Velocity Measurement by Symbiotic Combination of Conventional and Coherent Doppler Sonars

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Abstract—**Pulse-to-Pulse coherent Doppler sonar has the advantages of quick-response and high accuracy when compared with the conventional Doppler sonar and has become widely used in laboratories and for commercial products. However, this system has the limited range and ambiguity velocity, which limits more general applications. Multi-frequency and dual time intervals have been proposed to enlarge the ambiguity velocity, but it is still in adequate. Conventional Doppler sonar has no ambiguity velocity and its velocity range is virtually unlimited as we had expected, but the accuracy of conventional Doppler sonar is not good with short time lags. In this paper, the symbiotic combination method is introduced to take advantage of both conventional and coherent Doppler sonar. The symbiotic combination method can provide accurate velocity without ambiguity velocity and has a much shorter time lag compared to the conventional method. A simulation using symbiotic combination method was carried out with different SNR, and the results indicate that this method can be used to provide highly accurate velocity information with a short time lag.**

Keywords-conventional Doppler sonar; coherent Doppler sonar; dual time interval; symbiotic combination method;

I. INTRODUCTION

Accurate velocity information plays an important role in ocean exploration, especially for devices in the water. In recent decades the ocean development of nature resources has become more and more important, because land resources are becoming depleted and ocean contains huge amounts of useful resources. To develop the nature resources in the ocean, it is necessary to measure and control the velocity of operating devices, such as vessels and under water vehicles.

Currently we are able to measure the velocity of moving vehicles at sea. Normally, GPS, Electronic-magnetic, and Doppler sonar systems are used. The velocity information GPS (VI-GPS) system [1] can provide accurate velocity information relative to the earth with a resolution of 1 cm/s. But the GPS signal cannot be transmitted into water, which means the VI-GPS is limited to the surface and above. The Electronic-magnetic system is also limited, but by the measurement area. It is limited to a few kilometers of the measurement device. However, the Doppler sonar system can measure the velocity of objects both on the sea surface and in the water. But the velocity information of the conventional Doppler system includes a large time lag and lacks accuracy. In recent years, the Pulse-to-Pulse coherent Doppler sonar has been developed to measure the precise velocity with comparatively short time lag. Roger Lhermitte and Robert Serafin have looked into pulse-to-pulse coherent Doppler sonar signal processing techniques in detail [2]. L. Zedel has provided a simulation model of pulse-to-pulse coherent Doppler sonar to assist in sonar design [3]. And the Pulse-to-Pulse coherent Doppler sonar has also been used to explore turbulence and waves in the ocean [4], [5]. However, continued ambiguities in the range and velocity seriously limit more general applications. Methods to reduce the limit of ambiguity velocity have been proposed, such as multi-frequency methods [6], [7] and dual time intervals [8][9], and the proposed methods are accurate and precise for low range velocity tracking. Nevertheless, the ambient noise from the device and environment limits its usefulness for more high range velocity tracking.

In this paper, the symbiotic combination of conventional and coherent Doppler sonar is proposed to provide accurate velocity information with short time lag. First, the basic theory of symbiotic combination method is deduced from conventional method and coherent method. Next, error analyses of these methods are proposed. Finally, a simulation is carried out to evaluate the performance of the symbiotic combination method, and compare it with conventional and coherent methods. Our theoretical analysis and numerical simulation will show that the symbiotic combination method provides high accuracy velocity information with a short time lag.

II. METHODOLOGY

Symbiotic combination method is constructed in a combination of conventional Doppler sonar and coherent Doppler sonar. In this chapter, first the conventional and coherent methods are introduced, and then with the benefit of understanding of these two methods, the symbiotic combination method is explained.

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A. Conventional Doppler Sonar

In conventional Doppler sonar system the frequency shift is estimated by the auto-correlation of the spectra between the transmitted and received signals [10]. Normally a transmitted signal can be expressed as:

$$S_t = a(t)\cos(2\pi f_c t + \varphi) \quad (1)$$

where $a(t)$ is the real envelope;
f_c is the carrier frequency;
φ is the start phase.

In order to simplify the analysis, the analytic form of the transmitted signal is expressed in complex domain, and it is shown below:

$$\boldsymbol{S}(t) = \mu(t)\mathrm{e}^{j\omega_c t} \quad (2)$$

where $\mu(t) = a(t)\mathrm{e}^{j\varphi}$;
$\omega_c = 2\pi f_c$.

And then the received target signal will be

$$\boldsymbol{S_r}(t) = A\mu(t-t_0)\mathrm{e}^{j(\omega_c+\omega_d)(t-t_0)} + \boldsymbol{N_a}(t) \quad (3)$$

where A is the amplitude of received signal;
t_0 is the time delay;
$\boldsymbol{N_a}(t)$ is the noise which is considered as white noise.

If the time length of the received signal is long enough to cover the full pulse, the time delay can be eliminated in the conventional method, and we might just express the received signal as

$$\boldsymbol{S_r}(t) = A\mu(t)\mathrm{e}^{j(\omega_0+\omega_d)t} + \boldsymbol{N_a}(t) \quad (4)$$

The spectra of these signals are transformed into frequency domain by fast Fourier transform, and they are shown below:

$$\begin{aligned}\boldsymbol{S}(t) &\leftrightarrow \boldsymbol{S}(f)\\ \boldsymbol{S_r}(t) &\leftrightarrow \boldsymbol{R}(f)\end{aligned} \quad (5)$$

By the correlation of these spectra, the Doppler shift is calculated as:

$$f_d = \max_{0\le f_v\le f_c} \int_0^{f_c} S^*(f-f_v)R(f)df \quad (6)$$

where $\boldsymbol{S}^*(f)$ is the conjugate of $\boldsymbol{S}(f)$. With the Doppler shift the velocity of the moving object can be easily calculated by Doppler Effect.

B. Pulse-to-Pulse Coherent Doppler Sonar

The Pulse-to-Pulse coherent Doppler sonar estimates the velocities by comparing the phase of received signals from successive acoustic pulses. When there is a short time interval between two pulses, the received acoustic signals are correlated and the change in phase is proportional to the velocity of the object. When the received signals are reflected signals from some object, the relationship of the radial velocity and the change of the phase is given as

$$v_p = \frac{\varphi c}{4\pi f_c \tau} \quad (7)$$

where φ is the phase change of the adjacent received signals, c is the speed of sound in water, τ is the time delay between adjacent pulses.

With the limitation of phase measurement φ that is constrained from $-\pi$ to π , the ambiguity velocity is expressed as:

$$v_a = \frac{c}{4 f_c \tau} \quad (8)$$

The maximum achievable range which depends on time interval τ is shown as:

$$R_a = \frac{c\tau}{2} \quad (9)$$

By combining Eq. (8) and Eq. (9) together, it leads to the well-known ambiguity "range-velocity"

$$v_a R_a = \frac{c\lambda}{8} \quad (10)$$

where λ is the system wave length.

According to Eq. (10), the ambiguity velocity (v_a) is inversely proportional to the maximum achievable range (R_a) for a coherent Doppler sonar system. In order to expand the range of the ambiguity velocity, multiple carrier frequencies and dual time interval methods have been examined. Because the dual time interval method needs less complicated devices and the pulses are also convenient for conventional Doppler sonar, this method is adopted in our current calculations.

In dual time interval method, supposing the velocity of the moving object is constant, this velocity can be determined by the carrier frequency and the time interval between pulses according to Eq. (7). If this velocity is measured by two different intervals ($\tau_2 > \tau_1$), the velocity can be calculated as below:

$$v_p = \frac{c}{4\pi f_c(\tau_2-\tau_1)}(\varphi_2-\varphi_1) \quad (11)$$

where φ_1 and φ_2 are the phase changes determined by time interval τ_1 and τ_2 respectively.

The ambiguity velocity determined by Eq. (11) is given by

$$v_{1,2-a} = \frac{c}{4 f_c(\tau_2-\tau_1)} \quad (12)$$

Eq. (12) shows that the ambiguity velocity can be made arbitrarily large by making the difference of dual time interval small. However, in practice it is limited by the error of the phase measurement which is determined by the signal to noise ratio, and normally in dual time method, ambiguity velocity can be enlarged less than 5 times that of the single time interval method [11]. Eq. (11) is inherently much noisier than the single time interval method, because of the introduction of the two phase estimation. To compensate for this, the technique expressed in [7], [9] is used to improve the accuracy instead of reducing the ambiguity velocity.

C. *Symbiotic Combination of Conventional and Coherent Doppler Sonar*

As discussed before, the coherent method can provide accurate velocity information by phase measurement, but the ambiguity velocity seriously limits this method for wider applications. Therefore the symbiotic combination method is introduced. A functional block diagram of the symbiotic combination Doppler sonar is shown in Figure 1. At the receiver block, received pulse series are detected, and the received pulse series are forwarded to conventional and coherent Doppler sonar. At the start of the conventional sonar, Doppler shifts of the received pulses are calculated, and then a rough estimate of velocity (v_c) with error (ε_c) is obtained. In the coherent sonar, phase changes between adjacent pulses are calculated, and then the precise velocity (v_p) is given. However, the precise velocity calculated by the coherent Doppler sonar is limited by the ambiguity velocity (v_a). In order to eliminate the ambiguity velocity, the rough velocity is used to decide the wrapped number (n) of velocity ambiguity. Finally the unlimited and accurate velocity (v) is estimated by an addition of the wrapped number of the ambiguity velocity and the limited precise velocity.

One of the main functions of the symbiotic combination method is to calculate the wrapped number of velocity ambiguity. In order to carry out this calculation, there are two necessary assumptions. First, we assume the absolute error of the coarse velocity ($|\varepsilon_c|$) to be less than half the velocity ambiguity (v_a). For the second assumption, the measurement velocity v_p must have the same sign as velocity calculated by coherent Doppler sonar without noise. From these assumptions, the following two inequalities are obtained.

$$n-\frac{1}{4}<\frac{v_c}{2v_a}<n+\frac{3}{4}\quad (v_p > 0) \tag{13}$$

$$n-\frac{3}{4}<\frac{v_c}{2v_a}<n+\frac{1}{4}\quad (v_p < 0) \tag{14}$$

In these inequalities (13) and (14), n is decided by means of these two assumptions. With n integer decided, the measurement velocity calculated by the symbiotic combination method can be expressed as:

$$v = 2nv_a + v_p \tag{15}$$

According to Eq. (15), symbiotic combination Doppler sonar can provide an accurate velocity calculations over an unlimited range.

III. ERROR ANALYSIS

A. *Error analysis for Conventional Doppler sonar*

For conventional method, the rms error in estimating Doppler shift [10] is

$$\sigma_{f_d} = \frac{1}{\mathrm{T}_0\sqrt{2E/N_0}} \tag{16}$$

where E is the energy of real received signal;
$N_0/2$ is the noise power per Hertz for real noise waveform;

and

$$\mathrm{T}_0{}^2 = \frac{(2\pi)^2\int_{-\infty}^{+\infty} t^2|\mu(t)|^2 dt}{\int_{-\infty}^{+\infty}|\mu(t)|^2 dt} \tag{17}$$

If the transmitted signal is a zero phase characteristic signal with a simple Gaussian envelope, which is expressed as

$$a(t) = e^{-t^2/2\sigma^2} \tag{18}$$

then the rms error of Doppler shift with a sampling frequency of f_s can be expressed with signal to noise ratio as

$$\sigma_{f_d} = \frac{1}{\sqrt{2}\pi\sigma\sqrt{SNR\times f_s}} \tag{19}$$

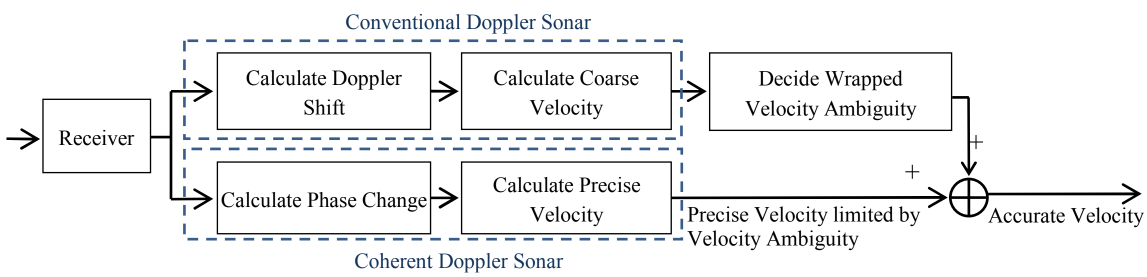

Fig. 1. Functional block diagram of symbiotic combination of Doppler sonar.

where SNR is the signal to noise ratio of the received signal. With the rms error of frequency shift, the standard deviation of measurement velocity can be expressed as:

$$\sigma_{v_c} = \frac{\sigma_{f_d}}{f_c} \times c \tag{20}$$

Because of the white noise affect, the measurement velocity by conventional method is also follows the Gaussian distribution, which is

$$v_c \sim N\left(v, {\sigma_{v_c}}^2\right) \tag{21}$$

Suppose the pulse interval is τ, and our purpose is to limit the velocity standard deviation to be σ_o, the average time we should use can be expressed as

$$t_{ave} = \frac{{\sigma_{v_c}}^2}{{\sigma_o}^2}\tau \tag{22}$$

B. Error Analysis for Coherent Doppler sonar

For coherent Doppler sonar the received signals are transferred into the complex domain by the processing method shown in Figure 2.

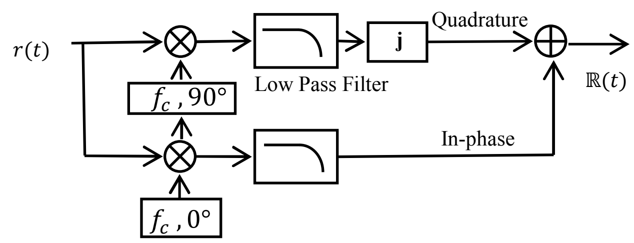

Fig. 2. Processing method to transfer the received signals to complex domain.

In this process, because of passing though a low pass filter for the in-phase and the quadrature components of the received signal in complex domain, the signal to noise ratio of the filtered signal (SNR_f) is improved significantly compared to the original received signal. The upper boundary of the auto-correlation ($\boldsymbol{R}_{12}$) of adjacent pulses [12] is shown as below:

$$\boldsymbol{R}_{12} \leq \frac{1}{2}E * \left(e^{j\phi} + r * e^{j\phi_r}\right) \tag{23}$$

where

$$r = 2 * \sqrt{\frac{1}{SNR_f} + \frac{1}{SNR_f}} \tag{24}$$

In Eq. (23), there are two signals. The primary term shows a correlation signal vector whose length is $E/2$ and phase is φ, while the second term shows a correlation noise vector with length of $Er/2$ and random phase φ_r. Consequently, the correlation vector $\boldsymbol{R}_{12}$ is composed by an addition of the correlation signal vector and the correlation noise vector. In Figure 3, the correlation vector $\boldsymbol{R}_{12}$ in the complex signal space is shown by the addition of the two vectors.

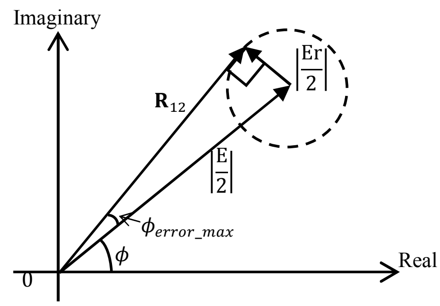

Fig. 3. The correlation $\mathbf{R}_{12}$ in complex

If $r < 1$, the maximum rms phase error for coherent Doppler sonar is

$$\phi_{rms\_max} = arcsin\left(2 * \sqrt{\frac{1}{SNR_f} + \frac{1}{SNR_f}}\right) \tag{25}$$

And the maximum rms of the velocity measured by coherent method can be expressed as

$$\sigma_{V_{p\_max}} = \frac{\phi_{rms\_max}}{\pi} V_a \tag{26}$$

C. Error Analysis for Symbiotic Combination method

For symbiotic combination method, when the integer number decided by conventional method for ambiguity velocity is right, the error of measurement is the same as coherent method. Therefore, the integer estimation is the main factor affecting the accuracy of the symbiotic combination method. As shown in the first assumption, symbiotic combination is successful only when the measurement error is less than half the velocity ambiguity. As discussed before, the measurement velocities of conventional method follow the Gaussian distribution. In accordance with these situations, the integer number can be estimated correct with a probability greater than 99% if σ_v is less than $\frac{1}{6}V_a$. When σ_v is larger than $\frac{1}{6}V_a$, the average time should be used to make it fit this situation, and the average time is expressed as

$$t_{ave\_com} = \frac{{\sigma_{v_c}}^2}{(\frac{1}{6}V_a)^2}\tau \tag{27}$$

Even with high SNR or by averaging the measurement velocity, the symbiotic combination method still cannot make the integer estimation 100% correct. When the wrong integer number occurs, the velocity will change dramatically and make it will appear as a spike or a pulse..

IV. SIMULATION

To evaluate the performance of symbiotic combination method, some basic conditions are used in the simulation, shown in Table 1.

In our simulation the transducer is considered as a fix point, and the hydrophone is moving away from the transducer with a constant velocity, which is shown in Figure 4.

With the simulation time of 50 seconds, the standard deviations of conventional and coherent methods with different SNR are shown in Figure 5. Figure 5 shows that the theoretical analysis results of standard deviation for conventional method fit the simulation results well, which means the average time calculation in Eq. (22) and Eq. (27) can be used. And it also shows that the velocity as measured by conventional method in low SNR is not precise, while the coherent method can provide precise velocity information even in low SNR.

In order for the standard deviation of conventional method to be 0.01m/s, the theoretical average time calculated by Eq. (22) shown in Figure 6 is used. The average is also carried out for the combination method to provide a creditable integer number. With the correct probability of integer number estimation at no less than 99%, the average time for combination method calculated by Eq.(27) is shown in Figure 6. In Figure 6 we find that, in large SNR situations both methods need short average times, but in low SNR the symbiotic combination method needs much shorter average times than the conventional method. One example of average results by conventional and symbiotic combination methods with the SNR of -22.7 dB is shown in Figure 7. Figure 7 shows that, with the shorter time average symbiotic combination method can provide much more velocity information in the same time period. And also even with shorter time average, the symbiotic method can provide much more accurate velocity information than the conventional method if the impulse noise is ignored.

The standard deviations of average conventional and symbiotic combination methods with the average time as expressed in Figure 6 are shown in Figure 8. According to this figure, we can see that the symbiotic combination method can provide the velocity information as precise as the coherent method with short time lag even in low SNR. However, the occurrence of impulsive noise significantly affects the measurement results.

TABLE I. SIMULATION CONDITIONS

Conditions	
Pulse envelope	Gaussian
Pulse width (σ)	1.7 ms
Carrier frequency	200 kHz
First time interval	40 ms
Second time interval	60 ms
Sampling frequency	10 MHz
Data refresh rate	20Hz
Sound speed	1500m/s
Moving speed	0.5m/s

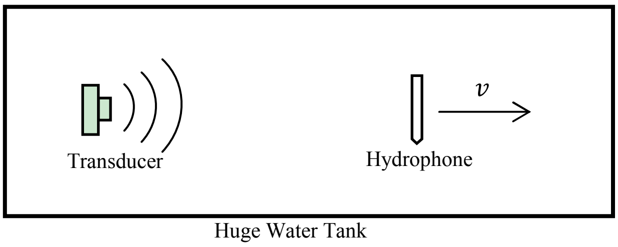

Fig. 4. Schematics of simulation.

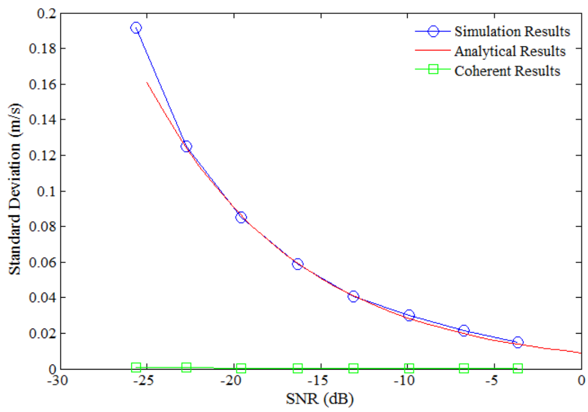

Fig. 5. Standard deviation of conventional and coherent method with different SNR.

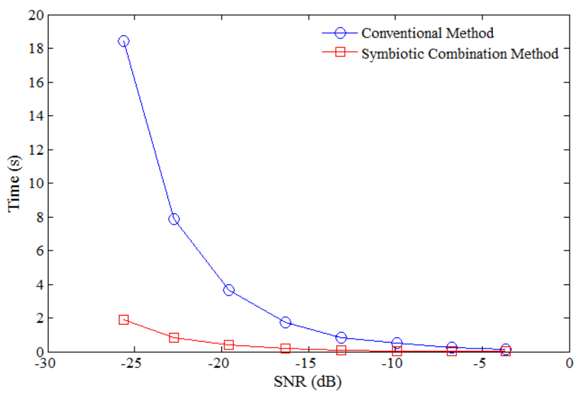

Fig. 6. Average time of conventional and symbiotic combination methods with different SNR.

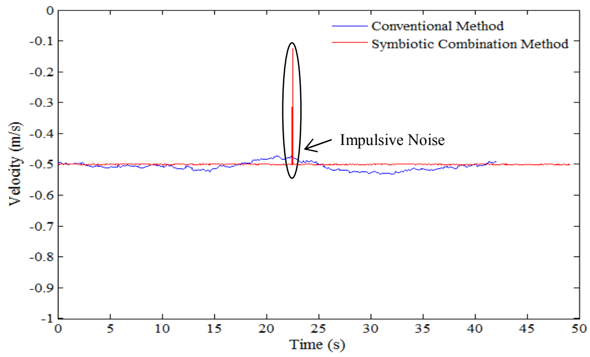

Fig. 7. One example of averaged conventional and symbiotic combination methods with SNR -22.7dB.

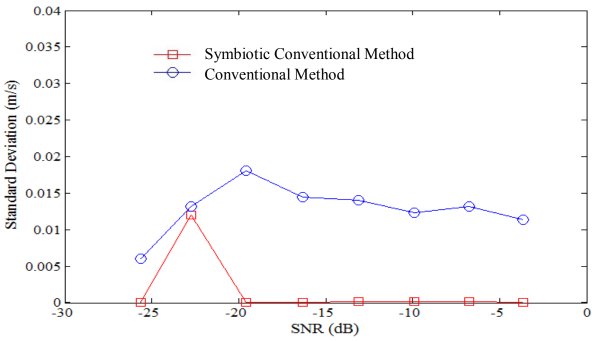

Fig. 8. Standard Deviation over average time of conventional and symbiotic combination methods with different SNR.

V. Summary and Conclusions

Comparing the simulation results of these three methods, some basic conclusions can be realized:

a) With high SNR of received signals, the conventional method can provide the velocity information as good as symbiotic combination method.

b) When the SNR is low, both the conventional method and symbiotic combination method need to be averaged. But with the same average time, the symbiotic combination method can provide much more accurate velocity information than the conventional method.

c) If the integer number for ambiguity velocity is wrong, the symbiotic combination method will generate a remarkable impulsive noise, which seriously affects the final result. To lower the probability of impulsive noise, the symbiotic combination method needs a longer time average.

In this simulation, only the basic effects of SNR are considered. The real world is more complicated and other factors and techniques should be considered, as described below:

a) Situations with multipath signals from sea surface, bottom or obstructions should be considered. In these situations, the velocity estimation will be much more complicated for conventional method, which will seriously affect the performance of the combination method.

b) The pulse width is also a very important factor. The rms error of conventional method is inversely proportional to the pulse width. In addition, the coherent method is unable to calculate the velocity information when the velocity is very large and pulse width is narrow.

c) The simulation in this paper only considered direct signals. The situation of significant reflections from bottom or moving objects is the same. But there is still another situation where only weak reflected signals from particles in the water are received, and the combination method should be tested in this situation.

d) The impulsive noise seriously affects the final results of symbiotic combination method. Some method should be considered to avoid the appearance of impulsive noise.

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