A Study on the Application of Pulse Doppler Radar in VTS

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This paper discusses the necessity and feasibility of the application of Pulse Doppler Radar in VTS through analysing the limitations of the non-coherent, single frequency, radar and the advantages of PD radar.

1. INTRODUCTION. Vessel traffic services (VTS) have made a great contribution to increasing the safety of vessel movements, the efficiency of shipping and protection of the marine environment. The economic and social effectiveness of VTS has been demonstrated by the numerous VTS systems which have been set up all over the world. A VTS is a complicated, large-scale system which is composed of three essential factors: namely, advanced technical facilities, scientific management regulations and well-trained workers. The basic technical facilities include the comprehensive application of advanced scientific technology such as radar, computers and communication equipment, etc.

The main functions of the VTS are: collecting information about vessel traffic in the waters concerned; data processing of this information; keeping watch over traffic in the waters concerned; and organising and providing traffic information. The traffic service cannot work without the collection of a vast amount of information on traffic monitoring and vessel movements. Radar is an ideal technical means to perform such a task. Therefore, the subsystem of radar is an important component of a VTS.

At present, a non-coherent single frequency radar is commonly used in VTS. It is simple to produce and the signals easy to process, the cost of the equipment is low, and it meets the basic requirement for detecting targets and determining the parameters of their positions; but, with the development of shipping, vessels have tended to become massive and travel at high speed. Also the density of the traffic and the movement of dangerous goods have increased. All these developments need a modern VTS which is better equipped and more advanced both in technology and function. On the other hand, the rapid improvement in the information storage and data processing capabilities of the computer system in a VTS require a higher quality of radar sensory information. Evidently, the limitations of common pulse radar cannot fit the developing trend. Studies of the application of a new radar system for VTS are now the order of the day.

2. LIMITATIONS OF A NON-COHERENT, SINGLE CARRIER FREQUENCY, RADAR. At present, the radar subsystem of a VTS mainly uses a non-coherent, single carrier frequency signal. Giving consideration to both the maximum range and the picture resolution, we usually change the pulse width

of the signal according to the range. That is, we use a wide pulse for long range in the form of a single carrier frequency rectangular pulse (approximately) and a narrow pulse for short range in the form of a single carrier frequency Gaussian pulse. The ambiguity function of the single carrier frequency rectangular pulse is:

$$|x(\tau,\zeta)| = \begin{cases} \dfrac{\sin \pi\zeta(T-|\tau|)}{\pi\zeta(T-|\tau|)}\left[\dfrac{T-|\tau|}{T}\right], & |\tau| < T \\ 0 & |\tau| > T \end{cases} \tag{1}$$

In this formula: τ is the delay of the target's echo, ζ is Doppler drift caused by the target's movement, T is the width of the pulse.

From equation (1) ζ can be equated to zero to give the ambiguity function for the distance:

$$|x(\tau,0)| = \begin{cases} \dfrac{T-|\tau|}{T} & |\tau| < T \\ 0 & |\tau| > 0 \end{cases} \tag{2}$$

From equation (1), we can also make τ equate to zero and derive the ambiguity function for the velocity:

$$|x(0,\zeta)| = \left|\frac{\sin \pi\zeta T}{\pi\zeta T}\right| \tag{3}$$

The ambiguity function of the single carrier frequency Gaussian pulse signal is:

$$|x(\tau,\zeta)| = \frac{\pi}{2} e^{-\left(\frac{\tau^2}{2}+\frac{\pi^2\zeta^2}{2}\right)} \tag{4}$$

From equation (4), ζ can be equated to zero to give the ambiguity function for the distance:

$$|x(\tau,0)| = \frac{\pi}{2} e^{-\frac{\tau^2}{2}} \tag{5}$$

Let τ be equal to zero, and the ambiguity function for the velocity is then:

$$|x(0,\zeta)| = \frac{\pi}{2} e^{-\frac{\pi^2\zeta^2}{2}} \tag{6}$$

In order to enhance the precision and to increase the resolution for the range, the most suitable form of the ambiguity function of distance is the strike function $\delta(\tau)$. We can use a similar level between the ambiguity function $x(\tau, 0)$ and $\delta(\tau)$ to judge the inherent resolution of the signal. The effective interrelated bandwidth (W_e) can be obtained through analysing the similar level of the two waves in the frequency domain. The larger the value of (W_e), the more similar are the shapes of $x(\tau, 0)$ and $\delta(\tau)$, and the higher is the resolution of the distance. It is clear that the range precision and range resolution are determined by the frequency domain structure. The wider the signal's frequency spectrum, the higher is the resolution of the distance. The frequency spectrum width of the single carrier frequency, rectangular pulse is:

$$W_{eR} = \frac{3}{2T} \tag{7}$$

The frequency spectrum width of a single carrier frequency Gaussian pulse is:

$$W_{eG} = \frac{1}{\sigma\sqrt{2\pi}} \tag{8}$$

in which T is the width of the pulse and σ is the parameter of pulsewidth about the Gaussian pulse.

It can be seen that the pulsewidth (T or σ) should be reduced in order to increase the range precision and range resolution.

A similar level of the ambiguity function of the velocity $x(0, \zeta)$ and the strike function $\delta(\zeta)$ can be used to judge the signal's inherent resolution of velocity. The effective interrelated time (T_e) is defined and used to illustrate the similar level of the functions $x(0, \zeta)$ and $\delta(\zeta)$. It is also called the signal's duration width. It is clear that the velocity precision and the velocity resolution are determined by the signal's structure in the time domain. The signal should possess a large duration time-width in order to increase the velocity precision and the velocity resolution. The duration time-width of the single carrier frequency, rectangular pulse, signal can be obtained by:

$$T_{eR} = T \tag{9}$$

The duration time-width of the single carrier frequency Gaussian pulse signal is:

$$T_{eG} = \sigma\sqrt{2\pi} \tag{10}$$

From formulas (7) and (9), the product of the time-width and band-width of the rectangular pulse is:

$$T_{eR}\,W_{eR} = T\frac{3}{2T} = 1{\cdot}5 \tag{11}$$

From formulas (8) and (10), the product of the time-width and band-width of the Gaussian pulse is:

$$T_{eG}\,W_{eG} = \sigma\sqrt{2\pi}\,\frac{1}{\sigma\sqrt{2\pi}} = 1 \tag{12}$$

This means that the large time-width and band-width cannot be obtained simultaneously by the single carrier frequency non-coherent pulse signal. Therefore, use of a non-coherent radar of single carrier frequency has its limitations in that:

(i) It cannot increase the range precision and the velocity precision simultaneously.
(ii) It cannot increase the range resolution and the velocity resolution simultaneously.

(iii) It cannot increase the range resolution and the maximum range simultaneously.

We can use a narrow pulse to increase the range precision and the range resolution, but its energy is limited and the maximum range is decreased. If we use a wide pulse to increase the maximum range, the range precision and range resolution are decreased.

3. THE CHARACTER OF PULSE DOPPLER (PD) RADAR. The PD radar transmits coherent pulse signals in an infinite sequence. When the beam scans, a finite sequence coherent pulse string is received. Analysis shows that a coherent pulse string signal has a large time-width and band-width. It retains the form of a narrow pulse signal with a definite band-width, so it has a high range resolution. It increases the continuous transmission time of the signal by using a coherent signal which means the time-width is increased so that a high-velocity resolution is obtained. Therefore, such a radar possesses the range resolution of the pulse radar and the velocity resolution of the continuous wave radar. It can distinguish the echo of moving objects better in a clutter background. In order to ensure single value results in measuring velocity and the velocity resolution, it requires:

$$f_{\mathrm{dmax}} \leqslant \frac{1}{2} f_r \tag{13}$$

In the formula: f_{dmax} is the maximum Doppler drift of the object, and f_r is the repeating frequency of the pulse.

In order to measure a high-speed object and get a high-velocity resolution, a high pulse repetition frequency (PRF) should be used. But in order to obtain a single value in range, it requires that:

$$t_{\mathrm{dmax}} \leqslant T_r \tag{14}$$

In the formula: t_{dmax} is the maximum time delay of the object echo relative to the transmitted pulse.

T_r is the repeating cycle of the pulse $\left(= \frac{1}{f_r}\right)$

If a single value is required in measuring velocity and range at the same time, the following relationship should be met:

$$f_{\mathrm{dmax}}\, t_{\mathrm{dmax}} \leqslant \frac{1}{2} f_r T_r = \frac{1}{2} \tag{15}$$

PD radar generally uses a master oscillator power-amplifier (MOPA) transmitter, the vibration source and power amplifier of which has a high stability to ensure the stability of the signal's frequency and phase.

The echo of a moving target is a phase coherent pulse string in a PD radar. Its frequency spectrum is composed of many lines with definite widths. The lines have corresponding Doppler drifts relative to the spectrum of the sending signal, so that a comb filter matching with the signals is used for the receiver. Information on the target's distance should be obtained before filtering.

4. THE FEASIBILITY OF USING PD RADAR IN A VTS. We find that PD radar is useful in increasing maximum range under the condition of limiting the transmitting power. It is known that: $R_{\max} \propto (P_t \cdot T)^{1/4}$ where P_t is the maximum power of the pulse and T is the pulse-width.

Since a PD radar has a large time-width, $R_{\max}$ can be increased without increasing the transmitting power (P_t). It is advantageous for the VTS's radar to improve its ability for detecting small objects. The range precision and range resolution will be increased using the PD radar which has a large band-width. On the other hand, the velocity precision and velocity resolution are also enhanced due to the PD radar's signal which has a large time-width.

In order to improve the navigation function of a VTS radar, it is necessary to provide timely information about a target's motion, to identify which are the moving targets and to track their movements. At the present time, a single carrier frequency non-coherent radar cannot meet these requirements. As a consequence, targets are frequently incorrectly tracked or missed. On the other hand, as soon as the data of a target's position are determined by the PD radar, its motion can be determined.

A PD radar is able to increase or enhance the following three pairs of performance criteria simultaneously, namely: the range precision and the velocity precision; the range resolution and the velocity resolution; the range resolution and the maximum range. All these facts demonstrate that it is necessary to use PD radar in a VTS. A question is raised on whether the application of PD radar in VTS can meet the demand for a single value function in determining velocity and range. The following is an analysis of a simple, single carrier frequency, PD radar.

When a ship enters a harbour, it should usually slow down and its velocity should be under 10 knots. Let us take a maximum radial velocity 10 knots to calculate the greatest Doppler drift:

$$f_{d\max} = f_T \frac{2V_{r\max}}{C} = 9400 \times 10^6 \times \frac{2 \times 10 \times 1852}{3 \times 10^8 \times 3600} = 322{\cdot}39(\mathrm{Hz})$$

where f_T is the working frequency of the radar, and is equal to 9400 MHz, and $V_{r\max}$ is the greatest radial velocity of the object, which is equal to 10 knots.

If the greatest working range in the harbour is 10 nautical miles, and the pulse repeating cycle has 20 percent remainder, the greatest time delay will be:

$$t_{d\max} = \frac{2R_{\max}}{C} \times 1{\cdot}2 = \frac{2 \times 10 \times 1852}{3 \times 10^8} \times 1{\cdot}2 = 148(\mu s)$$

According to formula (15), the condition to ensure a single value for measuring velocity and distances is:

$$f_{d\max}\, t_{d\max} \leqslant \frac{1}{2}$$

Since $f_{d\max}\, t_{d\max} = 0{\cdot}05 < \frac{1}{2}$. Therefore, it is possible to use a single carrier frequency, simple PD radar for a VTS.

At present, the contradiction between the information supplied by the single frequency non-coherent radar and the high-level data processing ability of the computer used in a VTS is becoming increasingly acute. A good way to solve this problem is to employ a new radar system. A PD radar is suitable for a VTS. Since the pulse-formation and data processing of the PD radar is relatively simple, and its range resolution and velocity resolution is high, it can meet the demands for determining the position and the velocity of a target, inhibiting clutter, searching and tracking, and so on. At the same time, the price of the PD radar is acceptable since the cost of high-performance electronic devices and microprocessors is decreasing day by day. In addition, the cost of a new radar system only represents a small proportion in the total investment in a VTS, and yet its excellent characteristics can bring beneficial results.

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KEY WORDS

1. Radar. 2. Vessel Traffic Services. 3. R&D.