LTP Interferometer - Noise Sources and Performance

David Robertson, Harry Ward, Christian Killow, Jim Hough - University of Glasgow for the LTP Optical Bench EM Team
Pre-investigations

The pre-investigation work had three main aims:

- Build a prototype optical bench using hydroxide catalysis bonding
  - Gain experience in the issues involved
- Install the bonding technology in RAL for EM build
  - Learn from prototype work
- Demonstrate the stability performance of the prototype optical bench
  - Also demonstrate the performance of LTP heterodyne interferometry
Prototype optical bench

- **Aim** - demonstrate the suitability of hydroxide catalysis bonding for the construction of the LTP and LISA optical benches
  - Build a test interferometer using hydroxide catalysis bonding
    - Study the procurement and alignment issues involved in constructing a bonded interferometer
  - Demonstrate the displacement stability at as close to the LTP displacement noise goal as possible

- **Approach**
  - Rigid interferometer – no moveable mirrors
  - Non-polarising heterodyne interferometer
  - Simplest possible layout
  - Zerodur baseplate, fused silica beamsplitters and mirrors
Heterodyne interferometry

- Original laser frequency shifted by 2 acousto-optic modulators (aoms)

- This generates 2 laser beams with a known frequency offset $\Delta \nu$

- At each photodiode we get a signal at a frequency $\Delta \nu$

- Output signal is the phase difference between $R$ and $M$ of the signal at $\Delta \nu$
Interferometry tests

Optical bench in vacuum tank

Phasemeter

Laser beam preparation bench

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Stopwatch Phase Measurement System

- **Aim**
  - Verify performance of optical bench
  - Simple lab based system
- **Want to measure phase of** $M$ relative to $R$
- Digitally count number of cycles of a fast clock during $t$ and $T$, signal $\phi = 2\pi t/T$

- **Potential noise sources**
  - Quantisation noise can be sufficiently low ($\sim 10^{-6}$ cycles/$\sqrt{\text{Hz}}$, ie $\sim 1\text{pm}/\sqrt{\text{Hz}}$) with a fast clock frequency of $\sim 100\text{MHz}$ and a heterodyne frequency of $\sim 100\text{kHz}$
  - Shot noise is irrelevant with the mW laser powers that are likely to be used
  - Care needs to be taken to keep phase changes in the analog electronics at a sufficiently low level

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Early interferometer performance

- Significant coupling of laser frequency noise
  - Coupling due to slight inequality of path lengths in the interferometer
  - Effect can be eliminated in post-processing or by laser frequency stabilisation
  - Some excess noise peaks remain around a few mHz

Excess noise “plateau” at <100mHz
Laser frequency stabilisation

- Laser frequency noise significant at sensitivities close to LTP interferometry goal
  - Implement a laser frequency stabilisation control loop
- Sense using unequal arm length interferometer
  - Error signal from phasemeter (data rate 10 kHz)
    - Very simple logic on digital input signals to phasemeter produces output error signal (one inverter and 2 XOR gates)
  - Analog feedback to laser temperature and piezo on laser crystal
- Frequency noise reduced by >100@1Hz
  - Reduces frequency noise to negligible levels at all measurement frequencies
- Bandwidth few*100 Hz
  - Could be greater, but this is already sufficient
Performance with laser frequency stabilisation

- Green trace is with laser frequency stabilised but with a frequency modulation peak at 0.9 Hz
- Similar performance to laser frequency noise subtraction in post processing
- Temperature driven noise at 3mHz?
- Excess noise “plateau” at <100mHz
Optical and electrical heterodyne signals

Phase locked oscillators:
- 80.00 MHz
- 80.01 MHz
- 10 kHz

Optical bench:
- Photodiode output signals at 10 kHz
- Signal
- Freq.-noise
- Reference

Piezo drive

Electrical signal at 10 kHz

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Stabilise phase of reference heterodyne

- Sense phase difference between electrical heterodyne and optical heterodyne
  - Electrical heterodyne into another phasemeter channel
  - Error signal from phasemeter (data rate 10 kHz)
    - Same simple logic as for frequency stabilisation
- Stabilise optical heterodyne phase by feeding back to piezo driven mirror directing light into one optical fibre
  - Loop bandwidth 10Hz
    - Probably limited by mechanical resonance
  - Residual fluctuations $<\pm 20$ degrees
Results with fibre path stabilisation

- Differential fibre path lengths stabilised
- Laser frequency stabilised
- Meets LTP interferometry goal over almost complete measurement band
- Temperature driven noise around few mHz
Why does stabilising the reference optical heterodyne to the source oscillator make a difference?

- Generation of spurious signals on the outputs of the photodetectors
  - at the heterodyne frequency
  - phase locked to the source oscillator
  - Unstable with respect to the optical heterodyne
Excess noise coupling

- Excess noise at <0.1 Hz caused by a combination of:
  - Spurious signal at the heterodyne frequency
  - Changing relative phase of optical and electrical heterodynes ("fibre" noise)
Possible causes of spurious signal-1

- Direct electrical interference into photodiode front ends at the heterodyne frequency (10 kHz)
  - Excluded after investigation

- Amplitude modulation of the diffracted light observed at the 80MHz rf frequency and multiples thereof, typically $\sim 10^{-3}$
  - In principle these signals should not produce 10kHz beat signals but undesired nonlinearities in the photodiode front end may allow the generation of a 10kHz beat
  - Such additional beats only present when the beams are recombined and are therefore invisible, being masked by the much larger heterodyne signal
Possible causes of spurious signal-2

- Electrical cross talk of rf signals resulting in each AOM being driven by a small amount of the rf signal intended for the other AOM
  - Observed as a 10kHz beat in light from a single AOM
    - ~90dB below main heterodyne signal size
  - Does not seem to be straightforward to further reduce this coupling significantly in our experimental configuration

Crosstalk at around -120dB

LASER

AOM

80.00 MHz

AOM

80.01 MHz

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Differential fibre-path stabilisation

- First attempt
  - PZT driven mirror on beam preparation bench
  - Works, but not suitable for LTP

- Second approach - fibre heating
  - Resistance wire wrapped round fibres
  - Works with lower bandwidth (4 Hz)
  - Currently adopted solution for LTP

Optical fibre (blue cladding)
Nichrome heater wire
Results

- Meets LTP and LISA stability goals over the whole frequency range...
- ...apart from some excess noise around few mHz
- Temperature driven effects
  - Consistent with expected effects in transmissive optics
  - Bench stability in lab. ~mK/rt(Hz)
  - LISA stability µk/rt(Hz)

Performance measured using Hannover phasemeter
Conclusions

- Prototype optical bench built
  - Lessons learned for EM build
  - (See posters on LPF EM Optical Bench)
- Optical bench stability
  - LTP and LISA
- LTP interferometry demonstrated
  - Laser frequency stabilisation
  - Unexpected noise source identified
  - Amelioration strategy demonstrated
    - Fibre path feedback
    - Necessary for performance demonstration on EM
- LTP compatible feedback demonstrated
  - Temperature feedback