White Paper: Obtaining Long-Term Soundscape Inventories in the U.S. National Park System

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Abstract

This paper outlines a research project for long-term soundscape inventories in the U.S. National Park System. The natural sonic environment of parks and wilderness areas is not well understood in a scientific sense, especially over long periods of time (days, months and years). Even in the National Park System—arguably the most studied natural sound environment—most existing studies have been associated with regulatory surveys of specific noise intrusions, rather than comprehensive analyses of the natural cycles and trends of the biological and ecological systems comprising the park soundscape. The proposed research includes proof-of-concept development of economical monitoring hardware using recent advances in portable low-power electronics, and creation of new analysis software suitable for off-line audio data processing.

Introduction

Visitors to U.S. National Parks expect to find unique natural features, sites of historical significance, wildlife living in a natural state, and lands set aside "...to conserve the scenery and the natural and historic objects and the wildlife therein and to provide for the enjoyment of the same in such manner and by such means as will leave them unimpaired for the enjoyment of future generations." (National Park Service Organic Act, 1916). Among the features identified by the National Park Service (NPS) for protection and monitoring is the natural acoustical environment, or *natural soundscape*, of each park (Director's Order #47, 2000).

Background

The term *soundscape* for the auditory sense is analogous to the term *landscape* for the visual sense. The natural soundscape refers to the inherent acoustical environment of an area without the presence of human-caused sound. Similar terms include *natural quiet* and *natural sound environment*. Natural quiet does not imply silence; rather it implies that only the natural sound sources are present. For example, the sound of wind blowing through a forest, the babble of water in a stream, the distant howl of a wolf, and the chirp of a bird may all be present in the realm of natural quiet, as would the rumble of an avalanche, the thunder and rain of a storm, the crash of ocean waves, and the deafening roar of a waterfall.

For many years influential authors have recognized the natural sound environment even without the benefit of scientific measurements, as indicated by the following short quotations:

> You feel the absence of sound—the oppression of absolute silence… But as it is, the spirit of man sympathizes with the deep gloom of the scene, and the brain reels as you gaze into this profound and solemn solitude.
>
> *Excerpt from Nathaniel Pitt Langford's 1905 publication regarding the 1870 Washburn Expedition's arrival at the Grand Canyon of the Yellowstone (pp. 30-32).*

> But for the time being, around my place at least, the air is untroubled, and I become aware for the first time today of the immense silence in which I am lost. Not a silence so much as a great stillness—for there are a few sounds: the creak of some bird in a juniper tree, an eddy of wind which passes and fades like a sigh, the ticking of the watch on my wrist—slight noises which break the sensation of absolute silence but at the same time exaggerate my sense of the surrounding, overwhelming peace.
>
> *Edward Abbey (1968, p. 11) on the sounds of Arches National Monument in the late 1950s.*

> And listen again to its sounds: get far enough away so that the noise of falling tons of water does not stun the ears, and hear how much is going on underneath—a whole symphony of smaller sounds, hiss and splash and gurgle, the small talk of side channels, the whisper of blown and scattered spray gathering itself and beginning to flow again, secret and irresistible, among the wet rocks.
>
> *Wallace Stegner (1969, pp. 42-43) recalling an experience of his youth near a mountain stream.*

> Silence belongs to the primitive scene. Without it the vision of unchanged landscape means little more than rocks and trees and mountains. But with silence it has significance and meaning. … The charm of a canoe trip is in the quiet as one drifts along the shores, being a part of rocks and trees and every living thing. How swiftly it changes if all natural sounds are replaced by the explosive violence of combustion engines and speed. At times on quiet waters one does not speak aloud, but only in whispers, for at such moments all noise is sacrilege.
>
> *Sigurd F. Olson (1972, pp. 51-52) considering the Quetico-Superior canoe country.*

As early as the 1940s the issue of wilderness soundscape preservation was reflected in Executive Order 10092, "Establishing an Airspace Reservation Over Certain Areas of the Superior National Forest in Minnesota," signed by President Truman on December 17, 1949. The Executive Order restricted air travel in what is now known as the Boundary Waters Canoe Area Wilderness of northern Minnesota by prohibiting floatplane landings, and banning flights of any kind lower than 4000 feet above mean sea level. The Order represented the first time a ban had been placed on aircraft flight in order to preserve the soundscape of public lands anywhere in the world. Although the Order's implicit intent was to eliminate commercial airborne outfitters within the wilderness boundaries, the explicit objective was to eliminate the aircraft noise.

Individuals and groups interested in recording commercial environmental soundtracks, monitoring acoustical ecology, and studying animal bioacoustics frequently carry out informal sound observations in the U.S. National Parks (Acoustic Ecology, 2003). These observations are typically conducted for relatively short periods by talented sound recordists using portable equipment. The observations are interesting and useful, but generally do not allow controlled comparisons and scientific analysis. Nevertheless, the care and skill with which these measurements are made can lead to new insights into the natural sound environment. One example is the *niche hypothesis* (Krause, 1987), which posits that animals have evolved their use of sound communication to minimize inter-species interference and to share the available acoustical spectrum.

Published reports and scholarly papers regarding sound in the U.S. National Park System began to appear in the late 1960s at the rise of the environmental movement in the United States (Welch, 1968; Shurcliff, 1970; Horwitch, 1982; Fletcher, et al., 1977; Fletcher, 1980; McKechnie and Gladwin, 1993). Prior to that time it is clear that park visitors and managers valued natural quiet as a resource, but little *formal* research was conducted.

Recent acoustical measurements have been performed primarily in response to substantial human-caused noise intrusions by tour aircraft (NPOA Report, 1995; Henry, et al., 1999a), personal recreational vehicles such as snowmobiles, motorcycles, ATVs, and small watercraft (e.g., Ross, et al., 2002), and nearby industrial operations such as surface mining and mineral exploration (e.g., Foch, 1992). The resulting acoustical studies have generally involved short-term acoustical monitoring using time-average sound levels and data interpretation according to the standard practices of community and regulatory noise monitoring (Henry, et al., 1999b; Miller and Menge, 2001; Miller, 2001).

What is needed?

The attribute largely missing from prior studies is **a truly long-term evaluation of the natural soundscape covering all hours of the day and all seasons of the year**. Very little is known in a scientific sense about the diurnal and seasonal variations in natural sound, nor about the long-term trends in the natural soundscape. This lack of data prevents scientists and NPS managers the ability to inventory and monitor the natural soundscape in order to provide accurate baselines and sustainable park management practices and guidelines. The availability of long-term sonic data can provide a different viewpoint for studying biology and ecology within the parks.

It is reasonable to consider whether occasional acoustical monitoring for short periods is sufficient for all soundscape studies. For example, one might arrange to observe the soundscape at a particular location for 12 hours beginning at midnight on the first Monday of a month, and find a few dozen identifiable events such as a particular bird song, a tree snapping and falling over in the wind, a bumble bee flying by, a helicopter overflight, and the howl of a coyote. Although this information may be useful, the measurement has not necessarily provided a statistically meaningful sample of the soundscape, since it is not know if the particular day is truly representative. Changes are expected due to temperature, wind, and other meteorological details, changes due to migration of wildlife, presence of wandering predators, growth of seasonal vegetation, etc. For some purposes, such as evaluating the characteristic sound level of a specific aircraft flight path, the data certainly can be temporally sparse and still provide useful insights. On the other hand, for research involving animal population studies, correlations between sound and meteorological conditions, and discovering diurnal and seasonal trends, data must be obtained and evaluated for weeks and months at a time.

By obtaining a long-term record (literally) of the soundscape in a particular location it becomes possible to make strong and statistically significant statements about trends, wildlife observations, the impact of management decisions, and so forth.

Long-term scientific soundscape data has been difficult to obtain due to the lack of affordable, effective, and easily deployed sound monitoring gear. The equipment used for most of the existing formal sound studies is expensive precision acoustical instrumentation costing $10,000 or more per setup (Fleming, et al., 1998). This gear requires special training to use. It is not intended for widespread deployment, nor is it typically designed for obtaining continuous audio signal recordings. The NPS and Federal Aviation Administration have used a monitoring system based on a laptop computer, but even this platform is bulky, delicate, and power-hungry (Ambrose, 2003a).

Proposed Research

Because it is difficult to anticipate all the information that may be desirable to glean from long-term sound inventories, attempting to specify acoustical preprocessing and data reduction properties in advance may be counterproductive. For example, most published acoustical studies in the National Parks have used *A-weighted* sound level measurements and one-third octave-band analyses that are suitable for assessing the audibility or annoyance caused by intrusive noise. The A-weighting is appropriate for noise assessment because acousticians generally use weighted sound levels for comparisons and regulatory purposes. Unfortunately, the common sound level data provide insufficient information about specific natural sound sources and their temporal distribution. This shortcoming is due to the assumption of human audibility and community noise standards with the explicit goal of assessing noise intrusion rather than the general soundscape evaluation and inventory now called for.

For example, A-weighted measurements use a frequency response filter (Figure 1) that is intended to model the non-uniform sensitivity of the human hearing system for low-level sounds. The filter results in a degraded signal-to-noise ratio because the signal level is deliberately reduced at low and high frequencies.

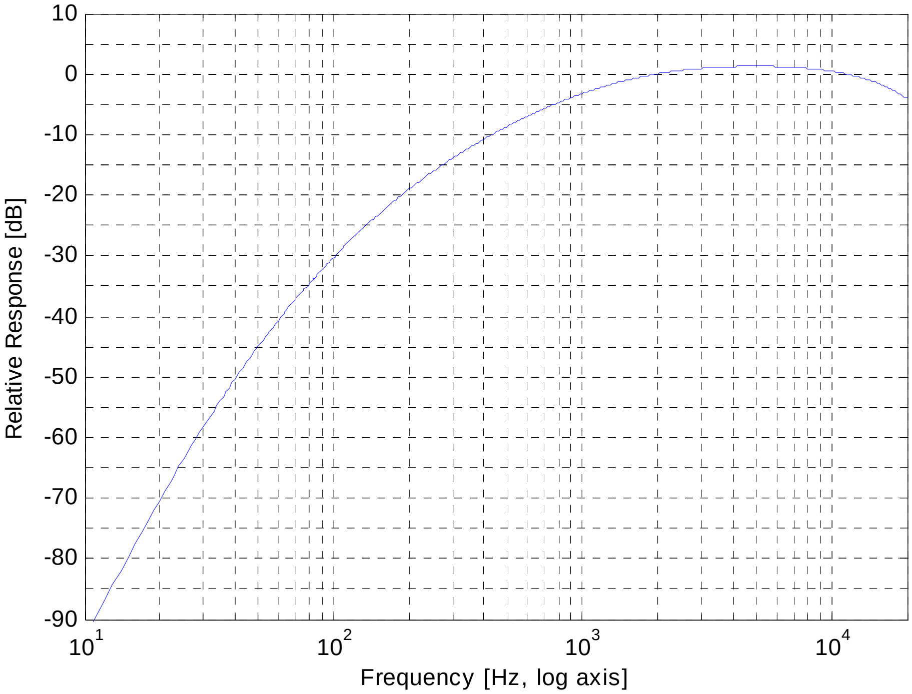

Figure 1: A-weighting filter response. The shape of the filter approximates the sensitivity of the average human listener at low to moderate sound levels (40 phon). A-weighting results in a substantial attenuation of the input signal frequencies below 2 kHz and above 10 kHz.

The weighting filter can degrade the signal detection capability of modern audio electronics, and may hamper the digital signal processing techniques to be used. Thus, it must be considered essential that future comprehensive soundscape inventories actually use unweighted, high-quality, and uninterrupted wideband (10Hz-20kHz at least) audio recordings.

Future long-term soundscape studies in the U.S. National Park System will require specialized—yet economical—test equipment. A truly useful acoustical inventory will require simultaneous monitors deployed in numerous locations for weeks and months at a time, ideally with essentially no day-to-day hands-on maintenance. Furthermore, it seems likely that the acoustical monitoring gear will be handled and deployed by non-technical personnel such as volunteers, so compact packaging, modular assembly, rugged design, and attention to human factors is vitally important.

The rather specialized nature of the proposed test equipment makes it difficult to count on commercial development. Rather, initially it is likely that it will be necessary to rely on custom development of prototype systems (Sanchez, 2003a). Nevertheless, the increasing availability of low-cost and low-power microelectronic components used in commercial portable products will provide an opportunity to develop custom acoustical monitors using commercially available parts.

The most significant research challenge will be in the interpretation and documentation of the acoustical data. Although human listeners are quite adept at detecting and classifying sounds in audio recordings, it is not sensible to assume that the hours of recordings from each monitoring system would be analyzed solely by human ears: new means for automated acoustical processing must be developed, tested, and refined. Reliable parsing of complicated audio recordings is a difficult, and remains an active research area in the field of signal processing.

These practical issues point toward two parallel research initiatives: (a) methods for acoustical data processing, and (b) prototype equipment design and evaluation. It is proposed that this research be conducted to provide long-term soundscape evaluation in the National Park System.

Acoustical Data Processing Research

Once a multi-day audio recording has been made, the data can be returned to the research lab for analysis. To begin with, a standard set of basic measurement algorithms will be performed to characterize the sonic environment. These simple measurements will include short-time and long-time average sound pressure level, percentage of time specific levels are exceeded, and estimates of the time-variant spectral envelope of the soundscape. Moreover, since the actual audio data has been recorded, it is entirely possible to perform many different analyses on the data at any time in the future.

Next, it will be desirable to identify and classify sounds within the recording. The extreme length of the measured recordings makes analysis by human listeners essentially impossible. An automated and reliable means to detect sonic events in the hours and hours of recorded data must be invented, implemented and validated.

Identifying sound events may seem trivial since everyday experience involves many situations in which one must recognize the phone ringing, a dog barking, or rain falling on the roof, but no reliable automatic algorithms for parsing multiple concurrent sounds in an audio recording have been demonstrated. Automated detection of sound level, changes in the background noise level, and similar general features can be quite effective, but this sort of segmentation may still require considerable manual intervention. Nevertheless, the fact that the entire audio recording has been obtained allows the ongoing advances in automated audio source analysis to be used as they become available.

An example of the time-variant spectrum of a natural sound audio recording is shown in Figure 2. Time (in seconds) runs horizontally from left to right, frequency increases from back to front, and intensity increases from bottom to top. Three vocalizations ("caw") from a crow are evident, as is a chirp from a starling or other bird near the end of the record.

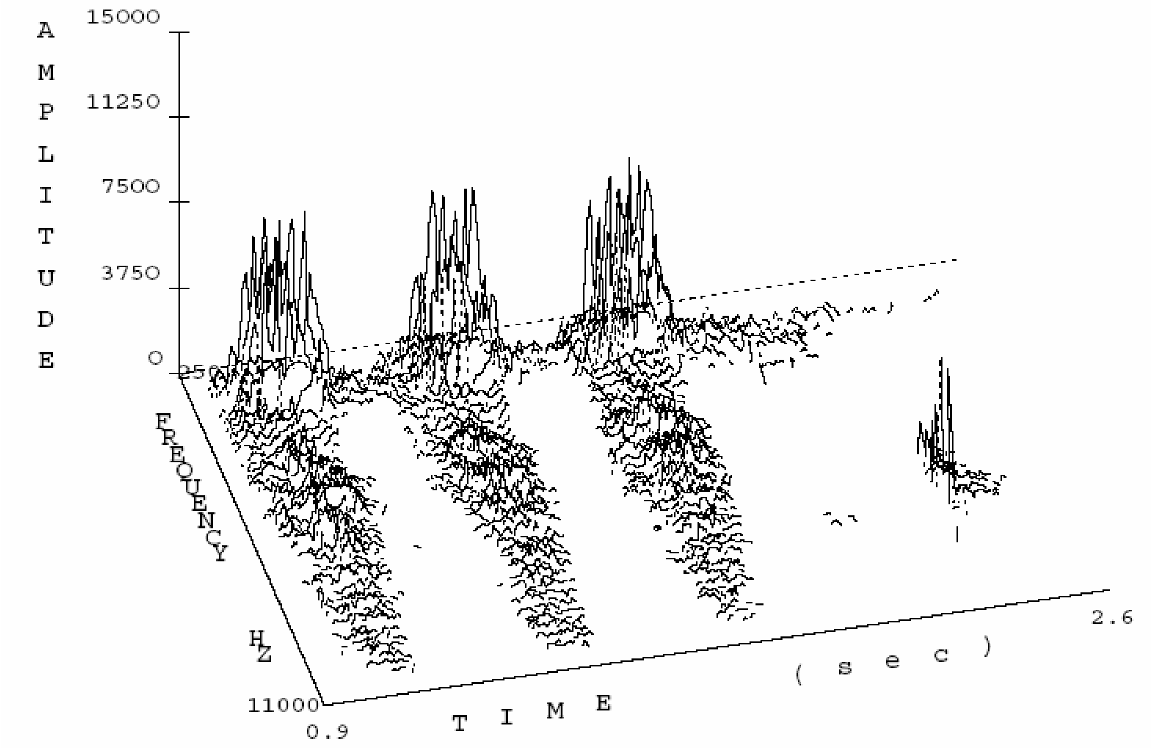

Figure 2: Example time-variant audio spectrum: three crow calls. The 3-D representation depicts time increasing from left to right, frequency increasing from back to front, and amplitude increasing vertically. The sparse spectral representation uses lines to show peaks in the time-variant spectrum.

Significant signal processing research will be conducted to identify and classify the natural sound sources, such as animal vocalizations, flowing water, and wind interacting with vegetation and terrain. Additional research will focus on reliable methods for extracting specific sound sources of interest such as aircraft, vehicles, and other mechanical sounds. The identification and classification framework will be carried out in software using a time-frequency decomposition of the input signal followed by a stimulus matching procedure (e.g., Bregman, 1990; Gygi, 2001; Arathorn, 2002).

The time-variant analysis depicted in Figure 2 contains a great deal of information. Note in particular that the three crow calls are similar in shape and time extent, but are not identical. It is necessary to construct a usefully sparse representation that captures the essence of the sound in order to achieve automatic identification and classification, and the matching procedure must be capable of handling the inherent background noise and aleatoric variations that are expected from natural sounds. The use of biologically inspired pattern matching techniques, such as the map-seeking circuit framework proposed by Arathorn (2002), show promise in this important area of research.

Another example can be derived from a long term audio recording. An hour-long natural soundscape recording was obtained in Arches National Park (Ambrose, 2003b). A time-variant analysis of this recording is shown in Figure 3. A variety of sound events (raised regions) can be seen even in this low-resolution depiction, although visual identification of the sound source is not particularly practical in this format. The importance of automatic pattern identification and classification is obvious when considering the duration and subtle qualities of natural soundscapes.

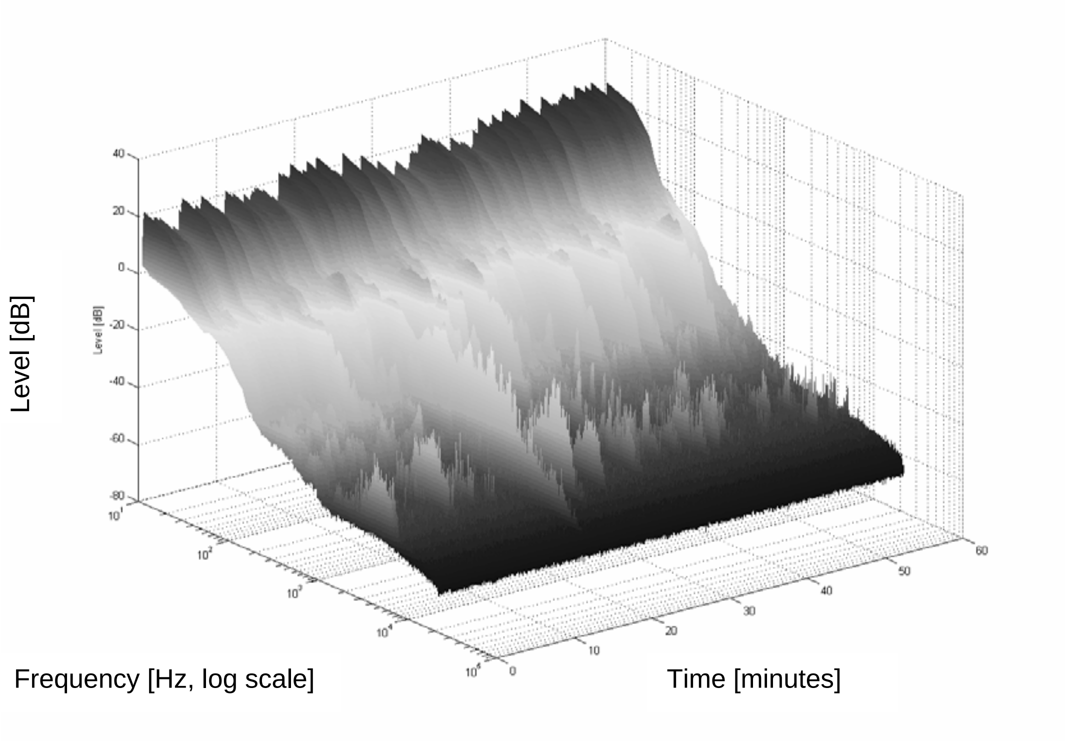

Figure 3: Example long duration time-variant audio spectrum: Arches National Park. The time interval runs left to right, the frequency range from back to front, and the signal magnitude increases vertically. The raised regions represent sonic events observed from time to time that emerged above the background noise level. These events can be tagged and automatically processed for classification and identification.

Proof-of-Concept Prototype Design

For the prototype design/evaluation phase a rugged and self-contained monitoring platform will need to be designed and constructed. There does not appear to be a standard catalog item that satisfies the continuous long-term recording requirements, but at least one specialized product is under development by Sanchez Industrial Design, Inc. The model PADR-100 Portable Audio Data Recorder (Sanchez, 2003b) is a development platform designed for long-term continuous recording (up to 7 days) with a variety of communication ports and optional accessories.

If time and cost constraints allow, it may also be feasible to develop a custom recording platform. The proposed platform would contain a digital signal processor (DSP), a calibrated microphone and data acquisition subsystem, a memory subsystem, and a power supply. The platform is intended to be deployed unattended in a remote location for at least 14 days at a time while continuously making a digital recording of the acoustical environment. Every 14 days the monitoring platform would be serviced: the recorded audio data on the hard disk drive would be brought back to the lab for subsequent off-line analysis, and the system battery would be swapped with a fresh power source. In some situations it might be possible to consider a wired or wireless data connection from the recording platform to a host computer, and perhaps rely upon remote line power so that the battery is used only for power backup purposes, but in general the platform must be designed to operate with full-time battery power and data storage for the entire 14 day period.

The proposed features of the prototype system include:

- Continuous wideband (at least 20Hz – 20kHz) 24-bit audio recording capability.
- Omnidirectional calibrated microphone system, ±0.5dB 20Hz – 20kHz, suitable for extremely low ambient sound levels (Fleming, et al., 1998).
- Overall system design capable of IEC Type 1 performance (IEC 61672-1:2002)
- Hard disk storage with at least 14 days@24 hours/day capacity.
- Low-power electronics designed for 14 day operation on one 36 amp-hour rechargeable battery.
- Design suitable for production at a cost below $1,000 per unit.
- Weather-tight, animal resistant, and easily portable physical design.
- Operating environment -25C - +85C (automotive temperature range).

The requirement of 14 day continuous operation on a 36 amp-hour battery leads to the following calculation for the average battery current:

$$\frac{36\text{ amp hour}}{1}\cdot\frac{1\text{ day}}{24\text{ hours}}\cdot\frac{1}{14\text{ days}}=107\text{ milliamps}.$$

The roughly 100mA average current at 6V indicates an average power consumption of just 600mW. This power limitation is particularly challenging because most existing hard drives require several hundred mA just to maintain the disk spinning. Therefore, it will be necessary to implement an audio cache system using solid-state memory (e.g., Flash memory) so that the disk need only be spun up when absolutely necessary. It is estimated that a 15 second spin up and write cycle every 10 minutes will meet the design goal.

It should also be noted that the battery size could be reduced (or battery life extended) if a supplemental power source such as photovoltaic panels (solar cells) or fuel cells were considered feasible.

The 14 day continuous recording capability will require considerable data storage capacity:

$$\frac{48\text{k samples}}{\text{second}}\cdot\frac{3\text{ bytes}}{\text{sample}}\cdot\frac{60\text{ seconds}}{\text{minute}}\cdot\frac{60\text{ minutes}}{\text{hour}}\cdot\frac{24\text{ hours}}{\text{day}}\cdot\frac{14\text{ days}}{1}=162\text{ gigabytes},$$

(where 1 gigabyte is 1,073,741,824 bytes). It is expected that the data storage requirement could be reduced by performing lossless data compression prior to placing the sound data onto the hard disk, so the actual storage necessary may be reduced to 80 GB or less. Drives of this size are becoming available in the sub-$150 range. Provision for more data channels, higher sampling rates, and other enhancements, would necessarily increase the required storage.

A block diagram for the proposed sound monitor system is shown in Figure 4.

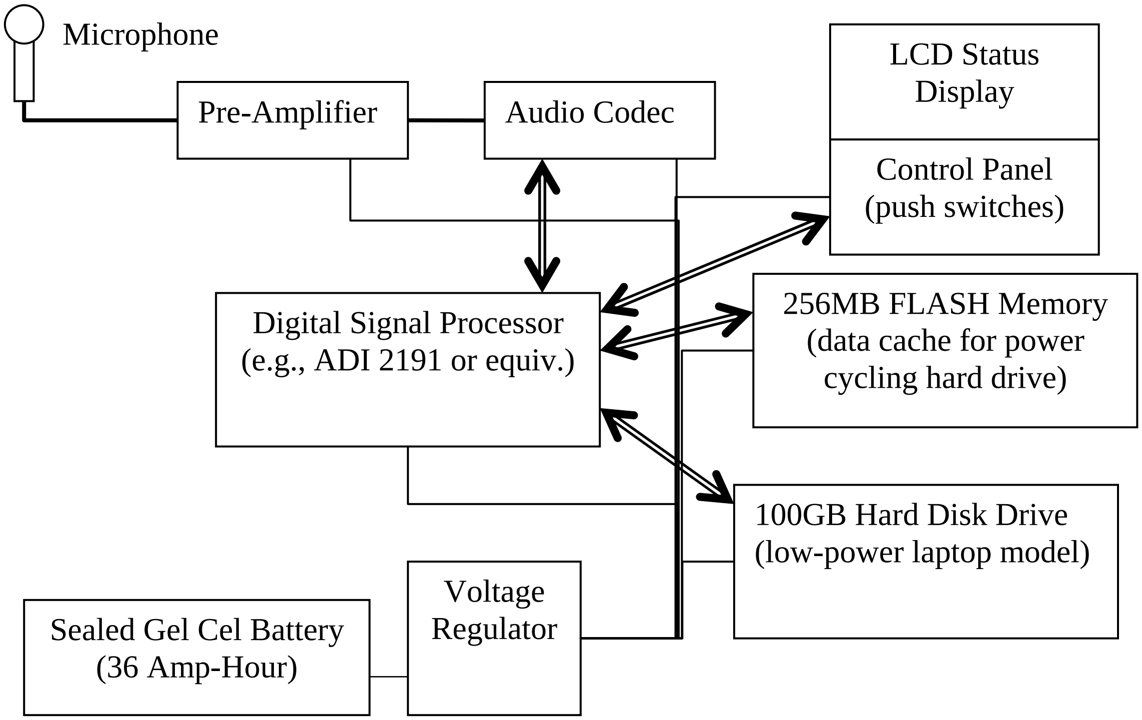

Figure 4: Proposed prototype system block diagram. The system uses a low-power digital signal processing microprocessor to collect, losslessly compress, and cache the continuous audio recording into Flash memory. The data are then transferred to hard disk as necessary. The hard disk is spun down when not in use in order to save battery power.

Development and Evaluation Plan

Design and implementation of the prototype audio monitoring platform is very appropriate for a university research project. The project's principal investigator (PI) and a qualified graduate electrical engineering student research assistant (RA) would work together to create a formal requirements document, development schedule, and budget.

A system mock-up and performance simulation could be conducted using existing laboratory equipment, test software, and hardware devices suitable for this purpose. Once the prototype design was complete and approved, the system would be constructed as the hardware is ordered and becomes available. The use of custom board fabrication would be minimized as much as possible in order to reduce the likelihood of assembly errors and delays.

Once the hardware was configured on the bench top, the system would be tested to verify signal integrity and audio quality. Bench testing of system current and component power consumption would also be conducted.

Development and validation of the prototype control software would require 4-6 calendar months. During this time the essential software modules needed to acquire, compress, and store the audio data and related time-stamp information would be ported from the simulation mock-up system to the actual target platform.

Finally, the completed prototype would be tested in a series of full-duration cycles to verify power consumption and system performance over the battery discharge cycle. Actual data collection in a remote location could be scheduled during the project completion phase.

The parallel effort to devise and assemble the offline audio signal processing software would be accomplished by the PI and an additional RA. The proposed audio analysis and signal identification software development is suitable for additional non-NPS research funding (e.g., NSF).

The proposed proof-of-concept project would require annual funding of approximately $55,000 per year (including 2 months PI salary, graduate student stipend and tuition, and overhead calculated with NPS' 15% rate) for at least two years.

Future Work

Several additional features are anticipated for future development, as listed here.

- Integration of a GPS module for precise time-of-day and position determination. This feature would allow acoustical beamforming and direction finding using time-aligned data from multiple sensors.
- Alternative power sources, including supplementary solar, fuel cell, and thermoelectric. Additional power for heating/cooling the system may also be needed for some applications.
- Streamlined packaging to allow NPS to send a system to a park superintendent with minimal training and configuration.
- High speed network access to allow data transfer from the recorder to a laptop or removable storage drive.
- Provision for additional data storage, such as meteorological observations.

It is expected that testing and evaluation of the prototype sound recording system will reveal the need for additional features and capabilities.

Conclusion

Long-term natural soundscape inventories are hard to obtain due to the lack of suitable instrumentation and signal analysis procedures. The U.S. National Park System has hosted various acoustical measurements in the past, and the proposed research will extend the existing knowledge base regarding the sonic environment of the parks. The proposed research will provide the means to obtain long-term acoustical recordings that are suitable for archiving, data analysis, park planning, and biological surveys. The availability of this data will allow correlation with other ecosystem measurements and trends, thereby improving our knowledge of the National Park environments and the ability to monitor and manage this resource for future generations.

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