USING THE FILTERING OCEAN NOISE EIGENVALUES (FONES) ALGORITHM TO IMPROVE THE SEA BED REFLECTION LOSS ESTIMATE DERIVED FROM AMBIENT OCEAN DATA

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1 INTRODUCTION

The loss of acoustic energy upon its interaction with the sea bed is an important parameter for underwater acoustic modelling. Without it estimates of underwater propagation are likely to be inaccurate, particularly for environments where multiple acoustic interactions with sea bed occur. This loss of acoustic energy, referred to as the sea bed or bottom loss, can have strong dependency on frequency and the angle at which the acoustic energy impinges upon the sea bed (grazing angle). Moreover, sea bed loss will vary widely depending on the properties of the sea bed, including sub-surface layers. Thus accurate prediction of underwater acoustic propagation requires an estimate of the sea bed loss as a function of both grazing angle and frequency.

Active survey methods for the estimation of sea bed loss rely on a man-made source radiating acoustic energy. Active methods have the advantage of using a known, controllable source with the potential for significant source levels and selection of signal properties to allow for sophisticated signal processing techniques to be applied. The disadvantage of using active methods is that a ship is required to conduct the survey. Although unmanned underwater vehicles (UUVs) are a fast developing area of technology the power requirements, both to operate and tow source transducers, will continue to constrain active surveys to manned ships. The consequence of this is the high survey costs associated with operating a manned survey ship.

An alternative to the use of active sources is the use of passive methods that replace the active source with natural ambient noise, such as that caused by breaking waves, rain etc. Natural ambient noise in the ocean has been well studied[1,2,3,4] and both theoretical and experimental studies have characterised it as a function of the frequency and angular dependence. Ambient noise has been and continues to be used to estimate sea bed loss[5,6]. The established method uses a vertical line array (VLA) of hydrophones located in the water column. Measured data is then beamformed, with the established method using a conventional beamformer. The upwards and downwards propagating energy is compared, with their ratio giving an estimate of the energy lost in interactions with the sea bed. For further details on the application and verification of the established method the reader is referred to the established literature.

Conventional beamformers have many advantages – they are simple to implement, have a low computational burden and are robust to equipment configuration errors. The established method defined by Harrison assumes that the energy measured by VLA is from natural ambient sources. If, however, there are non-ambient acoustic sources of sufficient amplitude these will violate the underlying assumptions of the method and have been observed to cause significant errors in the sea bed loss estimate. The most common source of non-ambient acoustic energy is from nearby shipping. These will, depending on the source level and proximity, act as strong interferers and prevent estimates of the sea bed loss. The most severe effects will occur when the conventional beamformer is steered in the direction of the shipping (and possibly in other steering directions that correspond to strong shipping multi-paths). If shipping presents itself as a sufficiently strong interferer there will also be degradation in the quality of the estimate away from these angles due to the energy leaking through the conventional beamformer's side lobes.

A possible method of overcoming this is to use adaptive filtering algorithms, such as the minimum variance distortionless response (MVDR) beamformer[7]. Another method that will be described in this paper is the filtering of the measured signal based on an eigenvalue approach, termed herein as the Filtering Ocean Noise Eigenvalues (FONES) algorithm. The filtered data can then be presented to the conventional beamformer with the effects of strong interferers already minimised. The paper is organized as follows: the eigenvalue filtering approach used is described in Section 2, before the method is applied to experimental data gathered during the REP14-MED trial in Section 3. Discussion is included alongside the presented applications. Conclusions are drawn in Section 4.

2 EIGENVALUE FILTERING

It is an established beamforming technique for the cross-spectral density matrix (CSDM) formed from hydrophone array data to be decomposed into its eigenvalues and their associated eigenvectors and to then be reconstructed from selected eigenvalues and their associated eigenvectors. A well know implementation of this is the MUSIC (MUltiple SIgnal Classification) algorithm[8,9]. This relies on the eigenvalues of the CSDM associated with a signal (as opposed to noise) being the largest, thereby enabling a subspace to be composed only from those eigenvalues associated with the signal.

MUSIC type algorithms exclude the eigenvalues and associated eigenvectors corresponding to the smallest eigenvalues of CSDM, with the assumption that these correspond to undesired noise. For the problem at hand this situation is reversed - the ambient noise is the desired signal, with the largest eigenvalues instead taken to correspond to dominant shipping[10]. The eigenvalues and associated eigenvectors corresponding to these largest eigenvalues are therefore excluded. In the terminology of the MUSIC algorithms we concern ourselves only with the noise subspace.

Defining the nth eigenvector of the CSDM, C, as u_n and the nth eigenvalue as λ_n, then the N channel CSDM at a given frequency can be decomposed as

$$C = \sum_{n=1}^{N} \lambda_n u_n u_n^\dagger$$

where a superscript dagger (†) denotes a conjugate transpose. The modified CSDM, $\bar{C}$, is then simply the reconstruction of the eigenvectors excluding those associated with the largest N_{lim} eigenvalues

$$\bar{C} = \sum_{n=N_{lim}}^{N} \lambda_n u_n u_n^\dagger$$

where we have assumed that the eigenvalues are ordered from largest to smallest during the decomposition.

Several problems are immediately apparent. The identification of the number of eigenvalues that belong to the signal subspace is, in common with the MUSIC-type algorithms, problematic. One can assume the number of sources a priori, but this is clearly not robust for operational usage. A suitable metric (let alone assigning a value of such a metric) for deciding whether or not to apply the eigenvalue filtering algorithm is not straightforward, and is only briefly touched upon in this paper. To test the fundamental operation of the eigenvalue filtering operation we therefore manually decide when to implement the algorithm and how many eigenvalues to remove. The work presented in this paper is concerned with the potential for eigenvalue filtering to minimise the impact of strong interferers in ambient noise based sea bed loss estimation methods. Further work is required to formulate robust implementations and enable an automatic decision to be made about if the filtering should be applied at all.

3 APPLICATION TO EXPERIMENTAL DATA

3.1 REP14-MED Trial

The Recognised Environmental Picture 2014 Mediterranean (REP14-MED) trial was organised by the Centre for Maritime Research and Experimentation (CMRE) involving 21 partners from 6 different countries. It was conducted in June 2014 off the Western coast of Sardinia from the NATO Research Vessel (RV) Alliance. The primary focus of the trial was the collection of oceanographic data; however a significant part of the RV Alliance's time was used to perform acoustic experiments. This included moored VLAs.

The VLA whose data is used for this paper consisted of 32 elements with a uniform spacing of 0.18 m. The sample rate was 50 kHz with the first hydrophone 20 metres from the sea bed in water approximately 170 m deep. The VLA was moored to the sea bed throughout (i.e. its location relative to the sea bed did not change). Full details of the trial can be found in the Cruise Report[11].

Shipping noise was generally distant when present, with the exception of noise from the RV Alliance. There were several periods in the measurement (mainly around the deployment and retrieval of the array) when the RV Alliance moved from being very close to the array to a significant distance from it (and vice-versa). The position of the vessel is known accurately throughout due to GPS tracking. This enables data both with and without a strong interfering source present to be compared, as discussed in the next section.

3.2 Illustration of Effects of Strong Interferers

Initially experimental data containing no strong interferers (i.e. ambient noise dominates) is compared to data with strong interferers present to demonstrate the anomalous results that this produces and to establish a baseline estimate. It is instructive to show not only the estimated sea bed loss as a function of frequency and grazing angle but also the output of a beamformer as a function of frequency and array look direction from which the sea bed loss estimate is derived.

Figure 1 (a) shows a conventional beamformer output in the absence of any strong interferers. At positive look direction angles (those above the horizontal) there is a significant band of energy that reduces with increasing frequency. This energy is from natural ambient noise originating at the sea surface. There is a notable band of energy at roughly corresponding negative look direction angles (those below the horizontal). This has less energy than that from the sea surface and corresponds to ambient noise reflected from the sea bed. We are, in this case, justifiably assuming that there are no sources on the sea bed and that the sound speed profile is insufficient to cause ray bending of significance. This latter assumption is borne out through examination of the oceanographic data measured during the experiment.

The sea bed loss as a function of frequency and grazing angle obtained from this data is shown in Figure 1 (b). The location of the critical angle is uncertain due to the angular resolution of the beamformer. The sharp falloff in the estimated sea bed loss at frequencies above around 5 kHz is due purely to array spatial aliasing and is thus a consequence of the hydrophone density used rather than any property of the sea bed loss. The estimated bottom loss in this profile has some unusual features such as patches of higher reflectivity. These are not discussed in this document as this data is being used only as a reference to evaluate the performance of algorithms aiming to mitigate the consequences of performing sea bed estimation using ambient noise when strong non-ambient sources of noise are present.

The beamformer output and estimated sea bed loss figures are reproduced in Figure 2 for data where a strong interferer was close by, in this case the RV Alliance at a horizontal distance of about

500 m from the array. It can be seen in Figure 2 (a) that the beamformer output is dominated by two peaks near to horizontal. The upper one of these corresponds to the direct path from the array to the interfering noise source and the lower one corresponds to the first order reflection of this noise source from the sea bed. Due to the geometry of the situation these two peaks are not symmetric about the horizontal; rather the lower peak will generally be measured at a larger array look direction angle. In addition to these two dominant peaks the ambient surface noise and reflected sea bed noise noted in the discussion of Figure 1 (a) have now been obscured.

Given the obscuring of the ambient noise away from the horizontal direction we would expect to see the introduction of significant anomalies into the sea bed loss estimate. Comparison with Figure 1 (b) shows that these are indeed visible in Figure 2 (b). The obscuring by the strong interferer of the ambient noise away from the horizontal direction has caused the sea bed loss estimate at high grazing angles to be corrupted by significant striations. At the low grazing angles there is a significant approximately frequency independent anomaly. This is non-physical and significantly exceeds both extremes of the colour scale of Figure 2 (b) (i.e. extends to comparable negative values of sea bed loss). These large low grazing angle undulations are caused because the established algorithm takes the ratio of the beamformer outputs at symmetric angles about the horizontal. As the direct and first order paths to the strong interferer produce large, asymmetric, approximately frequency independent features this produces the observed sea bed estimate at low grazing angles.

A metric of success in our attempts to mitigate the impact of these strong interferers is estimation of sea bed loss closer to that in Figure 1 (b) using the data in Figure 2 (a).

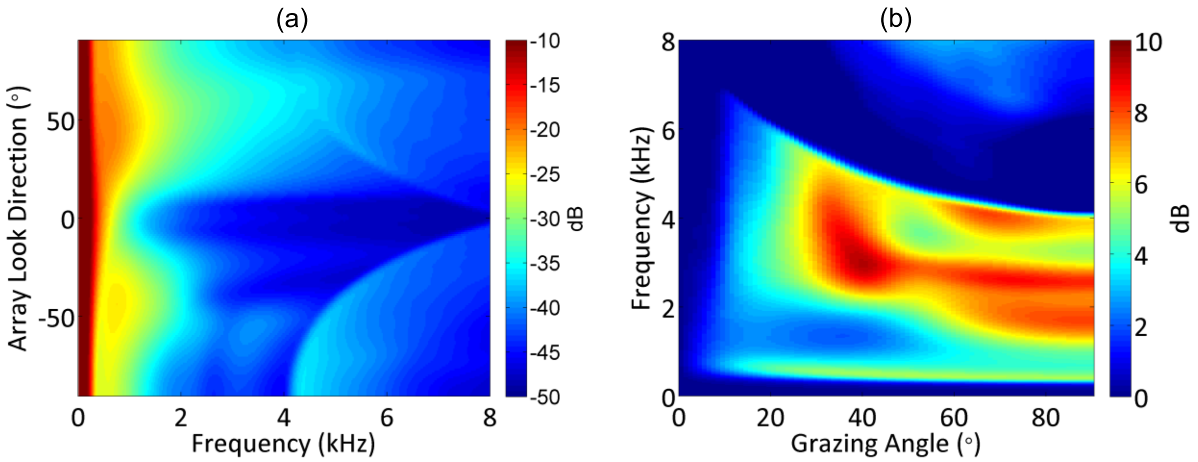

Figure 1 – REP14-MED data without any strong shipping noise present (a) beamformer output as a function of frequency and array look direction and (b) estimate of the bottom loss profile as a function of frequency and grazing angle.

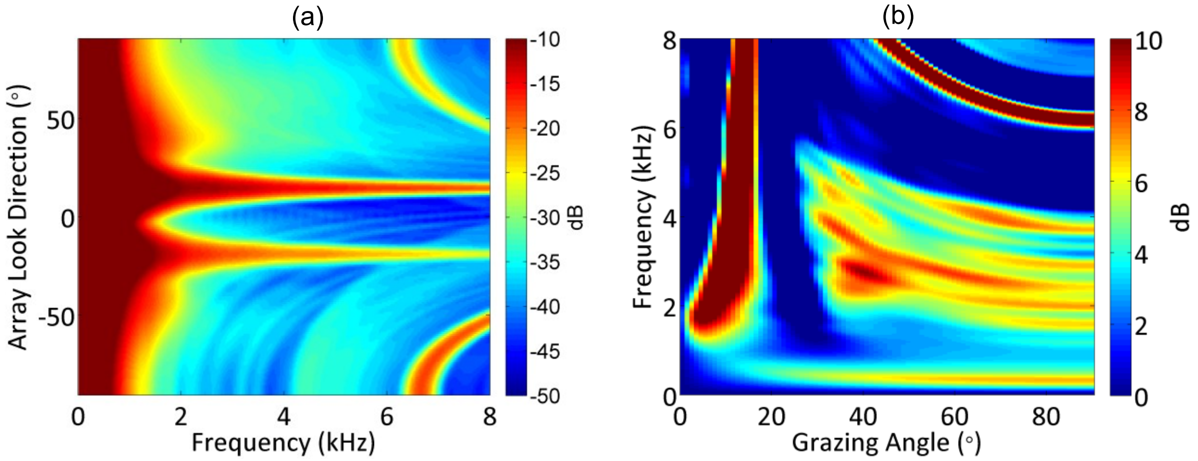

Figure 2 – REP14-MED data with nearby strong shipping noise present (a) beamformer output as a function of frequency and array look direction and (b) estimate of the bottom loss profile as a function of frequency and grazing angle.

3.3 Results and Discussion

The eigenvalue filtering method, as described in Section 2 of this paper, was applied to the REP14-MED data. The same data set was chosen as was used in the previous subsection. The CSDM is calculated for 5 minutes of data from the 32 element VLA. At each frequency this CSDM had the FONES eigenvalue filtering algorithm applied to it, removing the same number of eigenvalues and their associated eigenvectors at each frequency. In terms of implementation it would be a trivial to remove different numbers of eigenvalues as a function of frequency, with the greatest problem certainly coming from deciding how to vary the parameters of the algorithm with respect to frequency.

Figure 3 (a) shows the effect on the beamformer output of removing the largest eigenvalue from the CSDM at each frequency, and should be compared to the equivalent unfiltered beamformer output in Figure 2 (a). It is immediately apparent that the prominent peak associated with the direct path from the strong interferer to the VLA is removed, albeit somewhat harshly; the peak has been mostly removed but distortions have been introduced in the vicinity of its location. Although the changes in the energy measured from the sea bed are small (they are just about visible in the images displayed), as the sea bed loss is being estimated through finding the ratio between horizontally symmetric angles these small changes can significantly alter the estimated sea bed loss.

An estimate of the sea bed loss produced from Figure 3 (a) is not displayed as it will inevitably produce an extremely poor estimate. This is due to the asymmetry in the beamformer response once the largest eigenvalue – that associated with the energy from the direct path from the strong interferer – has been removed. As the established methods being used for estimating the sea bed loss from ambient noise relies on taking the ratio of the beamformer energy symmetrically about the horizontal, this will produce overwhelming errors. It is anticipated that the number of eigenvalues that need to be removed (or significantly reduced) will be an even number, as it would be expected that each direct path from a strong interferer will have an associated reflection from the sea bed.

Figure 3 (b) shows the effect on the beamformer output of removing the largest two eigenvalues from the CSDM at each frequency. Intuitively, the first order reflection path from the strong interferer to the VLA is removed in addition to the direct path. This is particularly intuitive given that this path will contain less energy than the direct path due to the interaction with the sea bed and therefore could be expected to be associated with the second largest eigenvalue. Excluding more than the largest two eigenvalues produces significant anomalies in the resultant beamformer output, leading to the conclusion that these eigenvalues are at least partially capturing information relating to natural ambient noise.

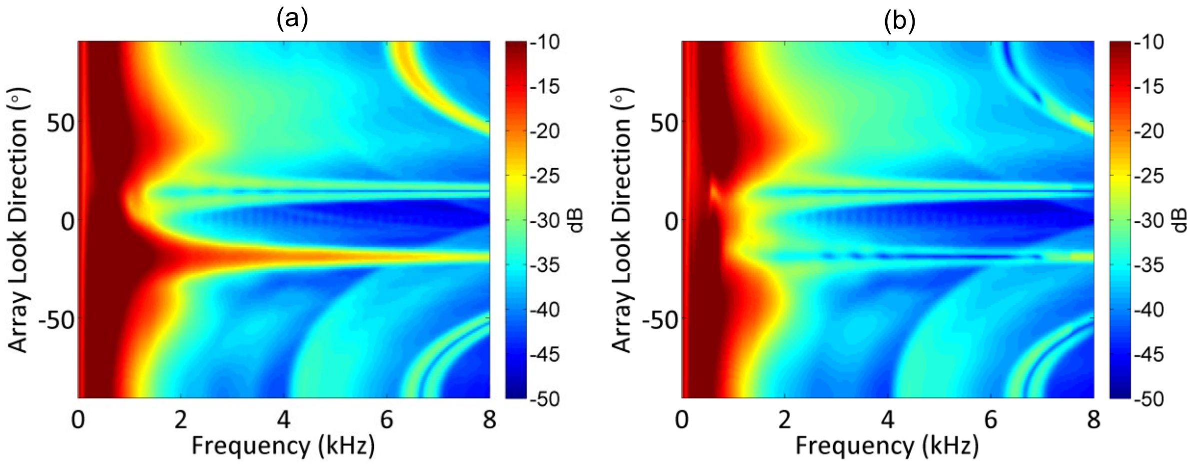

Figure 3 – Beamformer output as a function of frequency and array look direction for REP14-MED with nearby strong shipping noise present and (a) the largest eigenvalue set to zero (b) the largest two eigenvalues set to zero.

The sea bed loss estimated using the beamformer output in Figure 3 (b) (i.e. with the largest two eigenvalues removed at each frequency) is presented in Figure 4. This image can be directly referenced with Figure 1 (b), which is what we would expect to see if all the effects of the strong interferer have been removed, and Figure 2 (b), which is the result obtained if the strong interferer is present but we continue to apply the established method with the conventional beamformer. The FONES algorithm has significantly improved the estimate of the sea bed loss at higher grazing angles.

At low grazing angles the anomalies caused by the asymmetric beams still dominates, albeit the amplitude of these anomalies has been significantly reduced (the peak value being 10 dB lower). There may be ways of improving this result further, in particular by seeking to more smoothly 'shade' the eigenvalues i.e. reduce their contribution rather than simply set some to zero and leave others completely unaltered.

Complete removal of the strong interferers from the natural ambient noise at these low grazing angles will always be difficult, for the simple reason that it is of much higher amplitude whilst overlapping in frequency. Here we are neglecting the extreme case where the strong interferer is so close that the direct and first order reflected paths are at high grazing angles, as this is a rarer occurrence. In the angular region where the strong interferer dominates it is recommended that rather than try and remove it, it would be preferable to use it. The acoustic paths from the strong interferer to the VLA could be used to try and estimate the bottom loss. The FONES algorithm presented herein is suited to providing correct estimates at the higher grazing angles, where strong interferers cannot generally be exploited.

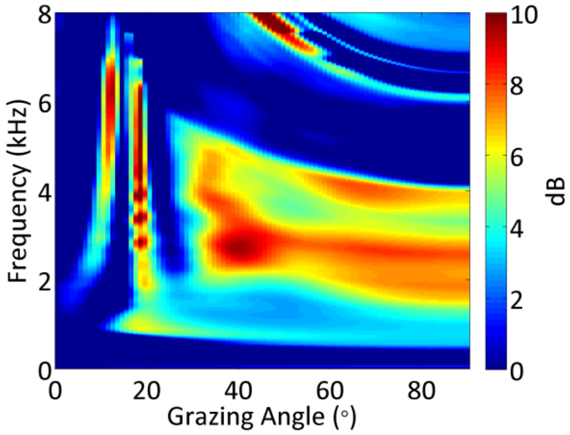

Figure 4 - Bottom loss estimate as a function of frequency and grazing angle derived from the data in Figure 3 (b).

4 CONCLUSION

This paper has proposed a method for mitigating the effects of strong interferers when using the established method of estimating sea bed loss using a vertical line array and natural ambient noise sources. This method is based around the concept of removing eigenvalues and their associated eigenvectors from a decomposition of the cross-spectral density matrix at each frequency for which it is calculated. The method has been demonstrated, using experimental data from the REP14-MED experiments, to remove anomalies in the estimated sea bed loss at high grazing angles. Anomalies persist at lower grazing angles, albeit at significantly reduced amplitude and angular extent. It is concluded that, in the presence of strong interferers to natural ambient noise, the proposed FONES algorithm could complement methods that rely on shipping noise to estimate the loss.

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