Acoustic Bathymetric Mapping in very Shallow Water Reservoir

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***Abstract*—The analysis of bathymetry of seas, oceans and lakes is a very important activity, since it allows the study of morphology of the floor and also can aid the channel modeling if underwater communication must take place. A Sonar is usually the device used for accomplish this task. It is an acoustic radar, able to send pulses and analyze the reflections. Hence, in this work we derive the bathymetric map of a very shallow water reservoir by using a sonar system characterized by two separated devices, one transmitting and one receiving so allowing the signal detection also during signal transmission. This allows to consider very shallow depths, of the order of few meters, and the system proposed is also low cost. It requires a transmitter, a hydrophone and a software processing tool to offline estimating depth.**

***Index Terms*—Acoustics, Bathimetry, Shallow Water, Ambiguity**

I. Introduction and Goals of the work

Using SOund Navigation And Ranging (SONAR) system for evaluating bathymetry is a consolidated technique even though it presents some drawbacks. Several applications ranging from *simple* sounding to synthetic aperture sonar (SAS) allow to estimate depth and, especially for SAS, obtain images of the water floor (see [1]-[3]).

In shallow water environments, the swath coverage and performance of sidescan bathymetric systems are influenced by the presence of interference due to multipath. So in [4] a hybrid sonar design that combines multibeam and sidescan technologies is proposed. This solution, tested through many computer simulations, offers extended swath coverage by suppressing multipath effects. Dealing with sea-floor mapping, in [5] an interferometry sonar installed on an underwater acoustic vehicle in addition to a side scanning sonar is employed to highly resolve bathymetry mapping. The interferometry sonar is composed by three hydrophones arranged in a L shape, allowing to get higher resolution data. Moreover, in order to improve the system performance synthetic aperture is applied. A possible way to increase the accuracy of bathymetry data is described in [6]. By processing the adjacent across-track and along-track beam pairs it is possible to improve the angle of arrival estimates. Then the improvements to the bathymetric data using narrow-beams monopulse techniques over conventional processing are evaluated. In [7] the use of high resolution methods and tracking algorithms is discussed. In order to mitigate the multipath interference effect a tracking algorithm based on a priori information on the sea-floor angle of arrival is introduced. Since the considered model is non-linear and data analysis suggest a non-Gaussian behaviour, the proposed algorithm is based on particle filter.

A typical feature of the above reported approaches is that the transmission and receiver sections are contained in a unique device. From one hand, this is an advantage since only one clock is needed and the device is compact. However, assuming that the pulse emitted lasts T_p seconds, it is in general impossible to detect possible reflections due to obstacles at a distance less or equal to $0.5T_pv$ where v is the speed of sound in the water, usually 1500m/s. This leads to conclude that for pulses lasting milliseconds or tens of milliseconds is not possible to detect reflections of object/obstacles including water-floor at few meters of distance (e.g. $T_p = 10ms$ leads to 7.5 meters distance impossible to detect). Usually this point is not so critical, but it becomes dramatic when a very shallow water reservoir is considered.

A. Goals

In this work we aim at proposing a low cost system characterized by a hardware/software integration for the study of the bathymetry of a very shallow water reservoir. We consider the reservoir in Rome, with coordinates 41.827990 N, 12.467959 E, since it is expected that the depth is less than 5 meters. As previously specified, analyzing so low values of depth requires very large bandwidth and this can be really costly. The analysis we carried out proposes the bathymetric map, as well as the distribution of the reflection (amplitude) so as to try to classify the water-bed.

The paper is organized as follows. Once introduced the system model in section II, we show how the signals are processed in section III so as to show the test results in section IV. Section V draws conclusion.

II. System model

We suppose to transmit a signal $s(t)$ as that generated by SAM-1 modem developed by Desert Star Systems LLC that is the evolution of AModem [8]. For very shallow water bathymetry, where transmitter and receiver are posed at a distance equating d_r, we can model the channel impulse response (as for communication purposes) as a two rays channel (see Fig.1). The first ray is the direct one and the propagation delay is $\tau_0 = d_r/v$. The depth of the water-floor is the half of the propagation time of the signal reflected by

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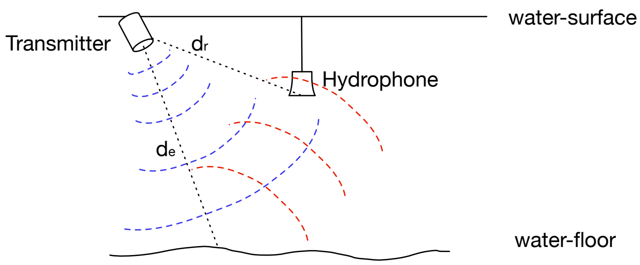

Fig. 1. Example of transmitter-hydrophone propagation due to reflections.

the floor, so $\tau_1 = 2d_e/v$. This implicitly means that the time distance the following equality holds

$$\Delta\tau = \tau_1 - \tau_0 = \frac{2d_e - d_r}{v}. \tag{1}$$

The above relationship allows to conclude that depth is

$$d_e = \frac{v\Delta\tau + d_r}{2}. \tag{2}$$

So, the signal acquired by the hydrophone is characterized by three components as detailed by the following relationship

$$y(t) = s(t) * [a\delta(t - \tau_0) + b\delta(t - \tau_1)] + n(t) \tag{3}$$

where the term $a\delta(t-\tau_0)$ considers the attenuation ($a < 1$) and delay (τ_0) of the direct path, while $b\delta(t-\tau_1)$ models the effect of reflection. Last $n(t)$ models the additive, generally colored, Gaussian noise. The above link equation can be rewritten as follows by considering (1)

$$y(t) = s(t) * [a\delta(t) + b\delta(t - \Delta\tau)] + n(t). \tag{4}$$

III. Bathymetric analysis

Moving to the Fourier analysis, it is possible to write the previous relationship (3) by recalling that the convolution in time becomes the product in the frequency domain and, more, $\mathfrak{F}\{\delta(t - \Delta\tau)\} = e^{-j2\pi f\Delta\tau}$

$$Y(f) = S(f)[a + be^{-j2\pi f\Delta\tau}] + N(f). \tag{5}$$

It is important to note that, following the Fourier theory, the term $n(t)$ is not directly transformable, but a discrete time implementation (via Discrete Fourier Transform - DFT) allows the computation of $Y(K)$, this latter being the sampled version of the received spectrum. So, moving to express the effect of the channel in the sampled frequency domain we obtain the following expression

$$\tilde{H}(K) = \frac{Y(K)}{S(K)} \tag{6}$$

whose power spectral density is given by

$$|\tilde{H}(K)|^2 = a^2 + b^2 + 2\,a\,b\cos(2\pi K\Delta\tau). \tag{7}$$

It is interesting to note that in the discrete frequency domain, the above expression is a sinusoidal tone so the distance among to maximum values is the frequency domain period, that is, $(\Delta\tau)^{-1}$. So, the distance among those two maximum (or minimum) values leads to obtain $\Delta\tau$ so allowing the evaluation of (2) since d_r is known as well as v. If we remove the assumption of having only two paths, the analysis carried out till now is, in general, no more valid since it can fail to be robust with respect to several reflections. The model in (4) becomes

$$y(t) = s(t) * \left[a\delta(t) + b\delta(t - \Delta\tau) + \sum_{i=2}^{M} \alpha_i\delta(t - \theta_i)\right] + n(t), \tag{8}$$

where α_i terms model the attenuation of the paths reflected by other surrounding objects and θ_i is the relative delay. The summation goes from 2 to M since it is assumed that M-1 reflective components may be present. This last considerations is mostly true when approaching the borders of reservoir or close to boats and so forth. A direct applications of the Fourier analysis leads to an expression not so easy to manage, since we arrive at the following relationship

$$Y(f) = S(f)\left[a + be^{-j2\pi f\Delta\tau} + \sum_{i=2}^{M} \alpha_i e^{-j2\pi f\Delta\theta_i}\right] + N(f). \tag{9}$$

and in this case it is not so straightforward to arrive at an expression like (7). This implicitly suggests to follow an alternative approach.

A. Cross-correlation method

In the simple case of only two paths present, as above assumed, we can evaluate the cross correlation between the signal transmitted by the modem/SONAR $s(t)$ and the received one $y(t)$. As a consequence, we obtain for the discrete time version, the following expression

$$\mu_{ys}(m) = a\mu_s(m) + b\mu_s(m - z) + \mu_{sn}(m) \tag{10}$$

that, when noise is low with respect to signal, and, since $a > b$, a very simple (post) processing can lead to subtract the term $a\mu_s(m)$ where a can be inferred by observing the maximum value of $\mu_{ys}(m)$. In this sense, by computing $\mu_{ys}(m) - \tilde{a}\mu_s(m)$ we obtain the following relationship

$$\mu_{ys}^{(b)} = \mu_{ys}(m) - \tilde{a}\mu_s(m) = b\mu_s(m - z) + \mu_{sn}(m) + \mu_\epsilon(m) \tag{11}$$

$\mu_\epsilon(m)$ being the residual error.
Expanding this approach to the case of surrounding objects, as for the previous case, we obtain the following expression

$$\mu_{ys}(m) = a\mu_s(m) + b\mu_s(m-z) + \sum_{i=2}^{M} \alpha_i\mu_s(m-q_i) + \mu_{sn}(m). \tag{12}$$

As for the previous case, we can subtract an estimated version of $a\mu_s(m)$ where the error is simply due to a since $\mu_s(m)$ is perfectly known. So we have

$$\mu_{ys}^{(b)} = \mu_{ys}(m) - \tilde{a}\mu_s(m) =$$

$$b\mu_s(m - z) + \mu_{sn}(m) + \sum_{i=2}^{M} \alpha_i\mu_s(m - q_i) + \mu_\epsilon(m) \tag{13}$$

A discussion about the relationship between $b\mu_s(m-z)$ and $\sum_{i=2}^{M}\alpha_i\mu_s(m-q_i)$ must be carried out. The performance expected by the proposed scheme strongly depends on b and α_i from one side and z and q_i. If the reflections of the surrounding objects are, from the amplitude point of view, stronger than b, it is possible that they are confused with the reflection of lake floor. In this respect, also the relationship between z and q_i is important since if $z >> q_i$ it is reasonable that the estimation of the delay related to the reflection of z does not give rise to ambiguity or errors. If $z > q_i$ and the difference is not so evident, ambiguity is also possible even though, low error is expected. The problem, from the performance point of view, is tied to the case when $z < q_i$ that can incur close to reservoir sides and when very close vessels/boats are present. So, the estimated (sampled) delay is given by

$$\tilde{z} = \arg\max_{m} \mu_{ys}^{(b)}(m) \tag{14}$$

so the continuous time delay is $\tilde{\tau}_1 = \tilde{z}T_s$. So, as previously anticipated, the distance (depth) is given by

$$\tilde{d}_e = \frac{v\left(\tilde{\tau}_1 - \tau_0\right) + d_r}{2} \tag{15}$$

IV. Test Results

We use the following setup for tests. The transmitter operates in the bandwidth 33-42 kHz and the power is 183 dB at 8V - 189 dB at 16V. We detail the bathymetric map for the detection operated with the Hydromic device [9] able to sample the signal at the hydrophone with a bandwidth of 192 Khz with 16 bit per sample. After we used the acquired file (in the .wav format) for be processed with Matlab software. Fig. 2 shows the cross-correlation between received signal and emitted acoustic ping. The main component is due to the main path (transmitter-receiver) while the second one is the effect of the reflection. The estimated bathymetry is obtained

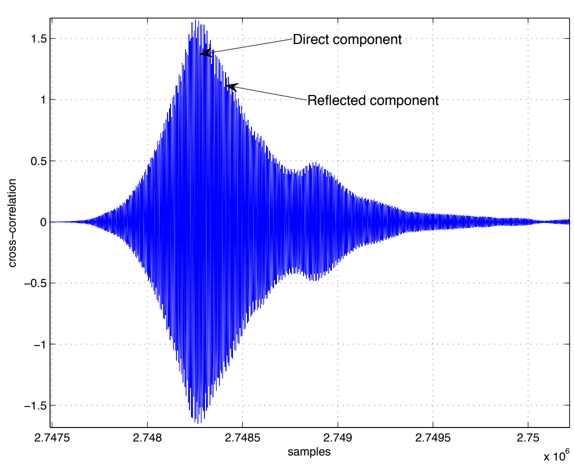

Fig. 2. Cross-correlation of transmitted signal with received one.

by sending 12 acoustic pings for each area and the depth is obtained by averaging on different measures. The area is characterized by its center (a square of 20m x 20m). The depth ranges from 1.80 meters to 3.90 with a maximum close to bridges due to reinforces concrete for pillars. This justifies also the shape of the bathymetric regions in the picture. Spanning the reservoir from left to right we can observe that at the beginning (extreme left) the depth is maximum, that is, a few centimeters less than 4 meters. The a *small floor step* is present and the depth is around 3.60 meters. Then two different areas are present (around 200m in the horizontal axis). The upper part is still around 3.50 meters while a step of 1 meter (leading depth to 2.60 meters) is present in the lower part. After, the lake present an increasing area in the upper and lower part (in correspondence of 400m horizontal axis). While the central zone (200 m vertical axis) the depth

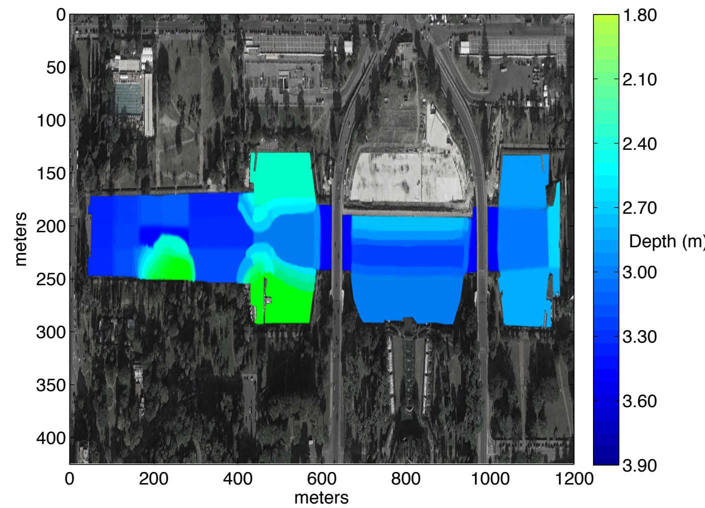

Fig. 3. Bathymetric map for reservoir.

is around 3.20 meters, the upper part presents a smaller depth while the lower part of the reservoir achieves 1.80 meters. This is justified by the presence of a jetty where the pedalos can be rent and start. As anticipated, under the pillars of the road passing on the reservoir the depth is the maximum. After, when the horizontal axis achieves 800 meters, the depth is around 3 meters even though in the upper part is a bit smaller. Then, after the second series of pillars (at 1000 meters on the horizontal axis), the depth decreases since it is between 2.40 and 2.10 meters. It is important to note that the expected error is higher in correspondence of the borders of the reservoir due to reflections by the walls and in the previously detailed jetty area since there some pedalos and small boats are present and reflections are rich.

In order to discuss about lake-floor composition we focused on the classification of the attenuation. We collected all the peaks related to reflection (the main component) and then we gathered them into a vector. Successively, we proceeded to draw the histogram in order to have a statistical description of the amplitudes of the reflections. We must preliminary consider the information available before this measurement campaigns. The lake-floor, despite of possible sediments, is characterized by asbestos. So, in this regard, it is possible to infer about possible sediments present and/or their absence. By considering the histogram and the two modes, one centered

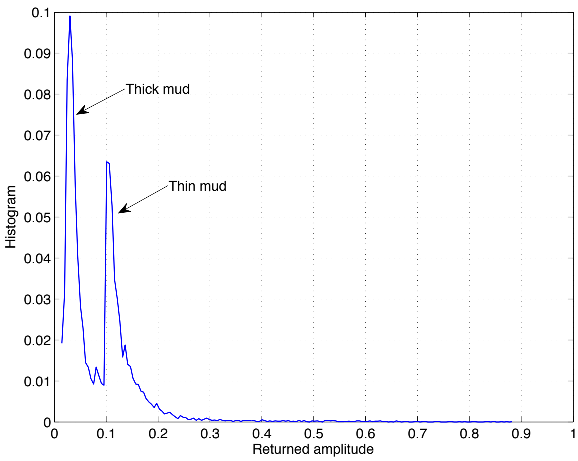

Fig. 4. Histogram of the returned amplitude, measured with the hydrophone.

around 0.02 and on around 0.12, by resorting to the studies in [10]-[12] it is possible to argue that the floor is characterized by mud essentially of two different kinds. One is thick since the signal is strongly attenuated (and this is the largest part) and one is thin mud. No values higher than 0.8 have been found even though, values over 0.7 are related to the part of the like under the two bridges. However, since the area spanned by the roads (under the roads) are very small if compared with the area of reservoir, the peaks obtained as reflection of the signal under the roads represents a very small percentage of the all the acquisition.

V. Conclusion

The proposed scheme for analyzing the bathymetry of very shallow water reservoir started from the requirement of limiting the cost both in terms of economical expenses and processing required to acquire such information. Two different schemes have been considered. The first one is based on Fourier analysis and the second one on correlation properties. Both the schemes are reliable when no surrounding objects are present while the second one is better when other reflections that are not due to water bed are present.

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