Summer School of Science 2017:
Ear in the wall

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Abstract

In this project we will study physical background of listening device based on resonant chamber with movable membrane. After constructing our own model of the device, we will test its properties using RF transmitter and receiver, which are Arduino-controlled.

1 Introduction

The Thing, also known as The Great Seal Bug, is one of the best known listening devices in the history of espionage. Leon Theremin's invention was one of a kind because it used passive techniques to transmit an audio signal. Since it was simplistic and did not use any batteries, wires or electrical components it was almost impossible to detect. The Thing was top of modern technology at the time.

To understand the principle of how listening devices function and to build our own replica of the Thing we had to learn the basics; we started form theory behind mechanical waves, then upgraded our knowledge with electromagnetic waves and oscillations. Afterwards we analyzed all parts of the Great Seal Bug to find out their purpose. Also, we talked about amplitude and frequency modulation and demodulation – theory that makes it possible to code message into a wave, transfer it and then decode.

Gathering new knowledge enabled us to build: a transmitter, receiver, resonator and the device itself, to conduct measurements and to discuss the results using modern technology.

2 Theoretical background

2.1 Waves

2.1.1 Mechanical Waves

Mechanical wave is disturbance that travels through the medium from one location to another. These types of waves travel when molecules in the medium collide with each other passing on energy. One example of a mechanical wave is sound. Sound can travel through air, water, or solids, but it cannot travel through vacuum. Other examples of mechanical waves include water waves, seismic waves, and waves traveling through a spring.

To be able to describe propagation of wave with exact mathematical formula we must be aware that shape of wave changes in time and coordinate. Therefore we must include both parameters into wave equation. Taken all things in consideration and with mathematical tools we were able to construct wave equation: $c^2 \cdot \nabla^2 u = \partial^2 u / \partial t^2$ where constant c is speed of light, ∇^2 is Laplacian (second order partial derivation by coordinates), u is displacement of a wave and t is variable of time. Solution of this equation is: $u = u_0 \cdot \sin(\omega \cdot t - k \cdot r)$ where u_0 is the amplitude, ω is natural frequency (frequency at which a system tends to oscillate in the absence of outside force acting on a system), t is parameter of time, k is wavenumber (number of full waves in a given unit of length) and r is the vector of coordinate.

Since mechanical waves are the simplest ones, we will observe possible ways for them to propagate, but those ways are valid for all types of waves. We distinguish:

1. Transverse waves - particles of the medium move in a direction perpendicular to the direction that the wave moves. Examples are: all the electromagnetic waves, S earthquake waves, ultraviolet waves.

2. Longitudinal waves - particles of the medium move in a direction parallel to the direction that the wave moves. Examples are: sound waves, tsunami waves, earthquake P waves, vibrations in gas, internal water waves, etc.

2.1.2 Electromagnetic waves

This kind of waves are formed when charged particles, like electrons, vibrate due to the various forces acting on them. The vibration of charged particles results in an emission of energy known as electromagnetic radiation. The magnetic and electric fields of an electromagnetic wave are perpendicular to each other and to the direction of the wave, which means that EM wave is transverse wave that propagates outward from the source (figure (1)).

Since we have two different components that create one wave we need to consider both of them in order to find time-space dependent wave equation. In process of finding it we used Maxwell's formulas:

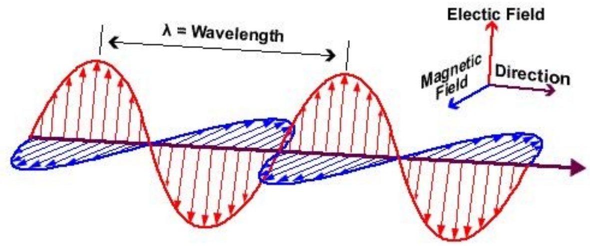

Figure 1: Electromagnetic wave.

$$\nabla \cdot E = \rho / \varepsilon_0, \tag{1}$$
$$\nabla \cdot B = 0, \tag{2}$$
$$\nabla \times E = -\partial B / \partial t, \tag{3}$$
$$\nabla \times B = \mu_0 J + \mu_0 \varepsilon_0 \partial E / \partial t. \tag{4}$$

First Maxwell's formula, known as Gauss' law for electricity, says that the electric flux out of any closed surface is proportional to the total charge enclosed within the surface. Second one, Gauss' law for magnetism, states that there are no magnetic monopoles (every magnet always has two poles). Third formula, known as Faraday's law, describes how a time varying magnetic field induces an electric field. The final formula, known as Ampere's law, states that magnetic fields can be generated in two ways: by electric current and by changing electric fields.

If we combine these formulas, and again use some math, we will get following expressions:

$$\nabla^2 E = \mu_0 \varepsilon_0 \cdot \partial^2 E / \partial t^2, \tag{5}$$
$$\nabla^2 B = \mu_0 \varepsilon_0 \cdot \partial^2 B / \partial t^2, \tag{6}$$

where E and B are electric and magnetic fields, μ_0 is vacuum permeability, ε_0 is vacuum permittivity and t is time.

These expressions remind us of those for mechanical waves so we expect similar solutions:

$$E = E_0 \cdot \sin(\omega t - kr), \tag{7}$$
$$B = B_0 \cdot \sin(\omega t - kr). \tag{8}$$

Given Maxwell's four equations we have shown that electromagnetic waves must exist as a consequence.

Unlike mechanical waves, electromagnetic waves don't need medium or matter; they travel through electrical and magnetic fields that are generated by charged particles. Therefore they can travel through vacuum (empty space).

Both, mechanical and electromagnetic waves show wave phenomena like: diffraction, refraction, interference, etc. We had to be aware of these phenomenas because they all could affect our measurements. Because of great wavelengths of radio waves, they can diffract from large surface like lamps in the park, bench, passerby, building, etc.

2.2 Resonance, resonant chamber and resonator

When a rest system is forced to oscillate by another system, or if it is forced to oscillate with greater amplitude than its own, we say that it experiences resonance.

A resonant chamber uses resonance to enhance the transfer of energy from incoming wave to the system it is part of. When a wave enters the chamber, it bounces back and forth within the chamber creating standing waves. As more waves enter the chamber, they combine with existing ones and reinforce the standing wave, increasing its intensity. Our resonant chamber was built from aluminum pipe.

In order to increase the range of transmitter we built a resonator out of a hollow plastic tube and we covered it with aluminum foil (all except for one hollow side). A resonator is hollow enclosure with conducting walls that displays electrical resonance.

2.3 Antennas

In radio an antenna, a metallic structure that receives and/or transmits radio waves, is the interface between radio waves propagating through space and electric currents moving in metal conductors. Receivers are antennas that catch radio waves and turn them into electrical signals feeding into something like a radio or television or a telephone system. A transmitter is a different kind of antenna that does the opposite job to a receiver: it turns electrical signals into radio waves so they can travel sometimes thousands of kilometers around the Earth or even into space and back.

The Thing had an antenna made out of 23 cm (9 inch) long copper antenna. It is necessary to pay attention to the dimension of antenna because if it is not precisely the right length for the frequency used, the radio waves cannot be emitted or captured efficiently.

2.4 Amplitude and frequency modulation and demodulation

To transfer the signal from one place to another it should be "added" to the carrier wave which will then carry encoded audio signal. The way to do this lies in changing some characteristic of carrier wave in accordance with the signal. Under such conditions, the audio signal will be contained in the resultant wave. This process, which can be performed by varying one or more of its signal components (amplitude, frequency, or phase) while keeping its other signal components constant, is called modulation. Doing this, information can be added as modulation to a signal.

If we only change the amplitude of high frequency carrier wave in accordance with the intensity of the signal, it is called amplitude modulation. Amplitudes of both positive and negative half-cycles of carrier wave are changed in accordance with the signal. For instance, when the signal is increasing in the positive sense, the amplitude of carrier wave also increases. On the other hand, during negative half-cycle of the signal, the amplitude of carrier wave decreases (see figure 2).

In frequency modulation, only the frequency of the carrier wave is changed in accordance with the signal (3). When the signal voltage is zero, the carrier frequency is unchanged. When the signal approaches its positive peaks, the carrier frequency is increased to maximum, as shown by the closely spaced cycles. However, during the negative peaks of signal, the carrier frequency is reduced to minimum, as shown by the widely spaced cycles.

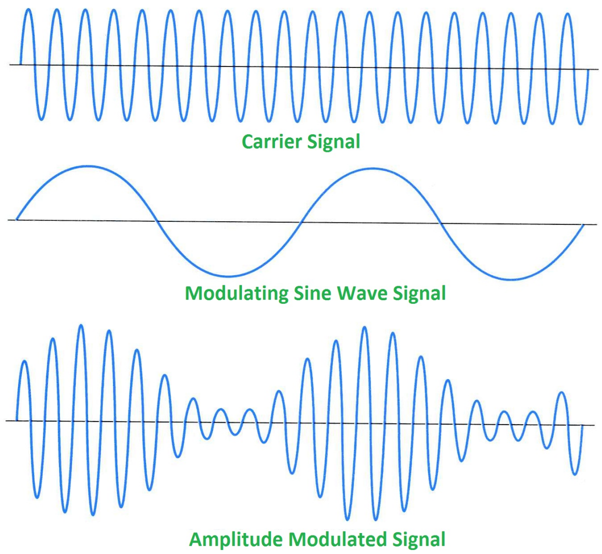

Figure 2: Principle of amplitude modulation.

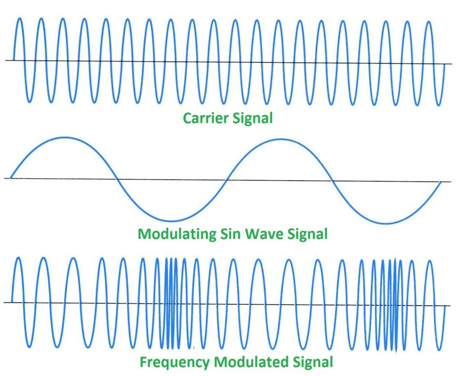

Figure 3: Principle of frequency modulation.

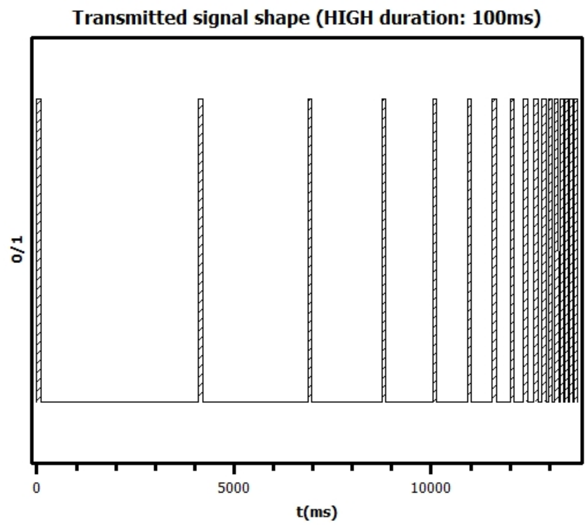

Figure 4: Arduino is programmed to repeatedly send via RF transmitter radio waves in patterns shown in this graph. Each "1" lasts for 100ms, and only during that time transmitter emits radio waves at 433MHz.

At the broadcasting station, modulation is done to transmit the audio signal over larger distances to a receiver. When the modulated wave is picked up by the radio receiver, it is necessary to recover the audio signal from it. The process of recovering the audio signal from the modulated wave is known as demodulation or detection.

3 Experimental setup

3.1 Transmitter and receiver

To see how resonant chamber modifies the electromagnetic waves we must first have a setup which allows us to emit known pattern, and receive clear signal without too much noise. To do that, first part of experimental setup consists of RF (radio frequency) emitter and transmitter at 433MHz connected to set of Arduinos. Transmitter is connected to one Arduino which repeatedly sends out signal with fixed shape shown in figure (4).

Receiver is connected to other Arduino where signal is monitored with Arduino IDE and plotted in QtiPlot.

As tricky as RF frequencies can be, we had to be extra careful to maintain approximately the same measurement conditions. That means no walking around the experimental setup once the measurement started, clear line of sight between emitting and listening station, same height from the ground plane (boxes!),... Once these requirements were met, results gave signals progressively growing worse with increasing distance between transmitter and receiver, as expected. However, Arduinos translate signals from input voltages to a number between 0 and 1024 so height of signal is seemingly constant. Degradation can be seen in shape of the signal. In figure (7) we can see rough evaluation of signal quality.

3.2 Resonator

Second important component in measurement setup is resonator. It is built from plastic tube which serves as skeleton for several layers of aluminium foil. Length is around 17cm, which makes it a quater-wavelength resonator. The purpose of this device is directing and cleaning the signal from some of environmental noise. Effects of resonator can be seen in figure (8).

3.3 Passive resonant chamber (Thing)

After determining the range of Transmitter-Resonator-Receiver setup, final step is inserting the listening device on the edge of the range, so that only signal from the Thing can reach receiver post. The Thing is actually a passive resonant chamber, which means that standing waves are formed inside tiny aluminium cylinder when it is illuminated with electromagnetic (EM) radiation of correct frequency. Oscillation of EM field is transferred to antenna via capacitor and transmitted further in space. Usually, resonant chamber is closed from all sides, but one detail that makes Theremin's resonant chamber a listening device is that one wall is replaced with thin metal foil. That membrane is movable and slightly changes the resonating frequency of the chamber when struck by sound waves. Chamber now emits

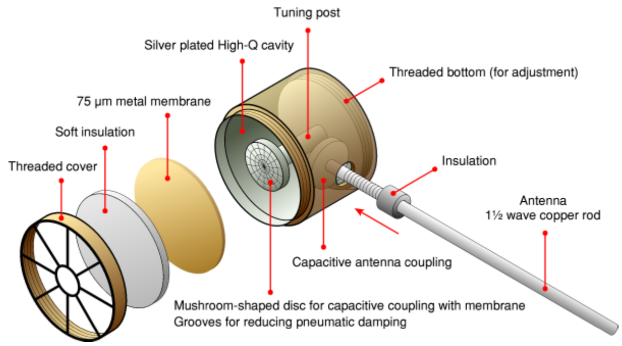

Figure 5: The structure of Theremin's listening device.

EM waves modulated by incoming speech. We built Theremin's listening device folowing specifications from [7], but dimensions where modified according to frequency we used. Scheme of the bug can be seen in figure (5), and the version we build is shown in figure (6).

4 Measurement and results

Measurements where conducted in course of several days in a local park in Požega. After finding the best placement for our setup that minimises wave interference and background noises, we discussed potential sources of background signals and went on to determine the effects of resonator on signal strength and quality (results of which can be seen in figure (8)).

Next step was determining the range of Transmitter-Resonator-Receiver setup. Due to weather conditions, these numbers would change almost on hourly basis, so once the range was determined, other measurement had to follow quickly afterwards. Learning how different parameters (clear line of sight, humidity of air and soil, RF post distance from ground, direction of transmitter, direction of transmitter+resonator,...) affect our results took few days, before final measurements took place. In the final measurements, signal was excellent first 25m, then signal shape stared to degrade. At distance of 40m only background signal was received (figure (9)).

After insertion of listening device in the middle, we got signal at 40m (figure (10)), but shape was distorted (even when no loud sound was reaching the bug). Some adaptation in position of the bug (bringing it closer or further away from the transmitter) affected the received signals, but as our time run out, we have no conclusive results about effect of bug's placement in relation to transmitting and listening post on quality of received signals.

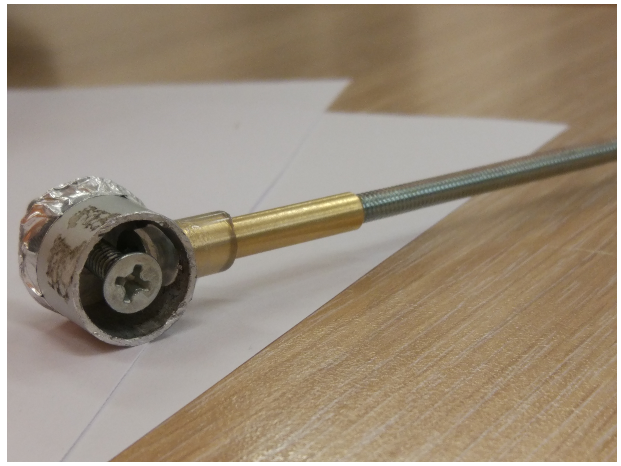

Figure 6: Listening device based on resonant chamber with movable membrane (the Thing) we built and tested during this project.

5 Discussion

Without getting clean signal from the bug in low sound-noise environment we could not test whether our bug works or not. However, it is possible that adhesive aluminium foil we used is too thick and rigid to serve as a movable membrane and distortions in signal simply come from dents and bumps made from everyday transport wear. Regardlessly, we proved that the chamber we built resonates at 433MHz and emits EM waves further in space, thus reaching the receiver post that was originaly out of range for a simple Transmitter-Resonator-Receiver setup. Transmitter-Resonator-Resonant chamber (Thing)-Receiver setup invites for further investigation, as many fascinating effects are, for the lack of time, still left just beyond reach of this project.

6 Conclusion

In this project we learned the physics behind wave phenomena. We studied different kinds of waves, starting from mechanical ones, due to their simplicity and everyday presence. Electromagnetic waves were another kind we studied in detail, along with resonators and resonant chambers that can be used for „catching“ waves. We discussed how current responds to outside electromagnetic wave in the antenna. After building Theremin's bug, we studied process of modulation which describes how electromagnetic waves can carry information. We spent few days in a local park trying to find the best location with lowest background noise and conducting countless test to determine what parameters affect our signals and how. On final day of measurement, we determined the range of Transmitter-Resonator-Receiver setup. Moving the receiver just out of range, Thing was added in the middle and signal was received again, thus proving that chamber resonates at used frequency. Due to lack of time, we could not conclusively prove whether resonant chamber truly picks up sounds from environment.

7 References

[1] Frank S. Crawford Jr., Waves Berkeley Physics course Vol 3, McGraw-Hill, 1968 [2] V. K Mehta, Principles Of Electronics, S. Chand Publishing, 2016 [3] Hugh Young and Roger Freedman, University Physics, Mark Zemansky and Francis Sears, 2007
[4]Physics classroom: Waves
[5]Resonance chamber
[6]433MHz RF transmitter and receiver
[7]CryptoMuseum: Great Seal Bug

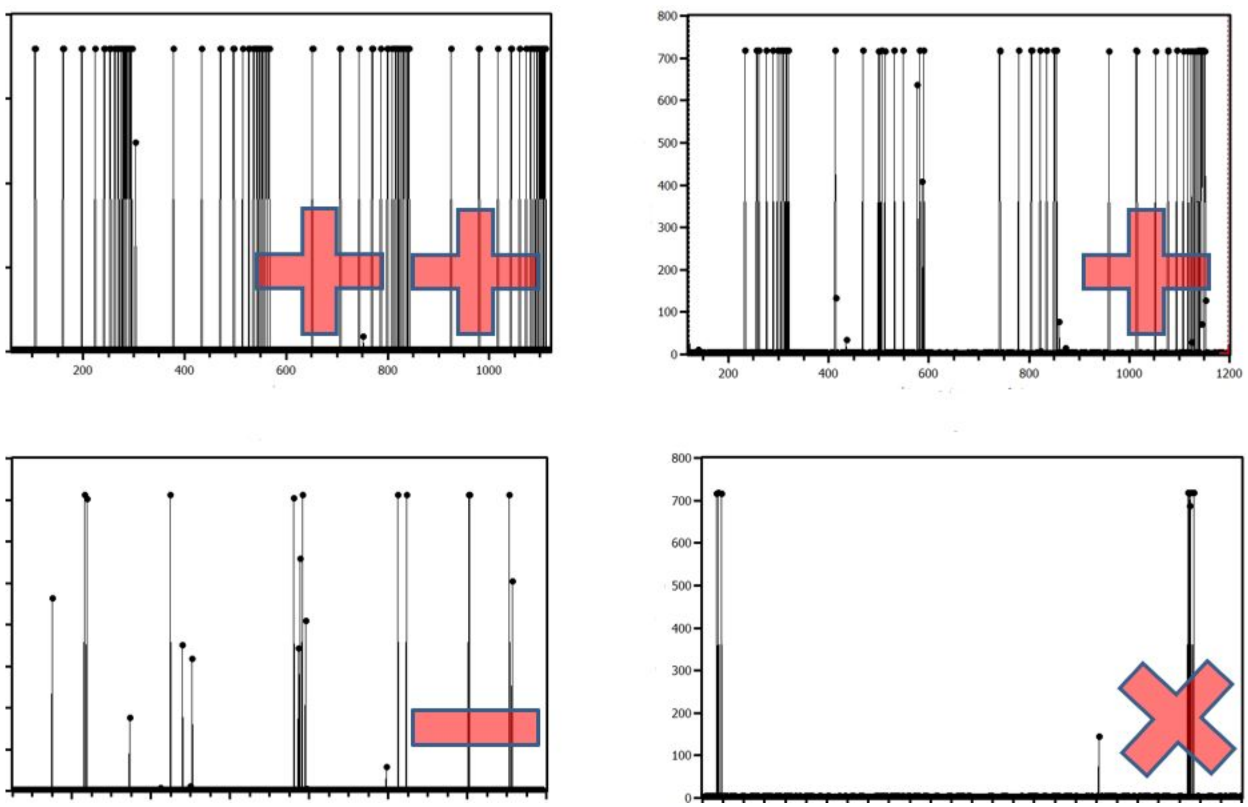

Figure 7: Rough evaluation chart for received signals.

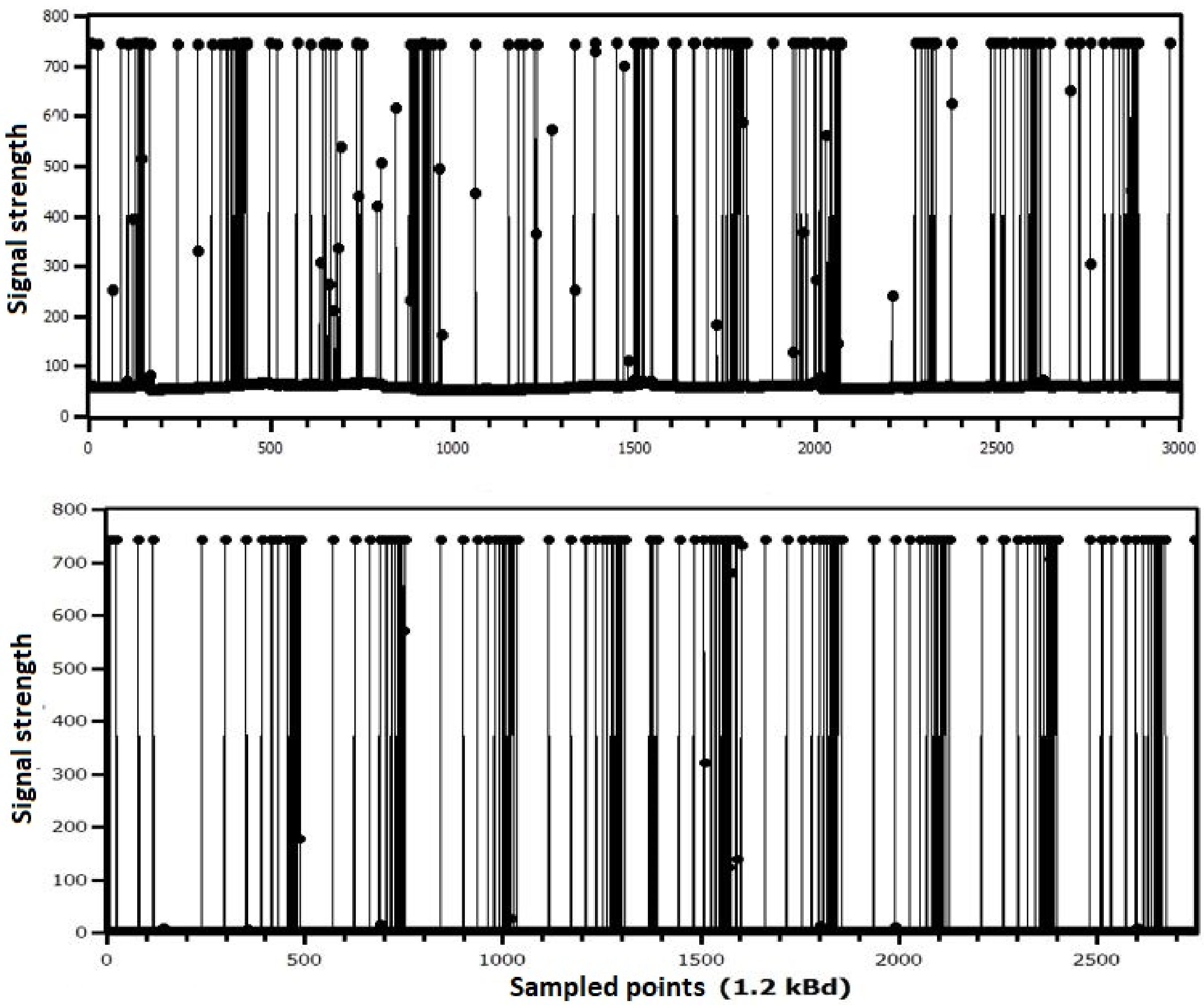

Figure 8: Effects of resonator on signal shape. Upper graph shows received signal without resonator. Improvements with inclusion of resonator can easily be seen in lower graph.

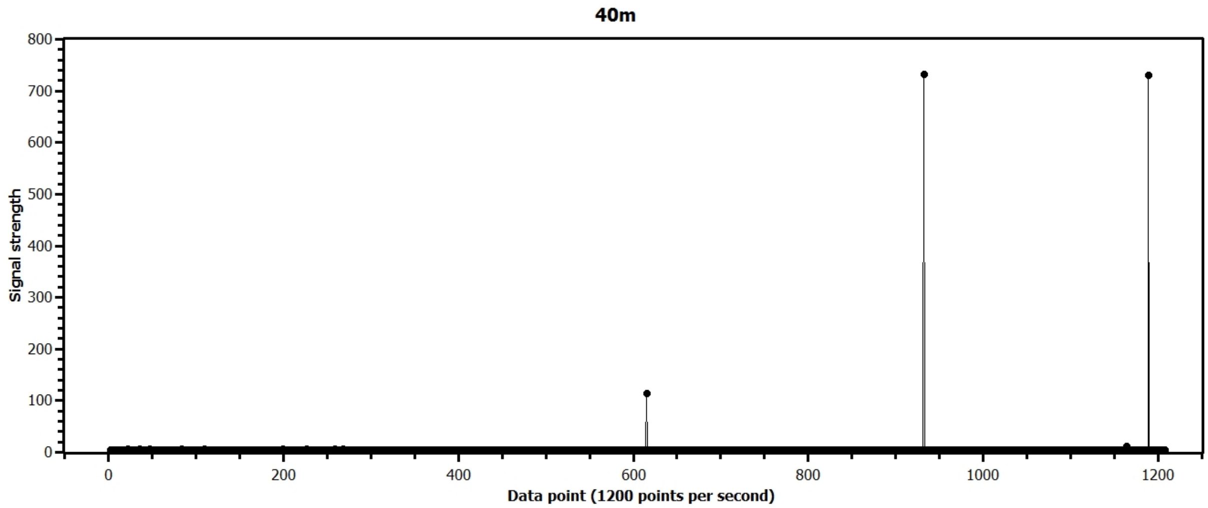

Figure 9: Test of the listening device. Received signal at 40m, without the listening device, corresponds to background noise.

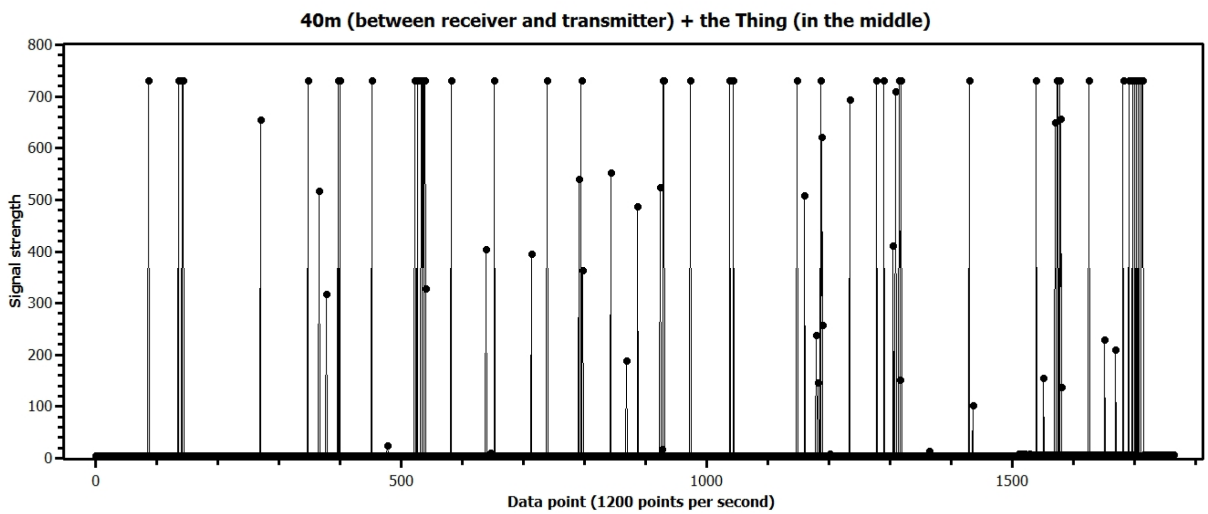

Figure 10: Test of the listening device. Received signal at 40m, when listening device is inserted at 20m from transmitter. Some of the transmitted signal is received, but signal shape is distorted.