Localization Experiments with two Different Configurations in an Artificial Water Depository

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ABSTRACT

The Laboratory for Underwater Acoustic Measurements of the Institute of Applied and Computational Mathematics conducted shallow water experiments in an artificial water depository. The purpose of these experiments was to test standard acoustic instruments in the field (under partially controlled conditions as a step from tank testing to open sea use), to verify their good operation and then to analyze the data collected using two different experimental configurations. The instruments used in the experiments were hydrophones, array of hydrophones, pingers, transducers, data acquisition cards etc. Some of the acoustic instruments were placed in fixed positions inside the water column while others changed position during the experiments. In this work the setup and planning of the experiments will be presented, the experimental procedures will be explained and the analysis of the data collected, for estimating the position of the fixed instruments will be presented. An acoustical localization method based on the identification of arrival times using signal processing will be presented. Then an attempt was made to estimate the position of the moving instrument (pinger or transponder). Since the exact position of the instruments was unknown the results were compared with GPS measurements and the maximum difference between them was of the order of 2-3%.

1. INTRODUCTION

The Laboratory of Underwater Acoustic Measurements of the Institute of Applied and Computational mathematics has several acoustic instruments that can be used in the open sea. These instruments have been tested in the small size (5m x1.5m x 1.3m) water tank of the laboratory. As a second step before these instruments deploy in the open see was to test them in a larger body of water under partially controlled conditions. An artificial water depository was chosen for this purpose. Two experiments took place during May and June of 2009. These experiments are presented in this work.

The main idea of the first set of experiments (after validating the trouble-free operation of the instruments) was the following: Using two transponders, fixed in the water column in two positions, a source (pinger) moving inside the water and a single hydrophone (also fixed in the water column), to estimate the distances between the fixed instruments and to estimate the position of the moving source.

There is extensive literature on single hydrophone localization methods (for example [1,2]), and the researchers on our Institute have recently developed several localization methods [3,4]. However, these methods either assume more than one hydrophones, or use not only the signal arriving directly from the source to the hydrophone but also its reflections. These methods cannot be used in our case, since the small dimensions of the water body result in the fact that the direct and reflected pulses are not separable.

During the second set of experiments different instruments were tested and used. A towed array (consisting of a flexible oil filled plastic tube) with two hydrophones, a pinger positioned next to one of the array hydrophones and a transponder positioned in different places inside the lake were used. The data of the experiment were once more analyzed in order to estimate the position of the transponder.

We will first describe the instruments, the location, and the setup of the first experiment. We will then present a method for estimating the position of the fixed instruments and for locating the moving source for the first experiment. Then the second set of experiments will be discussed and the procedure used to estimate the position of the moving source will be presented. A detailed description of the first experiment was presented by the authors in [5]

2. FIRST SET OF EXPERIMENTS

2.1. *The instruments used in the experiments.*

The following scientific instruments were used in the first set of experiments:

- 2 TDR's. (Temperature and depth loggers)
- 2 transponders (receivers and emitters of acoustic pulses) and 1 pinger (emitter of acoustic pulses)
- 1 omnidirectional hydrophone (1Hz to 120 kHz)
- 1 data acquisition card (100 kHz sampling rate),a signal amplifier and a low pass filter at 50kHz.
- A digital oscilloscope and a portable PC

Other instruments used were: a GPS navigator, a laser distance meter, a depth finder, a UPS inverter, batteries, a small boat, cables, weights etc.

2.2. *The location of the experiment*

Both experiments took place in an artificial water depository near the village Gergeri, 40 km from the city of Iraklion Crete. A picture of the depository is shown in Figure 1. In Figure 2 a Google Earth picture of the lake is shown. The area of the lake is about 41 km^2, and its maximum capacity is 244077 m^3. The maximum depth near its center is about 14m.

The depository is used during the summer months to water the crops of the area. A pump used for removing water from the depository was turned off during the experiments. There were no other noises except the physical noises (birds, frogs, wind etc.). There were no fish in the lake.

Figure1: A photo of the depository.

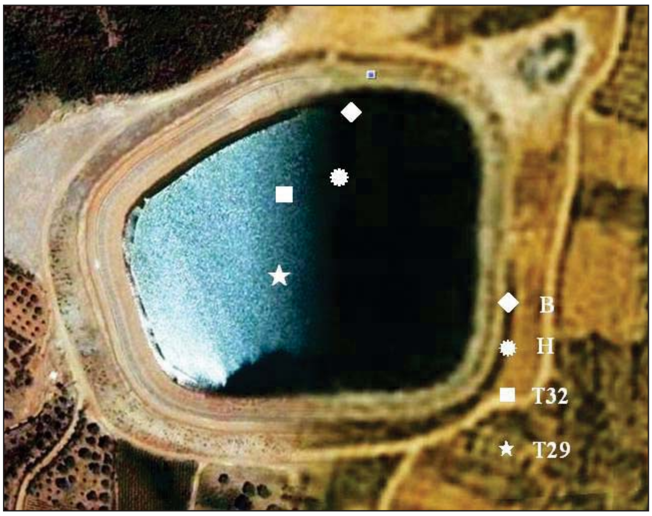

Figure 2. *The lake from Google Earth with the positions of the base (B), the hydrophone (H) and the transducers (T32 and T29).*

2.3. *Experimental setup*

All instruments were first moved to a platform (base B on Figure 2) on the lake's shore. There the PC, oscilloscope, batteries etc. were placed. The TDR's are autonomous devices logging the temperature and the depth during a time period. The time period and the logging time steps are adjustable by the user. One of the TDR's was put 10 cm above the hydrophone with a time step of 1 minute and the other was put next to the pinger with a time step of 1 second. The hydrophone (H) was deployed near the base and was connected with a 50 m cable to the amplifier, filter and data acquisition card which was connected to the PC. The two transponders (manufactured by Benthos) were put in two unknown position inside the lake. The transponders are autonomous acoustic instruments both emitters and receivers. They were set to emit an acoustic pulse, one of them in 29 kHz (called T29) and the other at 32 kHz (T32), 20 msec after they receive an acoustic pulse of 26 kHz. The pinger is only an emitter and was set up to emit an acoustic pulse (4 msec long) at 26 kHz, every 2.048 seconds.

The approximate positions of these instruments can be seen in Fig. 2. A schematic of the instruments put in fixed positions inside the water is shown in Fig. 3. A photo of the positioning of transponder T32 is shown in Fig. 4. The pinger (with the second TDR attached next to it) was placed in the water column under the small dinghy and was moving inside the lake. As the dinghy was moving in the lake, it stopped at a few points and the pinger with the second TDR attached was slowly lowered to the sea floor and raised to the surface. This was done in order to get measurements of the temperature at many points of the water column. These measurements were then used to calculate the sound speed in the water.

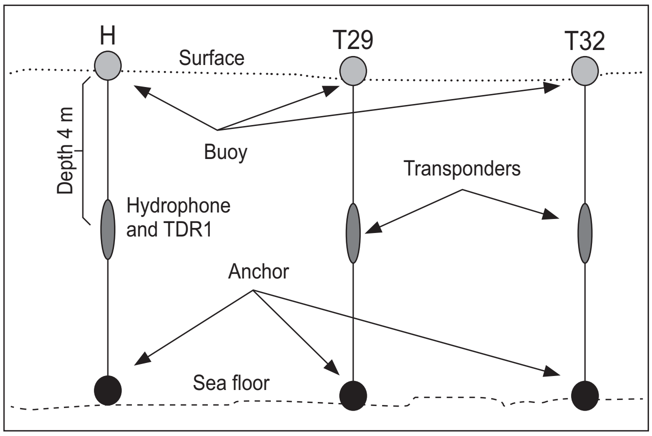

Figure 3. *The anchoring of the fixed instruments in the water column.*

Figure 4. *The positioning of first transponder (T32) in the small red circle. The position of the hydrophone is shown as a larger red circle on the left of the photo.*

During the experiment the pinger was continuously emitting pulses every 2.048 seconds. The signal received in the hydrophone was recorded by the data acquisition card and saved in the portable PC. Several 2 minute recordings were made for different positions of the pinger. The sampling acquisition rate was 100 kHz. The filter at 50 kHz was ensuring that no antialiasing phenomena were present in the recorded signal. GPS measurements were also made at the position of the hydrophone (H) and at the two transducers (T32 and T29).

2.4. Estimation of the sound speed in the water

Using the TDR measurements, temperature versus depth can be calculated. The results can be seen in Figure 5 (left) where the red line is the average profile in the lake. The temperature values can then be used to calculate the sound speed profile in the lake (Figure 6 right) and to calculate the way the sound propagates in the water column.

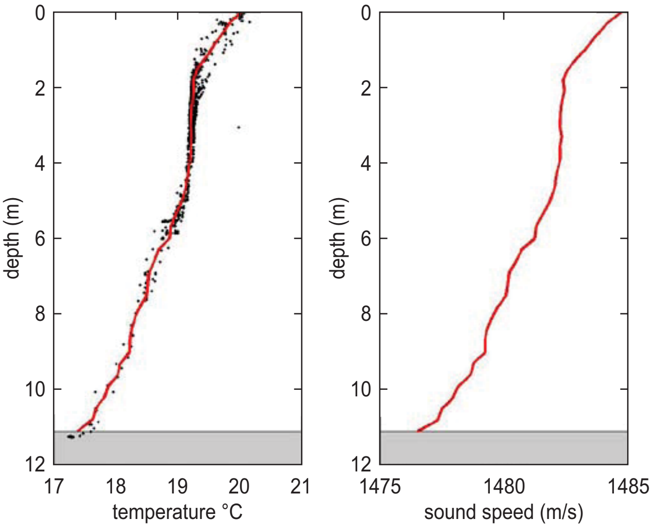

Figure 5. *Left: Temperature measurements (black dots) and the average temperature profile (red line). Right: Sound speed profile produced by the temperature measurements.*

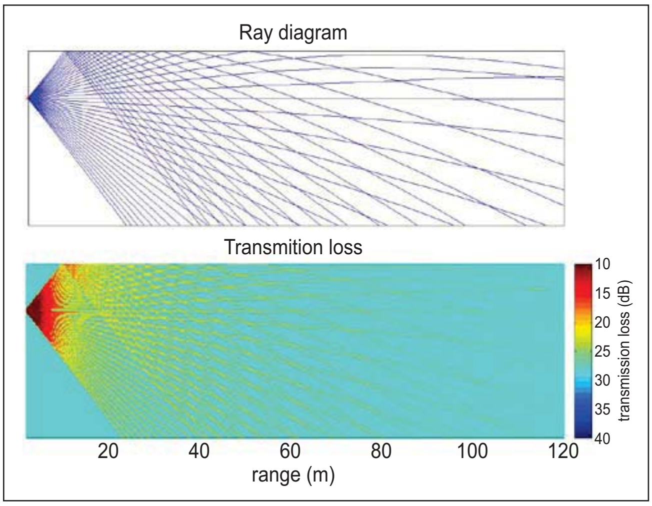

Figure 6. *The acoustic rays (top) and the transmission loss (bottom) in the lake.*

Figure 6 presents the acoustic rays (top) according to ray theory and the transmission loss (bottom). The seafloor was unknown but a soft bottom was used for the calculations of the rays. The sound speed calculated from these measurements was 1483.2 m/sec for a depth of 4 m. This value was used in the analysis of the arrival times presented in the following section since all our fixed instruments were put in about 4 meters depth.

2.5. Estimation of the position of the fixed instruments

The next step was to process the recorded data in order to estimate the position of the hydrophone (H), and the transponders (T29 and T32). All instruments were positioned at 4 meters depth. Our purpose was to estimate the distance between H, T29 and T32 α_1, α_2 and α_3 respectively (see Figure 7). If τ_1, τ_2, and τ_3 are the corresponding sound travel times between the three instruments and since the sound speed is known, it is enough to estimate the travel times.

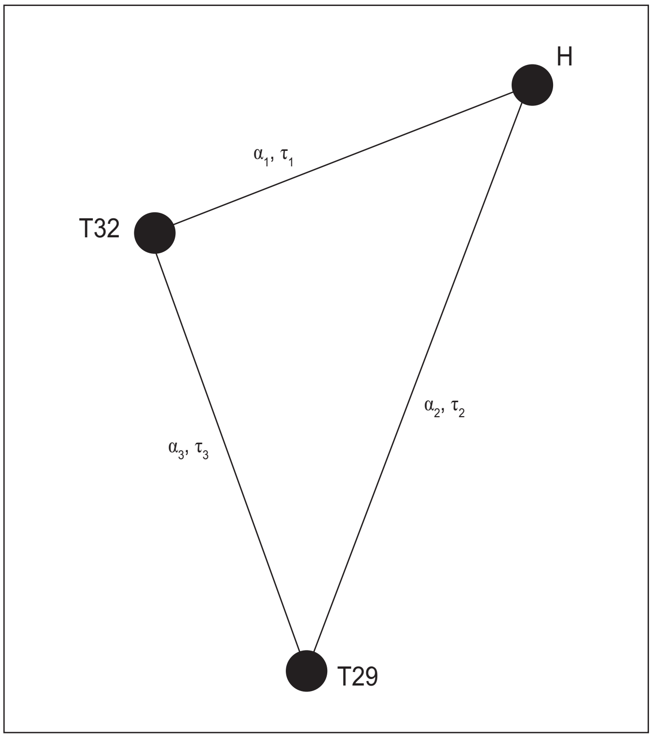

Figure 7. *The distance and travel times between the three instruments.*

The travel times were estimated using the signals when the pinger was next to the hydrophone and when it was next to T32 as follows:

2.6. *Calculation of the travel times*

In Figure 8a, a 0.5 second window of the signal recorded with the pinger next to the hydrophone is shown. The pulse from the pinger can be easily seen in this picture. However the pulses from the two transponders are not visible. These pulses were emitted 20 msec after the transponders received the pulse from the pinger. In order to be able to find the time position of these pulses the noise must be somehow removed from the signal. The following filter method was used for this:

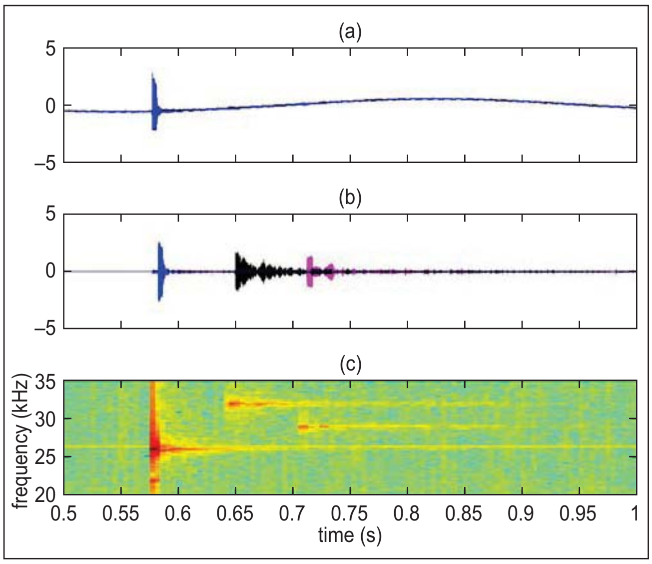

Figure 8. *The recorded signal (a), the signal after application of the filter method (b) and the spectrogram of the signal (c).*

A passband filter around the frequencies 26 kHz, 29 kHz and 32 kHz was applied to the signal. The filtered signal is shown in Figure 8b. The blue signal (first pulse) is the 26 kHz component, the black (second pulse) is the 32 kHz and the pink (third pulse) the 29 kHz component. The amplitude of the black and pink component was increased in order for the pulse to be visible. Finding the time of the maximum of each component, we can calculate the difference in time between the arrival times of each pulse. Let dt_1 be the time difference between the first and second pulse (H and T32) and dt_2 the difference between the first and third pulse (H and T29). We can thus estimate the travel times as follows:

$$\tau_1 = (dt_1 - 0.02) / 2 \textit{ and } \tau_2 = (dt_2 - 0.02) / 2$$

A second method based in the time-frequency analysis of the signals was also used. A Fast Fourier Transform was applied in a moving time window and the frequency content is obtained. Figure 8c presents the result (spectrogram) of such an analysis. The time position of the maximum at the frequencies 26, 29 and 32 were estimated and used to calculate the dt_1 *and* dt_2. We then proceed as in the first method. This method produced similar results and it is presented in [5].

2.7. *Estimation of the distances*

Since the travel times τ_1 and τ_2 were calculated the distances can also be calculated by:

$$a_1 = c \cdot \tau_1 \text{ , } a_2 = c \cdot t_2 \text{ with } c = 1\,483.2 \text{ m/sec}$$

The recorded signal contained 20 pulses and so this procedure was repeated for all pulses obtaining 20 values for the distances α_1 and α_2. In order to calculate τ_3 and the corresponding α_3 the signal recorded when the pinger was next to the transducer T32 was used. The method previously presented was also applied for this signal and the third distance was estimated. In this case 31 pulses were present in the signal giving 31 values for α_3. Their average values and standard deviations were calculated and shown in Table 1. The last column of table 1 contains the values of the distances obtained using the GPS measurements at the location of each instrument. The difference between the GPS data and our estimated values is less than 2%.

Table 1. *The results of the data analysis.*

	Filter method		GPS
	Mean value(m)	**Standard deviation(m)**	**(m)**
α_1	36.83	3	37.72
α_2	82.15	1	83.43
α_3	60.42	4	62.79

2.8. Estimation of the position of the pinger in the water

2.8.1. Calculation of the position

Now that the distances between the fixed instruments are known it is examined if it will be possible to estimate the position of the pinger in the lake at any point different that the position of H, T29 and T32. Figure 9 describes the problem. Let the pinger be at some point P in the water. The pinger was put at 4 meters depth as the rest of the instruments. From this point it emits a pulse and the signal is recorded in the hydrophone located in H. It is also recorded there the pulse emitted by T29 and T32, 20 msec after they “listen” to the pinger pulse.

Let x, y and z the distances from P to H, T32 and T29 respectively. Can these distances be estimated? The problem would be trivial if the travel time t_1 from P to H was known. Then the distances x, y and z are given by:

$$x = c \cdot t_1$$

$$y = x - a - c \cdot (dt_1 - 0.02)$$

$$z = x - \gamma - c \cdot (dt_2 - 0.02)$$

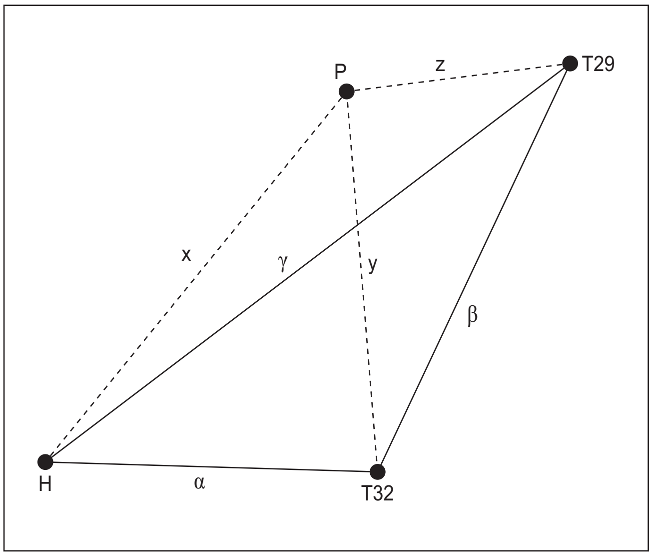

Figure 9. *Schematic of the position of the fixed instruments and the pinger (P).*

where dt_1 and dt_2 are the time differences between the pinger pulse and the pulse from T32 and T29 respectively.

However in our case the instruments were not synchronized and so the absolute travel time t_1 is unknown. The method used to overcome this problem was the following: Assume t_1 was known, then the point P would be located in the intersection of three circles with centers in H, T32 and T29 and with radii x, y and z respectively. However since all the travel times and distances were numerically calculated, they are not error free. So the three circles most likely will not intersect in one single point but they will form a curvilinear triangle (Figure 10). Let the area of this triangle be A. This was calculated using the method described in [6]. The method to find the appropriate t_1 is to define a time interval and a time step and for each time t in this interval to calculate x, y and z and then the area A of the triangle. The t with the minimum A will be chosen as the correct arrival time t_1. Then from the three apexes of the triangle we choose the one that is closer to H, T29 and T32 at the same time. This will be taken as the position P of the pinger.

2.8.2. Application to recorded data

We applied the method of the previous section to three different recorded signals.

The first signal was recorded as the pinger was located in a point between H and T29, the other as the pinger was somewhere in the middle of the area between H, T29 and T32 and the third recording was done as the pinger was moving from H to T29. The first two cases

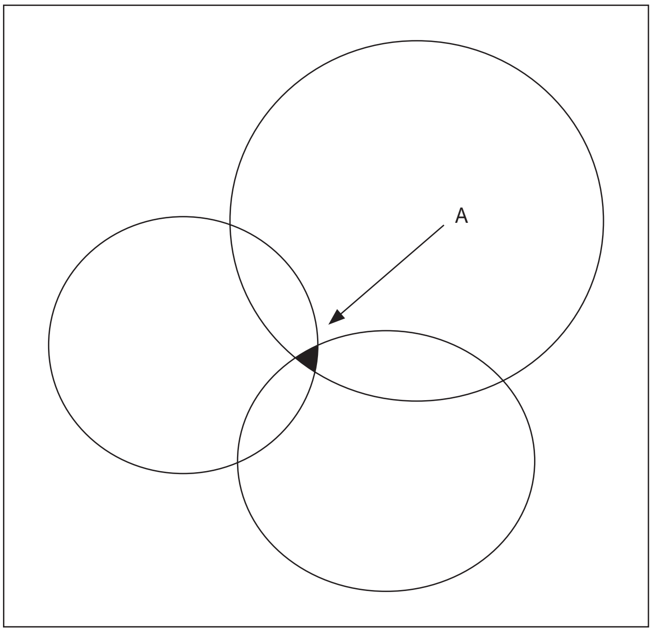

Figure 10. *The intersection of three circles and the curvilinear triangle they form.*

showed that the position of the pinger was estimated accurately enough ([5]). We will present here the results of the third case

The results of the analysis of the signals for the location of the pinger are shown in Figure 11. The black squares are the positions of the fixed instruments and the red circles the position of the moving pinger.

3. SECOND SET OF EXPERIMENTS

The purpose of the second experiment was to apply the localization technique discussed in the first experiment using a different experimental configuration with different instruments. The major change in this experiment was the use of a hydrophone array. The array is 10 meter oil filed flexible tube with three hydrophones inside and a 200 meters cable. The hydrophones inside the tube (H1, H2, H3) are shown in Figure 12. Either H1 and H2 or H1 and H3 can be used during an experiment. In our experiment we used hydrophones H1 and H3. Their distance - if the tube is straight - is 2.95 meters.

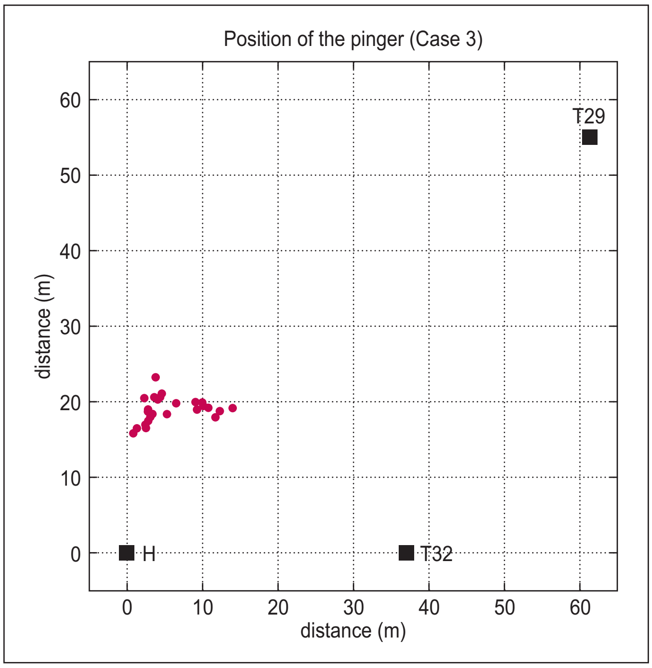

Figure 11. *The position of the pinger P estimated by our method (red points) as the pinger was moving inside the lake (case 3).*

3.1. *The instruments used in the experiments.*

The following scientific instruments were used in the second set of experiments:

- 2 TDR's. (Temperature and depth loggers) 1 transponder and 1 pinger
- 1 array of two omnidirectional hydrophones (1Hz to 120 kHz)
- 1 data acquisition card (100 kHz sampling rate) with a signal amplifier
- A digital oscilloscope and a portable PC

Other instruments used were: a GPS navigator, a laser distance meter, a depth finder, a UPS inverter, batteries, a small boat, cables, weights etc.

3.2. *The location of the experiment*

The location of the second experiment was the same as the one of the first experiment (section 2.2)

3.3. *Experimental setup*

All instruments were once again moved to a platform (base B on Figure 2) on the lake's shore. There the PC, oscilloscope, batteries etc. were placed. The pinger (P) was tied on the tube of the array at a position where hydrophone H3 was located (Figure 13).

Two floats were tied to the array (at the position of the hydrophones) with a 4m cable and two anchors were used (Figure 14). Then the array was put in the water 90 meters from the base near the center of the lake.

The transponder (T) was tied to a rope and the TDR was tied 10cm above the transponder and was programmed to log data with a time step of 1 second. Then the transponder was immersed in the water from the dinghy which was moving inside the lake at different positions. The depth of the transponder was 4 meters below the surface. The pinger emitted pulses 5msec

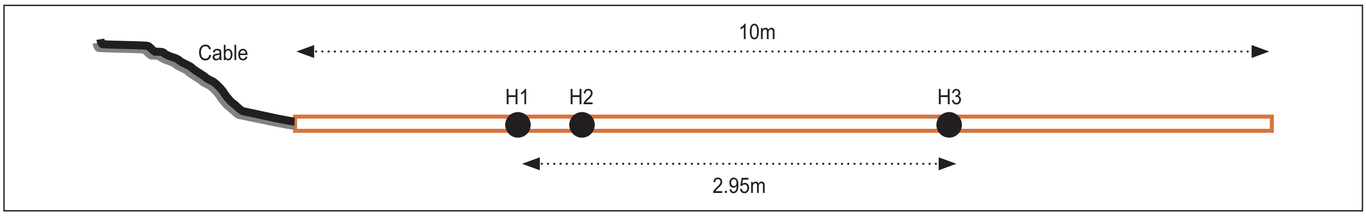

Figure 12. *The hydrophone array with the approximate location of the three hydrophones.*

Figure 13. *The hydrophone array with the pinger (black cylinder) tied on it.*

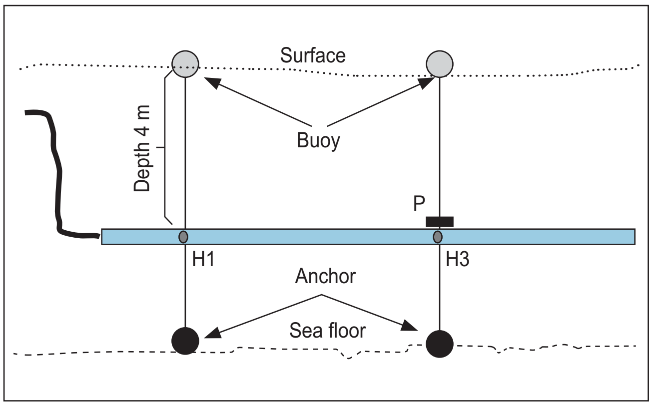

Figure 14. *A schematic of the positioning of the array inside the lake.*

long at 26 kHz every 2.048 msec and the transponder emitted a 4 msec pulse at 32 kHz after the arrival of the pinger signal at the transponder. The data from the two hydrophones were then recorded using the data acquisition card.

3.4. Estimation of the position of the transponder in the water

The recorded by the hydrophones signals were used to estimate the distance between the two hydrophones and the position of the transponder inside the lake. In Figure 15 two such signals are shown. The top signal is the one recorded from H3 and the one at the bottom from H1.

The signals in blue are the ones coming from the pinger and in red from the transponder. The rest of the signals in grey are either multiple reflection from the surface or the sea floor, or noise. From the two blue signals the distance between the two hydrophones can be obtained. The method used was the same as the first experiment. Using many such measurements the average distance from H1 to H3 was calculated at 2.76 meters. This indicates that the tube was not straight but it was bended since the straight distance between them is 2.95 meters. Using the arrival times of the blue and red signals in both hydrophones the distance from the transponder to the hydrophones was estimated. The method used was similar to the method used in the first experiment. Now the absolute times from the emission of the signal from the pinger are known since the pinger was located next to the hydrophone H3. Knowing the distance between

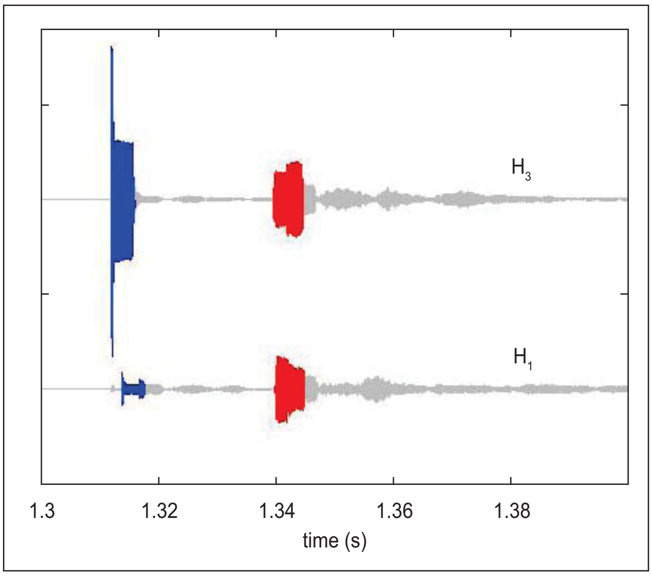

Figure 15. *Examples of the signals recorded at the hydrophones H3(top) and H1(bottom). The blue signal is the pinger signal and the red the signal from the transponder.*

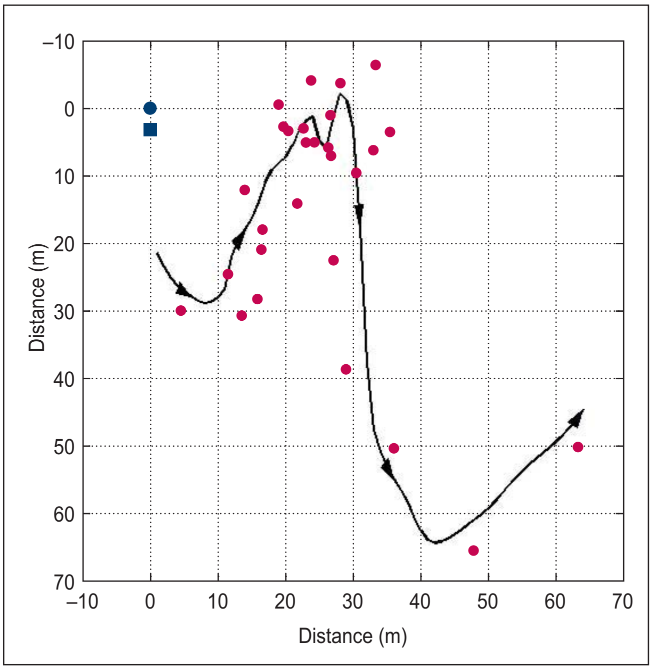

Figure 16. *Analysis results: The blue square and circle are the position of the hydrophones, the red circles are the position of the transponder using the analysis of the acoustical data and the black line is the position of the dinghy calculated from the GPS data.*

the transponder and the hydrophones its position can be estimated (with a left-right ambiguity) as the intersection points of two circles.

Figure 16 shows the position of the transponder as red circles using the method described above for a 30 seconds period. The blue circle is the position of H3 and the blue square the position of H1. The black curve is the position of the dinghy which was calculated by GPS measurements. The accuracy of the GPS position was about 4 meters. It is observed that the mean difference between the GPS data and the estimated values was 2.5%

4. CONCLUSIONS

The experiments in the artificial depository were done in order to verify that the instruments used will operate as expected and to identify any problems related to the deployment, operation and retrieval of the instruments before they can be used in the open sea.

At the same time the signals recorded were used to calculate several unknown parameters such as sound speed and distances between the instruments. Finally an attempt was made to track the moving source (pinger or transponder) for two different experimental configurations. The results were encouraging, verified with GPS measurements and they suggest that it is possible to measure distances with these experimental configuration.

Some problems related to the calculation of the arrival times need more investigation in order to avoid erroneous results.

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