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Bearing Estimation of Narrow Band Acoustic Signals Using Cardioid Beamforming Algorithm in Shallow Water

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Abstract

This paper suggests the Cardioid beamforming algorithm of the doublet sensors employing DIFAR (directional frequency analysis and recording) sensor signals in the frequency domain. The algorithm enables target bearing estimation using the signals from directional sensors. The algorithm verifies its applicability by successfully estimating bearings of a target projecting ten narrow-band signals in shallow water. The estimated bearings agree very well with those from GPS (global positioning system) data. Assuming the bearings from GPS data to be real values, the estimation errors are analyzed statistically. The histogram of estimation errors in each frequency have Gaussian shape, the mean and standard deviation dropping in the ranges -1.1°~6.7° and 13.3°~43.6°, respectively. Estimation errors are caused by SNR (signal to noise ratio) degradation due to propagation loss between the source and receiver, daily fluctuating geo-magnetic fields, and non-stationary background noises. If multiple DIFAR systems are employed, in addition to bearing, range information could be estimated and finally localization or tracking of a target is possible.

Keywords: *Cardioid beamforming, DIFAR, MRA*

I. Introduction

Modern military sonars employs one or more kinds of beamforming algorithms in discriminating target signals from background noises. As one of spatial filters, the beamformers enable to detect, classify, and track the underwater targets. Among many bearing estimation techniques, passive sonars generally use the methods of energy detection and cross correlation[1,2]. The energy detection method estimates bearings comparing beam outputs from the MRA (maximum response axis). That is, the estimated one is regarded as the bearing which gives maximum response. The resolution can be improved by interpolating between spatial bearings. On the contrary, cross correlation method computes the time delay of incident wave on the separated two sensors and then estimates the bearings from the delay information.

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Traditional methods of bearing estimation, using passive sonobuoys, include CODAR (correlation, detection, and ranging) and JULIE(common name of dancer) techniques. CODAR technique obtains rough bearing information using four LOFAR sonobuoys equally spaced around 360°. As one of echo ranging methods, JULIE just deploys LOFAR (low frequency analysis and recording) sonobuoys at some intervals and estimates target location using the echo signals from the sonobuoys, the echo being available when strong underwater sources (for example, explosive) are activated[3]. These methods, however, are hard to keep steady localization mainly due to sonobuoy drift with time. In addition, they are designed to be operated in an aircraft so that they are hardly applicable in sea experiments.

This study suggests a reliable algorithm of the Cardioid beamforming which enables the bearing estimation adopting dipole sensors on the same axis. The Cardioid beamformer has the maximum response of 6 dB on the MRA and the minimum at null point. The null point is very useful because one can exclude interference noises by matching it to the direction of noises.

The Cardioid beamforming can be realized by the two types of sensor arrangement. One is a method which applies doublet hydrophones of piezoelectric pressure. This method is valid when the phase delay between hydrophones satisfies the condition $\delta = kd \ll 1$. Here, k is wavenumber concerned and d the distance between hydrophones. The other method employs one omni-directional hydrophone and two directional velocity hydrophones. Typical system is a DIFAR sonobuoy utilizing the orthogonality and sum mode of the sensors.

We focus on the Cardioid beamforming algorithm in frequency domain and its application to the bearing estimation of underwater target in shallow waters.

II. Theory

A. Beamforming with Doublet Hydrophones

Omni-directional pressure hydrophone itself receives acoustic signals with same weight from all directions and thus gives no bearing information of targets. Hence, almost all sonars have more than one hydrophones arranged in specified pattern to guarantee high SNR and steered response at some direction.

Two omni-directional hydrophones can be arranged in

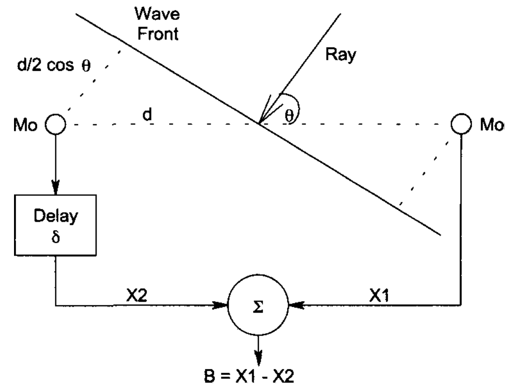


Figure 1. Cardioid beamforming principle using doublet hydrophones.

various manners to obtain various spatial beam patterns. That is, spatial beam pattern is a function of distance between hydrophones, output polarity coupling, and specified phase delay in one hydrophone. This kind of hydrophone arrangement is classified as doublet or super-directive hydrophones[4].

Let the received signal output be $x(\omega t)$, then, beam output of phase delay δ in time domain can be expressed as following equation,

$$b(t, \theta) = x(\omega t) - x(\omega t + kd\cos\theta + \delta) \tag{1}$$

The beam output can be transformed to frequency domain,

$$B(f, \theta) = X(f) - X(f)\exp[j(kd\cos\theta + \delta)]. \tag{2}$$

Here, $kd\cos\theta$ is phase delay of each direction due to the distance d between hydrophones and $X(f)$ is Fourier transform of $x(\omega t)$. Eq. (2) is normalized by $X(f)$ to give the following equation,

$$\left|\frac{B(f,\theta)}{X(f)}\right| = \sqrt{X_{comp}^2 + Y_{comp}^2} = 2 \cdot \left|\sin[(kd\cos\theta + \delta)/2]\right|,$$
$$X_{comp} = 1 - \cos(kd\cos\theta + \delta),\quad Y_{comp} = \sin(kd\cos\theta) + \delta. \tag{3}$$

Meanwhile, receiving voltage sensitivity of doublet hydrophones can be given as Eq. (4),

$$M = 2M_o\sin[(kd\cos\theta + \delta)/2] = 2M_oD,$$
$$D = \sin[(kd\cos\theta + \delta)/2]. \tag{4}$$

Here, $k=2\pi/\lambda$ is wavenumber, D effective diffraction constant, and M_o the free-field voltage sensitivity of pressure hydrophone determining the MRA response and receiving beam pattern.

Employing superdirective hydrophones, one can design beam pattern as a function of phase delay parameter. Pressure gradient (or simply velocity) hydrophone has two omni-directional hydrophones to produce dipole beam pattern. Two ceramics are attached on the same axis so that they have negative polarity each other. If the vibration occurs along the axis, there exists expanding force in one direction and compressing force in other direction at the same time resulting no cancelation of output signals. If the vibration occurs along other direction, two ceramics exert internal stress in the same direction cancelling output signals. This property of dipole pattern makes the hydrophones not receive acoustic signals in other axis except the detection axis and thus results in discriminating the signals into two components of parallel and normal to the axis.

B. Beamforming with DIFAR

Originally, DIFAR system was modified from LOFAR sonobuoy and designed in an attempt to detect underwater targets in an aircraft. DIFAR system has additional doublet sensors giving dipole beam pattern while LOFAR sonobuoy has only one omni-directional sensor. DIFAR system consists of two directional sensors having dipole beam pattern (north-south and east-west components), magnetic compass to measure the bearing of sensor axis relative to magnetic north, and an omni-directional sensor. In addition to the sensors, three parts comprise the system: signal cable producing low level of flow noise, electronic circuit modulating the acoustic signals, and surface buoy transmitting the modulated signals through VHF (very high frequency) channel.

Omni-directional sensor just receives signals in all directions without giving no bearing information of targets. DIFAR system obtains the bearing information by decomposing the received signals into quadrature components. The system transmits the acoustic signals from omni-directional sensors as well as the bearing information from directional sensors using the technique of frequency division multiplexing and transmission[5].

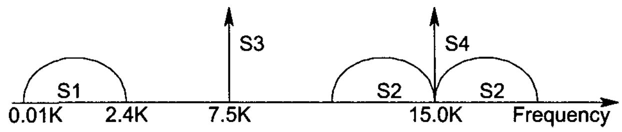


Figure 2. DIFAR transmission power spectra.

Each signal component is expressed as follows:

$$\begin{aligned} S1 &= E_0 \sin(\rho t+\psi) \\ S2 &= E_d \sin(2\omega t+\phi+\theta)\sin(\rho t+\psi) \\ S3 &= E_f \cos(\omega t-\varepsilon) \\ S4 &= -E_p \cos 2\omega t \end{aligned} \tag{5}$$

where, E_o, E_d, E_f, E_p=gain of each signal component, $\sin\rho t$=incident acoustic signal, θ=angle between incident signal and sensor Y-axis, ψ=angle between magnetic sensor Y-axis and magnetic pole, and ε = phase difference between magnetic sensor induced current and detection voltage.

$S1$ and $S2$ denote the signal components of omni-directional and directional hydrophones, respectively. In $S2$, it is also included the bearing information of phase difference $\varphi+\theta$. In recovering the modulated signals, it is needed the reference frequency component $S3$ and phase component $S4$.

Through the DIFAR demultiplexer, one can extract two modes of north-south (cosine) and east-west (sine) from directional sensors and omni-directional mode from an omni-directional sensor. These three modes (north-south→ N, east-west→ E, omni-directional→ O) can be expressed as following,

$$O = \int_0^{2\pi} s(\theta)\,d\theta, \tag{6}$$

$$N = \int_0^{2\pi} s(\theta)\cos(\theta)\,d\theta, \tag{7}$$

$$E = \int_0^{2\pi} s(\theta)\sin(\theta)\,d\theta. \tag{8}$$

Here, $s(\theta)$ is incident signal component and θ is the angle of incident signals relative to the magnetic pole. Beamforming technique in DIFAR system is to decompose the incident signals into cosine and sine components using orthogonality condition of dipole directional sensors. This decomposition is possible because the directional sensors are connected each other on the same axis.

In order to have precise beam pattern in frequency domain, one needs to normalize receiving pressure levels. To satisfy the normalization condition, the relation $O^2 = N^2 + E^2$ should hold and normalization factor can be defined as

$$\alpha = \frac{O^2}{N^2 + E^2}. \tag{9}$$

If the output of DIFAR system is calibrated, α has the value of 1. Consequently, the beam pattern in frequency domain may be expressed as following equation in steering angle β and normalization factor α.

$$B(\beta) = \frac{\alpha O + \cos(\beta) N + \sin(\beta) E}{1+\alpha}. \tag{10}$$

The beam pattern is simplified into the following four equation with four special bearings.

$$B(0^\circ)_{\text{North}} = \frac{\alpha O + N}{1+\alpha} \tag{11}$$

$$B(90^\circ)_{\text{East}} = \frac{\alpha O + E}{1+\alpha} \tag{12}$$

$$B(180^\circ)_{\text{South}} = \frac{\alpha O - N}{1+\alpha} \tag{13}$$

$$B(270^\circ)_{\text{West}} = \frac{\alpha O - E}{1+\alpha} \tag{14}$$

The beam patterns in the four bearings are displayed in Fig. 3.

Beam power in an arbitrary angle β is described as

$$\begin{aligned} P &= B(\beta) \times B(\beta)^* \\ &= [\ \alpha^2 O^2 + \cos^2(\beta) N^2 + \sin^2(\beta) E^2 \\ &\quad + 2\alpha\cos(\beta) ON + 2\alpha\sin(\beta) OE \\ &\quad + 2\cos(\beta)\sin(\beta) EN] \ / \ [\ (1+\alpha)^2\ ]. \end{aligned} \tag{15}$$

or as matrix form

$$P = \frac{1}{(1+\alpha)^2} [\alpha \quad \cos(\beta) \quad \sin(\beta)] \begin{bmatrix} O^2 & ON & OE \\ ON & N^2 & NE \\ OE & NE & E^2 \end{bmatrix} \begin{bmatrix} \alpha \\ \cos(\beta) \\ \sin(\beta) \end{bmatrix}$$

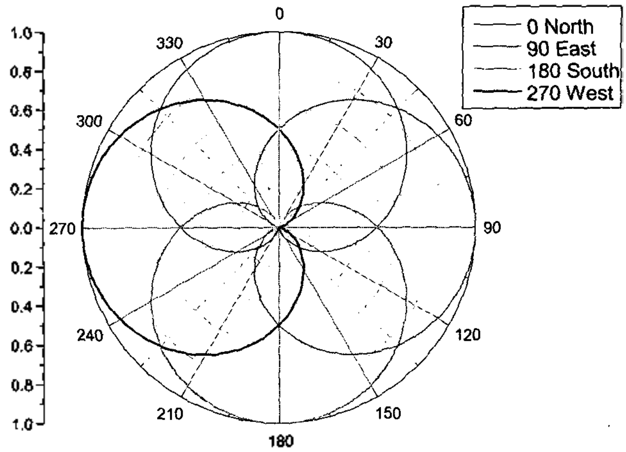


Figure 3. Beam patterns of the Cardioid beamforming using DIFAR.

$$= [B(\beta)]^T [CSM] [B(\beta)]. \tag{16}$$

Here, CSM means the cross spectral matrix.

Power pattern of the Cardioid beam is given as

$$BP(\beta, \theta) = \frac{[\alpha + \cos(\beta)\cos(\theta) + \sin(\beta)\sin(\theta)]^2}{(1+\alpha)^2} \tag{17}$$

III. Bearing Estimation of Narrow Band Signals

Receiving beam characteristics of the Cardioid beamforming is that it has one MRA and one null point 180o away. As one searches the maximum response, positioning the MRA at an angle around 360°, he or she can estimate the bearing which shows the maximum receiving level. Positioning the null point at any angle, one can reject the 'unwanted signals' from that direction. This property of the Cardioid beamformer may be utilized in developing an algorithm to estimate arbitrary narrow band signals using a DIFAR system. Establishing the steering angle to be 0°, 90°, 180°, and 270°, the basic searching modes, one can pick up the narrow band signal whose level is above a threshold. After the rough estimation at one frequency, detailed searching for the incident angle is performed by 1° interval in the bearing range -45°~+45°. As the suggested algorithm uses the MRA of the Cardioid beamforming in estimating incident angle, it promises 6 dB increase in the SNR for the narrow band signal. Figure

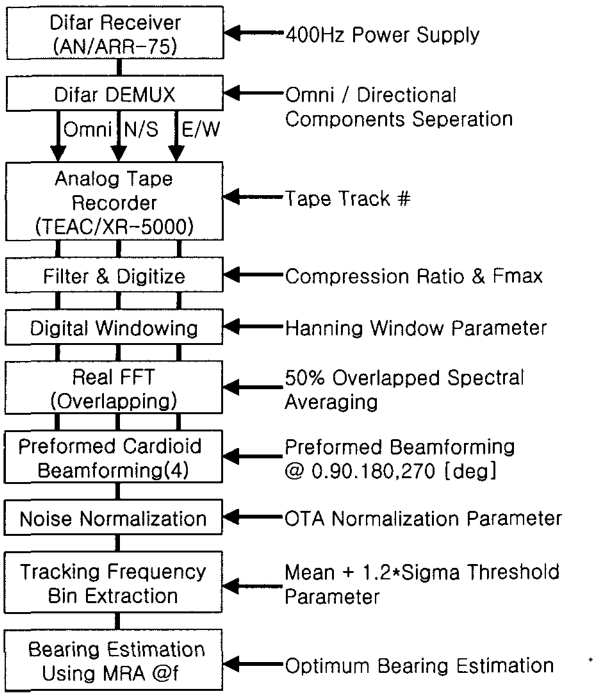


Figure 4. Block diagram of the bearing estimation process.

4 shows the block diagram of bearing estimation process. The process has six steps as follows.

Step I : Samples some amount of time domain data of omni-directional and directional sensors. The receiver (AN/ARR-75), which operates by 400Hz power supply, gathers the signals from a DIFAR system. And then, a demultiplexer decodes the received signals into three components: omni-directional, north-south and east-west. An analog tape recorder saves the decoded data that are finally converted into digital data for further process.

Step II : Applies the Hanning window to the time domain data in order to reduce energy leakage caused by discrete sampling[6].

Step III : For the analysis in frequency domain, performs 50% overlapping, linear average and FFT (fast Fourier transform) over the time domain data.

Step IV : Using the Cardioid beamforming, computes beam output for the basic bearings 0°, 90°, 180°, and 270°.

Step V : Normalizes background noises and extracts narrow band frequencies above the predefined threshold. In normalizing noises, the OTA (order-truncate-average) scheme[7] is used. The threshold is defined as $\mu+1.2*\sigma$, where μ=mean and σ= standard deviation[5].

Step VI : Searches frequency bins in detail for the incident angle by 1° interval in the bearing range -45° ~ +45°.

Figure 5 gives the bearing estimation result for the narrow band signals of 300 Hz. The estimation is conducted by changing the incident angle from 0° to 360° by 1° interval. It is also added the bearing errors from the magnetic sensor in DIFAR system. X-axis denotes incident angle while Y-axis estimated bearing (left) and compass bearing error (right). It is shown that the estimated bearing matches very well to that of incident signal within the compass error, ±1.5°.

An example of the Cardioid beam response, positioning the MRA at 180°, is given by Fig. 6. The figure clearly

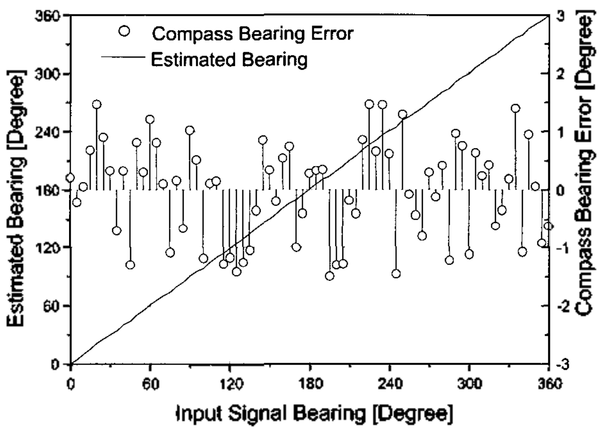


Figure 5. Estimated bearing and compass bearing error for the narrow band signals of 300Hz.

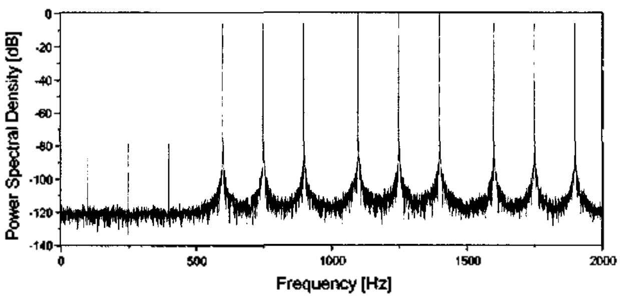


Figure 6. Cardioid beam response of DIFAR sensors at angle 180°.

shows the effect of spatial filter. That is, the signals from 180° (1100, 1250, 1400 Hz) keep 0 dB level but those from 90° and 270° decrease up to - 6 dB level showing the characteristics of the Cardioid beam pattern. The signals at the angle of 0° corresponds to the null-points of the Cardioid beam and thus gives significantly low levels. These results suggest that the generated signals can be sufficiently applied to computer simulation of the Cardioid beamforming.

IV. Application to Sea Experiment

A. Sea Experiment

The modified DIFAR system is deployed on the sea bottom of 40 m depth in the East sea of Korea. The signals, inherently CW (continuous wave) and omni-directional 10 tonals, are generated by a sound source (model HX-29). The source levels are made in 145 ~ 170 dB/ μP_a to keep higher than those of background noise. The sound source is towed at about 4-5 kts speed keeping 10m depth and predefined course. The source operates during the time 10:30 ~ 16:45 but suffers two breaks in 14:46 ~ 15:04 and 15:40 ~ 15:57 due to electric power problem. The bearing and range between the DIFAR system and the source are calculated referring to GPS data.

In analyzing the received data, the parameters are employed as follows:

- o FFT size 16384
- o Sampling Frequency 2500 Hz
- o Frequency Resolution 0.15 Hz
- o Tonals 100/130/165/205/255/320/405/505/635/805 Hz
- o No Overlapping
- o Linear Averaging 1 Minute

Tracking frequency window is chosen to have 3 Hz so as to accomodate Doppler effect, where the received signal level is calculated by summing maximum three peaks.

B. Results

To verify the accuracy of the algorithm over the sea experiment data, the reference bearings and ranges are calculated referring to GPS data from the source towing ship (Fig. 7). One can see that the sound source deviates almost around the DIFAR system (0° ~ 360°), the maximum range reaching about 13 km.

Figure 8 shows the results of bearing estimation for the source signals and their errors compared with the reference bearings. The ranges between the source and receive, calculated from GPS data, are also displayed in solid line. The estimation is performed over the signals of ten frequencies. The open circles converges within a limit except the two periods (14:46 ~ 15:04 and 15:40 ~ 15:57), where the periods correspond to those of source problem caused by electric power breakdown. The diverges of bearing estimation in the two periods imply that the estimation is performed over ship noises not source signals in the experiment area. In fact, many fishing boats are observed around the receiver. Besides the two periods, a few cases show that the errors are significantly large, implying that the DIFAR system fails to estimate exact bearings (Fig. 8b). This failure may be explained by two aspects. First, the large errors may be attributed to low SNR at the receiver. That is, when ships travel or stay near the receiver, they may produce many tonals similar to the signals as well as broad band noises. Both cases make the noises increase abruptly and the SNR decrease, where SNR absolutely determines the performance of bearing estimation. Second, as the linear average is conducted over one minute data, potential estimation errors near the

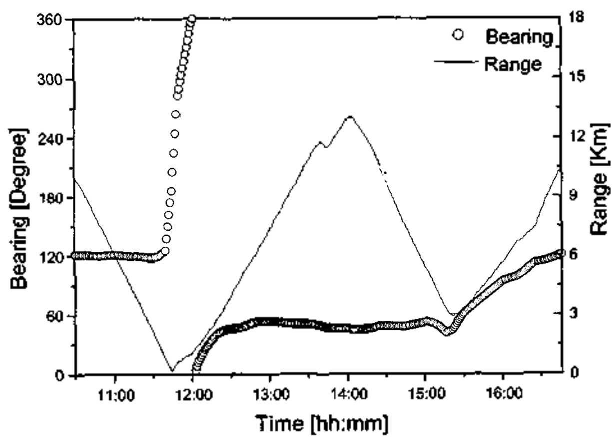
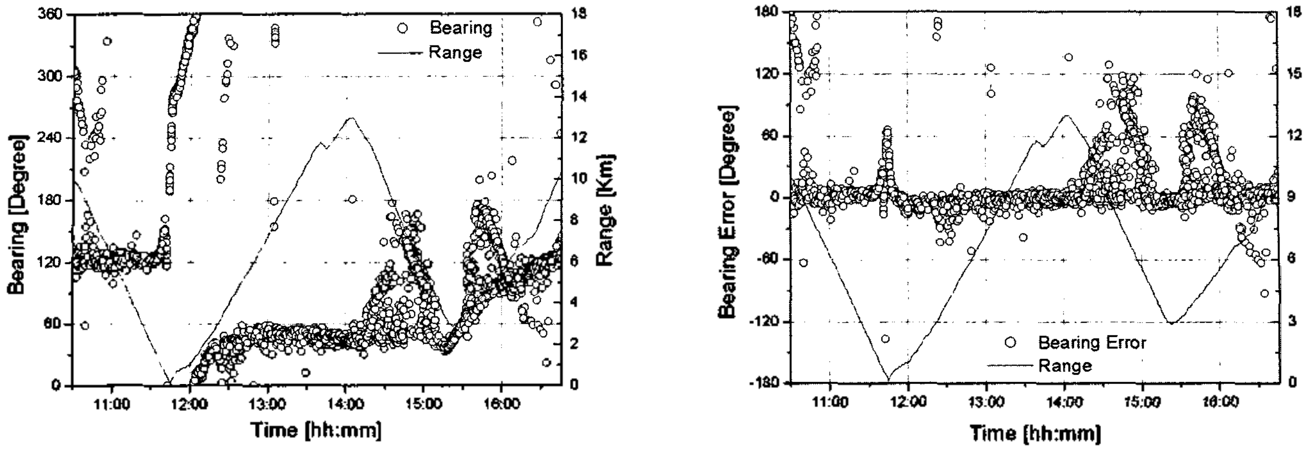


Figure 7. Reference bearings and ranges calculated from GPS data.



(a) Estimated bearings (b) Bearing errors compared with references

Figure 8. Bearing estimation for the source signals of ten frequencies.

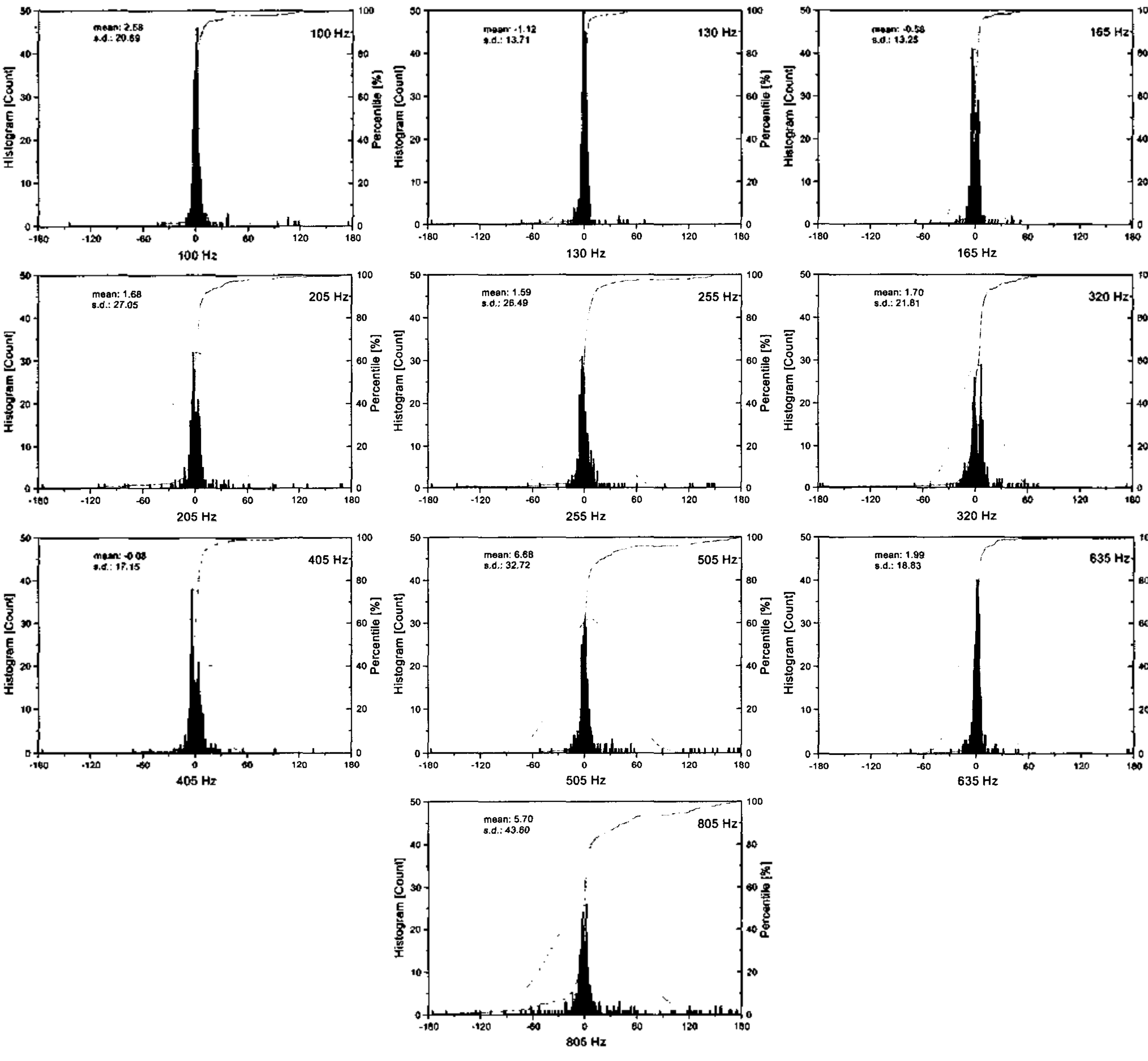


Figure 9. Histograms and cumulative probability distribution of bearing estimation errors.

receiver should be larger than those far away. Since the sound source towed in 4～5 kts, for one minute, range between source and receiver may reach up to 140 m. The errors when the source approaches nearest the receiver are regarded due to this effect.

For the quantitative analysis, histograms and cumulative probability distributions are given over the ten frequencies (Fig. 9). In the distributions, the data of the source problem (periods 14:46～15:04, 15:40～15:57) are excluded. The histograms give the fact that most of errors exist within very narrow band centered on 0°. The histograms themselves show Gaussian shape. Since the largest number of errors occurs around 0°, the cumulative distributions also appear to show sharp change around 0°. The Gaussian distributions in the figure are obtained by computing mean and standard deviation in each frequency.

Table 1 summarizes the probability distributions in each frequency. Mean of the bearing error drops in -1.1°～6.7° and its standard deviation in 13.3°～43.6°. In the table, it is also given the probability of occurrence within the bearing range corresponding -3 dB response on the MRA, ±65.4°. Most of estimation errors, more than 93%, exist in the range. Among the ten frequencies, the signal of 165 Hz gives the best results, showing the smallest standard deviation (13.25°) and thus the largest occurrence within the -3 dB response range (99.7%). Meanwhile, the signals of 805 Hz gives the worst results, the largest standard deviation and smallest occurrence within the range. The variation with frequency is thought to be caused by some factors. First, the propagation loss, from the source to receiver, is different with frequency. Particularly in shallow waters, the propagating waves inevitably interacts with the bottom, resulting high dependency on bottom characteristics (attenuation and reflection coefficients) and thus on frequency. In some areas, so called optimum frequency, which presents the best propagation with range, is reported to exist[8]. Magnetic sensor sensitivity operates as an another factor affecting the estimation error. Magnetic sensor basically has an accuracy of ±1.5°, its accuracy may vary with the fluctuation of geo-magnetic field in daily cycle. Third, narrow or broad band noises around the receiver act as a direct and utmost effect on the estimation errors causing the SNR degradation.

Table 1. Statistic results of the bearing estimation errors.

Freq. (Hz)	Mean (μ)	S.D. (σ)	-3dB (%)
100	2.58	20.69	97.9
130	-1.12	13.71	99.7
165	-0.58	13.25	99.7
205	1.68	27.05	97.9
255	1.59	26.49	97.6
320	1.70	21.81	99.1
405	-0.08	17.15	99.1
505	6.68	32.72	95.8
635	1.99	18.83	99.1
805	5.70	43.60	93.0

Background noises are inherently non-stationary and may affect the bearing estimation errors in non-stationary pattern as shown in Fig. 8[9]. Figure 10 shows the histogram and cumulative probability for all frequencies, the mean and standard deviation being 1.89° and 25.79°, respectively.

The bearing estimation errors are given in detail for the frequencies of 100 and 405 Hz (Fig. 11). As mentioned in previous, the errors drops around 0° implying that the estimated bearings agree well with those from GPS data. Between the two figures, one can see that big difference occurs in the second period of source problem (15:40～15:57). That is, contrary to other cases, the results at 405Hz gives no significant errors in that period. This phenomenon may be attributed to appearance of noise source of 405 Hz or neighbor frequencies.

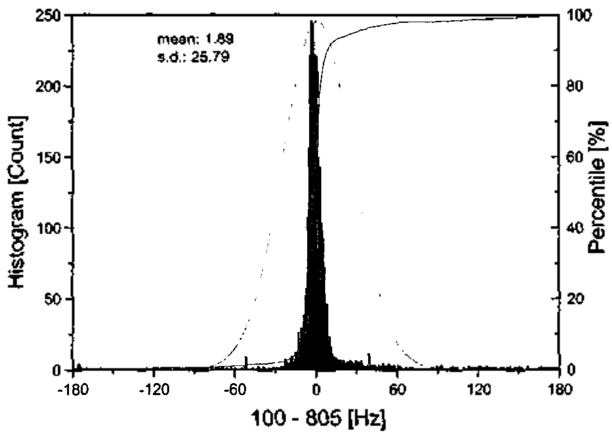


Figure 10. Histograms and cumulative probability distribution of bearing estimation errors for all frequency.

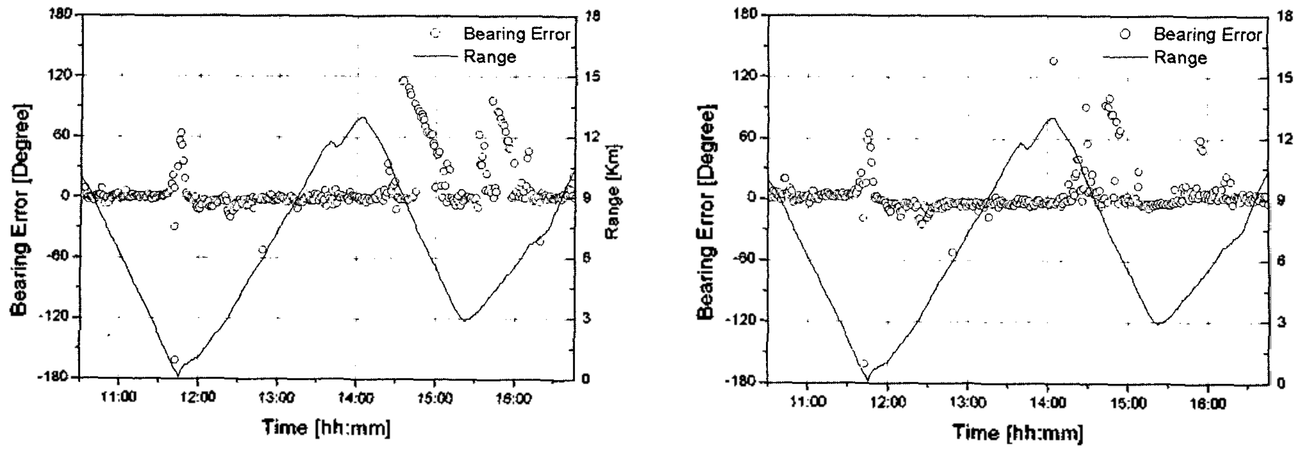


Figure 11. Bearing estimation errors for the signals of 100Hz (left) and 405Hz (right).

V. Conclusions

The estimated bearings agree very well with those from GPS data. Assuming the bearings from GPS data to be real values, the estimation errors are analyzed statistically. The histogram of estimation errors in each frequency have Gaussian shape, the mean and standard deviation dropping in the ranges -1.1° ~6.7° and 13.3° ~43.6°, respectively.

Estimation errors are caused by SNR degradation due to propagation loss between the source and receiver, daily fluctuating geo-magnetic fields, and non-stationary background noises.

If multiple DIFAR systems are employed, in addition to bearing, range information could be estimated and finally localization or tracking of a target is possible.

References

1. G. C. Carter, "Time Delay Estimation for Passive Sonar Signal Processing," *IEEE Trans. Acoust., Speech, Signal Processing*, 29 (3), 463-470, 1981.
2. C. H. Knapp and G. C. Carter, "The Generalized Correlation Method for Estimation of Time Delay," *IEEE Trans. Acoust., Speech, Signal Processing*, **24** (4), 320-327, 1976.
3. C. Barnes, "Sonobuoy Developments," *NAFO*, 61-65.
4. C. L. Leblanc, Handbook of Hydrophone Element Design Technology, *Naval Underwater Systems Center*, 6/15-6/35, 1978.
5. J.-H. Nho, D.-H. Kim, Y.-S. Kim, J.-Y. Han, DIFAR System (Preliminary Study), Agency for Defense Development, 1981.
6. T. P. Krauss, L. Shure, J. N. Little, Signal processing Toolbox for Use with MATLAB, *The Math Works Inc.*, 1/61-1/70, 1992.
7. R. O. Nielsen, *Sonar Signal Processing, Interstate Electronics Corporation Anaheim, California*, 143-149, 1991.
8. Y. Na, T. Shim, J. Choi, D. Chang, J. Han, "Propagation Loss Measurement of Underwater Sound Wave using Narrow Band Acoustic Signal," *J. Acoust. Soc. Kor.*, **13** (E), 5-15, 1994.
9. R. J. Urick, Ambient Noise in the Sea, *Peninsula Publishing*, 5/15-5/21, 1984.

[Profile]

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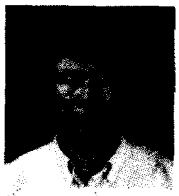

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