# LAYERS OF MEANING: THE OCEAN'S NATURAL ACOUSTICS AND THE MUSIC OF ITS DATASETS

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**ABSTRACT**

The transdisciplinary National Academies Keck Futures Initiative (NAKFI) conference on the Deep Blue Sea sparked a collaboration between sonification expert Mark Ballora and marine biologist and sound artist Heather Spence. Research involving long-term Marine Passive Acoustic Monitoring (MPAM) of the MesoAmerican Reef system forms the basis for a gradient of audio products: 1) layering a tour guide acoustic instrument over raw and manipulated soundscape recordings; 2) layering of multiple acoustic instruments over duty cycle interpretation sampling; and 3) layering of data sonification over the original data, with additional acoustic instrument layers. The audio products are designed to promote data exploration and understanding by researchers and students, as well as an emotional impact musically with conservation themes. Presentations have included live and virtual performances and workshops. Next steps include sonification of other correlated environmental data with the original sound data in raw, manipulated, and sonified forms.

## 1. INTRODUCTION

This project grew out of the National Academies Keck Futures Initiative (NAKFI) conference on the Deep Blue Sea [1]. Ballora, an Associate Professor of Music Technology, attended NAKFI with the goal of bringing sonification work into a new research domain and finding opportunities to demonstrate measurable impacts of sonification in research and outreach. Spence attended NAKFI as part of her pursuit to orchestrate creative solutions for ecologic and economic sustainability using sound, interdisciplinary coastal marine investigation, and dynamic educational outreach. They were introduced to each other prior to the conference by the director of arts programming, who suspected significant mutual interest between the two of them. During frequent fruitful discussions, both agreed that they would seek opportunities to work together. "Layers of meaning" (Figure 1) represents a union of oceanography, computer music, and auditory perception, as well as layering of sounds, soundscapes, and sonifications. This combination of art and science in service to each other is a healthy embodiment of NAKFI's goal of transdisciplinarity.

The geographic focus is the Mesoamerican Reef (MAR), also known as the Great Mayan Reef, which is the largest barrier reef system in the Western Hemisphere, extending from the tip of the Yucatán peninsula in Mexico along the eastern coast of Belize and Guatemala, to the Bay Islands in Honduras. While second globally in size only to Australia's Great Barrier Reef, MAR suffers from significantly less recognition in scientific literature and the media [2]. Even with minimal focus, vital features of MAR highlight the need for attention including the largest aggregations of whale sharks, barrier reefs, upwelling systems, and resident and migratory biota [2], [3], [4]. The MAR ecosystems support key tourism including the Cancun region. Threats to the MAR ecosystem health include storms and other natural factors, and anthropogenic impacts including water pollution, boat groundings, over-harvesting, and noise [5]. MPAs have been established to help ease pressures but lack of information about the reef hinders conservation policy [2].

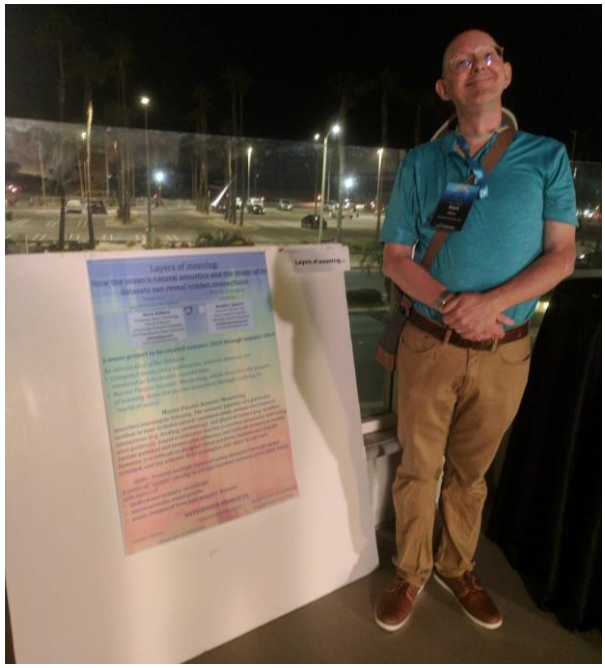

Figure 1. Mark Ballora with our "Layers of Meaning" poster at the mid-cycle NAKFI grant meeting

## 2. SOUNDSCAPE RECORDING METHODS

Marine Passive Acoustic Monitoring describes learning by listening. The acoustic tapestry of a particular location in time includes animal communication, animal - environment interactions (e.g. feeding, swimming), and physical factors (e.g. weather, wave patterns). Sound is central to marine ecosystem processes, indicating various patterns and factors that influence and indicate ecosystem health. However, it is difficult to decipher these patterns: humans are visually

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oriented, and the acoustic data is complex and 'alien' to our ears.

The nature of the sound environment varies with factors such as season, weather conditions, and according to cycles (e.g., tides, diel). Spence has collected and analyzed soundscape recordings from the MAR using primarily stationary hydrophone systems [2], [5]. Since there is no generally accepted standard for interpretation, the time is ripe for innovation and development of new methods. Acoustic data is often presented as visual graphs, but the visualization process removes important information: the sound of two fish may be readily discernible when heard but appear as a single shaded area on a spectrogram.

Sound-based studies of acoustic data also enable examination of aspects not typically part of marine biology methods, e.g., the harmonic content/timbre of signals such as dolphin calls or whale songs may encode important information but is typically overlooked. Bypassing barriers to analysis posed by artifacts of visual transformation opens the door to new ways of discovering key ecological patterns. Our findings could be an important contribution to the auditory display field by providing effective analyses of ecosystem health through acoustic indicators.

The MAR soundscape acoustic recordings were collected by Spence using a stationary hydrophone system, the ecological acoustic recorder (EAR), attached to a mooring resting on the sea floor [6]. Depths ranged from approximately 5 to 15 meters at sites along the northern Mexican Caribbean. The EAR hydrophone was a Cetacean Research Sensor Technology SQ26-01, an omnidirectional hydrophone with flat sensitivity up to 28 kHz and a fixed gain of 44 dB. The EAR was programmed to record 30 seconds of audio every 15 minutes (duty cycle) at a sampling rate of at least 64 kHz, day and night. Sound sources include dominant, broadband crackling from snapping shrimp, low pulsed grunts from fish, scratchy pulses from spiny lobsters, and loud drones from boat motors.

## 3. SOUND DESIGN

All compositions were assembled, processed, and mixed down using PreSonus Studio One 5 Professional (hereafter Studio One). This is a Digital Audio Workstation software. Any underwater ocean soundscape recordings incorporated into these compositions were first converted from the original bin file format to wav file format via Matlab (MathWorks) or Audacity. Acoustic instruments and vocals were recorded with smartphone recording apps or microphone (Shure SM58 cardioid microphone; with Focusrite Scarlett 2i2 audio interface).

The concept of sampling is a recurring theme throughout the works, from sampling the ocean soundscape, to sampling those samples, to sampling data, to the concept of sampling in music production. The approach and perspective on the limitations and value of sampling in these works is best summarized by a quote from Aristotle (translation from Metaphysics, second book. This is the version carved into the National Academy of Sciences):

"The investigation of truth is in one way hard and in another way easy. An indication of this is found in the fact that no one is able to attain the truth entirely, while on the other hand no one fails entirely, but everyone says something true about the nature of things, and by the union of all a considerable amount is amassed."


Figure 2. Heather Spence performing Reef Recall

### 3.1. Reef Recall

Reef Recall invites a live audience on a cello-guided tour of human connections to the ocean World of Sound, from aquatic womb memories to coral reefs resounding with shrimp snaps, to dolphin echolocation. Conceptually it explores marine soundscapes and ecosystems, human connection with the ocean, and the concept of ocean memory.

The composition combines raw and manipulated coral reef recordings with live cello performance. The cello serves as a tour guide, highlighting patterns in the soundscape, as well as embodying human interaction with marine ecosystems.

The composition unfolds in six movements. Prenatal Prelude recreates sounds in the womb, exploring how humans began in an aquatic environment. This created soundscape is built from filtered heartbeat, breath, brown noise, gurgling, and cello. Crustacean Chorus features the ever-present snapping shrimp crackle as a subtle tapestry to cello musings. Dolphin Divertimento explores rhythms of dolphin vocalizations - from echolocation clicks to squawks to whistles - with a 'conversation' with the live cello. Fish Fugue highlights fish sound production through both raw and pitch shifted samples, including some hidden morse code messages, and rhythmic cello. Masked Minuet raises issues of noise impacts on communication, including engine noise as an energy waste and conflicts between cello and soundscape. Pensive Prelude reiterates musical themes and connects the audience with calm, meditative cello vibe and ambient ocean soundscape.

Guidelines are provided to the cellist however not every aspect of the performance is prescribed. For example, in Fish Fugue, the cellist is provided rhythms of morse code, however placement and pitches of these patterns are left up for interpretation. Similarly, in Masked Minuet, the rhythmic pattern typical of the Minuet dance music is provided, but the melody is left up to the performer. In this way, structure is provided to the cello part while allowing for the performer to authentically respond to the soundscapes in real time, such that each performance is unique and draws attention to new details and discoveries.

Employment of cello as a bowed stringed instrument also references the reef ecosystem and soundscape, because bowed string instruments use a mechanism of sound production similar to spiny lobsters, crustacean contributors to the reef soundscape [7].

Reef Recall premiered at the Smithsonian Hirshhorn Museum on July 8, 2018 at the DC Listening Lounge event Soundscene XI: Mapping Memory (Figure 2).

### 3.2. Reef Recall Remix: Duty Cycle Mysteries

In Reef Recall Remix: Duty Cycle Mysteries, a recording of the live performance of Reef Recall was sampled to form the basis of a new work. The sampling methodology mimics the process of sampling the marine soundscape, and scales exactly with the duty cycle used in Spence's field research (30 seconds per 15 minutes in the field scales down to 2 seconds per 1 minute for Reef Recall Remix). These regularly spaced sound observations create the core, from which reverberant echoes fill the unknown. Reverb on the samples evokes extrapolation of the direct observation space into the spaces in which the recording device is "resting." Time evolves into a representation of scientific observation, through self-sampling and extrapolation, and quasi-familiar aerophonic musings in the form of new flute samples shape interpretation.

As inherent artifacts from the randomness of sampled material create new connections, the feasibility of complete and accurate observation is questioned, and new empathetic visions emerge. Reef Recall Remix explores the mysteries of what is not observed, the preciousness of data, and the necessity of sampling as a process - in oceanography, due to power and memory limitations of subsea instrumentation, in neuroscience, due to human selective attention, and in general due to the limitations of our own timescales. Our window into this foreign world in our home planet is small and valuable.

Reef Recall Remix premiered at a virtual concert on April 9, 2021 at the Stanford University Center for Computer Research in Music and Acoustics (CCRMA).

### 3.3. Night Fish

Night Fish is a composition based on a peer-reviewed scientific research article on nocturnal fish sounds in Quintana Roo Mexico [5]. This article highlights the high level of activity and diversity of fish sounds at night, and the need for more passive acoustic monitoring to study nocturnal animals and nighttime soundscapes. As in Reef Recall Remix, Night Fish explores the concept of sampling, though from different angles, including lyrics, and with references to modern popular music styles.

Soundscape components in the composition are all taken from the audio files from the scientific article, and are all reef soundscapes recorded at night. Due to the focus of the article, fish sounds are prominent, in the form of low frequency rhythmically repeated grunts and coos. Also prominent in the soundscape recordings is snapping shrimp crackling.

The methods of treatment of these soundscape recordings draw from modern popular music sampling techniques such as vocal chops and found object percussion sampling. The reef soundscape recordings are chopped up, repeated, and in some cases pitch shifted or filtered to achieve certain musical percussive sound functions in the music, such as kicks or high hats referring to drum kits. Perhaps unsurprisingly, snapping shrimp sounds provide excellent material for snap sounds. All of the percussive elements in this piece are generated from the soundscape recordings, and are extensive requiring eleven tracks. Rhythms reference modern popular music, with a latin influence, including a clave-like sound and rhythm present throughout.

The composition begins with familiar yet strange percussion generated from the soundscape, and ends with a fade to a more natural soundscape. This eases the listener from familiar to less familiar, into the underwater world of sound. While present throughout, the close of the work is where the listener is invited to focus more on the subtleties of the natural soundscape than on the derived musical elements.

The vocals in Night Fish are lyrics sampled from the text of the same scientific paper. Similar to the methods in Reef Recall Remix, the sampling ratio used was the same as that used for sampling the underwater soundscape. The lyrics are not in complete sentences, but the string of words gives some insight into what the paper is about, similar to the way research using sampling works. For example, one line of text in the lyrics is "site as Nizuc the as *albacares* site at the sensor audio employed." While lacking the detail of the actual paper, major themes and key information are still discernible. The research "site" is near "Nizuc." The word "*albacares*" is the species name of one of the fishes discussed in the paper (*Thunnus albacares*, Yellowfin tuna). The term "sensor" implies passive rather than active sensing, as is the case. And "audio" suggests that the sensor could be sensing sound. The lyrics of the chorus are drawn from the abstract, and the lyrics of the verse are drawn from the body of the paper. Much information is missing, but even with this kind of sampling it is still possible to capture important themes. Since humans are unable to obtain complete information about the ocean, it is good to know that we can still get valuable insights from sampling. And by interacting with the recordings we can get to know the ocean better.

In addition to soundscape and vocals, strings recordings were added to provide textural legato layers that add to the musical accessibility. Cello and viola da gamba are the chosen instruments because they are instruments played by Spence.

Night Fish premiered at a virtual concert on May 28th, 2021 at the Craft In America Summer Virtual Concert Series.

### 3.4. Reef REM Ember

Reef REM Ember explores reef soundscapes at night, and across lunar phases. Here, the reef soundscape itself is sonified, and this data sonification is layered over the original data, and flute. The sonification process engaged in here relates to the complexity of rhythmic structure of the soundscape, by applying music production quantization processes and sonifying at inflection points.

Soundscape samples (30 seconds each) were imported to Studio One. To lay the groundwork for the sonification process, each was processed using Studio One to detect transients. In music production, transients refer to the attack phase of musical sounds. The process of detecting transients identifies both the transient, which is the louder attack part of a sound, and the rest of the signal, or tail. Practically, transient detection identifies the rhythmic components of a segment of audio material.

Once transients are detected, it is possible to edit their timing relative to a tempo. In music production, this process is called quantization [8]. It is commonly used to correct for timing issues in performance, such as hitting a kick drum beat a little to early before a down beat, or a vocalist singing a bit behind tempo.

In Studio One, the separate rhythmic components to be quantized are delineated by lines called bend markers. The

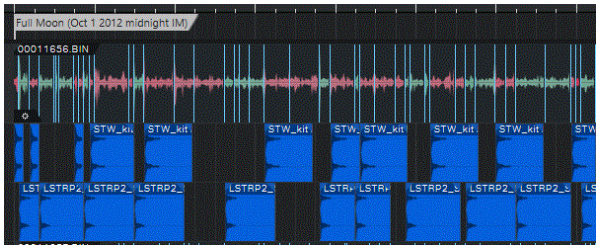


Figure 3. Digital Audio Workstation view of the bend marker sonification of sound process.

default setting in Studio One is to place bend markers at 80% of the detected transients. This is because musically, it would be unusual to edit all detected transients, which could have artifacts and/or produce an artificial sound.

For each soundscape sample, the default 80% quantization setting was applied, with a tempo of 100 beats per minute (chosen somewhat arbitrarily as a common human music tempo). This resulted in some segments of audio getting expanded (stretched) and some compressed. If a segment was compressed, it is colored green, and if it was expanded, it is colored red (Figure 3). The bend markers show up as vertical blue lines. This quantization information is the basis for the sonification.

For each soundscape sample, two tracks of rhythmic percussion were generated from the music quantization information. At each bend marker, in a separate track, a percussion sound was applied. One of two variants of the percussion sound was used, depending on whether the sound was expanded or compressed. The variants were similar in type with slight differences in timbre, for example, the two tracks could be both frame drum but from two different instruments. Percussion sounds used in this sonification process are samples from the Splice sounds library.

In Figure 3, the top track is the original reef soundscape, quantized. Red colored waveforms indicate the audio segment was stretched; green indicates it was compressed. The degree of coloration indicates the degree of compression or expansion, a variable outside of this sonification process. The two tracks below the soundscape track follow the pattern of stretched and compressed segments, respectively, with percussion samples placed at the start time (blue vertical bend marker) of the relevant segment. The result is two tracks of sonified rhythmic percussion per soundscape sample. Layers of sonification percussion were created by combining multiple sonified segments from the same lunar phase and hour of the night, each segment with different percussion instruments.

The process of sonifying sound in this method is an interesting indirect measure of complexity. A random sound tested in this process did not have bend markers. Non-reef natural sounds were also tested, including sounds familiar to humans that are often referenced when describing reef snapping shrimp noise: crackling fires, frying bacon, and popping rice cereal in milk. Sonifications of these sounds have subtly different rhythmic complexity and are included in the composition as reference points.

Separately, a flautist (Agatha Wang) was asked to improvise flute samples evoking different lunar phases, and these were incorporated as layers in the piece along with the raw soundscape and sonified percussion layers.

A portion of Reef REM Ember was presented at an Ecoacoustics lecture at Cornell University March 31, 2021.

### 3.5. Midnight Rhythm

The simultaneous goals of soundscape manipulation for analysis, education, and musical effect are not easily achieved equally together. Midnight Rhythm involves a similar sonification process to Reef REM Ember, yet where Reef REM Ember emphasized analysis, the shorter and more easily accessible composition Midnight Rhythm emphasizes education and musical effect. Midnight Rhythm invites the listener on a journey from new moon, to crescent moon, to full moon. The reef soundscape recordings are all from the midnight hour during these lunar phases. In addition to flute samples from Agatha Wang, cello samples from Spence are added to fill out the musical tapestry of sound. Additionally, recordings of water were added to provide an audible message of the physical soundscape component, and facilitate the listener's introduction to the aquatic environment.

Midnight Rhythm premiered at a virtual concert on May 28th, 2021 at the Craft In America Summer Virtual Concert Series.

## 4. OUTCOMES

Reef Recall, Reef Recall Remix, Night Fish, Reef REM Ember and Midnight Rhythm have all been used in educational settings, including live and virtual presentations, concerts, and workshops. Most feedback has been acquired anecdotally. Videos of sound samples are being prepared for usage with students in Mexico and the United States for more quantitative analysis.

Meanwhile, some written responses to these soundscape compositions were collected as part of exercises listening and describing sounds. Interestingly, these responses (to a very open invitation, i.e. what does it make you think of or feel) focused more on the sound sources in the soundscape compositions Reef Recall and Reef Recall Remix, shifting to more emotional and sound descriptive words in the sonification piece, Reef REM Ember. Word clouds were generated in Poll Everywhere from responses (Figure 4). Sample size (n=15) is small but indicates potential directions for further exploration. Of particular interest for further investigation and analysis are terrestrial references, such as "forest" (Reef REM Ember) and "fire" (Reef Recall Remix: Duty Cycle Mysteries), and conflicting emotional responses, such as "uneasy" and "creepy" occurring for the same work as "calm" and "content" (Reef Recall Remix: Duty Cycle Mysteries). Further presentations are planned throughout 2021.


Figure 4. Word Clouds of listener responses to sound clips from (Left) Reef Recall: Dolphin Divertimento; (Center) Reef Recall Remix: Duty Cycle Mysteries; and (Right) Reef REM Ember.

## 5. DISCUSSION AND FUTURE WORK

The spectrum of soundscape, instrumental, and sonification compositions holds a wealth of analysis and expression options. Reef Recall connects and educates audiences to ocean soundscapes with use of familiar musical frameworks and instruments. Reef Recall Remix: Duty Cycle Mysteries connects and educates audiences in an opposite way, evoking mystery. Night Fish hooks listeners with popular musical rhythms, hints at fish science, and eases into the night reef soundscape. Reef REM Ember immerses audiences in a rhythmic and melodic study of sonification of sound itself in a kind of choose-your-own-adventure exploration of nighttime in the reef. Midnight Rhythm explores lunar cycles and the complexity of rhythm at night on the reef. The challenge of combining data exploration, data expression, and emotional expression is immense, and methodologies have much room for refinement and assessment.

Throughout the three works, themes related to Ocean Memory are apparent as an additional NAKFI influence on Spence who currently serves as a co-leader on the project. Also funded by NAKFI, the Ocean Memory Project [9] explores transdisciplinary space related to the ocean and raises questions about how memories are stored and recalled in living and non-living ocean systems. Based on experiences with these works, soundscape and sonification explorations may likely serve as important tools in the investigation and field-formation of ocean memory.

Next steps will be to layer sonified environmental data over raw and manipulated soundscape recordings. These will include temperature, pressure, and other weather data, as well as anthropogenic influences such as day of the week, and tourism trends. Time scales will be examined to see how to manipulate soundscape recordings to best accompany longer time scale environmental data series. Since the human auditory system has inherently high sensitivity to changes in patterns occurring over time and is well suited for following multiple sequences of data simultaneously, it is hoped that these juxtapositions may yield new insights even from untrained ears and provide a ‘wow!’ factor in science engagement [10], [11], [12].

The combination of perspectives of the two authors stimulated recognition of potential new methods that merge disciplines. In the creation of music, scientific discoveries can be made; in the development of science, musical discoveries can be made. Partnerships among soundscape researchers, musicians, producers, composers, and sonification experts are encouraged and may help to better understand, appreciate, feel, and connect with our ocean planet.

## 6. ACKNOWLEDGMENT

The role of M.B. in this work cannot be overemphasized. While unfortunately what promised to be a long series of projects and collaboration was untimely shortened with his unfathomable loss, his remarkable perspective continues as a driving force. H.S. hopes to become interconnected with the ICAD community so important to him.

Resounding recognition and thanks go to M.B.’s wife, the superbly talented flautist Agatha Wang, who continues to be our muse as well as musician in this project. Thanks also to field project collaborator Raymundo Santisteban / The Stills Lifestyle Agency; the Mexican government for in-kind support and field expertise (Comision Nacional de Areas Naturales Protegidas); the DC Listening Lounge / Soundscene organizers and the Smithsonian Hirshhorn Museum. Additional thanks to Anna Davidson for ecoacoustics educational engagement; Yinan Wang for multifaceted support; and Ryan Tedder for methodology insights.

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