SURF MUSIC: SONIFICATION OF OCEAN BUOY SPECTRAL DATA

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ABSTRACT

The Coastal Data Information Program (CDIP) has been collecting data on ocean wave conditions since late 1975, first using arrays of pressure sensors, and more recently directional buoys. Fourier analysis of the data reveals the spectral and directional content of the wave-driven motions measured by the buoy. Shifting the spectrum to an audible range and synthesizing a time-domain signal creates an aurally interesting and illuminating sonification of ocean wave dynamics. The work done so far has been guided by artistic curiosity; but input from a senior oceanographer has given guidance toward interpretation and elaboration of the methodology.

Examples of ocean buoy spectral data sonification are presented, each illustrating important aspects of physical oceanography. Three forms of the data are sonified, from the least detailed to the most. The obvious sonic events are the effects of energy from storms, both local and far away. From the sonification one can estimate the energy of the storm, and the distance it originated. Entire years of data have been sonified in one to thirty minute durations for buoys in different regions, which demonstrate dramatic seasonal and regional differences. Also displayed are the time-lags of South moving storm energies at three distantly separated points on the West Coast of the United States.

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 swells, 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


Figure 1: *A CDIP buoy.*

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

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[1] http://cdip.ucsd.edu

[2] CDIP uses buoys made by Datawell: http://www.datawell.nl

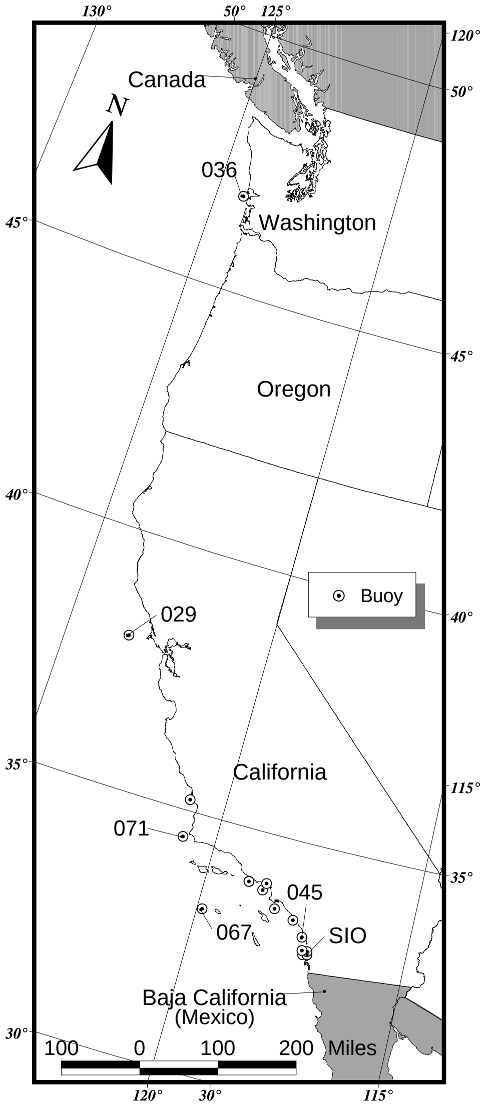

Figure 2: *Locations of current West Coast CDIP buoys. Labeled buoys are mentioned in the text.*

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.[3] 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.

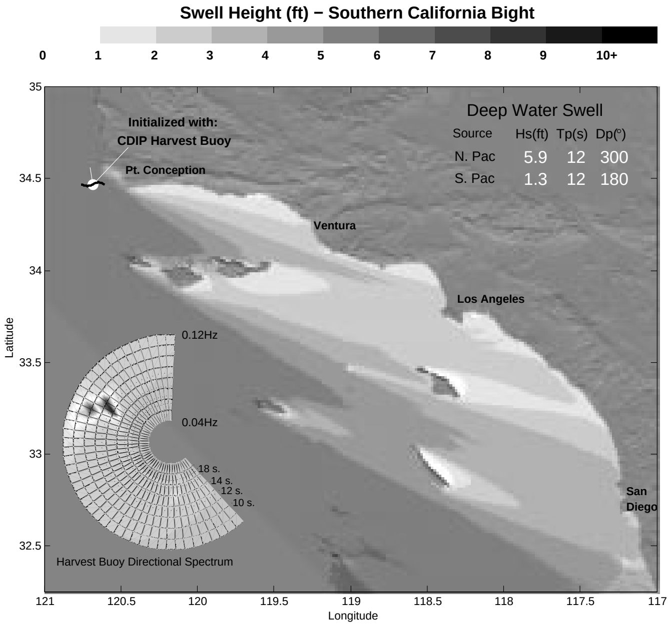

Figure 3: *Southern California wave conditions predicted using Harvest buoy data.*

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-

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[3] The data processing and reporting standards, e.g. Fast Fourier Transform of the directional data, peak period computation, are outlined in [3].

UTC yyyymmddhhmm	H_s (cm)	T_p (sec)	D_p (deg)	Energy cm^2 T Bands (sec) 22+	22-18	18-16	16-14	14-12	12-10	10-8	8-6	6-2
200201010444	287	11	301	30	293	134	330	1268	1480	839	359	422
200201010514	282	13	311	27	197	103	266	1384	1363	772	412	436
200201010544	288	13	287	27	259	115	193	1808	1388	589	381	422
200201010614	310	11	269	4	28	53	542	1772	2123	565	551	354
200201011644	292	13	293	3	19	104	465	1578	1508	819	509	324

Table 1: Buoy spectral data reduced to a nine-band summary format.

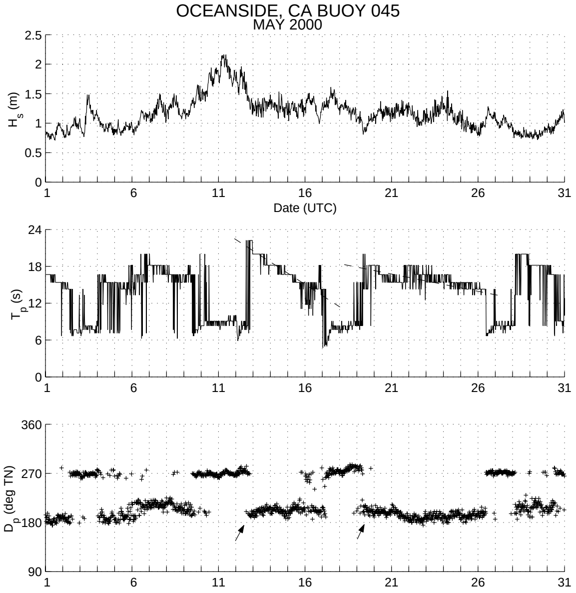

Figure 4: H_s, T_p, and D_p for 045, May 2000. *Dashed lines and arrows show swells from the South.*

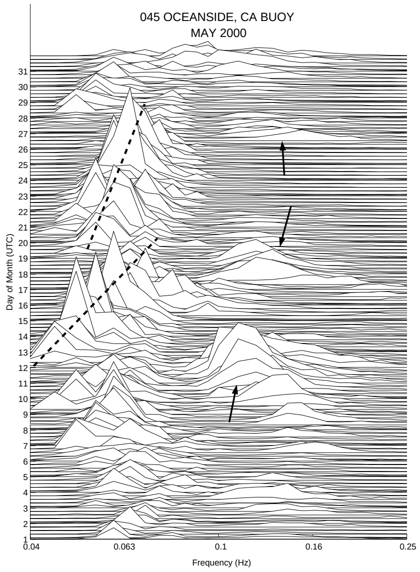

Figure 5: *Spectral energies for 045, May 2000, for* $T'_k > 4$ *seconds. Dashed lines correspond to those in figure 4. Arrows point to the effects of sea.*

stant overlap-add method (COLA) [4]. The general formula for sonifying a spectral record is:

$$S(n) = w(n)\cdot DFT^{-1}[X(k'-\phi(k))] = w(n)\cdot \sum_{k=0}^{K-1} A(\omega_k)D(k)X(k)e^{in\omega_k/F_s} \qquad (1)$$

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 F_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:

$$w(n) = \begin{cases} 1.0, & 0 \le |n| < \alpha\frac{N}{2} \\ 0.5 + 0.5\cos\left[\pi\frac{|n|-\alpha\frac{N}{2}}{(1-\alpha)\frac{N}{2}}\right], & \alpha\frac{N}{2} \le |n| < \frac{N}{2} \end{cases} \qquad (2)$$

where $0 \le \alpha \le 1$ controls the width of the cosine lobe. To satisfy the COLA condition,

$$\sum_{m=-\infty}^{\infty} w(n-mR) = constant \ne 0 \qquad (3)$$

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-

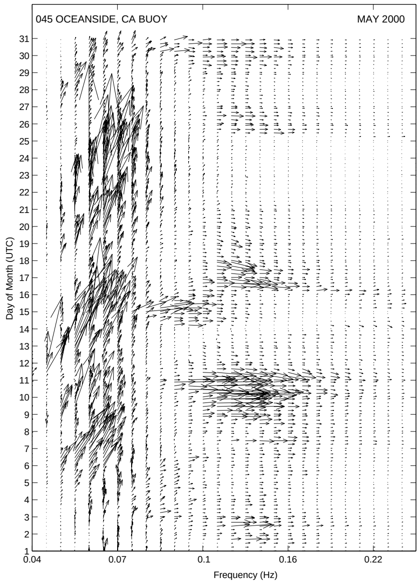

Figure 6: *Spectral directions for 045, May 2000, for $T'_k > 4$ seconds. Length of arrow corresponds to bin energy. Notice the onshore directions of the higher frequencies caused by shore-ward winds.*

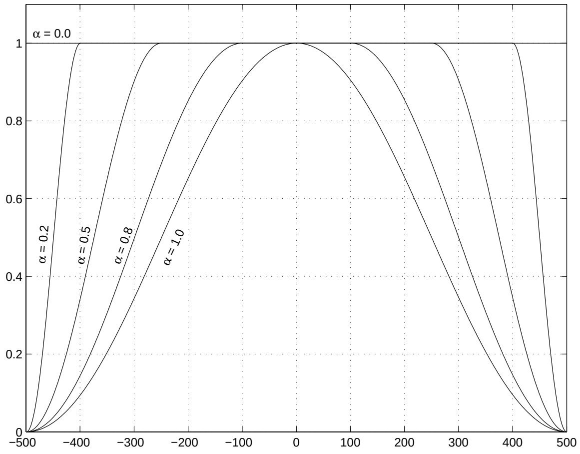

Figure 7: *Several Tukey windows. The best results come from using* $0.2 \leq \alpha \leq 0.5$.

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.

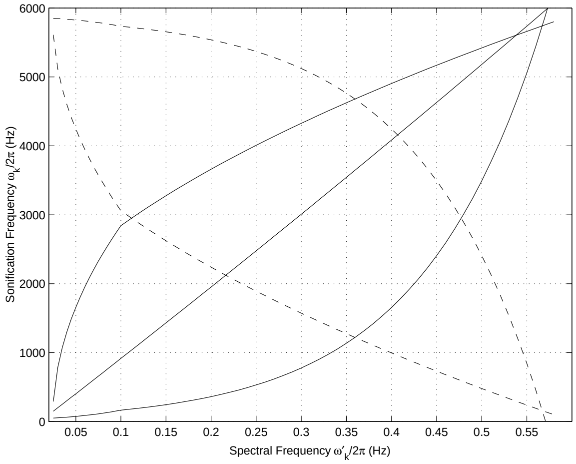

Figure 8: *Several examples of $\phi(k)$. Dashed lines are the inverse mapping, where decreasing sound frequency signifies decreasing wave period. A combination of these is possible to emphasize any spectral portion.*

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, α, 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 $w(n) = 1.0$.

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_s, 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+ 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 $10 \leq T'_k \leq 24$ seconds. And to hear the sea clearly there should be sufficient pitch change for $T'_k \leq 10$ seconds. Using an exponential scaling, e.g. 2^k, over $30 \leq \omega_k/2\pi \leq 22,050$ 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 $2 \leq T'_k \leq 6$ 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.

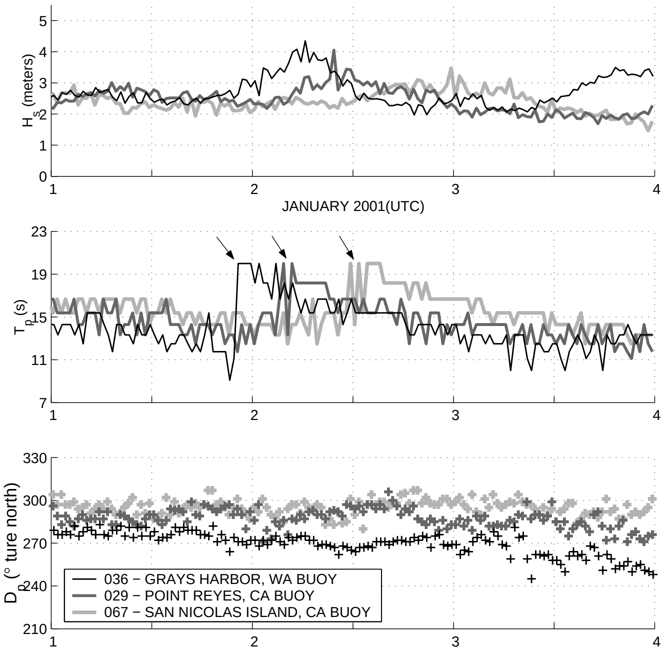

Figure 9: *Compendium plot showing a large swell moving South from 036 to 067. Arrows point to onset of wave trains.*

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 10* 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 (sst). A sonification was created utilizing this information by making $\phi(k, sst)$. If sst changes then the spectrum is either proportionally raised, lowered, squeezed or

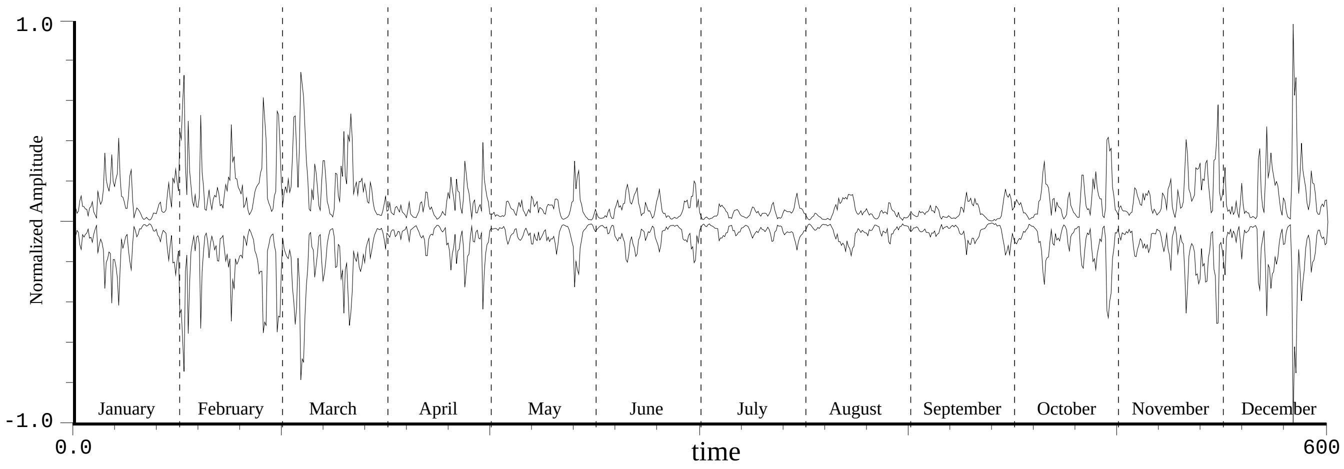

Figure 10: *Amplitude vs. time for the sonification of the year 2000 for 029. The seasonal differences in energy are apparent in the sonification as well.*

expanded. This extension was made for purely compositional interests, but demonstrates how other related variables can be integrated.

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.

6. ACKNOWLEDGMENTS

Much appreciation for the help, input, and direction of Dr. Richard J. Seymour, founder, director, and principal investigator of CDIP; and to Dr. Grant Cameron, and Corey Olfe, for their valuable input. Much appreciation to the entire CDIP crew for making my stay such a pleasant and fulfilling experience.

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[4] Australian composer Alan Lamb works with this material.