GENERAL ARTICLE

Pulse of an Ocean: Sonification of Ocean Buoy Data

Bob L. Sturm

ABSTRACT

The author presents his work in sonifying ocean buoy data for scientific, pedagogical and compositional purposes. Mapping the spectral buoy data to audible frequencies creates interesting and illuminating sonifications of ocean wave dynamics. Several phenomena can be heard, including both those visible and those invisible in graphical representations of the data. The author has worked extensively with this data to compose music and to produce *Music from the Ocean,* a multimedia CD-ROM demonstrating the data, the phenomena and the sonification. After a brief introduction to physical oceanography, many examples are presented and a composition and installation created from the sonifications are discussed.

Since 1975 the Coastal Data Information Program (CDIP) at the Scripps Institution of Oceanography (SIO), in La Jolla, California, has measured, disseminated and archived coastal environment data for use by coastal engineers, planners, scientists, mariners and the military [1]. CDIP operates approximately 20 near-shore buoys that monitor ocean conditions, including wave height, period and direction; air and sea temperature; and wind velocity [2]. The multidimensionality of the data and its periodic nature invite sonification and electroacoustic music composition.

Sonification is a parametric representation of data using sound, as opposed to a visual or graphic representation [3]. Two well-known examples of sonification are the Geiger counter and the heart rate monitor. A Geiger counter gives a qualitative impression of proximate radioactivity: a click is produced for every detected radioactive decay. One can listen to the clicks while walking with the device and note the relative danger in the vicinity. Used in a hospital, a heart rate monitor provides continuous feedback about a patient's status without requiring focused attention or the use of vision. One need not even be in the same room to notice a heart stop beating.

Using sonification not only frees the eyes for other tasks, but one can also take advantage of the auditory sense. For example, patterns, relationships and trends that are not clear in visual representations might be readily perceivable with the ears. Combining both visual and auditory representations can further enhance the interface to data; the number of dimensions for communicating information increases. This, however, can create more confusion if the design is not well thought out. Many benefits and drawbacks of sonification are presented in Kramer [4].

Sonification has been applied to a diverse range of data. Hayward and Dombois have separately investigated seismic data by listening to it as audio data [5,6]. Weather data has been sonified, usually by mapping parameters to different instruments or sounds [7]. To assist the blind, the "vOICe" system captures visual scenes using a wearable video camera and sonifies them [8]. Other data that has been sonified include heart rate [9] and electroencephalogram data [10], DNA and proteins [11], stock markets [12], quantum particle systems [13], molecular vibrations [14], and many areas of mathematics [15,16]. Though there has been some work in sonifying ocean salinity data [17], I have not found any prior work in sonifying ocean buoy data.

My method for sonifying this data is simple. The spectrum [18] of the buoy data is mapped onto audible frequencies and then transformed into sound. The spatialization of each frequency is determined by the direction from which it originates. A loud sound on the left side, for example, might mean that a significant amount of energy is coming from the south. The sonification mappings can produce diverse timbres, from bells and wind chimes to struck cymbals and droning telephone wires. These sounds and their counterpart scientific interpretations have inspired me to explore their usefulness for physical oceanography, for teaching about the ocean and for musical composition.

THE BUOYS AND DATA

The buoy used by CDIP is a 0.9-meter-diameter steel sphere that is tethered to the ocean bottom. This buoy can measure accelerations in three dimensions and sea surface temperature. Wave height is determined by vertical acceleration; wave direction is derived from accelerations in the horizontal plane. Over approximately 27 minutes, a buoy makes 2,048 measurements and then transmits the data via radio to an onshore field station. CDIP queries the field station twice per hour and makes the data freely available on the CDIP web page. Figure 1 shows the locations of all operational buoys owned by CDIP along the Pacific Coast of the United States as of 2002.

Present and near-future conditions can be determined using the buoy measurements. Forecasts of up to 72 hours are possible through the modeling of Pacific wind and wave fields. Figure 2 shows predicted wave conditions along the Southern California coast, based on the measurements from the Harvest buoy (071). The polar plot in the lower left corner of this figure displays the directional wave spectrum. This depicts the distribution of energy as a function of wave period [19] and direction. This spectrum shows a source of energy coming from just north of west with a period of about 11 seconds.

A spectral file is produced for each 2,048-sample record, which contains the spectral energies [20] and directions averaged to 64 components with a frequency range between 0.025 and 0.5 Hz [21]. Each spectral record is used to calculate a significant wave height H_s, peak period T_p and peak direction D_p observed during that time period. H_s is about half the height of the highest wave observed. T_p is the wave period (in seconds) with the most energy and D_p is the direction that peak period is coming from. Figure 3 plots these three values

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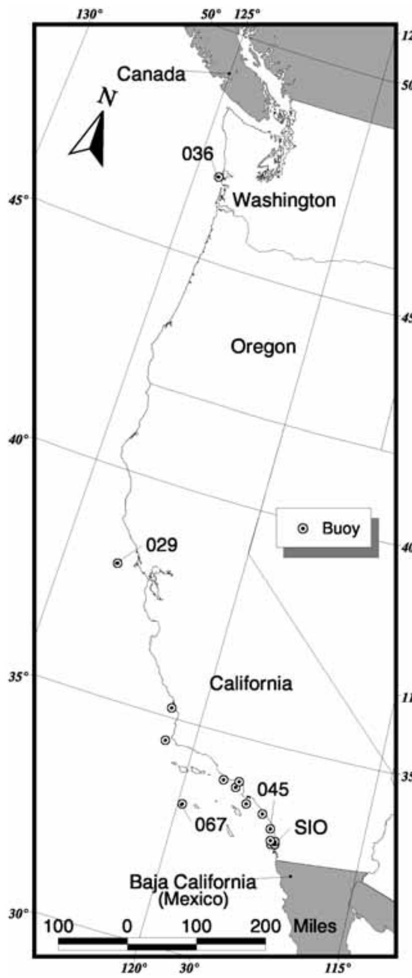


Fig. 1. Locations and station numbers of CDIP buoys on the Pacific coast of the United States, as of 2002. (© Bob L. Sturm) Labeled buoys are discussed in the text.

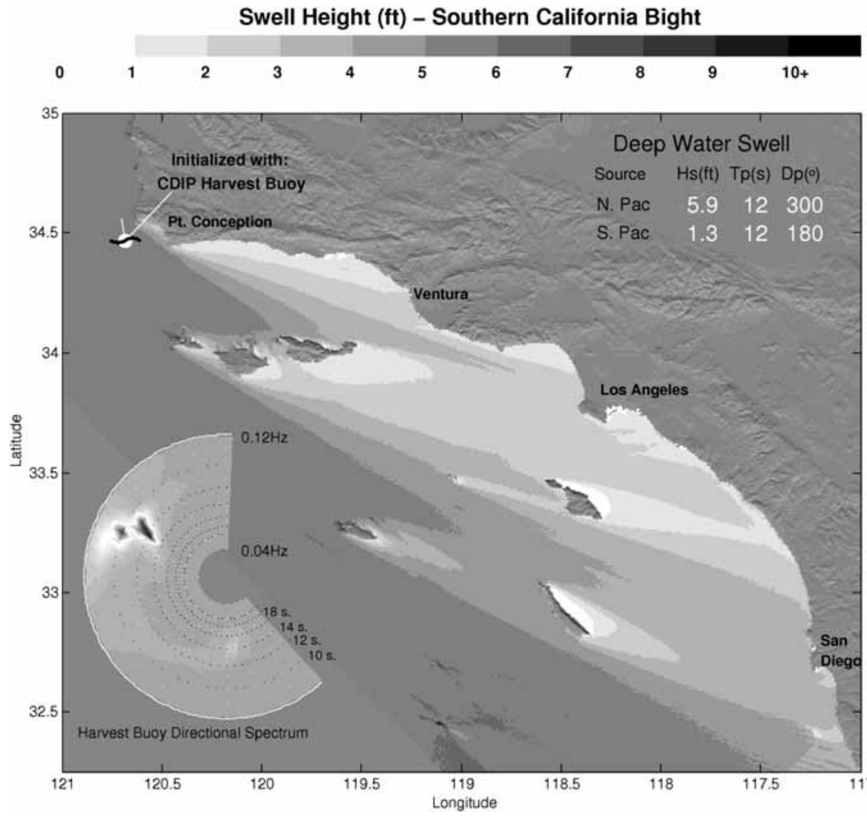


Fig. 2. Southern California wave conditions forecast using data from the Harvest buoy (071). (© Bob L. Sturm. Forecast model by CDIP.) Notice the shadowing of energy by the islands. The polar plot in the lower left corner shows directional distribution of spectral energy. A source of energy is coming from just north of west with a period of about 11 seconds.

during May 2000 for the Oceanside buoy (045). Figure 4 displays the distribution of spectral energy for the same dataset. This "mountain plot" shows the distribution of energy in the wave spectrum for periods between 1.7 and 33 seconds, every 4 hours.

For the month of May 2000, the Oceanside buoy produced 1,488 spectral records; for the entire year, it produced 17,540 records. This process generates a massive collection of data for all operational buoys. As of August 2004, the total size of the CDIP database was over 70 gigabytes—most of which is free and publicly accessible. Each day the CDIP database increases by approximately 15 to 20 megabytes (MB), or about 1 MB of data for each operational station. This amount of data provides a rich collection for sonification research.

Interpreting the Data

Oceans are vast entities of unprecedented complexity, the movements of which are studied in physical oceanography. CDIP buoys measure only waves and not the currents that transport water. Waves are the undulations of the ocean surface, which are produced by winds that grip and push even millimeter ripples. They are classified into two categories. "Sea" waves are irregular and choppy and break in the same area as the "fetch"—the distance over which wind and ocean interact. These waves are easy to see on windy days; the ocean surface is spotted with whitecaps. When a wave moves from the area of the fetch, it is classified as "swell." Swell has more energy concentrated in longer-period waves than sea, and thus has a smoother appearance. An important property of ocean waves is that their velocities are proportional to their periods. This means that long-period energy moves faster than short-period energy. Thus, energy created by strong winds gradually stretches out to become a "wave train" and travels hundreds to thousands of miles to break and release its energy on some distant coast [22].

There are many interesting features in buoy data. Figure 2 is a forecast of ocean conditions using data collected by buoy 071. The shadowing of energy by islands is very clear. Just like light waves, ocean waves bend, or refract, around obstructions. Unlike light, however, longer periods travel faster in water than shorter ones, and thus energy in the longest period will reach a buoy first. The T_p plot in Fig. 3 shows several episodes of long periods decaying to shorter ones, four of which are denoted by arrows. Each of these wave trains has a different rate of decay, from which the distance to the source of energy, usually a storm, can be calculated. A quicker decay denotes a shorter wave train and thus a closer source. The D_p plot shows that these wave trains originated south of the buoy. These same wave trains can be seen in Fig. 4, again as decreasing periods. In this plot, the higher a "mountain" is, the more energy that period has. Notice that a majority of the energy in ocean waves occurs in the period band 8–24 seconds.

Sonification

The sonification of this data is straightforward [23]. The amplitudes of the data record control a bank of up to 64 oscillators, one for each spectral component. The frequencies of the oscillators are mapped from the low frequencies of the ocean waves (0.025–0.58 Hz) to an audible range (20–20,000 Hz). This synthesis method is nothing more than additive synthesis [24]. Interpolating between records can be used to smooth the differences between records. Stereo sonifications can be created using the direction of each component. By making west (270°) pan center, north (0°) pan right, and south (180°) pan left, one can hear from where the energy is arriving. My multimedia CD-ROM *Music from the Ocean* (*MFTO*) demonstrates this sonification technique using many different mappings, settings and datasets [25].

The most important consideration for creating a clear and pleasing sonification of this data is the mapping of ocean wave frequencies to oscillator frequencies. This choice can create a well-fused timbre, a piercing buzz or several interfering voices that blur underlying phenomena. The first part of *MFTO* presents 13 different mappings applied to the same dataset to demonstrate their effects.

I have experimented with linear, exponential and random spectral mappings, as well as spectra chosen from other criteria, for example, the harmonic series starting at 30 Hz. Each of these produces very different timbres. Exponential mappings (*MFTO* tracks 6, 7) can sound like the telephone wire music of Alan Lamb [26]. When only half of the 64 spectral components are sonified, the result can sound like bells (*MFTO* track 31). Random exponential mappings (*MFTO* tracks 8, 9, 13) sound like brushed cymbals. Adding an element of randomness to the frequencies creates inharmonic relationships, which is a characteristic of cymbals [27]. Figure 5 shows examples of six spectral mappings used on *MFTO* and their mapping formulas [28].

A mapping can be chosen to focus on a particular set of frequencies—for instance, to emphasize sea or swell, or for aesthetic reasons. Large frequency differences are easier to perceive than small ones. On track 10, for instance, it is very difficult to perceive changes in wave periods between 8.3 and 40 seconds. Creating larger leaps at the lower end of the mapping, such as on track 11, will emphasize the decay of a wave train. Among the distributions in Fig. 5 are those that map increasing pitch to increasing wave frequency (tracks 8–9), as well as increasing pitch to increasing wave period (tracks 10–13). The difference between these mappings is that the decay of a wave train will either be an increase or decrease in pitch, respectively.

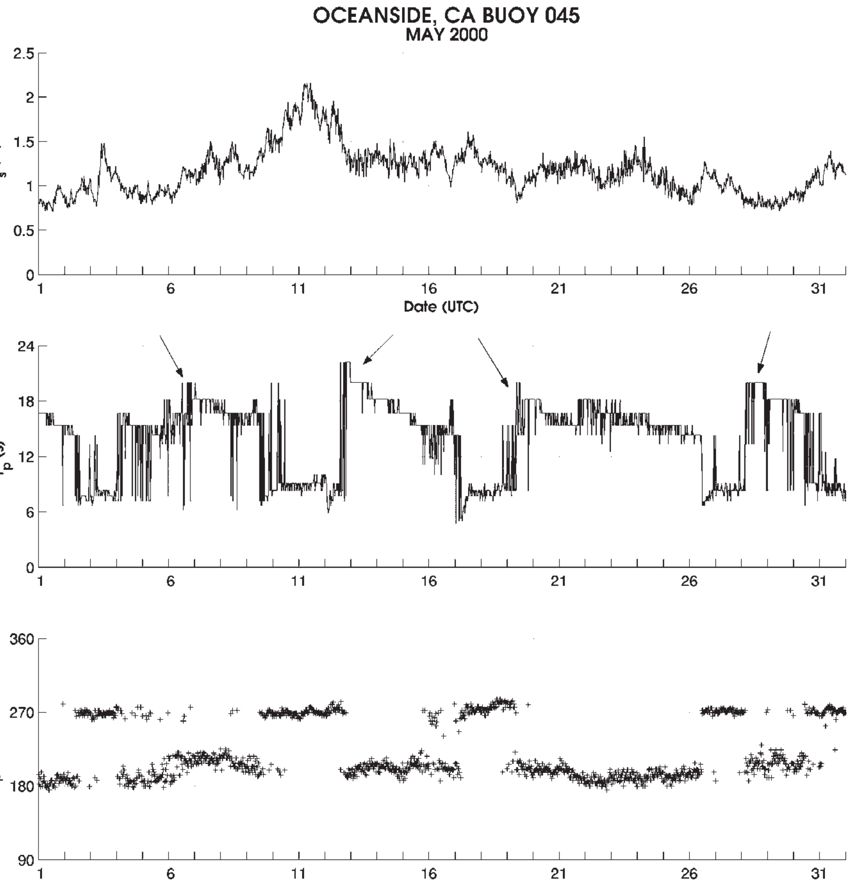


Fig. 3. Compendium of significant wave heights (H_s, meters), peak periods (T_p, seconds) and peak directions (D_p, degrees clockwise from true north, or 0°) for Oceanside (Buoy 045) May 2000. (© Bob L. Sturm) T_p is the wave period with the most observed energy, and D_p is the direction from which that energy is arriving. Arrows point to onsets of wave trains, which apparently are coming from the south (180°). This plot is a statistical reduction of the spectral magnitudes shown in Fig. 4.

There are several extensions that can be made to the sonification algorithm. The chosen mapping can be modulated, or morphed, depending on other data parameters. For instance, I have used sea surface temperature to expand or contract the spectral mapping (*MFTO* tracks 28, 32). When the water becomes warmer the mapping widens or rises; when it becomes colder the mapping contracts or lowers. I have also used existing sounds, for instance a marimba sample, as synthesis wavetables instead of sine waves [29]. Each spectral component reads through the wavetable at its frequency and attenuates the output by its amplitude. This creates an entirely different effect, but the signatures of sea and swell are still clear.

The sonification of ocean buoy data is simple and direct. In its most basic presentation, the ocean waves measured by the buoy are transposed to audibility. It is not important to keep the two spectra proportional. The most important elements to perceive are the concentrations of energy in portions of the spectrum, where they are coming from, and how they develop. Ideally the sounds produced are only a product of the frequency content in the observed ocean waves and are not characteristic of the buoy; given wave data measured another way, the same sounds would result [30]. If a buoy were malfunctioning, however, the sound would be very different because the data would be erroneous. CDIP only makes available data that passes strict quality controls.

Hearing Phenomena in the Sonification

The numerous phenomena described above are readily perceivable in the sonifications. A prominent feature of all the sonifications is the gradual sweep in frequency—an indication of a wave train. The louder the sweep is, the more energy it has. The longer a sweep lasts, the further away it originated. Another salient feature of the sonifications is a short-frequency sweep. There are at least 23

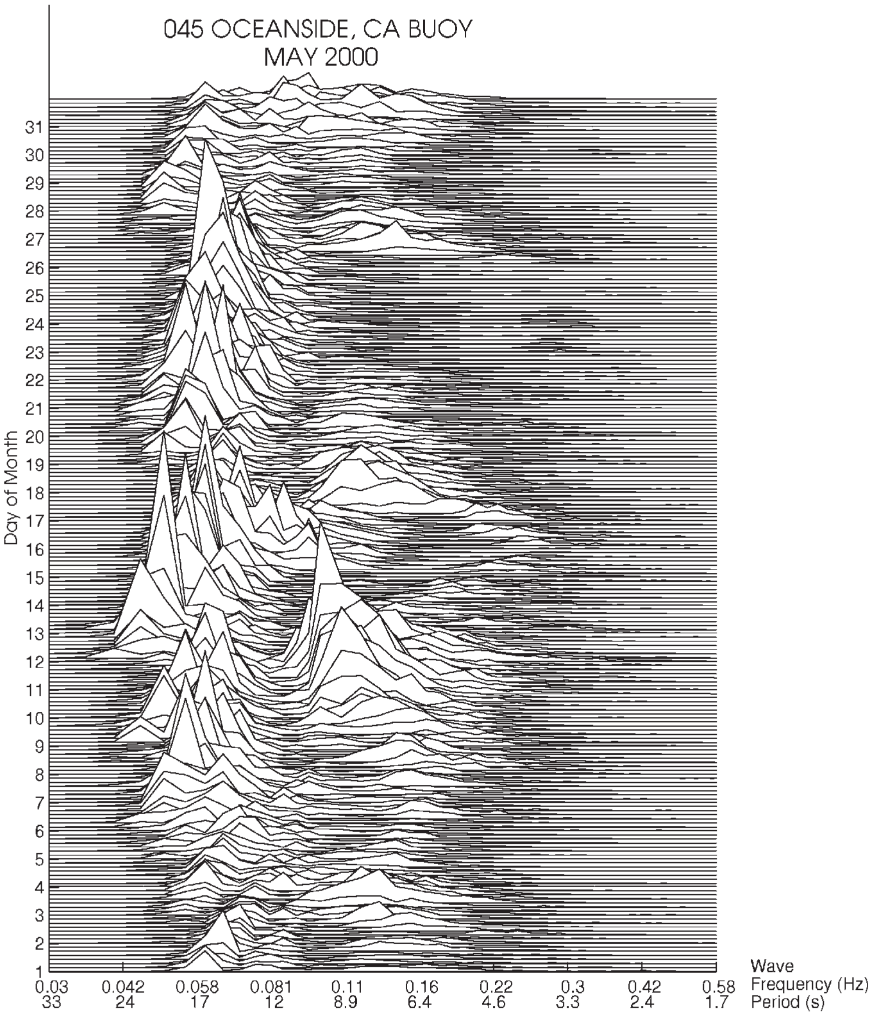


Fig. 4. Spectral magnitudes for Oceanside (Buoy 045) May 2000, plotted every 4 hours. (© Bob L. Sturm) Height of line, or "mountain," corresponds to the energy in each frequency and period (abscissa). The swells in Fig. 3 are apparent here as decreasing periods. This type of buoy data visualization provided the impetus for sonification because of its resemblance to spectral analyses of sound.

of these sweeps heard in the dataset shown in Figs 3 and 4, compared with only five gradual sweeps. These events—which are not visible in the figure because they occur over durations shorter than 4 hours—went unexplained even by senior oceanographers until I placed ticks demarcating midnight in the sonification (*MFTO* track 26). Immediately it was clear that these events, lasting only a few hours in the early to late afternoons, are caused by normal afternoon winds in San Diego. Displaying this phenomenon visually is difficult because of its time-scale and relatively small magnitude. Since each spectral record comes from 30 minutes of data collection, these effects happen over less than six records. When one is not looking for these events specifically, they are masked by the much larger energies in long-period waves.

The onset lag-times of wave trains can be heard by using data from several buoys (*MFTO* track 27). I sonified data collected during January 2001 by the buoys at Gray's Harbor, WA (036), Point Reyes, CA (029), and San Nicolas Island, CA (067). With sonification of Buoy 036 placed on the right, 029 in the middle, and 067 on the left, it is quite easy to hear the progression of the wave train from north to south. It is surprising to hear the similarity of the wave trains at each buoy, even after traveling over hundreds of miles.

Seasonal activity differences are clear when listening to a sonification of an entire year. *MFTO* contains three sonifications of the 17,540 records measured by Buoy 045 during the year 2000 compressed into 1-, 3- and 10-minute durations (*MFTO* tracks 22–24). In making the 1-minute sonification, each spectral record lasts only 4 milliseconds. This is an extreme form of data compression in which detail at the smaller time-scales is lost, but the shape of the year is clear. Strong sea is heard as quick downward slices, whereas swell is heard as longer-lasting "crunches." In the winter, swell is heard in the right channel, or coming from the north; it shifts toward the south during the summer. Figure 6 shows the amplitude silhouette of a 10-minute sonification of the complete spectral record of buoy 029 for the year 2000. It is clear that much more energetic phenomena occurs during the winter than at any other time in the Northern Hemisphere.

These sonifications have not been formally tested for their effectiveness in displaying patterns or trends contained in ocean buoy data. The visual presentations of Figs 3 and 4 are satisfactory for the needs of physical oceanographers. Still, it is not impractical to suggest that listening to the data aids its interpretation. The sonifications have been found to be very useful for pedagogical purposes. Presenting data in sonified forms has been shown to enhance the learning experience and improve performance in recalling information [31]. I have presented these sonifications many times to college students in oceanography and marine science classes using a lecture that introduces principles of physical oceanography with visual and auditory presentations of the data (included on *MFTO*). At the end of the lecture I ask students to mimic sonifications of various phenomena and explain why they sound the way they do. Once motivated by the sonifications and their novelty, most students appear more engaged with the material. A more formal study will be conducted to quantitatively assess improvements in learning the material and interpreting the data.

Application to Music Composition

The inherent beauty and characteristic qualities of the sonifications have inspired me to use them in composing music. This was in fact the impetus for my research. Sonification as a means for musical composition has fewer examples than its use for presenting data. Several works by composer Iannis Xenakis, such as *Pithroprakta* and *Acorripsis* [32], use random processes. Though Xenakis was not aiming to sonify them, the results are sonic embodiments of probability distributions [33]. Charles Dodge's electroacoustic composition *Earth's Magnetic Field* maps a year's worth of data of the fluctuating field onto pitches and rhythms

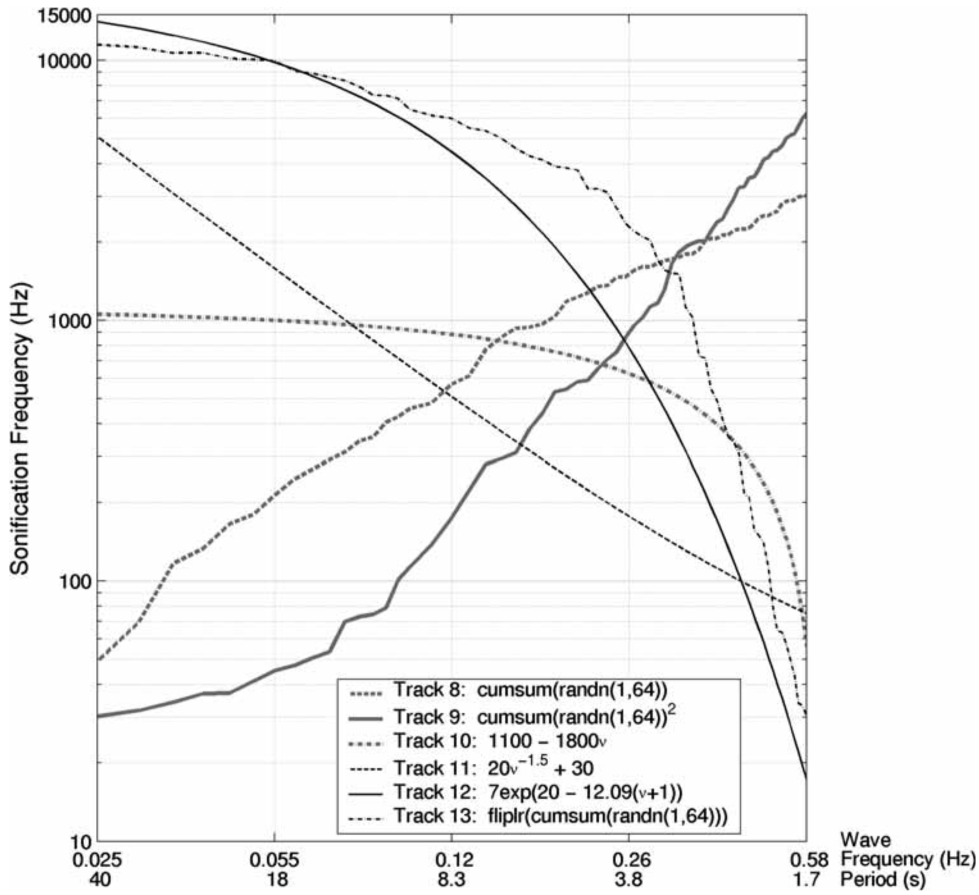


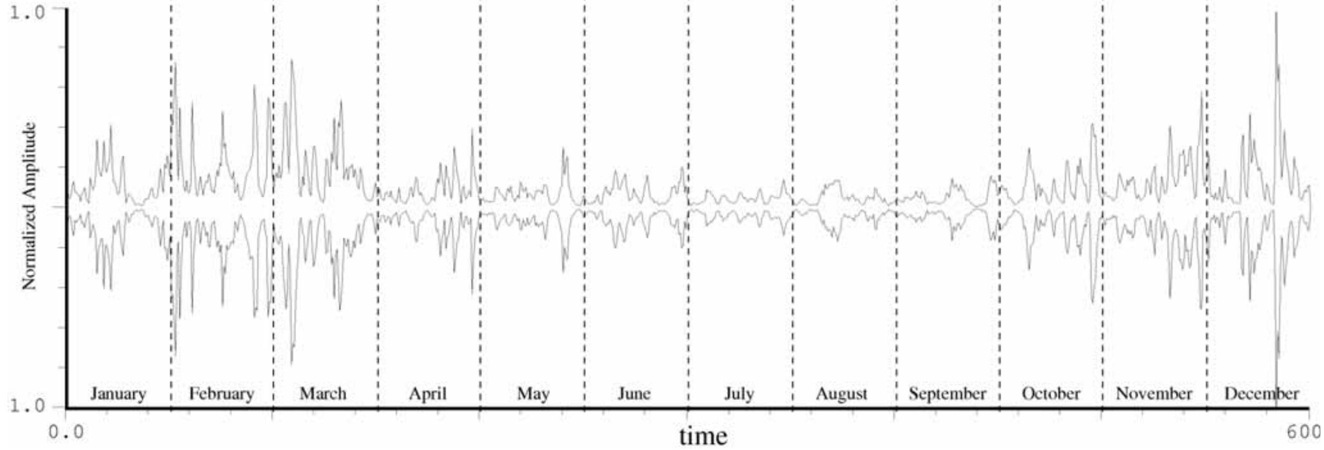
Fig. 5. Examples of spectral mappings used on the CD *Music from the Ocean.* (© Bob L. Sturm) The abscissa is wave period and frequency; the ordinate is the sonification frequency. For example, on track 8 the ocean wave frequency 0.055 Hz is mapped to an oscillator frequency of about 200 Hz. The formulas used to create them are inset.

[34]. Other examples of recent compositions using sonification include *50 Particles in a Three-Dimensional Harmonic Potential* [35], *Heart Rhythms: Healthy* [36], *Haiku* and *Tangents* [37], *The Climate Symphony* [38], and pieces written using DNA sequences [39] and fractals [40].

My eight-channel electroacoustic composition *Pacific Pulse* [41] is sculpted from sonifications of data from 14 buoys extending along the Pacific Coast of the United States. It is sometimes a mimesis of waves in deep and shallow water, and at other times a reflection of the sudden chaos created by storms. The data was collected during November and December of 2001, which were particularly active months. One swell removed 50,000 cubic yards of sand in one night from a single beach, leaving berms as high as 5 feet. The 14 datasets were sonified using several spectral mappings to create a total of 266 minutes of sound, of which 40 minutes was used.

Sonifications of the entire coast using different parameters are presented in the four main sections of *Pacific Pulse.* One section arranges these in a circle of speakers according to latitude to present the movement of wave trains from north to south as a circular gesture. Another section superimposes low rumbles under fast-moving currents, simulating the liq-

Fig. 6. Amplitude silhouette for the 10-minute sonification of data for the entire year 2000 (17,028 records) of Point Reyes (Buoy 029). (© Bob L. Sturm) Seasonal differences are apparent in energy and activity.

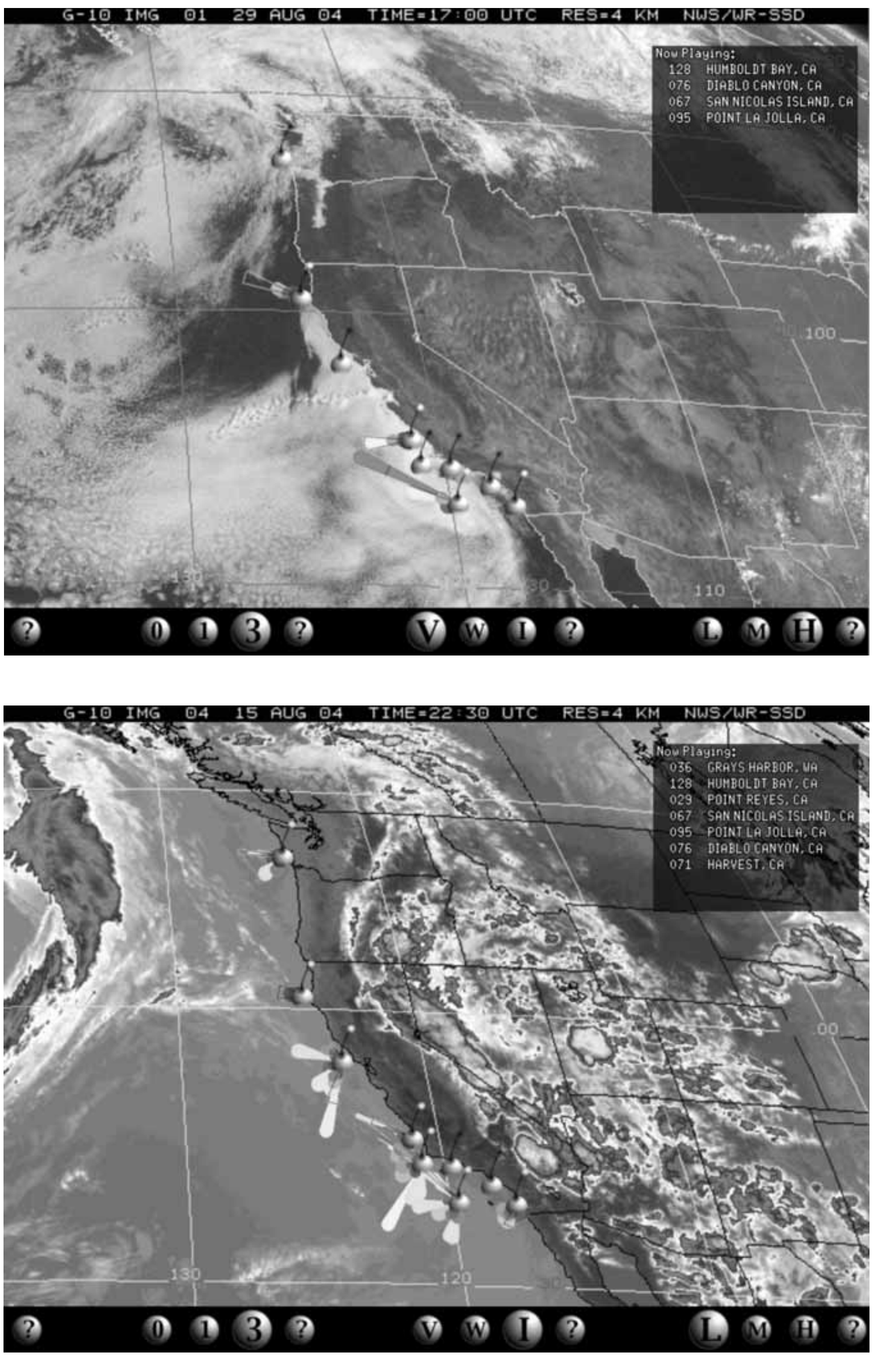


uid gap between the surface and the deep ocean floor. *Pacific Pulse* attempts to craft a sound-space as massive as the ocean. Curiously, the signal processing effect that gives the impression of immense space—reverberation—was unnecessary; the 14 buoys provide natural echoes of wave trains butting the coast.

Pacific Pulse was created such that it does not rely on its origins to affect a listener. Someone who has no idea about its genesis will still have a rewarding musical experience. To realize this goal I found it important to let go of the desire to keep the data in its natural order. In other words, the sonifications are used to sculpt the piece without regard for their temporal positions in the datasets. The same dataset was used for another composition in which I attempted to capture the energy present in the storm that destroyed the beach (*MFTO* track 29). My approach was to present the sonification in its natural order, concluding with the storm, and to minimize the influence of my own creative hand. The result was several minutes of uninteresting music with an interesting conclusion. Sculpting with the sounds instead produces an experience more rewarding for both the composer and the listener.

To further explore the idea of using these sonifications artistically, I have created an installation that displays the latest conditions along the Pacific Coast using synchronized sonifications and visuals (Fig. 7). A user can click on any number of buoys to hear sonifications of recent data and watch animated satellite imagery downloaded from the National Oceanic and Atmospheric Administration (NOAA) [42]. Essentially it is a musical instrument that is environmentally temperamental. The buoys can be seen as data beacons or musical instruments. Given the constantly evolving ocean conditions, each visit to the installation provides a different visual and aural experience. This multimedia application also provides an environment for observing the interaction between atmosphere and ocean, and could certainly be used by students to learn about physical oceanography [43].

Fig. 7. Screengrabs of an application using sonifications and visuals to illustrate the interactions between atmosphere and ocean. (© Bob L. Sturm) The user can activate any number of buoys to hear the most recent data synchronized with satellite imagery downloaded from NOAA. Three different sonification mappings can be heard along with three different image bandwidths: visible, water vapor and infrared. The "petals" stretching from the buoys show the most recent directional spectrum.



CONCLUSION

Though my sonifications of ocean buoy data have so far found little scientific use, they have proven effective for illustrating principles of physical oceanography. The sonification of ocean buoy data gives a visceral glimpse of the vast complexity of an ocean; the intriguing and beautiful sounds leave a lasting impression. Through composing with these sonifications, I have found that expressive large-scale structures do not come from within the datasets. The responsibilities of the sonification artist are much different than those of the composer. It takes a creative hand to fix the material into effective musical forms. The sound material provides only a palette of colors and sensations with which to paint. In the case of my composition *Pacific Pulse,* it helps express the immense power and complex beauty of the largest ocean on Earth.

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17. O. Ben-Tal and J. Berger, "Creative Aspects of Sonification," *Leonardo* **37**, No. 3, 229–232 (2004).

18. A waveform can be interpreted as a sum of elementary waveforms, e.g. sinusoids, at different frequencies. A spectrum shows how energy is distributed among these elementary waveforms for a set of frequencies. The energy is related to the amplitude of each waveform.

19. The period of a wave, the time it takes to go from peak to peak, is the inverse of its frequency. Low frequencies have large periods and short periods have high frequencies.

20. See Note [18].

21. M. Earle, D. McGehee and M. Tubman, Field Wave Gaging Program, "Wave Data Analysis Standard," U.S. Army Corps of Engineers Instruction Report, CERC-95-1 (1995).

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24. Additive synthesis produces complex waveforms by adding together elementary waveforms. For a good overview of additive synthesis see C. Roads, *The Computer Music Tutorial* (Cambridge, MA: MIT Press, 1996) pp. 134–144.

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27. N.H. Fletcher and T.D. Rossing, *The Physics of Musical Instruments,* 2nd Ed. (New York: Springer-Verlag, 1998) pp. 649–656.

28. The mapping formulas are given in MATLAB code: "cumsum" is cumulative sum; "randn" is normal distribution; "fliplr" is flip vector, left to right; and "exp" is natural exponent.

29. For a good overview of wavetable synthesis see Roads [24] pp. 90–103.

30. This holds true as long as the standards specified in Earle et al. [21] are used.

31. J.M. Keller et al., "Educational Testing of an Auditory Display Regarding Seasonal Variation of Martian Polar Ice Caps," Proceedings of the 2003 International Conference on Auditory Display [7].

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34. Liner notes from C. Dodge, *Earth's Magnetic Field* (New York, NY: New World Records No. 80521-2, 1970).

35. Two-channel reduction available at <www.composerscientist.com>; see also Sturm [13].

36. Ballora [9].

37. *Haiku* composed by J. Berger; *Tangents* composed by O. Ben-Tal. See Ben-Tal and Berger [17].

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39. Dunn [11].

40. D. Strohbeen, Fractal Music Lab web site: <www.fractalmusiclab.com>.

41. *Pacific Pulse* (7:32) premiered at the 2003 International Computer Music Conference, Singapore (3 October 2003). Two-channel reduction available at <www.composerscientist.com>.

42. NOAA web site: <www.noaa.gov>.

43. More information can be found at <www.composerscientist.com>.

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Bob L. Sturm worked at CDIP for 16 months as a "data janitor," constantly cleaning, shuffling and getting personal with buoy data. His research was not funded by, nor should it be associated with, CDIP or SIO. Sturm is currently a Ph.D. student in Electrical and Computer Engineering at the University of California, Santa Barbara, and is supported by a fellowship under the National Science Foundation's Integrative Graduate Education and Research Traineeship Program (IGERT) in Interactive Digital Multimedia (NSF Grant #0221713). His present research includes media signal processing and composition.