Invisible Forest

A sound installation by Augustine Leudar

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Part I - An artist's guide to plant electrophysiology

Introduction - on making tangible electrical signals in plants for audio or visual art

Electrical signals (known as action potentials) in animals have been known for over 100 years in animals and nearly as long in plants[1]. Action potentials in plants and animals both consist of the propagation of ions down a pathway, the axon in animals or the phloem in plants, due to the opening and closing of voltage gated ion channels across the cell membrane.[2]

The author spent several months consulting with plant electrophysiologists in Italy and around the world in effort to properly read electrical signals in plants and eliminate artifacts, the following paper is a result of these consultations. The picture derived from some of the foremost experts in the field demonstrates there is still many aspects of the field that are not clearly understood and still exhibit considerable controversy and certainly as an artist without a background in Biology the authors own understanding of the techniques and processes involved will also be limited. This being said, this paper seeks to pass on corrections and observations made by various helpful and knowledgeable engineers and electro-physiologists in reference to the development of the authors own techniques and those already practised by other artists in the hope that they will be of use to others working in the field.

Many artists have tried to convert bioelectrical signals in plants to artistic ends [3,4,5,6,7] Most of these artists are trying to make tangible a hidden world complex electrical activity however despite the fact that complex electrical activity in plant exists, due to technical errors the real electrical signals in the plants are often not being read at all in artistic practice. There are several common mistakes and ways of rectifying them which will now be covered.

1. Readings show the plant seems to be responding to touch or proximity

This is common assertion by artists[8,9,10,11,12]. Although it is well known that Mimosa Pudica (the sensitive plant) and Dionaea Muscipula (the Venus Flytrap) generate action potentials when touched and others may do as a resulting in thigmo-tropism[13] – in most cases the readings artists are taking are not the result of a reaction in the plant at all. What is really happening is that your body's own electrical field is using the plant as an earth – so the electrodes are really responding to electrical field of the person touching the plant and are not reading a response in the plant at all. In fact you can get the same results by touching a piece of damp cloth with the same two electrodes in it.

As one plant electro-physiologist put it: "*Earthing may be not the best term but yes it is an artefact, when you approach or touch the plant, you are changing its capacitance, and this is picked up and amplified. Nothing to do with what the plant's sensing* " [14]

Another electrical engineer put it like this:

"What is really happening is that when touching the plant a current path is created between the plant and the body and this can lead to an alteration of the plant's electric field. Consequently the electrodes are responding to this variation and are not reading a response in the plant at all."[15]

In scientific experiments a plant is usually put in a faraday cage to ensure there is no electrical interference from the surrounding environment [16] In such laboratory experiments it is a cardinal sin to touch a plant as it is well known that the human body's electrical field will affect the readings. Proximity to a plant can also cause a change in the readings for the same reason. Sometimes, such as in the cited video, it is claimed that plants exhibit different strengths of electrical response depending on how hard or softly you touch them [17]– again this is simply because the harder you touch something the better contact there is between the skin and surface being touched.

Having said all this plants DO respond to touch and is known as thigmo-tropism whereby plant growth is affected by touch[18] – however this is a completely different phenomena. In general it is best to avoid touching plants or even going near them if a faraday cage is not being used as despite the seemingly dramatic response it provokes in electrode readings, this is misleading and deprives the artist of an opportunity to present the true electrical processes happening within the plant. If a Faraday cage is not desirable then as much electrical activity in the environment as possible should be removed, the plant should be kept well away from any mains current and equipment such as laptops should run off battery power if possible. Filters which remove 50 Hz and 60 Hz (mains) should also be used in all cases – some electro-physiologists recommend a low pass filter as low as 20 Hz – others recommend band stop filters.

2. Plants are responding immediately to changes in light

Although this may be possible usually these fast dramatic responses to changes in light displayed by some artists are usually a result of the measuring equipment being on the same ground loop as the lights – so turning them off or on results in a spike in electrical measurements and is misinterpreted as a response in the plant. Again filtering mains electricity is recommended and wherever possible run equipment such as laptops from batteries (separate from the light).

3. Operation amplifiers

It is recommended that any operational amplifiers used to measure electrical signals in plants have an input impedance of at least 10 gigaohms[19]. The reason for that electricity takes the path of least resistance – if your measuring equipment offers less resistance than the plant any electrical signals in the plant will flow into your measuring equipment instead of continuing their natural course through the plant – this obviously makes it impossible to take accurate readings. Excellent op amps for this purpose are available for less than 5 euros.

4. Electrodes

Electrodes should be non – polarisable and should damage the plant as little as possible. Wounding in plants produces action potentials[20] so it is advisable to let a plant rest for a while if using invasive electrodes before taking any reading. AgCl electrodes are generally recommended for both invasive and non-invasive electrodes. For non-invasive readings non – polarisable Ag/AgCl pelleted electrodes can be used with ECG gel maintaining contact between the electrode and the surface of the plant[21]. For trees graphite electrodes can be used with ECG gel to increase conductivity by drilling a hole in the bark. It should be noted that for invasive electrodes scar tissue will eventually form around the electrodes, which will affect readings as electrodes will become insulated from currents in the plant – this should be taken into account if a long term art installation is planned.

The reference and working electrode should generally be both be placed in the same tree/plant or the reference electrode can be placed in the soil. For longer outdoor installations the reference electrode should not be placed in the soil as there is variability in soil conductivity due to variations in moisture content and salinity. Crocodile clips are inappropriate for measuring small electrical signals in plants.

5. Data Acquisition

Action potentials in plants can last for as little as 20 ms – some scientists say less. Therefore, in theory, to read an electrical fluctuation or signal that lasts 20 ms you need a 100 S/s sample rate (50 doubled due to Niquist), however in practise it is better to have a sample rate 10 times faster than the signal you are trying to read – in this case 500 S/s. Many standard multimeters used by electricians only have an sampling rate of 4 S/s and are therefore far too slow to measure electrical responses in plants (apart from variation potentials or VPs which are longer and slower). It is necessary to bear in mind that on most Daq, Arduino etc the sampling rate is divided amongst all the analogue channels so if a DAQ has a 500 S/s overall sampling rate and you are using 8 channels – each channel will have a sampling rate of less than 100 S/s which is insufficient.

If very high detail of the action potential is required for some artistic reason much higher sampling rates would be required. Niquist theorem should always be taken into account when assessing appropriate sample rates. In situations where there is a lot of ambient electrical noise or long cables differential readings can be made using two analogue inputs rather than single ended readings - this uses phase inversion to cancel noise in a similar way to an XLR audio cable.

6. Cabling

Shielded, single core low loss cable should be used if the measurement device is far away from the electrode. In this case the op amp should be placed close to the electrode with the longer length of cable between the op amp and the DAQ. For long cable lengths electrical engineers have advised me that multicore cable can cause phase problems with tiny electrical signals and is best avoided.

Conclusion

Real complex electrical signalling in plants exists but is yet to be properly harnessed by the artistic community as an avenue for creative expression and genuine interaction with the plant kingdom. The relatively few scientists in the field who are fully qualified to advise them are often too busy to offer advice and sometimes do not even agree, and some of the technical assistance offered to artists it not always by people familiar with the field. However despite these issues relatively few technical adjustments need to be made to allow correct implementation of plant electrophysiological techniques in artistic practice.

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Part II - Invisible Forest – Sonifying bioelectric activity in forest environments

Introduction

Invisible forest can be described as an "immersive 3d sound installation that allows both the plants and the listener to participate in the soundscape". Many artists have tried to harness electrical signals in plants in order to trigger sound. However there are significant technical hurdles and a lack of good technical information. For example several installations feature the public touching plants and thus causing a reaction (i.e. a sound is triggered), many artists interpret this as an electrical response in the plant and thus an indicator of some sort of plant sentience, however it is really just an artefact caused by the electrical field of the person touching the plant.

By harnessing electrical signals in trees and using them to influence the composition of a multichannel sound installation, the author seeks to make tangible hidden bioelectric activity in plants and consisted of a first step towards detecting signals traveling between trees possibly across the Mycorrhizal network. In addition to this the goal was to create a spatial audio composition that stands as a piece of art in its own right whether or not the listener is aware of the scientific background of the piece. A video "Invisible Forest" documents the sound installation.[22]

Technical details

The sound installation consisted of 16 speakers hidden amongst the trees and undergrowth of the woods. 4 of these were larger Mackie SRM 450 and the others were smaller Behringer MS16 speakers – the 4 large speakers were at ground level and created a quadraphonic soundfield across the whole woodland whilst the smaller speakers were placed in a grid of 8 in the treetops (See fig 1) as well as 4 additional small ground level speakers being placed next to trees from which electrical signals (Action potentials) were being read (See fig 2). It also consisted of a computer, a 16 channel sound card, 35 om of XLR audio and low loss single core shielded electrical cable for the electrodes. In addition to this an 8 channel Labjack U3 data acquisition device was used to read action potentials (electrical signals) in the trees using graphite electrodes.

Reading the action potentials

Action potentials in plants are similar to the electrical signals in animals through the polarisation and depolarisation of the cell membrane they are propagate through electrically excitable cells such as the ones found in the axon of the human nervous system –they are not simply "ambient static electricity"[23]. They are used to send signals to various parts of the animal or plant body often in response to environmental factors (e.g. a Venus flytrap sends an action potential instructing the "trap" to close once an insect has triggered two trigger hairs).

Recent research has shown that trees communicate with each other across the mycorrhizal network[24] – a network of fungal mycelia and plant roots. To accurately demonstrate whether action potentials travel across this network is beyond the scope of this installation though it represents the first step towards this goal.

In this installation action potentials from 4 different trees were measured. Operational amplifiers were used to increase input impedance of the electrodes. As the cables from the electrodes to the computer were long (20m in two cases) low loss shielded single core cable was used. Differential connections are also recommended for such long lengths of cabling – but this halves the amount of analogue inputs available.

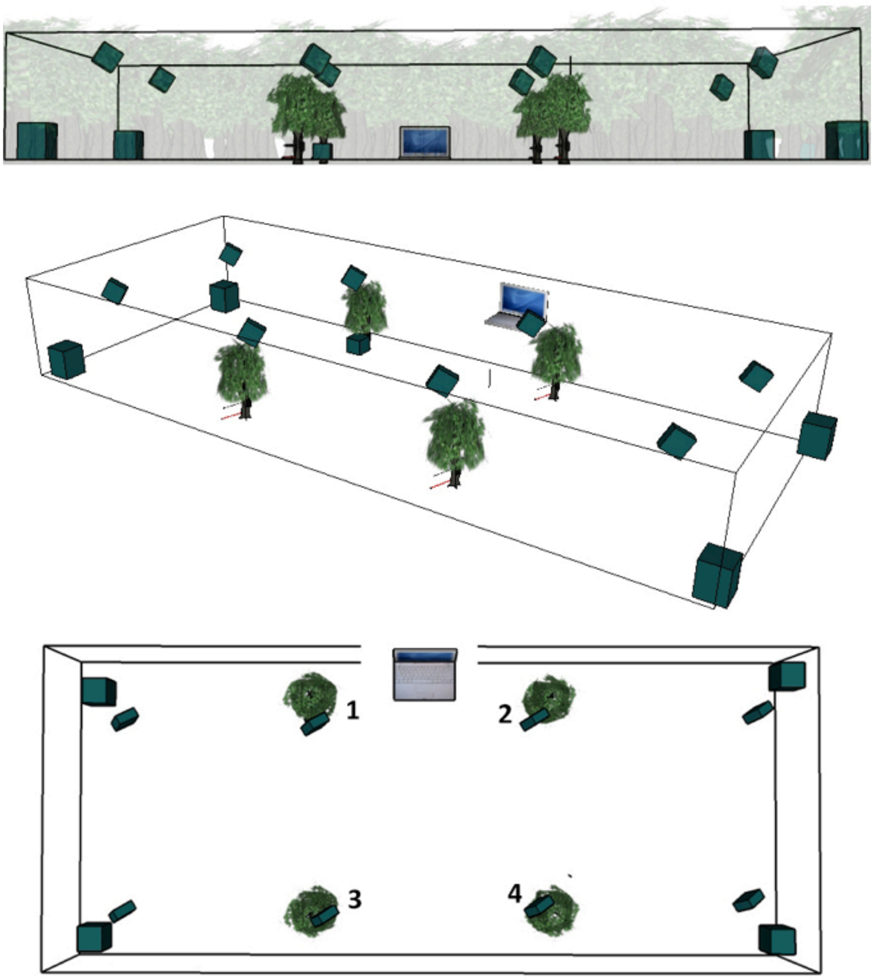

Fig 1. Shows four large speakers in each corner and 8 smaller ones in the treetops. The numbers 1,2,3,4 in the bottom picture show the presence of electrodes and another speaker for each tree.

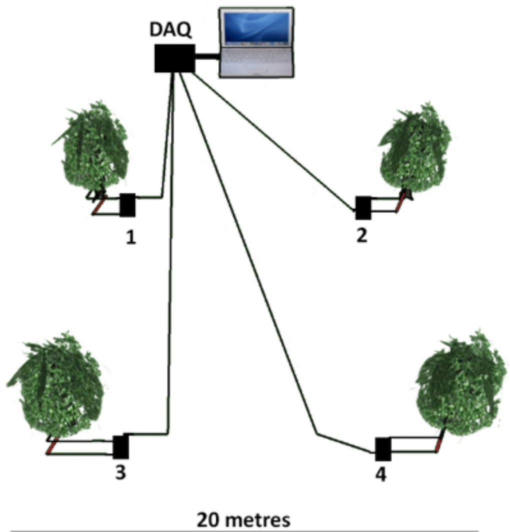

Fig 2. Positioning of oamps and electrodes, one for each of four trees

Construction of op amp units

Normally an electrometer costing upwards of £1000 would fulfil this purpose – the construction of a bespoke op amp unit with an input impedance of one terraohm is described here – the construction of each one channel unit cost less than £10. These units were designed by Italian engineer Matteo Masi and constructed by Matteo and the author specifically for this sound installation and for reading action potentials in trees in the field. [25]

Each op amp unit consisted of a printed circuit board (see fig 3), two capacitors (to reduce battery noise), 1x TL071 opamp, 2x 0.1uF ceramic capacitors, 1x photoresist PCB, 2x 9V batteries, wire and a plastic box to house it. (Fig 4)

We printed the circuit boards ourselves using light sensitive PCB techniques and acid to corrode copper surfaces – further details of the process can be seen with a video accompanying this document. The op amps in this unit need to have a very high input impedance to prevent the measuring device itself affecting the measurements. In this case we used a Texas instruments TL071 opamps in future it would be preferable to use a TL061 as it consumes less power. Each unit was powered by 2 9v batteries and consisted of two inputs and one output.

Fig 3. Circuit design to be opened with "Eagle" free software.

INSERTING THE ELECTRODES

A small hole was made in the tree for each electrode. Holes were kept as small as possible to minimise trauma but it was important that the electrode penetrated the fleshy inner layer of the tree (the phloem). Graphite electrodes were used – the conductivity of these can be further enhanced by using ECG gel which also helps minimise trauma. The electrodes should be allowed to rest for a while after being inserted as wounding potentials may take a while to subside. Both reference and the working electrode were placed in the trunk of the same tree and the op amp unit was placed close to the electrodes. Both were put out of reach of people to prevent tampering with and electrical interference from the public. They were also kept well away from electrical cabling.

Cables from the op amp units went back to the DAQ (Fig 2). The Labjack DAQ has a specially made external in MAX/MSP produced by labjack for the purposes of this sound installation. Once in Max MSP a threshold was set at around 60 mv (the background noise was around 20mv) if an action potential caused a spike above 60mv then a sound would be triggered, this threshold was adjustable in case background noise or the strength of potentials change significantly due to light levels, temperature or moisture. Each channel of the DAQ corresponded to a particular tree and also a particular audio channel (fig 5). These channels delivered audio to the speaker next to the tree in which the electrical signal had originally been generated. So channel 1 on the DAQ corresponded to channel 1 on the sound card, channel 2 on the DAQ to channel 2 on the soundcard and so on.

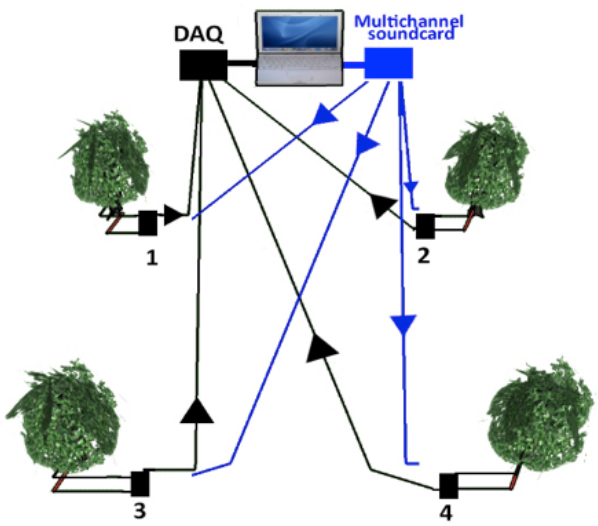

Fig 5. Electrical signals enter the DAQ (black lines) from the tree and are converted into audio in Max/Msp and are then sent back to a speaker next to the tree that put out the original signal (blue lines).

The composition

Ideally site specific sound installations are tailored to the environment in which they will be reproduced. Cognitive visual factors have a large influence on how sound is perceived[26] so the environment itself must be chosen (or created) carefully and may form an integral part of the composition. For this composition ancient deciduous woodland would have been ideal but was not available. Due to the aforementioned cognitive factors - the author likes to keep speakers hidden to help create a more convincing illusion. The context in which a sound installation is presented is also important – if the listener is not aware they have entered a sound installation, or if sounds can be presented in a more believable context – as if they might just be part of the real environment and not part of a "performance" the audience response can be markedly different. In this case most of the sounds were also composed in the site where they were later reproduced meaning the installation could be perfectly tuned to the acoustics of the environment. The artist was present on the site for several days before the venue opened.

There were three elements to the composition. The first was the sounds triggered by the electrodes, the second was the soundscape, which was present in the wider soundfield, which interacted with these electrodes, induced sounds and the third was hidden microphones, which allowed the public to interact with the soundscape and the sounds coming from the trees.

Various different sounds were triggered by the trees, some were bell like sounds which when triggered in any order would form a kind of tune or harmony – these sounds were slightly time stretched at the end and faded out with descending and ascending artefacts to allow them to "blend" and harmonise with each other. The other sounds used were time stretched and pitch shifted bird song. When slowed down, elements of bird song can be particularly eerie and primordial, suitable for the woods at night. As the sounds were coming from the trees that produced the signals covered a wide range of space - sounds seem to come from many different places in the darkness of the forest creating a sense of depth.

The wider soundscape

The four trees formed a cube in the centre of the sound installation. Interacting with and surrounding this cube was a wider soundscape (see fig 1). The wider composition was designed to integrate fluidly with the sounds produced by the trees and vice versa. The sounds used by the trees both informed the wider soundscape that was built around them but the sounds that were used by the electrodes were in turn altered to fit the soundscape, these sounds changed over time according to the whim of the artist. This is a kind ongoing process similar to automatic writing whereby the soundscape, once initial parameters and sounds were set in motion, begins to evolve by itself – the artist adopting almost a problem solving role in order to resolve the composition. As such the installation had a live element to it and sounded considerably different at the end of the three days than it did at the beginning. The sounds used changed according to the time of day both due to the activity of the trees and the artists deliberate manipulation.

Spatialisation

Spatialisation was an integral part of the composition. As the speakers were not surrounding the periphery of the listening area but rather spaced out within it, albeit mostly above the listeners, a convincing sense of depth could be achieved when panning sounds across them (see figs 6 and 7) this used a similar technique to DBAP (Distance based amplitude panning)[27] and was more effective at creating illusions of proximity than the artists previous experiments with wave field synthesis. The spatialisation was tailor made for the environment and would be difficult to replicate elsewhere, in reality it would be necessary to remix it for a different space. Unusual sounds such as flocks of bizarre birds were able to fly from tree to tree and blend with the sounds produced by the electrodes. Sounds were also able to travel downwards from the trees to speakers at ground level. Some of the panning relationships between the speakers are shown in figs 6 and 7

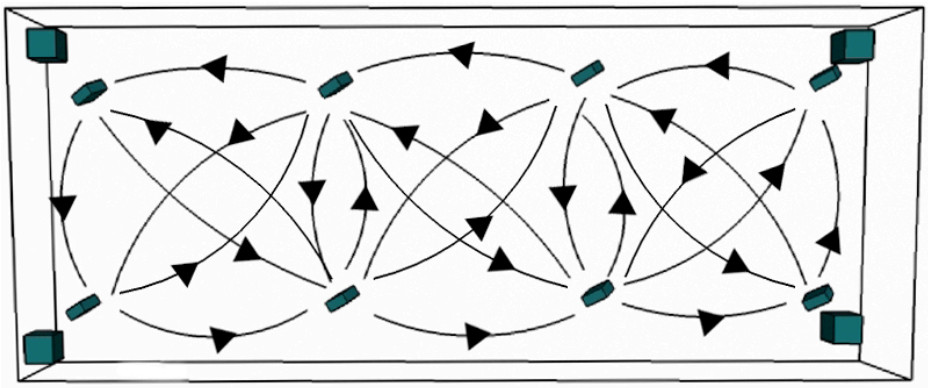

Fig 6. View from above the forest (diagram covers approx. 1acre) - some of the horizontal trajectories sounds could take through the treetops above the listener

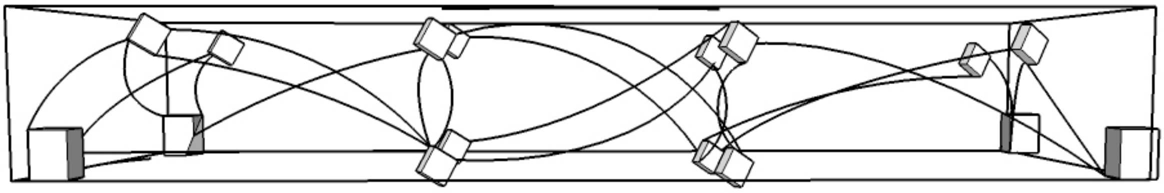

Fig 7. Shows a side view of some of the panning relationships used in the vertical and horizontal plane

MICROPHONES

Both artists and members of the public were curious as to whether their instruments or voices would be able to affect the electrical signals in the trees. They also wished to participate in the composition of the soundscape. This was made possible in two ways. Firstly a bunch of large flowers in the centre of the installation contained microphones in the stamen. The voice of the person singing into the flower was modified and restricted in such a way as to fit in aesthetically with rest of the soundscape. The voices were also spatialised amongst the trees in a way that allowed the voice to travel around the treetops. Instrumentalists were able to wear radio mics and as they moved around the forest the effects on their instrument would follow them. Instrumentalists were particularly keen on interacting with the sounds produced by the trees.

Although the aim of this installation was not to gather quantifiable data on whether or not bio electrical activity in the trees change in response to certain sounds or frequencies – a casual observation indicated that no such response was present.

PUBLIC RESPONSE

The public response was excellent appealing to a wide demographic from children to adults, several visiting sound artists from both Belfast and Europe expressed enthusiasm. About 2000 people in total experienced the installation. The artist "listened in" to many comments made about the installation without revealing himself as the artist and the response was favourable. Three elements of the installation captured people's imagination. Firstly the idea that trees could communicate with each other via an underground network and the idea that electrical signals in the trees had been made tangible. Secondly people playing instruments and singing into the flowers were enchanted by the idea that they could interact creatively with the sounds being produced by the trees. Thirdly the spatialisation of the installation surprised people – many members of the public were unaware that there were speakers hidden in the vegetation – this enhanced the sonic illusion and created a particularly vivid effect on people. Those who spoke into the microphone to hear their voice creep back through the treetops towards them in a substantially altered form couldn't work out how their voice had become "externalised" and returned to them, in the absence of any visible technology this seemed like a form of magic trick that they couldn't fathom. Those who were more familiar with sound installation or who had guessed that there were speakers hidden in the trees focussed on different elements of the installation such as how the sounds matched the environment and interacted with each other – this elucidates well how cognitive visual factors can be used as a tool to affect audience response. Whilst some children enjoyed shouting into the microphone flowers when dusk settled some of the more creatively inclined adults constructed improvised and subtle soundscapes upon the sound emitted by the trees and soundscape some of which were recorded. The sound installation was the subject of two interviews, part of which was shown on BBC2 arts show and the other for a local arts blog.

WHAT DIDN'T WORK

Although the electrical signals in plants were read as accurately as possible, and sounds were triggered by these signals, the author is not convinced that this demonstrated any form of communication between the trees. To do this far more electrodes would need to be used and it would be necessary to insure that they were placed in the same "channels", in other words that they were placed along routes along which signal travelled between trees. Nonetheless it proved an interesting first step towards sonfiying electrical signals in the forest.

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