Ambient Noise Imaging techniques and potential in warm shallow water

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Abstract

The class of acoustic imaging techniques known as Ambient Noise Imaging started with Acoustic Daylight, which has since been joined over the past decade by several other independent algorithms. To date, the algorithms described in the literature have generally been statistical approaches, treating the insonification by sources of opportunity as a random variable. In warm shallow waters, where snapping shrimp abound, there is the possibility of considering each locally-generated snap to be a deterministic source, and to beamform and search for scattering from possible targets in a coherent manner, using the direct received snap as a matched filter. Depending on the snapping shrimp density (number of snaps per square metre per second), there is usually a substantial gap in time between each locally-generated snap and the next (following a Poisson distribution in time), during which coherent matched filtering can be applied to search for scattered replicas of the snap. Within a range of 100-200 m, depending on the snap density, it is estimated that this method can produce more accurate and high-dynamic range images compared to statistical techniques, comparable to a multi-static active system. While the range is very short compared to most sonar systems, ANI is completely covert and can image completely silent targets. In shallow water, where the threat is often from smaller, very quiet vehicles and divers, this could be a useful tool in the shallow-water ASW armoury. Furthermore, using snapping shrimp implies a diversity of source locations and orientations to possible targets that potentially provides more information than conventional multi-static active systems, while remaining completely covert.

Introduction

The research area of forming images from underwater ambient noise began with preliminary ideas from Flatte' and Munk (who considered 'acoustic shadowing' by large objects for a JASON report) [1]. Prof. Buckingham and colleagues advanced this early idea of ambient noise shadowing to a more complete concept of 'Acoustic Daylight' (AD) [2], which included the possibility of increased illumination from 'front-lighting' in addition to silhouetting by 'backlighting' in a statistical sense. These ideas were based on a very close analogy with optical vision, where the visual clues are all spatial, the human eye being too slow to interpret temporal variability in the illuminating signals. This analogy is unnecessarily restrictive for the ocean acoustic case, where the temporal statistics are of a longer timescale and the sensors' response time much shorter than that of the eye.

While the theoretical possibility of imaging using the AD technique became demonstrated fact with the first deployment of ADONIS in 1994 [3], it must be admitted that the signal-to-noise ratio of such systems will usually be inherently low and the sources on which the system relies for its illumination are likely to be statistically complicated. Rather than consider these temporal variations as 'noise', to be averaged over to obtain some degree of suppression, in late 1995 the Acoustic Research Laboratory (ARL) of the National University of Singapore (NUS) began to explore the possibility that the variability itself could contain information. We showed that image information resides in both the spatial auto- and cross-correlations of the data (taken at zero time lag), second-order moments of the data [4]. Furthermore, we demonstrated that a model-based processor is able to estimate the presence of targets much more reliably in sporadic and unreliable illumination conditions than a linear estimator based on raw data [5]. As a result, several new imaging algorithms have been developed and are now considered as part of a suite of imaging approaches using ambient noise, so that AD has been joined by a number of siblings to form a new class of acoustic imaging approaches that we call Ambient Noise Imaging (ANI) algorithms.

The ANI methods outlined so far are all statistical in nature. In 2000 the ARL began to consider alternative ANI methods, including deterministic and coherent processing of opportunistic 'noise' transients of unknown time-series, location and onset timing. Such deterministic processing is fundamentally different from the statistical approaches, in that it is coherent and provides range information just as active sonar processing would, but is still different from traditional active sonar processing in that the signal is not under the control of the imaging system, is of unknown origin and there exists no matched filter.

Overview of existing statistical methods

Before presenting the new deterministic ANI ideas, we will briefly review the statistical algorithms that have proven successful on data from the Acoustic Daylight Ocean Noise Imaging System (ADONIS), built at the Scripps Institution of Oceanography.

The Acoustic Daylight Algorithm

The original ANI algorithm was called Acoustic Daylight (AD). AD relies on the optical analogy that we are able to see objects clearly in random, diffuse light fields, even if we are not illuminating the target ourselves and if the target is not emitting its own light. The primary way we see objects is by delineating the contrast in illumination brilliance and colour with the background. This requires:

- that the available light sources are not homogeneous or isotropic and propagate through the medium without significant volume scattering (we cannot see objects well in a 'white-out' or fog)
- that there is sufficient light (we cannot see in the dark)
- that the target reflects (scatters) light in a manner that differentiates it from the background behind (camouflage effectively masks objects) and
- that our imaging system has sufficient angular resolution to delineate the target (the human eye is some 10^4 wavelengths across).

AD works, but because the acoustic insonification sources are highly variable over time scales comparable to and longer than the sampling rate of our acoustic recording systems, the images created from this algorithm fluctuate. There are also many false target images from spatial inhomogeneities in the source field that are interpreted as backscattered sound by the algorithm.

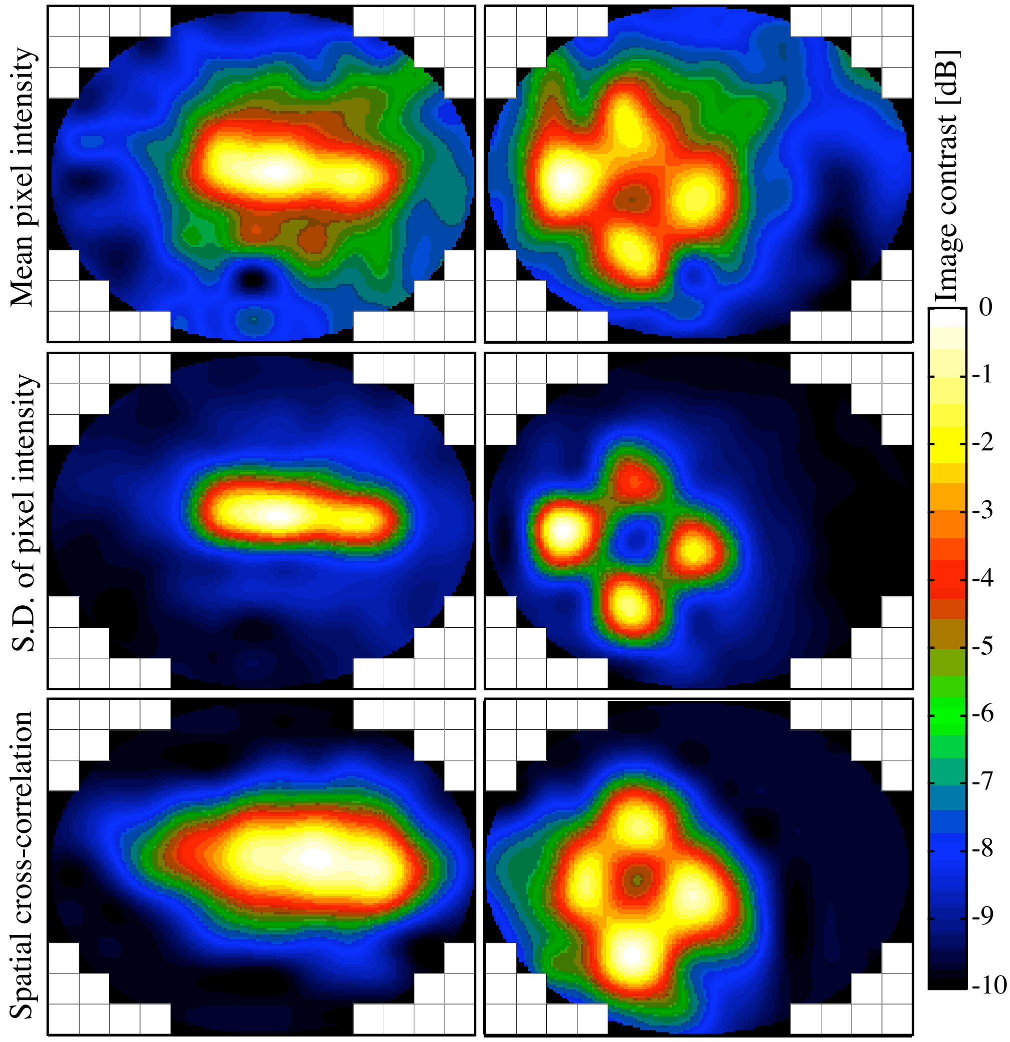

Figure 1. Images of the 'bar' (left) and fenestrated cross (right) targets formed by the AD (top), temporal second moment (centre) and spatial second moment (bottom) algorithms applied to ADONIS data, taken from [5].

Second moment algorithms

While considering how to deal with the spatial and temporal variability in the insonifying noise, the ARL realised that the very fluctuations we were trying to remove contain information about targets in the field of view. Thus were borne the second-moment algorithms, relying on the temporal and spatial second moments of the sound field.

Second-order temporal statistical imaging

The first and second-order moment images are shown in Fig. 1, where the relatively coarse raw data has been spatially interpolated using bi-cubic splines, a process which considerably improves the eye's ability to delineate important features. The left-hand side of Fig. 1 shows, from the top down, the configuration for the 'horizontal bar' target, a mean intensity image, followed by one formed using the standard deviation of the intensity, and the bottom panel showing the spatial coherence imaging discussed in the next subsection.

It is clear that a substantial amount of image information is extracted from the statistical second moment, not only sufficient to produce a very acceptable image, but one with a superior contrast to that obtained from the mean intensity.

The right-hand column shows the same panels as for the left, but using 'fenestrated cross' target data. Again, the second statistical moment proves superior in contrast, though both methods produce excellent images. The differences in the means and characteristic widths of the target and non-target pixel intensity distributions are very clear. Despite presenting the more difficult task with regard to resolution, the 'fenestrated cross' target is better contrasted with its background than the 'horizontal bar'. The distributions show that this occurs both because the non-target pixel distribution is narrower, and the target distribution wider, than their counterparts for the 'horizontal bar' target case.

We should emphasis that the first and second moments of the data represent orthogonal information, providing a genuine increase in total imaging information that can in principle be combined in a number of ways to form more stable images of higher contrast.

Second-order spatial imaging

The temporal variance of a pixel's energy is identical (within an additive constant) to its autocorrelation at zero time lag. A spatial extension of this idea is to consider the spatial cross-correlations of pixels at zero time lag, the off-diagonal elements of the correlation matrix. The underlying idea is that not only the average level and variance, but also the specific non-statistical time history of intensity variations will be correlated for imaging beams which receive energy from neighbouring regions. Since reflecting targets are expected to cause very different source regions to illuminate the receiving beams than where there are no targets, it is anticipated that the cross-correlations will fall into two broad sets. We might expect that pixel (beam) energy histories would correlate well with other members of the same set, and poorly with members of the other set. One set would then essentially comprise target-filled pixels, the other non-target. Attempting to class the pixels in this way so as to maximise summed correlation products within each set and minimise those products with the conjugate set does indeed provide a clear division of pixels.

The bottom panel of Fig. 1 shows images from the spatial cross-correlation method, formed by sorting pixels according to a summed minimum error routine and then grading them according to how well they correlate with the smaller (presumed target) set. The familiar forms are clear, confirming that the spatial cross-correlation at zero time lag also contains substantial useful information. Indeed, the image contrast is better both for the spatial and temporal second-moment methods than it is for the traditional mean intensity (AD) image.

Deterministic processing principle

We shall restrict ourselves in this paper to considering the deterministic processing of snapping shrimp transients, since these are the predominant sources of high-bandwidth impulsive noise in warm shallow seas [6,7]. The ideas presented here are analogous to those being investigated for radar using opportunistic FM or TV broadcast signals [8]. The principle has similarities with multi-static active sonar processing, where the transmitter(s) and receiver(s) are not co-located. Multi-static active sonar processing has several advantages over monostatic active sonar and can be applied in shallow waters. One of the advantages of multi-static sonar is that it denies targets the opportunity to present unfavourable target aspects to the sonar, since the source and receiver(s) are separated and the position of the receiver(s) is/are unknown. Using distributed random sources further enhances this advantage. In our case, however, we do not have access to the original transmitted time-series of the source, nor do we know the location of the source or the time of its emission. Therefore, to apply multi-static active sonar approaches, we must first estimate these unknowns and then guard against 'mistaken identity' as follows:

- Identify an incoming snapping shrimp impulsive signal at a planar or volume array receiver and estimate it's time-series
- Beamform to establish the azimuthal and elevation angles of arrival
- Estimate the range from the known geometry of the receiver and bottom (snapping shrimp live only close to the bottom)
- Estimate the time-of-emission of the source signal given the range
- Proceed to process subsequent data samples at the array for secondary scattered arrivals as for a multi-static active system
- Guard against incorrectly processing new incoming original snapping shrimp transients as if they were scattered 'echoes' of a previous signal.

The reader will note that the success or failure of these steps will depend on having a highly-resolving planar or volumetric array to accurately estimate azimuthal and elevation angles of arrival and on the somewhat troublesome rejection of new original incoming snap signals. We describe some of the tools that can be used to achieve these aims in the following sections.

Typical waveguide structure and implications

In warm, shallow water, the acoustic waveguide is typically well-represented by an homogeneous, isotropic water column overlying the seabed which, at high frequencies, can be considered an unconsolidated semi-fluid that may lie on a denser, shear-wave supporting substrate. We must focus on high frequencies (typically 10-100 kHz) in order to obtain the angular resolution necessary for this type of processing from a planar or volumetric array of reasonable and manageable proportions. Surface roughness due to wave action and vessel wakes (in busy port areas such as Singapore) will significantly impact high-frequency propagation since the acoustic wavelengths are comparable or shorter than the surface roughness wavelengths. In some areas and at some times, the water column may be far from homogeneous, exhibiting both horizontal and vertical sound-speed gradients. These will modulate the anticipated arrival angles and times of surface and bottom-reflected replicas of the signal.

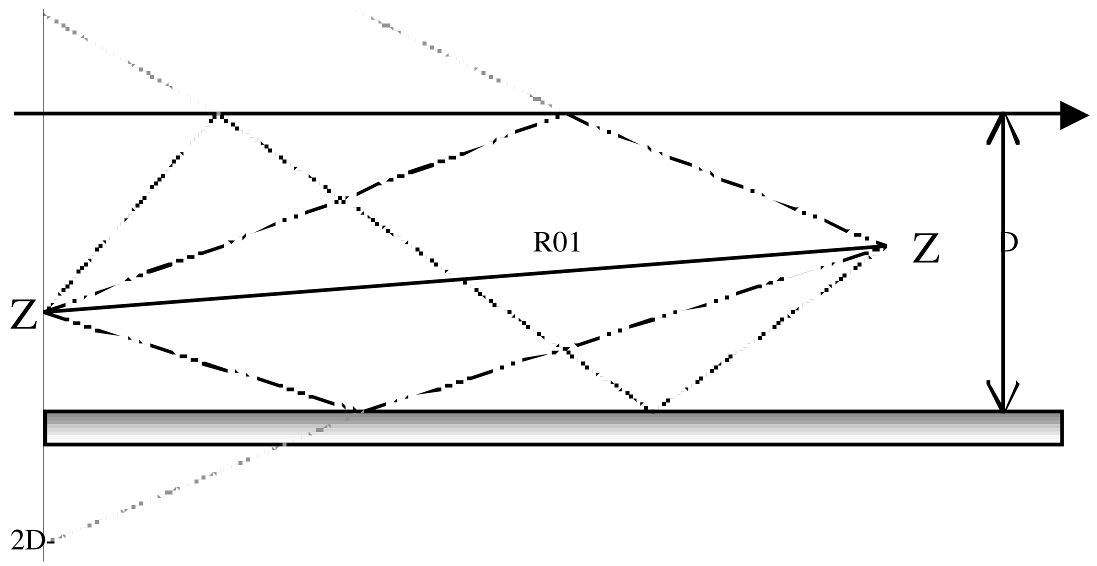

Figure 2. Idealised homogeneous shallow-water waveguide, with multipath arrivals visualised using the method of images

We shall assume a linear model is applicable to the waveguide, so that the received signal at our array consists of a series of delayed, amplitude-modulated (within +/- 1 to allow for phase inversion on reflection from a pressure-release boundary) replicas of the initial source signal. We choose to visualize the process by the method of images indicated in Fig. 2.

The first observation is that, since the source is very close to the seabed, the direct and bottom-reflected paths will be very close together in time and space. In this way, the estimated 'direct' signal time-series will be a composite of the actual snap and its bottom-reflected counterpart, delayed by some small amount. Since a typical 'snap' lasts in the region of 0.1 ms, the source signal and it's bottom-reflected echo will not be separable. This is not a problem, because all subsequent arrivals, be they reflected from targets, surface or multiple reflections, will all be amplitude-modulated copies of this combined dual signal. We thus take the combined dual signal as the source we wish to estimate.

The second observation is that once the azimuthal bearing is obtained for the source, the surface and multiple-interface reflection arrivals must all lie close to the same azimuth, with approximately known elevation angles and time delays (since the local bathymetry and geometry is known) so that all the surface and bottom multiply-scattered arrivals can be easily identified from the beamformed data. This has the added advantage that these time delays and angles can then be used to refine the original range estimate obtained crudely from the elevation angle and known height of the receiver above the sea floor. This can then be used to refine all estimates obtained so far.

The next task is to detect scattered replicas from possible targets in the area. This may be achieved by replica-correlating the estimated source doublet (of direct and initial bottom-reflected signals) with beamformed time-series data within the field of view of the array. Genuine target-scattered echoes must satisfy the following constraints:

- The normalised cross-correlation matched filter output must be less than unity.
- Furthermore, the normalised cross-correlation matched filter output must be less than a limit (<1) imposed by the spherical spreading law applied over the time delay from the estimated source emission and the receive time at the array.
- The elevation angle of any such arrival must result in an estimated depth within the water column when the arrival time and angle are used to estimate scattering target depth. This eliminates both new original snap signals and multiply-scattered target reflected copies of the sought signal.

If these steps can be accomplished, the result will be more effective than using statistical imaging techniques, since the range of the target can also be estimated, just as in active multi-static sonar, but without losing the covert nature of a passive or ANI sonar. The advantage of an ANI approach, of course, is that the sonar is silent (retaining covertness) and yet can image silent targets (undetectable by conventional passive sonars).

It is easy to see that, as the delay time increases from the arrival of an original snap at the receiving array, the probability of incorrectly matching a new snap as a target-reflected echo increases. This translates into an effective range limitation of this deterministic ANI approach. The question is then to estimate the effective range of applicability of this approach, before one is better off to switch to a statistical ANI method.

Limitations of the deterministic approach

In order to investigate the limitations of this deterministic ANI approach, we first consider the nature and limitations of the source, the snapping shrimp.

Snapping shrimp as sources

Snapping shrimp are small crustaceans (a few tens of mm long) with an asymmetric claw that they use to snap rapidly shut, creating a loud impulsive noise that has been attributed to the collapse of a cavitation bubble behind the jet of water that is ejected as the claw closes [9].

The instantaneous source level can be very high, in the region of 185 dB re 1 microPascal at 1m [10]. A sketch of a snapping shrimp, its time-series and spectral power are shown in Fig. 3.

Range limitation due to background ambient noise

One limitation on the range at which this deterministic ANI approach can be successful is obviously that the target-scattered replica must be detectable against the

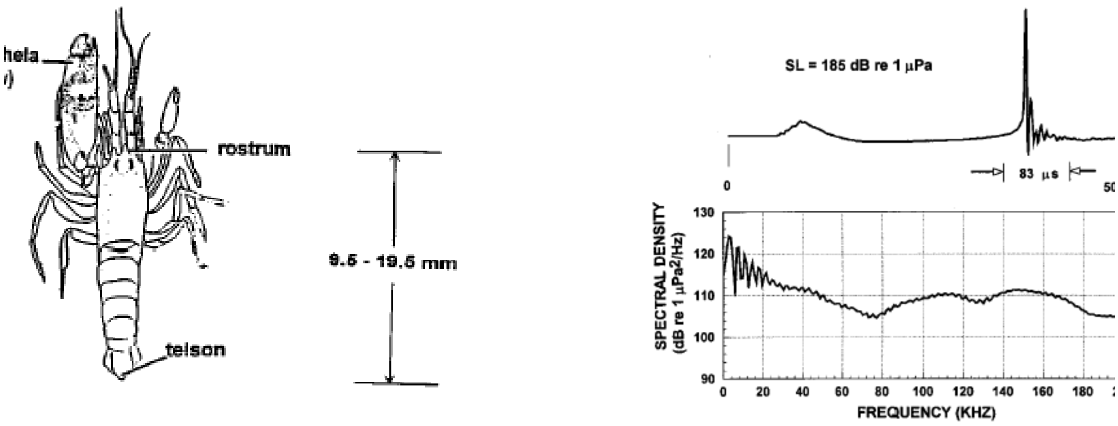

Figure 3. Drawing of a snapping Shrimp (left), time-series pulse (top right) and

incoherent background ambient noise. Given the magnitude of the snap (A), the propagation distance R, the target strength (or the bottom/surface loss) TS, the noise level 'Noise' and the travel distance for a source-target-receiver configuration (obtained by solving the elliptical equations for a multi-static system) ∂R, we have

$$\frac{A*TS}{R_{Shrimp->Receiver} + \partial R} \geq Noise \qquad \text{equation 1}$$

But $\partial R = c\tau_{TR_i}$ so that:

$$\frac{A*TS}{R_{Shrimp->Receiver}\left(1+\frac{c\tau_{TR_i}}{R}\right)} \geq Noise \qquad \text{equation 2}$$

and we can plot this as a function of range and linear target strength as shown in Fig. 4.

The curve suggests that, for the noise level chosen, that operational ranges can be as good as 200 m for target strengths of 0.67, or –3 dB. Beyond this range, it will become increasingly necessary to switch to statistical techniques.

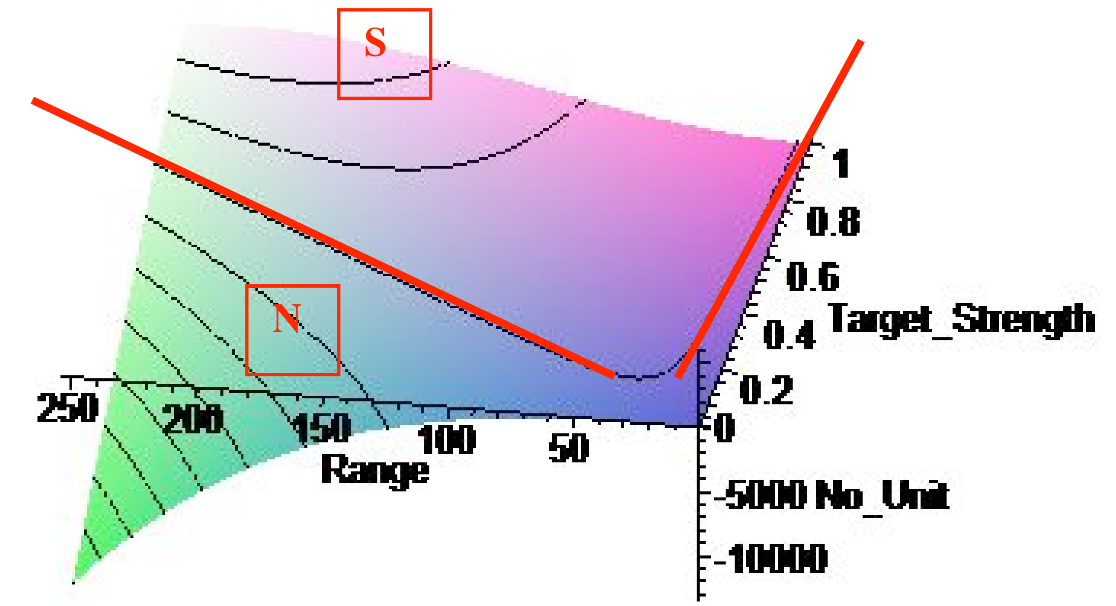

Figure 4. Range limitation surface as a function of range [m] and linear target strength. The red curve indicates the result for 0 dB snr. The region marked by the red 'S' indicates a suitable operating range, whereas 'N' indicates Not suitable.

Snap identification error limitations

The second major limitation to the useful range of a deterministic ANI algorithm is in the probability of correctly/incorrectly estimating incoming snaps as replicas of the original sought signal or new snaps. The probabilistic models of this process are complex and uncertain, since the temporal and spatial distribution of snaps both play a major role and neither are well-known at present. Evidence does suggest that the temporal energy-density distribution of snapping shrimp is well-approximated by a log-normal distribution [10]. There is uncertainty as to the degree to which the shrimp are spatially homogeneously-distributed as opposed to clustered in colonies. Either mode of distribution could explain the temporal energy distribution, depending on whether the shrimp chorus or not. These questions are currently being addressed by a separate project at the ARL that employs a 5 MSa/s 4-channel acoustic acquisition system with a tetrahedral array [12].

On of the key parameters in assessing the probabilistic model is the number of snaps per square metre of seabed per second. Current estimates for Singapore littoral waters vary between 0.01 and 0.1 snaps/m^2/sec. Clearly, the higher this number, the shorter the time that is likely to elapse before echoes of a snap from targets are drowned out by new incoming snaps and their echoes. The paradoxical result is that the workable range of this deterministic ANI approach actually decreases as the insonification rate (number of sources) increases! An example of snapping shrimp data that illustrates this process is given in Fig. 5.

Our current estimates for Singapore waters indicate a maximum workable range for this technique of between 100-200 m, based on 0.05 snaps/m^2/s. This suggests that the constraint of mis-identifying incoming snaps as echoes instead of new snaps is a

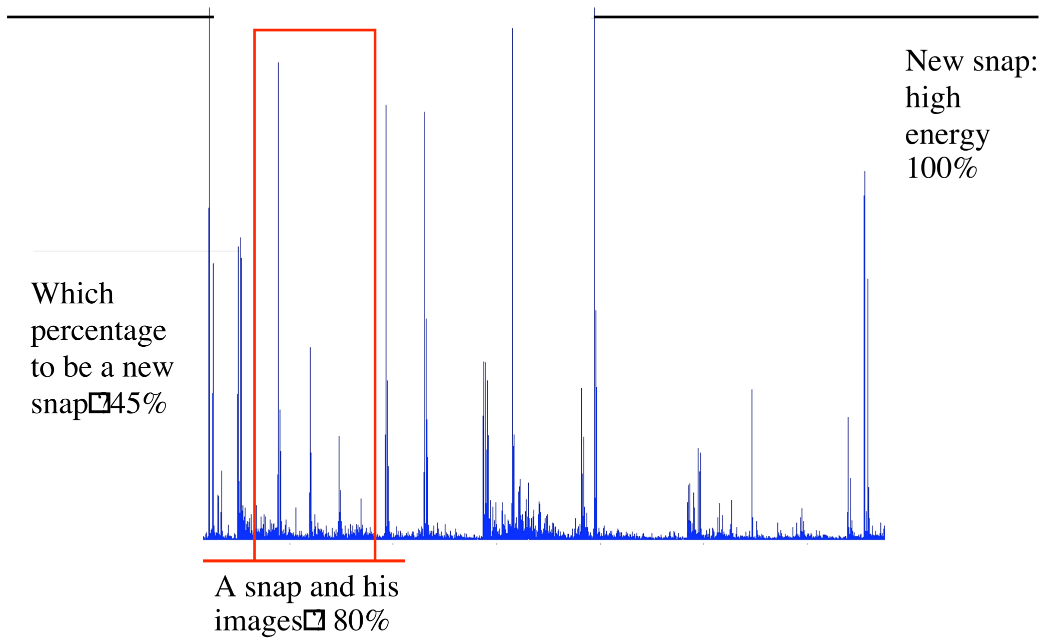

Figure 5. Time series envelope of ambient noise with snapping shrimp signals, indicating possible target reflections and new snaps that limit the processing time, and hence maximum operating range.

more severe one that picking out the snaps from the background ambient noise level. We thus anticipate that the signal processing will be limited more by this aspect than poor signal-to-noise, which encourages us to believe that matched filter processing in the time domain will yield good results for workable ranges. This is in turn important because matched filtering provides the highest resolution temporal resolution, which in turn converts to source angle and range estimations.

Conclusions

The field of Ambient Noise Imaging (ANI) started with Acoustic Daylight, expanded to include other parallel statistical techniques and is now adding deterministic techniques to the original suite of statistical ones. The deterministic processing of sources of opportunity opens the door to a number of productive processing avenues more akin to multi-static active sonar processing. As such, the field of ANI is becoming increasingly blended into the established fields of active and passive sonar signal processing. As the field matures, we can ultimately expect to see a seamless integration of approaches that combine to form a suite of imaging methods used in parallel in any given situation, weighted to optimize information retrieval for a given environment and task.

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