A Portable Impulse Response Measurement System

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ABSTRACT

This paper describes the implementation of a portable impulse response measurement system (PIRMS). As an extension to a typical field recording scenario, the design of a PIRMS enables artists and researchers to capture high quality impulse response measurements in remote locations and under physically restrictive conditions. We describe the design requirements for such a multipurpose system. The recording of environmental sound and impulse responses is considered from both a philosophical and technical standpoint in order to address aesthetic and practical concerns.

1. INTRODUCTION

Acoustic field recording is employed by a wide range of scientific and creative disciplines ranging from biodiversity studies, composition, sound design, and Foley. In all of these fields, one might imagine many types of recording priorities ranging from the capture of the full ambient sounds of an environment (a *soundscape*) to a situation that is more interested in documenting a single sonic element from within an environment, for example a rare animal call embedded within the complex sonic ambiance of an ecosystem. In this latter situation, highly directional hyper-cardioid microphones—often with devices such as parabolic reflectors—are utilized to improve the acoustic focus on a specific event. Both of these types of field recording can be categorized as documenting the sounds within a given environment at a specific time.

In both cases, these tasks are concerned with documenting the sounds produced within an environment, but not necessarily the acoustic qualities of the encapsulating space itself. In this paper, we describe a portable recording system capable of making acoustical measurements—impulse responses—in addition to being capable of functioning in more typical field recording situations. In particular, our goal is to study, preserve, and creatively use the unique resonances, dampings, and enveloping characteristics of *non-traditional* spaces (e.g., caves, chambers, and culverts with limited access). By recording impulse responses, we can capture acoustic snapshots which characterize a space. Pertinent acoustical features can be derived from these measurements, and the impulse responses themselves can be used for creative as well as research applications.

While room impulse response measurement is relatively straight forward indoors, it becomes more challenging in outdoor locations. In addition to the fact that locations with interesting acoustical features are often difficult to access, one also encounters high noise floors and a lack of access to AC power. Here, we present guidelines on designing and using a portable impulse response measurement system (a PIRMS) that balances affordability, portability, and deployability without compromising audio quality. Our design is lightweight and consists primarily of components that can be carried inside a backpack.

The remainder of the paper is organized as follows: section 2 discusses the design of PIRMSs. Then section 3 presents results from measurement trips completed with PIRMSs. Finally, section 4 offers concluding remarks and directions for further research.

2. DESIGN ELEMENTS

In order to design a mobile IR measurement and recording system that fits in a backpack, there are several constraints. The most important design element is that the system both produce and capture high quality audio.[1] In addition, we must be cognizant of the cumulative weight of the rig's elements (microphones, speakers, cabling, etc) and the ease that it can be deployed. The elements must be rugged enough to withstand being transported and operated outdoors. Last, the entire system must be able to run off its own power. This set of design elements informs how the chosen, primarily off-the-shelf gear is selected and the criteria by which it is assessed.

2.1 Impulse Response Measurement Methods

There are several methods for capturing impulse responses, all of which involve finding a method for putting a high amount of energy into a space such that the resulting impulse response measurement is robust against background noise (i.e., has a high signal to noise ratio). For this project, we built a system that allows us to use a loudspeaker-based measurement protocol.

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[1] We have decided to use a minimum audio quality of 24 bit-depth and 48 kHz sample rate which is compatible with the Library of Congress's archival recommendations [1].

Balloons and starter pistols both produce high energy signals but there are reasons that they are inconvenient or inappropriate for some of our ongoing uses. For example, while measuring impulse responses with balloon pops seems easy, we see this as being ecologically irresponsible. The shrapnel created by a popped balloon must be cleaned up and removed; if the balloon is popped in an inaccessible location, it may be impossible to sufficiently clean up the area. With starter pistols, permits might be required, they may not be allowed in some spaces, and one might not be able to cross political borders with them. Last, we think that an integrated impulse response method may cause less stress on the animals in an environment compared to impulsive and loud transient sounds.

Some commonly used integrated impulse methods include exponentially swept sinusoids [2, 3], maximum length sequences (MLS)/Golay Codes [4], and allpass chirps [5, 6]. For this project, we use a combination of sinusoidal sweeps and allpass chirps as they are more impervious to clock drift errors than Golay codes.

2.2 Impulse Production (Loudspeaker)

The speaker needs to have a reasonably full-range frequency response and also be lightweight. For this project, we used a Klein and Hummel M 52 single driver speaker which weighs 1.7 kg. In the future, we hope to build our own speaker enclosure. This would allow us more flexibility in how we deploy the speaker as well a reducing the overall weight of the speaker.

2.3 Recording Device

Convolution reverb using impulse responses has made the mimetic recreation of any acoustical space possible. Since the early 2000's, the form factor of recording devices has shrunk while the total recording time and quality has greatly increased. This has opened up possibilities for all manner of field recording situations [7, 8].

For this project, we need the ability to record multichannel, high fidelity audio. Some flash recorders produced by Zoom, Tascam, Sony, etc. are relatively inexpensive and have on-board pre-amplifiers so one can use external professional-grade microphones. If recording balloon pops or other impulsive based measurements, only a recorder with a microphone is necessary. If recording a speaker-produced signal, there are three possible methods for synchronizing the excitation and response signals:

1. Use a device that can simultaneously playback the excitation signal while recording the impulse response.
2. Use separate playback and recording devices and use some signal or optimization routine to resample and time-align both sets of signals.
3. Use separate playback and recording devices, but use an input on the recording device to track the excitation signal (effectively resample at the time of recording).

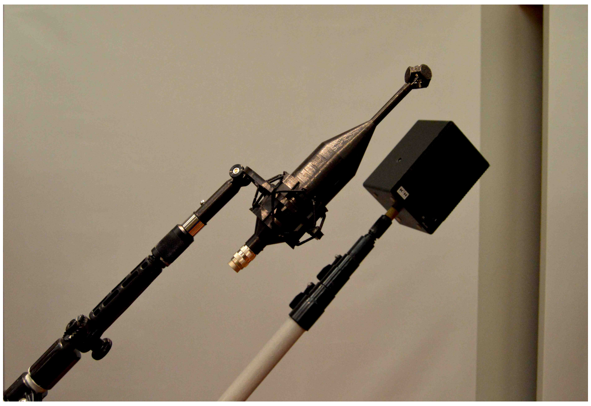

Figure 1. PIRMS speaker and microphone mounted on poles.

Method 1 is desirable, however we found few affordable devices that offer this feature. We tested method 2 by using a sine sweep with audible beeps both preceding and following the excitation signal as markers for time alignment and resampling. While this technique was successful, in highly reverberant spaces one may have to allow a significant amount of *dead air* between the beeps and the sweep signal so that they do not overlap in time when filtered by the environment. For us, method 3 was the most successful. Devices, such as the Zoom F8, are capable of recording up to eight channels and have become more prevalent. For playback of the sine sweep, we use a cellphone connected to a stereo direct box with one channel fed to the speaker and the other to the recording device.

2.4 (Spatial) Microphones

Regardless of the recording devices' specification, the quality of any recording device is limited by the microphone(s) used. Until the relatively recent introduction of surround microphones, even the highest quality monophonic or stereophonic microphone setups provided limited resolution for the replication of environmental soundscapes. In professional settings, multichannel audio is often recorded, but this is more challenging in the field, especially for those with a limited research budget and/or technical crew. Using multiple remote microphones can also be wrought with calibration and positioning problems.

Supported by the work of [9], we are able to open up the possibility of recording spatial audio with relatively inexpensive, home-built microphone arrays. This 4-capsule microphone in a tetrahedron configuration enables us to have four, cardioid microphones that produce ambisonic formatted impulse responses.

2.5 Power

Recording in remote locations means that a PIRMS has to be able to run entirely on batteries as there is no guarantee that there will be access to AC power. In order to work effectively in the field, all of the electronic devices have internal batteries except our speaker which is powered by a ChargeTech Portable Power Outlet.

Figure 2. PIRMS Components (clockwise from top left) power cable, headphones, XLR, soundfield mic cable, loudspeaker, mic shockmount, soundfield microphone, battery, Zoom H6 Recorder, direct box, two painter's poles, and various adapters.

2.6 Positioning

In situations where a mic stand or tripod is inappropriate, we employ two extendable, fiberglass poles, seen in Fig. 1 to position the speaker and microphone. We use a PIRMS for examining the acoustics of spaces where there are only small entry points such that a human could not physically enter them. Similarly, in the future we plan to record impulse responses at different levels of forest canopy to better understand the acoustic habitats for the creatures that occupy different strata. This will require a more sophisticated positioning mechanism.

2.7 Transporting the System

The current iteration of a PIRMS weighs less than 5 Kg and with the exception of the telescoping poles, fits inside an ergonomic backpack as seen in Fig. 3. As a point of comparison, a common day-pack weighs 2–7 Kg and a fully packed expedition backpack will range between 18–27 Kg [10]. In addition to a backpack, a dedicated shoulder bag for the recorder is convenient to keep the cables organized and the recorder within hand's reach while still being hands-free.

2.8 Some Notes on Recording and Impulse Response Capture and Processing

When making measurements, we recommend doing the bulk of the processing back in the lab to preserve batteries. In our experiments, we recorded the measurement signal in addition to the 4-channel microphone signals. This allowed us to record several sweeps without stopping the recorder. By finding the amplitude envelope of the measurement signal using the Hilbert transform, we were able to calculate a useful synchronization signal for segmenting the long recordings in the processing step. Each sweep was located by tracking when the envelope of the measurement signal rose above and fell below some threshold value. An amount of pre-/post-roll were allowed before the measurement signal and responses were snipped out of the longer tracks. Fig. 4 shows the results of our sweep detection and segmentation. Once segmented, the sweeps can be converted to impulse responses by

Figure 3. PIRMS components packed inside a black backpack.

$$h(t) = \mathcal{F}^{-1}\left(\frac{\mathcal{F}\left(r(t)\right)}{\mathcal{F}\left(c(t)\right)}\right), \tag{1}$$

where $c(t)$ is the measurement signal, $r(t)$ the response signal, and $\mathcal{F}(\cdot)$ the Fourier operator using the method described in [2]. Fig. 5 shows an example of a sweep response from the Marin Headlands and Fig. 6 shows the spatial (ambisonic) impulse response that results from converting the sweep in Fig. 6 into impulse responses.

3. EVALUATION

We have successfully deployed the full system on several occasions in different environments. One recent trial included a recording session in the Marin Headlands, north of San Francisco, to measure the acoustics of an abandoned naval bunker complex and some wooded areas. With these decaying structures and sensitive habitats, one is not permitted to make loud, transient noises, making this a perfect case study. Due to the wind and traffic noise, some of the

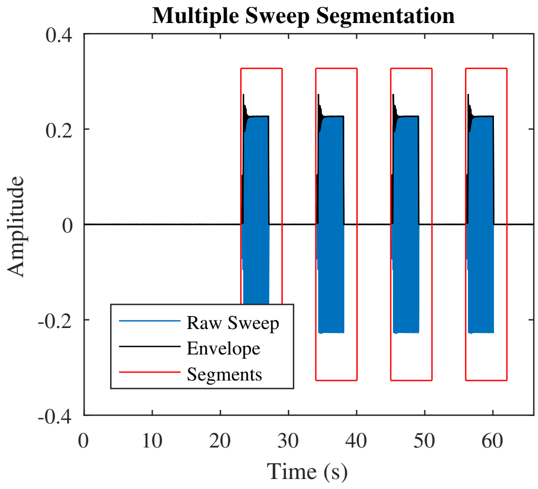

Figure 4. Time-domain plot of a long response capture showing the amplitude envelope and segmentation.

measurements were compromised but more than 90 percent of the measurements were usable. We had no issues with battery powered devices. We also successfully made measurements in underground spaces that were inaccessible to humans in a variety of locations. IR measurements collected on these various trips have been used in art installations and music compositions.

4. CONCLUSION AND FUTURE WORK

In this paper, we present an ongoing project for creating a system for measuring impulse responses in remote locations as well as being capable of producing sophisticated field recordings. This system is small enough to fit in a backpack, light enough to transport through difficult terrain—all without compromising audio quality. We are now planning to test the robustness on PIRMSs in increasingly hostile environments were humidity and moisture might be significant.

Similar in concept to time-lapse photography, we are exploring ways in which multiple IRs can be captured in a single location over an extended period of time. This collection of data from a single vantage point tracks how a space acoustically changes over time, much the way [11] analyzes long time duration field recordings.

Finally, ambisonic impulse responses from our measurements have been incorporated into several musical compositions and installations. We anticipate more new works exploring virtual acoustic environments that rely on our measurements.

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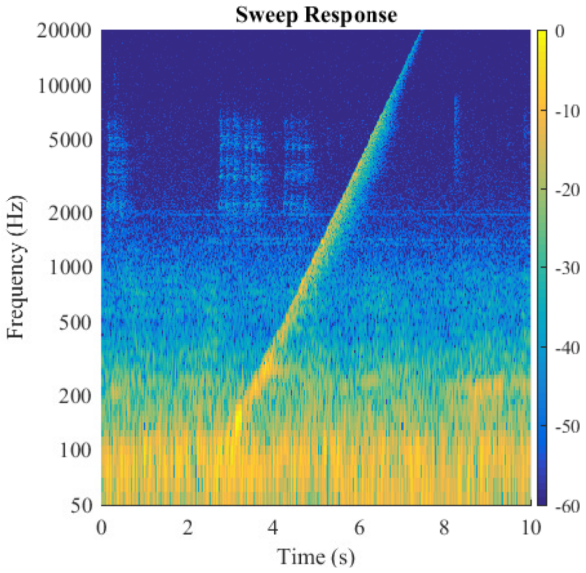

Figure 5. Spectrogram of a sine-sweep response recorded in the Marin Headlands. Note the bird sound in the high frequencies preceding the sweep will not be present in the converted impulse response.

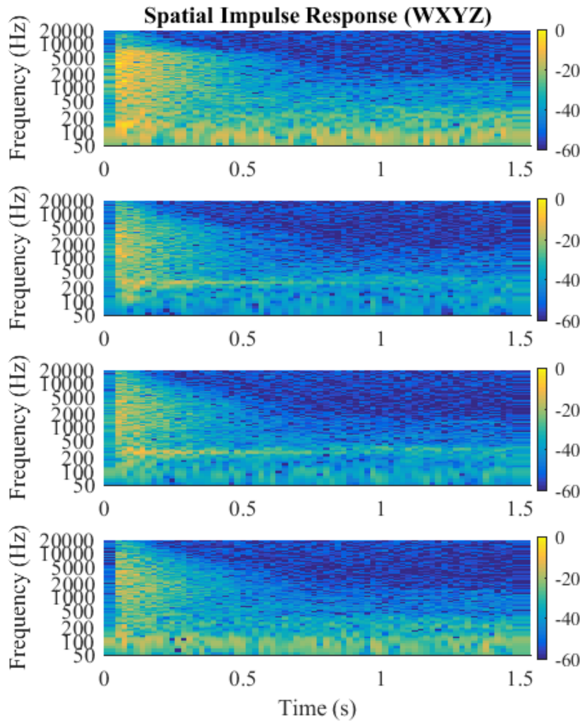

Figure 6. Spectrograms of a spatial impulse response recorded with a PIRMS in the Marin Headlands.

ily represent the official views of the National Academies Keck Futures Initiative or the National Academy of Sciences. The authors would like to thank Timothy Weaver and Jonathan Berger for their involvement and Jonathan Abel, Carlos Sanchez, and Fernando Lopez-Lezcano for their helpful suggestions.

5. REFERENCES

[1] "Recommended formats statement," 2017. [Online]. Available: https://www.loc.gov/preservation/resources/rfs/audio.html

[2] A. Farina, "Simultaneous measurement of impulse response and distortion with a swept-sine technique," in *Proceedings of the 108th Audio Engineering Society Convention*, 2000.

[3] ——, "Advancements in impulse response measurements by sine sweeps," in *Proceedings of the 122nd Audio Engineering Society Convention*, 2007.

[4] S. Foster, "Impulse response measurement using golay codes," in *Proceedings of the IEEE International Conference on on Acoustics, Speech, and Signal Processing*, 1986.

[5] D. Griesinger, "Impulse response measurement using all-pass deconvolution," in *Proceedings of the 11th International Audio Engineering Society Conference*, 1992.

[6] E. K. Canfield-Dafilou and J. S. Abel, "An allpass chirp for constant signal-to-noise ratio impulse response measurement," in *Proceedings of the 144th Audio Engineering Society Convention*, 2018.

[7] R. Grotke, "Field recording equipment," http://content.ornith.cornell.edu/UEWebApp/data/bin/RecordingEquipment.pdf, 2004.

[8] B. McQuay, "Cornell lab of ornithology: Audio equipment," http://macaulaylibrary.org/documents/AudioEquipment.pdf, 2008.

[9] F. Lopez-Lezcano, "The *SpHEAR project, a family of parametric 3d printed soundfield microphone arrays," in *Proceedings of the 139th Audio Engineering Society Convention*, 2016.

[10] C. Lindsey, "Pack weight is relative," http://www.backpacking.net/packwate.html, 2015.

[11] M. Towsey, L. Zhang, M. Cottman-Fields, J. Wimmer, J. Zhang, and P. Roe, "Visualization of long-duration acoustic recordings of the environment," in *Proceedings of the 14th International Conference on Computational Science*, 2014.