# Sentinel: Versatile real-time acoustic autonomous monitoring system for studying natural soundscapes

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**Abstract**
This paper presents the development of an acoustic autonomous monitoring system specially designed for the study of the soundscape in wild areas.
The system, denominated Sentinel, operates on a single board computer with micro-electro-mechanical systems microphones and a mobile communication board for data transmission. This design allows in situ calculation of indices and their transmission in real time for remote monitoring of natural soundscapes. Sentinel's versatility allows obtaining acoustic and bioacoustic indices that provide information on the spectral content, complexity, diversity, entropy and temporal dynamics of soundscapes. These indices allow remote monitoring of the biophonic, geophonic and anthropophonic components present in natural environments and how they evolve over time. Sentinel has been conceived as an open-source and low-cost tool, to facilitate equity in its access. The results of the tests carried out in Protected Areas in Northwest Argentina are presented.

**Keywords:** Sentinel, natural soundscapes, passive acoustic monitoring, protected sites, low cost

## 1 Introduction

The environmental soundscape is a complex and dynamic system made up of a multiplicity of interrelated elements. These elements belong to different domains of knowledge and respond to different scales of time and space. Soundscape is concerned with what is happening in and around an environment, as well as with what is happening elsewhere and can be heard by the individuals in the environment, or indirectly generates sounds in the environment [1].
Soundscape plays a key role in the understanding and protection of biodiversity, as ecosystems involve complex and dynamic acoustic processes [2]. Both the information about the environment contained in acoustic waves and the use of sound for communication between living beings represent fundamental mechanisms for life on the planet [3]. These biological mechanisms can be affected by anthropogenic noise, especially technological noise [4,5]. Some ecosystems harbour vulnerable or endangered endemic fauna that may be highly sensitive to noise, especially avifauna that depend on acoustic communication for life processes [5].
The soundscape of each ecosystem is unique and allows the recognition of its components and conservation status, and can therefore operate as an indicator of biodiversity. This assessment tool, due to the physical properties of sound propagation and the way it is modified by the environment, allows the detection of anomalies in ecosystems that are not easily detected by means of other assessment techniques [6]. In this sense, the soundscape informs about anthropogenic-induced changes taking place in natural environments, thus reflecting the health of ecosystems [7].

One way of assessing the health of ecosystems, their present biodiversity and the degree of intervention is by means of eco-acoustic indices, which are obtained by processing the audio signal recorded during the periods of interest. These indices are multiple and diverse, but can essentially be classified into three types: energetic, spectral, and entropic. Among the group of energetic indices are the Acoustic Complexity Index (ACI) and the Bioacoustic Index (BI) [8, 9]. In the group of spectral indices, we find the Normalized Difference Soundscape Index (NDSI), the Acoustic Evenness Index (AEI) and the Acoustic Diversity Index (ADI) [6, 10, 11]. Entropy indices include Spectral Entropy (Hf) and Temporal Entropy (Ht) [12].
Acoustic monitoring allows the collection of these data over extended periods of time, as scheduled, in a continuous or iterated way, achieving conservation management decisions by identifying the habitat of acoustically active species. In the literature, the most widely used acoustic monitoring systems are passive (PAM), based on the placement of a series of monitors in a determined territorial area with the objective to record all the present sound events. Also, depending on the niche to be evaluated, it’s selected the type of temporal sampling and the use of monaural or multi-channel recording systems. Blumstein et al. al [13] have carried out a detailed study of multichannel systems for acoustic monitoring in which the main objectives of each system are realized [14].
The use of sensors for acoustic monitoring has grown greatly in the mid-2000s with the emergence of inexpensive electronic components and processors. It is possible to find on the market private developments and high quality audio such as Wildlife Acoustics [15] and low cost monitoring systems, based on MEMS sensors such as Audiomoth [16]. On the other hand, it’s possible to look at innumerable developments in devices for specific cases [17].
In this context and inspired by the review of different PAM devices and related methods, the aim of this work is to achieve a versatile low-cost monitoring and analysis system for the study of Natural Soundscapes. This system,named Sentinel, was conceived to process audio in situ and send data through GPS communication in real time. It is presented as a PAM system with the support of two receivers and the ability to perform acoustic monitoring, allowing the investigation of several aspects related to seasonal activity and population dynamics [18]. Sentinel is developed from open source hardware and software, which are presented in this article. Besides, this work shows some results obtained from the preliminar field tests conducted in two ecoregions of the Argentine Northwest, which were chosen due to their contrasting biological and landscape diversity.

## 2 Materials and Methods

The Sentinel system design is based on prioritizing the dimensions of versatility, scalability and maintainability, under the constraints of being low-cost and open source. Versatility, in this case, refers to the need to perform multiple functions: (a) REC: make continuous high-quality recordings with minimal directional information, (b) PAM: monitor passively several soundscape parameters and uploading this data in real time to a server, (c) SED: implement a sound event detection system for monitoring activity of targeted species or creating alerts of anomalous or undesirable sound events. Scalability, in turn, is required since the system must be able to handle from a bare minimum system for a REC+PAM only system to a memory-hungry neural network for an accurate SED system. Finally, maintainability, being an open-source project, demands the use of well-tested hardware and software frameworks, along with a strong community support.

### 2.1 Hardware

In Figure 1 we display a schematic of the main hardware components and a view of a Sentinel module. The core data capturing and processing of the system is based on a Raspberry Pi 4 (8 GB RAM model) single-board computer. This choice was made following the design criteria mentioned above. The device is powerful enough to run “state-of-the-art” neural networks (e. g. with MobileNet architecture) and, on the other hand, flexible enough to run functions at the GPIO level, such as I2S bus standard for audio, serial communication and eventually I2C sensors, simultaneously. The maintainability of the system is also guaranteed since the Raspberry Pi is the most widely used single-board computer, with a well-established community of support. Stereo sound is captured through a pair of digital MEMS microphones (Knowles SPH0645LM4H). These microphones are placed at opposite sides of the case, behind a pair of small drill holes and were chosen due to their popularity, low cost and environmental resiliency. A GPS/GSM/GPRS module based on the Sim808 chip provides time/date/location services and internet connectivity through mobile networks. Lastly, the system is powered by a pair of external 12V 7Ah AGM batteries. The tested autonomy on the field was over 48 hours. The overall size of the Sentinel module (without a windshield) is 135x90x70 mm.

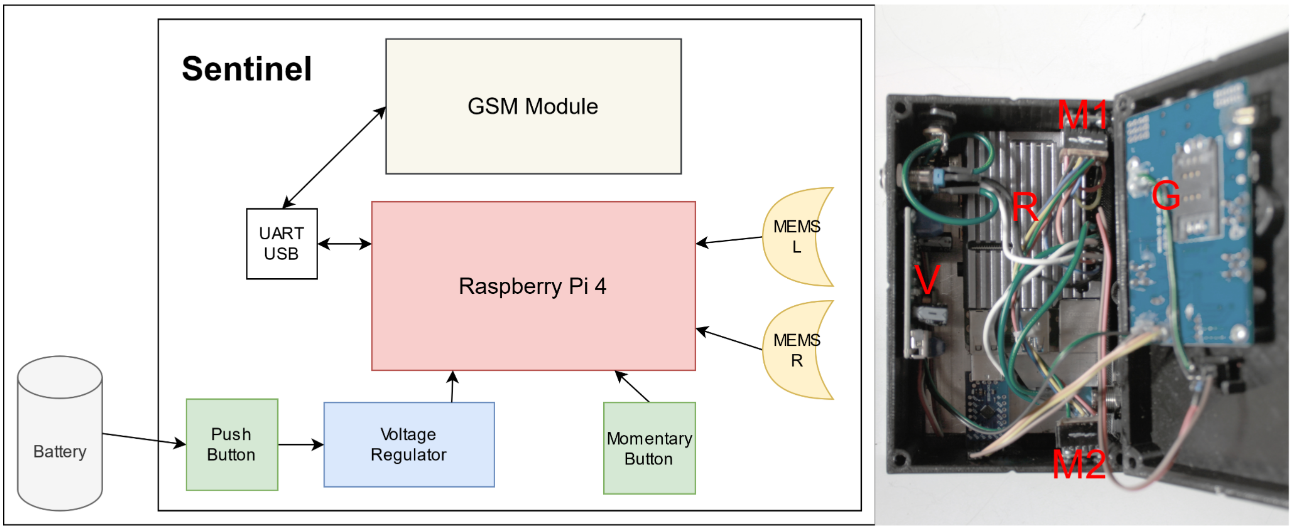


Figure 1:Schematic (left) and open case view (right) of the Sentinel hardware. The main processing is made by a Raspberry Pi 4 (R) interfacing with two digital MEMS microphones (M1, M2) through the I2S protocol and a GPS/GSM/GPRS module (G) through UART. The system is powered from an external 12V battery pack through a voltage regulator (V).

### 2.2 Software

The software is based on the Raspbian Buster operating system (kernel version: 5.10.17) with the addition of a custom I2S kernel module, and is available at https://github.com/proyecto-grapa/sentinel.

Figure 2 displays a block diagram of the main components of a basic REC+PAM system. There are three services running:

(a) READPIN starts at boot time and manages the location, time/date services and the interaction with the user. When powered up, both LEDS of the push and momentary buttons are on. After a long press of the momentary button, READPIN performs a system check to see if: the microphones are receiving signal, there is enough space in the SD card, the GSM/GPRS is up and connected to the network. If some of the conditions are not met the LEDS blink with a specific code. If all tests are passed, or the user chooses to resume using a second long press, both LEDS are turned off and the RECORDING service is started. A further long press of the momentary button starts a graceful shutdown process.

(b) RECORDING runs a single respawning process that records continuously at 48 kHz / 24 bits and stores PCM files of fixed size in the SD card.

(c) WATCH_PROCESS starts at boot time and watches for newly created PCM files. Each time a new file is created, its content is processed with a python routine (soundscape_process) for extracting the desired eco-acoustic indices and storing them in a log file and a FIFO queue. This routine depends on a custom python module for soundscape analysis (acoustic_field) developed by the authors, which is loosely based on the R package Seewave [19] and is also available at https://github.com/meguia/acoustic_field A second process (gsm_send) connects to the GSM/GPRS module and tries to upload the content of the queue to the cloud for real-time monitoring. Also, a python code based on the plotly/dash library receives the values sent by the gsm_send process to a remote host and displays them in HTML format.

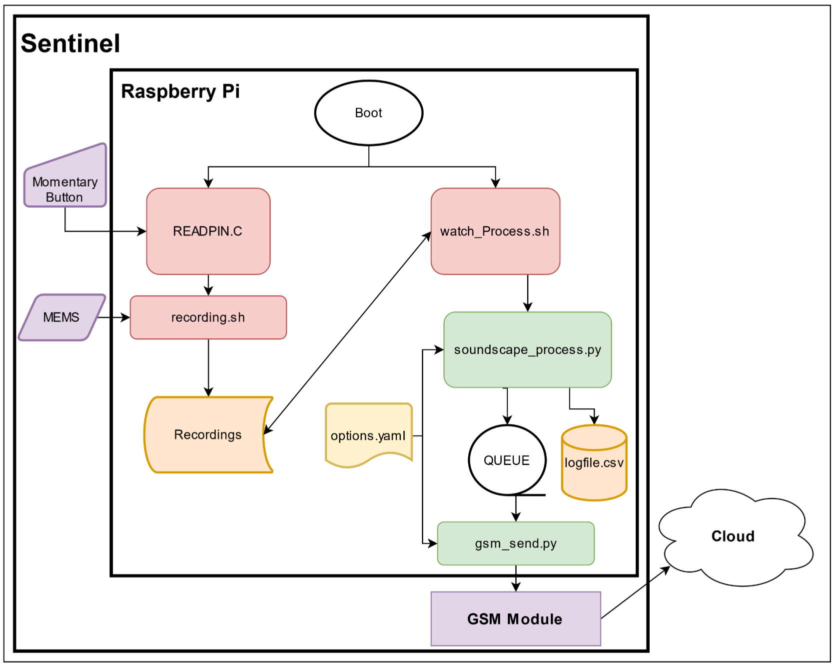


Figure 2: Block diagram showing the main workflow of Sentinel. The three services in red, readpin, recording and watch_process manage the interaction with the user, the recordings and the processing respectively. The computed eco-acoustic indices are stored in a log file and sent to the cloud via a GSM module.

# 3 Deployment and testing

A series of recordings was made in two protected areas in Salta province (Argentina). These regions are representative of two contrasting ecosystems: the Yungas jungle (Acambuco Flora and Fauna Reserve) and the Puna grasslands (Poma region) [20].

## 3.1 Recording areas

A total of five records, with a spatial distribution greater than 20 km between them, were obtained (three devices were deployed in Acambuco and two in the Poma region). In the following we will concentrate in the two representative locations that are displayed in Figure 3 for the sake of clarity: Acay for the Poma region and Quebrada de Astilleros in Acambuco.

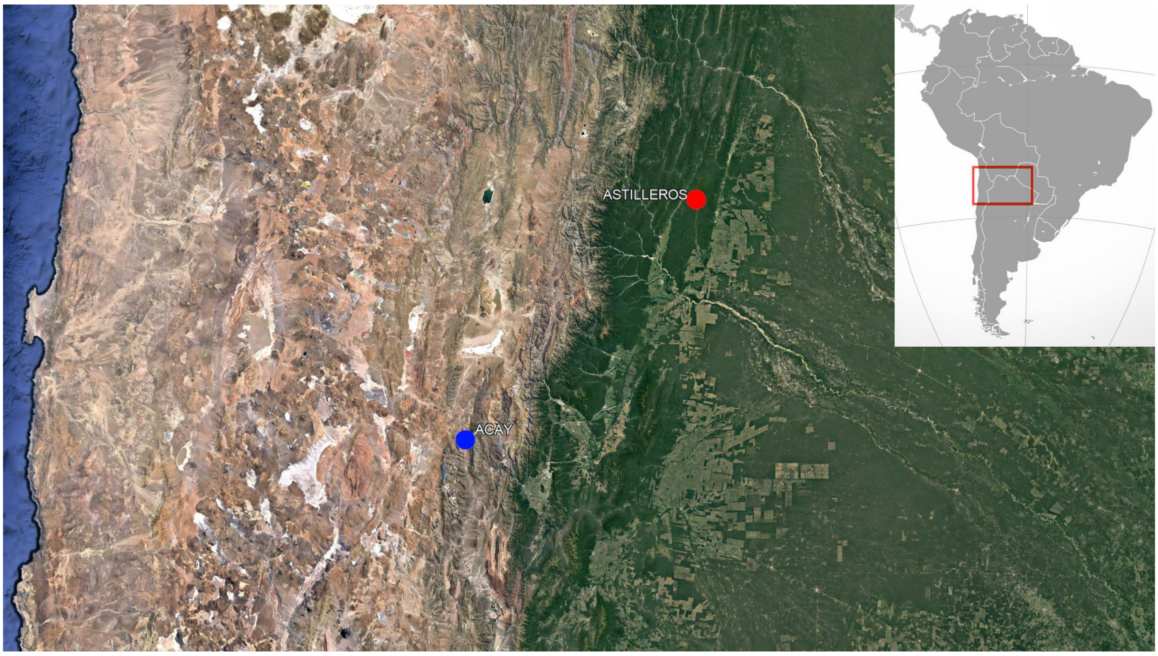


Figure 3. Map showing the two locations under analysis. In blue, Acay, belonging to the Poma region (Puna grasslands). In red, Quebrada de Astilleros within the Acambuco Flora and Fauna Reserve (Yunga jungle). The inset displays the approximate extent of the satellite image (source earth.google.com)

*Acay* is a location that corresponds to a mountain range 3511 meters above sea level. Dry climate of dry and low shrubs (valleys and Puno shrubs) [21], high winds. During the recording period, the temperature range was -3° C to 6° C, the humidity 20-40% and winds between 25 and 35 km/h. Sunset time was 18:53

Figure 4. Views of the two locations under analysis: Acay (left) and Quebrada de Astilleros (right). Image credit: Juan Barthe

*Quebrada Astilleros* corresponds to a set of saws and yungas with high diversity (Selvas Pedemontana and Selva Montana) and 715 meters above sea level. Its climate is warm temperate, moderate rainy, with a non-rigorous dry winter [22]. The temperature range was 7° to 18° C, the humidity 50-85% and winds between 5 and 25 km/h. Sunset time was 18:41.
In Figure 4 we display two views of the locations, where the contrast between the two landscapes is apparent.

### 3.2 Samples obtained

In Figure 5 we display two six-hours snippets of the records around the sunset for both locations and six of the seven eco-acoustic indices recorded (Ht behaves in a very similar way to Hs). Although this is an exploratory study and there is no possible generalization from a single measurement, interesting contrasts can be observed between the recordings on both locations.

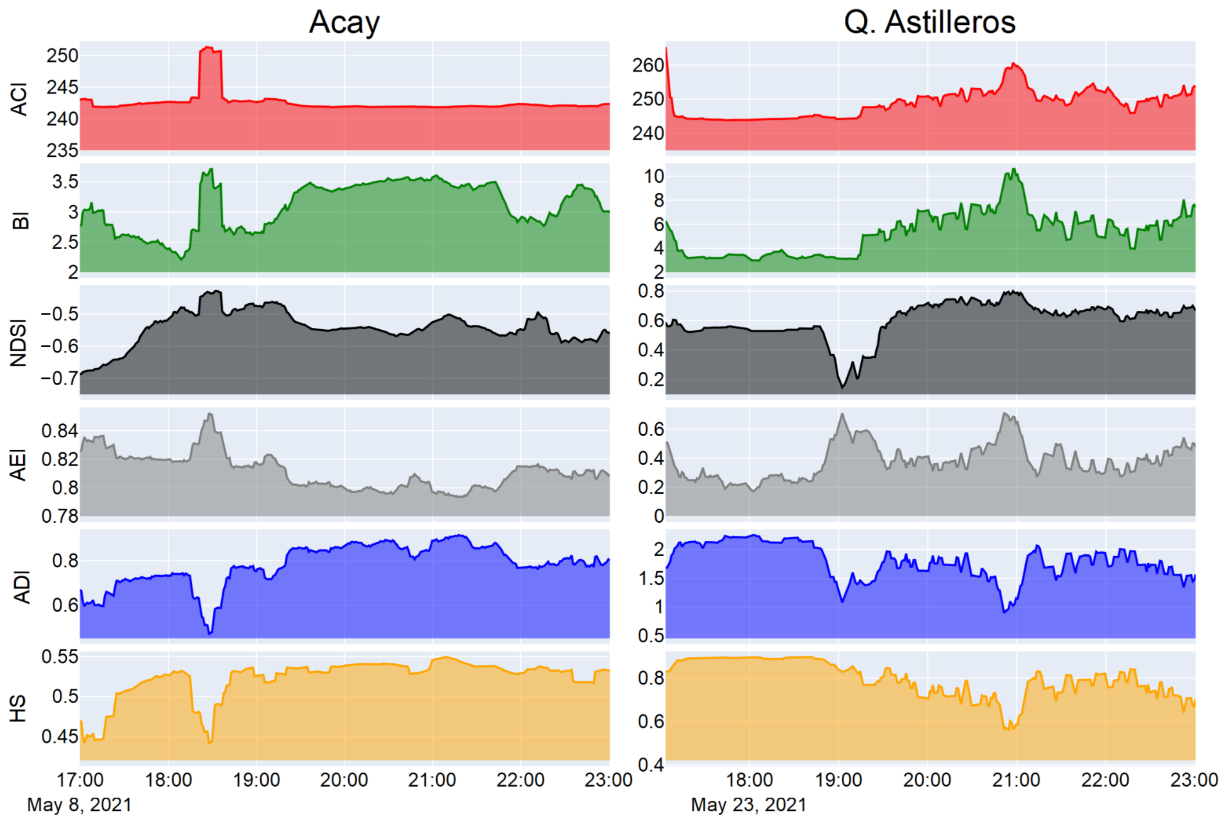


Figure 5. Computed eco-acoustic indices taken two hours before and four hours after the sunset for both locations (left panels: Acay; right panels: Quebrada de Astilleros). These data can be monitored in real-time.

All eco-acoustic indices recorded in Quebradas de Astilleros (Figure 5, right panels) display a sudden change of behavior around 19 hrs (after the sunset). This change seems to be related to an increase of the biophonic activity (see for example the BI index in the second row). The rise of the ACI index also points to a more diverse and varied content of the soundscape after the sunset. On the other hand, both the ADI index and the Entropy decrease and become less regular, indicating that the sound spectrum turns to be less uniform, with the possible appearance of sound events, such as animal vocalizations. After inspection of the sound recordings, it turns out that this sudden change of behavior occurs simultaneously with the onset of the anuran vocalizations.

In contrast, the eco-acoustic indices recorded in Acay (Figure 5, left panels) do not display this pronounced change of behavior after the sunset. The ACI index, for example, is almost flat with the exception of a strong peak around 18:30 hrs. This peak is also noticeable in the recordings of the BI, NDSI and AEI indices, while ADI and HS indices exhibit a sharp dip. For this location, the soundscape is dominated by sound sources with less temporal dynamics, such as running water and winds, which is a possible explanation for the greater stability observed in the indices. The pronounced peak and dips that take place in the different indices around 18:30 hrs is concurrent with the appearance of strong gusts of wind, caused by the temperature drop before the sunset in such a dry region.

## Conclusions

Preliminary tests of Sentinel showed great potential for remote monitoring of the soundscape in natural environments with different characteristics. In particular, the ability of the developed PAM system to process the audio signal in situ for real-time acquisition and transmission of acoustic and bioacoustic indices is particularly noteworthy.
Furthermore, due to Sentinel's design, its computational power allows expanding its functionality for the potential detection of sound events by means of machine learning.
The features offered by Sentinel provide a good tool for the monitoring, diagnosis and presentation of ecosystems sensitive to anthropogenic noise.
The next phase of hardware work consists of improving communication performance in wilderness areas with low connectivity. For longer recording periods, the use of solar panels is foreseen. On the software side, work is being done on the detection of specific sound events using deep learning tools processed in situ.

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