Multi-target CW interferometric acoustic measurements on a single optical beam

YA ZHANG,1 CHATHURA P. BANDUTUNGA,1,* MALCOLM B. GRAY,2 AND JONG H. CHOW1

1Center for Gravitational Physics, Department of Quantum Science, Building 38, Research School of Physics and Engineering, Australian National University, Canberra, Australia
2National Measurement Institute, Bradfield Rd., Lindfield, 2070, Australia
*chathura.bandutunga@anu.edu.au

Abstract: We present a free-space, continuous-wave laser interferometric system capable of multi-target dynamic phase measurement at acoustic frequencies up to a Nyquist bandwidth of 10.2 kHz. The system uses Digitally-enhanced Heterodyne Interferometry to range gate acoustic signals simultaneously from multiple in-line reflections while isolating coherent cross-talk between them. We demonstrate sub-nanometer displacement sensitivity across the audio band for each individual reflection surface and 1.2 m resolution between successive surfaces. Signals outside the 1.2 m range-gate of the system were suppressed by greater than 30 dB in amplitude, enabling high fidelity independent acoustic measurements.

© 2019 Optical Society of America under the terms of the OSA Open Access Publishing Agreement

1. Introduction

A well-known technical challenge in high precision interferometric measurement has been the management of spurious noise due to unwanted coherent reflections. For extraction of signals from single point reflections, mitigation strategies such as anti-reflection coatings and oblique incidence angles may be used to reduce coupling of spurious optical interference. However, in the presence of persistent parasitic reflection or backscatter, these strategies no longer apply, and gating techniques need to be employed to isolate the signal of interest. In this work we use Digital Interferometry to demonstrate, in an in-line optical system, a multi-target continuous wave interferometric readout of dynamic phase and displacement signals at acoustic frequencies while rejecting spurious interference.

Multiplexing architectures have been developed to meet the fast data transfer requirements of modern communication systems. These techniques exploit one or more properties of an optical system to allow for simultaneous transmission of multiple channels of information, and can be broadly separated into two categories. Time-domain phase interrogation methods rely on pulsed or swept sources, with spatial resolution limited by the physical pulse width [1] or sweep period [2, 3]. This enables gating of optical signals, allowing for both multiplexed readout and rejection of spurious interference. The bandwidth of these systems however is limited by the repetition rate, and averaging time required to extract phase information, reducing the measurement duty cycle [4, 5]. These hardware constraints present a challenge when adapting these methods for continuous readout at acoustic frequencies.

Multiplexed acoustic measurements have also been demonstrated using wavelength division multiplexing techniques. These use spectral separation of signals to enable multiplexed, continuous wave interferometric measurements. Such techniques have the required measurement bandwidth and sensitivity for acoustic sensing, as demonstrated by hydrophone and geophone arrays [6–11]. However, the scalability of these systems also presents a challenge as each channel requires its own transceiver. In applications that require large numbers of sensors, the increase in both optical complexity and hardware cost can become prohibitive.

In this work we utilize the multiplexing capabilities of a continuous wave technique; Digital
Interferometry (DI) [12]. The technique exploits the autocorrelation property of unique pseudo-random codes to enable time-of-flight gating of continuous wave signals, with the additional benefit of spurious interference rejection afforded by spread spectrum modulation. While similar to RM-CW LIDAR techniques [13, 14], DI builds on the fundamental principle of heterodyne interferometry to retain the high displacement sensitivity seen in interferometric sensors [15]. This allows the optical complexity and multiplexing to be transferred into the digital signal processing realm [16]. As a result, DI systems are both optically simple and robust, enabling deployment for field applications.

Earlier demonstrations of DI have shown picometer displacement sensitivities and the ability to isolate up to three unique displacement signals at infrasonic frequencies [15, 17]. In this work we extend the DI bandwidth to acoustic frequencies, and demonstrate simultaneous, multi-channel signal extraction in a free-space optical system. We show the separation of audio-band displacement signals from four in-line reflection surfaces, with sufficient fidelity and isolation for applications in perimeter monitoring and surveillance.

2. Experimental demonstration

In the experimental setup shown in Fig. 1, we isolate and measure the phase and subsequently displacement of four in-line reflective surfaces up to a Nyquist frequency of 10.2 kHz. The system used an Orbits Lightwave 1550 nm fibre coupled laser, split between an interrogation arm and a local oscillator. The local oscillator (LO) was frequency shifted by 40 MHz using an Interaction acousto-optic modulator (AOM), producing a heterodyne beat note which was demodulated at the output. The heterodyne beat note was spectrally broadened using a pseudo random noise (PRN) code, which was phase modulated onto the interrogation arm by a Photline 10 GHz bandwidth electro-optic modulator (EOM). In post-processing, the PRN code was demodulated by correlating the received spread-spectrum signal against a digital copy of the PRN code. By applying a pre-determined delay to the demodulation code, we recover the heterodyne beat note for the optical time-of-flight corresponding to that delay. The spatial resolution of the gating is dependent on the symbol rate of the modulated code. The symbol (chip) frequency of the PRN code in this demonstration was 125 MHz, corresponding to a 1.2 m spatial resolution. Once tagged with the PRN code, the interrogation arm was launched as a free-space beam which interrogated the target reflectors.

The generation of the local oscillator drive signal and PRN code was handled by a high speed Virtex-5 field-programmable gate array (FPGA) coupled with high speed digital-to-analog converters (DACs) operating at 500 MS/s. Following the digitization of the photodetector output at 250 MS/s, the FPGA was used to apply the delayed decoding PRN code to recover the heterodyne beat note, which was subsequently demodulated using an IQ demodulation. Phase extraction through an arctangent operation and data recording was handled by a networked computer.

The optical setup for this experiment was constructed on a mechanically dampened optical bench using reflection coated glass plates to act as intermediate reflection surfaces, shown in Fig. 1. All three reflectors were mounted on low voltage piezo-electric transducers, allowing for the injection of up to three unique acoustic signals into the system. A fourth reference reflection was extracted from the collimator front surface. The four reflectors were then mechanically isolated from each other by mounting two of the piezo mounted plates onto individual Sorbothane isolated breadboards to reduce mechanical cross-coupling between reflectors.

Each reflector in the interrogation arm was driven by a unique audio frequency signal through the piezo-electric transducer and the resultant displacement was measured using the induced optical phase shift. To do this, we measure the spread spectrum signal at the photodetector containing phase information from all reflectors. On the FPGA, multiple demodulation PRN codes were generated simultaneously, each at differing delays, allowing for the concurrent demodulation
Fig. 1. The experimental layout can be split into the input optics, free-space optics and digital components. The input optics, including both EOM for PRN phase modulation and AOM for LO frequency shifting, are fiber coupled. The collimator sends the PRN encoded interrogation beam through three free-space piezo actuated reflectors with Delays 2, 3 and 4, with the first reflection provided by retro-reflection from the collimator itself. The return signal is separated using a circulator and recombined with the LO before detection. After digitization, the heterodyne signals A, B and C for each reflection are recovered by mixing with appropriately delayed PRN codes. The recovered heterodyne beat notes are passed to separate IQ demodulation processes. This is done in parallel for all four reflections, all in real-time on a FPGA. The IQ demodulation output is passed to a networked host computer and recorded to disk, and in post-processing the phase is recovered.

of multiple reflection surfaces. This allowed for the simultaneous phase measurements to be made between the reference reflector and three signal reflectors. Although a total of four simultaneous demodulation channels were demonstrated in this work, this number was not a limit of the signal processing and further demodulation channels may be added as required.

3. Acoustic signal extraction and cross-talk

With this experimental setup we demonstrate the isolation and reproduction of three unique audio signals played during one simultaneous measurement. Improving on previous work [15, 17–19], the experiment was able to increase the measurement bandwidth of a digitally enhanced readout by approximately two orders of magnitude, up to a 10.2 kHz Nyquist frequency. It is in principle possible to demonstrate ultrasonic sensing with this setup, up to 2 MHz, but buffering constraints when recording extended data sets currently poses a technical limit.

The initial audio demonstration is presented in Visualization 1, which highlights the isolation of each channel. In this demonstration, we compare the digital interferometric readout with a traditional heterodyne measurement, which was carried out under the same experimental conditions with the exception of the DI modulation. Through the demonstration, we hear both channel isolation and removal of spurious interference effects such as fading.

As with any multiplexed system, one of the primary limits of a digital interferometric readout is the crosstalk between separate channels. In digital interferometry, the suppression of extra signals is dependent on the length of the PRN sequence used, the averaging time and the ratio between the heterodyne and PRN frequencies [12]. Given the parameters used in our system, the
maximum suppression of residual phase signals is predicted to scale according to Eq. (1) [12].

\[
\Phi_R = -20 \log_{10} \left( \frac{2}{\pi \sqrt{N}} \right) \text{dB} \tag{1}
\]

In Eq. (1), \(N\) corresponds with the length of the PRN sequence used. For this experiment, a 2047 element code was used, leading to a predicted maximum suppression of 37.03 dB.

The crosstalk of the acoustic setup was characterized by injecting single frequency sinusoidal tones through the three separate piezo inputs. In Fig. 2 we plot the resultant amplitude spectral density of each channel, zooming in at 5800 Hz for Signal A, 1257 Hz for Signal B and 2115 Hz for Signal C, and quantify the suppression of all other channels relative to the signal of interest. We see 31 ± 4 dB of suppression on Channel 2, 35 ± 2 dB on Channel 3 and 31 ± 2 dB on Channel 4.

![Fig. 2](image-url)  
Fig. 2. The amplitude spectral density of three injected sinusoidal tones into the system, at 5800 Hz, 1257 Hz and 2115 Hz respectively. The three subplots, Fig. 2(a) shows the coupling from Channel 2, 2(b) from Channel 3 and 2(c) from Channel 4 into the other channels. By comparing the signal amplitude between the injection channel and background channels, the crosstalk was quantified. The measured crosstalk agrees with the expected cross-talk suppression from digital interferometry.

This measurement coincides with the predicted crosstalk suppression from Eq. (1) for Channel 2 and 3. The higher coupling in Channel 4 was determined to be due to direct mechanical coupling between it and other optical components on the table. This was measured through a mechanical isolation test where the last piezo mirror was optically blocked and driven with a sinusoidal signal. The response was measured in the remaining optically active channels. As there was no optical interaction, the residual coupling can be attributed solely to mechanical coupling from Channel 4. Comparing this with the optical response of Channel 4, we measured 32 dB of suppression from direct mechanical coupling. This confirmed mechanical coupling to be a major source of crosstalk from Channel 4.

### 4. Frequency response and displacement sensitivity

As with all acoustic sensors, the frequency response of the system is critical for accurate reproduction of acoustic signals. In this system, the piezo actuated reflectors all had unique transfer functions with fundamental resonances below 1 kHz. The transfer function of the readout itself however was flat over the measurement bandwidth and is shown in trace (a) of Fig. 3 with the transfer function of Channel 2-4 shown in trace (b)-(d) for comparison.
The transfer functions were measured by injecting white noise into the system. The readout transfer function was measured by phase modulating the local oscillator AOM to provide a direct differential phase shift. The piezo-reflector transfer functions were measured by directly injecting a white noise signal for displacement. In the latter case, the dominant limitation on the frequency response is therefore the transducer used to couple the acoustic signal into a physical displacement.

As the transducer properties will be dependent on the application, the displacement sensitivity of the readout will determine compatibility with different transducers. A better displacement sensitivity would allow for signal extraction from lower response, poorly impedance matched acoustic transducers. The displacement sensitivity of the device was measured by calculating the amplitude spectral density of the phase noise, shown in Fig. 4, and calibrating to provide a noise equivalent displacement. The data was recorded under normal laboratory conditions, without any injected signals. We can see acoustic band pickup from 4 Hz to 1.5 kHz on the free-space channels, corresponding with ambient noise in the laboratory. This is reduced for Channel 4 which had a larger inertial mass and therefore lower coupling. This pickup is altogether removed for Channel 1 which corresponds with a measurement of the lead fiber noise in the system.

Below 10 Hz we see a low frequency roll up in the noise equivalent displacement. This is attributed to laser frequency noise, which was independently measured using a fiber frequency reference [20]. As previous demonstrations have shown, measurements from successive reflections may be combined with Time-Delay interferometry to remove common laser frequency noise [17, 21]. Above 10 Hz we demonstrate similar performance to other DI systems reaching a noise floor on the order of $80\mu$rad/$\sqrt{\text{Hz}}$ in phase, corresponding to a displacement sensitivity of 10pm/$\sqrt{\text{Hz}}$ [15].

While we demonstrate single point phase measurements, in adapting this architecture for
Fig. 4. Amplitude spectral density measurement of the noise floor for each individual channel. Trace (a) shows the lead fiber noise measured on Channel 1. Traces (b), (c) and (d) correspond with the free-space reflectors, with (d) having higher inertial mass, and therefore lower coupling of environmental noise. We see the ambient audio band pickup on all channels between 10 Hz and 1 kHz. The low frequency roll up below 10 Hz was measured to be laser frequency noise. The high frequency noise floor reaches a displacement sensitivity on the order of $10 \text{ pm/} \sqrt{\text{Hz}}$.

Atmospheric or perimeter monitoring applications, consideration must be given to the effect of distributed noise sources. These noise sources, including back-scattering from particulates such as dust or aerosols, can lead to cyclic phase errors similar to those seen in fiber interferometers [22]. Here, the temporal gating afforded using digital interferometry suppresses coherent interference from scattering outside 1 PRN symbol of the target reflection. The gating is a function of the PRN modulation frequency, and can be improved by increasing it.

5. Conclusion

In this paper, we have demonstrated a multiplexed interferometric readout of four measurement channels, showing isolation of three audio band signals using Digitally enhanced Heterodyne interferometry. We achieve a flat readout frequency response and DI limited crosstalk performance over a 10.2 kHz Nyquist bandwidth. This bandwidth is only limited by computational and data acquisition speeds and can be scaled in order to accommodate higher frequency signals or more readout channels. As an interferometric technique, we achieve sensitivities better than $10 \text{ pm/} \sqrt{\text{Hz}}$ above 10 Hz, allowing for high fidelity recordings to be made whilst using low response acoustic transducers. At present the spatial separation of our acoustic signal source needs to be larger than 1.2 m as dictated by our PRN chip frequency and hence our range gate. With higher chip frequencies, multi-point acoustic sensing is possible in centimeter scale structures.

Funding

Australian Government Research Training Program (RTP) Scholarship.
References

1. A. Rosenthal, D. Razansky, and V. Ntziachristos, “Wideband optical sensing using pulse interferometry,” Opt. Express 20, 19016–19029 (2012).
2. J. Zheng, “Triple-sensor multiplexed frequency-modulated continuous-wave interferometric fiber-optic displacement sensor,” Appl. Opt. 46, 2189–2196 (2007).
3. H. Gabai, I. Steinberg, and A. Eyal, “Multiplexing of fiber-optic ultrasound sensors via swept frequency interferometry,” Opt. Express 23, 18915–18924 (2015).
4. J. Chen, Q. Liu, and Z. He, “Time-domain multiplexed high resolution fiber optics strain sensor system based on temporal response of fiber fabry-perot interferometers,” Opt. Express 25, 21914–21925 (2017).
5. T. Liao, M. Hameed, and R. Hui, “Bandwidth efficient coherent lidar based on phase-diversity detection,” Appl. Opt. 54, 3157–3161 (2015).
6. S. Goodman, S. Foster, J. V. Velzen, and H. Mendis, “Field demonstration of a dfb fibre laser hydrophone seabed array in jervis bay, australia,” in Proc. SPIE 7503, 20th International Conference on Optical Fibre Sensors, vol. 7503 (2009).
7. S. Foster, A. Tikhomirov, J. Harrison, and J. van Velzen, “Demonstration of an advanced fibre laser hydrophone array in gulf st vincent,” in Proc. SPIE 9634, 24th International Conference on Optical Fibre Sensors, vol. 9634 (2015).
8. I. C. M. Littler, M. B. Gray, J. H. Chow, D. A. Shaddock, and D. E. McClelland, “Pico-strain multiplexed fiber optic sensor array operating down to infra-sonic frequencies,” Opt. Express 17, 11077–11087 (2009).
9. I. C. M. Littler, J. H. Chow, D. A. Shaddock, D. E. McClelland, and M. B. Gray, “Multiplexed fiber optic acoustic sensors in a 120 km loop using rf modulation,” in Proc. SPIE 6770, Fiber Optic Sensors and Applications V, vol. 6770 (2007).
10. I. C. M. Littler, J. H. Chow, D. A. Shaddock, D. E. McClelland, and M. B. Gray, “Multiplexed fiber optic sensor array for geophysical survey,” in Proc. SPIE 7004, 19th International Conference on Optical Fibre Sensors, vol. 7004 (2008).
11. I. C. M. Littler, M. B. Gray, T. T. Lam, J. H. Chow, D. A. Shaddock, and D. E. McClelland, “Optical-fiber accelerometer array: Nano-g infrasonic operation in a passive 100 km loop,” IEEE Sensors J. 10, 1117–1124 (2010).
12. D. A. Shaddock, “Digitally enhanced heterodyne interferometry,” Opt. Lett. 32, 3355–3357 (2007).
13. J. L. Machol, “Comparison of the pseudorandom noise code and pulsed direct-detection lidars for atmospheric probing,” Appl. Opt. 36, 6021–6023 (1997).
14. N. Takeuchi, H. Baba, K. Sakurai, and T. Ueno, “Diode-laser random-modulation cw lidar,” Appl. Opt. 25, 63–67 (1986).
15. G. de Vine, D. S. Rabeling, B. J. J. Slagmolen, T. T.-Y. Lam, S. Chua, D. M. Wuchenich, D. E. McClelland, and D. A. Shaddock, “Picometer level displacement metrology with digitally enhanced heterodyne interferometry,” Opt. Express 17, 828–837 (2009).
16. L. E. Roberts, R. L. Ward, A. J. Sutton, R. Fleddermann, G. de Vine, E. A. Malikides, D. M. R. Wuchenich, D. E. McClelland, and D. A. Shaddock, “Coherent beam combining using a 2d internally sensed optical phased array,” Appl. Opt. 53, 4881–4885 (2014).
17. D. M. R. Wuchenich, T. T.-Y. Lam, J. H. Chow, D. E. McClelland, and D. A. Shaddock, “Laser frequency noise immunity in multiplexed displacement sensing,” Opt. Lett. 36, 672–674 (2011).
18. A. Sutton, D. M. R. Wuchenich, T. T. Lam, and D. A. Shaddock, “Digital enhanced homodyne interferometry for high precision metrology,” in Proceedings of the International Quantum Electronics Conference and Conference on Lasers and Electro-Optics Pacific Rim 2011, (Optical Society of America, 2011), p. C770.
19. K.-S. Isleif, O. Gerberding, S. Köhlenbeck, A. Sutton, B. Sheard, S. Gößler, D. Shaddock, G. Heinzel, and K. Danzmann, “Highspeed multiplexed heterodyne interferometry,” Opt. Express 22, 24689–24696 (2014).
20. T. G. McRae, S. Ngo, D. A. Shaddock, M. T. L. Hsu, and M. B. Gray, “Digitally enhanced optical fiber frequency reference,” Opt. Lett. 39, 1752–1755 (2014).
21. S. P. Francis, D. A. Shaddock, A. J. Sutton, G. de Vine, B. Ware, R. E. Spero, W. M. Klipstein, and K. McKenzie, “Tone-assisted time delay interferometry on grace follow-on,” Phys. Rev. D 92, 012005 (2015).
22. S. Ngo, D. A. Shaddock, T. G. McRae, T. T.-Y. Lam, J. H. Chow, and M. B. Gray, “Suppressing rayleigh backscatter and code noise from all-fiber digital interferometers,” Opt. Lett. 41, 84–87 (2016).