DETERMINING INFRASOUND PHASE VELOCITY DIRECTION WITH A THREE-ARM OFIS

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ABSTRACT

Optical fiber infrasound sensors (OFIS) are long, compliant tubes wrapped with two optical fibers that interferometrically measure pressure change. Because the differential pressure variation is integrated along the length of the tube, the instrument response is a function of the orientation of the OFIS relative to the orientation of the wavefront. We show with real data recorded at Pinion Flat Observatory in southern California and in the 2006 White Sands Missile Range II experiment in New Mexico that this spectral property can be exploited with multiple OFIS in different ways to determine the phase velocity of infrasound signals. We identify the strengths and weaknesses of such techniques, and compare them to time-delay techniques used with traditional microbarometer arrays. We also introduce two new techniques that should be significant improvements upon the technique we use to estimate phase velocity direction from OFIS data. As this research is ongoing, this paper is written as a progress report.
OBJECTIVES

The overall objective of our research is to further the development of OFIS. The original motivation for this research was to reduce the detrimental effects of wind noise by averaging pressure change along a line. However, we also recently became interested in how well an OFIS can obtain signal orientation parameters (phase velocity direction) as the signal propagates across the recording site because a multi-arm OFIS occupies less space than a traditional microbarometer array (Figure 1).

Figure 1. A typical 8-element infrasound array (left) and a 5-arm OFIS on the right. Rosettes are spatial filters created by an array of inlets connected to underground pipes that all connect to a centrally located microbarometer.

The specific objective of this research that we report on here is to develop and test techniques for resolving infrasound signal phase velocity direction with a 3-arm OFIS. We deploy and collect real signals at Pinion Flat Observatory (PFO) and as part of the March 2006 White Sands Missile Range (WSMR) controlled-source infrasound experiment to validate the theory we base our algorithms on, and to determine if an n-arm OFIS can resolve phase velocity direction better than an n-arm microbarometer array.

RESEARCH ACCOMPLISHED

We present below the most current details of our phase velocity determination research with a multi-arm OFIS. But we present first the obstacles that we encountered, what we learned from them, and how we dealt with them during our research.

Obstacles and Miscellaneous Accomplishments

Several obstacles developed during this research. In the past we relied on a commercial software package called Progressive Multi-Channel Correlation (PMCC) to obtain phase velocity direction for real signals. We generally assumed these PMCC results to be accurate and therefore be the “ground truth” in our comparisons (Walker et al., 2005). The PMCC software package gives results in a compact form, leaving out a lot of additional information about how well constrained the results are. Because our research requires us to make precise comparisons between the “ground truth” and the results of our algorithms, we developed a beamforming software package that provides the additional information about accuracy and resolution not available in our PMCC package. Using this new software, we discovered that we were not accounting for a known timing error associated with one of the elements of the I57US array. We confirmed that this error could have significantly degraded our previous PMCC-derived calculations. With our new beamforming software, we have calculated the phase velocity direction for 327 new high-quality signals at PFO as well as the signals obtained at station BACA during the WSMR II experiment.

Another obstacle that we encountered in our research was a source of noise that we needed to better understand because it is quite pervasive in the time series. In previous reports (Walker et al., 2005) we called this problem “spiking,” and suggested it was due to creaking between the fiber and silicone tube, which gave rise to sharp steps in the optical fiber path length difference and resulting pressure change. We call this “spiking” because we often observe the filtered version of these offsets, which resemble spikes in the time series. This spiking problem occurs...
when the sun begins to set and lasts for many hours. We also see spikes during the morning, although they are not as pronounced. We needed to better understand this problem because about half of the signals detected at PFO occur during these spiking periods. Unfortunately this was a lengthy experimentation process. We created some new OFISs, modified the design, and performed some pressure and controlled-temperature tests. The problem generally revealed itself when we suspended an OFIS above the ground—the spikes are most likely due to the relative motion of the silicone tube on the ground itself as the tube expands and contracts with temperature change.

A minor issue that affects uptime is polarization change in the fibers wrapped around the OFIS, which is strongly correlated with temperature change. We briefly performed an experiment on a variation of a polarization diversity detector to determine if one could obtain a stable ellipse by splitting the recombined signal into two different orthogonal polarizations and photodetectors, then using the lock-in amplifier to lock in to the summation of the photodetector outputs. The idea was that when one ellipse was collapsing, the other was getting larger, but the summation of the two would always produce a well-formed ellipse. Our brief experiment suggested that this technique does not yield the results we desire.

**Sensor Directivity**

The instrument response, \( R \), of an OFIS relative to a point detector is a function of the orientation of the signal propagation with respect to the length of the OFIS:

\[
R(f) = \operatorname{sinc}\left(\frac{L f}{V_a} \cos(\theta)\right)
\]

where \( f \) is frequency, \( L \) is the length of the OFIS, \( V_a \) is the sound speed at the Earth’s surface (~330-350 m/s), and \( \theta \) is the angle between the incident ray path and the OFIS

\[
\theta = \cos^{-1}(\cos(\theta_b) \cos(\theta_e))
\]

where \( \theta_b \) is the back azimuth, and \( \theta_e \) is the elevation angle. For typical infrasound signals from distance sources, \( \theta_e \) is 0–30° (subhorizontal) and \( \theta B \theta_e \). Figure 2a shows a polar plot of \( R \) as a function of angle from the long axis of the OFIS for three typical infrasound signal frequencies.

![Figure 2. Frequency response \( R \) for a 90 m long OFIS as a function of frequency and angle \( \theta \) from the length of the OFIS (Eqs. 1–2).](image)
The response $R$ is dependent on the ratio of the OFIS length to the frequency (Figure 2b). For low frequencies and long wavelengths relative to the OFIS length, the OFIS is effectively a point sensor and records the wavefront perfectly. For higher frequencies and shorter wavelengths, the OFIS attenuates some part of the signal because many of the peaks and troughs in the wavefront tend to average out along the length of the OFIS. The sinc form of this response can be thought of as the Fourier transform of a boxcar time series function, which represents the averaging of an impulse function signal as it propagates across the OFIS. For rays perpendicular to the OFIS, the impulse signal is recorded perfectly (flat amplitude spectrum) since the wavefront is parallel to the OFIS. For rays at lower angles to the OFIS, the impulse is smeared in time into a boxcar shape with a lower amplitude, resulting in the sinc function for the amplitude spectrum.

Typical power spectral densities (PSDs) of infrasound signals show modest levels of microbarom and wind noise. Figure 3a shows a hypothetical PSD example of a signal recorded by an OFIS oriented 29 degrees from the signal phase velocity direction. Although infrasound signals from distance sources have been observed in the ~0.7–15 Hz range on microbarometers, this OFIS only detects the signal in the ~0.7–7 Hz band because of the averaging property ($R$, Figure 3b). The slope as a function of frequency of the PSD from about 2–7 Hz provides valuable information about the true signal spectrum and the signal propagation direction with respect to the OFIS orientation. However, we have found that for the signals recorded on the 90 m OFIS at PFO, the most practical bandwidth to isolate this slope information is ~ 2–5 Hz. For longer and shorter OFIS lengths, this optimum range will shift to lower and higher frequencies, respectively, but will also be dependent on the bandwidth of the signals of interest.

![Figure 3. Details of the relationship between recorded signals and the instrument response function. A hypothetical infrasound signal recorded by an OFIS that is oriented 29 degrees from the propagation direction shows two peaks in the power spectral density (a) due to the directional instrument response (b).](image-url)
Since $\theta$ is known in this case to be 29 degrees, one could deconvolve $R$ from the recorded signal $S_r$ in frequency space to determine the actual signal spectrum and waveform $S_w = S_r / R$. Ideally what is left is the signal spectrum, which is a convolution of the source and path term, in the 2–5 Hz band for a 90 m OFIS. However, traditional deconvolution is unstable in this case because the denominator $R$ has near-zeros for certain frequency bands. To get around this problem, we have been using a water-level deconvolution method, which increases the amplitude of $R$ in these troughs to 2% of the maximum (Figure 3b). This water-level technique introduces noise into $S_w$, but we have developed a better deconvolution technique that uses a least-squares inversion of the recorded frequency spectra of several OFIS (discussed later).

**Phase Velocity Direction Determination Techniques**

We typically want to obtain $\theta$ and the signal source spectrum from our infrasound sensors. One obvious way to do this is to have an array of several circular OFIS in a configuration optimized for time-delay beamforming in the frequency band of interest (Figure 4). However, the instrument response of a linear OFIS is highly dependent on the ray orientation, and so we can exploit this dependence by forming an array comprised of linear OFIS arms in different orientations. Therefore, for each possible ray orientation, there is a transfer function $R$ that is unique to each OFIS that relates the signal spectrum $S_w$ to what should be recorded by that OFIS. Quantitatively, the recorded OFIS signal is $S_r = f(S_w, \theta, L)$, where only $S_w$ and $\theta$ are the unknowns. One can therefore estimate $S_w$ and $\theta$ if one records the signal on two OFIS with different orientations (Figure 4a)

$$S_{r1} = f(S_w, \theta_1, L, V_a)$$
$$S_{r2} = f(S_w, \theta_2, L, V_a)$$

where $\theta_1$ and $\theta_2$ are related by the array configuration. One can do this by substitution, i.e., using $S_{r1}$ to predict $S_w^p$, and then $S_{r2}^p$

$$S_{r2}^p = S_w^p R_2 = S_{r1} R_2 / R_1.$$  \(4\)

We perform a grid search over trial $\theta$ (back azimuth and elevation angle; Eq. 2) to minimize the L2 misfit between the inverse Fourier transforms of $S_{r2}$ and $S_{r2}^p$. The global minimum corresponds with the phase velocity direction. Knowledge of the L2 misfit function allows us to calculate formal 2$\sigma$ error bars by assuming the misfit function is the sum of squares of a random chi-squared noise process. We determine the number of degrees of freedom based on the average recorded signal bandwidth, which frees us from the typical assumption that the observed signal samples are independent of each other (white spectrum). This method calculates the misfit function by using one OFIS (e.g., OFIS 1) to predict what the other OFIS (e.g., OFIS 2) is observing. We have verified that the method is more stable by also calculating the misfit function in the other direction (using OFIS 2 to predict OFIS 1) and summing the two misfit functions.

The above method is ideal for two OFIS separated by 90 degrees (Figure 4a). The 90 degree separation offers identical spectral resolution for phase velocity directions in all of the quadrants. In addition, it is computationally fast because one only needs to do the grid search within one of those quadrants to get the spectral resolution. For each trial, we can therefore obtain the spectral constrains, and then the time shift constraints (since the centers of the OFIS arms are separated) by time shifting the resulting inverse Fourier transformed waveform four times (corresponding to the four possible quadrants) to calculate four separate misfit values. It can be shown that the amount to time shift is

$$dt = (h_2 \cos \alpha_2 - h_1 \cos \alpha_1) \cos \theta / V_a$$  \(5\)

where $\alpha$ is the angle between the trial $\theta$, and the OFIS azimuth and $h$ is the distance from the array center to the center of the OFIS arms.

The 2-90 configuration has been tested on real signals recorded at the PFO (Walker et al., 2004; 2005). A 2-90 works well for sub-horizontally propagating signals with a good amplitude signal-to-noise ratio (SNR>2). However, it does not work as well for signals that are propagating close to, but not quite parallel to the OFIS, because the
predicted difference in the time shift that distinguishes between two of the four possible quadrants is very small (Figure 4a). A fundamental limitation of any two-arm OFIS configuration is that it cannot be used to determine a phase velocity direction within the vertical plane defined by the azimuth in between the two OFIS.

Figure 4. Possible OFIS configurations. Configurations a–d could be used in directional instrument-response dependent beamforming, and could provide a better phase velocity direction estimate if the wind noise suppression is good. Configuration e could be used in the same sense as pipe rosette filters or hose arrays. Configuration a, b, and e has been tested against pipe and hose arrays. For some signals the SNR is better on the OFIS. For other signals the SNR is better on the pipe and hose arrays.

We refer to the technique above as the “water-level deconvolution-predicted-OFIS comparison” (WLD-POC) technique. WLD-POC can be applied to OFIS in different configurations (Figure 4a–d), but the computational time for the above method is proportional to $n(n-1)$ and there is an additional doubling of CPU time associated with going from a 2-90 configuration to 3-120 or 5-72 configuration because one does not have quadrant symmetry anymore with regard to spectral resolution, but rather hemisphere symmetry. A 5-22.5 configuration still benefits from quadrant symmetry, but does not have the same degree of time separation resolution as the 3-120 and 5-72 configurations. For lower frequency signals (e.g., 0.5-2.0 Hz for 90 m OFIS), the time shift information is critical in determining the phase velocity direction.

Promising New Techniques

The WLD-POC technique is inherently unstable because of the deconvolution step. We have developed two new algorithms that avoid this step, but we have yet to confirm that they work better than the above method. The first method we call the “array response comparison” (ARC). We recall that the observed signals for two OFIS are $S_1 = S_a R_1$ and $S_2 = S_b R_2$. We can multiply both sides of these equations by the opposite response function $S_1 R_2 = S_a R_1 R_2$ and $S_2 R_1 = S_b R_2 R_1$. Because of the commutative property of multiplication in the frequency domain, the right hand side of these two equations are equal, and therefore $S_1 R_2 = S_2 R_1$. We call this quantity the “array response” to the signal waveform. Each OFIS can be used to generate an array response for some given phase velocity direction. For the correct phase velocity direction, the array responses estimated from each OFIS should be equal. Therefore, we can perform a grid search over trial phase velocity direction and minimize the misfit between the estimated array responses. One could do this for $n$ OFIS arms, where for each trial direction each OFIS recording would be convolved with $n-1$ instrument responses before being inverse Fourier transformed back to the time
domain where the misfit is evaluated. The ARC technique completely avoids deconvolution in determining the phase velocity direction. However, it does not inherently provide us with an estimate of the true signal spectrum.

Another technique we have developed is called the concurrent array deconvolution (CAD) technique, which replaces the water-level deconvolution step in the WLD-POC method. CAD is used in the POC grid search approach to estimate the signal spectrum by weighting, as a function of frequency and trial phase velocity direction, the recorded spectra of the OFIS arms such that only those OFIS arms that are in a good position to estimate $S_w$ are effectively used. For example, if one had a 4-arm OFIS that recorded a signal with a phase velocity direction that was 0, 29, 58, and 87 deg from the OFIS arms, respectively (Figure 2b), at a frequency of 7 Hz, CAD would determine the signal spectrum from the OFIS spectra weighted from heaviest to least in this order: OFIS 4, OFIS 2, OFIS 3, and OFIS 1. Due to length restrictions, we postpone deriving this technique until we have tested it on real signals.

Figure 5. Back azimuth comparison.

Three-Arm OFIS: Analyzing Real Data

Using the WLD-POC method, we tested the 3-120 configuration and WLD-POC algorithm on many infrasound signals of good signal-to-noise ratio recorded during 2005-06 (Figure 5). Some of these results were reported in Walker et al. (2005); however, those previous results were not plotted correctly and we replot them correctly here along with some new measurements. We compare our estimated phase velocity directions with those obtained from the co-located I57US with the PMCC algorithm and our newly developed time-domain beamforming (TDB) software. The blue symbols indicate PFO signals that were analyzed by WLD-POC and PMCC. The PMCC results may have been affected by a timing error on one of the array elements (H2), and have questionably small error bars. The red symbols are PFO signals that were analyzed by WLD-POC and TDB (shown in more detail later). These signals are known to have signal-to-noise ratios greater than two and are from the analysis of eight time windows that comprise an infrasound wavetrain originating from an airplane above PFO. The green symbols represent WSMR II (BACA) signals that were analyzed by WLD-POC and TDB (also shown later). The WSMR II line-of-sight back azimuths to the launch pad and explosions provides some measure of ground truth. In all non-PMCC estimates, the 2σ error bars are shown. We do not know what level of certainty the PMCC error bars represent. In general there is a root mean square (RMS) deviation of about +/-10 deg. If we assume that the non-OFIS measurements represent the true back azimuths, then the error bars associated with the OFIS azimuths are consistent with the deviations. Based on some previous synthetic tests, this deviation would likely be less if we were using a 5-72 or 5-22.5 configuration.

An airplane that flew above PFO created an infrasound wavetrain that was recorded on both the 3-120 OFIS and three elements of the co-located I57US array (Figure 6). The three elements used at PFO were the 18 m underground rosettes, which are separated by 150–180 m, for a footprint of ~220 m. Each of the three OFIS arms is 90 m long.
for a footprint of about 180 m. The footprints are about the same in size. The phase velocity direction and 2σ error bars are obtained for each of the eight 6 sec time windows. The back azimuths of these measurements are also presented in Figure 5. Both sensor systems tracked the plane fairly well. Although the OFIS error bars include the pipe array estimate most of the time, the pipe array consistently yielded smaller error bars, even though the method for obtaining these error bars was the same for both. This is also reflected by the linearity of the pipe-array flight path (red line) as compared to the more rugged OFIS flight path (blue line), and is consistent with measurements of the signal-to-noise ratio for each of the time windows. Unfortunately the array elements are not co-located with the OFIS. Although this could explain the signal-to-noise differences, the rosette filters could also be reducing wind noise better than the OFIS arms. At such high elevation angles, the instrument response is almost flat for all three OFISs, so the OFIS instrument response is not the reason the signal-to-noise is lower. These results prove that not only is the back azimuth constrained by a 3-120 OFIS array, but the elevation angle is also constrained.

Figure 6. The results of the analysis of the airplane-induced infrasound wavetrain. The flight track defined by the 3-arm OFIS results and the 3-element pipe array is shown in (a). The average (for all sensors) signal-to-noise ratio of the time windows are shown in (b).

Figure 7 shows the analyzed waveforms and corresponding misfit functions for one of the time windows of the airplane signal in Figures 5 and 6. The grid shown is the log10 of the misfit for presentation purposes. The OFIS misfit function is more complex, although the misfit region is still fairly well defined and includes the pipe array solution. On the right hand side of Figure 7a are the predicted OFIS waveforms compared with the observed OFIS waveforms. For example, the bottom trace (OFIS 1->2 p/o) is OFIS 2 predicted from OFIS 1 (red) as compared with the observed OFIS 2 (black) for the optimum OFIS solution. The correlation coefficient between the two is shown on the left of the traces. The average is shown at the bottom and ideally should be 1.0 in the presence of no noise and with a perfect deconvolution technique. The estimated signal waveforms and the result of stacking these traces are shown in blue. For the pipe array, the time-shifted signals are also stacked together, and the correlation coefficients are with respect to this stack.

White Sands Missile Range II (WSMR II) Experiment Results

We deployed a new 4-arm OFIS, a 50 ft circular OFIS, and some array sensors at a remote site in New Mexico (BACA) during the 2006 WSMR II controlled-source infrasound experiment. Two small rockets were launched in the early morning hours from White Sands to 35 km altitude where they exploded. BACA was located about 115 km from the explosion epicenters. We used the WLD-TOC and TDB to analyze the several detected signals (Table 1; see also Figure 5). For both techniques, we assumed a velocity of 330 m/s based on the ambient temperature, and bandpass filtered the signals between 1 and 6 Hz. There were two suites of detected signals. Signals of around 0.2 Pa before the predicted explosion arrival time, with a back azimuth between 208 and 221 degrees, are interpreted as due to shockwaves associated with the acceleration of the rocket to supersonic speeds above the launch pad, which had a predicted azimuth (paz) of 216 degrees. The second suite of signals arrived at the predicted travel time for the explosions with amplitudes of 0.33 and 1.0 Pa for shot 1 and 2. The phase velocity directions are similar, but significantly different in some cases (bold). Some measurements are significantly different than the line-of-sight estimate (red). In general, the OFIS error bars are larger than those for the hose array. However, the hose array used 4 sensors as compared to 3 sensors for the OFIS, so this likely contributed to the smaller error bars.
Figure 7. Comparison between the resolution of a 3-arm OFIS (a) and a 3-element pipe array (b) for a time window of an airplane infrasound signal at PFO (left) and a signal during the WSMR II experiment (right).

Table 1. WSMR II phase velocity direction comparison between OFIS and hose array results at station BACA

<table>
<thead>
<tr>
<th>Signal</th>
<th>UTC</th>
<th>Max Amp</th>
<th>Paz</th>
<th>OFIS az</th>
<th>OFIS σ</th>
<th>OFIS cor</th>
<th>OFIS snr</th>
<th>HOSE az</th>
<th>HOSE σ</th>
<th>HOSE cor</th>
<th>HOSE snr</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-lnch</td>
<td>09:0538</td>
<td>0.21</td>
<td>216</td>
<td>209</td>
<td>6.5</td>
<td>0.63</td>
<td>13.8</td>
<td>221</td>
<td>3.5</td>
<td>0.88</td>
<td>8.8</td>
</tr>
<tr>
<td>1-exp.</td>
<td>09:0555</td>
<td>0.06</td>
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<td>259</td>
<td>24.0</td>
<td>0.86</td>
<td>2.6</td>
<td>258</td>
<td>14.0</td>
<td>0.85</td>
<td>3.4</td>
</tr>
<tr>
<td>1-exp.</td>
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<td>256</td>
<td>258</td>
<td>7.5</td>
<td>0.91</td>
<td>8.0</td>
<td>264</td>
<td>3.5</td>
<td>0.97</td>
<td>11.5</td>
</tr>
<tr>
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<td>216</td>
<td>209</td>
<td>8.0</td>
<td>0.78</td>
<td>5.3</td>
<td>222</td>
<td>5.0</td>
<td>0.93</td>
<td>6.5</td>
</tr>
<tr>
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<td>256</td>
<td>6.5</td>
<td>0.95</td>
<td>26.0</td>
<td>265</td>
<td>3.0</td>
<td>0.96</td>
<td>30.1</td>
</tr>
</tbody>
</table>
The analysis for the 1.0 Pa explosion signal for shot 2 is shown in Figure 8. Although the 95% confidence region is smaller for the hose array, it is significantly different than the line-of-sight back azimuth, but much closer than the OFIS to the line-of-sight elevation angle of 17 degrees. We note here that the azimuths of the OFIS were well determined with a Brunton compass, and the lengths were well determined in the lab. The array elements were positioned with a handheld GPS without a wide area augmentation system (WAAS) correction, which likely had a horizontal error bar of 5–10 m. We performed a simple experiment by randomly mislocating each array element by up to 5 m to determine the impact on the resulting TDB solution. The deviation from 265 was as much as 4 degrees, with no significant modification of the 3 degree error bar. We repeated this experiment with random mislocations of up to 10 m and found deviations by as much as 7 degrees. However, for such large deviations the 95% confidence region also expanded in size to include 265 degrees. If the elements were mislocated in a non-random manner, it may be possible to achieve a 9 degree mislocation without a significant increase in the error bar. This demonstrates the importance of accurate element positioning.

A noise study was also performed at site BACA. Preliminary results suggest that the 4 OFISs that were out in an open area were quieter than the hose array elements, most of which were beneath a short tree canopy. In addition, the amplitude envelope of those hose array elements was highly correlated with the wind speed whereas there was no significant correlation with the OFISs.

**CONCLUSIONS AND RECOMMENDATIONS**

The spiking problem is due to slip between the fibers and the ground as the OFIS moves during temperature fluctuations. The TDB algorithm we wrote works better for our comparisons than the PMCC software package. An OFIS is rugged, can be used for temporary deployments, and does not require thermally stable conditions for the electronics. A 3-120 OFIS configuration can resolve the back azimuth and elevation angle (phase velocity direction) of typical infrasound signals from distance or local sources using the WLD-POC method. The confidence region is usually better defined by using simple time-domain beamforming with a 3-element microbarometer array. The TDB solution also appears to be the most accurate based on analysis of a PFO airplane signal. The RMS difference in the back azimuths between the two methods appears to be about 10 deg for signals with SNR > 1.5. We currently interpret this discrepancy to be due to noise introduced by the WLD technique, and are in the process of evaluating two new techniques. We will also investigate in more detail the wind-noise reducing properties of the OFIS, and will create a very long OFIS to record the WSMR III signal at PFO and compare it with the co-located I57US array. We also plan on testing a 5-22.5 OFIS configuration if we obtain favorable wind-noise reduction results.

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