Eloc: Locating Wild Elephants using Low-cost Infrasonic Detectors

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***Abstract*—A significant number of human and elephant lives have been lost due to the human-elephant conflict in Sri Lanka. To save lives of humans and elephants, it is therefore important to minimize encounters between them. In this paper, we present Eloc, a system that detects the presence of elephants using their infrasonic emissions near human habitats and then localize their positions. The high cost of infrasonic detectors is an important challenge to the real-world deployment of such localization systems, in particular in developing countries where the human-elephant conflict occurs. In order to address this problem, we design a low cost infrasonic detector that can be easily built using commodity off-the-shelf hardware. We present promising results in localizing an artificial infrasonic source and real-world experiments that suggest that we can localize free ranging elephants in the wild using this low cost infrasonic detector with an accuracy of around 10 m at distances of several hundred meters.**

I. Introduction

While Sri Lanka is a small island it has almost 6000 elephants [8]. As human habitats expand into forested areas for cultivations and housing, the human-elephant conflict has become a life-threatening consequence to both humans and elephants. For example, in 2010, 81 people lost their lives in elephants attacks [8] while every year about 200 elephants die as a result of these collisions. To hinder elephants from entering human habitats, some farmers set up electric fences. Electric fences, however, cannot cover every possible area under risk because of the high cost. Further, technical failures and breakages are common. A simpler method and common practice, however tedious, is that farmers stay awake throughout the night to detect elephants and then drive them away using firecrackers. Some farmers even use illegal methods such as shooting elephants and poisoning their food in order to get rid of the elephant population around their habitat [4].

Elephants emit infrasonic waves as a means of communication [6], for example, to communicate among the members of a herd. An elephant rumble contains low frequency sound waves that propagate longer distances without significant power attenuation and hence can be detected from several hundred meters away [12]. In a study performed in an African forrest, Thompson et al. [17] have detected an average of 440 elephant rumbles per day based on a continuous recording session performed over 38 days. Payne et al. [14] have reported hundreds of infrasonic calls from an Asian elephant in a recording performed in two nights. Previous research efforts have shown the possibility of using these infrasonic emissions of wild elephants to detect their presence and possibly localizing them. However, there are only very few efforts that have attempted to implement such a system [23].

In this paper, we present a system that can detect and localize wild elephants by their infrasonic emissions using a low cost hardware setup. Our system does not use collars since this is intrusive and it is difficult to place collars on wild elephants. Our system is a part of our long term attempt to minimize human-elephant conflicts by early detection of elephants near human habitats. Moreover, the elephant localization system we present can help elephant conservation in the future by providing valuable information about their presence in different areas of the island to biologists and conservation researchers [7].

This paper makes the following contributions:

1) We present the design of a low-cost infrasonic detector called `Eloc` that is more than 90% cheaper than the currently available infrasonic detectors in the market. Therefore, it is suitable for a developing country like Sri Lanka where lower cost for deployment and maintenance of a system is the key for long term sustainability.
2) We provide the details of our elephant localization system using the low-cost hardware setup which we can use to provide early warning to people about approaching elephants. Our system can calculate the location to an elephant with an average error of 10 meters.

The paper proceeds as follows. In the next section we describe where our localisation system fits into a larger system for taming the human-elephant conflict. In Section III, we introduce our low-cost infrasonic detector. Section IV describes how we use infrasonic detectors to localize wild elephants. We present our experimental results in Section V. Section VI discusses related work and Section VII concludes the paper.

II. A System to Tame the Human-elephant Conflict

Localization System. In this paper, we focus on the design of our low-cost infrasonic detector called `Eloc` node and the elephant localization system that uses a few such nodes. The whole localization system is a tiered system where individual farmers have a pair of nodes and there is a back-end system that receives input from the farmers' nodes. Based on the data from the farmers, the on-site processing unit then computes *(i)* if the infrasounds stems from elephants and if this is the case *(ii)* transmit individual calculations to the back-end in order to build the accurate mapping of the elephants' locations. The back-end then conveys to the affected farmers the elephants' positions close to their farm. This communication can happen via the cellular network that is available also in rural areas in Sri Lanka.

We envision that a farmer deploys a pair of `Eloc` nodes within the premises of his/her house since 96% homes in Sri Lanka have been electrified by year 2013 [15]. As we present in a later section, a pair of `Eloc` nodes can be used to find the direction to an elephant while multiple such pairs determine the exact location. Deploying a pair of `Eloc` nodes in one's premises is a voluntary task in order to be a part of the localization system. Farmer communities are already working together in order to maintain electric fences and therefore it is possible for such a community to deploy the elephant localization system with distributed `Eloc` node pairs to protect their farmlands and neighbourhoods. In order to save energy, it is still valuable that only one of the two nodes is active and wakes up the other node when it detects infrasound for localization.

A complete system for elephant detection. The localization system is just a part of the whole system. Our final goal is a system with various inputs including the localization system we present in this paper. Another subsystem is an elephant behavior model which can estimate where the elephants would be. Elephants tend to have a regular timetable in which they move from the forest to the watering hole and back. A map of the terrain could provide information about the forest areas and the availability of lakes inside, e.g., a national park. The idea is to take all these inputs and then use a particle filter to fuse the inputs into a system that presents elephant locations together with estimates of the probability that there is an elephant at the given location.

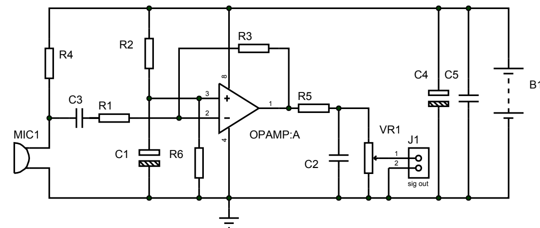


Figure 1: The preamplifier schematic used in an `Eloc` node. It consists of an operational amplifier in inverting mode and a low-pass filter which attenuates frequencies above 150 Hz.

III. Low-cost Infrasonic Detector

There are various sources of infrasonic signals in the environment, both natural and man-made. Natural infrasonic sources include earthquakes, volcanoes, lightning, wind noise as well as living creatures such as elephants and whales. Researchers studying lightning activities in the atmosphere and seismic activities also use infrasonic detectors. While the devices have a wide price range, the cheapest device we could identify in the market is the *Infiltec Model INFRA-20* [1]. This device costs about USD 350. To tame the human-elephant conflict we aim to deploy elephant localisation systems using infrasonic detectors. In countries like Sri Lanka it is necessary that such systems are inexpensive. Towads this end, we design a low-cost infrasonic detector.

A. `Eloc` Nodes

We design and implement a low-cost infrasonic detector we call `Eloc` node. The heart of an `Eloc` node is a Panasonic WM-61A omnidirectional back electret condenser microphone [2]. Compared to ordinary condenser microphones, this microphone consumes less electric current and is therefore usable in low-power devices such as battery-operated embedded systems. An `Eloc` node consists of such a microphone and a small preamplifier circuitry connected to it inside a sealed plastic container. As shown in Figure 1, the preamplifier consists of an operational amplifier in inverting mode and a low-pass filter. The low-pass filter attenuates frequencies above 150 Hz since we are interested only in infrasonic frequency components.

The microphone manufacturer has specified a sensitivity range from 20 Hz to 16 kHz. Acoustic calls of Asian elephants have, however, fundamental frequency components from 14 Hz to 24 Hz [14]. To evaluate the usability of the microphone for low audio frequencies, we conduct an experiment in which we play a chirp from 10 Hz to 100 Hz using a subwoofer. Our earlier work has shown [5] that subwoofers can replay elephant sounds that include fundamental frequency components in the infrasonic range with sufficient output power to emulate a real elephant. Figure 2 shows that the microphone is sensitive to much lower frequencies than 14 Hz and hence can be used for the task at hand.

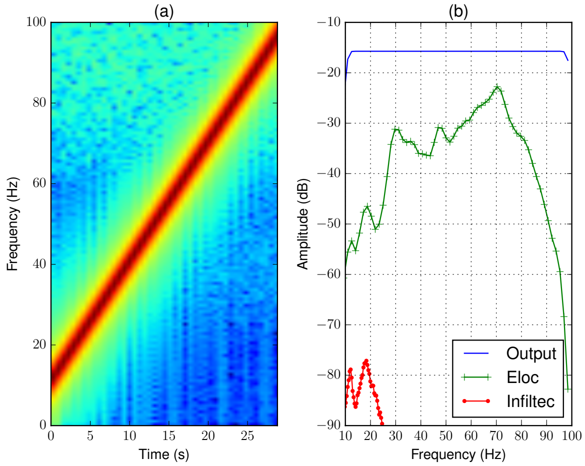


Figure 2: Sensitivity comparison of the microphones for different frequencies. The spectrogram (a) shows the played chirp from 10 Hz to 100 Hz and the graph (b) shows the received power by an `Eloc` node and an Infiltec device.

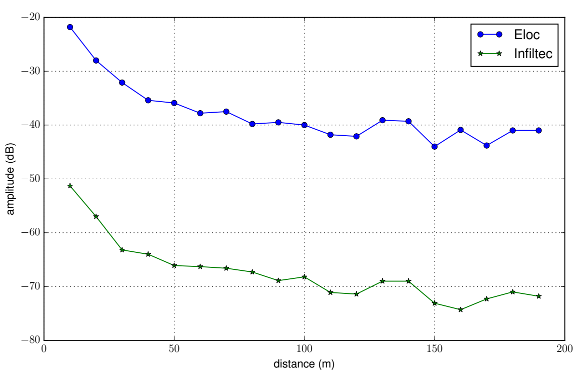
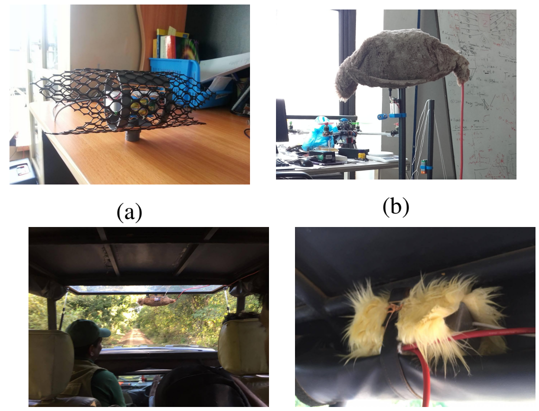


Figure 3: Sensitivity variation of the microphones for a 20 Hz tone with different distances from the subwoofer. `Eloc` node outperforms *Infiltec* device even in longer distances.

Meanwhile, Figure 3 illustrates the variation of sensitivity of an `Eloc` node with the distance to an infrasonic source. The figure shows that `Eloc` nodes outperform the expensive *Infiltec Model INFRA-20* device at all distances.

Since we are interested in low frequencies, the noise imposed by the wind plays an important role. Initial experiments indicated that the `Eloc` nodes are unable to detect low frequency sources since they are submerged under the wind noise floor. Therefore we devise a *wind barrier* around the microphones to protect them from wind noise as shown in Figure 4 a and b. This wind barrier consists of a wireframe with a soft material attached to it. An `Eloc` node is placed inside the wireframe using a vibration-proof mounting. We used different soft materials for the fur layer on the wireframe as well as several shapes for the wire frame



(a) (b)

(c) (d)

Figure 4: In (a) and (b), shows the microphone and pre-amp circuitry placed inside a sealed plastic box with a wire-frame which is covered with a soft material to cancel wind noise. In (c) and (d), two `Eloc` nodes mounted in the front and back of a vehicle for field experiments.

to identify the most appropriate combination. The selected fur layer consists of a cheap artificial fur material we found off the shelf. Note that our solution is based on trial-and-error approach rather than an approach based on, e.g., signal processing. Our results in Section V show that nevertheless our approach works very well for the target scenario.

B. `Eloc` Cost

Our localization system requires a single geographical location to hold a pair of `Eloc` nodes and a single board computer. We call such a setup a *deployment unit*. A deployment unit requires Internet access to transmit the calculated angles to a central server in order to calculate the exact location of the infrasonic source based on the inputs from multiple deployment units. Since we plan to distribute the responsibility of deploying and maintaining the total elephant infrasonic localization system among a farming community, a single farmer only has to consider the cost and energy consumption of a single deployment unit. Table I illustrates the cost for a single infrasonic detector available in the market with the cost of an `Eloc` node. Our nodes consists of simple components making them cheaper than the existing infrasonic detectors. Reducing the cost per infrasonic detector is necessary since we require multiple infrasonic detectors in our elephant localization system.

A setup consists of a pair of `Eloc` nodes and the single board computer with proper housing which is about US $73. One setup can detect elephant infrasonic signals and make an alarm to the owner in addition to calculating the angle of approaching elephant. In order to accurately localize the elephant, at least two such setups which are deployed in two places and a server computer which is located in a central place is required. The more `Eloc` node pairs available in the area, the better.

Table I: Comparison of the cost for a single infrasonic detector from different manufacturers.

Device	Manufacturer	Cost
IFS-41xx	Hyperion Tech.	$2284
INFRA-20	Infiltec	$345
Eloc node	this work	$9

We found that a single deployment unit while capturing data from a pair of `Eloc` nodes and processing the captured data on the single board computer consumes an average current of 492.6 mA with a voltage supply of 5 V. In addition to grid power supply, it is possible to power such a deployment unit over 24 hours using a battery bank if it has a capacity of about 15000 mAh. A suitable battery bank with a solar charging unit costs about 45 USD. Sri Lanka, being a tropical country, is exposed to sun throughout the year making solar power supply feasible. Therefore, it is possible to sustain an `Eloc` deployment unit in the field without constant battery replacements.

C. `Eloc` *Network*

A deployment unit with a pair of `Eloc` nodes continuously collects sound samples. We envisage number of such units scattered around an area of interest. The angle calculation is not a computationally heavy task and therefore, a single board computer, such as a *pcDuino*, of the deployment unit can easily calculate it on-site. These calculated angles are sent to a central server via the cellular network to estimate the position of the source of the infrasound.

Since elephants are not the only infrasonic source in an environment, it is important to calculate and transmit angles for elephant generated sounds. We have trained a Support Vector Machine (SVM) for this purpose. Our preliminary results show that it takes less than 0.5 ms to run this SVM on a sound clip of 10s on a pcDuino with an ARM Cortex 8 processor. We intend to use the following strategy to reduce the data transmission rate. The deployment unit collects data for 10 seconds and then feed them to the SVM. If the SVM indicates the presence of elephant sounds the angle to the source is calculated. The calculated angle and the sound clip, for further analysis, are sent to the central server.

Note that the work on the SVM and the `Eloc` network is at an early stage of research. We presented them here to give an idea about the whole system to the reader. We will not discuss them further in this paper.

IV. Localizing Elephants

Localization of objects with tags that emit electromagnetic waves is a well studied problem [13]. An example application are radio collars placed on elephants [3]. Placing wireless devices on wild animals is, however, intrusive to the natural behavior of the animals and hence such techniques are frowned upon by animal conversationalists. In addition, the difficulties in physically reaching elephants to attach these devices also makes this a cumbersome solution. Our objective is to localize elephants by detecting their infrasonic emissions using `Eloc` nodes. Wang et al. have studied the use of acoustic sensor networks to passively localize wild animals [20]. While many different sound localization methods are available, we use a technique based on time difference of arrival (TDOA) [10] to locate infrasonic sources.

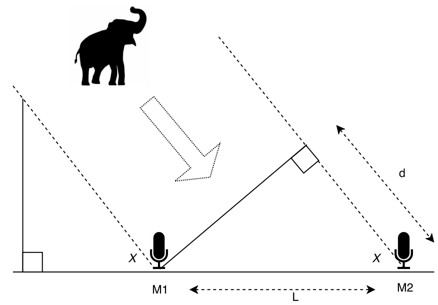


Figure 5: Basic setup to calculate the direction to an infrasonic source using *time difference of arrival* where the `Eloc` node pair is capturing data in a time synchronized manner.

Localization technique. Figure 5 illustrates the basic setup to calculate the direction to an infrasonic source using two `Eloc` nodes. We denote the distance the wavefront travels from $M1$ to $M2$ as d and the time delay for this journey as D seconds. We estimate the time delay of arrival (D) by taking the *cross correlation* of the signals captured by $M1$ and $M2$. The lag towards the peak in the cross correlation graph indicates the phase shift between the two signals due to the delay D. This phase shift can be measured as a number of samples, n. If the sampling rate at each microphone is f, we can have a representation of the time delay D as follows.

$$D = \frac{n}{f} \tag{1}$$

According to the geometry in Figure 5, we can write another equation for the time delay D where v_{sound} is the speed of sound.

$$D = \frac{d}{v_{sound}} = \frac{L \cos x}{v_{sound}} \tag{2}$$

From Equations 1 and 2,

$$x = \cos^{-1}\left(\frac{n v_{sound}}{L f}\right) \tag{3}$$

Using Equation 3, we can calculate the angle to an infrasonic source if we know the sample lag between the same sound captured by two `Eloc` nodes. Figure 6 illustrates the complete process of locating an elephant using the infrasonic data. In the first step, two `Eloc` nodes capture infrasonic data in a time synchronized manner. Secondly, we break the data set into multiple windows of equal sizes. Then we take each corresponding window pair from the two channels and

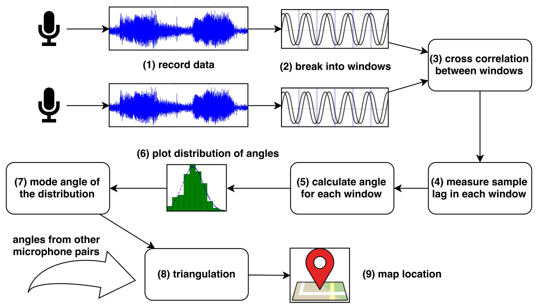


Figure 6: Process of calculating the location of an elephant. A pair of `Eloc` nodes capture elephant sounds which we break into windows, cross-correlate, calculated the sample lag and finally use it as an input for the angle calculation.

calculate the cross correlation between them (Step 3). The number of sample points (i.e., the lag) to the peak of the cross correlation is the phase shift n in Equation 3 that we compute in the fourth step. Using this value, we calculate the angle to the infrasonic source for each sample window in Step 5.

Since we have multiple windows, we get multiple angles to the infrasonic source which may not necessarily be the same value due to the noise in our recorded data. Then we plot the distribution of calculated angles for multiple windows for a known sound source. We consider the statistical mode of the distribution as the most representative angle for the sound source. When multiple such `Eloc` node pairs are deployed, we can perform triangulation based on the angles calculated using each node pair to compute the position of the elephant as the final step.

Accuracy of angle calculation. According to Equation 3 the angle calculation depends on the speed of sound, distance between the `Eloc` nodes, sampling rate of the nodes, and the lag taken from the cross correlation. All these parameters are constants except the lag, n, towards the cross correlation peak. Therefore, the calculated angle is a non-linear function of n. The minimum difference in n that we can measure depends on the sampling rate of the analog-to-digital conversion (ADC) on the connected computer. For a sampling rate of f, the minimum resolution of time measurement is $\pm 1/f$. Since n has the same resolution, the error in n becomes $\pm 1/f$. According to the error theory [16], the error, Δx, propagated to the calculated angle x is,

$$\Delta x = \sqrt{(\frac{\partial x}{\partial n})^2(\Delta n)^2 + (\frac{\partial x}{\partial v})^2(\Delta v)^2 + (\frac{\partial x}{\partial L})^2(\Delta L)^2}$$

where, Δn, Δv, and ΔL are the the measurement errors in the lag, speed of sound and the distance between `Eloc` nodes. We can assume that the speed of sound and the distance between the nodes are constants which leads to,

$$\Delta x = \frac{dx}{dn}\Delta n$$

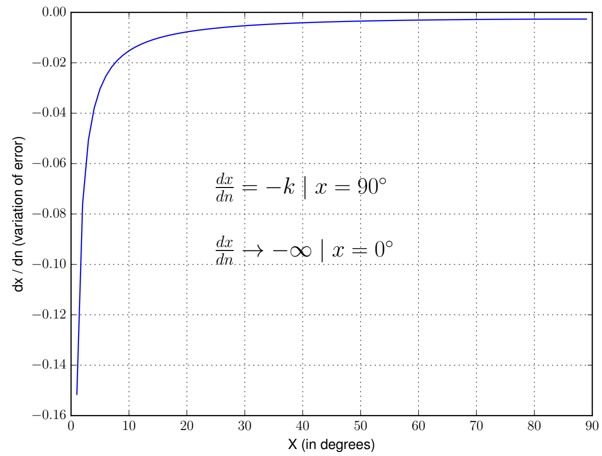


Figure 7: The variation of the error in angle calculation. The absolute value of the error increases drastically when the angle gets closer to $0°$.

We differentiate Equation 3 by n to get,

$$\frac{dx}{dn} = -(\frac{v_{sound}}{Lf})\frac{1}{\sin x}$$

During the time period of the experiments, we assume that the speed of sound (v_{sound}), the distance between the two microphones (L) and the sampling rate of the microphones (f) are constants. Therefore,

$$\frac{dx}{dn} = -k(\frac{1}{\sin x}) \quad (4)$$

Figure 7 illustrates this error behavior for angles between $0°$ to $90°$. The figure shows that the smaller the phase difference, the larger the error of the angle calculation. Our experimental evaluations agree with this phenomena as we show in Section V. With the method presented here, we can calculate the direction to an elephant using a pair of `Eloc` nodes. We use multiple pairs of `Eloc` nodes placed at different locations in an area affected by the human-elephant conflict to localize the presence of an elephant using triangulation techniques. As we calculate the angles pairwise, tight time synchronization between different pairs of microphones is not necessary. However, a precise time synchronization among the two nodes in a pair is necessary. Since a pair of `Eloc` nodes are connected to the same single board computer through the analog-to-digital converter (ADC) pins, the node pair is inherently time synchronized.

V. Experimental Evaluation

In this section, we evaluate our system for localizing elephants, showing the following key findings:

- Detectability of infrasonic patterns using `Eloc` nodes greatly increases with the use of fur filter.

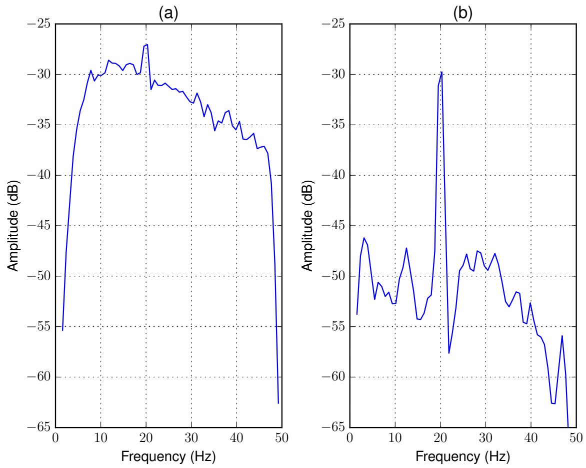


Figure 8: Frequency domain of a 20 Hz sound emitted using the subwoofer and captured (a) without and (b) with the fur filter. The fur filter significantly reduces the wind noise floor.

- Our Eloc nodes can capture elephant infrasonic patterns with a significant number of harmonics using an Eloc node.
- A set of Eloc node pairs can help to calculate the location of elephants with a reasonable accuracy even in the wild.

A. Effectiveness of the Wind Shield

As discussed in Section III, we need to protect the microphone from infrasonic noise generated by the wind. Various forms of physical shields have been proposed [19], [9]. While large dome-like structures can protect an infrasonic microphone array from the wind, we apply shieldings to individual Eloc nodes so we can place the Eloc nodes easier. Therefore, we develop the structure shown in Figures 4a and 4b and evaluate the effect on the infrasonic detection capability.

Scenario. We place an Eloc node 5 meters away from the subwoofer and play a 20 Hz tone continuously. To induce sufficient wind noise, we artificially create a wind flow over the Eloc nodes using a fan. We capture recordings of 30 seconds with and without the wind shield.

We select a frequency of 20 Hz since the fundamental frequency components of Asian elephant infrasonic vocalizations are in the range between 14 Hz to 24 Hz. Moreover, 20 Hz is a frequency that the subwoofer can emit with a significant output power.

Results. Figure 8 presents the data recorded with and without the wind shield in the frequency domain. The left part illustrates the effect of the wind noise where the peak caused by the 20 Hz sound of the subwoofer is barely noticeable. With the wind shield, the Eloc nodes are able to suppress the wind noise and hence the 20 Hz peak stays above the low frequency noise floor which enables us to identify the peak at 20 Hz.

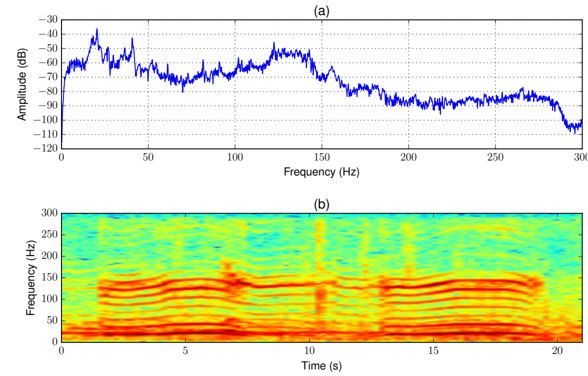


Figure 9: The frequency domain (a) and the spectrogram (b) of an elephant rumble recorded using a pair of Eloc nodes where a number of higher harmonics of the fundamental frequency is visible.

B. Elephant Sound Recording in the Wild

The previous experiment confirms that Eloc nodes together with the wind shield can identify infrasonic frequencies inside the controlled environment of a laboratory even when there is wind. However, real deployments pose further challenges such as vehicle noise from nearby areas, vibrations that occur on the Eloc nodes when dust and vegetation hits with them. Therefore, we evaluate the effectiveness of Eloc nodes to identify low frequency elephant sounds in the wild.

Scenario. We take a pair of Eloc nodes to a national park in Sri Lanka where free ranging elephants live. We mount the nodes inside an off-road vehicle and park it in a location where we can observe elephants visually while recording sounds. The vehicle engine is turned off during the recording time. Other external noise sources such as wind and vehicles in the nearby areas are present. We note the presence of elephants and their behavior in the visual range and compare them against the data we record. We take support of a zoologist to verify whether the recorded patterns are from an elephant.

Results. Figure 9 illustrates the waveform, frequency domain and the spectrogram of an elephant sound identified by a zoologist from our field recordings. As the figure shows, Eloc nodes can clearly capture the fundamental frequency component of the sound that is below the 25 Hz in addition to the higher frequency harmonics. The figure also shows that the Eloc nodes' low-pass filter significantly attenuates the unwanted frequencies above 150 Hz.

C. Estimation of the Sound Direction

In this experiment, we evaluate the feasibility and accuracy of using Eloc nodes as the infrasonic detector

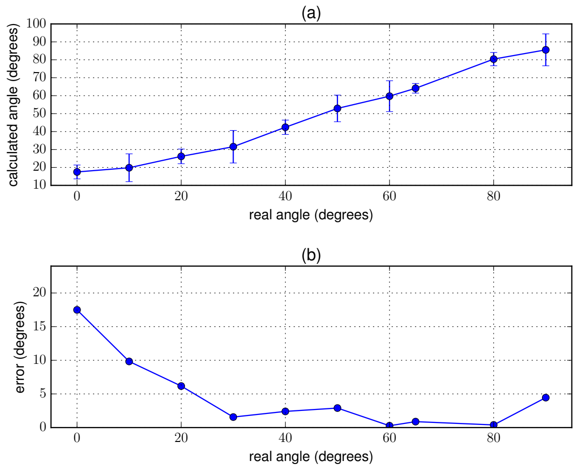


Figure 10: Accuracy of calculating the direction to an infrasonic source using a pair of `Eloc` nodes. (a) shows the relationship between real and respective calculated angles while (b) shows the variation of the error in calculation against the real angle in consideration.

for localization using the method in Section IV. In this experiment, we use a subwoofer as an artificial infrasonic source since real elephants might not emit infrasonic signals throughout the experiment.

Scenario. We place a pair of `Eloc` nodes in an open field and place the subwoofer in different locations around the node pair. We maintain a constant distance of 20 m between the subwoofer and the `Eloc` node pair in each of our placements. If two signals coming from the node pair are in a 180° degrees or a higher phase difference, the correlation and sample lag calculation step may incorrectly detect it as a different phase. To avoid that, distance between two `Eloc` nodes should be equal to or less than the wavelength of the frequency we use for the localization. We therefore select 3 m as the distance between the `Eloc` nodes which is roughly the wavelength of the frequency 120 Hz under the atmospheric temperature of 30 °C.

Results. Figure 10 (a) presents the variation of calculated angles against the real angles. For the considered angle range from 0° to 90° degrees, there is an error in the calculated angle which makes it different from the real angle. This error is illustrated in Figure 10 (b). The figure shows that the absolute value of the calculated error is large for the angles closer to 0° and gets smaller as the angles get close to 90° which corresponds to the theoretical foundation laid in Section IV. For an angle of 0° degrees, the theoretical value we get should be infinite. However, due to the measurement and random errors in experiments, the angle is not infinite but 17°. For all the other angles approaching 90° degrees the absolute value of error is quite low as Figure 10 (b) shows.

For the range between 30° to 90° angles, we get an average error which is approximately 1.8° and a maximum error of 4.5°. This result indicates that we can reliably use an angle value calculated using a pair of `Eloc` nodes if the angle to the infrasonic source is at least 30° degrees. By using multiple pairs of `Eloc` nodes deployed at different angles to each other, we can select the most reliable node pairs for the final location by ignoring the ones which measure an angle less than 30° degrees to the infrasonic source.

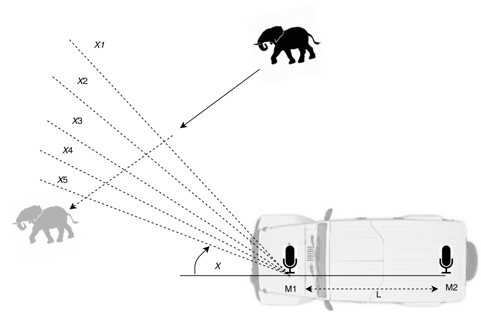


Figure 11: We calculated the angles of infrasonic emissions from a moving elephant using two `Eloc` nodes mounted in the front and back of a jeep. The calculated angles agree with the visual observation of the elephants movement direction.

D. Localization of an Infrasonic Source

We perform an experiment using multiple `Eloc` node pairs to find the accuracy of pointing the exact location of an infrasonic source by integrating our method for angle calculation at multiple `Eloc` node pairs.

Scenario. We place our subwoofer in an open field and put three `Eloc` node pairs at three arbitrarily selected locations keeping a distance of about 300 meters from the subwoofer. The subwoofer plays a clip of elephant infrasonic recordings continuously. We performed angle calculation algorithm at each node pair and used triangulation to get the location of the infrasonic source.

Results. We could calculate the location of the infrasonic source with an average error of about 10 meters compared to the real location of the subwoofer.

E. Localization of Elephants in the Wild

So far, we performed experiments for angle calculation and location estimation using artificial infrasonic sources since we have a guarantee that an infrasonic source exists during the time period of the recording.

Scenario 1. The setup of this experiment is the same as in Section V-B, i.e., we mount a pair of `Eloc` nodes in the front and the back of our field vehicle with L=3 meters distance between them. While recording elephant sounds, we visually observe the elephants and their movements and continuously calculate the angle to their position.

Results. Figure 11 illustrates a situation we came across with this setting. We observed an elephant moving from an open area into the jungle where the thick vegetation blocked

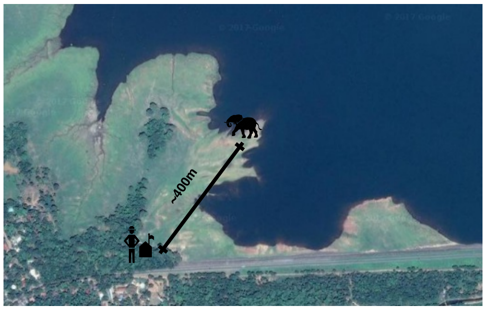


Figure 12: The map illustrates the location of the `Eloc` node deployment and the herd of elephants inside a wildlife park.

the visibility of the elephant from the location of the vehicle. The infrasonic patterns we captured resulted in the angles, X_1, X_2, X_3, X_4 and X_5 with values $47.5°$, $41.5°$, $35°$, $34°$ and $32.5°$ respectively which agrees with the movement direction of the elephant.

Scenario 2. We place two pairs of `Eloc` nodes in a location inside a national park in Sri Lanka. The deployment is in an open field next to a lake where a herd of elephants visits regularly (see Figure 12). The two `Eloc` node pair were placed in a V shaped manner so that they do not generate the same angle for the same infrasonic source. Additionally, the opening side of the V shaped `Eloc` node pair is oriented so that it directly oversees the location of the elephant herd about 400 m ahead.

Results. We identified several-low frequency patterns from spectrograms of the recorded data which looked similar to the elephant rumble patterns published by biologist in previous works [6]. When calculate the angle to the sources, we received $37.49°$ and $23.64°$ degrees from the `Eloc` node pairs which roughly points to the direction where we visually observed the elephant herd.

Scenario 3. Since the infrasonic source of the previous scenario was a herd of elephants which was dispersed within few tens of meters, the location of the infrasonic source is a rough estimate. In order to perform an angle calculation with a better ground truth, we select another location where a domesticated elephant exists. We place a pair of `Eloc` nodes about 72 meters away from the location of the elephant.

Results. Figure 13 illustrates the position of the elephant with respect to the location of the domesticated elephant. While the real angle to the elephants location from the node pair is $65°$, our calculations for the infrasonic localization of the elephant indicates the angle as $63°$.

VI. Related Work

Payne et al. are among the first biologists to discover that Asian elephants make acoustic calls that contain infrasonic waves [14]. Their studies indicate that the acoustic calls of Asian elephants have fundamental frequency components from 14 Hz to 24 Hz. They have also shown that when the distance between two elephants is longer than 300 m,

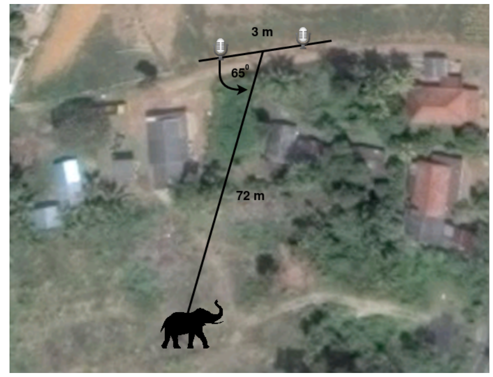


Figure 13: The map illustrates the locations of the pair of `Eloc` nodes and the domesticated elephant in the third scenario.

they hear their infrasonic emissions best since the higher frequency components of their acoustic calls attenuate more with distance than lower frequencies.

Langbauer et al. [11] revealed that elephants exhibit behavioral responses to the playback of their own sounds even at distances such as 2 km. However, wind and various other low frequency noise source make it difficult to identify fundamental frequency components of elephant sounds. Zeppelzauer et al. [24] studied signal enhancement techniques to detect these frequency components under noisy conditions. However, their experiments are based on African elephants which have different acoustic characteristics from those of Asian elephants. Moreover, they do not present the details of the infrasonic detectors used for these experiments.

An initial work to implement an elephant infrasonic detection system is presented by Zeppelzauer et al. [23]. They are considering frequencies from 0 Hz to 500 Hz where they have the advantage of detecting higher harmonics of the fundamental frequency components. Their work does not attempt to localize elephants. Moreover, similar to the previous work of the same authors, this work considers only recordings of African elephants. In contrast, we focus on localizing Asian elephants using a low-cost microphone setup which requires further studies to adapt the methods presented by Zeppelzauer et al. [23]. Venter et al. [18] have studied methods to automatically identify infrasonic emissions of African elephants without human intervention. Further research is required to adapt these methods to identify the emissions of Asian elephants, a topic we intend to tackle in future work.

In earlier work, we have detected infrasonic emissions from Asian elephants from distances up to 500 m using devices with a per-device cost around USD 350 [5]. In this paper, we present the design of an infrasonic detector that is both cheaper and more sensitive.Werner-Allen et al. [22] have used wireless sensor motes attached to cheap condenser microphones as detectors to monitor the emissions of an active volcano. In our work, we use a condenser microphone with similar characteristics for our infrasonic detector.

VII. Conclusion

We presented the design of `Eloc`, a system to localize wild elephants based on low cost infrasonic detectors. While the acoustic localization is not a novelty, the application of infrasonic localization using low-cost hardware for elephants is not done before. We successfully used `Eloc` with two nodes to find the direction of an infrasonic source. Moreover, we used the same system with multiple pairs of `Eloc` nodes to find the direction of moving and stationary wild elephants under real-world conditions in the wild. A zoologist was able to detect elephant rumbles in the sound recordings that we have done in the wild with `Eloc` nodes, thus establishing their effectiveness in capturing elephant infrasonic calls.

The system with two `Eloc` nodes is cheap enough for large-scale deployments. Two `Eloc` nodes can find the direction of an infrasonic source, but with two additional nodes we can also localize the elephants. We plan to deploy several such systems to detect and localize elephants. The system is simple enough and does not require experts to maintain the nodes.

While the presented approach is suitable to locate elephants using their infrasonic emissions, multiple elephants in the area of `Eloc` node deployment can cause difficulties in localization. Wang et al. have presented methods that in simulation studies identify multiple sound sources [21]. In future work, we plan to evaluate such methods to identify multiple elephants.

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