Experimental Results of Combined Method of Conventional and Coherent Doppler Sonar

Peng LIU*, Nobuyoshi KOUGUCHI* and Takashi KUBOTA‡
* Kobe University, Graduate School of Maritime Sciences ‡ National Institute of Technology, Oshima College

***Abstract*—Conventional (usually used) Doppler sonar, though unlimited by velocity range ambiguity, takes seconds to return valuable velocity readings. Coherent Doppler sonar has been proposed to provide accurate velocity with short time lag for current or turbulent. However the velocity ambiguity seriously limits its general application. In this paper, combined Doppler sonar is proposed to overcome the disadvantages of both conventional and coherent Doppler sonars. An adaptive algorithm is used for combined Doppler sonar to provide accurate and precise velocity information at a wide range of SNRs. Experiments are carried out to evaluate the performance of combined Doppler sonar proposed. Based on experimental results, with suitable ambiguity velocities, combined Doppler sonar can provide accurate and precise velocity information at a wide range of SNRs.**

Keywords-conventional Doppler sonar; coherent Doppler sonar; combined Doppler sonars; adaptive algorithm

I. INTRODUCTION

Accurate velocity information of maritime moving objects plays an important role in navigational safety, bathymetric work and precise control of AUVs. Conventional Doppler sonar (CNDS) has been the default tool to provide this vital velocity information. However, the velocity measured by CNDS contains substantial margin of error and necessitates seconds to generate velocity readings [1]. Pulse-to-pulse coherent Doppler sonar (CHDS) has been developed to measure the velocity of waves or turbulence accurately with more efficiency than CNDS; however, its inherent velocity ambiguity seriously limits its applicability [2] [3]. In this light, this paper proposes combined Doppler sonar (CMDS). CMDS overcomes the weaknesses of CNDS and CHD by providing accurate and precise velocity data with short time lag [4]. An adaptive algorithm will contribute to the accuracy and precision of velocity measurement by CMDS at a wide range of SNRs [5].

In this paper, the theoretical underpinning of CMDS will be introduced. After explaining the measurement methods of CMDS with and without an adaptive algorithm, the comparative experiments are carried out in a shallow water tank, whose results will be presented in SECTION Ⅲ. Compared with the measurement results of CNDS and CHDS, CMDS utilizes suitable ambiguity velocities to provide velocity information as precise as CHDS but avoid velocity ambiguity at a wide range of SNRs.

II. MEASUREMENT METHOD

A. Comined Doppler Sonar

CHDS can provide accurate velocity information by phase measurement, but its velocity ambiguity prevents it from being used more widely. Some adaptations have been made to expand the range of ambiguity velocity for CHDS. Dual time intervals, for instance, are introduced to widen the measureable velocity range [6]. But this method decreases data rate. Multiple frequency method is also used [7], but wide band sensors it requires are not affordable to everyone. The best solution so far is altering dual time interval and dual frequency method, which has been exploited in some weather radar systems to provide velocity information with a large scale [8]. Though its more advantageous compared to the previous two, it

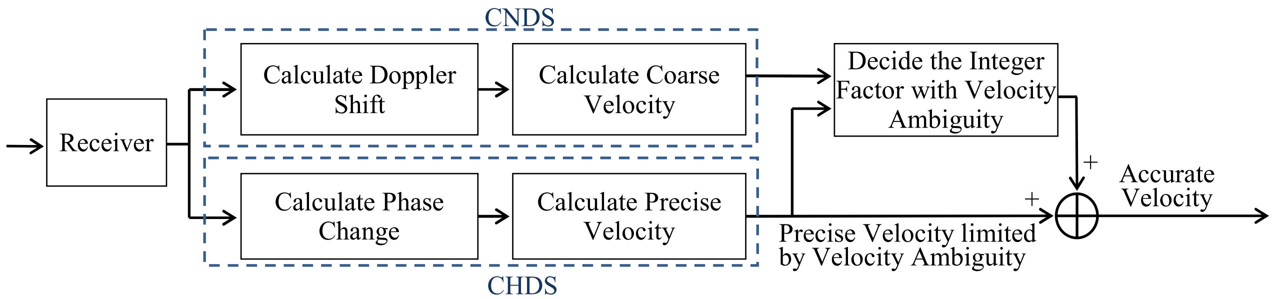


Fig. 1 Functional block diagram of CMDS.

978-0-933957-43-5 ©2015 MTS

is still unable to overcome the inherent limitation of CHDS as none of the three can cancel the velocity ambiguity. Therefore CMDS is introduced to solve the problem. A functional block diagram of CMDS to measure the velocity v_0 is shown in Fig. 1. At the receiver block, received pulse series are detected and forwarded to CNDS and CHDS. In CNDS, Doppler shift of the received pulses is calculated based on fast Fourier transform, and a coarse velocity (v_{n}) with error (ε_{n}) is obtained. In CHDS, phase changes between adjacent pulses are calculated, and the precise velocity (v_{h}) with error (ε_{h}) is given. In order to eliminate the velocity ambiguity, the measurement results of CNDS and CHDS are used to decide the integer factor n. Finally an unlimited and accurate velocity (v_{m}) is calculated by an addition of the ambiguity velocity with the integer factor ($2n\Delta v$) and the velocity v_{h} measured by CHDS.

The core calculation of CMDS is to determine the integer factor n. In a noise-free process, v_0 measured by CNDS without noise can be expressed as v_{n0}, and v_{h0} is the velocity measured by CHDS including the ambiguity velocity. Accordingly, the relationship between v_{n0} and v_{h0} can be expressed as:

$$v_{\mathrm{n0}} - v_{\mathrm{h0}} = 2n\Delta v \ . \quad (1)$$

In the actual process of measurement, each measurement noise, ε_{n} for CNDS and ε_{h} for CHDS, should be considered, and the difference between the two measurement values, v_{n} by CMDS and v_{h} by CHDS, can be expressed as:

$$\begin{aligned} v_{\mathrm{n}} - v_{\mathrm{h}} &= (v_{\mathrm{n0}} + \varepsilon_{\mathrm{n}}) - (v_{\mathrm{h0}} + \varepsilon_{\mathrm{h}}) \\ &= 2n\Delta v + (\varepsilon_{\mathrm{n}} - \varepsilon_{\mathrm{h}}) \ . \quad (2) \end{aligned}$$

It can be changed as

$$\frac{v_{\mathrm{n}} - v_{\mathrm{h}}}{2\Delta v} = n + \frac{\varepsilon_{\mathrm{n}} - \varepsilon_{\mathrm{h}}}{2\Delta v} \quad . \quad (3)$$

We propose using the left side of Eq. (3) as the decision variable to determine the integer factor. If the absolute value of error component $(\varepsilon_{\mathrm{n}} - \varepsilon_{\mathrm{h}})/(2\Delta v)$ is less 0.5, then the inequality used to determine the integer factor n, can be expressed:

$$n - \frac{1}{2} < \frac{v_{\mathrm{n}} - v_{\mathrm{h}}}{2\Delta v} \leq n + \frac{1}{2} \quad . \quad (4)$$

With determined integer factor n, the measured velocity by CMDS is

$$v_{\mathrm{m}} = 2n\Delta v + v_{\mathrm{h}}. \quad (5)$$

B. *Adaptive Algorithm*

As shown in Eq. (4), integer factor is determined correctly based on the situation error component $(\varepsilon_{\mathrm{n}} - \varepsilon_{\mathrm{h}})/(2\Delta v)$ less than 0.5. With the decrease of SNR, the increased measurement errors ε_{n} and ε_{h} will direct the value of $(\varepsilon_{\mathrm{n}} - \varepsilon_{\mathrm{h}})/(2\Delta v)$ larger than 0.5, which introduce a wrong estimate of integer factor n. Impulsive noise that seriously affected the measurement result of CMDS will be generated according to wrong estimation of integer factor n. In order to decrease the wrong estimation of integer factor n at low SNRs, an adaptive algorithm is introduced.

A functional block diagram of CMDS using the adaptive algorithm is shown in Fig.2. Signals are received by hydrophone and sent to CNDS and CHDS. In CNDS, coarse velocity including noise (v_{n}) is measured and forwarded to the decision algorithm of integer factor. Based on the measured SNR from received signals, the adaptive algorithm is used to determine the optimum range of ambiguity velocity (Δv_{a}) based on the minimum CMDS error. The measurement error of CMDS with white Gaussian noise can be deduced by the measurement error of CNDS and CHDS theoretically [4] [5]. Then precise velocity (v_{h}) measured CHDS with the optimum ambiguity velocity is calculated. With course velocity v_{n}, precise velocity v_{h} and optimum ambiguity velocity Δv_{a}, integer factor can be estimated correctly. Finally, accurate and precise velocity v_{m} can be calculated by Eq. (5) with the ambiguity velocity Δv replaced by Δv_a at each measured

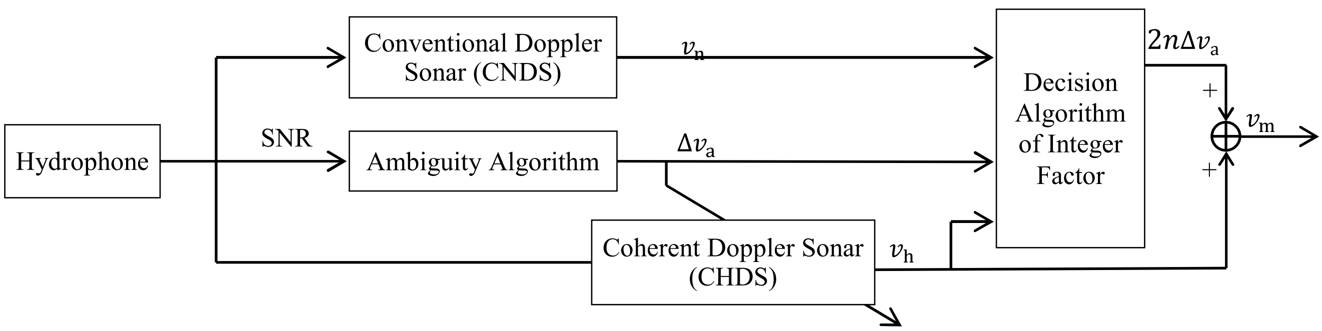


Fig. 2. Functional block diagram of CMDS using adaptive algorithm.

SNR.

CMDS using the adaptive algorithm needs variable ambiguity velocity at different SNRs. However, for CHDS a larger ambiguity velocity means a smaller measureable space range. To realize the adaptive algorithm, dual time interval method is used to provide the required optimum ambiguity velocity.

III. EXPERIMENT

A. Method

The basic structure of experimental system for CMDS is shown in Fig. 3. The system is established by waveform generator, amplifiers, projector, and hydrophone and data acquisition card. Transmitted pulse signals are generated by the waveform generator and are sent at different time intervals. Then the generated pulses are amplified by the amplifier and transmitted by the projector in a shallow water tank. The sound signals received by hydrophone are amplified by another amplifier. Both the transmitted and received signals are sampled by the NI acquisition card and stored in high-speed disk. The speed information is provided by a three dimension moving device with an accuracy of 1 mm/s.

The experimental system is shown in Fig. 4. The projector is moved by one axis of three dimension moving device and the hydrophone is fixed. The established platform is located in the shallow water tank (60 m × 6 m × 2 m). Except projector, hydrophone and moving device installed on the platform in water, other devices are placed out of the water to control movement, sample signals and calculate measurement results.

1) Static experiment

Waveform generator used in these experiments cannot automatically adjust ambiguity velocities according to each measured SNR. Therefore, instead of different ambiguity velocity for each measured SNR, only one ambiguity velocity was used for a range of SNRs. The ambiguity velocities used at different ranges of SNRs are shown in TABLE Ⅰ. In order to obtain the SNR of received signals when the projector is located in different position, the projector is first set as fixed in the experiment. With the changing of the distance between the projector and hydrophone, and the power of transmitted signal, the SNRs of received signals are measured.

In this situation, the velocity measurement error is only affected by the noise generated from the electronic devices, such as the signal generator, amplifiers, sensors and the environment. Noise from all these devices is normally considered as white Gaussian noise, which means the experimental conditions are the same as theoretical analysis conditions. The detail parameters used in the experiment is shown in TABLE Ⅱ.

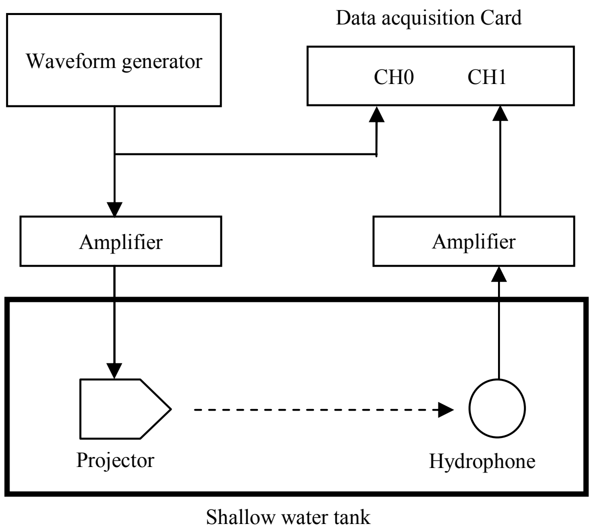


Fig. 3 System structure of experiment.

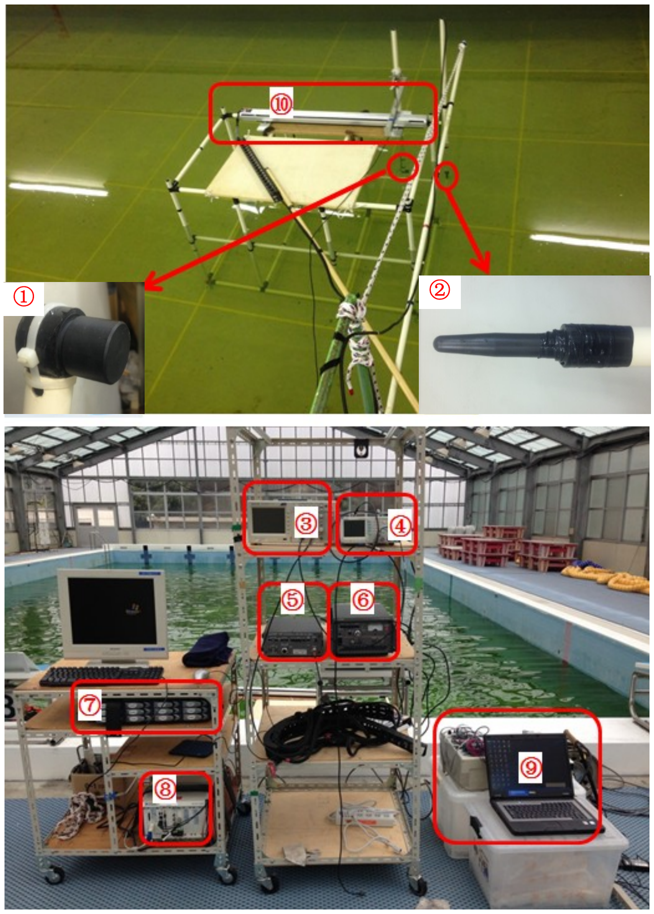


Fig. 4 Experimental system. ①, projector; ②, hydrophone; ③, oscilloscope; ④, waveform generator; ⑤ and ⑥, amplifier; ⑦, high-speed disk; ⑧, NI Pxie-5122 data acquisition card; ⑨, control panel of three dimension moving device; ⑩, one axis of three dimension moving device.

TABLE I AMBIGUITY VELOCITIES USED AT DIFFERENT RANGES OF SNRS

Range of SNRs: 4 dB

SNR (dB)	(-12,-8]	(-8,-4]	(-4,0]	(0,4]	(4,8]	(8,12]	(12,16]	(16,20]
A.V. (m/s)	1.050	0.713	0.450	0.300	0.188	0.150	0.113	0.075

Range of SNRs: 8 dB

SNR (dB)	(-12,-4]	(-4,-4]	(4,12]	(12,20]
A.V. (m/s)	0.938	0.375	0.150	0.075

Range of SNRs: 16 dB

SNR (dB)	(-12,4]	(4,20]
A.V. (m/s)	0.563	0.113

TABLE II EXPERIMENTAL CONDITIONS

Pulse envelope	Square
Pulse length (ms)	0.6
Carrier frequency (kHz)	200
Sampling frequency (MHz)	10
Sound speed (m/s)	1500

2) Dynamic experiment

The second situation of experiment is to make the projector moving with a constant velocity of 0.200 m/s approaching and leaving the hydrophone. Velocity generated by one axis of three dimension moving device. The parameters used are the same as the static experiment.

In this situation, the projector is vibrated by the force generated from the three dimension moving device. For the experiment system, this vibration is a desirable noise which is not white Gaussian noise. Therefore, the experimental results will not follow the theoretical analysis. To deal with this situation, ambiguity velocities are used as several times of measurement error of CNDS. In this experiment, four times is adopted.

B. Results

1) Static experiment

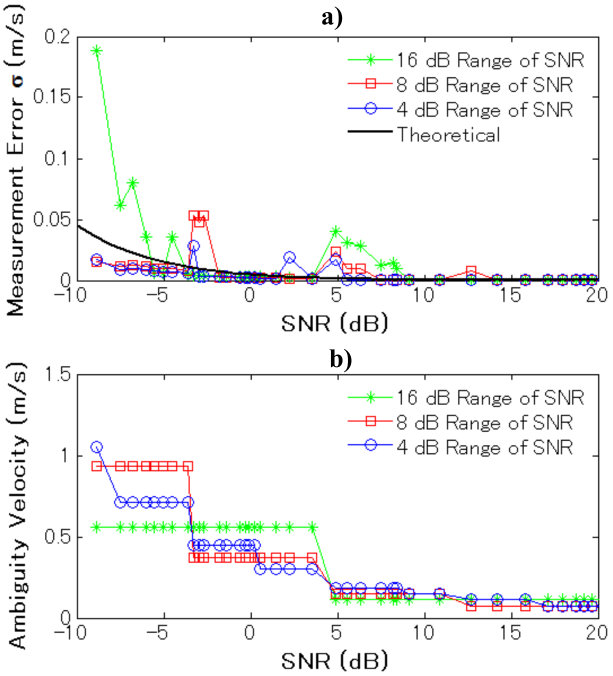


Fig. 5 Measurement errors of CMDS using adaptive algorithm at different ranges of SNRs. a), measurement and theoretical error of CMDS; b), ambiguity velocities used at different ranges of SNRs.

Based on the ambiguity velocities used at different ranges of SNRs in TABLE Ⅱ, the measurement error of CMDS is shown in Fig. 5. Measurement error of CMDS at 16 dB range of SNRs is larger than the theoretical analysis, especially the results at low SNRs of each range. When the range of SNRs decreases, the measurement error of CMDS also decreases. As shown in Fig. 5, CMDS at 4 dB range of SNRs provides the minimum measurement error in proposed three ranges of SNRs. Ranges of SNRs are used, because the ambiguity velocity cannot be adjusted immediately, if the SNR changes. According to the performance of CMDS shown in Fig. 5, the measurement error of CMDS will fit the theoretical analysis if the range of SNRs was infinitesimal. Theoretical analysis of CMDS can be used to evaluate the performance of CMDS. In addition, the measurement error of CMDS at 4 dB range of SNRs is small, even at low SNRs. Based on the measurement error shown in Fig. 5, CMDS can provide accurate and precise velocity at wide SNRs.

3) Dynamic experiment

One example of the measurement results is shown in Fig. 6. The experimental results of CNDS, CHDS and CMDS using fixed ambiguity velocity of 0.375 m/s at the SNR of -2 dB are presented. All of measured velocities have more large errors than the static results, because the measured velocities were contaminated by tiny vibration generated by moving arm. For next experiment, the vibration of the moving arm should be

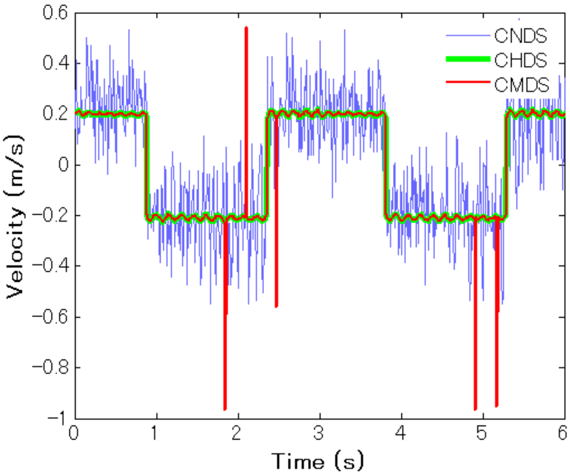
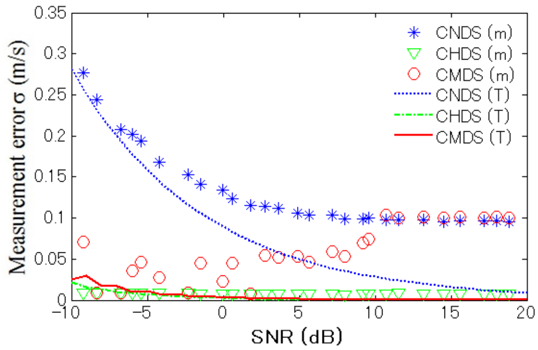


Fig.6 Measurement results of 0.200 m/s by CNDS, CHDS and CMDS using the ambiguity velocity of 0.375 m/s at the SNR of -2 dB.

a)



b)

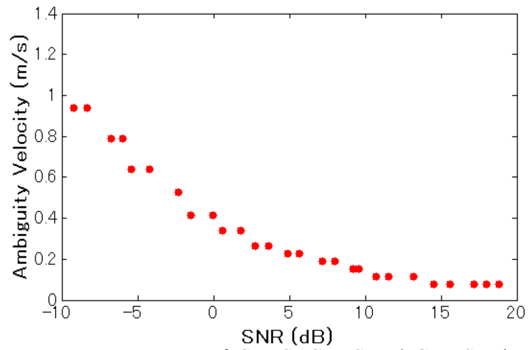


Fig. 7 Measurement errors of CNDS, CHDS and CMDS using four times of standard deviations of measurement error by CNDS as the ambiguity velocities. a), measurement errors; b), used ambiguity velocities.

cleared off, but unfortunately we cannot remove it.

Based on measured velocity by CNDS, CHDS and CMDS, measurement errors of these three methods are calculated in Fig. 7. Ambiguity velocities in Fig. 7 b) were used to carry on the adaptive algorithm, but the measurement error of CNDS (blue asterisk) is clearly larger than theoretical result (blue line). The reason is that the measurement errors of CNDS were contaminated by vibration of the moving arm, especially at the area of high SNR, therefore smaller value of the ambiguity velocity makes an impulsive noise increase.

IV. Summary

Static and dynamic experiments were carried out to evaluate the performance of combined Doppler sonar system. In the static experiment, the noise in the whole system is white Gaussian noise. Measurement errors of CNDS, CHDS and CMDS fit the theoretical analysis well. CMDS can provide accurate and precise velocity at a wide range of SNRs using adaptive algorithm. However, when the velocity generated by three dimension moving device reaches 0.200 m/s in the dynamic experiment, the measurement error exceeds the theoretical estimate due to introduced vibration. The CMDS using the ambiguity velocities deduced from theoretical analysis provides a larger measurement error than theoretical analysis. Consequently, under white Gaussian noise, CMDS can measure velocity accurately and precisely using adaptive algorithm at a wide range of SNRs.

References

[1] R. Pinkel, “On Estimating the Quality of Doppler Sonar Data,” Current Measurement, Proceedings of the 1982 IEEE Second Working Conference, Vol. 2, pp.113-116, 1982.

[2] A. Lohrmann, B. Hackett, and L.P. Roed, “High Resolution Measurements of Turbulence, Velocity and Stress Using a Pulse-to-Pulse Coherent Sonar,” Journal of Atmospheric and Oceanic Technology, pp.19-37, 1990.

[3] J. Dillon, L. Zedel and A.E. Hay, “Asymptotic Properties of an Autocorrelation Coefficient for Coherent Doppler Sonar,” Journal of Atmospheric and Oceanic Technology, Vol. 28, pp.966~973, Jul. 2011.

[4] P. Liu, N. Kouguchi, “Combined Method of Conventional and Coherent Doppler Sonar to Avoid Velocity Ambiguity,” the Journal of the Marine Acoustics Society of Japan, Vol.41, No.3, pp.103-112, Jul. 2014.

[5] P. Liu, N. Kouguchi, “Measurement Error Analysis of Combined Doppler Sonar using Adaptive Algorithm,” the Journal of the Marine Acoustics Society of Japan, Vol.42, No.1, pp.11-22, Jan. 2015.

[6] R.G.A. Craig, C. Loadman, B. Clement, P.J. Rusello and E. Siegel, “Characterization and Testing of a New Bistatic Profiling Acoustic Doppler Velocimeter: The Vectrino-II,” Proceedings of the IEEE/OES/CWTM Tenth Working Conference on Current Measurement Technology, pp.246-252, 2010.

[7] A.E. Hay, L. Zedel, R. Craig and W. Paul, “Multi-Frequency, Pulse-to-pulse Coherent Doppler Sonar Profiler,” Proceedings of the IEEE/OES/CMTC Ninth Working Conference on Current Measurement Technology, pp.25–29, 2008.

[8] S. Torres, R Passarelli Jr, A Siggia, and and P. Karhunen, “Alternating Dual-Pulse, Dual-Frequency Techniques for Range and Velocity Ambiguity Mitigation on Weather Radars,” Journal of Atmospheric and Oceanic Technology, Vol. 27, pp.1461~1475, Sep. 2010.