we keep the test masses still?

**Displacement sensing noise:**  
Can we measure the stillness?
The Optical Bench Interferometer (OBI)
- Has to physically fit into the space available
- Plays a structural role
- Has to survive launch and radiation environment
- Measure 10 picometre longitudinal variations and 20 nanorad angular beam motion (in band) in milliHertz regime
- Be non-magnetic
- Beams have to hit the Test Masses (TMs) within 25 μm of absolute nominal

This leads to a lot of derived requirements
- And a lot of paperwork
Heterodyne interferometry for LTP

- Compare phase of beatnote between red and blue beams at QPD1 and QPD2
- Should be stable if the paths DBE and DCE are stable
- For LTP we replace a mirror on the stable structure with a test mass
The optical layout was originally designed by the AEI, Hannover.

The design incorporates:
- Four Mach-Zender interferometers
- Path length matching of all interferometers
- Equal transmission through beamsplitters for all interferometers

Enabling technology: hydroxide-catalysis bonding
● Lots of detailed work went in to what is a very complicated assembly
  - There’s no time for details here!
We developed the technique to precision locate a component and then bond it in place.
- This uses hydroxide-catalysis bonding to form quasi-monolithic assemblies.
- Once built the assembly is permanently aligned.
- Demonstrated picometre stability.

Component placement at the sub-μm and 20 μrad level.
Each alignment stage was carefully planned
The flight OBI underwent considerable testing

- More details in Robertson et al. Class. Quantum Grav. 30 (2013) 085006

- Properties of the optical chain
  - Transmission efficiency
  - Photodiode responsivity

- Alignment to the IAF Frames

- Beam DC positions and scaling

- DWS Calibration
  - Operating point
  - k-coefficients

- Other Optical Properties
  - Interference contrast
  - Path length matching

- Thermal Vacuum cycling

- Vibration and shock
Delivered!

The LISA Pathfinder Optical Bench Interferometer - a fine vintage!
The University of Glasgow has provided the ‘jewel in the crown’ flight Optical Bench Interferometer for LISA Pathfinder of LISA Pathfinder
- We are now using our experience to further the readiness of eLISA
- As well as performing knowledge transfer activities to multiple new areas

And a lateral thought…
- Delivering flight hardware is more than ‘just’ hardware
- >45 GB SVN file repository
  - >10000 updates!
  - Plus 10 GB of lab photos (N~7000)
Further information

- https://www.elisascience.org/whitepaper/
- Robertson et al. Class. Quantum Grav. 30 085006 (2013)
- Killow et al. fibre coupler paper in preparation for Optics Express
- Search ‘LISA Pathfinder’ on YouTube

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