Ambient noise environments in shallow tropical seas and the implications for acoustic sensing

John R. Potter, Lim Tze Wei & Mandar Chitre

Acoustic Research Laboratory, c/o Dept. Physics, NUS, 10 Kent Ridge Crescent, Singapore 119260.

Abstract

Oceanographic in-situ measurements are becoming increasingly expensive as remote sensing tools concurrently enjoy a continuing expansion of capability. While in-situ observations will never be replaced completely, the current trend is clearly to make as much use of inferential and remotely-garnered observations as possible. In the ocean, acoustics is one of the foremost tools to use for remote interrogation of the environment. It represents the only mechanism for quickly propagating energy (and hence also information) over large distances. As a direct result, a large array of acoustic tools have been developed for communication, navigation, sonar, current profiling and so forth. All of these tools, passive more than active, are impacted by the natural background noise of the region in which they are deployed. In warm, shallow waters, the ambient noise environment is very different from colder and/or deeper waters, being dominated for some 80% of the usable bandwidth by snapping shrimp. The noise levels in the range 2-250 kHz can easily be 20 dB above that expected in similar conditions in deeper or cooler water. This is predominantly the case for SE Asian coastal regions, and even for considerable distance offshore where shallow water persists. In order to optimise the design and operable performance of acoustic systems, we need to understand the spatial and temporal statistics of this noise. Ambient noise results are presented from several tropical sites and some robust statistical features are identified. Physical models for these attributes are developed, and some strategies suggested for improving acoustic system performance in the face of this cacophony.

Introduction

The ambient noise environment of Singapore is substantially different from many sites for which data are available, being tropical, shallow over large areas and dominated by an unusually large collection of merchant vessels. These qualities are matched by many SE Asian coastal regions, so that results obtained here are likely to be typical. Little is known about the natural soundscape of these waters, so the ARL began a project to acquire a suitable acoustic data collection capability and to begin making measurements. A data acquisition system has been built which is compact, flexible and suitable for operation from small vessels of opportunity. We are currently collecting data from a number of representative sites around Singapore and elsewhere. The soundscape at these sites has been examined, and some preliminary results are now available which provide the first elements of an acoustic description of shallow waters in the region. It has been confirmed that snapping shrimp (*Alpheus & Synalpheus*) dominate most of the usable passive acoustic bandwidth for all geographical locations investigated so far, as anticipated for warm and shallow water environments. Although these animals have long been recognised as major contributors to ambient noise (Johnson et. al., 1947) the statistical behaviour of shrimp colonies has received scant attention to date. Ahn et. al (1993a and b) have investigated the individual noises made by these animals, as has Au more recently in Kaneohe Bay, Hawaii (1996). It is known that they produce substantial energy up to frequencies well above 200 kHz (Cato and Bell, 1991). Yet their collective and spatial behaviour is still largely unknown.

Data acquisition

Directional and seasonal data are required to construct a reasonably complete model of an acoustic environment, but omni-directional data provides a good start, requiring much simpler equipment and permitting a wider geographical coverage for the given resources. Regarding bandwidth, it was felt that as large a range of frequencies as possible should be examined, so as not to preclude important and unrealised aspects of the soundscape. Below 10 Hz or so, noise is dominated by flow around the sensor and (if such self noise can be suppressed) non-linear surface wave interaction and micro-seisms. While these processes are of considerable theoretical interest, such frequencies are very difficult to measure reliably, and the practical uses are somewhat limited. At the opposite end of the spectrum, above 100 kHz absorption and thermal noise limit the passive use of sound in the ocean. Higher frequencies are of interest to short-range active systems, but in this case the signal is already substantially above the ambient noise level.

We have acquired broadband hydrophones with internal preamplifiers, to prevent EM-coupled noise from overwhelming the signal. A notebook-based data acquisition and storage unit was selected, with an external A/D and filtering stage which allows filter poles, amplifier gains, channels, and sampling frequencies to be configured. A total sampling rate of 1 MHz can be supported over a maximum of 16 channels. The data are recorded directly to internal removable hard drive, avoiding analogue recording and/or subsequent conversion and transfer problems. Secondary recording systems are based on portable DAT recorders. This paper presents ambient noise data collected by these systems from three geographical locations:

- Haifa, Israel
- Singapore
- San Diego, CA.

These locations are all in warm, shallow water. We shall present results for the spectral and time domains separately.

Ambient noise data examples: spectral characteristics

We present data from each site in turn.

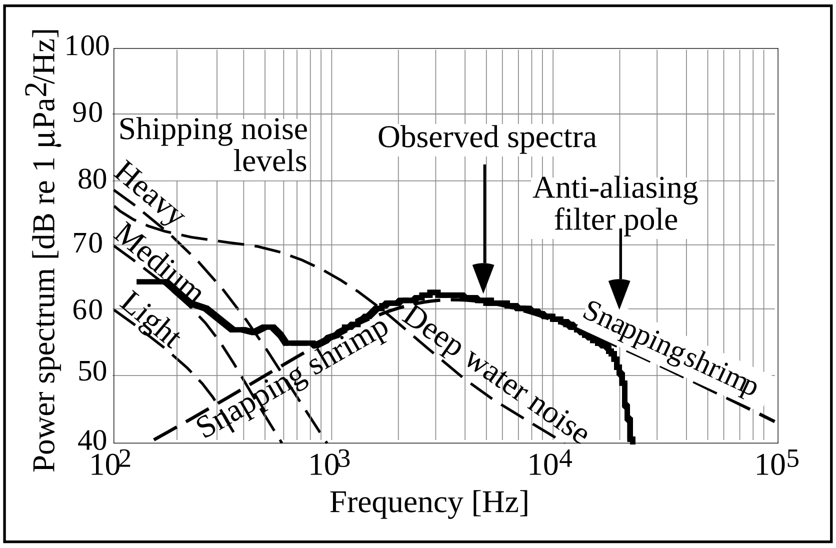

Fig. 1. Ambient noise spectra from Haifa, Israel & model curves

Haifa, Israel

The first example comes from the Eastern Mediterranean. The data were collected on a portable DAT recorder from a small power boat and kindly provided by Etienne Douaze. A hydrophone was lowered over the side to 4-5m depth in shallow water. The site was 500 m offshore on an open coastline, neither near nor sheltered from merchant ships. The spectrum (averaged over a 5 minute record) is shown in Fig. 1, where the vertical dB units are referenced to an arbitrary absolute calibration level and should not be taken as absolute. The heavy solid line shows the spectral shape. The dashed lines are various models of ambient noise producers. The family of three shown at lower frequencies are the classic heavy, moderate and light shipping noise levels adapted from Urick, 1984. The dashed line marked ‘Deep water noise’ is adapted from Urick, 1967. The curved dashed line, peaking near 4 kHz labeled ‘Snapping shrimp’ is an empirical estimate of the broadband noise at close range due to the impulsive ‘clicks’ or ‘snaps’ made by the claws of these animals. It is clear that the site exhibits some moderate shipping activity, and that snapping shrimp dominate the spectrum above a few hundred Hz, exceeding anticipated levels by 20 dB or more above 10 kHz up to the anti-aliasing filter pole at 20 kHz.

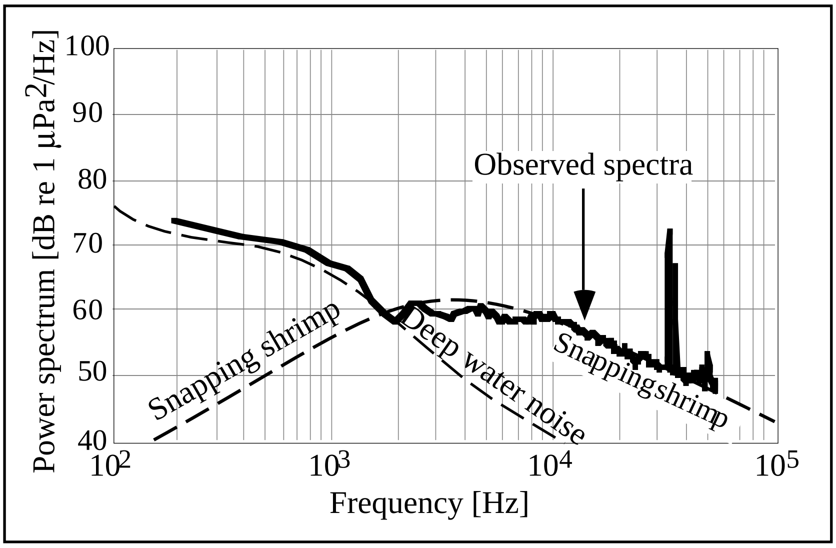

Fig. 2. Ambient noise spectra from Singapore & models

Singapore

The second example comes from a shallow water site in Singaporean waters. For this data, a broadband hydrophone was used, and sampled at 200 kHz. The anti-aliasing filter pole was set to 80 kHz, so that we can see the effect of snapping shrimp up to much higher frequencies than is possible from the DAT data (limited by the 20 kHz filter). The average spectrum results are displayed in Fig. 2. The sharp peaks near 35 kHz are system artifacts. Above 2 kHz the observed spectrum agrees extremely well with the same empirical model snapping shrimp curve that we used in Fig. 1, continuing to fit into the high tens of kHz frequencies. Below 2 kHz, the spectrum is well-approximated by the deep water noise curve from Urick. Why this is so for a shallow water site is not yet clear.

While there are some differences between these sites in the lower frequencies, this is easily understood in terms of the larger-scale geographical variations in shipping and other long-range-propagating noise. The most striking observation is that these two sites share a powerful common feature at higher frequencies: their soundscape is dominated by snapping shrimp with very nearly the same spectral shape.

Ambient noise data examples: Probability density characteristics

We have seen that snapping shrimp not only dominate shallow warm water acoustics above a few kHz, but also that they have strikingly similar spectral shapes despite being collected from widely-separated geographical locations. Now we are curious to investigate if the similarities might be as strong in the time domain as they are in the frequency domain. Clearly one cannot simply compare one time series with another, the snapping process is a random one and the results must be treated stochastically. The simplest way forward is to describe the time series in terms of its underlying energy probability density function (pdf), estimated from a suitably large set of data to provide a smooth pdf estimate, while ensuring that the discrete time windowing is sufficiently long to guarantee statistical stationarity.

The issue of stationarity is a difficult one, in that it is not obvious that any length of data will provide a stationary series, there being relatively long-term variations in the snapping levels as the animals respond to tides, solar cycles etc as well as the short-term statistical variability due to finite sample size. In practice, we have found that a time window of at least

10 ms, and perhaps as long as 100 ms is required before the statistics pass standard stationarity tests. When several thousand energy realisations are required to produce a reliable and smooth estimate of the pdf, this implies that ideally some 1000 sec of data must be analysed. In many cases we have only a few hundred seconds of data, so that the pdf estimates are rather jagged. Nevertheless, the central features are clear, as is shown below.

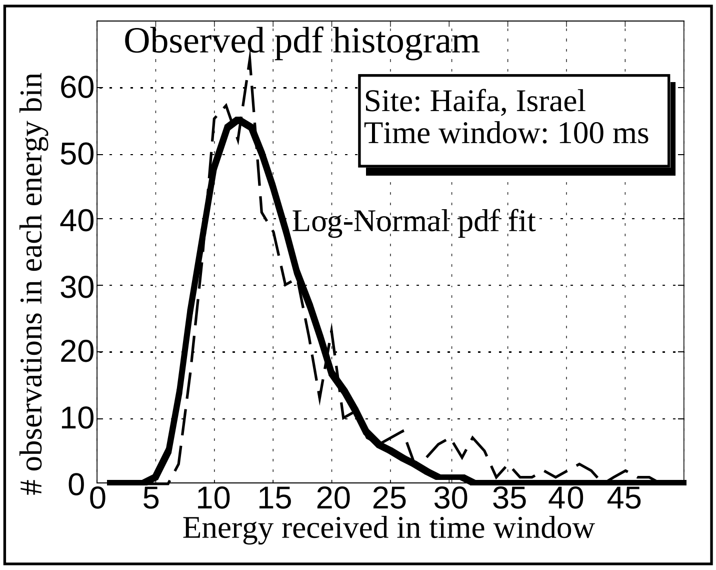

Fig. 3. Estimated pdf (dashed) & log-normal fit (heavy)

Haifa, Israel

The pdf estimated from the Haifa data is shown in Fig. 3, where the estimate is shown as a dashed line, and a best-fit log-Normal distribution has been drawn in a heavier solid line. The Chi-squared statistical test confirms that the estimated pdf is indistinguishable from a log-Normal one for the number of degrees of freedom. This is a remarkable result. Most populations arising from a large number of random, apparently unrelated events approach Gaussian, or perhaps Poisson statistics. Where the mean and variance are large, there is generally very little if any significant asymmetry, and a Poisson distribution can be well-approximated by a Gaussian of equal mean and variance. Yet these data clearly depart significantly from this expectation.

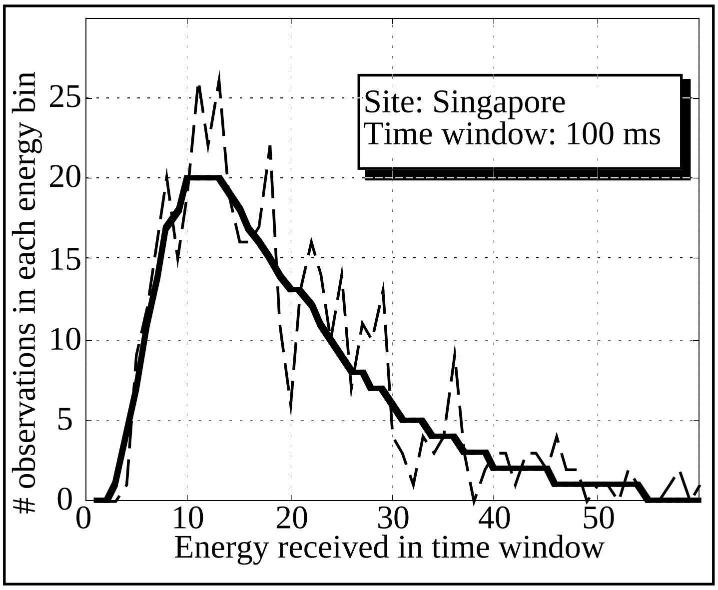

Fig. 4. Estimated pdf & log-normal fit for Singapore

Singapore

Estimating the pdf for the Singapore data, as before for the previous sites, we obtain the result shown in Fig. 4. Once again, the striking log-Normal characteristic appears, even though in this case the data were taken with very different equipment, both in regard to sampling rate and hydrophone types.

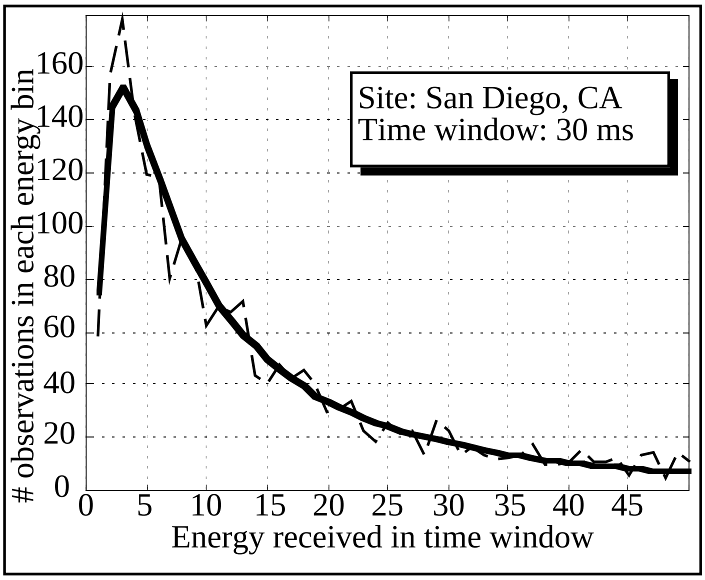

Fig. 5. Estimated pdf & log-normal fit for San Diego

San Diego, California, USA

Finally, when calculating pdf's, it is possible to use data collected by the Acoustic Daylight Ocean Noise Imaging System (ADONIS) which was deployed in San Diego, California in 1994. These data were pre-processed to give spectral estimates in 16 frequency bins every 30 ms. Although the spectral estimates are thus too crude to compare in the previous section dealing with that domain, the total energy in each 'frame' of 30 ms can be used to estimate a pdf. The results are shown in Fig. 5. Despite the shorter time window, it is immediately seen that the pdf from San Diego also obeys the log-Normal distribution law, showing even greater asymmetry than in the previous examples.

These results, showing robust similarities across large geographical ranges in both the frequency and time domain, strongly suggest that these are fundamental features of the snapping shrimp noise and perhaps can be relied upon over a wide range of geographical spread and times. Obviously it is important to have a good physical model for why this should occur, if we are to have any confidence in this apparent robustness. Two such models are presented in the following sections.

Spatial and tempo ral models

We have developed two physical models which can explain the log-Normal pdf found in the snapping shrimp data to date. The first is based on geometric considerations, and assumes that the individual shrimp snap independently. The second is based on behavioural considerations, and assumes that the probabilities are inter-dependent. the two models lead to a spatial and temporal explanation of the distributions, respectively.

Spatial model pdf

The most natural assumption on which to base a physical model is that the noise accrues from a large number of shrimp, all of whom snap at (independent) random times. If we take a large population of N shrimp at range R, then (neglecting absorption for the moment) we can calculate the probability of receiving a total energy E in time dt from the binomial distribution formula as follows:

$$p(E) = C_m^N p_o^m (1 - p_o)^{N-m} \qquad \text{eqn. 1}$$

where p_o (<<1) is the probability that a single shrimp will snap in time dt and m is the number of shrimp that are required to snap in dt to produce the observed energy, given by

$$m = E/E_o \qquad \text{eqn. 2}$$

and E_o is the energy received at range R from one snap. We assume here that there is zero probability that any one shrimp can snap more than once in the time window dt. As the normal limits are taken, we approach the usual Gaussian distribution approximation with mean received energy μ and variance σ^2 given by

$$\mu = Np_o E_o, \qquad \sigma^2 = Np_o E_o (1 - p_o). \qquad \text{eqn. 3}$$

So, the model so far gives us a Normal distribution, rather than the asymmetric log-Normal pdf displayed in Figs. 4-7. To extend the model to provide an explanation for the log-Normal pdf, we shall assume that the shrimp occur in either a homogeneous sheet on the seafloor, or that if they are clumped, the clump sizes and inter-clump spacing is small with respect to the radius over which clumps contribute significant energy. The final pdf can then be thought of as arising from a summed effect of a series of independent Gaussian distributed variables, associated with a succession of annular rings as shown diagrammatically in Fig. 6.

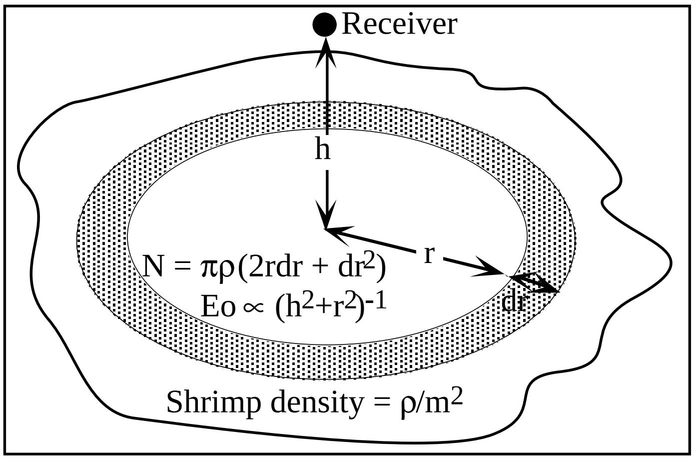

Fig. 6. Schematic shrimp density distribution model

Whereas the central limit theorem guarantees that a superposition of a large number of random distributions will converge on a Gaussian joint distribution, this is not the case for a deterministic series, such as is provided by the series of annular rings. This is because the mean and variance of these distributions display a progressive trend with increasing radius, as can be seen by evaluating N and E_o as follows:

$$N = \pi\rho(2rdr + dr^2); \qquad E_o = E^s/(r^2 + h^2); \qquad \text{eqn. 4}$$

(where E^s is the source energy from a single snap). Substituting into eqn. 3 yields

$$\mu = 2\pi\rho P_o E^s dr/r; \qquad \sigma^2 = 2\pi\rho P_o (1 - P_o) E^s dr/r; \qquad \text{eqn. 5}$$

providing in general that $r >> h$ and $dr \rightarrow 0$.

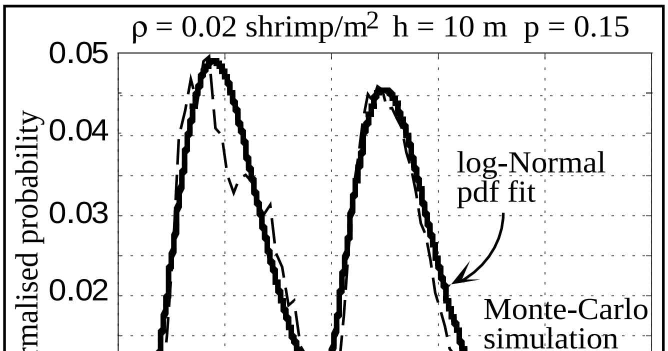

Fig. 7. Monte-Carlo simulations & log-Normal fits

The pdf of successive rings therefore display monotonically decreasing means and variances with a decay sufficiently fast that absolute convergence is guaranteed, even without absorption. Furthermore, it is easy to see that the resulting joint pdf will be asymmetric, with a sharp rise at low energies (dominated by the small variance distant annulae) and a long high-energy tail (determined by nearby small-number shrimp statistics). Monte-

Carlo simulations confirm this characteristic, as illustrated in Fig. 7 which shows two Monte-Carlo simulation results. The one shown on the left is for 5k realisations and the one on the right for 65k realisations (the latter shifted to the right for clarity) evaluated out to maximum radii of 500m and 1 km respectively. The smooth curves are log-Normal pdf fits to the simulations. At the 5k realisation level, the log-Normal fit passes the Chi-squared test, and the spatial model is therefore entirely consistent with the ambient noise observations. At the 65k realisation level, a noticeable and statistically significant 'bump' appears in the pdf, which may or may not be a feature of the data. Without continuous extensive time records (of between 1 and 2 hours), it will not be possible to acquire a sufficient number of data realisations to detect whether this 'bump' appears in the data or not.

We now have a simple physical model which correctly explains the observations that we have been able to make, and confirms that this distribution can be expected to be a robust feature of distributed snapping shrimp fields. The major assumption is that the shrimp are distributed in a smooth manner over spatial scales appropriate for the acoustic propagation. If this condition were relaxed, so that the shrimp were considered resident in significantly localised groups, then we would lose the non-Gaussian pdf result, unless some other mechanism were invoked.

Temporal model pdf

An alternative model can be constructed as follows; Suppose that the shrimp are present in only a small number of discrete clumps (within absorption range), so that the spatial biasing of contributions does not occur in the way indicated in the spatial model. If the shrimp snaps were not independent, but correlated, this could also give rise to an asymmetric pdf. Indeed, if the population were so clumped, it already implies that the groups are behaving in some communal co-operative way. It is not known why these shrimp snap their claws, but the advantages it confers are presumably balanced in part by disadvantages of advertising one's presence, to potential predators, for example.

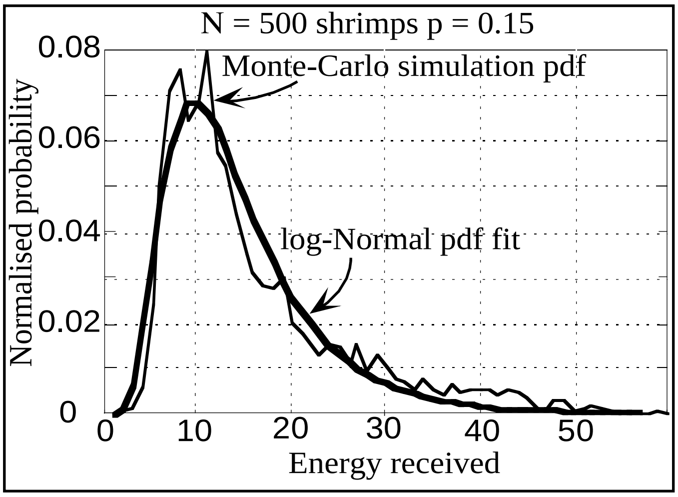

Fig. 8. Monte-Carlo simulation & log-Normal fit

In this case, it is entirely possible that some of the disadvantages could be mitigated (without overly compromising the advantages) by snapping in chorus, much as birds flock and fish school together. This tendency can be modelled by perturbing the independent probability p_o to become $(p_o + \delta p)$, where δp is proportional to the difference between the observed received energy level and the expected unbiased energy level over some recent time history. This biases each shrimp to be more likely to snap if it's neighbours have recently snapped, and vice versa. The result is that the Monte-Carlo model tends to 'chorus' and produce an asymmetric pdf, without invoking the spatial effects described previously. An example of a behavioural Monte-Carlo simulation is given in Fig. 8.

As in Fig. 7, the agreement between the Monte-Carlo pdf and the log-Normal distribution is excellent. We thus have two quite independent models to explain the observed pdf; a spatial and a temporal (behavioural) model. In practice, the reality is likely to be that a mixture of these two processes will act to create the observed distribution. Whether one or the other is predominant cannot be determined until an experiment is performed which can resolve the spatial-temporal ambiguity. This should be considered an objective of the highest priority, given that the shallow-water operating environment of all high-frequency ocean acoustic systems is determined by these animals.

Implications for high-frequency underwater acoustic systems

For active systems, performance may be limited by reverberation or ambient noise levels driving the signal to noise ratio below a critical level. Preliminary consideration of standard ambient noise texts may indicate that ambient noise is not a limiting factor above a few kHz, but we have shown that snapping shrimp noise alone exceeds documented levels in cooler and deeper waters by 20 dB or more above 10 kHz. Furthermore, this is a feature common to all warm and shallow waters and will be the rule rather than the exception in SE Asian coastal waters. As such, the potential impact of snapping shrimp is substantial. Our investigations have shown that the noise has a very stable spectral form, which can be used to accurately estimate the best frequencies of operation. The results presented here can therefore be used as a design tool for optimising these systems for use in SE Asian coastal areas. Furthermore, the discovery of an apparently universal log-Normal pdf permits more reliable false-positive and false-negative target detection estimates for systems. Gaussian assumptions will lead to severe underestimates of the system robustness in the face of ambient noise, due to the much longer non-negligible probability tail associated with the log-Normal distribution.

With regard to passive systems, particularly for Ambient Noise Imaging (ANI), Potter & Chitre (1996a) have demonstrated that higher-moment imaging is an independent statistical technique which can provide equal or better information about objects than the mean illumination for ambient noise imaging. The concept is that information is encoded not only in the mean received intensity, but additionally in the higher moments of the temporal statistics. The discovery of the ubiquitous log-Normal nature of the observed pdf indicates that the second moment of the statistics will be useful in this way, but that higher moments will contain no further information. A log-Normal distribution has only two degrees of freedom, and the mean and variance of the data (for example) therefore completely define the statistics. This result is a powerful one, allowing us to avoid wasting resources attempting to interpret null third-order moment information in the data such as skewness or curtosis.

The spatial models of snapping shrimp noise also suggest an alternative ANI technique, correlation imaging. As Potter & Chitre (1996b) have demonstrated, the time series correlation of ambient noise data contains sufficient information to form ANI images. This has been successfully employed to process data provided by Scripps Institution of Oceanography taken by the ADONIS (Buckingham et. al, 1996). With an improved physical understanding of the ambient noise illumination mechanisms, more accurate simulations can be performed to predict the performance from future ANI systems, extending the work begun by Potter (1994).

Conclusions

Data collected from several tropical or semi-tropical shallow-water sites, including Singapore, have confirmed that snapping shrimp dominate the soundscape (> 2 kHz) over much of the frequency range of interest (10 Hz - 100 kHz).

Examination of snapping shrimp noise has revealed two robust features; Firstly, the spectral form at all sites is well-approximated by a smooth curve extending from a few kHz to over 100 kHz peaking near 5 kHz. Secondly, the probability density function appears to be log-Normal. This has been successfully modelled by both a spatial and temporal behaviour models. It is not yet possible to resolve the spatial-temporal ambiguity and attribute the observations to one or the other of these mechanisms. It is anticipated that both processes are responsible to some extent. The implications for ambient noise imaging are that the higher statistical moments cannot be used above second order and that correlation imaging should be useful. To explore these potentials further, the spatial-temporal ambiguity must be resolved as a matter of the highest priority.

Acknowledgments

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