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Study of ultrasonic transmissions

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1. Introduction

As radio amateurs, one of our goals is to experiment with the possibilities of transmitting information from one location to another, regardless of the technological form this transmission may take. Indeed, this can be achieved by the following means (non-exhaustive list):

- electromagnetic radio waves: from ELF (3 to 30 Hz) to EHF (30 to 300 GHz),
- laser signals,
- magnetic field alone (for underground transmissions),
- electric field alone (for localized transmissions, as the electric field is strongly attenuated by matter, unlike the magnetic field),
- Internet (with or without DSTAR repeaters or other means),
- via repeaters, satellites, or the Moon, etc.

In this article, I propose a "new" means of communication: ultrasound. In fact, it's nothing new, as it's commonly used for applications such as gate remote controls. That said, even though this type of transmission certainly won't allow for DX, nothing (except your dog, who might find these tests unpleasant) prevents us from testing this type of transmission and providing clues for other experiments.

Remember that ultrasound is an acoustic wave with a spectrum between 20 kHz and 10 MHz and is inaudible to the human ear.

By comparison, the useful acoustic spectrum for a conversation is between approximately 200 and 3000 Hz.

A very simple experiment is proposed, with traditional electronic functions implemented digitally using software.

Before describing the experiment in §3, a description of the generation of these waves and some of the laws related to acoustic wave propagation will be provided in §2. This will provide a starting point for other possible experiments.

The devices used by the author in this article are as follows: an HF voltmeter, an HF generator for 21 kHz, and a frequency meter.

Notations

In the following text:

- "Ultrasound" can be replaced by "US" for simplicity.
- The simple product is denoted " * " or " . " » or « x ».
- Powers of 10 are denoted Ex or 10^x (for example, 10^{-7} or E-7).
- The power of a variable is denoted ^ or with the exponent (x^2 or x^2 , for example),
- The square root is denoted \sqrt{x} rather than $x^{0.5}$ or $x^{0.5}$.
- « Pa » refers to the pressure unit « Pascal » equal to 10^{-5} bar.

2. Study of ultrasonic waves

2.1 History and General Information

Ultrasonic waves were discovered at the end of the 19th century by Francis Galton.

In 1915, Paul Langevin created the first ultrasonic generator ("US") using a triplet of piezoelectric ceramics held between two metal parts. These have the property of mechanically deforming when subjected to a sinusoidal electric current which frequency corresponds to the mechanical resonance frequency of the ceramics. The mechanical sinusoidal displacement is in the order of a few microns to 20 microns peak-to-peak. This displacement can then be amplified by mechanical devices ("booster" or "sonotrode").

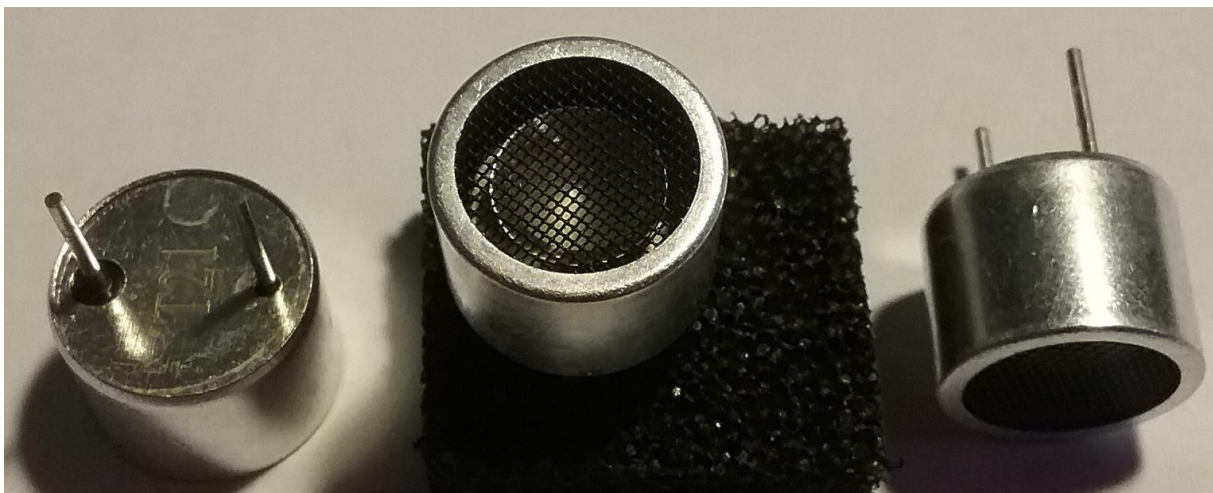
An application that will soon be made is the (discreet) detection of ships: we send a salvo of ultrasounds (little absorbed by water) which, if reflected by a ship, will be detected by a dedicated receiver (SONAR).

2.2 US transmitters and receivers

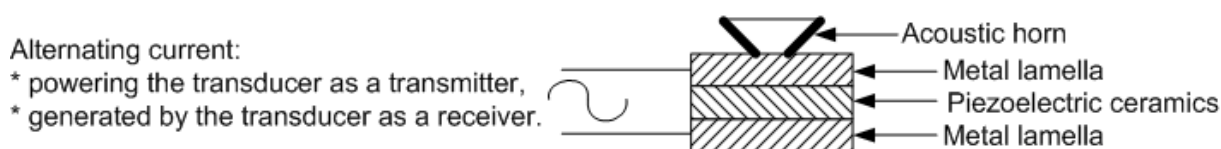
These devices are called piezoelectric "transducers" because they convert electrical energy into mechanical energy and vice versa.

In transmitting, the goal is to achieve the best possible efficiency and a high sound level, while in receiving, the aim is to increase the received signal level and the signal-to-noise ratio.

Below are photos of some transducers. Note that externally, the transmitting transducers (marked with an engraved "T") are very similar to the receiving transducers (marked with an engraved "R").



A schematic diagram of these transducers is given below:



In the common "open" structure (above), the piezoelectric ceramic layer is attached (via the metal lamella) to a sort of small acoustic horn that allows the high acoustic impedance (see below) of the ceramics to be matched to the low impedance of the ambient air, with a ratio of almost 100,000 between the two impedances. This is a problem similar to that of matching components in electronics. Another example: out of the water, it is very difficult to be heard by someone in the water because the impedances of air and water are very different (most of the acoustic waves will be reflected by the water's surface).

Note that these impedance breaks give rise to reflected waves with coefficients similar to those found in electromagnetism.

Regarding the general operation of the transducers:

- In reception, the acoustic pressure received through the ambient air, via the acoustic horn, is transformed into mechanical stress in the ceramics, which generate electrical charges at the electrical output, which is seen as a capacitor.
- In transmission, the electrical voltage at the transducer input (seen as a capacitor) generates mechanical deformation of the ceramics, which is transformed into acoustic pressure applied to the ambient air, via the acoustic horn.

This acoustic horn not only adapts the acoustic impedances of the two media (ceramic/air) but also focuses the generated US within a specific solid angle (similar to antennas). Thus, a directivity angle is defined in the transducer characteristics.

Note that piezoelectric ceramic behaves like a quartz. It is therefore equivalent to a series RLC circuit, and to R only at resonance.

As such, the characteristics (sound pressure generated at the transmitter and sensitivity at the receiver) degrade rapidly outside the resonant frequency. These transducers must therefore be used at their nominal frequency.

2.3 Operation of a US transmitter

The operation of a US transducer in transmission mode is described below. The reception mode will not be described because it is symmetrical to the transmission mode. For simplicity, phase shifts are ignored.

The transducer is powered by an alternating voltage U at the nominal operating frequency f_0 (often 40 kHz), i.e. $U (V) = U_0 \cdot \sin(2 \cdot \pi \cdot f_0 \cdot t)$. This voltage is applied to the metal plates across the ceramic terminals, the assembly forming a capacitor since ceramics are dielectric. An electric field E will then form through the dielectrics: $E (V/m) = E_0 \cdot \sin(2 \cdot \pi \cdot f_0 \cdot t)$.

Due to the piezoelectric properties of ceramics, under the effect of the electric field, they will produce a mechanical deformation ϵ (m) = $\epsilon_0 \cdot \sin(2 \cdot \pi \cdot f_0)$, which amplitude will also depend on the Young's modulus of the ceramics (modulus relative to their compressibility). We will ignore the acoustic horn and assume that the upper metal lamella is in contact with the air.

The air in contact with this lamella will be subjected to compression/expansion due to the periodic mechanical deformation of the ceramics.

These pressure variations (in Pa) around atmospheric pressure form what is called the acoustic pressure p . It will be denoted as: p (Pa) = $p_0 \cdot \sin(2 \cdot \pi \cdot f_0)$,

These pressure variations will generate variations in the speed of the air particles V (m/s) = $V_0 \cdot \sin(2 \cdot \pi \cdot f_0)$, with $V_0 = p_0 / Z_{ac}$, Z_{ac} being the acoustic impedance.

V is called "acoustic velocity."

A word about acoustic impedance Z_{ac} (in kg/(m²·s)). It corresponds to the resistance of the medium (ceramic or air) to the passage of the acoustic wave. Remember that, generally speaking, an impedance is a "cause/effect" relationship, such as " $Z = U/I$ " for example. Z_{ac} is defined by the formula: $Z_{ac} = p/V$, where p (in Pa) is the acoustic pressure and V (in m/s) is the velocity (called "acoustic") of the particle associated with the medium. Like pressure, Z_{ac} is an intensive quantity (which depends neither on mass nor size). Z_{ac} can also be defined as $Z_{ac} = \rho \cdot c$, where ρ is the density of the medium (kg/m³) and c is the velocity (the speed of propagation of sound waves in the medium). The velocity is approximately 330 m/s in air.

These pressure variations will be propagated gradually at the sound speed (or velocity). The human ear is sensitive to these pressure variations when they are not US. Note that the pain threshold is 20 Pa (in effective value) and that the reference pressure is 20 μ Pa, a value which corresponds to the threshold of perception of a sound.

For more details, see the documents in references [\[1\]](#), [\[2\]](#), and [\[3\]](#) and, of course, Wikipedia for keywords such as "Acoustic Impedance", "Velocity", etc.

2.4 Laws related to acoustic wave propagation

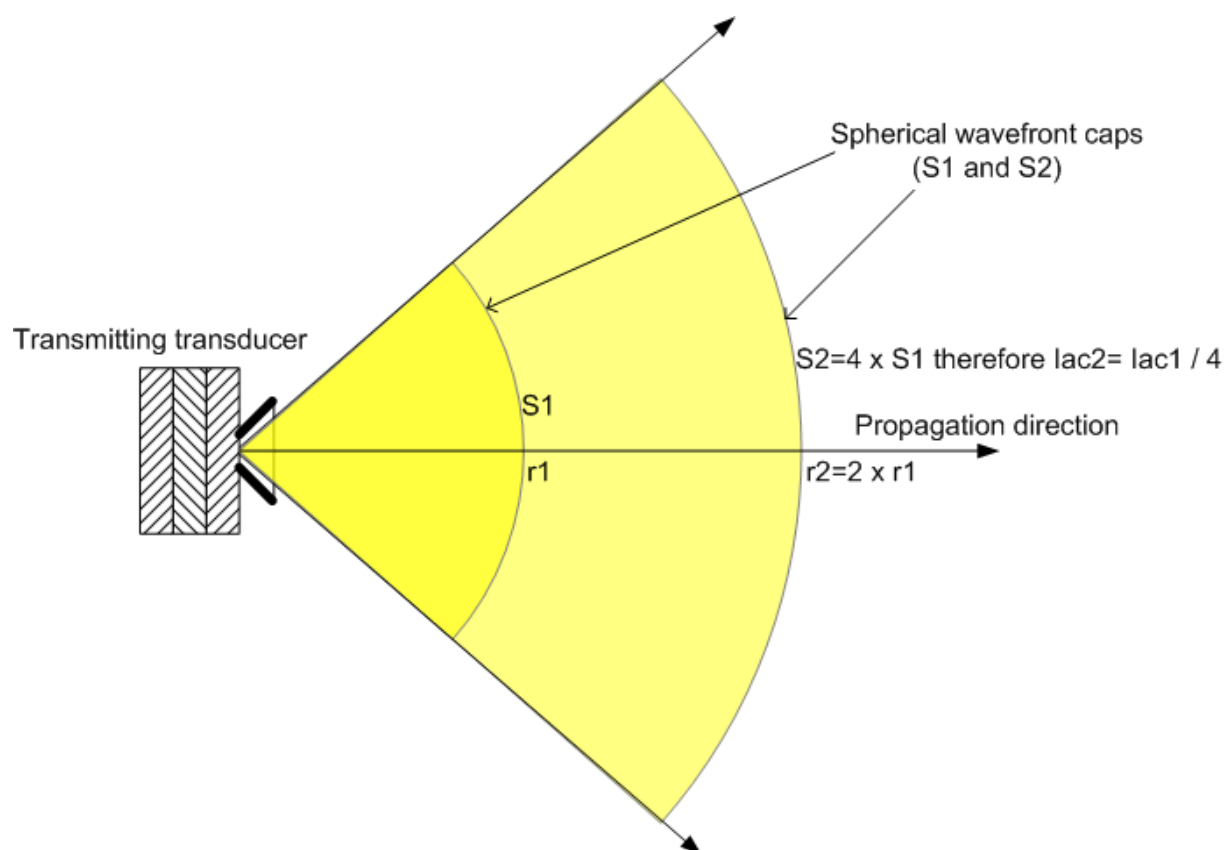
US acoustic waves obey a number of laws.

Let us define:

- Acoustic power P_{ac} , with $P_{ac} = p \cdot S \cdot V$, where p is the acoustic pressure (in Pa), S is the wavefront area (in m²), and V is the acoustic speed (in m/s). Note that $p \cdot S$ is a force (in N).
- Acoustic intensity I_{ac} , with $I_{ac} = p \cdot V$. This is therefore the acoustic power per unit area. Since $V = p / Z_{ac}$, it follows that $I_{ac} = p^2 / Z_{ac}$. Note that, consequently, $P_{ac} = p^2 \times S / Z_{ac}$. As the acoustic power is (ideally) linear with the electrical power P_{elec} feeding the transmitter with $P_{elec} = U^2 / Z_{input}$, it follows that p and U are proportional and evolve in the same way.

Regarding the propagation of acoustic waves from the transducer, it must be considered that it is a point source and that the waves will propagate at the same speed in all directions within the solid scattering angle. The wavefronts will then be spherical caps.

It is assumed that there is no absorption of acoustic energy by the atmosphere, therefore the overall acoustic power received at a wavefront remains constant regardless of the distance from the source. In this case, the decay in acoustic intensity will be in r^2 , where r is the distance from the source. For example, for a doubling of the distance from the source ($r_2 = 2 \times r_1$), the intensity I_{ac} will be reduced by a factor of 4 because the surface area of the spherical cap will be multiplied by 4 ($S_2 = 4 \times S_1$), as indicated in the diagram below.



If we express the acoustic intensity in dB, we see that doubling the distance will cause a 6 dB attenuation of the acoustic intensity (division by 4) and that a distance 10 times greater will therefore cause a 20 dB attenuation (division by 100).

Note: since $I_{ac} = p^2 / Z_{ac}$, the attenuation of the acoustic pressure is equal to the square root of the attenuation of the acoustic intensity. It is therefore proportional to r . For example, for a doubling of the distance r , the acoustic pressure will be divided by 2.

All this would be quite simple if it weren't a phenomenon of wave absorption by the atmosphere. This attenuation is roughly proportional to the distance from the source and to the square of the frequency used, so very high-frequency sound waves can only be used at very short distances. For example, at 10 m, the attenuation of the acoustic intensity at 20 KHz is negligible but it is approximately 7 dB at 80 KHz (see reference [2]).

A link budget is difficult to perform for our OM links. Indeed, the specifications provide:

- the sound pressure at 30 cm if the transducer is powered with an AC voltage of 10 V rms. This is a value in dB referenced to 0 dB at 20 μ Pa,
- the transducer sensitivity. This is a value in dB referenced to 0 dB at 10 V/Pa. The raw sensitivity value is therefore in V/Pa. This value is not sufficient because we do not have a signal-to-noise ratio to which we could compare the minimum signal-to-noise ratio for the transmission mode used. This value is more appropriate for a voltage threshold receiver (on-off).

Let's take an example, assuming that the voltage threshold receiver must detect a minimum voltage of 1 mV rms to close a circuit. We assume that the transmitting transducer is powered with a voltage of 5 V rms.

Assume that the sound pressure generated at 30 cm is 120 dB (with 10 V rms). Since electrical power is proportional to the square of the voltage, the power delivered at 5 V rms will be 1/4 that delivered at 10 V rms (i.e. -6 dB). Assuming that the transducer is linear, the sound pressure ("p") will then be $120 - 6 = 114$ dB, or in Pascal: $p = 20 \times 10^{-6} \times 10^{(114/20)} = 10$ Pa (at 0.3 m from the source).

At a distance r from the source, taking into account attenuation, the sound pressure will be equal to: $p(r) = 10 \times (0.3/r)$ Pa (neglecting absorption).

Assume that the sensitivity S is -63 dB, or in V/Pa:
 $S = 10 \times 10^{(-63/20)} = 7.08 \times 10^{-3}$ V/Pa.

The voltage U(r) received at distance r will therefore be equal to: $U(r) = p(r) \times S$

The voltage threshold will be triggered if the voltage received at distance r is greater than 1 mV, or in other words, if $U(r) > 0.001$ V, or $10 \times (0.3/r) \times 7.08 \times 10^{-3} > 0.001$

The maximum reception distance r will be such that $U(r) = 0.001$ V, or

$$10 \times (0.3/r) \times 7.08 \times 10^{-3} = 0.001$$

This deduces that $r = 10 \times 0.3 \times 7.08 \times 10^{-3} / 0.001 = 21.1$ m

3. The US link

3.1 Principle

The proposal is to transmit US signals from a PC's sound card ("modulator"), in digital Ham mode, to the sound card of another PC used as a receiver ("demodulator").

Standard sound cards have a sampling rate of 48 kHz. Therefore, a spectrum from 0 to $48/2 = 24$ kHz (Nyquist frequency) can be used. The standard frequency of US transducers is 40 kHz, which is incompatible with the bandwidth of standard sound cards.

Note: 96 kHz (or higher) sound cards exist, but they are expensive.

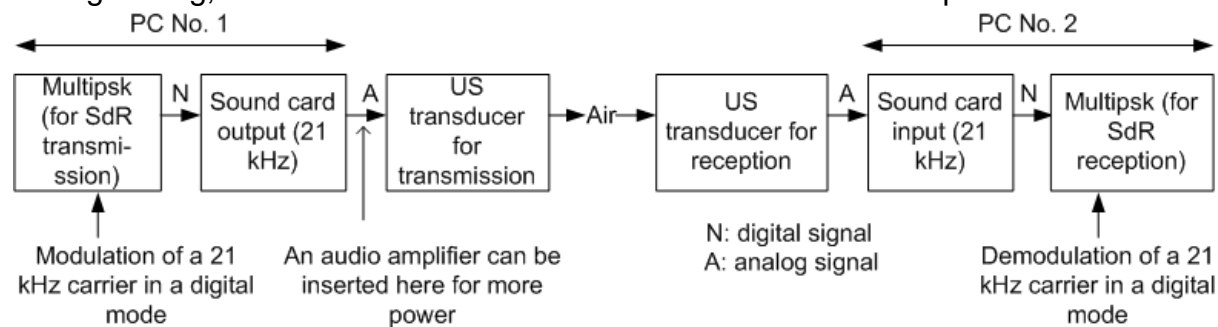
However, 21 kHz US transducers, compatible with standard sound cards, can be found on the Chinese market. For example, type "16mm ultrasonic probe sensor transceiver 21 kHz" into your favorite search engine (with the repetition...).

To modulate and demodulate the 21 kHz transmission, we will use the SdR component of Multipsk.

3.2 US link diagram and photo

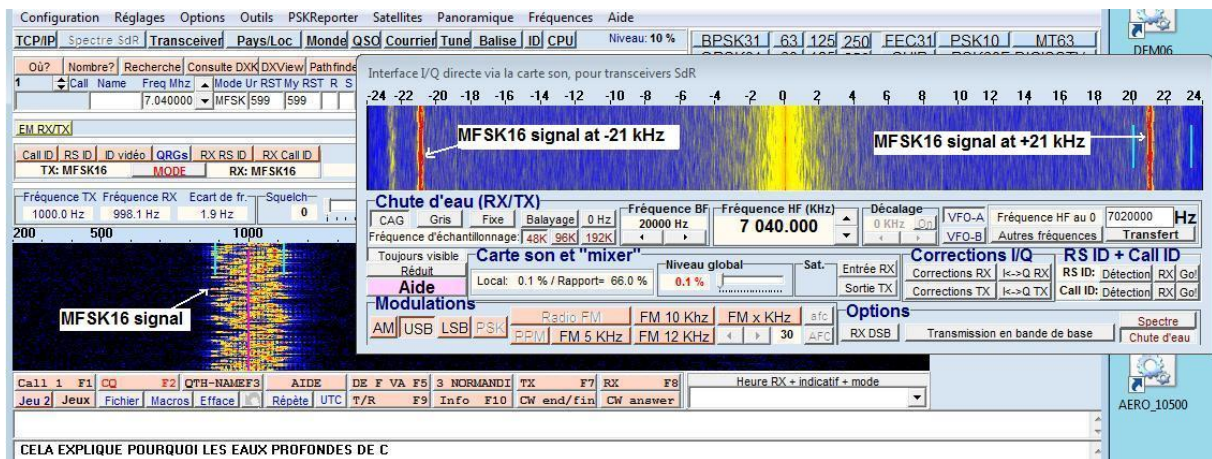
The schematic diagram of this US link is shown below.

During testing, the link will be tested with and without an audio amplifier.



Note: Multipsk is used in its SdR interface function, but obviously only one output (I or Q) is used here.

Similarly, there is only one input on the sound card. We will therefore see 2 signals on the SdR spectrum, one at -21 KHz and the other at +21 KHz, as shown below for a signal transmitted in MFSK16 mode.



Indeed, a real signal corresponds to two opposite frequencies, as explained below.

The amplitude of a real signal can be expressed in the form $A = \cos(\omega_1 t)$, with ω_1 being the radial frequency, equal to $2\pi f_1$. We can therefore write:

$$A = (\cos(\omega_1 t) + i \sin(\omega_1 t)) + (\cos(\omega_1 t) - i \sin(\omega_1 t)) / 2, \text{ or}$$

$$A = (\exp(i \omega_1 t) + \exp(-i \omega_1 t)) / 2,$$

which corresponds to two vectors, one rotating at radial frequency ω_1 and the other at radial frequency $-\omega_1$, in opposite directions. Their moduli are therefore represented by the spectrum:

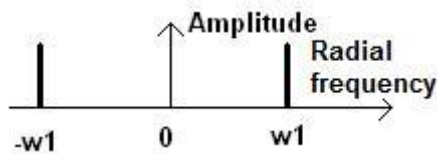
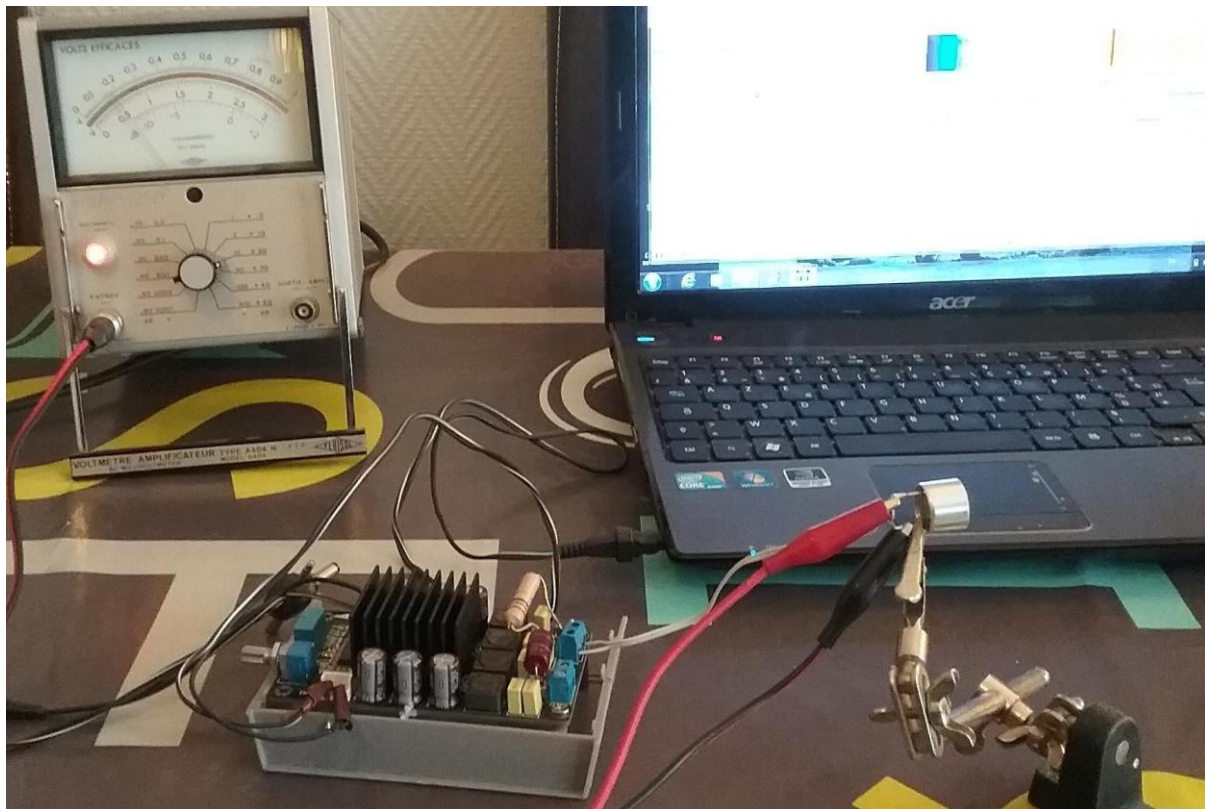


Photo of the transmitter section (with amplifier)

Top left, we see the RF voltmeter measuring the voltage across the transducer terminals, and bottom left, the amplifier connected to the PC's sound card output and, moreover, the transducer.



3.3 Some hardware details

Sound Cards

I measured the 21 kHz AC voltage delivered by the sound cards installed in several PCs. On average, the effective voltage is approximately 0.5 V. However, on one PC (such as a Windows 10 hybrid tablet), I found 0.02 V, which is low, but on another PC, I found 1.1 V.

Note that I also tested an audio amplifier powered by the sound card output. At maximum output, it delivers 9.8 V.

Transducer (open type)

The supplier specifications are as follows:

- The sound pressure level at 10 V is 115 dB.
- The sensitivity is -68 dB.
- The capacitance "at 1 kHz and < 1 V" is 2400 pF.

Note: using a generator and an RF voltmeter, I took some measurements to determine the input (electric) impedance of the transmitting transducer at 21 kHz. The value varies enormously from one transducer to another.

This impedance can be estimated at approximately 1600 ohms +/- 800. Therefore, even at 10 V rms, the power consumption remains low: $10 \times 10 / 1600 = 0.06 \text{ W}$.

3.4 Tests performed

The principle is to transmit a text in digital mode via the transmitting US transducer and to receive it on the other PC via the receiving US transducer.

Multipsk is configured as an SDR interface ("Direct via sound card" button on the first screen). For the SDR spectrum, we set it to 20 kHz, in USB, and for the AF spectrum, it is set to 1 kHz (we will therefore transmit and receive at 21 kHz).

We add gain (+20 dB) to the microphone amplifier of the receiving PC to receive a minimum signal level.

Without Amplifier

We power the US transmitter with the sound card, which delivers a maximum voltage of 0.85 V rms for this PC. The maximum distance achieved in PSK10 (very sensitive mode), without error, is 1.27 m.

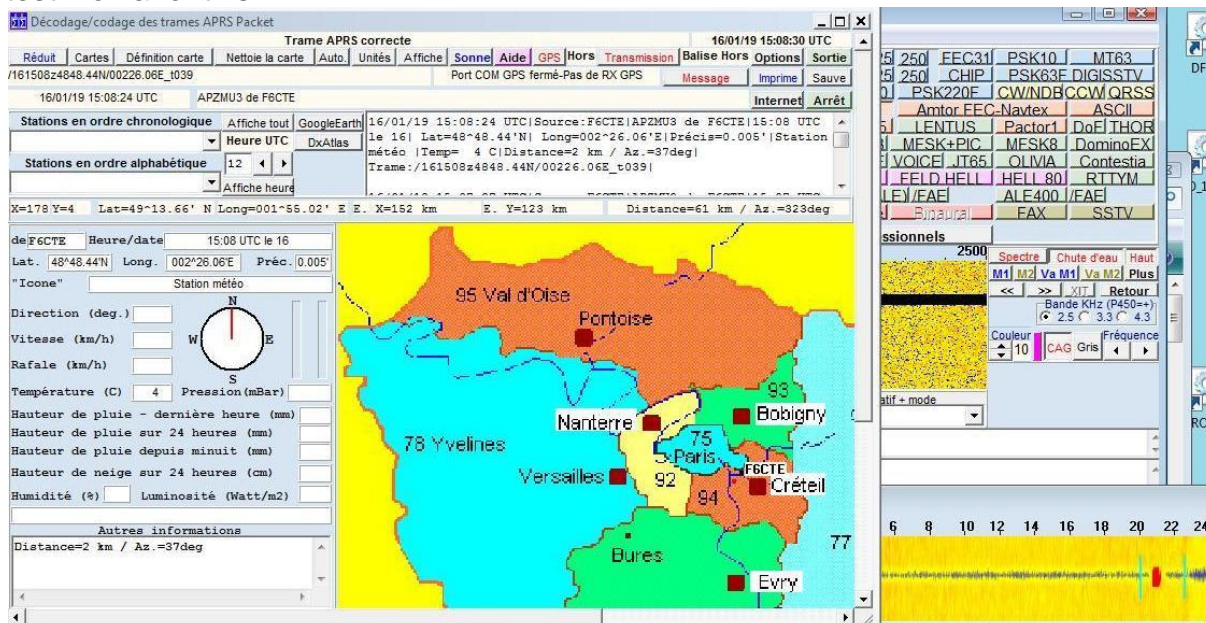
We can deduce that the maximum distance, in PSK10, would be at 10 V rms, equal to: $1.27 \times 10 / 0.85 = 14.9$ m.

With Amplifier

We power the US transmitter with the output of an audio amplifier, itself powered by the sound card (see previous photo). We separate the RX/TX transducers by 4.1 m and determine the minimum voltage required to ensure transmission. We find 2.8 V rms in PSK10 and 6 V rms in BPSK31. We can deduce that the maximum distance would be:

- in PSK10 at 10 V rms, $4.1 \times 10 / 2.8 = \underline{14.6 \text{ m}}$, which confirms the previous result,
- in BPSK31 at 10 V rms, $4.1 \times 10 / 6 = 6.8$ m.

I performed a final test using APRS at 300 baud (APRS at 1200 baud did not seem to be able to transmit due to the excessive bandwidth). By setting the amplifier to its maximum level (9.8 V eff.), I obtained a maximum distance of 1.45 m (☺). Below, a testimonial of this DX!



Note the APRS frame (thick, short red line) to the right of the SdR spectrum.

4. Conclusion

In principle, this type of transmission is only useful indoors or outdoors for short distances. Transmissions should not have a too wide bandwidth (say, 1 kHz maximum). However, given the low power consumption of transducers, there's nothing to prevent them from powering several, each focused in a specific direction. Aside from curiosity, the benefit of this type of transmission for Hams is limited.

References

[1] http://anso.pagesperso-orange.fr/corps_le_son_physique.htm

This document does seem no more available on the Web.

[2] https://www.ee.columbia.edu/~kinget/EE6350_S14/DM6350_web/files/murata.pdf

[3] Thèse « Conception et modélisation d'un capteur acoustique » by Slimani Abdoun (available on the Net)