

Preliminary Acoustic Study of 3D Localization of Buried Pipe.

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ABSTRACT

Acoustic waves are commonly used to locate buried polyethylene pipes. In this preliminary study we are particularly interested in pipes depth. To obtain depth information we are moving towards a multi-sensor solution. Several estimators are implemented and tested on real data. A depth estimator according to the relative delays between sensors is proposed. We compare two relative delays estimators : the method using the cross-correlation and the one using the coherence function. We will verify on real measurements that the second method is much more efficient than the first one. Before discussing the results we will present another approach which consists in adapting the MUSIC (Multiple Signals Classification) algorithm to our problem.

Keywords : acoustic method ; buried pipe ; weakly heterogeneous medium ; inverse problem

1. INTRODUCTION

Detecting and locating gas pipelines is a major challenge for network operators. We are interested in buried polyethylene pipelines which is a non-conductive material. Methods have been developed and marketed for years to trace and locate pipes [1]. Other methods exist, like seismic methods (interferometry [2], surface waves dispersion [3] etc) for the investigation of near-surface structures, or invasive electromagnetic methods (insertion of metallic cable in the pipe). Here we are interested in acoustic methods. Different acoustic methods, including the pipe excitation and the vibration excitation of the ground surface have been developed [4]. We have chosen to focus on the pipe excitation method. The advantage of this one is to discern the interest pipe in a dense pipe network. Tools based on this method allow us to estimate the pipe plumb but do not provide any information on

the pipe depth. The objective is to obtain some estimates on its depth with an accuracy of 0.1 m, with a non-destructive or non-invasive method and without 'a priori' information on the surrounding basement. Indeed, this method must be applicable regardless of the location. This preliminary study goes in this direction.

To focus on the depth estimation, we use, first, estimates on the pipe plumb given by the Gas Tracker. This instrument has been developed several years ago, by MADE-SA company. The principle is to inject a low frequency monochromatic acoustic signal at one end of the pipeline. Information on propagated signals energy distribution can be then obtained from mobile sensor on ground surface. By locating the maximum energy measurement points, we get a pipe plumb estimate.

We know that the celerity of the sound in the pipe is equivalent to that of the sound in the air. Depending on the difference in wave propagation velocity between the pipe and the underground, the pressure waves contribution is more or less attenuated but the shear waves contribution stays high. Moreover, we consider that the pipe is analogous to a cylindrically secondary source which radiates through the heterogeneous ambient medium to receivers (geophones) [5,6]. To support this assumption, we can observe the experimental measurements presented below.

We first present, section 2, the considerations about problem modeling. Relative time delays and depth estimators, will be developed section 3, and we will show, section 4, the MUSIC algorithm adapted to our problem. We will present results of numerical simulations in section 5. Experimental setup (electronic and acquisition system developed for our measurements in situ) will be described section 6, with

experiments in semi-controlled conditions. Finally we will present results section 7, before concluding, section 8.

2. PROBLEM MODELING

i) Geometrical set-up

Considering the vibrating pipe as a cylindrical source and resulting symmetries, we can consider a pipe normal plane to model the problem. Sensors observe the signal scattered by the pipe section located in the plane. We consider this source seen by receivers as a point source. The trench is not taken into account here. On figure 1, we can see the model scheme. Sensors are placed in a line following the perpendicular to the pipe plumb and sensors position is known. We consider a single weakly heterogeneous propagation medium with an unknown average velocity in the medium, noted V_0 . The coordinates of S are S_x , the X-coordinate which represents the plumb deviation, and S_z , the Z-coordinate which represents the pipe depth. For the receivers, S is seen as a source. We note the i^{th} receiver R_i , its X- coordinate is r_{ix} and its Z-coordinate is r_{iz} .

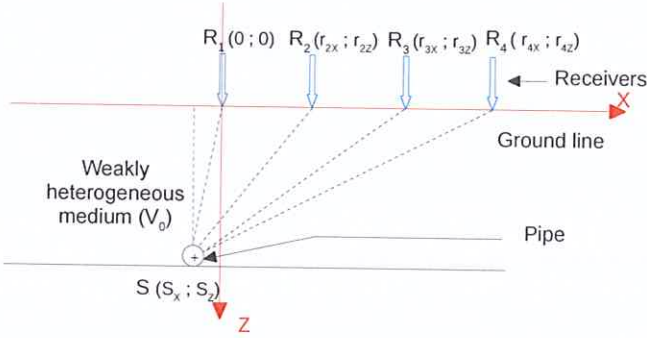


Figure 1 : Model scheme, R_i geophones (mobile receivers), S the point source (pipe). A specific low frequency acoustic signal [100 – 1,000 Hz] is injected at one end of the pipe.

ii) Experiment

We conducted an experiment to support the cylindrical source assumption in our problem. A 0.1 second pulse was injected into the pipe and a geophone was placed at the pipe plumb. On the figure 2, we observe the signal received by sensor. We note that the received signal width is approximately of the same range that transmitted signal. We can see on figure 3, the power evolution of the received signal, and we also note that the peak width of the received energy is on the same order that transmitted signal. The sensor receives the signal from a pipe small portion closest to it. We can conclude that the direction of the scattered signal is principally radial.

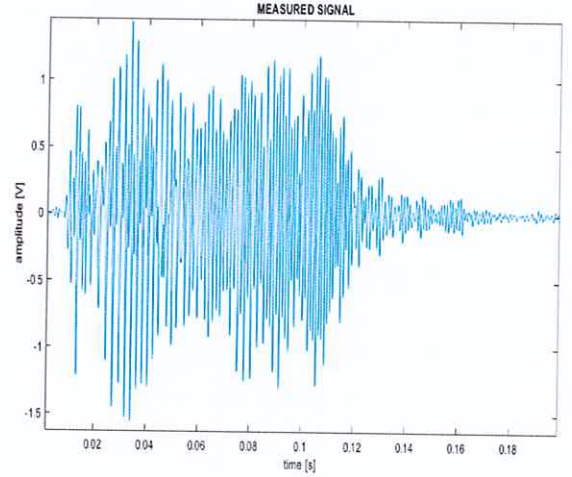


Figure 2 : Signal measured on a geophone placed at the pipe plumb, the emission is a 0.1 second pulse.

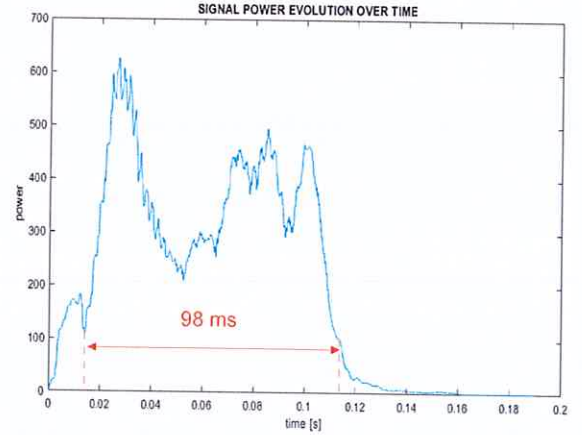


Figure 3 : Signal power evolution over time, the emission is a 0.1 second pulse.

3. ESTIMATES

i) Estimators of relative delay times

The source seen by sensors is the pipe (cylindrical secondary source), but we do not know the exact time when the signal is scattered from the pipe. For these reasons we are interested in the relative delay times between sensors. Estimating relative delay times is an important issue, because the estimate of the pipe depth depends on it.

We will use two different methods to estimate the relative delay times. First using the classical cross-correlation and then, using the smoothed coherence transform (SCOT) [7,8].

The SCOT weighted cross correlation method is based on coherence function. The coherence function $G_{XY}(f)$ between two stationary random processes x and y is equal to the cross-correlation Fourier transform $\Gamma_{XY}(f)$ divided by the square

root of the product of the two autocorrelation Fourier transform $\Gamma_{XX}(f)$ and $\Gamma_{YY}(f)$.

$$G_{XY}(f) = \frac{\Gamma_{XY}(f)}{\sqrt{\Gamma_{XX}(f) \Gamma_{YY}(f)}} \quad (1)$$

We will verify in the results section 7 that the estimator using the SCOT weighted improves the estimates on our real data.

ii) Depth estimator from relative delay times

We want to estimate model unknown variables of models from the relative delay times. We will use generalized least squares to define an estimator [9,10]. Here, sensor one is the reference, all relative delays are calculated from it. Let be

θ the parameters vector to be estimated :

$$\theta = \begin{bmatrix} S_x \\ S_z \\ V_0 \end{bmatrix} \quad (2)$$

S_x is the pipe plumb, S_z the pipe depth and V_0 the average propagation velocity in the medium.

We note τ_{ii} the relative delay between receivers 1 and i :

$$\tau_{ii} = \frac{|SR_i| - |SR_1|}{V_0} \quad (3)$$

$i = 2, \dots, K$ with K the number of receivers. The relative delays is then written as a function of the vector θ .

$$\tau_{ii}(\theta) = \frac{\sqrt{[S_x - r_{ix}]^2 + [S_z - r_{iz}]^2} - \sqrt{[S_x - r_{1x}]^2 + [S_z - r_{1z}]^2}}{V_0} \quad (4)$$

We define the following criterion :

$$C(\theta) = [\tau^m - \tau(\theta)]^T [\tau^m - \tau(\theta)] \quad (5)$$

τ^m is the relative delays vector estimated from the measurements and $\tau(\theta)$ is the vector of $\tau_{ii}(\theta)$, the symbol $[.]^T$ means the transposed operator.

$C(\theta)$ is the sum of the squared errors. We minimize the criterion $C(\theta)$ in a nonlinear least squares sense. It will be interesting, to weight the criterion later, in order to take into account the correlation of the measurement noises between sensors since we consider relative delay times.

4. ANOTHER APPROACH WITH MUSIC ALGORITHM ADAPTED TO OUR PROBLEM

The MUSIC algorithm is classically used in the far-field to estimate sources number and its directions of arrival (DOA) [11]. It can be adapted in near-field to estimate sources distance in addition to their DOA [12, 13,14]. In our case, we are looking for a single source in the near-field, we want its 3D

location, specially the depth, but we have no knowledge of the propagation velocity.

In the far-field case, we can identify the following steps of the algorithm:

i) Estimate the variance-covariance matrix of the system from signals received by the sensors. We note this matrix M .

ii) Decompose the matrix M into eigenvalues and eigenvectors.

iii) Define the noise subspace with the eigenvectors corresponding to the smallest eigenvalues. We note V_b the matrix containing the eigenvectors which constitute the noise subspace.

iv) From the information on the propagation medium and the knowledge of the antenna array (four geophones), we construct a family of vectors "a" parameterized by the theoretical relative phase state ϕ . In the case of a linear and regularly spaced antenna array we have :

$$a(\phi) = [1 \quad e^{-j\phi} \quad e^{-j2\phi} \quad e^{-j3\phi} \quad \dots \quad e^{-j(K-1)\phi}]^T \quad (6)$$

v) Projection of the vector family $a(\phi)$ onto the noise subspace and definition of a criterion.

$$P_{\text{MUSIC}}(\phi) = \frac{1}{a(\phi)^H V_b V_b^H a(\phi)} \quad (7)$$

The symbol $[.]^H$ represents the conjugate transposed of $[.]$. From the ϕ estimate which maximizes the criterion P_{MUSIC} , we can deduce the DOA.

In our case, the step (iv) is modified. We construct the vector family "a" parameterized by S and V_0 from equation (3).

$$a(S, V_0) = \begin{bmatrix} 1 & e^{-j2\pi f_0 \frac{|SR_2| - |SR_1|}{V_0}} & \dots & e^{-j2\pi f_0 \frac{|SR_K| - |SR_1|}{V_0}} \end{bmatrix}^T \quad (8)$$

Where f_0 is the central frequency of the signal.

We can define a criterion in the same way as equation (7).

$$P_{\text{MUSIC}}(S, V_0) = \frac{1}{a(S, V_0)^H V_b V_b^H a(S, V_0)} \quad (9)$$

5. NUMERICAL SIMULATIONS

In this section we present results of numerical simulations. We calculate the Cramer-Rao Bound (CRB) to obtain information about the estimation accuracy [15]. The CRB represents the smallest possible standard deviations of all unbiased estimates of the model parameters. We observe, figure 4, the standard deviation evolution of the depth estimate as a function of the standard deviation of relative delay times estimates. This curve is obtained for a distance between the sensors of 0.2 m, an average propagation velocity (V_0) in the basement of 500 m/s, a deviation on the ground from the plumb (S_x) of 0 m and for the case of two depths (S_z) 0.4 m and 1 m.

We note that to achieve 0.1 meter depth accuracy, relative delay times accuracy in the microsecond range is required.

The standard deviation evolution of the depth estimate is presented figure 5, as a function of the standard deviation of the average velocity estimate. This curve is obtained for a distance between the sensors (geophones) of 0.2 m, a deviation of geophones from the plumb (S_x) of 0 m, a depth (S_z) of 0.4 m and for different values of the average acoustic velocity (V_0) through the basement.

We note that to reach an accuracy of 0.1 meter of depth, it is necessary to have an accuracy on the average velocity which varies according to its real value. The lower the value of this velocity, the more precise it must be estimated.

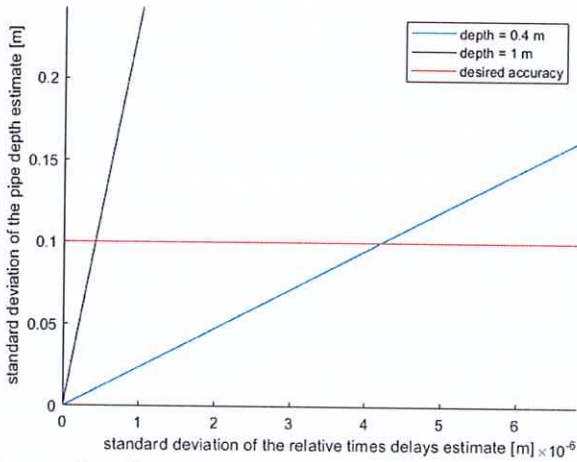


Figure 4 : Standard deviation evolution of the depth estimate function of the standard deviation of relative delay times estimates.

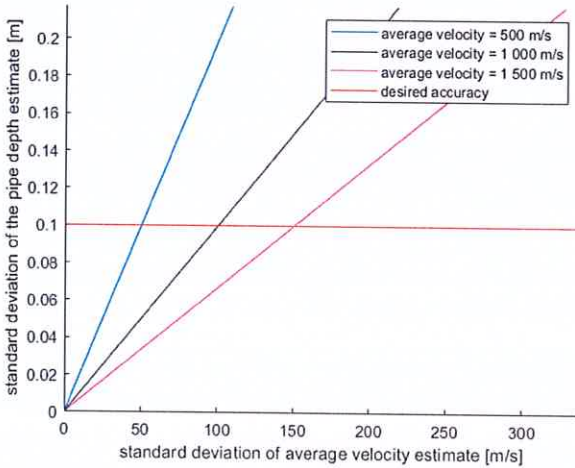


Figure 5 : Standard deviation evolution of the depth estimate function of the standard deviation of the average velocity estimate.

We present results of the estimators tests by Monte Carlo method. The principle is to run a large number of noise

draws to characterize one estimator. Here, we evaluate the statistics of the estimators on 1,000 runs of the noise. Table 1 shows results obtained for the least squares estimator from the relative delay times. The case considered for this simulation is a depth (S_z) of 0.42 m, a plumb deviation (S_x) of 0.05 m, an average propagation velocity (V_0) of 500 m/s and sensors are spaced at 0.2 m. We noise the theoretical delay times given by the model with a centered Gaussian noise of standard deviation 10^{-6} . We note that for an accuracy of microsecond range on the relative delay times we obtain the desired accuracy on the depth.

Table 2 shows results obtained for the MUSIC estimator adapted to our problem. The case considered for this simulation is a depth (S_z) of 0.42 m, a plumb deviation (S_x) of 0 m, an average propagation velocity (V_0) of 500 m/s and sensors are spaced at 0.2 m. We noise the theoretical signals given by the model with a centered Gaussian noise of standard deviation 10^{-1} .

Table 1 : Statistics on the least squares estimator by Monte Carlo method.

	mean	Standard deviation	true value
Depth S_z [m]	0,423	0,018	0,42
Plumb deviation S_x [m]	0,0497	0,0016	0,05
Average velocity V_0 [m/s]	498	10,5	500

Table 2 : Statistics on the MUSIC estimator by Monte Carlo method.

	mean	Standard deviation	true value
Depth S_z [m]	0,414	0,013	0,42
Average velocity V_0 [m/s]	507	10,2	500

6. EXPERIMENTAL SET-UP

We carried out experimental measurements on a semi-controlled test area in order to test methods on real measurements. We have developed an acquisition system (emission (Fig.6) and multi-reception (Fig.7) chain) adapted to our experimental needs. The source signal is controlled by computer to adjust signal parameters (time evolution, duration, frequency band, sampling frequency, repetition of the sequence, period, ...). At the reception, acoustic signals are amplified and filtered analogically by the electronic cards. At the input of electronic cards, signals are filtered with a high-pass filter with a cut-off frequency of 100 Hz and at the output with a low-pass filter with a cut-off frequency of 100 kHz. This wide analog filtering allows us to digitally refine the filtering and to have an experimental flexibility. Moreover, the

amplification chain is adjustable between 0 dB and 112 dB. Its also allows us to have experimental adaptability.

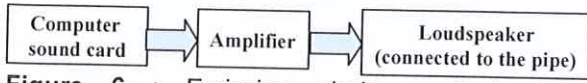


Figure 6 : Emission chain used to take measurements presented.

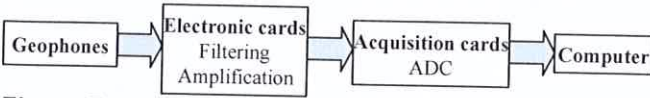


Figure 7 : Acquisition chain used to take measurements presented.

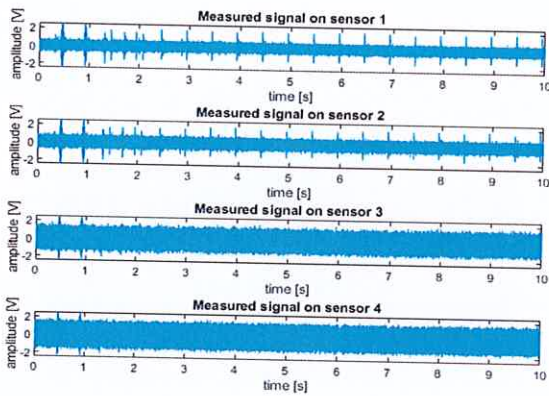


Figure 8 : Signals received during the experiment.

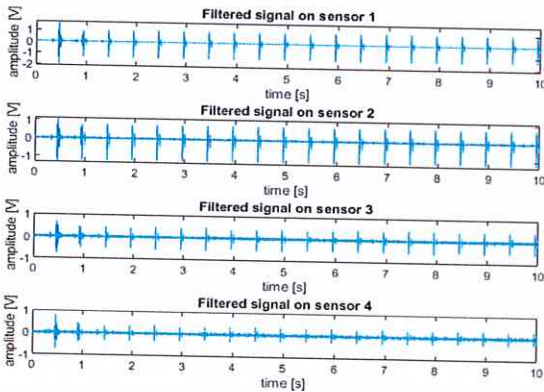


Figure 9 : Digitally filtered signals with a bandpass filter between 300 Hz and 1,000 Hz.

The semi-controlled test area is tarred, a pipe filled of air is buried at 0.42 meter depth and the pipe plumb is known. However, the propagation medium is unknown. To take experimental measurements a line of four geophones is placed perpendicular to the pipe plumb. The sensor 1 is at the pipe plumb and the others are at distances increasingly remote from

the plumb. Distance between sensors is 0.2 m and pipe depth is 0.42 m. The source signal injected in the pipe is a sweep from 300 Hz to 1 kHz with a duration of 10 ms repeated every 0.5 s. Signals are synchronously recorded on the four sensors. The acquisition time is 10 seconds with a sampling frequency of 100 kHz. On the figure 8, we observe the received signal. On the figure 9, signals have been digitally filtered with a bandpass filter between 300 Hz and 1,000 Hz.

7. EXPERIMENTAL RESULTS & INTERPRETATION

In this section, results obtained on real measurements are presented. These results come from the most favorable sets of measurements but, for the moment, the results can be very variable from one measurement location to another. In Table 3, we observe the estimation of interest parameters with the least squares estimator (section 4). Results of these estimates are given and compared for the two methods of relative times delays estimates described in section 3. Using the cross-correlation to estimate the relative times delays, we obtain a depth estimate of 0.18 m. Using the coherence function, we obtain a depth estimate of 0.31 m. The method using the coherence function to estimate the relative lags improves the depth estimate significantly. However, the depth estimate accuracy still needs to be improved.

Table 3 : Interest parameters estimation from relative times delays (presented in section 4).

	Estimated value using cross- correlation	Estimated value using coherence function	Reference value
Depth (S_z)	0.18 m	0.31 m	0.42 m
Distance to the pipe plumb (S_x)	0.02 m	0.01 m	Approximately 0
Average velocity (V_0)	490 m/s	420 m/s	unknown

In table 4, we compare the estimated relative times delays with the theoretical ones according to the estimated velocity ($V_0 = 420$ m/s). We can be seen when sensors are further away, the error of relative times delays estimation is higher.

Table 4 : Comparison estimated relative delay times with the theoretical relative delay times calculated from the estimated propagation velocity (presented in section 3)

	Estimated value using coherence function	Theoretical value (depth = 0,42 m and velocity = 420 m/s)
Between sensors 1 and 2	0.150 ms	0.108 ms
Between sensors 1 and 3	0.490 ms	0.381 ms
Between sensors 1 and 4	0.890 ms	0.744 ms

In Table 5, we present the result of the estimation using the MUSIC algorithm adapted to our problem. We obtain an estimate of 0.37 m for a reference value of 0.42 m, that is an error of 0.05 m. We obtained the best results with the high resolution algorithm MUSIC.

Table 5 : Estimation with the MUSIC algorithm adapted to our problem (presented in section 5).

	MUSIC algorithm adapted	Reference value
Depth (S_z)	0.37 m	0.42 m
Average velocity (V_0)	450 m/s	unknown

8. CONCLUSION AND PERSPECTIVES

Results obtained are encouraging since we reach the expected accuracy. However, depending on where in the test area we are, the results are very different.

We have an equations number equal to unknowns number. To increase the equations number we need to increase the number of sensors or measurements. Relative delays estimation with the coherence function shows that the error increases with the distance between sensors. The signal-to-noise ratio are strongly degraded. On the other hand, the depth estimation accuracy is improved by increasing the distance between sensors. We have to find the right compromise. Relative delay times estimate is also related to signal richness. We may increase the bandwidth of sensors or work on the source signal.

We plan, at last, to include in MUSIC algorithm, the signal attenuation (e.g. for strongly heterogeneous medium). If it is interesting to evolve the model, we have to take into account the increase of parameters number (e.g. the trench).

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