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MODELING A TURBULENT ATMOSPHERE AS A DYNAMIC CHANNEL FOR NARROW-BAND ULTRASONIC SIGNALS

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ABSTRACT
This work proposes a semi-empiric model for a turbulent atmosphere as a dynamic channel of transmission of narrow-band ultrasonic signals. It is based on a theoretical expression for the coherence time derived in a previous paper, and on the results obtained from the experimental analysis of propagation of a 50 kHz ultrasonic tone under different turbulence conditions. The model is used to predict the effects of a turbulent atmosphere on the propagation of binary encoded signals and their consequent detection by matched filtering. These predictions are compared with the results obtained with a real pulse compression system operating outdoors.

INTRODUCTION
High-precision applications of airborne ultrasonic sensory systems are usually restricted to indoor environments. There are only few works that propose the use of ultrasonic sensors outdoors, and these sensors are usually part of a more complex sensory system where they have been assigned low-precision tasks, such as the detection of very close obstacles with which there exists a real risk of collision [1], or the coarse ranging of large navigation landmarks [2]. This situation is mainly due to the large influence that meteorological phenomena have on the propagation of these mechanical waves, being atmospheric turbulence the most problematic of these phenomena due to its intrinsic random nature.

When an acoustic wave propagates through a turbulent region, it encounters a variety of eddies with different sizes, velocities and temperatures. Each one of these eddies acts as a strong scatterer of acoustic energy and their combined effect alters the initial coherence of the wavefronts, which will no longer be spherical and with identical amplitude after crossing the turbulent region. A receiver placed at a certain distance from the emitter will record random fluctuations in the amplitude and phase of the acquired signals. Clearly, the measurements provided by a classical system, based on threshold detection of the signal envelope, are extremely sensitive to the conditions of operation. This problem can be overcome by encoding the signal and introducing pulse compression techniques that have been already used with success in the design of high-performance indoor sonars [3][4]. Nevertheless, the use of these signals outdoors entails a new challenge since, depending on how much their shape is modified by turbulence, they could not be properly recovered by matched filtering.

In a recent work [5], the authors have derived a theoretical expression for the time during which the characteristics of an acoustic wave propagating through a turbulent region remain essentially invariant. This so-called *coherence time* t_c is given by:

$$t_c = \frac{1}{v_n \cdot \left(0.545 k^2 C_n^2 r\right)^{3/5}} \qquad \text{(Eq. 1)}$$

where v_n is the transversal component of the wind; k is the wavenumber; r is the propagation distance; and C_n^2 is the structure parameter of the refractive index, which is a measure of the turbulence strength. In the same work, it is shown that this theoretical time is closely related to the empirical *Doppler coherence time* $t_{c,d}$, that can be obtained as the reciprocal of the spectral spreading undergone by a pure tone that is continuously emitted in a turbulent atmosphere for a long enough period:

$$t_{c,d} = \frac{1}{B_d} \qquad \text{(Eq. 2)}$$

being B_d the width of this spreading.

EXPERIMENTAL MEASUREMENT OF AMPLITUDE AND PHASE FLUCTUATIONS: MODEL FOR A TURBULENT ATMOSPHERE

With the aim of gaining a better understanding of the effects that atmospheric turbulence has on the propagation of ultrasonic signals, an exhaustive analysis of the amplitude and phase fluctuations undergone by a 50 kHz tone continuously emitted under different turbulence conditions have been performed.

This analysis has been carried out by splitting the received signal in segments of 16 samples, corresponding to one cycle of a 50 kHz tone sampled at a rate of 800 kHz. Amplitude fluctuations were studied by calculating the energy of the samples contained in every segment. To analyze phase fluctuations, a set of 16 pattern vectors were generated corresponding to the 16 identifiable phases obtained when sampling a 50 kHz tone at a rate of 800 kHz ($-\pi + k \cdot \pi / 8$ with k = 0, … ,15). The phase of the segment under analysis was chosen as the phase of the pattern vector whose Euclidean distance to this segment is minimum. Fig. 1 shows the amplitude and phase fluctuations registered outdoors under very strong turbulence conditions for one second.

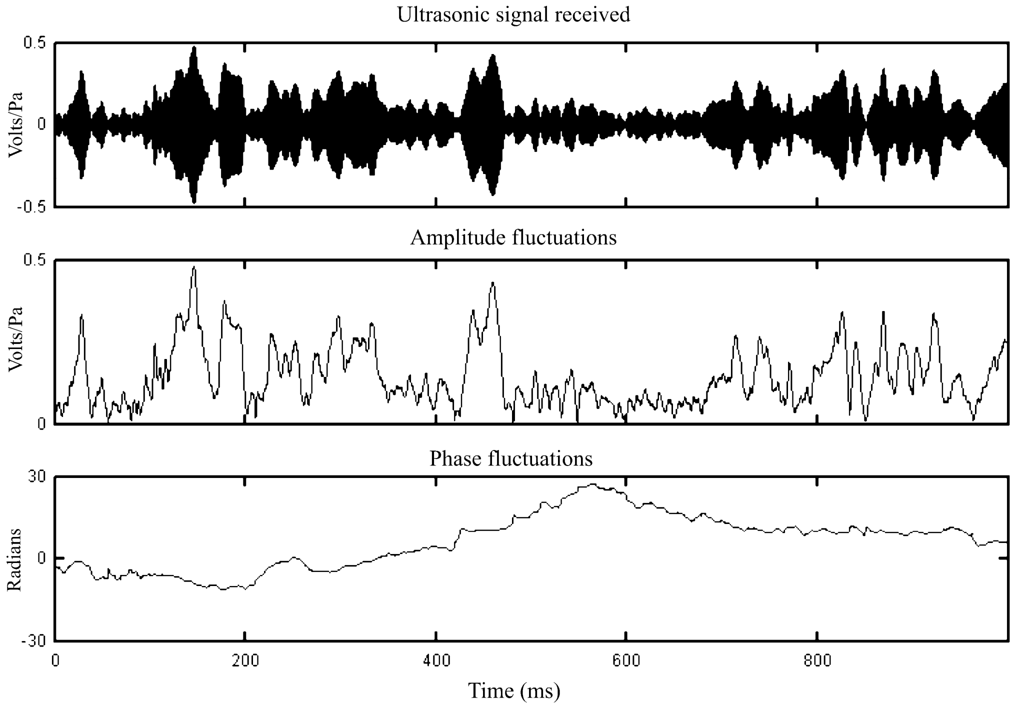


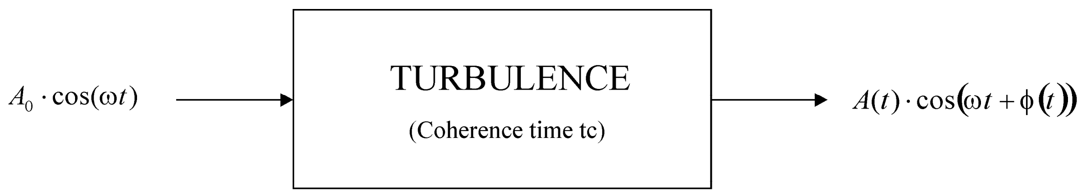
Figure 1.- Amplitude and phase fluctuations observed outdoors for a 50 kHz ultrasonic tone continuously emitted under very strong turbulence conditions.

After analyzing a total of 200 emissions, 2 seconds long each, it has been observed that, under strong and very strong turbulence conditions, phase ϕ fluctuations fit well to a uniform distribution, whereas amplitude *A* fluctuations do the same to a Weibull distribution as follows:

$$p(A) = \left(\frac{\beta}{A}\right) \cdot \left(\frac{A}{\eta}\right)^{\beta} \cdot \exp\left[-\left(\frac{A}{\eta}\right)^{\beta}\right] \qquad \text{(Eq. 3)}$$

where β and η are the shape and scale parameters of this distribution respectively. Values of β in the interval [1.3 - 3.1] have been measured, although this value is typically around 1.6. The scale parameter η is directly related to the expected amplitude in absence of turbulence A_0 as $\eta \approx A_0/2$. Under these strong turbulence conditions, the coherence time acquires a clear physical meaning as the time for which the rates of change of the amplitude and the phase are essentially constant.

All these results have led to the proposal of a semi-empiric model for a turbulent atmosphere as a dynamic channel where an ultrasonic tone can undergone, after a coherence time, any phase change between $-\pi$ and π radians with identical probability. Also, after this time the amplitude can take any positive value with a probability given by a Weibull distribution characterized by $\beta = 1.6$ and $\eta = A_0/2$. The model assumes that during a coherence time, both the amplitude and the phase vary linearly between two random values. Fig. 2 shows all the mathematical relations defining this model, and in Fig. 3 the amplitude and phase fluctuations predicted by this model can be seen for a coherence time of 10 ms (very strong turbulence conditions).



<u>Amplitude model</u>

$$A(t) = A_{\lfloor t/t_c \rfloor} + \left[A_{\lfloor t/t_c \rfloor + 1} - A_{\lfloor t/t_c \rfloor}\right]\left[\frac{t}{tc} - \lfloor t/t_c \rfloor\right]$$

With $A_i \geq 0$ following the distribution:

$$p(A_i) = \left(\frac{1.6}{A_i}\right) \cdot \left(\frac{2 \cdot A_i}{A_0}\right)^{1.6} \cdot e^{-\left(\frac{2 \cdot A_i}{A_0}\right)^{1.6}}$$

<u>Phase model</u>

$$\phi(t) = \sum_{i=0}^{\lfloor t/tc \rfloor} \Delta\varphi_i + \Delta\varphi_{\lfloor t/tc \rfloor + 1} \cdot \left[\frac{t}{tc} - \lfloor t/t_c \rfloor\right]$$

With $-\pi \leq \Delta\varphi_i < \pi$ following the distribution:

$$p(\Delta\varphi_i) = \frac{1}{2\pi}$$

$\lfloor t/tc \rfloor \longrightarrow$ Integer quotient of $\frac{t}{tc}$

Figure 2.- Proposed model for a turbulent atmosphere

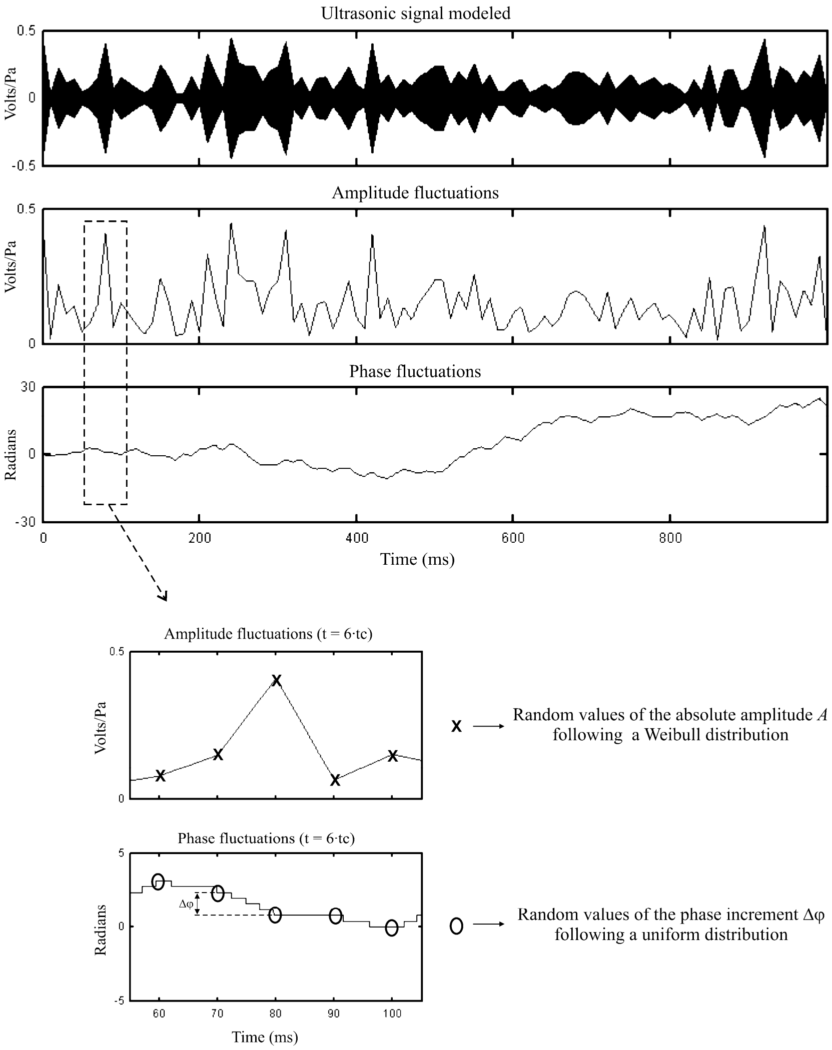


Figure 3.- Amplitude and phase fluctuations predicted by the model for a 50 kHz ultrasonic tone and a coherence time of 10 ms

The main virtue of this model is that it accurately predicts the spectral spreading of an ultrasonic carrier propagating under strong turbulence conditions. This prediction is shown in Fig. 4 for a 50 kHz tone and a coherence time of 10 ms.

MODEL PREDICTIONS FOR THE EMISSION OF ULTRASONIC ENCODED SIGNALS

The model presented in the previous section for the propagation of pure tones can be easily adapted to the propagation of modulated signals with a narrow bandwidth around the carrier frequency. In this case, the model assumes that the ratio between the real amplitude and the expected one follows the same Weibull distribution. Besides, after a coherence time the signal can undergone with identical probability any compression or expansion between zero and one half the carrier cycle. This is equivalent to assume that, as in the model for a pure tone, the carrier can undergone any phase change between $-\pi$ and π with identical probability, whereas the rest of spectral components experience a phase shift proportional to their frequency. Note that this model is only valid for narrow band signals, since it does not consider the dependence on frequency of the coherence time predicted by (Eq. 1).

This model has been used to study the effects of a turbulent atmosphere on the detection of ultrasonic encoded signals by matched filtering. Particularly, the performance of a real pulse compression system that employs the Polaroid series 600 transducer [6] to emit complementary sets of four sequences along a propagation distance of 14 meters has been analyzed. These sets are BPSK modulated with a symbol of two 50 kHz cycles, adapting the spectrum of the emissions to the 14 kHz effective bandwidth of the transducer. The detection of these signals is achieved by means of an efficient correlation stage that notably decreases the total number of operations to be carried out, thus allowing the real-time operation of the system. A detailed description of this system can be found in [5].

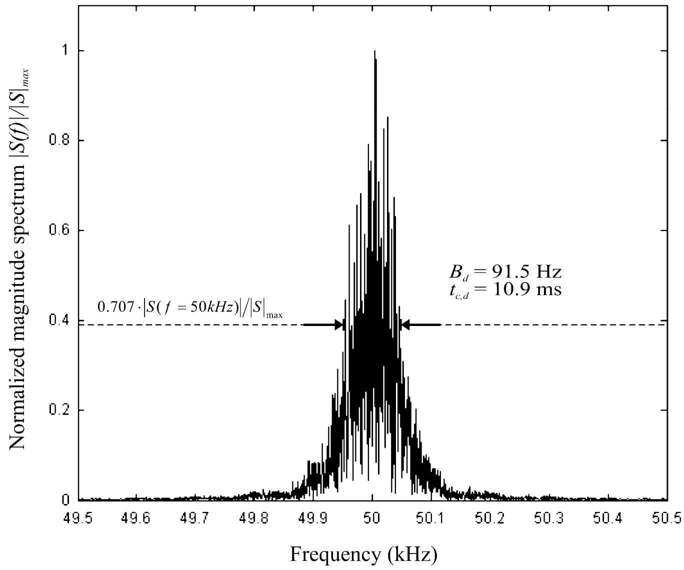


Figure 4.- Spectral spreading predicted by the model for a 50 kHz ultrasonic tone and a coherence time of 10 ms

Fig. 5 shows the results obtained when the model of a highly turbulent atmosphere (t_c = 10 ms) is applied to the continuous emission of sets of 64-bit sequences. The duration of each one of these sets – 10.24 ms – is similar to the coherence time, and therefore, all the sets should be detected and no strange phenomena should be observed. This is precisely the situation depicted in Fig. 5, where a correlation peak is obtained in the moment of arrival of every set. Fig. 6 shows the results predicted by the same model for the emission of sets of 256-bit sequences. In this case, when the duration of each emission – 40.96 ms – is clearly above the coherence time, the model predicts the appearance of spurious peaks in the detection process, a phenomenon that has been previously experimentally observed in [5].

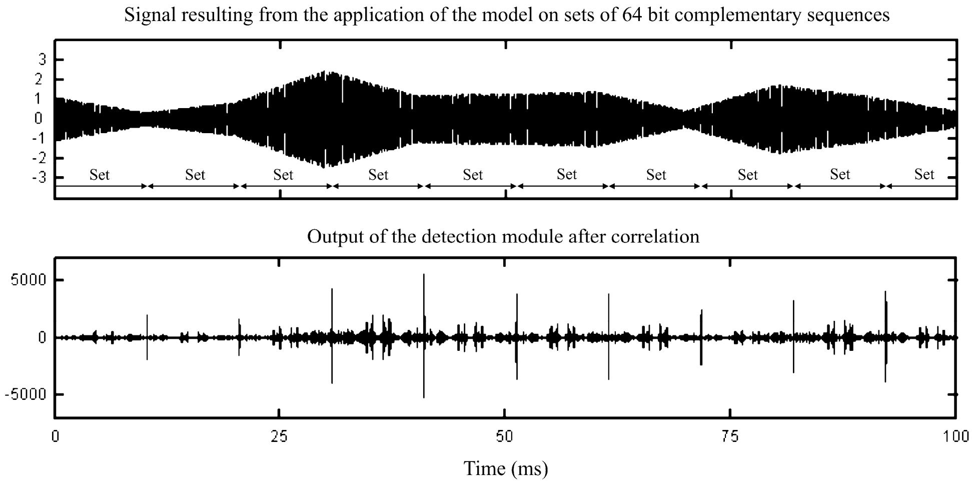


Figure 5.- Results obtained with the model for the continuous emission of sets of 64-bit sequences (10.24 ms) and a coherence time of 10 ms

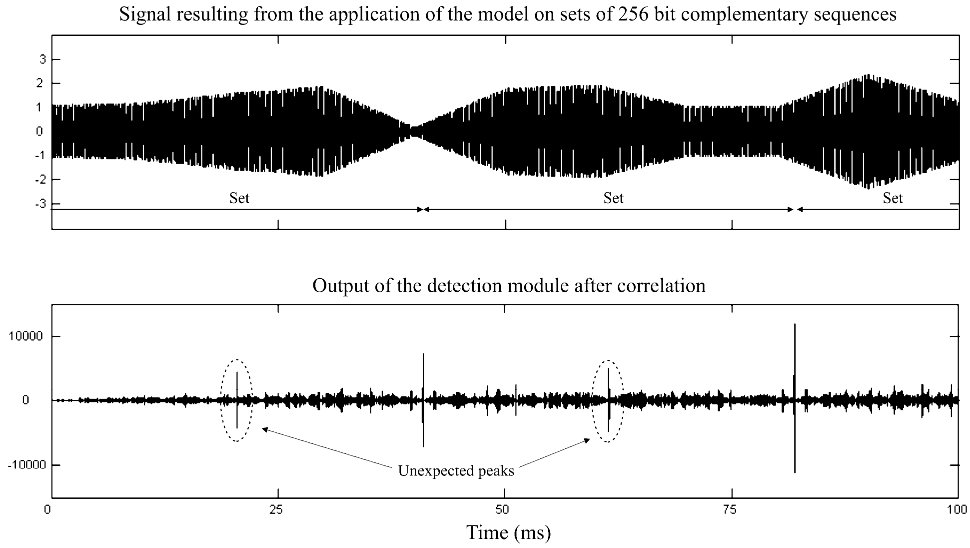


Figure 6.- Results obtained with the model for the continuous emission of sets of 256-bit sequences (40.96 ms) and a coherence time of 10 ms

CONCLUSIONS

This work has presented a semi-empiric model for a turbulent atmosphere that predicts the spectral spreading undergone by an ultrasonic tone propagating under strong turbulence conditions. The model can be easily extended to narrow-band modulated signals to predict the appearance of spurious peaks in the detection of these signals by matched filtering, a phenomenon experimentally observed previously when the duration of the emitted signals is above the coherence time. Further work must be done to generalize this model to weak turbulence conditions and to wide-band signals, taking into account the dependence on frequency of the coherence time.

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