# The Earth Vision Time Machine:

## A Design for the Collaborative Sharing of Wireless Sensor Data

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## Abstract

The emergence of available wireless sensor platforms for development and experimental deployment has energized many scientific communities. These low-power wireless sensors, when dispersed over an area, can collect relatively small quantities of data over long periods of time. Typically, an environmental sensor collects data such as temperature, humidity, barometric pressure, and ambient light. In many habitat-monitoring programs, data from dozens of wireless sensors is combined with high-resolution images and high-fidelity audio, linking microclimate sensor data with large volumes of data taken from one or two central locations. After collecting the data, exploration and collaboration begins. Scientists and educators need to annotate, experience, and collaboratively discuss the data. This paper describes the design of the Earth Vision Time Machine (EVTM), a simple collaboration environment suitable for exploring data sets from wireless sensor deployments.

## 1 Introduction

Multidisciplinary investigations using wireless sensor networks in the field have linked electrical engineers and computer scientists with climatologists studying glaciers [1], zoologists studying seabird nesting [2], and vulcanologists monitoring the infrasonic signals generated from volcanic activity [3]. These varied applications of wireless sensor networks in field deployments demonstrate the adaptability and diversity of the wireless sensor systems deployed.

Habitat monitoring been the focus of several wireless sensor deployments. Culler et al. and scientists from the Intel Research Laboratory at Berkeley University deployed sensors on Great Duck Island to monitor individual bird burrows [2]. At the Center for Embedded Network Sensing (CENS), Estrin et al. have deployed sensors to observe microclimates at the James Mountain Reserve [9]. They have also explored the use of sensors for tracking observable wildlife. Each of these deployments gathers vital data about the ecology of the area. The data is then studied and shared among investigators looking for insight into the climate and ecology of the habitat. Both the data collected and the goals of the investigators influence how a collaboration environment might be designed and implemented.

# 2 Habitat Monitoring

## 2.1 Acoustic Recording

For decades, zoologists have used audio recordings to study everything from whales in the Pacific Ocean to poison dart frogs in the rain forest. Wildlife vocalizations have been used to track migration patterns, identify species, understand behavior, and trigger surveillance cameras. Acoustic surveying lends itself to rapid assessment of the biodiversity of specific regions [4], largely because numerous animals are heard more often than seen or trapped. This translates into not only higher species counts but also faster estimations of biodiversity. In just seven days, Parker [5] recorded the vocalizations of 85% of the 287 species of avifauna his team of ornithologists inventoried during 54 days of intensive field work within a 2 $km^2$ area in Amazonian Bolivia, which included 36,804 mist-net hours. If this is representative of the advantages of monitoring birds acoustically, then the same is likely true for both stridulating insects and vocalizing anurans, particularly since they are even less visually conspicuous. In a field sampling of bats, O'Farrell and Gannon [6] compared acoustic sampling simultaneously with mist nets and double-frame harp traps in 57 locations. They found that 86.9% of the combined species present were detected acoustically. However, only 63.5% of the species detected were captured. While short-duration audio sampling can be used to quickly identify active species whose populations are healthy, rare species require long-term deployments for accurate monitoring. Long-term monitoring is also required for studying migration and seasonal population variations.

## 2.2 Wireless Sensor Networks

Wireless sensor data alone can be useful for some types of habitat monitoring, such as understanding microclimates and varied environmental zones, for example from the ground to the top of a rain forest canopy. However, by combining the data collected via wireless sensor networks with acoustic monitoring, data becomes more valuable for several reasons (see Figure 1). First, combining the two datasets makes it possible to more accurately understand the conditions under which the vocalizations were made. Temperature, humidity, light, and other weather conditions affect wildlife behavior and the observed vocalization patterns of species. The data from motes deployed around the acoustic monitoring station, at all locations within the microclimate, can be used during data analysis. Second, depending on the capabilities of the motes, simple sound source localization can also add distance and direction vectors to some portions of the data [7, 8]. Third, atmospheric conditions such as humidity, temperature, and barometric pressure affect the transmission of sound, and

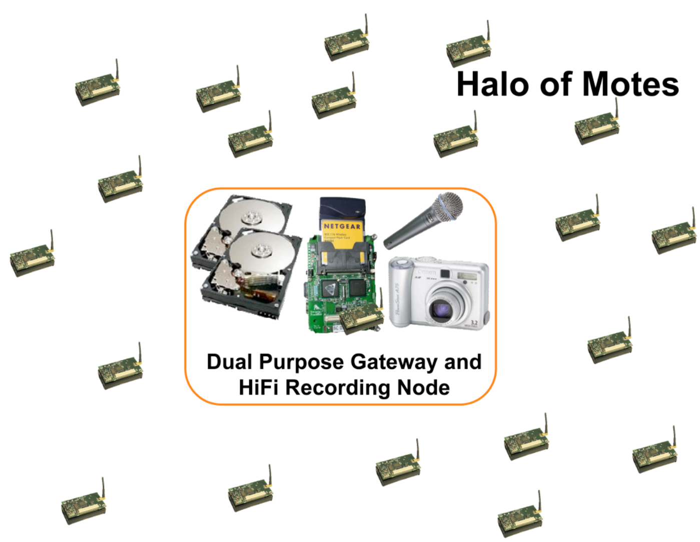


**Figure 1: A combined acoustic recording, high-resolution image and wireless sensor network**

therefore the recorded signature. Combining acoustic recording and wireless sensor network data gathered around the recording site enables improved ecosystem monitoring and, aids understanding the data.

## 2.3 Digital Stills

Another very useful type of data comes from digital stills, periodically captured along with the high-fidelity audio. A simple digital camera capable of taking high-resolution stills dramatically augments the audio and sensor data streams, revealing amazing details about the habitat. The colors of a sunset or the approach of dark storm clouds can't be easily captured by wireless sensors. Likewise, the condition of the plants and trees, such as that caused by a drought cannot easily be inferred from simple rainfall gauges.

## 2.4 Deployment Details

While the specific details of sensor message-passing protocols, event processing, and audio codecs are beyond the scope of this paper, there are some deployment details that are key to understanding how data sets are organized and natural methods for presentation to educators and scientists.

Sensor data is relatively low-bandwidth and generally slow to change. Humidity and temperature may, for example, may remain nearly constant for hours. The well-documented position of each sensor is very important. For microclimate experiments, the height above the ground is critical. Similarly, the general exposure of the mote to weather, whether under a rainforest canopy or on the ground in a clearing or prairie, as well as its position relative to important geologic features such as bodies of water, heat-retaining cliffs, etc will have dramatic affects on the mote data. Therefore each stationary sensor has relative position to the base station, ground height, and a general classification of terrain and important features as part of its identifying information.

Time synchronization is another important issue in field deployments. The sensor data, audio, and image data is all globally indexed by a unified time base. Likewise, the time base becomes the most important index while exploring the combined data sets.

## 2.5 Storage Requirements

A full year of compressed stereo audio requires between 250 gigabytes to 400 gigabytes of storage depending on the audio quality and compression ratios. Similarly, saving a high-resolution 5 mega-pixel image every 3 or 4 minutes for an entire year requires about 400 gigabytes of storage. Combined with the relatively small data requirements from the wireless sensors, an entire year of habitat data could be carried around in the form of two 400-gigabyte FireWire disk drives.

With the proper collaboration infrastructure, the trio of wireless sensor data, high-fidelity audio, and high-resolution images can provide a wealth of data that can be mined for species vocalizations, their activity, and migratory patterns all in the relationship to the microclimate and local conditions of the forest.

# 3 Key Components for Exploring the Data

Imagine the data collected for an entire year in a jungle rainforest in Central America. One year of birds, insects, bats, wind, rain, and sunlight collected as audio, sensor readings, and still images. As we examine the most important features both educators and scientists need in a system to explore the data, we find three key components that affect the design of a collaboration framework:

1) **The Time Base**. Exploring the data in relation to the time base includes some obvious operators: forward, reverse, and seek. These concepts are quite familiar to users, and therefore shared controls for manipulating the direction and flow of time are relatively straightforward. It is also likely that most collaborative interactions involving two or more sites sharing a data set will be synchronized, with each site experiencing the same time base.

2) **Annotation**. The audio stream will provide a very rich, dynamic environment for exploring the data. A very important element for the collaboration environment will to allow both expert and student annotation of the audio. From bats to birds to insects, unique and sometimes difficult to distinguish vocalizations will be available throughout the dataset. One well-trained ornithologist may be able to identify and annotate the calls of several species, while another scientist other species. Or, he may be able to confirm the identification of the species. Of course, annotating what is curious, and worthy of further inspection is also valuable. In a collaborative environment, these annotations could be made in parallel, with each observer adding or modifying their "field notes" to the data stream.

3) **Sensor Data**. The relatively low-bandwidth sensor data is generally used to gain perspective. How are vocalizations different during hot sunny days? What happens when dramatic variations in the microclimate occur? Historical reference is also extremely important. For example, is the day being viewed hot compared to most other days, or cooler than normal? What is the trend? A collaborative environment for experiencing the data must provide good visual indicators for not only the raw data values recorded by the sensors, but also their relative positions and historical values.

The high-resolution images collected from a deployment are relatively straightforward to display and permit several obvious modes for interaction. However, with still images or even video, the display will be central for visualizing and sharing sensor data and annotations in real time.

# 4 Earth Vision Time Machine

The Earth Vision Time Machine (see Figure 2) is an extremely simple concept. An Apple Mac Mini, one or more VGA projectors, and speakers will turn field data into exciting data that can be discussed and shared. Many times, data collected in the field is not readily accessible or exciting to educators and scientists. However, audiovisual environmental data is well suited for the classroom and collaborative annotation. Students love learning with their eyes and ears. Today's students are also interested in and knowledgeable about conservation activities, diminishing wildlife habits, and extinction. Discussing, exploring, sharing, and annotating data will be quite exciting with the correct tool sets at hand. For a grade-school student, the simplest form of EVTM looks like a shared MP3 player. Using a simple wireless mouse, students will be able to control the Earth Vision Time Machine in the same way they use an Apple iPod click wheel: "play," "pause," "forward," and "backward." For the scientist, the EVTM must provide powerful shared annotations and ways to collaboratively explore and corrolate data. In this section, we outline the display and interaction mechanisms proposed for the EVTM collaborative interface. We assume two or more sites, representing two groups sharing the data collaboratively. They have at a minimum audio (telecon or VoIP) for discussing the data during interactions. Each sight either has a copy of the data, or has sufficient bandwidth to receive the data from a transmitting site similar to the behavior of the Access Grid.

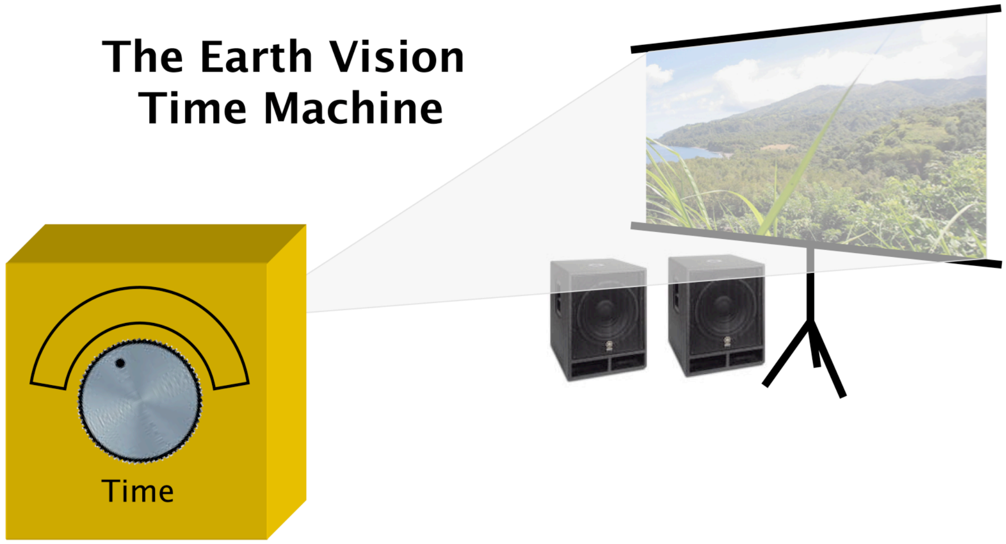


**Figure 2: A simple, high-fidelity system for student interaction with collected field data**

### 4.1 Controlling the Flow of Time

We envision a large aircraft-style throttle along the bottom dashboard of the EVTM. Like shared keyboard and mouse controls available via VNC, any participant can grab the throttle and speed up the images and audio both forward and backward though time. A simple slider across the entire bottom screen also provides feedback and control for the current position with dataset. By using the keyboard, a site could jump everyone to a specific day, such as June 1$^{st}$, or the vernal equinox. The throttle will also clearly indicate speed, with "normal" clearly marked.

### 4.2 Annotation

We expect making and viewing annotations to be one of the most important features of the EVTM. Consider for a moment an expert annotating the extremely unique call of the Central American Oropendola. The expert would rock the forward and reverse buttons repeatedly until she was satisfied the call was correctly annotated. Then, the expert would mark the beginning and end of the call, along with the species name and some other metadata. This information would be shared between participating sites. However, experiencing the annotations while viewing and listening to the data is where the shared exploration takes shape.

**Figure 3: Beat Mania video game**

We propose the "Beat Mania" interface to viewing annotations in real time. Video games where participants mix music or play drums along with given sound track often use a falling or cascading symbol that approaches a "beat line" to mark the beginning and ending of timed events. Such a system is ideal for marking audio annotations. For example, a small bird icon labeled Oropendola could fall toward a thin beat line, making it clear an intereting event was approaching, and when to listen for the beginning of the bird's amazing call. Similarly, annotations of odd, unidentified calls could be displayed as question marks, falling toward the beat line. Collaborators could search forward or back together to find and discuss previously annotated sounds.

Another view of the annotated data could be to present species identified like a catalog. It would be possible to see what types of environmental conditions were most likely when vocalizations were identified, and jump to examples in the data. Color gradients could represent the likelihood of specific species being identified during times, temperatures, or conditions.

As more and more annotations to a shared data set are made, statistical correlations and queries become possible. For example, are there vocalizations of two different species that often occur together? Or, jump to the time base for the highest density of vocalizations.

### 4.3 Exploring Sensor Data

Several arrangements of the sensor data are possible, and the exact display mode should be locally selectable at each site. One mode, for example, may be a set of small bar graphs along the bottom of the display. High and low bars could indicate highs and lows for different periods, such a day, week, month, or year. Alternatively, the individual widgets, each representing the data from a single sensor, could be displayed spatially, mapping the X and Y coordinates of the display to the grid coordinates of the habitat. Shaded sections and trend arrows could mark historical data and trends.

One interesting use of the sensor data widgets is as input device. By selecting a widget, for example a temperature dial, one could set the indicator on the dial and then click forward or back to skip ahead to when that reading was taken. This would be extremely useful for understanding what was occurring during certain high and low values. For instance, jump forward to when the wind speed was 20 mph and the temperature was 95 degrees Fahrenheit.

## 5 Conclusions and Future Work

At this point, the Earth Vision Time Machine is just a design. Based on our ongoing work with wireless sensors however, we are confident that combining high-fidelity and data with wireless sensor data will provide new modes for collaborating and studying the environment.

For example, with the EVTM as presented, students would be able to assign "Virtual Field Work", allowing even young students to conduct field studies. Imagine, for example, a class of 24 students, each assigned several different hours of data to take home (on CD). Depending on their age, students could classify or identify some bird vocalizations and chart them against the wireless sensor network environmental data for the area, or simply plot the periods of greatest audio activity against the sensor data. They could annotate the vocalizations they identified and then merge them all together and play the data back for scientists or experts in remote locations, discussing their observations and soliciting suggestions for improvement.

Finally, it is possible to imagine such a resource branching out to hundreds or thousands of loosely-coupled participants, each of whom is experiencing an "EVTM channel". Like an Internet Wiki, hordes of interested people could annotate and "mark up" the data set. Keeping the annotations private for some period of time would make it possible to allow large, independent evaluations and annotations of the data set. The data could then be merged, and confidence intervals included with the metadata.

The University of Chicago Computation Institute and Argonne National Laboratory has deployed a set of wireless motes, and continues to explore new ways to investigate and share the data collected.

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