Worldwide Low-Frequency Ambient Noise

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Hydrophone stations deployed for ensuring compliance to the Nuclear-Test-Ban Treaty offer a tremendous tool for monitoring and understanding the underwater acoustic environment.

Introduction

The United Nations Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) has a broad spectrum of sensors to monitor the earth for nuclear explosions. Included in that sensor suite are underwater hydrophone systems that have collected and stored acoustic underwater ambient noise. This article discusses that data, its value to the research community, and some potential uses.

Discussion of low frequency ambient noise in the ocean inevitably results in a long list of "sub-topics," which is NOT the intent of this article. The focus is on three subjects: the change of ambient noise with time, the use of it to monitor meteorological conditions in remote locations; and the introduction of a technique to better define the source properties of ambient noise.

At very low frequencies (e.g., less than 100 Hz), the physical conditions in the ocean allow for very efficient sound propagation. Briefly, sufficient energy from the source must make its way to the depth of the minimum sound speed, referred to as the sound channel axis, which, as illustrated in **Figure 1** has some variation in each major ocean basin and also varies with latitude in all basins, ranging from the nominal depth values indicated in **Table 1**, to at, or near, the ocean surface at polar latitudes.

Figure 2 illustrates the fact that acoustic signals, if they reach the sound channel axis at angles of the order 0-15 degrees with respect to the horizontal, will travel without encountering the ocean boundaries, and at low frequencies with low energy losses, have the potential to travel long distances and still retain enough signal strength to be detected by hydrophones in the sound channel. This characteristic provides the potential to monitor the world's oceans with a few sensors strategically located geographically, and placed at the sound channel axis. This is exactly what the UN's CTBTO (Auer and Prior, 2014) has done to assure international compliance with the Comprehensive Nuclear-Test Ban Treaty. Three of the hydroacoustic systems of the International Monitoring System (IMS), and the data collected by those sites are the subject of this discussion.

Table 1. Locations and depths of the three hydrophone arrays used in this discussion

ID	Location	Latitude	Longitude	Depth (m)
HA08	Diego Garcia	7° S	72° E	1300
HA10	Ascension Island	8° S	14° W	850
HA11	Wake Island	19° N	166° E	740

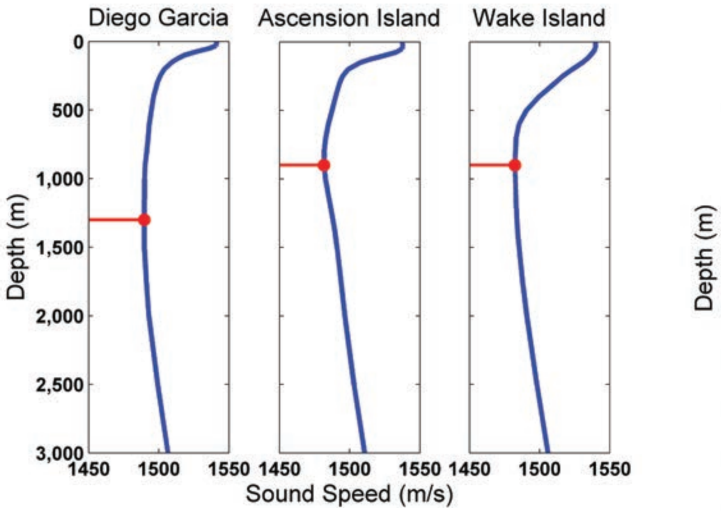


***Figure 1**. Sound speed profiles for the three hydrophone stations, retrieved from the World Ocean Atlas (NOAA, 2001). The depth of the sound channel, located at the sound speed minimum, is marked in red.*

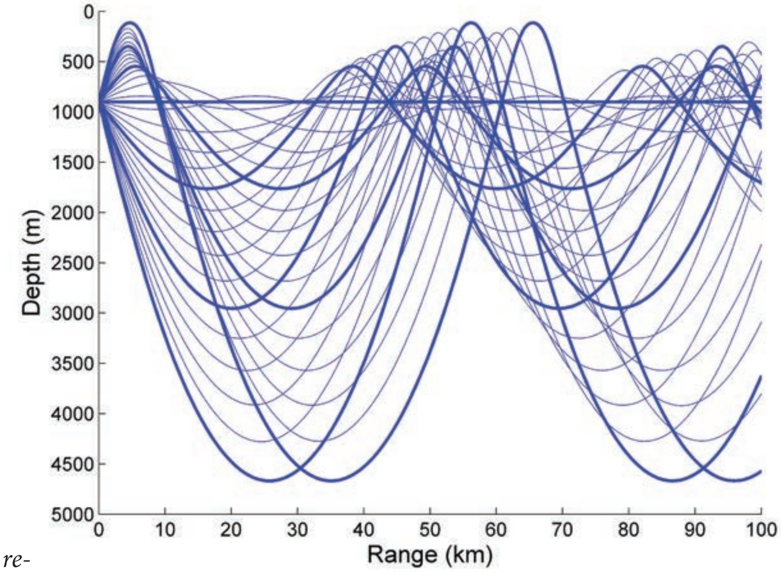


***Figure 2**. Propagation paths of sound from a source at the sound channel depth, in the sound speed profile reported near Wake Island. Ray launch angles range from -15 (Below the horizontal) to +15 degrees (Above), with an interval of 1 degree. Every fifth ray is drawn with a bold line for ease of viewing.*

***Figure 3.** Map of the three hydrophone arrays providing the data for this discussion. The three island stations are: Diego Garcia in the Indian Ocean, Ascension Island in the Atlantic Ocean, and Wake Island in the Pacific Ocean.*

The ambient noise data discussed were obtained from the hydroacoustic stations located at Diego Garcia (Chagos Archipelago), Ascension Island, and Wake Island, shown in **Figure 3** and described more precisely in **Table 1** (Lawrence, 2004). Each of these stations consists of a pair of triangular hydrophone arrays (three hydrophones) at the sound channel axis, situated on opposite sides of a host island. This arrangement helps to limit the area of detection due to the acoustic shadow zone produced by the host island and also provides some degree of directionality of the sound field. Each hydrophone is equipped with a preamplifier/filter and a 250-Hz digitizer. Buried fiber optic cables carry the digitized ambient noise signals from the moored hydrophones to a station on the surface of the host island, where they are transmitted via satellite to the CTBTO headquarters in Vienna for monitoring (Auer and Prior, 2014). The data is also available from the host country (of the site) via contact with the appropriate government agency. While these stations were built with the primary purpose of monitoring the world's oceans for unsanctioned nuclear weapons testing, the nearly continuous recordings produced by this network, spanning over 10 years in duration at some locations (data logs received from CTBTO), constitute one of the best collections of low-frequency ambient noise data currently available.

The Data: Details and Some Characteristics and Comparisons with Other Ambient Noise Data

The requirements of the CTBTO monitoring system limit the acoustic bandwidth of the data recorded to range from approximately 1 to 100 Hz. This region is where the dominant sources of acoustic signals are non-linear sea surface wave interaction; seismic activity; some biologic; and finally, commercial shipping. More about each of these sources later. The underwater acoustics community, since 1962, have used what are casually called "The Wenz Curves" as the "standard" for ocean ambient noise, so the normal procedure is for experimentalists at sea to collect and plot the data under consideration on those curves to provide a "sanity check." Since the Wenz Curves are accepted by researchers to be typical of ambient noise for various environments encountered at sea, the comparison gives confidence that the current data collected is good data. In keeping with that process, first consider some long term average levels from the Indian, Pacific, and Atlantic Oceans in the context of the Wenz curves (Wenz, 1962) (**Figure 4**):

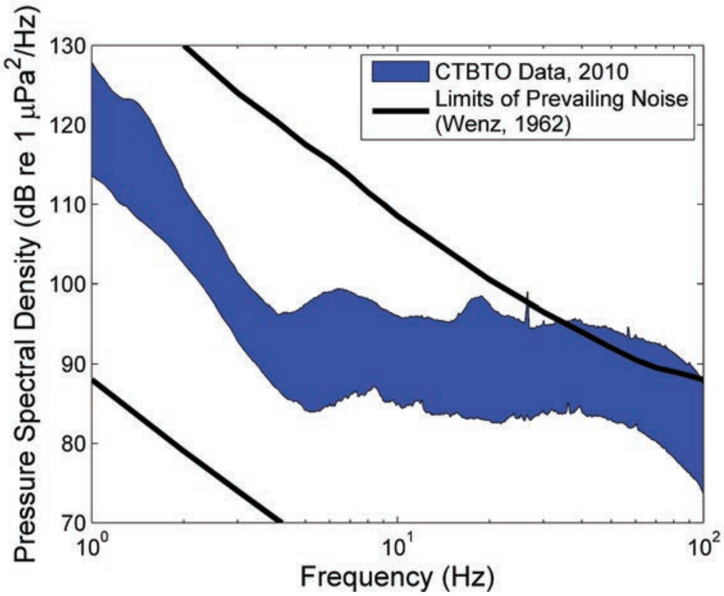


Figure 4. *Ambient noise levels measured at the CTBTO hydroacoustic monitoring stations for 2010. The reported levels are superimposed on the "Limits of Prevailing Noise" curves published by Wenz (1962).*

Figure 4 shows a full year (2010) of data from CTBTO sites in the Atlantic, Pacific, and Indian Oceans, superimposed on the limits of prevailing noise, as published by Wenz in 1962. The large blue band shows the range of year-averaged spectral levels seen across the three sites. At frequencies below 5 Hz, the very steep spectral slopes appear reasonably well centered as averages, as expected. Above 5 Hz, the flatter spectrum is a combination of biologic, anthropogenic (usually shipping, but can be other human-caused sources), and geophysical sound sources. As one approaches the upper frequency limit of the CTBTO System around 100 Hz, the more recent averages move to above average and even exceed the upper limit seen by Wenz more than 50 years ago. Since the acoustic sources, as 100 Hz is approached, are considered to be dominated by shipping, those anthropogenic contributions were predicted to increase (Ross, 1987, 1993) and recent measurements have borne out that hypothesis over the intervening five decades. This behavior was expected and clearly illustrated in the figure.

A more graphical way to emphasize this increase is seen in **Figure 5**, which displays both the Wenz values from the 1950's and 1960's and more recent data from the Pacific Ocean, west of California, collected in the late 1990's and early 2000's (Andrew et al., 2002), together with the averaged values of the present data for the frequency region 10 to 60 Hz.

Much of the recent attention given to underwater noise is concerned with the effect of human activity on the ambient noise levels in the ocean (Hawkins and Popper, 2014; Ketten, 2014). Since many marine mammals rely on sound as their primary means of communication, increasing levels of noise may hinder their ability to survive in an environment that is changing faster than their ability to adapt, and over geographic regions large enough to impact their established travel patterns (Southall et al., 2007; Hawkins and Popper, 2012). Several studies have reported that noise levels in the frequency range of shipping activity have increased since the 1960s. The data from Andrew et al. (2002), between 10 and 60 Hz, shows that noise levels measured at a receiver located in the Eastern Pacific Ocean were more than 10 dB louder in the late 1990s than in the mid-1960s. Several measurement sites, including the three of interest here, are clearly louder than they were in the 1960s, but the rate of increase appears to be leveling off, or even decreasing (Andrew et al., 2011).

Acoustic (and Meteorological) Weather

A major contributor to noise from 1-5 Hz is sea surface motion caused by storm (high wind) events. Because there is also another wind generated contribution at frequencies above the 100 Hz upper limit of the CTBTO data, some explanation is necessary. The phenomena generating this very low frequency noise is a non-linear effect (Longuet-Higgins,

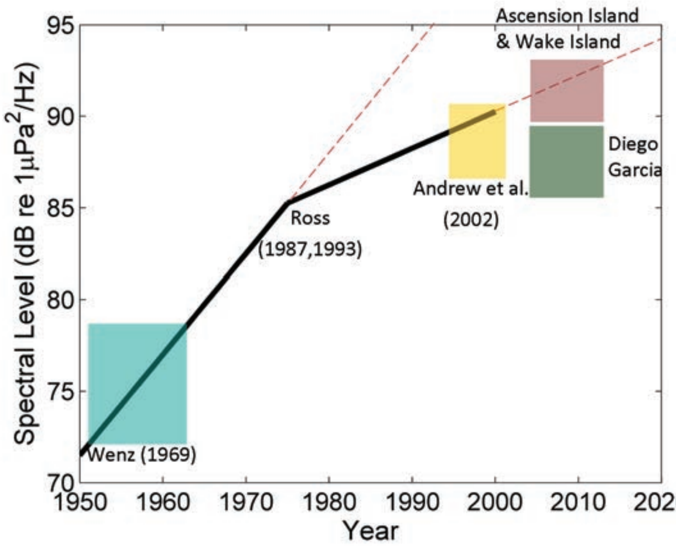


***Figure 5**. Comparison of ambient noise levels over time, based on measurements reported by Wenz (1962) and Andrew et al. (2002), with data from the CTBTO stations for 2010. The black lines, and extrapolated dashed lines, show two differing ambient noise trends noted by Ross, with a prediction that the noise levels would only increase 5 dB in the last quarter of the twentieth century (Ross, 1987 and 1993).*

1950) resulting from two ocean surface waves that are traveling toward one another and their consequent interaction, creating a standing wave which results in a pressure change sensed by the hydrophone(s). Below 5 Hz, it has been noted that the amplitude of the pressure variations produced by the Longuet-Higgins mechanism correlate well with surface wind speeds (McCreery et al., 1993).

As winds blow along the surface of the sea, surface waves start to develop, which increase in amplitude as wind speeds increase. Logically, surface wave heights can only increase up to a certain point before they start to break, limiting the height of a wave. Since longer wavelength waves can support higher amplitude than shorter wavelength waves before the onset of breaking, the height limit of a surface wave is dependent on its frequency. For oceanic surface waves of frequencies between about 0.1 and 10 Hz, this limiting height spectrum, often referred to as a “saturation spectrum”, is proportional to frequency^{-5} (Pierson and Moskowitz, 1964).

The effect of the surface wave saturation spectrum is demonstrated in **Figure 6**, with measurements made near Diego Garcia over the year 2010. In this plot, the ambient acoustic spectrum is grouped by the surface wind speed at the time of measurement. As surface winds increase, noise levels below 5 Hz increase up to a similar saturation spectrum, but not that of the acoustic ambient noise. As derived by Hughes (1976) and Lloyd (1981), the saturation spectrum of the noise generated by the Longuet-Higgins mechanism is proportional to frequency^{-7} below about 5 Hz.

To illustrate the contribution of a passing storm to the ambient sea noise background, a typical storm passing Wake Island was “tracked” acoustically and displayed in **Figure 7**, which displays a nine day period near Wake Island, during which wind speeds quickly rise, and then gradually decay. As the wind speeds increase, so do the sound levels at 1 Hz, with some delay time to allow wave heights to build up.

The acoustic energy in the 1 -5 Hz band, illustrated in **Figures 6** and **7**, is "local" in the sense that the wave interaction phenomena and its resultant acoustic signal are present in the water column. The signal can, and does, propagate. In fact, its initial discovery was observed by land based seismometers, often many kilometers from the location of the signal generation. The contribution of ambient noise from a passing weather system that enters the sound channel noted in the introduction is still a research issue. With the assumption that a reasonable estimate (prediction), or a measurement can be made to quantify that contribution, the use of the CTBTO hydroacoustic arrays as remote "weather" stations has a value in the global mapping of weather conditions and their change over time. It must be emphasized, however, that any given hydroacoustic site would be integrating the effect of a number of simultaneous storms over a potentially very large oceanic surface area, depending on storm intensity and size, so the value is one of averaging (smoothing) the impact of (likely) a number of storms. The use of hydroacoustic sites to provide, via an "acoustic weather" metric, a view of averaged atmospheric weather, has an interesting potential.

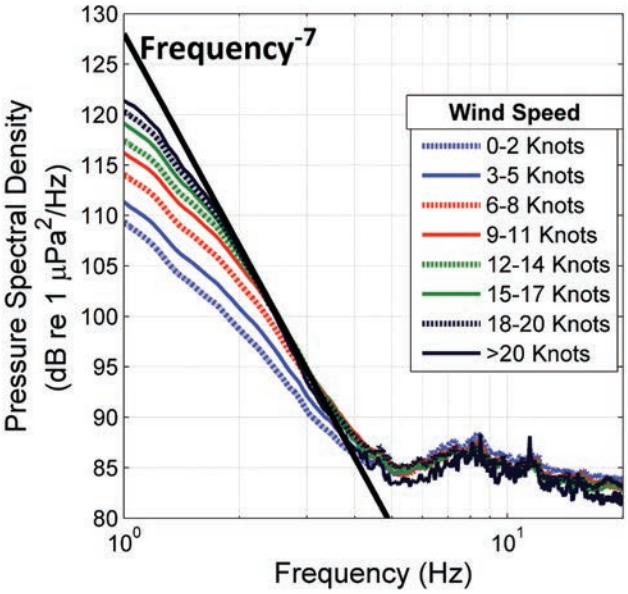


Figure 6. *Ambient noise spectra measured near Diego Garcia during the year 2010, divided into groups based on the surface wind speed at the time of measurement.*

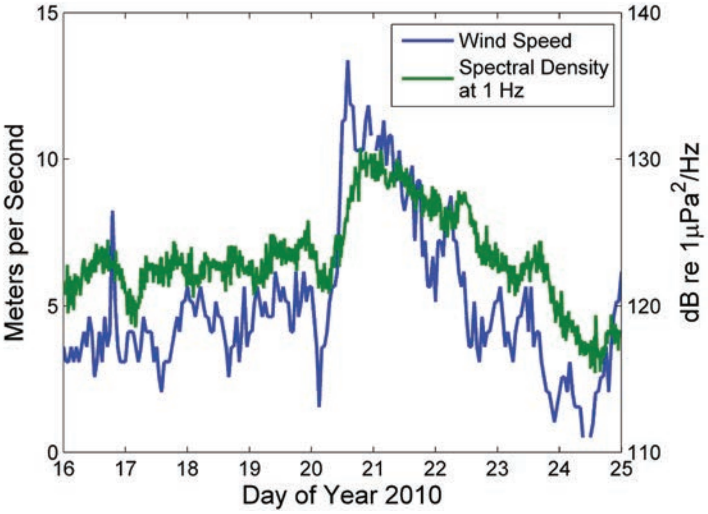


Figure 7. *Wind speeds and 1 Hz noise levels measured from January 16th to 25th, 2010, near Wake Island.*

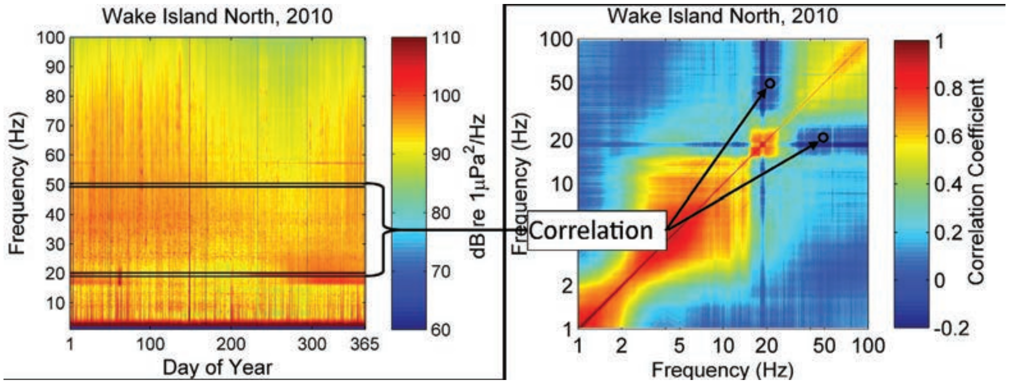


Figure 8. Illustration of the correlation process in which spectral levels pairs of frequencies are correlated, populating a matrix of correlation coefficients which is symmetric around the main diagonal.

What do you mean, "Biologics"?

The answer expected is "A North Atlantic Right Whale mother signaling its calf to 'stay close.'" A conundrum faced in underwater acoustics and one of its consequences is the use of words like "seismic events," "distant shipping," or "biologics" to describe sources of sounds that clearly should have much more precise definitions. A value of the CTBTO data sets is the opportunity to examine hundreds, if not thousands, of "events," and to consequently isolate those events that have a common source. To be sure, enormous advances have been made in the marine biology world, as each form of life has a taxa, hence a specific source can be (and is) identified and associated with a received and catalogued acoustic signal. (Stafford et al., 2004; Neukirk et al., 2012).

Searching for methods to isolate specific source functions leads to the application of a correlation technique that has been used (Nichols and Sayer, 1977; Curtis et al., 1999; Nichols and Bradley, 2013, 2014), where the frequency content of a specific signal is displayed in a manner that emphasizes the correlation (or similarity) between (or lack thereof) a particular frequency value and other frequencies, also contained in the same signal. The technique appears to provide unique and repeatable "structures" for a number of those sources that are typically labeled by a generic title such as "seismic event." The technique, illustrated in **Figure 8**, displays the correlation coefficient between spectral levels at two frequencies for a period of time (in the figure, it is one year, but the time "window" selected would be driven by the time associated with a particular phenomenon, or an estimate, if an actual measurement is not available).

Figure 9 (a)-Ascension Island (North), (b) Diego Garcia (North), and (c) Wake Island (North), displays a full year (2010) of averaged behavior using this correlation method and provides strong evidence that the detailed contributions to the ambient noise at each site has distinct differences. All have a contribution due to storms at the below 5 Hz; this contribution is seen as a region of high correlation in the low frequency (bottom left) corner of each figure. Looking to higher frequencies, each of the locations behaves differently. At Ascension Island in the Atlantic Ocean, the dominant source of noise (at least, in 2010) is geophysical exploration, which creates the high correlation region between 4 and 100 Hz in **Figure 9(a)**. Noise from these surveys was detected nearly every day of the year near Ascension Island. Within the 4 to 100 Hz high correlation region produced by the survey noise, a pair of plus-sign shaped features at about 18 and 26 Hz denotes the presence of a source which is relatively uncorrelated with the seismic survey noise. These features within the correlation matrix denote narrow-band whale vocalizations which are present for a large portion of the year (Nichols and Bradley, 2013).

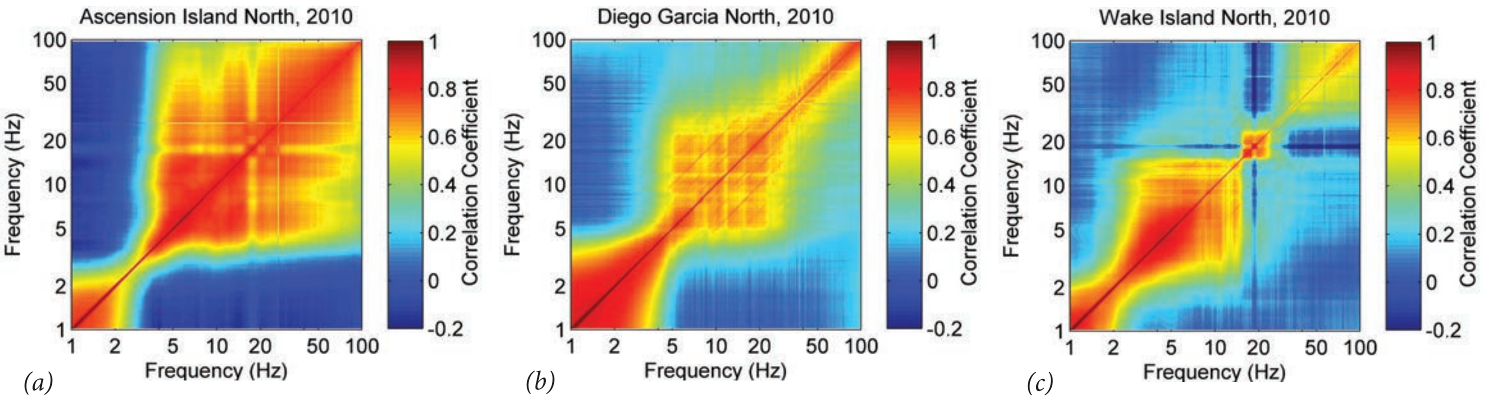
Near Diego Garcia in the Indian Ocean, seismic activity (solid earth movement) is responsible for a great deal of acoustic energy over the course of the year, as is evidenced by the region of correlation between 5 and 30 Hz in **Figure 9(b)**. Within this frequency band, parallel diagonal lines occur where the ratio between the two frequencies is an integer ratio. These integer ratio diagonal lines correspond to the harmonic nature of ship noise.

Figure 9(c) illustrates the acoustic activity near Wake Island in the Pacific Ocean. Similar to **Figure 9(b)**, the region of higher correlation from 3 to 18 Hz indicates the predominant region of seismic activity noise. The high end of this region is followed by a band of correlation ranging from about 18 to 22 Hz. This region consists of a larger band of correlation, spanning from 18 to 22 Hz, and a narrower band, from 19 to 20 Hz. The dual-band feature shows the presence of two different types of whale vocalizations.

The richness of variability in these correlation displays, both in location and time (not discussed here), will contribute to the acoustic ambient noise source function descriptions.

Summary

The CTBTO data sets provide an enormous storehouse of information that can be (and is being) mined for information on the details of oceanic acoustic ambient noise. Comparison with similar data collected decades ago clearly displays



(a) (b) (c)

Figure 9. *Correlation matrix of the acoustic field measured near (a) Ascension Island, (b) Diego Garcia, and (c) Wake Island during the year 2010.*

an increase in the levels of ambient noise in those frequency bands that are dominated by anthropogenic sources. The potential of using the CTBTO system to provide an acoustic "weather" counterpart to meteorological weather, which is a temporal and spatial average, more amenable to tracking long term changes should be investigated. Finally, the use of a frequency correlation method to better define ambient noise source functions removes the indistinctness of terms like "shipping" or "seismic events."

Biosketches

David L. Bradley received a Ph.D. in Mechanical Engineering in 1970 from The Catholic University of America. His work career has been a combination of US Navy supported research, Laboratory Directorship at the NATO Undersea Research Centre, La Spezia, Italy and university research and academic activity at The Pennsylvania State University, the Applied Research Laboratory. Currently a Professor of Acoustics, he is funded by the Office of Naval Research. He has served as President and Associate Editor for the Acoustical Society of America. A Fellow of the Acoustical Society, he has served on the Executive Council and chaired Society committees.

Stephen M. Nichols is a graduate research assistant at the Applied Research Laboratory at The Pennsylvania State University. He earned his B.S. in Physics from the University of California, Los Angeles in 2011. He is currently working on his Ph.D. in Acoustics at Penn State. His graduate work is focused on the analysis of large sets of very low frequency underwater ambient noise, looking primarily at the source mechanisms responsible for creating the ambient noise field.

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