

**Fundamental standards for
acoustics based on optical
methods – Phase two report
for sound in water**

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FUNDAMENTAL STANDARDS FOR ACOUSTICS BASED ON OPTICAL METHODS – PHASE TWO REPORT FOR SOUND IN WATER

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ABSTRACT

This report documents the progress of work towards the development of fundamental standards for acoustics based on optical methods for sound in water between 1 kHz and 500 kHz. The favoured approach for achieving this is particle velocity measurement using heterodyne interferometry and a reflecting membrane in the acoustic field. The report focuses on the development of a new optical configuration based on an all-fibre interferometer system and presents some initial result obtained using an early prototype of this system.

A review of current progress on the project is also presented with recommendations made for the direction of work to be undertaken in the third phase of the project. This report is the Deliverable for the Phase Two Work Package for Project 3.6 of the NMS Quantum Metrology Programme for the UK Department of Trade and Industry. The sound in water aspect of the project is being undertaken by a consortium of the National Physical Laboratory and Loughborough University, with Laser Optical Engineering Ltd. as a sub-contractor.

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1 INTRODUCTION

1.1 Project details

This project aims to lay the foundation for a new generation of primary acoustical measurement standards based on optical techniques for both sound in air and sound in water. The project entitled ‘Fundamental standards for acoustics based on optical methods’ is Project 3.6 of the National Measurement System (NMS) Quantum Metrology Programme of the UK Department of Trade and Industry. The project is being undertaken by a consortium of the National Physical Laboratory (NPL), Loughborough University (LU), Edinburgh University (EU), with Laser Optical Engineering Ltd. (LOE) and QinetiQ as sub-contractors. This report details progress on Phase Two of the project and addresses only the sound in water aspect of the project for which the project team consists of NPL, LU and LOE.

The first six months of the project work was reported in the first stage report [1], which included a comprehensive review of the literature, detailed the requirements for new sound in water standards, the reasons for using optical methods and proposed laser heterodyne interferometry for laser Doppler measurement using a reflecting membrane in the acoustic field for water as the most suitable method.

1.2 Background

1.2.1 Reciprocity hydrophone calibration

As described in the stage one report [1], the current primary standard calibration method for hydrophones used in underwater acoustics is the three-transducer spherical-wave reciprocity method [2]. Although this method is long established and widely used, in terms of a primary standard it has a number of limitations:

- It is reliant on at least one of the hydrophones being reciprocal (i.e. linear, passive and reversible), a difficult thing to prove in practice to better than 1% or 2%.
- The method depends on assumptions about the geometry of the acoustic field, for example that it is spherically spreading. This is sometimes difficult to achieve in a laboratory tank.
- The method does not make a direct measurement of an acoustical quantity, and hence does not directly establish the SI unit of acoustic pressure.

In the frequency range 1 kHz to 500 kHz, the overall uncertainties in the reciprocity method are of the order of 5% (expressed for a 95% confidence level). Whilst this level of accuracy meets the needs of many current industrial customers, for the most demanding requirements there is a need to improve the absolute accuracy by a factor of two. Furthermore, there is currently little “headroom” between existing primary standards and the uncertainties of approximately 0.5 dB to 1 dB sought by the majority of users.

1.2.2 Laser Doppler method of acoustic measurement

In order to perform a free-field calibration of a hydrophone, it must be exposed to a known acoustic pressure, p , in a plane-wave field at the position of the hydrophone before it was introduced. Although interferometry does not provide a direct measure of acoustic pressure, it

offers a method to measure directly, the acoustic particle velocity, u , from which the acoustic pressure can be derived using Equation (1) for a plane-wave acoustic field.

$$p = \rho c u \quad (1)$$

where ρ is the density of the medium and c is the speed of sound in the medium. Thus an acoustic pressure of 50 Pa is equivalent to an acoustic particle velocity of $30 \mu\text{m s}^{-1}$. Direct measurement of acoustic particle velocity can be achieved by employing a laser Doppler interferometric technique, where the interferometer is designed to be sensitive to a frequency shift between the reference arm and the measurement arm. The Doppler frequency shift, $\delta\nu$, can be related to the laser wavelength λ and the particle velocity vector u by the following equation [3]:

$$\delta\nu = \frac{2u}{\lambda} \cos \beta \cos \left(\frac{1}{2} \phi \right) \quad (2)$$

where β is the angle the velocity vector u makes with the bisector of the incident and reflected beams. In practice, the incident and reflected beams are aligned so that they traverse similar paths such that $\phi \rightarrow 0$. The Doppler shift can therefore be written as:

$$\delta\nu = \frac{2u}{\lambda} \cos \beta. \quad (3)$$

With knowledge of the laser wavelength, this Doppler beat frequency obtained from the detector allows determination of the absolute particle velocity.

The method for calibration would then be similar to the direct comparison method used at NPL for the calibration of hydrophones above 500 kHz [4].

1.2.3 Heterodyne interferometer options

The choice of interferometer design and configuration for this project has been dictated by a number of factors:

- The requirement for a measurement within the acoustic field.
- Complete understanding of signal processing.
- The ability to provide traceability to the wavelength of light via a quantified route.

As described in the Phase One Report [1], the desired method of acoustic pressure determination is the measurement of acoustic particle velocity, using a heterodyne interferometer with the measurement beam incident on a reflective, acoustically compliant membrane in the acoustic field. There are essentially three possible optical configurations of heterodyne interferometer that could be used:

1. A commercial bulk optic interferometer or vibrometer system.
2. A bulk optic interferometer with a fibre delivery system.
3. An all-fibre interferometer configuration.

In some cases, it may be possible to use an arrangement such that the laser beam can be directed through an optical window in a suitable water tank, thus allowing the use of a bulk optic heterodyne interferometer or commercial vibrometer. However, at lower acoustic frequencies, it is necessary that a larger tank be used (large NPL open tank measures 5 m by 5.5 m), making the optical window approach impractical. One solution to this problem is to physically place the optical head in the water, at the desired distance from the reflective membrane. With a bulk optic system, the size of the optical head would perturb the acoustic field, causing reflections and a subsequent reduction in the measurement time window. The use of a fibre delivery system integrated into a bulk optic system would allow the transmit and receive optics to remain in the acoustic field, with the bulk optical head removed from the water and operated remotely from the acoustic field. The transmit and receive optics would be much smaller than the bulk optical head and thus not perturb the acoustic field in the same way. The use of fibre delivery also opens up other opportunities for the use of interferometry in underwater acoustics. An example of this would be the use of interferometry in the NPL Acoustic Pressure Vessel (APV). The ability to make optical measurements in the APV would allow the characterisation of the acoustic field from a transducer to be made for a wide range of temperatures and hydrostatic pressures, which given a standard bulk optic system would be unrealisable.

Work with LOE on the design of a new optical configuration has created the opportunity to feed on experience gained in the optical communications field. The crossover in these scientific fields has enabled the consortium to consider what might be a ‘riskier’ option of implementing the interferometer optical configuration completely in fibre. This requires not only the use of optical fibre throughout, but also the use of ‘pigtailed’ optical components in place of bulk optical components. Although this is essentially an uncharted approach, it yields several areas for improvement over existing commercial systems. One major advantage of a complete fibre measurement system would be its potential robustness. Underwater measurement laboratories are not commonly the cleanest of environments and generally suffer from moisture content in the air. The use of a fibre optical configuration in the interferometer would make the system inherently tolerant to dusty or high moisture environmental conditions. Another advantage is the sensitivity gained by the use of ‘pigtailed’ photodiodes, which offer significant sensitivity gains by efficient collection over a small surface area. Designing the interferometer from the ground up has also allowed it to be optimised for the application of acoustic particle velocity measurement in water. An example of this is the use of a green (532 nm wavelength) laser rather than a red (633 nm wavelength) laser. Green light can propagate much farther through water than red, which for a propagation distance of 1 metre is subject to an absorption by scattering of 33% compared with only 7% for green. For applications in the large NPL tank this would be essential given that the required propagation distance could be up to 5 m to the reflective target and back. The heterodyne signal demodulation will also be focussed towards the relatively small Doppler shifts encountered in underwater acoustics compared with industrial vibrometry applications, which use commercial vibrometers capable of measuring velocities of several metres per second. The optical and signal processing design of the all-fibre heterodyne interferometer will be discussed in more detail in Section 3.

Ultimately, the aim of this project is to lay the foundations for a future primary standard for underwater measurement. For any primary standard it is essential that each stage of the measurement device be completely understood so that its effect on the overall output can be quantified. The hardware, software and signal processing used to correlate the physical target velocity to the dynamic output provided mean that a complicated transfer function exists.

Understanding this transfer function is critical if a heterodyne interferometer is to be used to form the basis of a primary standard for underwater measurement.

It is also vitally important that each stage can be calibrated so that the output velocity is traceable to standard units with established uncertainties. As can be seen from Equation (3), a direct measurement of the Doppler shift $\delta\nu$ at any instant in time provides an instantaneous measure of velocity that is traceable to the wavelength of light, thus to the standard metre. In reality, an uncertainty occurs in realising the Doppler shift at a point in time and in many commercial devices, the hardware and software signal processing used between the photodiodes and the output of the device make it exceedingly difficult to quantify accurately the uncertainties in measuring $\delta\nu$. A system developed in collaboration with NPL provides the opportunity for a complete analysis of each component/stage and would further provide the opportunity for calibration against electrical standards that are several orders of magnitude more accurate than required acoustically. This would allow a complete understanding of the transfer function of the interferometer, with the traceability provided to the wavelength of light with established uncertainties.

1.3 Outline of report

The structure of the report is as follows. Chapter 2 explains the principles of heterodyne interferometry and how it can be employed for acoustic measurement. It introduces FM theory and how demodulation techniques can be used to obtain acoustical information from the laser Doppler shift in the interferometer. Chapter 3 gives a detailed overview of the all-fibre heterodyne interferometer being developed as part of this project, offering a detailed description of the design and development stages of the device. It goes on to set out some testing and experimental results obtained using the prototype version of the all-fibre interferometer in the small NPL test tank. Chapter 4 considers the other studies underway for the sound in water work and its future direction. This includes work planned for the project guest worker, Wang Yuebing from the Hangzhou Applied Acoustics Research Institute (HAARI), and also considers the implementation of optical configurations that would allow in-fibre correction for any external disturbance along the fibre path to be made.

The final chapter briefly reviews the achievements of Phase 2 of the project and makes recommendations for Phase 3. In particular, it suggests how best to achieve the objectives in Phase 3 and what the issues might arise during the delivery of the particular objectives.

2 HETERODYNE INTERFEROMETRY

2.1 Introduction

Interferometers used for acoustic or vibration measurement can be broadly described as either an optical phase device which determines the target displacement by interference of the target beam with a fixed length reference beam or as a Doppler device which by detecting changes in frequency of the reflected light can provide a measure of the target velocity. The first type is most commonly employed as a homodyne Michelson interferometer similar to that used for the calibration of hydrophones above 500 kHz [4]. The second type, which is commercially referred to as Laser Doppler Vibrometry (LDV) differs from a displacement homodyne interferometer in two main respects. Firstly, the reference beam is optically frequency shifted or heterodyned. Secondly, it is the Doppler shift imparted on the laser light that is determined and not the path length change in the returning beam. Optical frequency shifting is commonly achieved using an acousto-optic device such as a Bragg cell placed in the path of the reference beam. A typical bulk optic heterodyne configuration showing both the optical components and the signal processing units is depicted in Figure 1. The required signal processing indicated in Figure 1 is discussed further in this Section and Section 2.2.

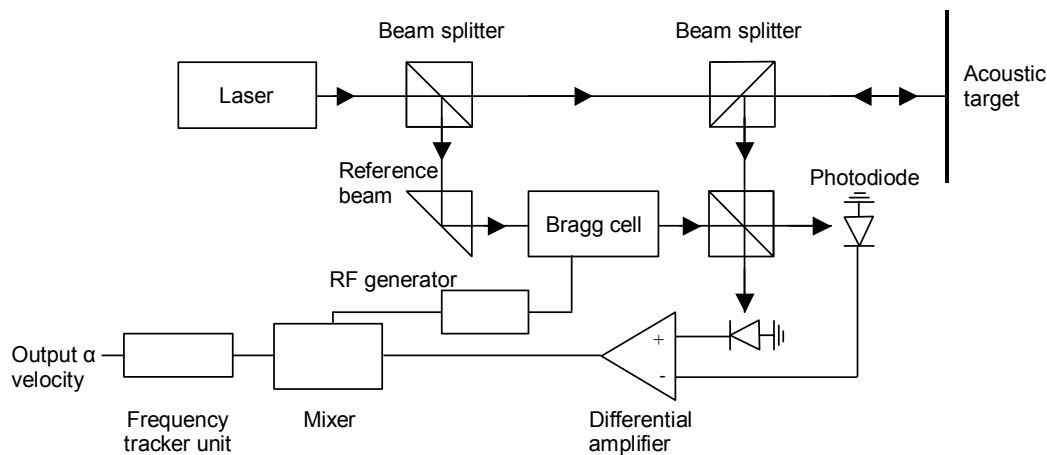


Figure 1. Typical bulk optic configuration of a heterodyne interferometer.

During a measurement, the returning laser beam from the target undergoes a frequency shift from the moving target. If the target is moving towards the laser beam, then the imparted Doppler shift will be positive; thus the returning laser light from the target is of a higher frequency than that of the reference beam. The difference between the beams is referred to as the beat frequency or Doppler shift. In the reverse case, where the target is moving away from the laser beam, the returning light from the target will be of a frequency less than that of the reference beam.

However, the imparted frequency shift on the laser light is very small compared to the frequency of the laser light, which is higher than the response speed of many photodiodes. It is therefore common to use an optical frequency shifter to shift the reference beam to a more manageable frequency on which the Doppler shift can be carried.

Shifting the reference beam by an amount greater than the maximum Doppler shift imparted by the target, will allow the direction of the target motion to be determined. The resultant frequency observed by the photodiode at any instant in time will be either above or below the

shift frequency applied to the reference beam, which it is centred on or carried by. In practice, the frequency shift is usually large, up in the Radio Frequency (RF) region and subsequently mixed down to a more suitable frequency for processing. This approach is shown in Figure 1 and discussed further in Section 2.2.

The main reason for using heterodyne interferometer approach over the homodyne displacement interferometer is that the homodyne device has an inherently limited dynamic range. Of course, the fact that the heterodyne device can provide a direct measure of velocity is a major advantage.

The Michelson small displacement interferometer uses phase locking techniques to determine the light intensity on the ‘zero crossing’ linear section of a fringe. For small changes in target displacement, a small change in phase between the reference and measurement beams will result in a drift across the linear section of the fringe where the light intensity (or photodiode voltage) is proportional to the target displacement. However, if the target displacement exceeds the linear range of the fringe, the light intensity and thus the photodiode voltage will no longer be in direct proportion to the target displacement. Its range of operation is therefore limited to displacements that are a fraction of a fringe, where the fringe corresponds to half the wavelength of the laser light. The linear operational limit for a Helium-Neon based Michelson interferometer with a wavelength of 633 nm would usually be around 80 nm peak-peak. This limited linear range also makes the Michelson interferometer particularly susceptible to large amplitude vibration. The presence of large amplitude vibrations that exceed the linear range of the interferometer mean that the signal cannot simply be filtered to obtain the desired acoustic signal, as the interferometer would be operating non-linearly. The use of phase locking can be used to overcome this for low frequency, large amplitude vibrations. However, phase locking can become ineffective if lateral vibration takes place such that the returned light level undergoes a change. This could occur because of small surface imperfections or because of lateral movements of optical components.

Since the heterodyne interferometer approach considers the Doppler shift imparted by the target and not the path length change to the target, it is not limited by this linear regime. This not only allows it to measure velocities that correspond to large displacements, but also means that it is inherently more robust in the presence of vibration. Decoding the frequency modulated carrier frequency and providing a voltage output that is proportional to the Doppler shift allows the acoustic signal, in principle, to be accurately reconstructed in the presence of intensity modulation or other amplitude variations at the receiving photodiodes. Such intensity variations can commonly be caused by intensity instabilities in the laser and varying light level return from the target. In the case of a displacement interferometer any intensity variations would be undesirable as the sensitivity of the interferometer is directly proportional to the light intensity.

2.2 Principles of Doppler measurement

As described in Section 2.1, the use of a heterodyne arrangement allows directional discrimination of the target velocity. This can be done as the frequency modulated (FM) signal will enable the Doppler shift to be determined as either a positive or negative component, centred around the carrier frequency, f_s (reference arm shift). For a sinusoidal target displacement amplitude a ($a(t) = a_0 \cos(2\pi ft)$), it has been shown [3] that the output of a heterodyne interferometer can be described by,

$$V = V_0 \cos\left(2\pi f_s t + \frac{4\pi a_0}{\lambda} \cos 2\pi f t\right) \quad (4)$$

where f is the acoustic frequency of the target, λ is the optical wavelength and t is the time. V_0 is a constant determined by the sensitivity of the photodetectors and the overall gain of the system. For small displacements, the sidebands produced at multiples of the acoustic frequency, either side of the carrier or shift frequency, are proportional in amplitude to that of the target displacement. Figure 2 shows the spectrum produced by Equation (4) for an acoustic frequency of $f = 3$ kHz and a shift/carrier frequency $f_s = 25$ kHz. In this case the laser wavelength is $\lambda = 532$ nm and the target displacement amplitude is $a_0 = 30$ nm. As an arbitrary case, a value of unity is given to V_0 .

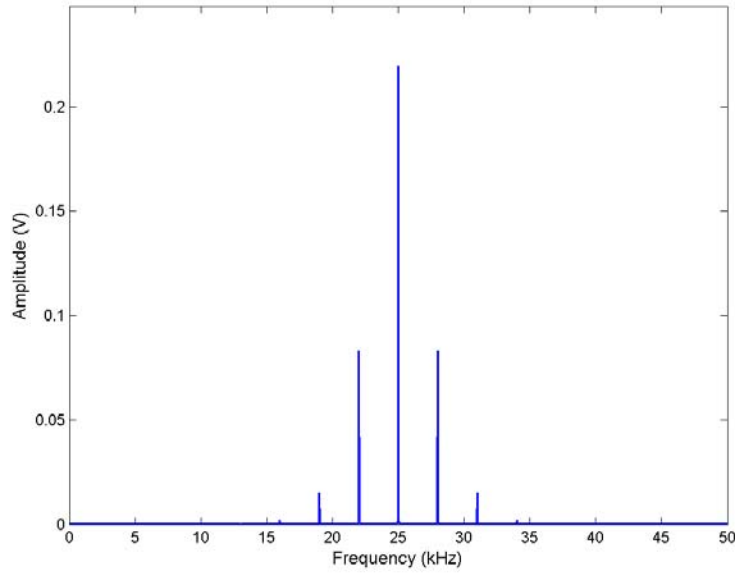


Figure 2. Heterodyne spectrum showing sideband spaced at the 3 kHz acoustic spacing around the 25 kHz carrier frequency.

The target velocity from a heterodyne interferometer or LDV can also be determined, which does not have the small dynamic range limitation of the displacement method. Velocity determination can be achieved by demodulation of the carrier signal. Under general FM theory, the shift frequency of the reference beam is referred to as the ‘carrier’ frequency and the acoustic frequency is referred to as the ‘signal’ frequency or the ‘modulating’ frequency, where the velocity or Doppler determines the ‘depth’ of modulation.

The resultant FM signal produced in the case described above and shown in Figure 2 is plotted in Figure 3a. Although not obvious from Figure 3a, the carrier frequency is varying between $f_s + \delta\nu$ and $f_s - \delta\nu$ at the cyclic rate of the target (acoustic frequency). The demodulated signal is also plotted in Figure 3b to demonstrate this, with the plot corrected for the maximum Doppler shift using Equation (3) and then plotted around the 25 kHz shift frequency. It can be seen from Figure 3b that the 30 nm displacement results in a peak Doppler shift of just over 2 kHz.

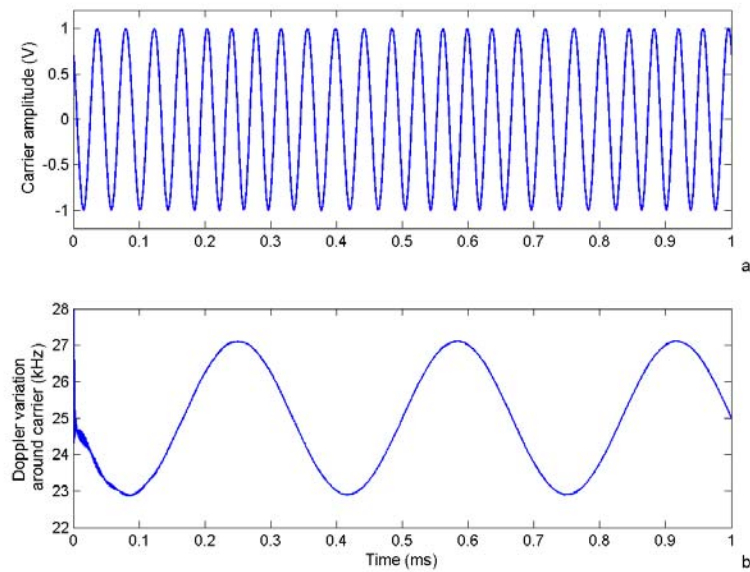


Figure 3. a) Simulated FM signal similar to that produced by a heterodyne interferometer for a target displacement of 30 nm. b) Demodulated result of FM signal in Figure 3a.

The modulation depth, or the ratio of the maximum carrier deviation to modulation frequency, in Figure 3 is small and so the variation on the carrier is not obvious. To accentuate the Doppler variation, Figure 4 shows a similar plot with an increased modulation depth. The displacement has been increased to 85 nm with all other parameters remaining the same. It can clearly be seen how the lower frequencies in the FM waveform shown in Figure 4a correspond to negative Doppler frequencies (below the carrier frequency) in Figure 4b.

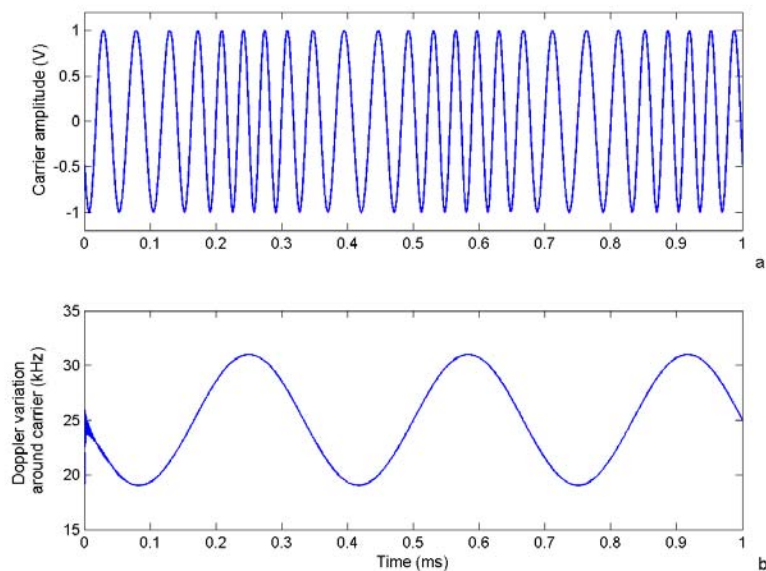


Figure 4. a) Simulated FM signal similar to that produced by a heterodyne interferometer for a target displacement of 85 nm. b) Demodulated result of FM signal in Figure 4a.

The demodulated signal shown in Figures 3b and 4b were obtained using the MATLAB 'demod' command provided in the Signal Processing Tool Box. This demodulates the FM waveform by modulating the Hilbert transform of the FM signal by a complex exponential of frequency $-f_s$ and obtains the instantaneous frequency of the result, as stated in the MATLAB

help guide. It can be seen at the beginning of each acoustic waveform in Figures 3b and 4b that there is some initial error associated with the software demodulation. The actual cause is unknown, although it is most probable that it is an effect of the Hilbert transform and should therefore not be present in the event that a hardware frequency tracker is used to demodulate the signal.

In practice, the acoustic signal and velocity would be extracted or decoded in real-time using frequency tracking techniques implemented in hardware. The most common method for achieving this is to use a phase-lock-loop (PLL) arrangement, which will provide an output voltage proportional to the instantaneous frequency or the difference between a reference frequency and the FM signal. A typical phase lock loop arrangement is depicted in Figure 5.

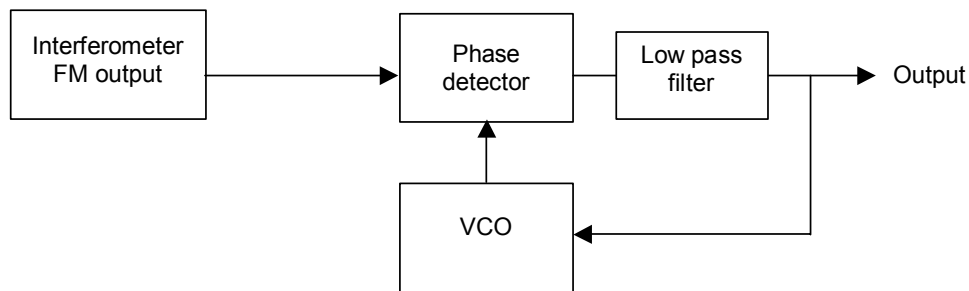


Figure 5. Typical phase lock loop arrangement.

This would generally be achieved by comparing the interferometer output with the frequency output f_s , of a voltage controlled oscillator (VCO) in a phase detector, which is controlled by a feedback loop from the phase detector output, where the phase detector provides an output or 'error voltage' which is proportional to the phase difference between the interferometer signal and the VCO, from which the Doppler shift and thus the velocity can be found.

3 DESIGN AND DEVELOPMENT OF NEW ALL-FIBRE HETERODYNE INTERFEROMETER

3.1 *Initial design specification*

As described in Section 1.2.3, although not stipulated as a requirement for the project, it was chosen to implement the interferometer optical configuration entirely with fibre. In addition to this, the initial requirements for any optical system developed for this project are:

- A 532 nm laser source to minimize absorption in water.
- A frequency range from 1 kHz to 500 kHz.
- An RMS noise equivalent velocity floor less than $10 \mu\text{m s}^{-1}$ below 25 kHz.
- A velocity range up to 3 mm/s below 10 kHz and 5 mm/s above this.
- A stand off distance from a few millimetres to 5 m.

The typical values of the acoustic field parameters that are encountered in calibration work vary with frequency. At frequencies of hundreds of kilohertz where directional acoustic sources are more commonly used, acoustic pressures typically around 2 kPa may be encountered. This is equivalent to an acoustic particle velocity of around 1.4 mm/s. At low kilohertz frequencies, during free-field calibrations and where omnidirectional sources are commonly used, acoustic pressures of 50 Pa or lower may be observed, equivalent to only 30 $\mu\text{m/s}$ in terms of acoustic particle velocity. The initial specification stipulated for the new all-fibre interferometer is therefore quite broad, where a full 5 mm/s dynamic range will not be necessary at all acoustic frequencies.

It can be shown using Equation (1), that for a 5 mm/s particle velocity, the Doppler shift imparted on green laser light is around 19 kHz. The fact that the reference beam/arm is optically shifted by a Bragg cell means that the dynamic Doppler shift will in reality be seen as an oscillation around the optical shift frequency, as described in Section 2.2. The use of a Bragg cell for frequency shifting generally means resultant shifts in the RF region, often at tens of megahertz, which in theory would allow Doppler shifts to be determined that correlate to velocities of several metres per second. For this application, such large frequency shifts are not required, in which case it is common to mix down the shift frequency to a more suitable frequency before demodulation, as shown in Figure 1.

3.2 *Design and development*

The development of the all-fibre heterodyne interferometer system has essentially been divided into two distinct themes, covering the optics and the electronics or signal processing. Although much of the work on the optics and the electronics is now complete, there are still optimisations to be made. In addition to optimisations to the electronics, there is also work still required on the Doppler decoding at the post mix down stage.

3.2.1 *Optics*

The optical unit developed for the project interferometer system is different from a standard bulk optic interferometer or LDV design due to its all-fibre implementation. Complete fibre implementation also means that fibre equivalent or ‘pigtailed’ components also replace existing bulk optic components. A complete systematic description of each optical component used in the development of the project ‘all-fibre’ interferometer is given in this

section, along with component specifications and an overall light budget for the ‘all-fibre’ system.

3.2.1.1 Optical elements

Laser: In place of the standard laser (usually Helium Neon) used in bulk optic interferometer systems or commercial LDV’s, the system developed for this project will employ a short cavity 100 mW (currently 50 mW), frequency doubled Nd:YAG solid state laser with a fibre delivery system. The advantages of this laser are:

- 532 nm wavelength for good transmission through water
- Shorter wavelength more suited to interferometry
- High power capability
- High stability single frequency mode
- High intensity stability
- Supplied as a fibre coupled device
- Compact size
- Passive cooling

Fibres: Due to the wavelength of the laser and the requirement for single mode transmission fibres, the core diameter of the fibre used is very much stipulated by the wavelength of the light. In this case, the fibres used throughout the system have a core diameter of around 3 μm . Where necessary, the fibres are joined using either a low loss splice or SMA connectors. Many of the components used have been fitted with connectors for easy replacement. Connectors have also been used where the laser enters the optical interferometer unit and also where the target fibres exit and enter the interferometer unit. The fibres used to deliver and collect the laser light to and from the target are terminated with small collimating lenses that collimate the delivered beam for a target spot size of around 1 mm diameter and then collect the reflected light from the target for focussing back into the fibre.

Beamsplitters: The fibre optic equivalent of the non-polarising beamsplitter is the directional coupler. An idealised coupler is shown in Figure 6.

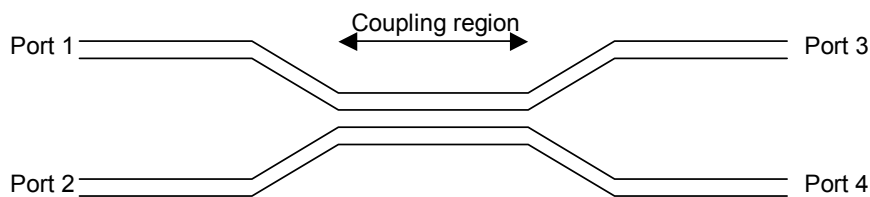


Figure 6. Fibre optic coupler.

The guided sections across the coupling region, are sufficiently close to promote an overlap of their transverse fields. Light launched into Port 1 is guided exclusively by that wave-guide until it enters the coupling region. In this region, power transfer of light takes place from one wave-guide to the other and back following a $\sin^2$ and $\cos^2$ relationship.

For example, for light of power P_1 launched into Port1 an output power at Port 4 of P_4 can be given by,

$$P_4 = P_1 \sin^2(\kappa l) \quad (5)$$

Where l is the length of the coupling region and κ is a constant known as the coupling coefficient, which is dependent on the wave-guide geometry refractive index and losses. Thus light inputted into any of the ports can be split into two at a ratio determined by the coupling length and the coupling coefficient. The fibre coupler can therefore be used as a beamsplitter equivalent. It is however, completely reversible and therefore, cannot be used as a direct replacement for a polarising beamsplitter. This limitation does lead to some fundamental optical design differences to a standard bulk optic system that employs polarising beamsplitters (see Section 3.2.1.2).

Detectors: The choice of photodetectors was based on requirements of response time and the necessary ‘pig tailing’ to fibres. The use of receptacle photodetectors has the advantage of high gathering efficiency from the fibre, which allowed Si PIN-photodiodes to be used to provide rapid response times at the expense of sensitivity and noise. This type of photodetector can be used instead of an avalanche type providing the light level at the photodiodes is sufficient for the required signal-to-noise. The photodetectors used in the current system are Si PIN types with built in pre-amplification. The built in amplification includes automatic gain control (AGC) circuitry to maintain a constant output voltage in the presence of low frequency light variations.

Optical frequency shifter: Acousto-optic devices are generally used for optical frequency shifting. A high frequency acoustic standing wave in a crystal cavity essentially acts as a Bragg diffraction grating with the spacing set by the distance between wave peaks. Bragg cells usually operate at tens of megahertz, 10-40 MHz being common for interferometry applications. The project all-fibre interferometer uses a ‘pigtailed’ Bragg cell which operates at 80 MHz. ‘Pigtailed’ acousto-optic frequency shifters for 532 nm operation are not standard components and so the operational frequencies are limited, with 80 MHz being the lowest available. The crystal used for shifting needs to interact with a number of the high frequency acoustic cycles to produce an effective grating. A higher frequency crystal therefore allows for a more compact device, as is often required for ‘pigtailed’ components. The acousto-optic frequency shifter is paired with a high stability 80 MHz frequency generator. The acousto-optic unit is pictured below in Figure 7 with coupled input and output fibres on the left and the right.



Figure 7. Fibre pigtailed acousto-optic frequency shifter.

3.2.1.2 Optical configuration

The optical system implemented using a fibre arrangement is different from that of a bulk optic system. The current all-fibre optical configuration is shown in Figure 8, from which it

can be seen that the reference arm does not in any way use a reference mirror since the reference arm path is set by the fibre. A photograph of the actual system is shown in Figure 9 for reference. The second point to note is that the reflected measurement arm signal from the target is coupled directly into the coupler which combines the measurement and the reference arms of the interferometer. This does not have to be the case. A third fibre coupler could be placed in the measurement arm, where a beam splitter would normally be used to isolate the transmitted beam and the received beam from the target. For a bulk optic system, a polarising beam splitter would normally be used for this purpose. For a fibre system, there is no direct equivalent of a polarising beamsplitter and since fibre couplers are 4-way reversible systems, light will always be sent back the wrong way through the measurement arm to the laser. This will inevitably lead to laser instability, and isolation of back propagation will inherently lead to further light losses.

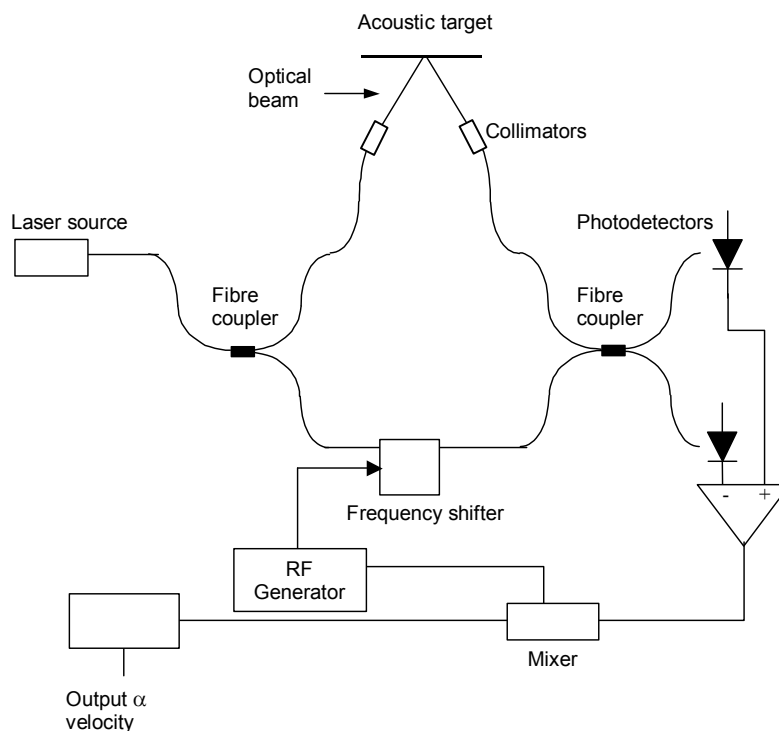


Figure 8. Layout of the all-fibre heterodyne interferometer.

As is commonly the case with most interferometers, the all-fibre interferometer employs a two-detector arrangement. The use of a two-detector system and a differential amplifier with photodiodes inputs that are 180° out of phase allows a balanced output that improves noise rejection and thus increases signal to noise. Since the fibre coupler will always provide light in both output paths, using a balanced detector arrangement also maximises the efficiency of the system.

One of the major disadvantages of a fibre system is the coupling of light into the fibre. A bulk optic system is much more efficient in this way, where large collection lenses can be used to gather diffuse light from the target and losses are minimal at internal components with suitable dielectric coatings. Although the fibre system benefits from fewer components and receptacle photodetectors, it does however suffer from light losses at each stage where coupling or focussing into a fibre is necessary. Connectors are also a cause of loss which is indicated in Table 1.

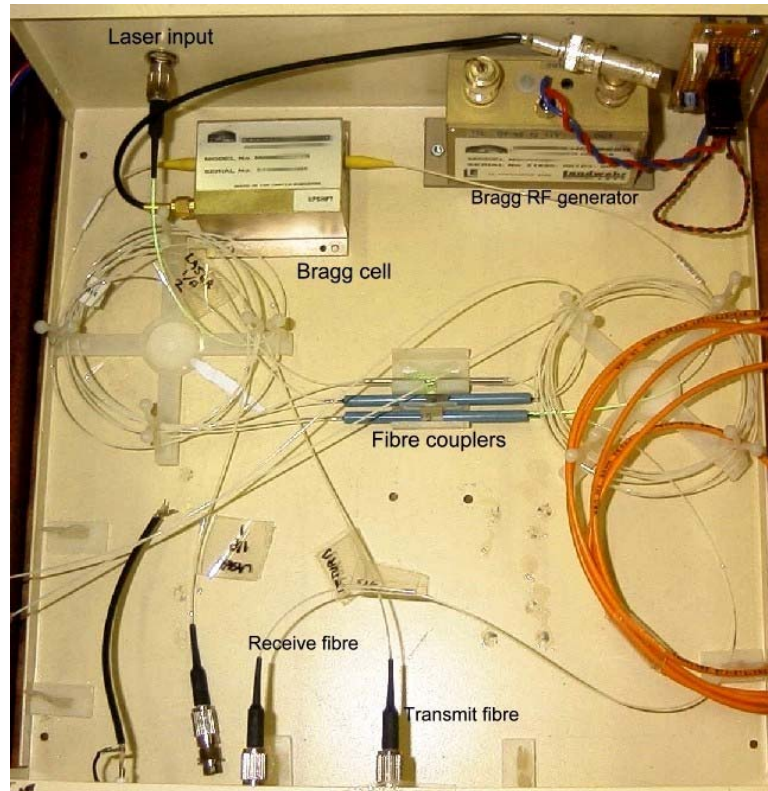


Figure 9. Photograph of the internal optical arrangement of the all-fibre interferometer.

3.2.1.3 Light budget

Initial testing of the all-fibre interferometer indicated that the light level reaching the photodiodes was insufficient to extract a clean FM signal. The initial testing was performed with a 100 mW laser similar to that planned for final use. The fibre coupling arrangement proved to be very inefficient. Comparisons with a commercial vibrometer based on the signals proportional to surface amplitude showed that this early configuration was 3-4 times less sensitive than the commercial instrument. Several estimated light budgets were put together to identify areas that could offer potential light level gains at the photodiode, from which several areas for improvements were identified. Improvements were made, including better connections between components, the removal of several spliced sections and overall reduction in fibre length. Other enhancements came from changing to a lower power laser that offered a small improvement through more efficient coupling into the fibre. Parallel improvements were made to the electronics which are discussed further in Section 3.2.2.

The prototype system used a 50 mW laser with a retro fitted fibre delivery unit, with around 60% of the laser power delivered into the fibre. The light path was systematically traced through the system and light losses estimated for each connection, component and other loss mechanisms were used to produce a light budget. The aim of the light budget was both to ascertain the required laser power to obtain a usable light level at the photodetectors and also highlight any high loss areas that could be optimised. A comprehensive estimated light budget was performed and compared with light loss measurements made at limited locations through out the system. The light budget with measured comparisons is tabulated in Table 1.

Table 1. Light budget of all-fibre interferometer.

Stage no.	Description	Estimated loss %	Estimated % of input power	Estimated power mW	Measured % of input power	Measured power mW
1	Laser Power	0	100.00	50.00		
2	Laser/fibre interface	40	60.00	30.00		
3	Attenuation in fibre	1.5	59.10	29.55		
4	Fibre mismatched at connection	20	47.28	23.64	100.00	30.00
5	Connector transmission efficiency	20	37.82	18.91		
6	Interface efficiency into coupler	3	36.69	18.34		
7	Coupler excess loss	76	8.805	4.403		
Reference Arm						
	Input power to Reference arm		16.69	2.201		
8R	Interface efficiency into fibre	0	16.69	2.201		
9R	Attenuation in fibre	0.5	16.61	2.190		
10R	Splice efficiency	5	15.78	2.081		
11R	Overall loss in Bragg cell	100	0.000	0.000		
12R	Splice efficiency	5	0.000	0.000		
13R	Attenuation in fibre	0.5	0.000	0.000		
14R	Interface efficiency into coupler	0	0.000	0.000		
	Output power from Reference Arm		0.000	0.000		
Measurement Arm						
	Input power to Measurement arm		16.69	2.201		
8M	Interface efficiency into fibre	0	16.69	2.201		
9M	Attenuation in fibre	1.5	16.44	2.168	6.510	1.953
10M	Connection loss exciting box	20	13.15	1.735		
11M	Attenuation in fibre	4.5	12.56	1.657		
12M	Loss indelivery optics	8	11.56	1.524		
13M	Medium loss to target	0	11.56	1.524	4.450	1.335
14M	Target loss (reflectivity)	20	9.244	1.219		
15M	Medium loss back to receiver	0	9.244	1.219		
16M	Collection efficiency	50	4.622	0.610		
17M	Loss in receiving optics	8	4.252	0.561		
18M	Loss in delivery into fibre	90	0.425	0.056	0.100	0.030
19M	Attenuation in fibre	4.5	0.406	0.054		
20M	Connection loss entering box	20	0.325	0.043		
21M	Attenuation in fibre	1.5	0.320	0.042		
22M	Interface efficiency into coupler	0	0.320	0.042		
	Output power from Measurement arm		0.320	0.042		
	Resultant power into combined beams		0.160	0.0422		
23	Coupler excess loss	69	0.050	0.0131		
24	Coupler insurion loss	50	0.025	0.0065		
25	Attenuation in fibre	0.5	0.025	0.0065		
26	Incident power on photodiode		0.025	0.0065	0.0090	0.0027

The light budget given in Table 1 provides a detailed list of each loss component with an associated stage number. Stages 1 to 6 considered the path of light produced at the laser as it travels to the first coupler. This included the coupling loss into the fibre, loss in the fibre, the connector into the interferometer box and the loss in a second fibre which delivers the light to the coupler. The manufacturers insertion loss stated for the coupler is less than 4 dB, which for a 3 dB (50/50) coupler translates to a 1 dB (20.6%) excess loss. Testing of both couplers in the interferometer by using a reference input and measuring the output of each port showed that the actual excess loss was closer to $65 \pm 10\%$. This value was used as the estimated loss in the light budget as opposed to the stated specification although the reason for the disagreement is unknown.

After passing through the coupler, the light is split into the two arms of the interferometer. The reference arm undergoes minimal loss due to the limited number of components. The largest loss component in the reference arm is in fact the Bragg cell. The Bragg cell is essentially a ‘pigtailed’ bulk optic component, meaning that the light entering the cell must be collimated prior to entering the crystal before and then focussed back into the fibre with an optical collection arrangement. This leads to larger losses than might be expected from a bulk acousto-optic frequency shifter. The Bragg cell can be adjusted to allow tuning of the intensity ratio between the reference arm and measurement arm, with a maximum transmission of 50%. To simplify the comparison of the estimated light budget with the measured values, the Bragg cell was turned off, meaning that no light exits the cell. Given that the reference arm would normally dominate the light level at the photodetectors, the light budget was therefore aimed towards a quantification of losses in the measurement arm. In practice, the reference arm power would be set to some multiple of the measurement arm power for optimum performance.

The measurement arm suffers much greater loss than the reference arm for several reasons. Following the 50/50 reference/measurement arm split in the first coupler, the measurement beam exits the box through a connector before entering the external delivery fibre. This process can be relatively inefficient with estimated connector transmission efficiencies of around 80% being typical. After exiting the fibre through the transmission lens, the amount of light returned to the receiving lens is then a function of the target reflectivity and propagation losses through the medium. The receive lens has a diameter of only 3 mm, so collection efficiency is very much dependent on a good spectral reflection from the target. The greatest loss in the measurement arm however, is the coupling of the light back into the fibre which could lead to losses as high as 90%. Following this, the fibre then has to re-enter the interferometer box via a connector before entering the second coupler for comparison against the reference arm. From there the light is split for reception at the photodiodes.

The optical measurements for the light budget were performed using a reference power input to the input connector of the interferometer unit, measured at 30 mW. Light power measurements were then performed at accessible points throughout the measurement arm of the interferometer using a Newport model 815 optical power meter. Figure 10 indicates where these measurements were performed and what their relative levels were compared with the reference input at the input connector. The first measurement made which is entered in Table 1 at stage 9M accounted for losses in the input connector, the coupler excess loss, the coupler insertion loss and also the attenuation in the fibre. The second measurement, entered in Table 1 at stage 13M was the light measured exiting the transmitter lens. This was the light power that would be incident on the target (assuming negligible losses through the air) and accounted for the connector loss exciting the box, fibre attenuation and transmission losses in the collimating optics. The target used for these measurements in air was an aluminium coated Mylar pellicle, which is similar to the type of target used for underwater acoustic measurements using optical methods. The third measurement was performed at the connector interface of the receiving fibre entering the optical unit. Measuring at this location provided accumulative losses from target reflectivity, collection inefficiency at the receiving optics, coupling back into the fibre, connection loss into the interferometer box and attenuation in the fibre. This measurement is included in Table 1 at stage 18M. Each measurement performed is on top of previous losses accumulated throughout the system. The final measurement performed was the power incident on each of the photodiodes which are entered in Table 1 at stage 26. The measurement at the photodiode accounted for insertion and excess loss in the coupler and attenuation in the fibre. During operation, the Bragg cell

would be set such that the power in the reference arm would be several times greater than the power in the measurement arm. For a 10:1 reference to measurement arm power ratio, this would provide a power of around 27 μW at the photodetectors.

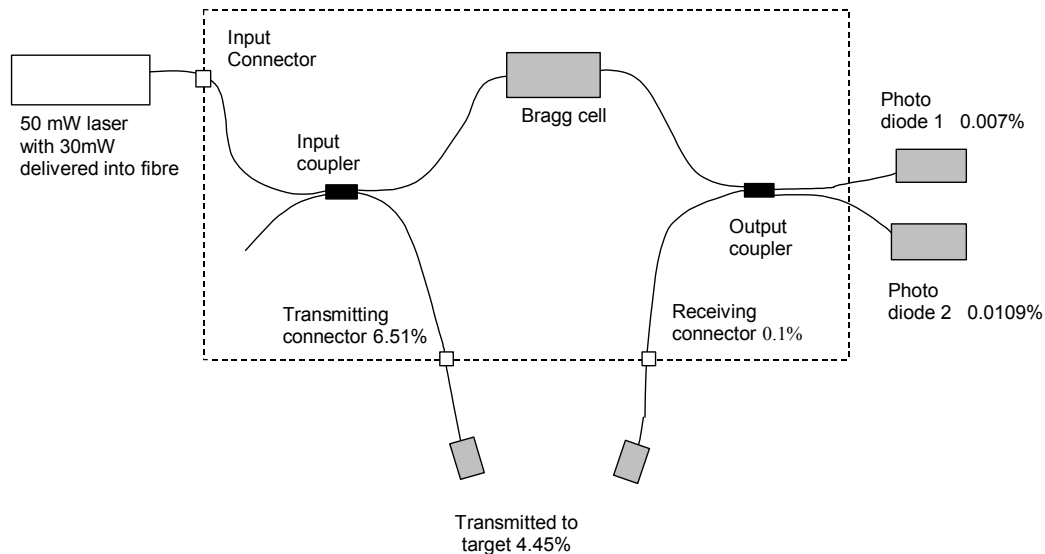


Figure 10. Measurement of cumulative power losses through the optical system.

It is clear from the light budget that collection and coupling of light back into the fibre is a major source of loss in the measurement arm and severely limits the amount of light that can be collected from the target. Improvement in this area are on going and is currently being addressed by using larger collection optics to both collect more light from the target and to more efficiently couple it in to the fibre.

Plans are currently underway to replace the current 50 mW laser with a 100 mW model that is to be supplied complete with a highly efficient fibre delivery system. It is estimated that this will allow around 70 mW of power to be injected into the interferometer, more than two times currently available. The 50 mW laser used in the prototype interferometer also exhibits inter-mode beats due to the presence of a second mode in the laser cavity. The intermode beating in the laser cavity can lead to an effective frequency modulation of the laser, which under certain circumstances results in an apparent path length difference between the measurement arm and reference arm. The laser cycles through intermode beats as the laser temperature stabilises. This effectively means that the interferometer cycles through usable and non-usable periods. The 100 mW model is a pure single mode laser and will thus offer greater usability.

3.2.2 Hardware signal processing

3.2.2.1 First stage testing of prototype signal processing hardware

Initial testing of the pre-demodulation prototype electronics was undertaken at NPL. The aim of the testing was to investigate sources of electrical noise that had been observed during some preliminary acoustic measurements performed using the interferometer.

The electronic layout of the pre-demodulation electronics is shown in Figure 11, where the output from each of the photodiodes feeds directly into a dedicated pair of pre-amp stages

which share a common power supply. The output of each pre-amplifier is then fed directly into each of the inputs of the double-balanced mixer integrated circuit (IC). The primary aim of the mixer stage is to mix down the heterodyned signal from the photodiodes by the frequency present at the local oscillator stage. The double-balanced mixer IC also employs a differential input and internal gain, negating the need for a separate differential amplifier stage in the circuit. It should be noted that the photodiode outputs are 180° out of phase when making interferometer measurements. For the measurement of an oscillating target, the output from the mixer stage would therefore be a frequency modulated signal centred on the difference frequency between the heterodyne frequency and the local oscillator drive frequency, where the amount of frequency modulation would be determined by the velocity of the target.

The testing procedure was to stimulate the circuit electrically in the absence of the photodiodes. Since the aim was to test noise and electrical interference in the circuit, only frequency tone was used and not a frequency modulated source. A number of tests were performed from which a number of conclusions were drawn and recommendations for improvement made.

Test 1: The first test was to directly excite each pre-amplifier input in turn with a small (around $30 \text{ mV}_{\text{p-p}}$) sinusoidal input of frequency 79.5 MHz. For testing, the local oscillator drive was provided by the 80 MHz Bragg cell RF generator, giving a resultant shift of 500 kHz. Monitoring the circuit at several stages showed that there was severe RF cross-coupling between each of the input channels or between each input channel and the local oscillator circuit. Disconnecting one channel showed improvements at the output, which indicated cross-coupling between channels.

Test 2: Increasing the drive voltage showed that any voltage greater than $70 \text{ mV}_{\text{p-p}}$ at the pre-amplifier input would cause distortion at the mixer stage output. This was not a limitation of the pre-amplifier design, but due to the internal gain of the double-balanced mixer IC. The gain of the pre-amplifier stage was around 2, giving a maximum input to the double-balanced mixer IC of around $150 \text{ mV}_{\text{p-p}}$ before the output exhibited distortion. For this drive level, the output from the mixer stage was over $1 \text{ V}_{\text{p-p}}$. Use of the double-balanced mixer IC will therefore place a limit on the dynamic range possible with the photodiodes. At present, this upper limit is not realised due to the low light levels at the photodiodes. However, with improved light level it maybe necessary to monitor and limit the input voltage to the double-balanced mixer IC.

Test 3: Disconnecting the pre-amplifier stages and coupling directly into the double-balanced mixer IC inputs and repeating the procedure carried out in Test 1 allowed a more isolated evaluation of the circuit to be performed. The tests still showed RF cross-coupling between the local oscillator drive and the output stage of the double-balanced mixer IC. General testing of the circuit board also showed that the 80 MHz local oscillator drive was coupling into the ground plane of the board. This highlighted the need for improved RF design, isolation and grounding.

Test 4: The frequency of the drive signal was varied between 79.9999 MHz and 79.0000 MHz. This provided an effective shift frequency from 0.1 kHz to 1 MHz over which the linearity of the double-balanced mixer IC was tested. Over this range, the double-balanced mixer IC proved to have a linearity better than 2%. This is relatively good given

that the frequency variation due to the frequency modulated signal will always be less than ± 20 kHz for a peak velocity of 5 mm/s.

Initial observations:

Although the basic functionality of the detector electronics was proven, a number of limitations were identified. The dynamic range of the input to the amplifiers was limited; this could be critical when using the system. Given the sensitivity of the photodiodes at their peak, they will produce an output voltage sufficient to cause distortion at the double-balanced mixer IC output for an optical power of 0.07 mW. Currently the light budget shows a power of 0.0027 mW from the measurement arm, which would lead to a light level at the photodiodes of around 0.03 mW for a 10:1 reference to measurement arm power ratio. Although the photodiodes are somewhat less sensitive to the 532 nm green light than they are at their sensitivity peak, there still exists the risk that for improved light level, the output from the photodiodes may be sufficient to cause distortion at the double-balanced mixer IC output.

It was concluded that particular emphasis should be placed on RF issues in re-engineering the circuit. It was decided that aspects of cross-coupling and overall performance would be improved if the various functions (two input amplifiers, demodulator, local oscillator buffer and final amplification) were all separated with power supply/ground linkages through decoupling circuits (C-L-C). Also, placing the detectors and their respective amplifiers on separate small boards would significantly improve shielding. Shielding each part of the high frequency circuit using a screened enclosure would further provide better isolation of each stage. Earth loops were also identified as issues that needed addressing in the re-engineering of the circuits.

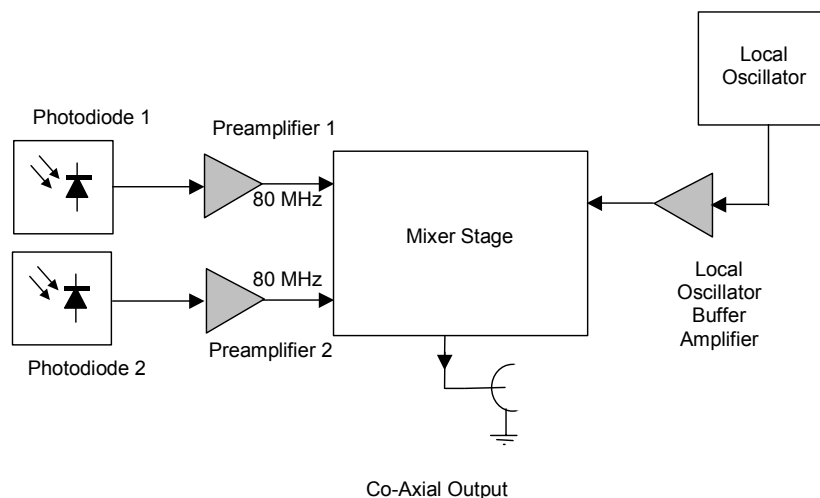


Figure 11. Layout of pre-demodulator electronics.

3.2.2.2 Testing of RF engineered electronics

Following the recommendations from the initial testing, the circuit layouts were reworked using improved RF circuit techniques. The design and engineering improvements made to address the RF cross-coupling issues were:

- Pre-amplifiers implemented on isolated circuit boards
- Mixer stage and local oscillator implemented on isolated circuit boards
- Improved ground plane

- Short coaxial cables join stages to minimise cross-coupling and RF interference
- Decoupling of local oscillator
- Decoupling of power supply

The isolated stage design was chosen to reduce RF cross-coupling between a) each of the input stages at pre-amplifier level, b) each pre-amplifier stage and the mixer stage output, c) each pre-amplifier and the local oscillator drive and d) the mixer stage output and the local oscillator drive.

Each input amplifier was designed with a gain of 2.2-2.6 at 80 MHz which provided a signal-to-noise ratio of 50 dB for typical input signals provided by the photodiode.

Comparisons with the prototype electronics showed a 3-23 dB reduction in RF cross-coupling measured at the mixer stage output between each input stage and the double-balanced mixer IC output. The poorest isolation was observed on the second input channel where the input pin on the double-balanced mixer IC is physically closest to the output pin on the double-balanced mixer IC. The improvement in cross-coupling between the local oscillator stage and the mixer stage output was measured to be around 8 dB less than that measured on the prototype electronics.

For measurements carried out on a pellicle in air for a 25 kHz ‘offset’ or shift frequency, output levels were measured at the mixer stage output with a 60 dB signal-to-noise ratio (SNR). This was around a 30 times improvement over the SNR measured with the prototype electronics.

A thorough investigation of the spectral noise content at the output of the mixer stage found substantial interference components at 1.23 MHz, 1.79 MHz, 2.38 MHz, 5.92 MHz, 7.19 MHz, 52.1 MHz, 66.8 MHz, 97.1 MHz and 111.2 MHz. Some of these have been identified and removed, although a few still remain. The resultant shift or carrier frequency used for velocity measurement can be carefully chosen to avoid any of these interference spikes and the use of narrow band filtering around the carrier frequency will provide a significant signal-to-noise improvement.

3.3 Initial testing and performance

Initial testing of the fibre interferometer was carried out to establish the velocity of an acoustic target by processing of the FM signal output from the mixer stage. The testing procedure was to measure the acoustic velocity of a pellicle in air that was excited by an air coupled loudspeaker. The transmit and receive optics were approximately 200 mm apart and the target to optics distance along the bisecting axis between the transmitting and receiving beams was 514 mm. The target pellicle was positioned approximately 40 mm in front of the 40 mm diameter loudspeaker so that both shared a common central axis. The experimental arrangement is shown in Figure 12.

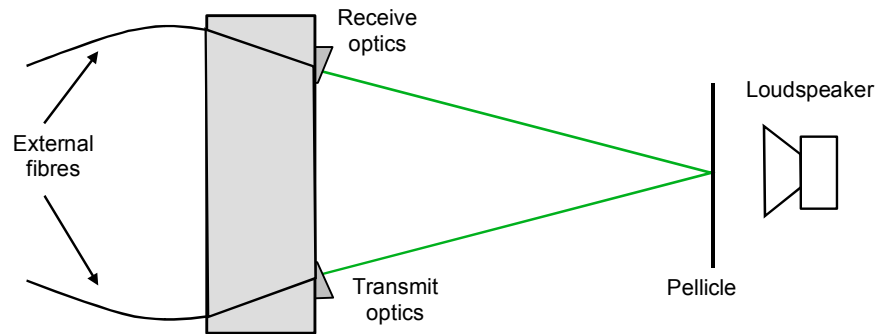


Figure 12. Experimental arrangement used for initial testing.

The loudspeaker was then driven using a function generator over a range of amplitudes by a 3 kHz sine wave. The optical beam was then aligned as shown in Figure 12, to be sensitive to the motion of the pellicle as a result of the air coupled loudspeaker. The frequency applied to the local oscillator drive of the mixer stage was 79.975 MHz, resulting in a 25 kHz shift or carrier frequency after mixing with the 80 MHz optically shifted output from the photodiodes. The FM signal from the mixer stage of the fibre interferometer, centred on the 25 kHz shift was then captured using a Tektronix TDS 520 oscilloscope at a rate of 250,000 samples per second.

A screen capture from the oscilloscope is shown in Figures 13 with the FM time waveform at the top of screen capture figure and the associated frequency spectra below.

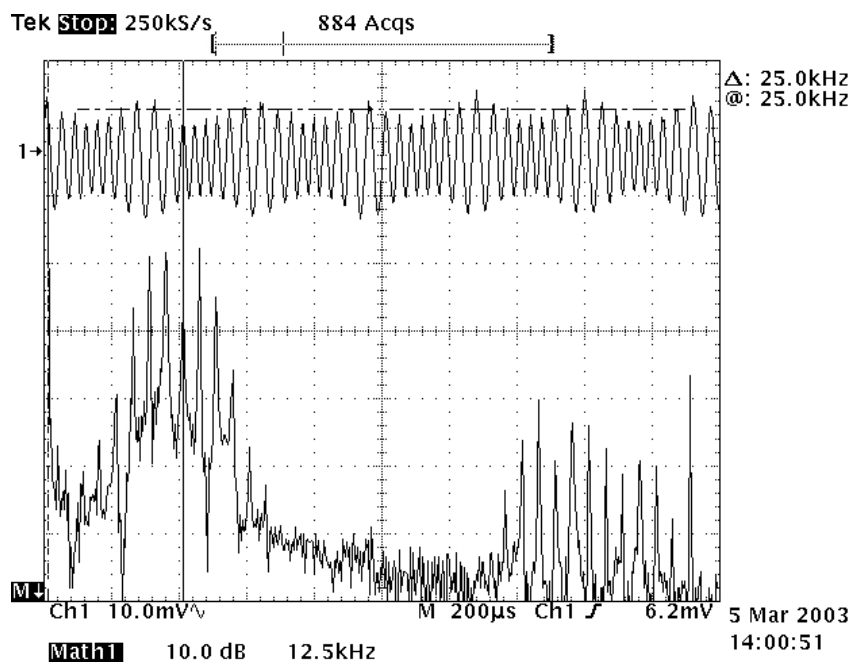


Figure 13. Screen capture of time and frequency plots for a 3 kHz acoustic frequency with a resultant shift frequency of 25 kHz.

The time waveform in Figure 13 clearly shows the 3 kHz frequency modulation of the 25 kHz carrier. Also present is an amplitude modulation at the acoustic frequency. It was thought that this might have been caused by deflection of the pellicle surface. However, one

would naturally expect the best alignment to occur when the pellicle passes its zero position, which would also be the point of highest target velocity. It would therefore be expected that the FM signal in Figure 13 would exhibit a maximum amplitude (for maximum light return) when the Doppler shift is maximum. Figure 13 indicates the opposite. The most probable reason for the amplitude modulation is that the output of the mixer stage exhibits some roll-off with increased frequency. This might lead to reduced amplitudes of the higher frequency components present in the FM signal, although one might expect the effect to be very small for the modulation depth shown in Figure 15. However, frequency demodulation techniques are generally insensitive to amplitude variations. From the frequency spectra shown in Figure 13, it is possible to see the series of sidebands around the carrier frequency spaced at frequencies from the carrier that are integer multiples of the acoustic frequency. This was described in Section 2.2 and shown for a theoretical case in Figure 2. In Figure 13, each division of the frequency axis represents 12.5 kHz. Thus the carrier frequency is centred on the 2nd division with each acoustic sideband being around a quarter of a division apart. Above 80 kHz there was evidently some interference present. Although some of these components have been identified as power supply noise from the laser, some show the same system of sidebands and therefore must have been present in the mixer stage. These were most likely due to sources of noise that were present in the local oscillator or the mixer stage which resulted in secondary mix down frequencies.

Measurement of the maximum and minimum frequency in the FM time signal allows the positive and negative Doppler shift around the carrier frequency to be calculated by subtracting the carrier frequency from the measured instantaneous frequency. The difference obtained is the peak Doppler frequency, which using Equation (2) can provide the positive and negative peak components of the target velocity. The ϕ term in Equation (2), in this instance is not zero as the optical beam is not normal to the surface of the target, although this makes little difference for small angles (approximately 11°). The peak acoustic velocities measured at the surface of the pellicle for a range of loudspeaker drive levels are shown in Figure 14. It should be noted that the accuracy of the velocity determination is limited by the shift frequency for the way in which the velocity has been determined. The instantaneous frequency was measured from the half cycle period of the zero crossing points. Given that there are approximately 8.3 cycles in the FM signal per acoustic cycle, the measurement resolution is severely limited. However, the results do show that for a velocity range from 0.5 mm/s to around 2.5 mm/s the device is in fact linear.

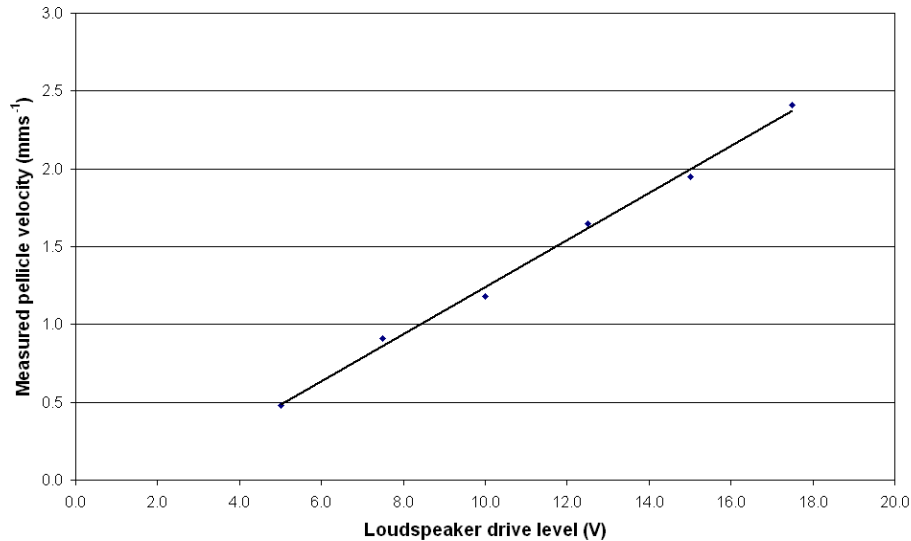


Figure 14. Interferometer measurement of velocity as a function the loudspeaker drive level.

By back extrapolation of the gradient in Figure 14, it appears that the zero velocity occurs at around 1.9 volts. This is most likely due to the crude source arrangement of the loudspeaker air coupled to the pellicle. Even using simple techniques for determining the Doppler shift, the results clearly demonstrate that velocity measurements are possible down to 0.5 mm/s. This is encouraging given that significant improvements will be gained by the use of hardware Doppler decoding or Phase Lock Looping in the final system.

3.4 Testing in NPL small tank

The all-fibre interferometer was brought to NPL for testing in the small NPL test tank with the aim of testing its operation under more realistic operating conditions. The advantage of testing in the water tank was that it allowed higher frequencies to be used than was possible in air. The test was performed in two parts; the first considered a continuous wave projector and the second a tone-burst projector. The experimental procedure was to place a 23 μm Mylar pellicle coated with 40 nm of aluminium in the water at a set distance x_1 from the optical window in the side of the tank. The pellicle used was a standard ring support type that is usually used for high frequency acoustic pressure measurement. The disadvantage of using a small pellicle for this experiment was that its diameter of around 95 mm was not sufficiently large compared to the acoustic wavelength. An acoustic projector was then placed in the tank a distance x_2 from the pellicle, which were both, aligned along the centre axis of the optical window in the tank. The interferometer delivery fibres were then aligned on the pellicle, with the laser beam from the delivery fibre passing through the optical window and reflecting off the pellicle to return to the collection fibre. A diagram showing the experimental set-up is provided in Figure 15. The angle between the transmitted beam and reflected beam at the pellicle was 22° . The angle between the beams meant that the device would also be sensitive to refractive index changes in the acoustic field. Even for this arrangement, testing would still be beneficial in demonstrating the response of the interferometer to an acoustic field.

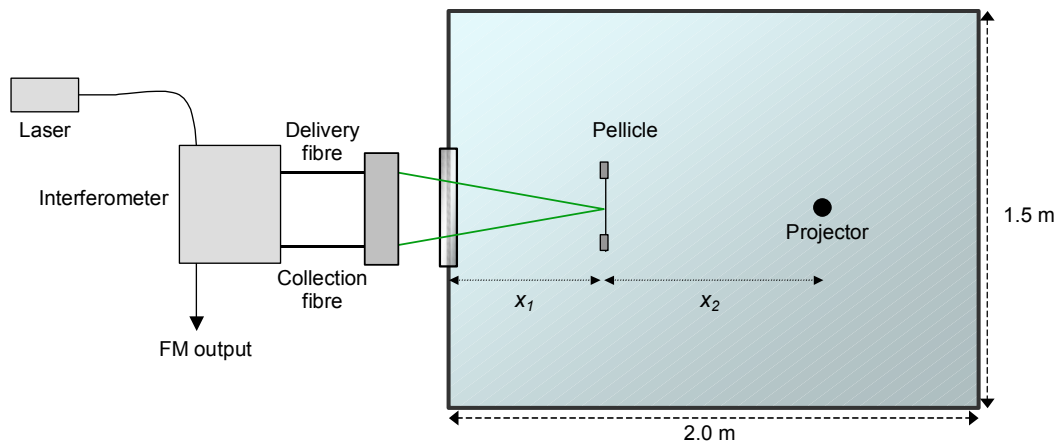


Figure 15. Experimental arrangement for measurements in small NPL water tank.

The window to pellicle distance and the pellicle to projector distance for the continuous wave measurements were $x_1 = 420$ mm and $x_2 = 300$ mm respectively. A different arrangement was used for the tone-burst measurements which resulted in distances of $x_1 = 350$ mm and $x_2 = 500$ mm. The delivery/collection fibre and optical window arrangement is pictured in Figure 16, with the circular pellicle visible through the window. The fibre clamp is mounted on a camera tripod to provide maximum adjustment.

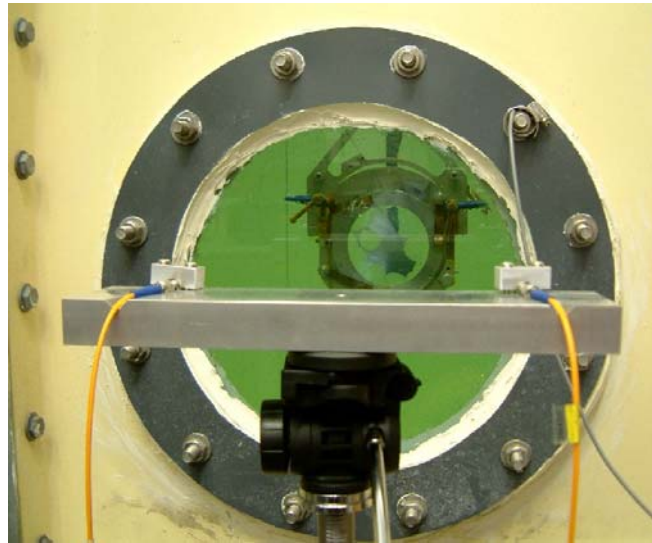


Figure 16. Delivery and collection fibres aligned on pellicle through an optical window in the tank.

A top view of the small NPL tank, with the pellicle and acoustic projector in place is provided in Figure 17. Both the pellicle and the acoustic projector were mounted on the tanks positioning system, which allowed horizontal (x and y) adjustment and height (z) adjustment to an accuracy of $10\text{ }\mu\text{m}$. The positioning system also allows rotation of the device around the z -axis to an accuracy of 0.01° . The projector pictured in Figure 17 was an ITC1042. This was used for the second part of the tests where a series of tone-bursts were used between 40 kHz and 80 kHz.

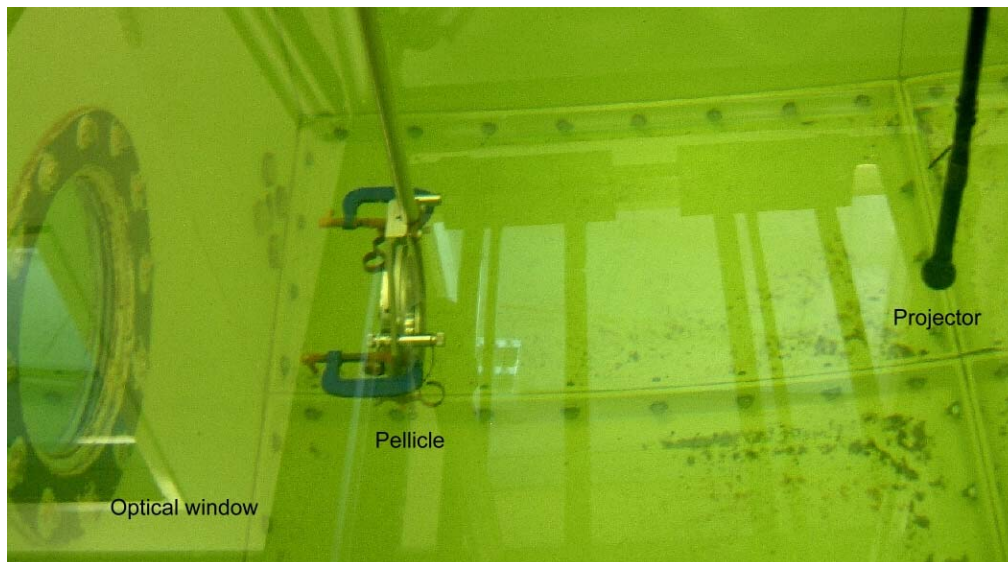


Figure 17. Projector and pellicle position in the small water tank.

For the continuous wave excitation, an ITC1001 was used to generate a 12 kHz acoustic field. Once aligned, the interferometer was then used to make a series of measurements using a range of shift or carrier frequencies. The shift frequencies used as the carrier in the FM output of the interferometer were 100 kHz, 200 kHz, 500 kHz and 1200 kHz, which were a result of mixing the optically shifted 80 MHz output signal down by an external frequency of 79.9 MHz, 79.8 MHz, 79.5 MHz and 78.8 MHz respectively in the mixer stage. The external frequency was applied to the local oscillator drive by a Gould SSG220 function generator. The output from the mixer stage was then captured using a Tektronix TDS 5054 oscilloscope at a sample rate of 250 MS/s. The captured signal was then analysed in MATLAB using a routine that measured the distance between the zero-crossing points of the waveform to provide the half period and thus the average Doppler shift every half cycle. This technique was used to produce the results shown in Figures 18-21. Figures 18a-21a show the captured FM signal outputs from the interferometer mixer stage, where the green circles indicate the zero-crossing points used to measure the half period. To improve the signal-to-noise in the FM signal and thus improve the extracted acoustic signal shown in Figure 18b-21b, a software Butterworth filter was applied to the FM output signal. The filter was a 3-pole pass-band design with a -3 dB width approximately 4 times the peak Doppler shift centred on the carrier frequency. Unfortunately, without an improved design or a broader filter pass-band, variations in phase of the demodulated signal are unavoidable due to the phase response of the filter.

It should be noted that the resolution of the technique is poor for low carrier to acoustic frequency ratios. This may not necessarily be the case for hardware de-modulation techniques such as Phase Lock Looping or frequency tracking, where a higher carrier frequency may place limitations on the smallest Doppler frequency that could be resolved.

It can be clearly seen from Figures 18-21 how the Doppler shifts were derived from the frequency variation in the FM signal. Negative Doppler shifts were a result of frequencies below that of the central carrier frequency and positive Doppler shifts from frequencies above the central carrier frequency. There is also amplitude modulation (AM) which is not completely understood at present, although it is known that it was not a result of filtering. Further work is required to establish the source of the AM and also to determine if its impact on the overall frequency demodulation is of consequence.

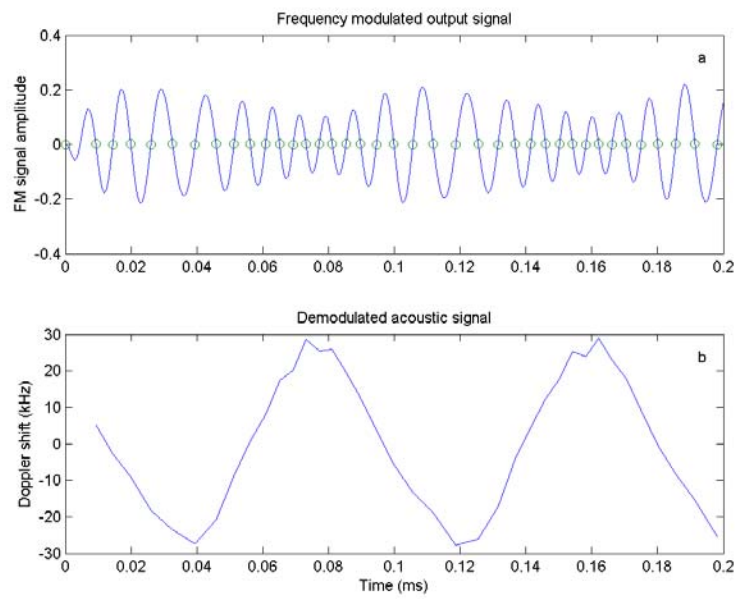


Figure 18. a) FM output with modulation centred on 100 kHz shift frequency.
b) Demodulated 12.5 kHz acoustic signal.

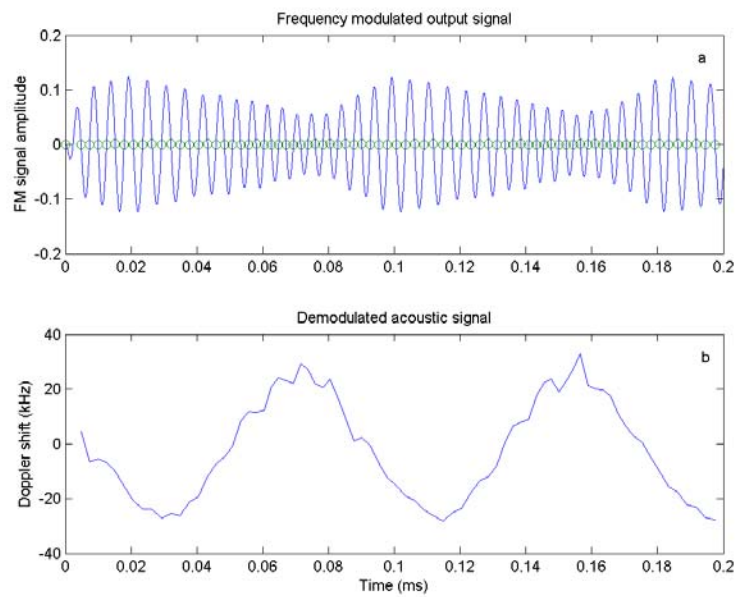


Figure 19. a) FM output with modulation centred on 200 kHz shift frequency.
b) Demodulated 12.5 kHz acoustic signal.

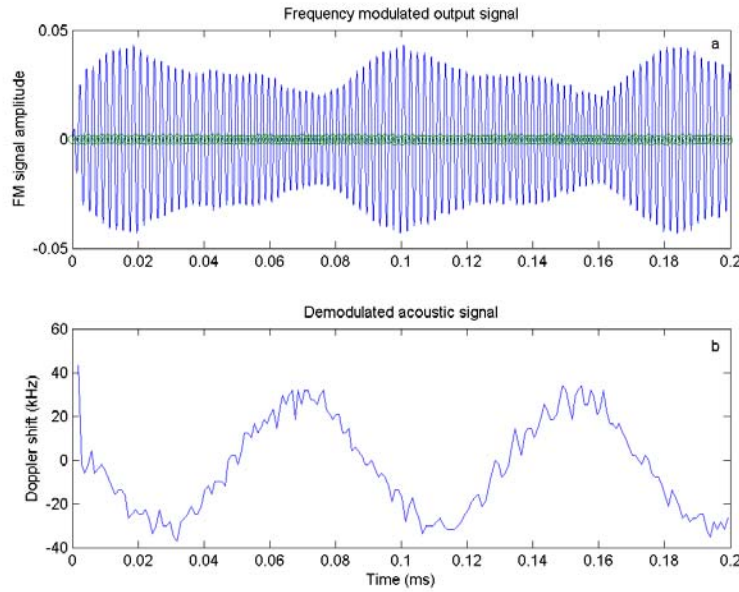


Figure 20. a) FM output with modulation centred on 500 kHz shift frequency.
b) Demodulated 12.5 kHz acoustic signal.

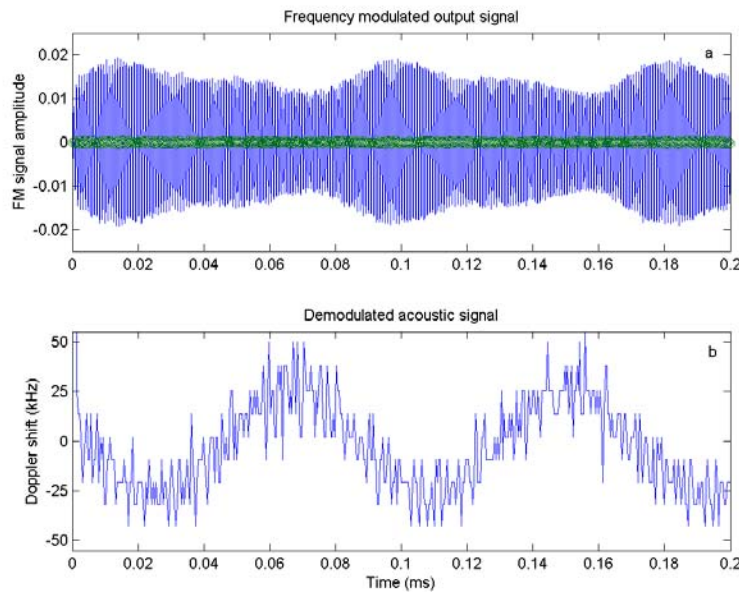


Figure 21. a) FM output with modulation centred on 1200 kHz shift frequency.
b) Demodulated 12.5 kHz acoustic signal.

The presence of amplitude noise in a demodulated acoustic signal is generally a result of phase noise at the inputs of the demodulator. In reality, both amplitude and phase noise will in fact be a cause of amplitude noise in the demodulated signal. For the results presented in Figures 18-21, narrow band filtering was applied to the FM signal to improve the signal-to-noise. Therefore, the amplitude noise present in the demodulated acoustic signal was most likely due to phase noise in the FM signal. As with electronic demodulation techniques, the software technique applied here produces an output amplitude that is proportion to a phase or frequency difference. The result of this is that any unwanted phase variations in the FM signal will result in unwanted amplitude components in the demodulated signal. The

interferometer arrangement used for the tests presented in this report employed, as shown in Figure 11, a local oscillator source to mix with the 80 MHz optically shifted signal from the photodiode. Any cycle-to-cycle variation or instability between these two oscillators will invariably be a major cause of phase noise where the frequency of the noise produced in the demodulated signal will in general have some dependence on the shift or carrier frequency. This is evident in Figures 18-21 where the lower carrier frequency results have noise components of lower frequency than those with the higher carrier frequency. The signal-to-noise is also reduced for higher shift frequencies as a result of some higher frequency roll-off in the output electronics.

The experimental procedure used for the tone-burst measurements was to position the pellicle 350 mm from the optical window, with the ITC1042 positioned 500 mm from the pellicle. The ITC1042 was then driven with a gated tone-burst over a range of frequencies between 40 kHz and 80 kHz. An interferometer measurement was made at each frequency, followed by a repeat set of measurements using a calibrated B&K 8104 hydrophone positioned in place of the pellicle. The output of the hydrophone was amplified with a gain of 20 dB. The calibration factor of the hydrophone at 60 kHz, near its resonance was -203.13 dB re 1 V per μPa . Taking account of the gain in the system provided an overall sensitivity of 697.43 μV per Pa. The results plotted for the hydrophone in Figure 22b are therefore given in terms of acoustic pressure. The interferometer output after software demodulation is shown for comparison in Figure 22a.

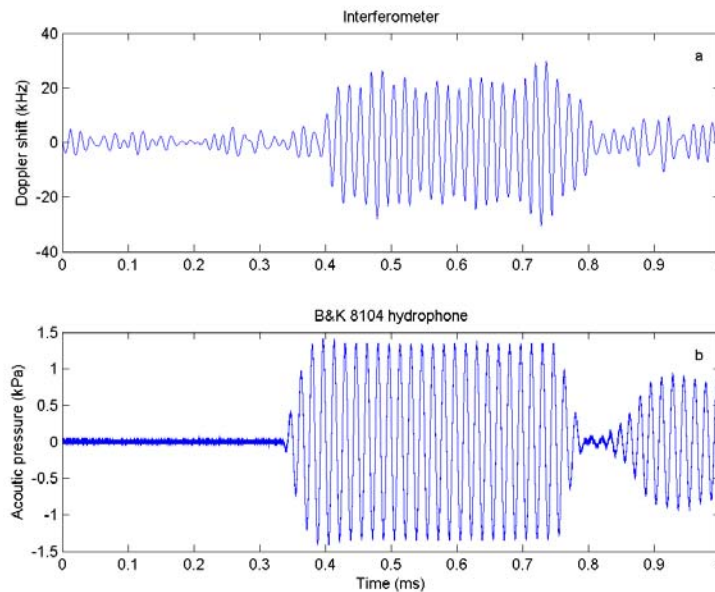


Figure 22. a) Doppler shift imparted on interferometer measurement beam for a 60 kHz tone-burst. b) Hydrophone measurement for same acoustic field.

The acoustic pressure measured by the hydrophone gave a particle velocity of less than 1 mm/s. However, the Doppler shift imparted on the measurement beam of the interferometer indicated a velocity much higher than this. Using Equation (2) would suggest a target velocity of just over 5 mm/s. The Doppler shift was measured directly from the interferometer with relatively good resolution, from which the velocity was determined using Equation (2) where $\lambda = 532 \text{ nm}$, $\beta = 1$ and $\phi = 11^\circ$.

There are two possibilities as to why there might be disagreement between the interferometer measurements and the hydrophone measurements. Reflections from the pellicle mount could lead to acoustic interference, which would make comparisons difficult. Future tests will use a pellicle designed to minimise reflections and maximise the free-field window.

It is also likely that the acousto-optic effect would contribute to the signal. The acousto-optic effect has been shown [5] [6] [7] to provide good sensitivity to optical interferometer beams crossing the acoustic beam. For the case of the optical beam traversing the same path as the acoustic beam, the effect is generally a simple correction factor [8], provided there are sufficient acoustic cycles present in the optical path. The experiments reported in this section however, used an optical beam which was misaligned with the acoustic beam by 11° , and where a simple plane or spherical wave could be assumed. The optical beam therefore had a component that crosses the acoustic beam and thus approaches a situation similar to that investigated by Harland [5], which showed significant optical sensitivity to the apparent path length change due to refractive index variations in the acoustic field. It is thought however, that the 11° would only contribute a small amount to the signal and so it is probable that the large acoustic velocity observed was a result of reflections from the circular pellicle mount. The reflections could cause a significant increase in the deflection of the pellicle.

Although not showing absolute measurements of particle velocity present in the free acoustic field, the initial tests using the fibre interferometer in the NPL small tank have demonstrated its response to acoustic field parameters in a working environment. To take the interferometer forward, several key areas for further development have been highlighted, both as a result of the work in Phase 2 and which were already planned from the beginning of the project. These can be summarised as:

1. Signal-to-noise improvement of the FM output signal is required with consideration given to filtering options.
2. Real-time demodulation electronics are required to cover both the frequency and dynamic range specified.
3. Development to the optical head is required to enable a linear optical path to be used. This should also be suitable for placing in the water.
4. A pellicle should be developed to maximise the reflection free window.

This work is planned for the next phase of the project and should provide significant improvements to the performance and usability of the all-fibre interferometer.

3.4 Comparison with a commercial vibrometer

A direct comparison of the LOE prototype all-fibre interferometer and the Polytec heterodyne vibrometer was performed in air measurement. The Polytec vibrometer was the OFV3000 model utilising the OFV302 head. Optically, the device was identical to that used for the measurement performed in Section 3.3. However, a prototype demodulation circuit was present at the post mixer stage to provide an output voltage proportional to the Doppler shift. The prototype demodulator was based on a Phase Lock Loop (PLL) IC with a 455 kHz ceramic bandpass filter used at the input.

The aim of the comparison was to demonstrate the all-fibre interferometer working with a hardware Doppler decoder that shows an output response consistent with that of a commercial vibrometer. This was necessary since many of the measurements performed in

Section 3.3 exhibited poor signal to noise. The reason for this was thought to be the presence of phase noise, but it was difficult to quantify. Furthermore, DAQ quantisation errors and the software method used for Doppler decoding both contributed significantly to the overall noise in the Doppler signal. The output from the Polytec vibrometer provides a time waveform with the amplitude proportional to either displacement (obtained by fringe counting) or velocity (obtained by Doppler decoding). Although the calibration uncertainty for the Polytec is not known, a calibration factor is provided for the amplitude output to provide a measurement of velocity.

The measurement procedure was to focus both devices simultaneously on to an identical point on the surface of an aluminium coated pellicle driven from behind by a loudspeaker, as shown in Figure 23. A single continuous wave 1.5 kHz tone was used at various levels to drive the loudspeaker.

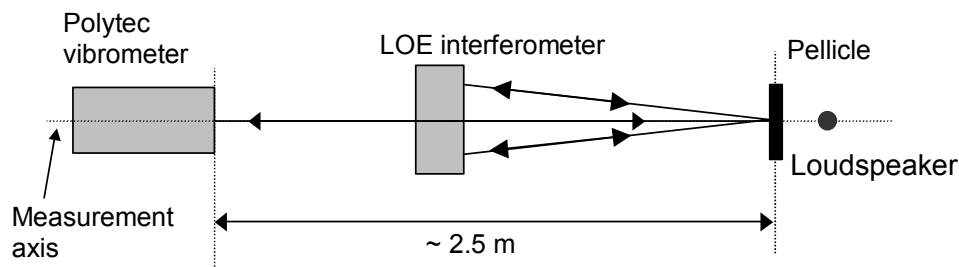


Figure 23. Measurement configuration.

A local oscillator frequency of 79.54 MHz on the mixer stage of the all-fibre interferometer was used to give a resultant mixed-down frequency of 360 kHz when combined with the 80 MHz carrier frequency. The PLL circuit was then used to demodulate the frequency modulated component of the mixed-down signal, thus tracking the 1.5 kHz acoustic component introduced in the measurement arm of the interferometer from the pellicle and providing an output amplitude proportional to the Doppler shift. The outputs from the Polytec vibrometer and the all-fibre interferometer demodulator were then captured on a Tektronix TDS 520 oscilloscope for comparison at 2,500,000 samples per second.

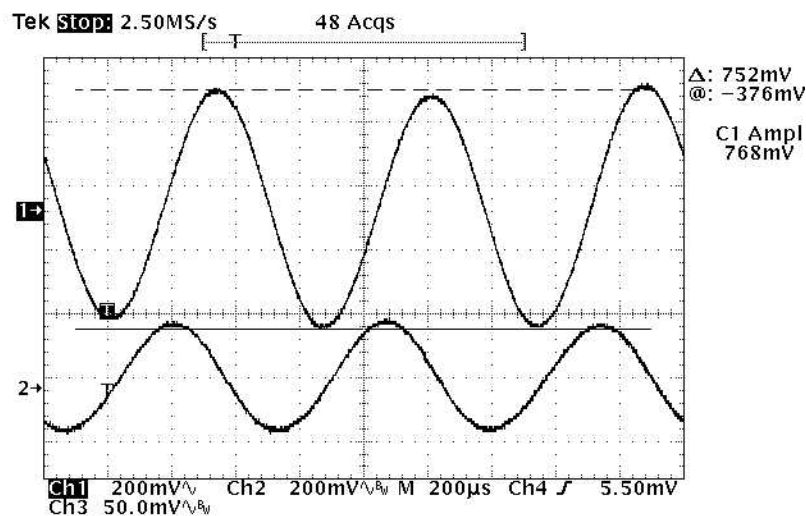


Figure 24. Polytec v LOE interferometer outputs 1.5 kHz 5V acoustic drive level.

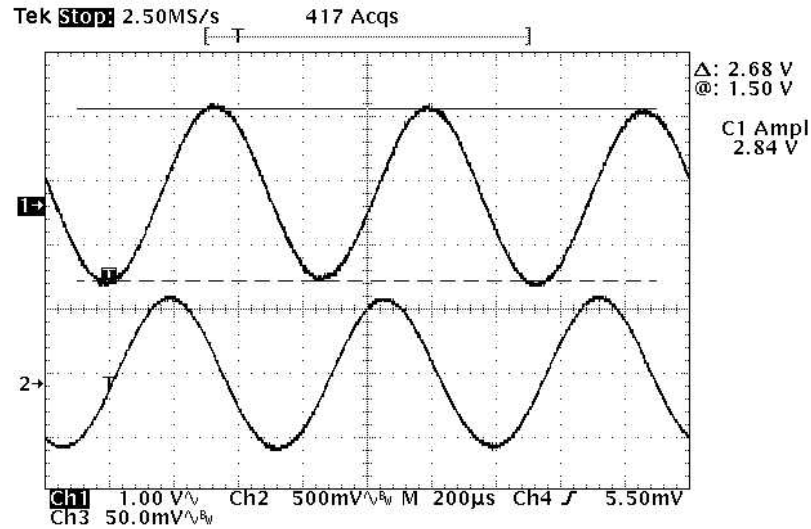


Figure 25. Polytec v LOE interferometer outputs 1.5 kHz 10 V acoustic drive level.

Figures 24 and 25 show the Polytec vibrometer output on channel 1 (upper trace) compared with the output of the PLL output of the LOE all-fibre interferometer on channel 2 (lower trace) for two acoustic drive levels. Figure 24 shows the output response for both devices for a 5 V_{p-p} drive across the loudspeaker. Figure 25 is for an identical set-up except of 10 V_{p-p} drive across the loudspeaker. Note that different scales are used for each figure. In both cases the sinusoidal response of the 1.5 kHz acoustic signal is well represented. The relative phase shift between the two is due to variations in internal amplifier / filter transfer functions and is clearly consistent across the length of the waveform. Figure 26 shows the amplitude obtained from the LOE all-fibre interferometer as a function of the Polytec amplitude for a range of loudspeaker drive levels.

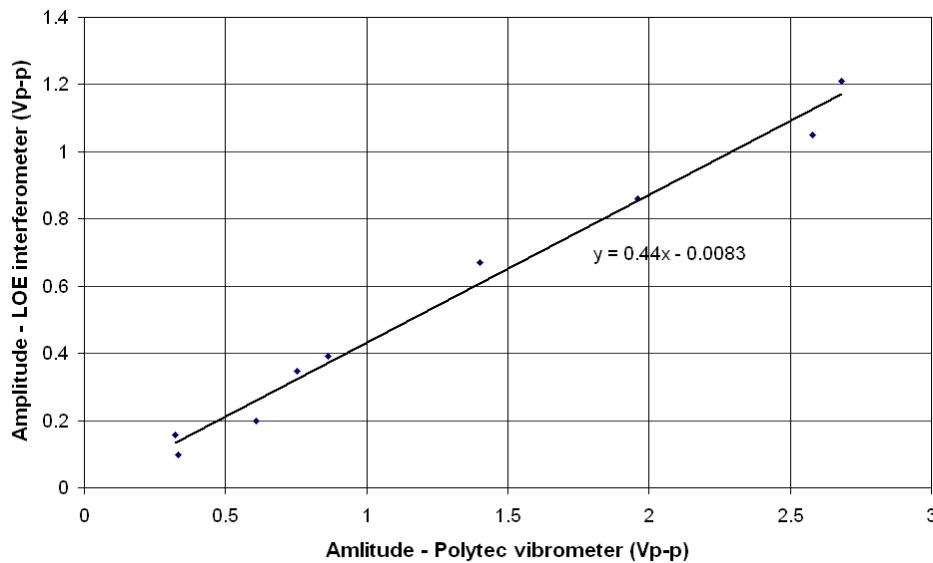


Figure 26. Device outputs for a 1.5 kHz acoustic signal at increasing loudspeaker drive levels.

Figure 26 shows the relative output response for each device at a single frequency but various acoustic drive levels. The linear trend line shows that both devices are tracking the frequency modulation component due to Doppler shift in the carrier in a similar manner with increasing / decreasing acoustic drive level. For the Polytec the voltage range 0.1 to 1.2 V_{p-p} corresponds to 0.035 to 0.42 mm s⁻¹. The actual level response of the LOE interferometer is lower than that of the Polytec vibrometer resulting in a gradient of 0.44. Both responses however tend to very close to zero for decreasing acoustic drive levels showing that this could be corrected using a simple geometric scaling and is primarily due to differences in the post PLL amplifiers gains on the two devices.

The comparison was performed at 1.5 kHz because of the limitations of the PLL circuit. Although this frequency approaches the lower frequency range required in this project, the comparison did demonstrate that the signal to noise of the prototype all-fibre heterodyne interferometer is comparable, even at this early development stage, to a widely used commercial device. The results of the comparison were also encouraging as it demonstrated the prototype capable of measuring down to less than 0.05 mm s⁻¹.

3.5 Further development

This chapter has discussed much of the development process for the all-fibre heterodyne interferometer. The development and improvement of the device is however, a continuous process within this project and the areas for further development can be summarised as follows:

- Modification to optics to allow single beam alignment.
- Investigation into new optical configuration for in-fibre acousto-optic correction.
- Develop and design final Phase Lock Loop system.
- Characterisation of electrical transfer function.

As described in Section 3.2.1.2, implementing a single beam arrangement in the all-fibre heterodyne interferometer is more demanding on the optical configuration than for an equivalent bulk optic device. However, it is essential for the proposed measurement method of using a reflective acoustically compliant membrane that a single beam device be used. This problem was highlighted by the measurements described in Section 3, where the acousto-optic effect dominated the interferometer response. Implementing a single beam configuration would also significantly simplify the alignment of the optical beam with the target. Progress has already been made on modifying the optics to a single beam arrangement. Current developments have employed an optical head consisting of a bulk optic beam splitter and large collecting lens. Work will be focussed on developing this arrangement for use in water and will further consider methods for miniaturising the optical head.

It is also planned to investigate methods of developing the optics such that the measurement arm and the reference arm follow common paths. This would significantly increase the interferometers tolerance to external noise sources. If correctly designed, it could also offer the ability to correct for any in-fibre acousto-optic effects for a situation where the fibres may be in the acoustic field. This would be the case where the optical head is close to the pellicle and therefore in the acoustic measurement window. Of course, this could only be realised if the optical head were small enough not to perturb the acoustic field.

Following measurements using the prototype PLL circuit, work is planned to design and develop a complete demodulation hardware solution that will offer the required dynamic range, acoustic frequency range, velocity measurement resolution and noise floor. Initial indications are that it will be difficult to achieve the required specification with a single PLL. It may therefore be necessary to use a number of carrier frequencies and demodulation stages to achieve the required dynamic range and measurement bandwidth.

4 ACOUSTIC CONSIDERATIONS

4.1 Acousto-optic investigation

For the calibration of hydrophones using an optical method, the refractive index change in the water as a result of the acoustic field, or the ‘piezo-optic coefficient’ must be accounted for [8]. This has been considered by both Drain [3] and Bacon [4] [8] [9] in the literature and has been applied in practice for the calibration of high frequency hydrophones at NPL for many years [10] [11].

4.1.1 Plane wave

For a plane wave front, where the optical beam enters a water tank through an optical window and propagates a length L through the water before reflection from the pellicle as shown in Figure 27, an ‘effective’ refractive index, n^* , can be applied in place of the standard refractive index, n , of the propagating medium (water).

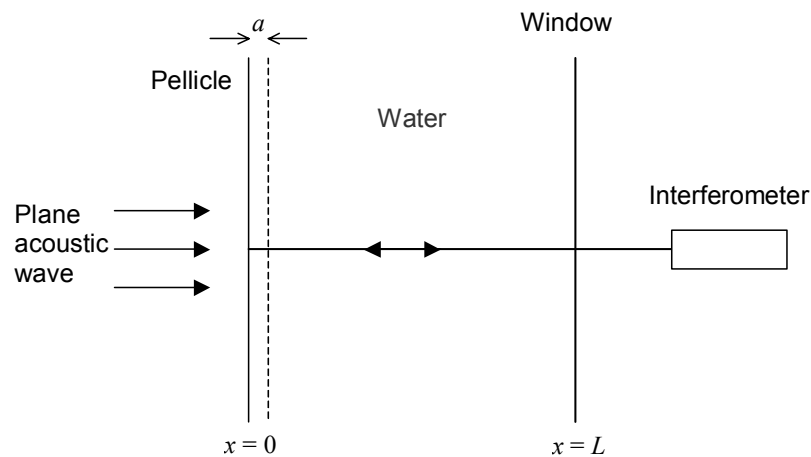


Figure 27. Schematic of the arrangement for calculation of acousto-optic coefficient in the presence of a plane acoustic wave.

For the arrangement depicted in Figure 27, both Drain [3] and Bacon [8] [9] have derived the required ‘effective’ refractive index.

4.1.1.1 Drain method

The pellicle surface moves a small distance, a , in response to the acoustic wave. Since the initial optical path length in the absence of the sound wave is $2n_0L$, and the refractive index is given by $(n_0 + \delta n)$, the difference in optical path length, q , caused by the presence of the acoustic wave is:

$$\begin{aligned}
q(t) &= 2 \int_{a(t)}^L n \, dx - 2 n_0 L \\
&= 2 \int_{a(t)}^L n_0 \, dx + 2 \int_a^L \delta n \, dl - 2 n_0 L \\
&= 2(n_0 L - n_0 a(t)) + 2 \int_{a(t)}^L \delta n \, dx - 2 n_0 L \\
&= -2 n_0 a(t) + \int_{a(t)}^L \delta n \, dx
\end{aligned} \tag{6}$$

where L is the distance from the pellicle to the window and x is the variable along the axis of tank transducer and laser beam. It should be noted that, the optical beam traverses the path twice (to the pellicle and back) and that the displacement, a , is actually a function of time.

If we consider the mass of the material contained within the surface of the pellicle and the window within a cylinder of cross sectional area A whose axis is along direction of propagation:

$$\begin{aligned}
M &= A \int_{a(t)}^L (\rho_0 + \delta \rho) \, dx \\
&= \rho_0 A L - A \int_0^L \delta \rho \, dx - a(t) \rho_0 A
\end{aligned} \tag{7}$$

This shows the steady state mass (first term) and the varying part (the second terms). Since we have assumed a plane wave condition such that there is no sideways movement of the water particles, the mass must remain constant, i.e.

$$\rho_0 a + \int_0^L \delta \rho \, dl = 0 \tag{8}$$

Assuming a linear relationship of refractive index and density (justifiable for small amplitudes), the above equations give:

$$q(t) = x \left(n_0 - \rho_0 \frac{dn}{d\rho} \right) \tag{9}$$

We can then define an effective refractive index, n^* , such that:

$$\begin{aligned}
n^* &= n - \rho \frac{dn}{d\rho} \\
&= n_0 - n_1
\end{aligned} \tag{10}$$

where n_1 is the elasto-optic coefficient. To find n_1 and thus calculate n^* it is reasonable to assume that,

$$(n - 1) \propto \rho \quad (11)$$

which assumes that the increase in optical path is proportional to the increase in the number of particles in the path of the optical beam and therefore to the mass. In this case, the effective refractive index, n^* is exactly equal to unity.

The adiabatic variation of refractive index, n , with pressure and with density can be related by the following expression given by Raman and Venkatamaran [12] and later repeated by Riley and Klein [13]

$$\rho \frac{\partial n}{\partial \rho} = \frac{1}{\beta} \frac{\partial n}{\partial p} \quad (12)$$

where $\beta = 1/\rho c^2$ and is the adiabatic compressibility of the medium. The term $\rho(\partial n/\partial p)$ (equal to n_1 in Equation (10)) is termed the elasto-optic coefficient and can be used to accurately calculate n^* from Equation (10). These coefficients have been determined experimentally and values are available from the literature [13] [14] [15] [16]. Values available in the literature of 0.323 for 633 μm light and 20 °C, giving a value of n^* of 1.009.

4.1.1.2 Bacon method

In his work, Bacon [8] starts with,

$$q(t) = 2 \int_{a(t)}^L n dx - 2 n_0 L. \quad (13)$$

In order to be able to perform this integration, we must know the variation of refractive index with acoustic pressure. To a *first order* approximation (perfectly acceptable for the amplitudes of <100 kPa generally used), a linear dependence can be assumed and a first order Taylor series expansion used:

$$n = n_0 + \frac{dn}{dp} p \quad (14)$$

where n_0 is the value of n at the ambient pressure (p_0), p is the acoustic pressure, and the partial derivative is taken under adiabatic conditions.

This is convenient since the term $(\partial n/\partial p)$ can now be written as $n_1/\rho c^2$ where n_1 is the elasto-optic coefficient. Inserting this into the above equation and simplifying gives for small displacements:

$$q(t) = -2 n_0 a(t) + 2 \frac{n_1}{\rho c^2} \int_0^L p(x,t) dx \quad (15)$$

therefore, in the case of a plane wave (which has no propagation losses), this can be reduced to:

$$q(t) = -2 n^* a(t) \quad (16)$$

where $n^* = n_0 - n_1$. So, for *plane waves* the effect of the acousto-optic interaction can be accounted for by the use of an effective refractive index.

Although the effective refractive index, n^* is deduced under the condition that the tone-burst fills the region between the window and the pellicle, this is not necessarily the case. The position of the window can be regarded as a reference plane and can be set arbitrarily to be anywhere along the length of interaction, such that Equation (10) is tenable before the wavefront reaches the optical window.

4.1.2 Spherical wave

A spherical wave case has been considered by Yuebing [17] [18] as part of his work at HAARI and also as part of initial investigations at Loughborough University into the acousto-optic interaction on this project.

Figure 28 shows the case of a spherical wave incident on a pellicle with the laser beam aligned through the center of transducer, perpendicular to the pellicle.

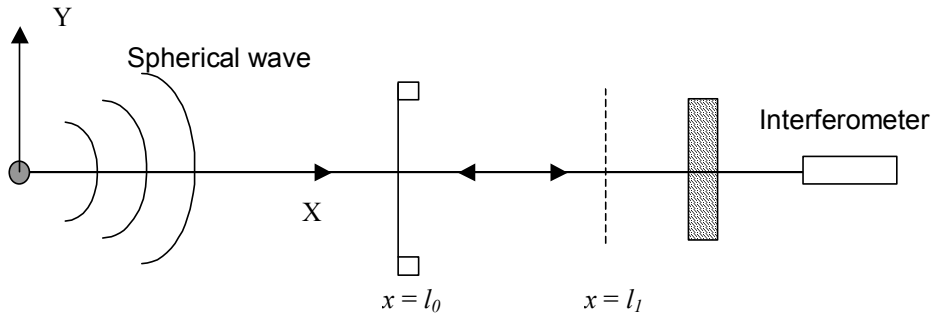


Figure 28. Schematic of the arrangement for calculation of acousto-optic coefficient in the presence of a spherical acoustic wave.

Supposing that the pellicle is positioned in the plane $x = l_0$, and $x = l_l$ is a plane of reference which can be described as the position of the wavefront at the time t , then the pressure of the spherical wave can be described as,

$$p(x, t) = A_0 e^{j(\omega t - kx)} / x. \quad (17)$$

The displacement amplitude at the position of $x = l_0$ can be expressed as,

$$a(t) = \frac{A_0 e^{j(\omega t - kl_0 - \varphi_0)}}{l_0 \cdot (j\omega \cdot |Z_0|)} \quad (18)$$

Where, $|Z_0| = \frac{\rho c k l_0}{\sqrt{1 + (k l_0)^2}}$ and $\varphi_0 = \tan^{-1}(1 / k l_0)$.

From Equations (6) (for small displacements), (17) and (18) the refractive index can be deduced

as,

$$n^* = -n_0 \frac{kl_0 - i}{kl_0} + n_1 kl_0 e^{ikl_0} \left(\frac{e^{-ikl_1}}{kl_1} + i \int_{kl_0}^{kl_1} \frac{e^{-ix}}{x} dx \right) \quad (19)$$

In contrast to the ‘effective’ refractive index, n^* , for a plane wave case, n^* for the spherical wave case is dependent on both frequency and the position of l_0 and l_1 . This arises partly because of the variation in amplitude of the wave encountered by the laser beam and partly because the simple relationship between displacement and acoustic pressure no longer applies [8].

Figure 29, calculated by Yuebing [17], shows the calculated ‘effective’ refractive index as a function of frequency using Equation (19) for a measurement arrangement such that $l_0 = 0.3\text{m}$ and $l_1 = 0.9\text{m}$.

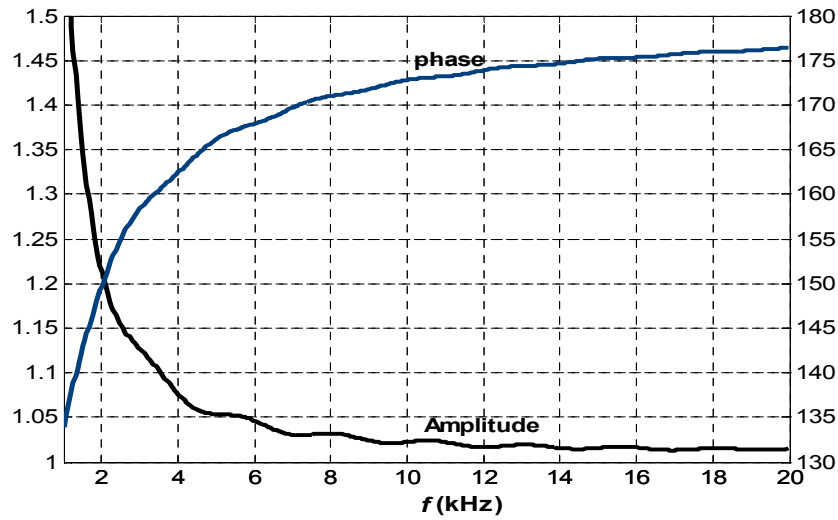


Figure 29. Calculated effective refractive index, n^* , as a function of acoustic frequency, f .

Figure 29 shows that above around 15 kHz, the effective refractive index will tend to a constant of 1.01 with negligible error, which is the effective refractive index used for current high frequency calibrations at NPL [8]. At lower frequencies however, the correction is not so simple and constant correction cannot be used. The current project aims to calibrate hydrophones between 1 kHz and 500 kHz, so the effective refractive index used for each particular measurement will have a strong dependence on frequency.

It is planned to experimentally validate the 1.01 acousto-optic correction used at higher frequencies using the total reflection method, where a pellicle is placed at the surface of the water with an acoustic projector positioned in the water below the surface. The advantage of this technique is that the measurement of acoustic pressure at the pellicle is not influenced by the acousto-optic effect because the laser is in air. Comparison can then be made between this method and the case where the pellicle is submerged in the water with the laser propagating through the acoustic field in the water.

Further work is also necessary within this project to validate the acousto-optic relationship at lower frequencies and if possible simplify Equation (19) without appreciable loss of accuracy in determining the effective refractive index.

4.2 Pellicle design

The acoustic particle velocity measured at the pellicle surface is done so after the acoustic wave has passed through the pellicle. Therefore, any reflection or absorption in the pellicle layer will influence the measurement velocity. The effect of the pellicle transmission was investigated by Bacon [8], and later by Esward and Robinson [10] using an insertion method to experimentally determine the extent of transmission loss at higher frequencies. The transmission losses at 10 MHz and below were small but measured, and allowed a correction to be made when calibrating the high frequency hydrophone. At the lower frequencies encountered in this project (below 500 kHz), the transmission loss is expected to be negligible. To predict the transmission losses below 500 kHz, a simple 3-boundary transmission model was used. The results are shown in Figure 30, based on a 23 μm and a 50 μm Mylar membrane coated with a 40 nm aluminium film in water.

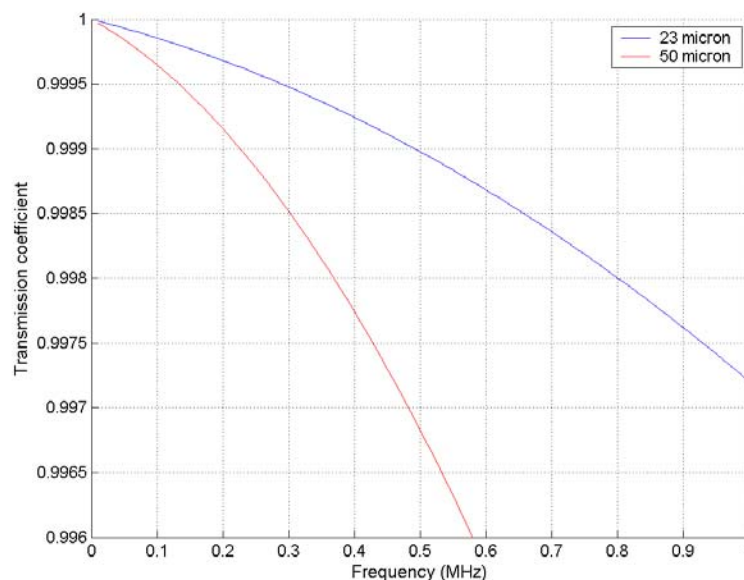


Figure 30. Acoustic transmission through aluminium coated Mylar pellicle.

Using a 23 μm membrane has negligible affect on the transmission of the acoustic wave up to 500 kHz and should therefore comply closely with the acoustic particle oscillation. Increasing the thickness of the membrane or pellicle, as expected, increases the transmission loss, although it is still very small even for a 50 μm membrane.

Further work needs to be undertaken to explore the effect of pellicle thickness. As the membrane thickness increases, or the transmission coefficient decreases it is expected that the membrane will be less compliant to the acoustic field and could lead to errors in the measurement. It is intended that this be explored further by performing a series of measurements of acoustic particle velocity at the pellicle surface for different thicknesses of pellicle when subject to the same acoustic field.

Further work is also necessary to extend the mount for the pellicle to provide an echo-free window of around 1 ms.

5 CONCLUSIONS

Initial findings from both Phase One and Two of the project showed the heterodyne interferometer to be the most suitable optical measurement method for this project. The proposed method of measurement was to optically measure the target velocity of an acoustically compliant membrane in the acoustic field. The main reasons for choosing the heterodyne interferometer configuration are its ability to measure linearly over extended displacements, its inherent robustness to external vibration, its direct measurement of target velocity and its relative insensitivity to returning light level. The all-fibre heterodyne interferometer design, proposed in Phase One of this project has now been developed to a first prototype specification and has been extensively tested as part of Phase Two of the project. Initial tests were performed at several stages of its development and results have been presented that show its response to acoustic field parameters. Significant improvements in signal-to-noise of around 30 times were achieved by RF engineering of the prototype pre-demodulation electronics and other gains were achieved by optimisation of the optics following a comprehensive light-budget to identify areas for potential improvement.

With significant improvements made to overall performance of the interferometer, it was then tested at NPL using the small open water tank. These measurements were performed to demonstrate the interferometers response to acoustic field components in a calibration environment similar to that for which it would be used. The results were analysed using software Doppler decoding and showed disagreement with comparative measurements made with a calibrated hydrophone. It was thought that the disagreement was due to the interferometers response to the refractive index change in the water of the acoustic field. Had the interferometer used a single beam configuration, this would not have occurred. However, this was not possible with the prototype model. The acousto-optic interaction and the ease of alignment of the interferometer make the development of a single beam optical head of vital importance. This type of configuration has already been investigated and will be further developed as part of Phase Three of the project. Other plans for improvement to the optical configuration include investigating the possibility of using common path reference and measurement arms in the interferometer, to make it tolerant to external vibration and to possibly correct for any in-fibre acousto-optic effects when used in water.

Recent developments to the interferometer have been the addition of a first prototype demodulation circuit to decode the Doppler frequency shift. Initial comparison against a commercial Polytec vibrometer unit were encouraging, showing a comparable signal to noise performance and response to a target velocity of less than 0.05 mms^{-1} . Development of a suitable Doppler decoder for the interferometer output is a high priority task for Phase Three and will be undertaken with external consultation to produce a demodulation stage specifically designed for the velocity and frequency range of interest.

The recent addition to the project team of the visiting academic from the Hangzhou Applied Acoustics Research Institute (HAARI), China, has enabled some initial investigations into the acousto-optic effect to be performed. A mathematical analysis has been applied to both plane and spherical wavefronts to derive the effective refractive index required. For low frequency acoustic measurement, where the number of acoustic cycles propagated by the optical beam is reduced, the calculation of the effective refractive index becomes highly dependent on the acoustic frequency and the optical path length through the measurement medium. Further work is planned to experimentally validate the effective refractive index. It is also planned to investigate the effect of pellicle thickness on the measured acoustic field.

6 ACKNOWLEDGEMENTS

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