1. INTRODUCTION

Since 1975 the Coastal Data Information Program (CDIP),\(^1\) within the Scripps Institution of Oceanography (SIO), at the University of California, San Diego (UCSD), has measured, disseminated and archived coastal environment data for use by coastal engineers, planners, and managers as well as scientists, mariners, military, and surfers. CDIP operates approximately twenty off-shore and near-shore buoys, arrays, and platforms, which record ocean conditions including wave height, period, and direction, air and sea temperature, wind velocity and direction, and barometric pressure.\(^1\) Such multidimensionality and its cyclic multivariate wave nature is inviting for sonification and computer music composition.

The basic sonification mapping is quite direct. The spectrum of the original time-series is shifted and then transformed into an audible signal. Thus the frequencies in one domain are proportional to frequencies in the other. Amplitudes are determined by energies present in the corresponding bins. The spatialization of the spectral component is determined by the direction from which it is originating. Low frequencies are long period waves, which are good for surfing; high frequencies are short period waves, which create choppy water. During several intervals there are clear frequency sweeps from low to high, which signify passing energy from a storm.

1.1. Introduction to Physical Oceanography

The ocean is a vast body which has unprecedented complexity, the movements of which are the subject of study for physical oceanography. The CDIP buoys only measure waves and not currents, which actually transport water. Waves are only the undulations of the ocean surface, which are mostly produced by winds that grip and push even the centimeter ripples. Waves can also be produced by earthquakes, volcanic eruptions, and massive underwater mudslides.

Waves are classified into two categories. “Sea waves” are locally generated which are irregular or choppy, and peak in the same area as the “fetch”—the area over which the wind and ocean interact. When the waves leave the area of the fetch they are classified as “swell waves.” The velocities of ocean waves are proportional to their periods, so the longer periods outrun their shorter counterparts. Thus the previously localized energy becomes a “wave train” and moves often thousands of miles to finally break and release the energy on some shore [2].

2. THE BUOYS AND DATA

The buoy in figure 1 is a 0.9 meter diameter steel hull that weighs approximately 180 kg, and is tethered to the ocean bottom with a mooring line and 450 kg of ballast chain.\(^2\) This buoy can measure temperature and accelerations in the three dimensions. Wave height is determined by vertical acceleration; wave direction comes from the measured accelerations in the xy-plane. Non-directional buoys just measure temperature and vertical acceleration. Typically CDIP buoys are in regions 500 meters deep, but are used closer to shore in as shallow as 20-meter depths. Figure 2 shows the locations of all currently operational West coast buoys operated by CDIP.

The buoy makes 2,048 measurements at a sampling rate of 1.0 Hz and then transmits the data via radio to an onshore field station. Every thirty minutes CDIP queries the field station, downloads the

\(^1\)http://cdip.ucsd.edu

\(^2\)CDIP uses buoys made by Datawell: http://www.datawell.nl
data, processes it, and then disseminates it to the National Weather Service and makes it freely available on the CDIP homepage. Reporting latencies are usually thirty minutes to an hour after data retrieval. The Fast Fourier Transform (FFT) of raw buoy data uses no window and no zero-padding. CDIP does not correct for spectral leakage since it is assumed that this has minimal effect on wave parameters such as significant wave height, and peak period. Since the data is taken over long periods the wave heights are corrected for tidal changes.

There are several products derived from buoy measurements, including current and near-future conditions. Forecasts of up to 72 hours are available through modeling of Pacific wind and wave fields. Figure 3 shows a ‘snapshot’ of current wave conditions along the Southern California coast, based on the measurements from the Harvest Buoy (071). As one travels south however there is an increasing time lag since it the conditions measured at the buoy take time to propagate South—approximately 8 hours from Harvest to San Diego. The polar plot in the lower left corner displays the directional wave spectrum of 071. This depicts the distribution of spectral energy as a function of wave period and direction. This one shows three sources of energy: two significant ones coming from just North of West and a very small one coming from the South. This picture also shows the shadowing of swell energy by islands.

A spectral file is produced from each 2,048 sample measurement containing the mean energies and directions for each bin—usually 64 bins with a range of 0.025 – 0.58 Hz. Each spectral file is used to calculate significant wave height $H_s$, peak period $T_p$, and peak direction $D_p$ for that record. These three values are plotted in figure 4 for the Oceanside Buoy (045) during May, 2000. A reduced nine-band spectral summary is also created, an example of which is seen in Table 1.

For the same month of 045, figure 5 shows a spectral waterfall plot, and the peak directions are shown in figure 6. The mountain plot demonstrates how easily this data lends itself to sonification and computer music curiosity.

For the month of May, 2000, 045 made 1,488 measurements; for the entire year, it made 17,541 measurements. This many measurements makes for a humongous collection of data. The total size of the current CDIP database is over 50 gigabytes and spans twenty-six years—all of which is freely and publicly accessible. It increases each day by approximately 15 – 20 megabytes (Mb), or about 1 Mb of data for each operational station.

3. THE SONIFICATION

The sonification of this data is straight-forward discrete Fourier theory. The Inverse Discrete Fourier Transforms ($DFT^{-1}$) of the shifted spectral data are time-shifted and combined using the con-
sonifying a spectral record is: constant overlap-add method (COLA) [4]. The general formula for sonifying a spectral record is:

\[ S(n) = w(n) \cdot DFT^{-1}[X(k') - \phi(k')] = \sum_{k=0}^{K-1} A(\omega_k) D(k) X(k) e^{i\omega_k T_k} \]

where \( X(k) = X(k' - \phi(k')) \) is the spectrum shifted by the function \( \phi(k') \), \( k' \) being the original bin. As always \( \omega_k = 2\pi/T_k \), where \( T_k \) is the shifted period \( T_k \). The directional spectrum \( D(k) \) is the spatialization function and \( A(\omega_k) \) is an amplitude scaling function. The window is \( w(n) \), \( K \) is the number of bins, and \( E_s \) is the sampling rate of the sonification.

The window used initially was a rectangular one which predictably created discontinuities in the sonification at the edges. A Hanning window resulted in audible pulses. The Tukey window, or tapered cosine, gave the best results by smoothing the transitions but maximizing the window length at unity [5]. An \( N \)-length Tukey window is described by:

\[ w(n) = \begin{cases} 1.0, & |n| < \frac{\alpha N}{2} \\ 0.5 + 0.5 \cos \left[ \frac{\pi}{\alpha} \frac{|n| - \frac{\alpha N}{2}}{N - \frac{\alpha N}{2}} \right], & \frac{\alpha N}{2} \leq |n| \leq \frac{\alpha N}{2} \\ 0, & |n| > \frac{\alpha N}{2} \end{cases} \]

where \( 0 \leq \alpha \leq 1 \) controls the width of the cosine lobe. To satisfy the COLA condition,

\[ \sum_{m=\infty}^{\infty} w(n - mR) = \text{constant} \neq 0 \]

where \( m \) is the window number and \( R \) is the shift amount. As long as \( R = \frac{\alpha}{2}(N - 1) \), the Tukey window satisfies COLA. Figure 7 shows five different Tukey windows.

When creating a stereo sonification the directional spectrum, \( D(k) \), spatializes a component based upon its significant direction. For buoys on the West coast, 360° is pan-right, and 180° is pan-left, and anything in-between is split proportionally. Sonifying the data depicted in the polar plot in Figure 3 would put most of the sound just right of center with two higher frequency groups, plus a lower frequency clump in the left channel with a much smaller amplitude.

The amplitude function, \( A(\omega_k) \), currently employs a crude Fletcher-Munson equal loudness scaling so perceptual distortion is minimized [6]. This function has also been employed as a filter to selectively remove or magnify particular bins.

This acoustic conversion is simple and direct. The spectral composition of the sound is the shifted spectrum of the wave-
driven motions measured by the buoy. The energies within the spectral components are the amplitudes of the sonification spectral components. The spatialization of a spectral component is determined by the direction from which that component is observed originating. In its most basic presentation, the original ocean waves are being scaled to audibility.

3.1. Sonification Considerations

The two most important considerations for the sonification are choosing an adequate shifting function, $\phi(k)$, and the window length and taper. These choices can either create a well-fused timbre, or several interfering voices. Work has been done with linear and exponential mappings, and spectra chosen from other criteria, i.e. the harmonic series starting at 30 Hz. Figure 8 shows some general shifting functions. Since oceanographers speak more about periods than frequencies, it might be better to reverse the mapping so that decreasing aural frequency corresponds to decreasing wave period.

The window length $N$ limits $\phi(k)$ because the lowest frequency that can be completely represented in a window is $F_s/N$. To make a one minute 44.1 kHz sonification of the year 2000 for 045, 17,541 windows would require a length of at most $N = 300$ samples. Thus the lowest frequency which could be used would be 146 Hz. The highest possible frequency is still the Nyquist limit, $F_s/2$.

The percentage of transition time of the entire window, $\alpha$, is also important to consider. The transform using windows close to rectangular, $\alpha \approx 0.0$, sounds much different than when using a Hanning window, $\alpha \approx 1.0$. The smoothest sonifications result when $0.2 \leq \alpha \leq 0.5$. This makes the transition time between windows 0.1 to 0.5 times the sustain time, i.e. the time during which $\omega(n) = 1.0$.

Depending on the resolution required the sonification can begin pulsing when there are less than ten windows each second. This is similar to the pixelation of an enlarged digital image. This could be alleviated by interpolating the spectral record, but this may only be warranted for compositional purposes, since events like wave trains that begin quite suddenly may become too blurred.

4. APPLICATION

Three different sets of the spectral data have been sonified. First is simply the $H_s$, $T_p$, and $D_p$, for each spectral record. Second is the nine-band summary. And third is the complete spectral record. The data record lengths vary from single days to whole years, with the sonifications being anywhere from seconds to more than thirty minutes in duration. The sonifications discussed below are of May, 2000 for 045 which was sonified at 44.1 kHz, 16-bits, stereo, over 45- and 90-second durations.
The first data set is the most simple. Only one voice is present with pitch determined by $T_p$, amplitude by $H_x$, and spatialization by $D_p$. It is essentially the sonification of figure 4. The aural display is simple to follow, but very fatiguing over 90 seconds; it has nominal success as interesting music. The decreasing periods are clear as well as their direction. The transitions from swell to sea (on the 2nd, 10th, 17th, and 26th) are very apparent but unnaturally abrupt. The energies, i.e. amplitudes, are not clear at all presumably because of a lack of reference amplitudes.

The second data set is the nine-band summary of the spectral record in the period range of $2 - 22+ \text{ seconds}$. All energies within a bin's range, e.g. 10-8 seconds, are summed. This sonification gives a more complete picture of the data. The upward sweeps are very clear, as are the moments when the sea dominates the swell. In the previous sonification the two cannot be heard simultaneously, but the overlaps in this sonification sound more natural. The perception of amplitude for this aural display is much more clear as well because there are juxtaposed frequencies which serve as references. This sonification is also much less fatiguing; it is pleasant and easy to concentrate upon.

The complete spectral record give the most rich sonification of all three data sets. The type of spectral shifting used significantly affects the sonification. To hear the swell clearly there should be sufficient pitch change for $10 \leq T'_p \leq 24$ seconds. And to hear the sea clearly there should be sufficient pitch change for $T'_s \leq 10$ seconds. Using an exponential scaling, e.g. $2^k$, over $30 \leq \omega_b/(2\pi) \leq 22,050 \text{ Hz}$ creates a massive sound in which both sea and swell can easily be perceived. In the 90-second sonification the swell that goes from $5/13-17$ spans 12 seconds, which is a long time to perceive and remember that the pitch is rising—especially with all the other activity going on in the higher frequencies. All swell durations are shortened by half in the 45-second sonification, making them hard to miss. Of all three data sets, this one produces the least fatiguing and most impressive aural display. It is a half step removed from composition, requiring only a title.

4.1. Results

The most prominent features of all the sonifications are the upward frequency sweeps. As explained above, this is the passing of a wave train. Also telling is the duration of the sweep. A longer sweep means that the energy source is further away, since the higher frequencies have fallen more behind. The second dashed line in figure 4 shows another passing wave train, but this one lasts twice as long as the previous one. Clearly this source was further away from 045 than the previous one since its short periods took longer to arrive. On the converse, quick sweeps are generally local storms or sea.

In addition to these upward sweeps there are downward sweeps which have proven very puzzling. They are more numerous than swell and happen over much shorter time periods. For 045 in May 2000 there are at least 23 downward sweeps, compared to only five upward sweeps. These seem to be daily events, and may be caused by afternoon winds creating sea. Why the periods increase rather than decrease is unknown at this time. These particular sweeps are not apparent in the former data set sonifications since the 34 bins between $2 \leq T'_s \leq 6 \text{ seconds}$ are summed.

It was duly noted that when presenting these materials and concepts to a senior oceanographer graphics were repeatedly requested. There was a strong desire to interact with the sound and data, such that portions could be zoomed and selectively compared with other portions, or particular bins could be filtered in and out, or shifted. Even better would be an interactive animation of the spectrum in the form of figure 3 or the polar plot. The author found that it was unrealistic to present a sonification of this buoy data without having handy a graphic score of the original data. With sound and graphics together the experience and comprehension are more complete and satisfying.

4.2. Other Applications

Another sonification was made illustrating the onset time-lags of storm energy. Figure 2 shows the location of three buoys used to sonify storm energy onset lag times: Gray’s Harbor, WA (036); Point Reyes, CA (029); and San Nicolas Island, CA (067). Three aural streams were created from spectral data from the beginning of January, 2001. In the right channel is placed 036 data, 067 is placed on the left, and 029 is put in the middle. It is quite easy to hear the progression of the wave train from North to South, shown graphically in figure 9. It is surprising to hear the similarity of the wave train at each buoy, even after traveling over thousands of miles.

Figure 10 shows the amplitude silhouette of a ten-minute sonification of the complete spectral record of 029 for the year 2000. This buoy made 17,028 measurements that year so each window lasts about 40 milliseconds. This sonification gives a pleasant macroscopic perspective of the activity throughout that year. What is most apparent in this sonification and figure 2 are the seasonal differences. There is much more energetic phenomena during the winter than in any other time.

In addition to measuring wave spectra the directional buoys track sea surface temperature ($s$). A sonification was created utilizing this information by making $\phi(k, s)$. If $s$ changes then the spectrum is either proportionally raised, lowered, squeezed or...
5. CONCLUSION

Ocean data has been used for various other sonifications, including temperature and salinity in the Mediterranean [7], and a few musical treatments. The seismic waves produced by breaking ocean waves have been heard in sonifications of seismic data [8]. Other than these there is no record found yet of sonification work similar to that presented here. This is surprising because looking at figure 5 immediately inspired the author to pursue this research.

The ocean buoy spectral data of CDIP lends itself well to auditory display by its being not only cyclic and dynamic, but a measurement of waves. Since the database is very large it provides a rich collection of data for auditory display experimenting and algorithmic composition. Further work is underway which will enable real-time interaction with this data, image, and sound.

The sonifications using these methods are immediately interesting and captivating. With certain scalings of the nine-band and complete spectrum, the sound created is much like a large bell, or singing bowls. It is as if a set of chimes are placed in the ocean and resonate when fundamental frequencies are present. Particularly with exponential scalings the sound is similar to contact-microphone recordings of long telephone wires. 4

Without knowing the science, the sounds are still influential. One co-worker suggested that if he knew the data sounded like that his job would be more interesting and dramatic. Other auditors have remarked how calming it is, some suggesting the addition of whale sounds, foghorns, and sea gulls. At the outset the author had no knowledge of physical oceanography, but has since learned enough to analyze the data and comprehend the sonifications. The author has also developed an obsession with surfing, but has yet to figure out how to sonify that.

4 Australian composer Alan Lamb works with this material.

6. ACKNOWLEDGMENTS

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7. REFERENCES


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