A New High Accuracy Super Short Base Line (SSBL) System

Marvin Watson, Chester Loggins and Y. Thomas Ochi
Sonatech, Inc.
watson@sonatech.com

ABSTRACT

This paper describes a recently patented acoustic Super Short Baseline (SSBL) tracking system capable of tracking up to twenty targets simultaneously, accurately and at long ranges. The design of the hydrophone array is similar to that of conventional SSBL arrays, but uses greater inter-element separation to provide much better tracking accuracy. With this design, the bearing and elevation of targets at ranges greater than 10 km can be tracked with an accuracy better than 0.1 degree.

The application of SSBL to target tracking is not new as witnessed by several SSBL products on the market. Recent applications require tracking accuracy's for ranges that exceed those of existing SSBL systems. In these applications a significant improvement in the bearing and range accuracy of the SSBL system can substantially reduce operational cost. These applications include: full ocean depth SSBL systems for ROV navigation and tracking; towbody tracking; integrated LBL and SSBL navigation; and long seismic streamer tracking.

This paper discusses the design and performance of an integrated SSBL/LBL system that provides 0.1% slant range accuracy at ranges greater than those achievable using currently available SSBL tracking systems.

INTRODUCTION

Long Base Line (LBL), Short Base Line (SBL) and Super Short Base Line (SSBL) or Ultra Short Base Line (USBL) Systems have long been used to accurately locate and track underwater objects. Any of these systems, or a combination thereof, can be used to track a ship or a towbody.

LBL systems, because of their long baselines, provide the most accurate position estimates. A disadvantage of typical, commercially available LBL is that the position update rate is on the order of a minute in deep water. Another disadvantage is the time required to deploy, calibrate and recover transponders.

SBL systems require the installation of hydrophone elements at several widely spaced, carefully surveyed locations on the ship or the platform ("the vessel" in the following discussion). This installation is best performed at the time of vessel manufacture or, minimally, in dry dock. A disadvantage of SBL systems is that some of the hydrophones may be placed in high noise areas (such as near the screws or machinery), which degrades tracking performance. An SBL system provides more accurate position estimates than traditional SSBL systems, but less accurate estimates than LBL systems. Once the SBL array is installed it provides more cost-effective surveys since deployment and calibration of a transponder grid is not required. However, a single transponder to provide a fixed reference position is still desirable during mapping operations.

SSBL systems usually provide less accurate position estimates than the other two tracking system types. Unlike LBL and SBL tracking systems, SSBL systems use only a single, compact hydrophone array that is installed on a vessel. This array is mounted as a single unit at a location where flow and structure noise are low. In the long term, SSBL systems provide the most cost-effective tracking since a transponder grid is not required. With proper design the SSBL system can provide accuracy approaching that of SBL or LBL. As with SBL systems, in mapping operations, a reference transponder is desirable.

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Oil, ocean mining, geological survey industries and others have requirements to survey large ocean areas accurately and cost effectively. The approach presented in this paper provides a system with both state-of-the-art accuracy and cost advantages over traditional approaches.

SYSTEM APPROACH

The basic approach utilizes the same equilateral-triangle configuration of hydrophone elements used in most conventional SSBL systems. In conventional SSBL systems transducer elements are separated by λ/2. This separation eliminates ambiguities and enables a direct computation of bearing from the inter-element phase differences. The disadvantage to this close spacing is relatively poor accuracy. Accuracy is improved by increasing inter-element spacing. In this new SSBL approach, the separation between array elements is several λ. However, the large inter-element spacing causes ambiguous bearing estimate. Additional processing and design features are required for ambiguity resolution. Techniques for ambiguity resolution are described below.

The Sonatech SSBL hydrophone array has an inter-element spacing of several λ to improve inter-element bearing estimation accuracy. This inter-element spacing is consistent with desired accuracy and is compatible with available mounting space on most vessels. The configuration discussed here is a hydrophone array that provides 3λ to 5λ spacing at a nominal frequency of 16 kHz for low band frequency operation, and 19 to 32 kHz for medium band frequency operation. This array is of practical size for easy mounting while providing very high accuracy.

With 5-λ spacing a bearing accuracy 10 times more precise than with λ/2-spaced elements is obtainable. The bearing estimates derived directly from inter-element phase differences from the 5λ-spaced array are ambiguous, but several techniques are available to resolve these ambiguities. Coarse bearings can be estimated from inter-element time delays, or can be provided by additional array elements spaced at λ/2. The first technique requires substantial cross-correlation processing; the second requires at least two additional array elements and their associated receiver channels, as well as additional processing.

The approach developed offers a simpler and less expensive means of ambiguity resolution that has several advantages not provided by conventional systems. The proposed method provides a direct, unambiguous high-resolution bearing estimate without cross-correlation and without requiring additional hardware. In addition, it permits computation of a real-time estimate of the standard deviation of the estimated bearing. This feature also permits the processing software to identify and use only the portion of the acoustic return unaffected by multi-path. The final estimate of the standard deviation (of the real-time estimate) provides an assessment of the quality of the bearing estimate.

SYSTEM ANALYSIS

The phase difference values between hydrophone elements are computed using :

$$\phi_{12}(n) = phase\{(I_1(n) + jQ_1(n)),(I_2(n) - jQ_2(n))\}$$

$$\phi_{23}(n) = phase\{(I_2(n) + jQ_2(n)),(I_3(n) - jQ_3(n))\}$$

$$\phi_{13}(n) = phase\{(I_1(n) + jQ_1(n)),(I_3(n) - jQ_3(n))\},$$

where $I_i(n)$, $Q_i(n)$ are the in-phase and quadrature components of the n^{th} signal sample for hydrophone element number i.

As long as the signal amplitudes exceed a minimum threshold value, the average phase value and variance are computed over several samples for each of the phase differences. The process is repeated until the end of the pulse unless an increased variance indicates signal corruption. The resulting average phase difference and phase variance are stored in a digital signal processor. Several pulses at different frequencies are transmitted and the phase values measured from each pulse is stored. These phase values lie along a straight line and the slope of this line is computed using a least square fit.

The slope of this line yields :

$$slope = (\frac{2\pi d}{c})\sin(\theta)$$

where θ is the bearing angle being measured, d is the separation between elements in meters, c is the local sound speed in m/sec, and $slope$ is the slope of the best-fit straight line to the phase-difference as a function of frequency data.

For a zero degree elevation angle, the bearing angle can now be estimated from

$$\theta = Arcsin\left[(slope\,(\frac{c}{2\pi d})\right]$$

Note that the bearing estimates derived in this way are unambiguous. The three bearing estimates obtained from ϕ_{12}, ϕ_{23}, and ϕ_{13} are used to estimate the bearing and elevation angles [1].

SYSTEM COMPARISON

The estimated direction of signal arrival is determined from the relative time difference of arrival (TDOA) for each pair of hydrophone elements. The accuracy of the relative time delay estimation depends upon the signal bandwidth, the signal-to-noise ratio, the noise bandwidth, and multipath.

The traditional solution to the problem of multipath involves transmitting a series of chirp pulses with sufficiently short duration to avoid interference between direct path and multipath signals. Each chirp is received and digitized by each of the hydrophone receiver channels. The generalized cross-correlation method, Figure 1, is used to measure the relative time delays of the signals. After a series of time delay estimates have been obtained, the mean value of the time delay estimates can be used to provide a more accurate time-delay estimate as shown in Figure 2.

The frequency response of the projector, signal absorption in the water, and frequency response of the hydrophones combine to convert the square wave pulses into sinusoidal pulses in the receiver electronics. The received signals are digitized and processed using a variation of the generalized cross-correlation method.

The performance of this approach was compared with the performance obtained from the traditional chirp-based approach using a Monte Carlo Simulation. Two tests of 100 trials were run. The performance of the new approach is compared to conventional chirp processing in Table 1. This Table shows the mean and standard deviation of the estimated time-difference-of-arrival for a single hydrophone pair, as computed using the chirp approach and the new approach just described.

Table 1 TDOA Estimation Performance

	Test #1		Test #2	
Waveform Type	Mean Error (μsec)	Std Dev (μsec)	Mean Error (μsec)	Std Dev (μsec)
Chirp	-.031	1.72	.043	1.48
New Approach	-.035	0.79	-.026	0.68

Predicted accuracy was also computed from the 100 bearing estimates obtained for each Monte Carlo simulation. Results are provided in Table 2.

Table 2 Predicted Bearing Accuracy

	Test #1		Test #2	
Waveform Type	Standard Deviation for Time-of-Arrival (μsec)	Equivalent Angular Accuracy (degrees)	Standard Deviation for Time-of-Arrival (μsec)	Equivalent Angular Accuracy (degrees)
Chirp	1.72	0.25	1.48	0.21
New Approach	0.79	0.11	0.68	0.097

The described approach provides better than a factor of two improvement in the standard deviation in time-of-arrival estimation. When converted to an equivalent angular accuracy, based on the 0.6-m spacing between the hydrophones, the computed time-of-arrival error yields a predicted accuracy in bearing measurement of 0.1 degrees.

The solution described offers several advantages over the traditional approach. Because square waves signals are transmitted, the transmitter design is simpler and more efficient than the design using the chirp waveform. The signal processing involves fewer computations for time of arrival, and the resulting direction of arrival estimates have improved accuracy over those obtained using the traditional chirp-based method.

For an array with elements separated by 60 cm and with near-normal incidence angles, the 0.7 μsec standard deviation in the time delay estimate corresponds to a direction of arrival accuracy of 0.1 degrees.

SOUND SPEED MEASUREMENT

Each SSBL hydrophone is capable of transmitting signals which can be received by other hydrophones within the array. Knowing the precise locations of hydrophones, the sound velocity at the hydrophone array is measured very accurately by performing multiple phase measurements and averaging the results.

TRACKING RANGE

Assume that the hydrophone array is mounted on a ship, where the noise environment is approximately 14 dB above Sea State 6. Also assume that the ship is tracking a towbody. Tracking accuracy is directly related to signal-to-noise ratio (SNR), and good tracking cannot be achieved with low SNR. Estimated SNR values were computed at potential operating frequencies for the towbody tracking system. Table 3 shows the assumed ship which generates relatively high background noise levels near the hydrophone array mounting position. Sea State 6 noise levels are provided for comparison.

Table 3
Ship Background Noise Level

Frequency	Ship's Noise Level (dB//μPa per root Hz)	Sea State 6 Level (dB//μPa per root Hz)
10	68*	53.5
15 kHz	64*	50.3

* Total Noise Level for a speed of 8 kt.

Now consider the propagation losses for a slant range of 10 km. The spreading loss (LO_{sp}) is given by

$$LO_{sp} = 20Log_{10}(10000) = 80 \text{ dB}.$$

The absorption loss (LO_{ab}) is

$$LO_{ab} = 10000\alpha,$$

where α is the acoustic absorption in dB/meter.

To minimize array size and achieve accurate bearing estimates, the operating frequency should be selected as high as possible. Absorption losses limit the maximum useful operating frequency, and therefore frequencies above about 18 kHz are not viable for a range greater than 10 km. Frequencies in the range from 10 kHz to 15 kHz were considered, and are consistent with obtaining accurate bearing estimates with a relatively small array.

The absorption losses for the maximum range scenario are accumulated along a path originating at great depth, 4500 m, and continuing on to the hydrophone array near the surface. The coefficient of absorption, α, decreases with depth. For 4500-m depth, the decrease is substantial -- at 15 kHz, $\alpha = 1.2\text{x}10^{-3}$ dB/m at 4500 m vice $\alpha = 2.3\text{x}10^{-3}$ dB/m near the surface (at the same temperature). Using an "average" or "harmonic" absorption coefficient equal to average of the deep and shallow coefficients, the estimated absorption losses (for 10 km) are:

$$LO_{ab} = 10 \text{ km}(0.75) = 7.5 \text{ dB at } 10 \text{ kHz} \quad (\alpha = 0.75\text{x}10^{-3} \text{ dB/m}),$$

$$LO_{ab} = 10 \text{ km}(1.6) = 16.0 \text{ dB at } 15 \text{ kHz} \quad (\alpha = 1.60\text{x}10^{-3} \text{ dB/m}).$$

Assume a source level (SL) for the towbody responder of 205 dB//µPa at 1 m. Then the signal level received at the array from a 10 km range is:

$$S = SL - LO_{sp} - LO_{ab}$$
$$S = 205 - 80 - LO_{ab}$$
$$= 117.5 \text{ dB} \quad \text{at 10 kHz}$$
$$S = 205 - 80 - LO_{ab}$$
$$= 109.0 \text{ dB} \quad \text{at 15 kHz}$$

and the noise level is:

$$N = \text{Ship's self Noise} + 10\text{Log}_{10}(BW)$$
$$N = 68 + 10\text{Log}_{10}(250)$$
$$= 91.8 \text{ dB} \quad \text{at 10 kHz}$$
$$N = 64 + 10\text{Log}_{10}(250)$$
$$= 87.8 \text{ dB} \quad \text{at 15 kHz}$$

using a 250 Hz receiver bandwidth. The SNR is then:

$$SNR = S - N = 117.5 - 91.8 \text{ dB}$$
$$= 25.7 \text{ dB} \quad \text{at 10 kHz}$$
$$SNR = S - N = 109.0 - 87.8 \text{ dB}$$
$$= 21.2 \text{ dB} \quad \text{at 15 kHz.}$$

These SNR values are sufficient to obtain a bearing estimation accuracy of 0.1 degree or better.

CONCLUSION

The recently patented SSBL acoustic tracking system described will track an underwater object with an accuracy of 0.1 degree to ranges of 10 km, providing a level of performance not achievable with available tracking systems.

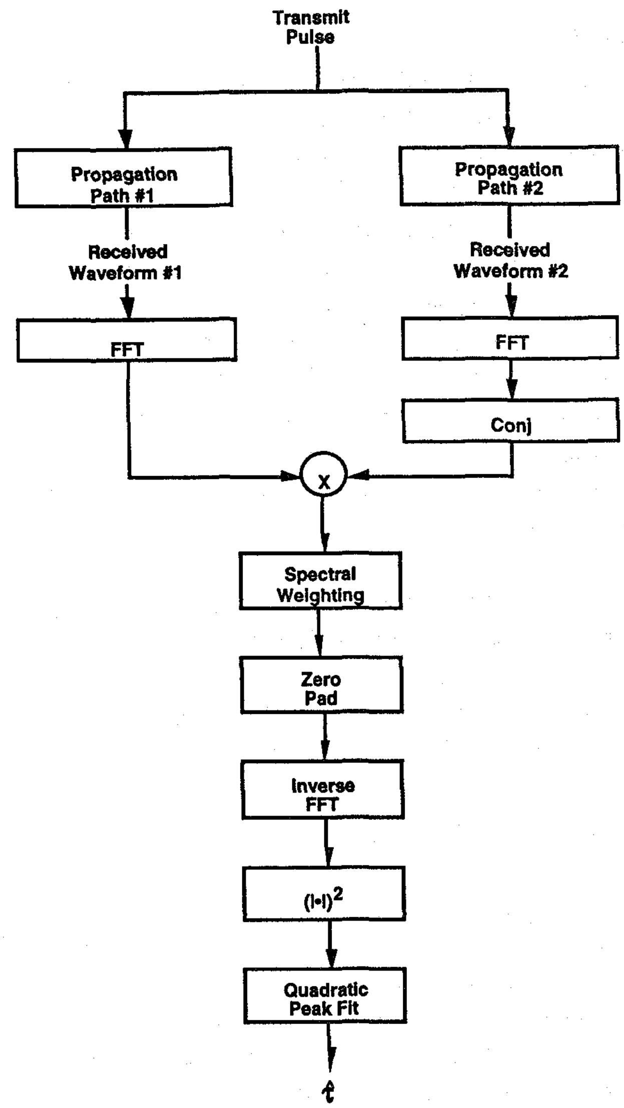

Figure 1. Generalized Cross-Correlation Method

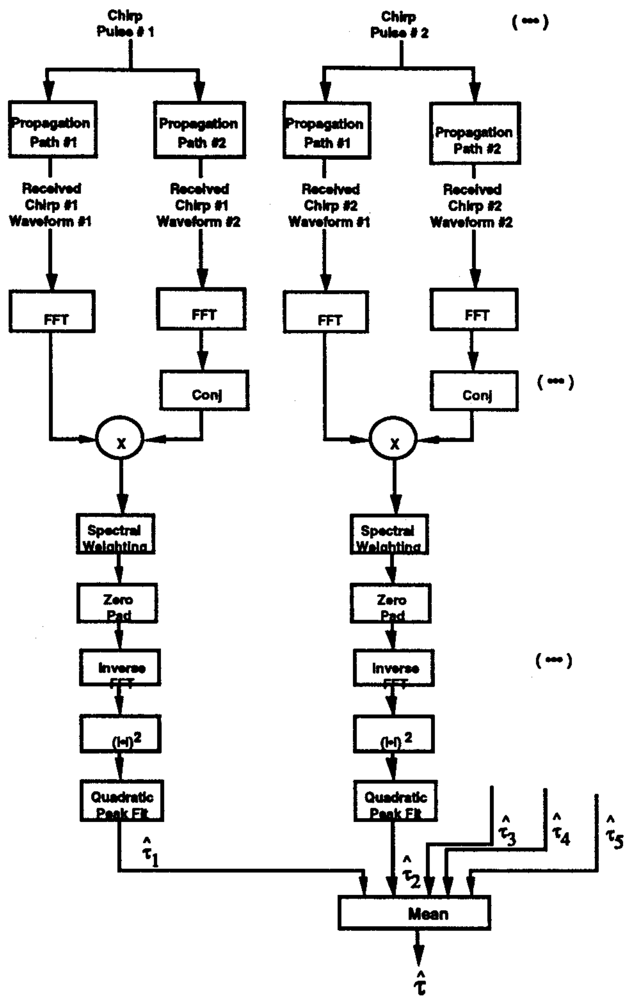

Figure 2. Multiple Chirp Cross-Correlation Method

Reference

[1] Marvin Watson, et. al,
"Super Short Baseline Acoustic Tracking System,"
IEEE Oceans proceeding, 1984