SINGLE HYDROPHONE PASSIVE ACOUSTIC SPERM WHALE RANGE AND DEPTH ESTIMATION

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ABSTRACT

Sperm whales (Physeter macrocephalus) emit acoustic signals when diving to search for food. Because they dive to depths of over 1500 m, conventional localization methods are impractical. Sperm whales produce a series of loud impulsive echolocation sounds called 'clicks' at a fairly constant rate, and these signals can be used for localization. A geometric approach is considered using signals from the direct and surface reflection paths. The time difference of arrival (TDOA) between these paths is used for localization. Real sperm whale data from the Atlantic Undersea Test Center (AUTC) is used to evaluate the proposed method.

Index Terms— Passive localization, Sperm whale, Sea surface reflection

1. INTRODUCTION

The behaviour of sperm whales (Physeter macrocephalus) has been of great interest to scientists over the last few decades. An interesting characteristic of these mammals is that they can dive to depths of over 1500 m in search of food [1]. They are endangered due to human activities on the sea surface such as acoustic navigation, air gun operation, sonar and shipping that produce significant interference in the ocean [1]- [4]. Sperm whales use distinct sounds called 'clicks' for orientation, communication and prey detection. Thus understanding this interference and decreasing its effect on sperm whales and other marine mammals is an important subject which is being investigated by many academic and government institutions.

The use of underwater sound tests has been suspended through courts orders because they disrupt sperm whale behaviour [4]. This has increased interest in marine mammal detection and localization. Mammal visual surveillance is commonly employed along with acoustic monitoring. For example, an autonomous underwater vehicle (AUV) and a hydrophone array have been used for sperm whale tracking [5, 14]. However, this technique may not provide accurate results because sperm whales become silent due to the interference produced by the AUV [4]. Thus a more useful approach for marine mammal identification is passive acoustic tracking. This can be employed in a wide range of weather condition and at any time of the day or night. Hyperbolic fixing is a common passive acoustic technique for marine mammal localization [6]- [8]. It exploits the difference in the time of arrival of sperm whale clicks on multiple hydrophone pairs. An acoustic propagation modelling method has been developed to increase the accuracy of this approach in shallow water environments [9]. An ambiguity surface is obtained to identify the most probable whale position, but only in the horizontal plane.

Sperm whale localization using tagging was recently employed to collect continuous diving behaviour data [10]. However, human activity on the sea surface to obtain tag signals can disrupt this behaviour. In addition, finding whales in the ocean is not an easy task. Other techniques are based on signals from multiple paths, but using echoes from the ocean floor is not practical due to the low received signal levels. A single hydrophone has been used to estimate the depth and range of foraging sperm whales [11], but an operator must record the signals and calculate the delay values required for localization. Automated click detection and delay calculation has recently been developed for real-time localization [12]. This method employs geometric techniques with reflected signals from the sea surface and sea floor. Sea floor echoes are typically reflected off a rough surface, travel long distances, and have high incidence angles. Thus these signals can be of very poor quality. Passive hydrophone arrays have recently been used for sperm whale depth estimation [15], but this approach requires an initial range estimate and the angle of arrival of the signal.

In this paper, a single hydrophone is used for passive sperm whale localization, including the range and depth. The proposed technique employs acoustic click sequences from the direct path and sea surface reflection. A geometric approach is used with these signals to develop a system of equations to obtain the range and depth. The remainder of this paper is organized as follows. Section 2 explains sperm whale behaviour in terms of their diving profile and acoustic sounds. The problem formulation and signal model are

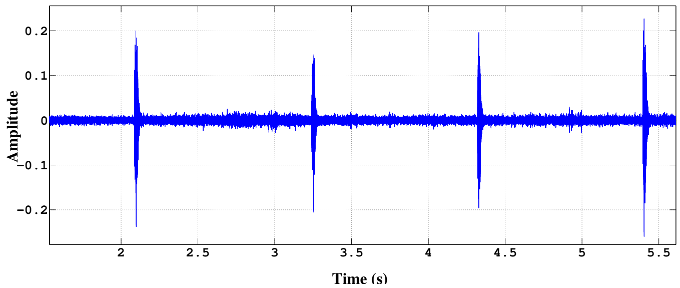

Fig. 1. A sperm whale click sequence.

presented in Section 3. Performance results are presented in Section 4 to show the effectiveness of our method, and finally some conclusions are given in Section 5.

2. SPERM WHALE DIVING BEHAVIOUR

Sperm whales use a diving and breathing sequence while foraging in the ocean. They remain on the sea surface to breathe and then dive down to a hunting depth of 1500 m or more. The duration of a dive is typically between 30 to 90 min, and then the whale returns to the sea surface for approximately 10 min [1, 13]. They behave like an active sonar and observe the environment using acoustic sound clicks. Both male and female sperm whales produce high intensity impulsive clicks while diving.

A typical sperm whale click signal detected using a single hydrophone is shown in Fig. 1. Each click signal includes sea surface and sea floor reflections. The time delay between the direct and surface reflection paths is denoted as $\Delta\tau$. The sea floor reflection has very little relative energy and thus is not significant compared to the direct path signal. The click rate is between 0.5 to 2 clicks per second. The variation in the click rate depends on the sperm whale activity, i.e., moving upward, downward or hunting. Each click has a duration of approximately 5 ms which can be considered as the time resolution for segmenting these signals.

The clicks have significant energy compared to the ambient noise so the signal to noise ratio (SNR) for received acoustic data is quite good. Therefore, an energy-based threshold can be employed for click detection [16]. This threshold can be determined adaptively based on the average energy of the preceding segments. Once a click is detected in a segment, the detection time is defined as when the absolute value of the signal reaches its maximum.

3. SINGLE HYDROPHONE LOCALIZATION

The objective here is to determine the range and depth of an encountered whale. Towards this goal, the signal geometry is now examined. Fig. 2 shows that this geometry in two

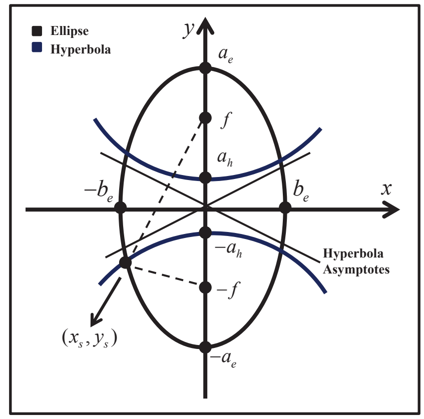

Fig. 2. The localization geometry model.

dimensions (vertical plane) consists of an ellipse and a hyperbola. Both the ellipse and hyperbola have focal points f and $-f$ on the vertical axis. The major and minor axes are shown aligned with the Cartesian axes. The equations for the ellipse and hyperbola can be written as

$$\frac{y^2}{a_e} + \frac{x^2}{{b_e}^2} = 1, \tag{1}$$

and

$$\frac{y^2}{a_h} - \frac{x^2}{{b_h}^2} = 1, \tag{2}$$

respectively, where a_e is the semi-major and b_e the semi-minor axes of the ellipse, a_h is the distance between the center of the cartesian axes to either vertex of the hyperbola, and b_h is the perpendicular length to the asymptotes from each vertex of the hyperbola. The focal points are the same for the ellipse and hyperbola and are given by

$$f^2 = {a_e}^2 - {b_e}^2, \tag{3}$$

and

$$f^2 = {a_h}^2 + {b_h}^2, \tag{4}$$

respectively.

Consider the bottom branch of the hyperbola and its intersection point (x_s, y_s) with the ellipse. Let d_1 and d_2 be the distances from this intersection point to the focal points. The sum and difference of these distances are

$$d_2 + d_1 = 2a_e, \tag{5}$$

and

$$d_2 - d_1 = 2a_h, \tag{6}$$

respectively. Substituting (3)-(6) into (1) and (2) gives

$$\frac{y^2}{(d_1 + d_2)^2} + \frac{x^2}{(d_1 + d_2)^2 - 4f^2} = \frac{1}{4}, \tag{7}$$

and

$$\frac{y^2}{(d_2-d_1)^2} - \frac{x^2}{4f^2-(d_2-d_1)^2} = \frac{1}{4}, \tag{8}$$

respectively.

Figure 3 shows a sperm whale radiating a sequence of clicks while diving. A single hydrophone receives these signals from both the direct and surface reflected paths. Sea surface echoes have sufficient energy to easily be detected while sea floor echoes are ignored because of the longer distances and low signal levels. It is assumed that the speed of sound is a constant c, therefore we neglect any minor variations in the speed of sound in sea water [10].

The sperm whale is located at (x_s, y_s) where x_s is the horizontal distance to the hydrophone and y_s is the whale depth from the sea surface. The hydrophone is at a known depth h from the sea surface. A sequence of direct path clicks and its surface echoes are received by the hydrophone. The reflected signal is shown assuming the sea surface is smooth at the reflection point. Therefore, the indirect signal path yields a virtual hydrophone at a height h above the sea surface equal to the hydrophone depth. The real and virtual hydrophones result in an ellipse and hyperbola with focal points $f = \pm h$ that pass through the sperm whale location. These are shown as dashed lines at the sperm whale location in Fig. 3. From this figure, the difference between the direct and indirect path distances can be written as

$$r_s - r_1 - r_2 = c\Delta\tau, \tag{9}$$

where $\Delta\tau$ is the time difference of arrival (TDOA) between the signals from the direct path r_s and the surface reflected path $r_1 + r_2$. Equating Figs. 2 and 3, gives $r_s = d_1$ and $r_1 + r_2 = d_2$. Therefore, substituting (9) into (8) results in

$$\frac{4{y_s}^2}{(c\Delta\tau)^2} = \frac{4{x_s}^2}{16h^2-(c\Delta\tau)^2} + \frac{1}{4}. \tag{10}$$

Considering the sum of the direct and indirect path distances $r_1 + r_2 + r$, (7) can be rewritten as

$$\frac{{y_s}^2}{(r_s+r_1+r_2)^2} = \frac{1}{4} - \frac{{x_s}^2}{(r_s+r_1+r_2)^2-4h^2}. \tag{11}$$

From Fig. 3, we have

$$r_s + r_1 + r_2 = \sqrt{{x_s}^2+(y_s-h)^2} + \sqrt{{x_s}^2+(y_s+h)^2}. \tag{12}$$

After detecting the direct and sea surface reflected signals, the delay between the paths $\Delta\tau$ can be calculated. Substituting c, $\Delta\tau$ and h into (10) gives one equation with unknowns x_s and y_s, and substituting (12) and h into (11) gives a second equation. Therefore the sperm whale range and depth can be obtained by solving these two equations. Two different solutions will be obtained, but if the origin of the coordinate system is on the sea surface directly above the hydrophone, the true sperm whale position is $(-x_s, -y_s)$. The other solution is (x_s, y_s), which is behind the hydrophone and so can easily be eliminated.

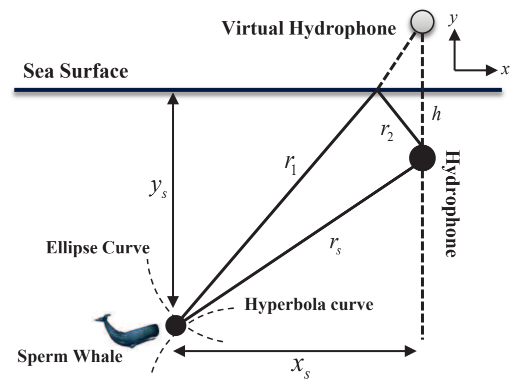

Fig. 3. The sperm whale acoustic signal environment.

4. PERFORMANCE RESULTS

The performance of the proposed passive localization method is presented in this section. The sperm whale location is computed from the extracted click signals using the geometric technique developed in the previous section. The time delay between the direct and reflected paths, $\Delta\tau$, was calculated using real sperm whale data from the Atlantic Undersea Test Center (AUTC). In particular, deep ocean data from the abyssal plain of the Mediterranean Sea recorded in August 2004 was employed. The data was recorded using a bottom mounted hydrophone at a depth of $h = 1.5$ km in the tongue of the ocean at a sampling frequency of 48 kHz. The speed of sound was assumed to be $c = 1500$ m/s. The resulting sperm whale range and depth are shown in Figs. 4 and 5, respectively, along with the real trajectory. Over the 400 s period, the depth varied from 440 m to 600 m, and the range varied from 4472 m to 4530 m. The difference between the real trajectory and the results using the localization algorithm shows the accuracy of the proposed technique is very high. The mean square error (MSE) for the depth is 11.38 m^2 and for the range is 13.72 m^2. The error in the range and depth tracking is due to variations in the sea surface echo delay and the speed of sound underwater. The mean square error (MSE) can be decreased by employing accurate estimates of the speed of sound underwater. However, the results obtained are suitable for applications that require sperm whale localization.

5. CONCLUSION

In this paper, a new single hydrophone method was presented to estimate the range and depth of a sperm whale. A geometric technique based on the intersection of an ellipse and hy-

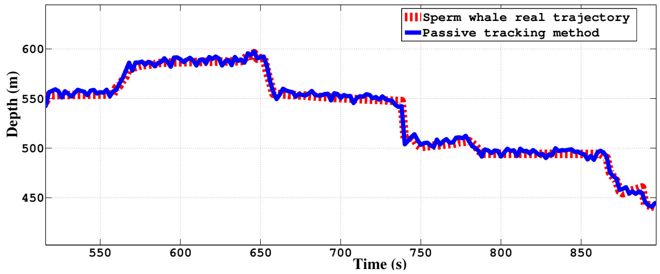

Fig. 4. Sperm whale depth tracking trajectory using real data.

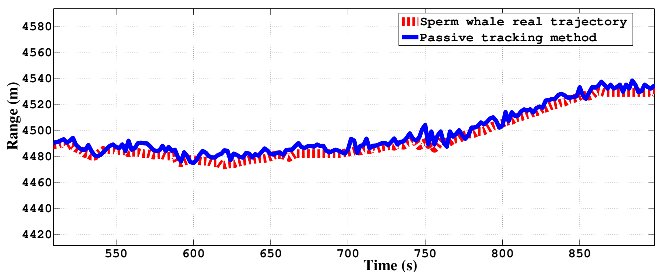

Fig. 5. Sperm whale range tracking trajectory using real data.

perbola was developed which uses direct and sea surface reflection signals. Performance results using real data were presented which verify that the proposed method is effective for sperm whale localization. Thus it is a very useful technique that can be used by biologists to investigate sperm whale behaviour. The advantage of the proposed approach is that it is passive and thus does not disturb natural sperm whale activity. Therefore it can be used to investigate whale disruption due to man made interference. This method can be extended to utilize a hydrophone array for multiple sperm whale localization and/or to improve accuracy.

6. REFERENCES

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