Method of Measuring Doppler Shift of Moving Targets Using FMCW Maritime Radar

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Abstract— **During the operation of an FMCW (frequency modulated continuous wave) maritime radar, the system transmits a continuous radio energy with a frequency modulated by a triangular or sawtooth-shaped signal. As a result, the frequency of the transmitted signal varies gradually with time. When the signal is reflected by an object, the received waveform will build up a delayed replica of the transmitted waveform, with the time delay as a measure of the target range. If the target is moving, the radar system will register a Doppler shift within the received signal. Compared to the frequency of the emitted signal, the received signal will show a higher frequency when the target is approaching and a lower frequency when the target is moving away from the radar location. Thus, the total Doppler shift may result from the superposition of both source and observer motions. Specifically, the amount of Doppler shift is directly proportional to the radial speed of the target. The Doppler shift can be determined after performing the range Fourier transform (*range FFT*) first. For a target of interest, we can repeat the range FFT until we have enough data to perform the second level of FFT. The result of this second FFT is a two dimensional complex valued matrix, whose spectral peak corresponds to the Doppler shift of the moving target. This method is known as Doppler FFT. Some results of the measurement of target speed using this method are presented in this paper.**

Keywords- Doppler FFT, radial speed, FMCW, radar, computer simulation

I. INTRODUCTION

In the frequency modulated continuous wave (FMCW) radar, a signal that constantly changes in frequency around a fixed reference is used to detect objects and to measure its ranges. In the normal operation of an FMCW radar, the system transmits a continuous radio energy with a frequency modulated by a triangular or sawtooth-shaped signal. As a result, the frequency of the transmitted signal varies gradually with time. If there is an object within the actual radar range then its echo return will be received by the radar antenna (Rx antenna). It is observed that the received waveform is a delayed replica of the transmitted waveform, with the time delay as a measure of the target range.

In order to determine the range of the target, the system mixes the received signal with the transmitted signal to produce a beat signal. As shown in Fig. 1, a portion of the transmitted signal is used as a reference signal that is needed to generate the requested beat signal frequency. This signal part is then introduced directly into the receiver via a cable or other direct connection. The resulting frequency of the beat signal is amplified and limited to remove any amplitude fluctuations [1].
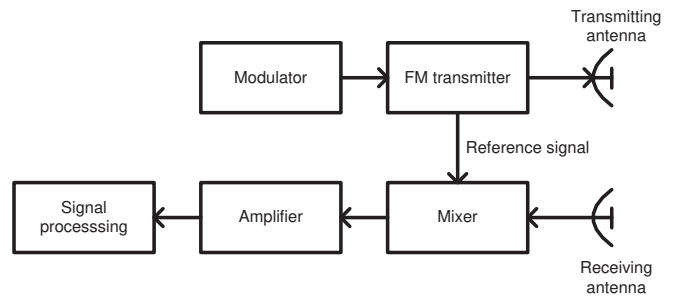

Figure 1: Block diagram of FMCW radar, adopted from [1].

In the real operation many FMCW radars use a sawtooth-shaped frequency modulation when transmitting its signal, as depicted in Fig. 2. The frequency of the transmitted signal is linearly increased by ΔF within the sweep time t_s. This cycle of procedure is repeated for every azimuth position during the scanning process.
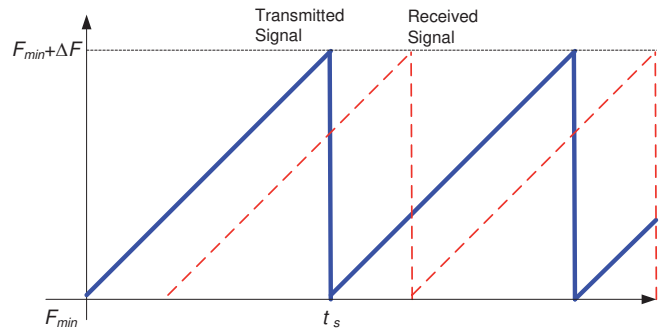

Figure 2: Sawtooth shaped frequency modulation.

By looking at the fact that a signal wave will propagate at the speed of light c, the signal reflected by a target at the distance R from the radar location will generate a beat signal with the frequency f_R

$$f_R = \frac{2F_m}{c} R,\qquad(1)$$

where F_m is the slope of the graph shown in Fig. 2

$$F_m = \frac{\Delta F}{t_s} \cdot \qquad (2)$$

Hence, there is a linear relationship between the beat frequency f_R and the distance R of the target. Information about the frequency of the beat signal is obtained by performing the Fourier transform, which is expressed mathematically as

$$S(f) = \int_{-\infty}^{\infty} s(t) \cdot e^{-j2\pi \cdot f \cdot t} dt, \qquad (3)$$

where $s(t)$ and $S(f)$ are the beat signal and corresponding amplitude spectrum respectively. In this amplitude spectrum, the ranges or distances of targets can be determined by measuring the distances of the spectrum peaks from the axis origin.

II.   PROCESSING STEPS

When detecting a moving target, the radar system will be able to record a Doppler shift within the beat signal. Doppler shift is the change in frequency of a wave measured by an observer moving relative to the source of the wave. The received signal frequency is higher (compared to the original frequency) when the target is moving towards, and lower when it is moving away from the radar location. Thus, the total Doppler shift may result from both motions of the source and the observer. Specifically, the Doppler shift is proportional to the radial speed of target.

For signal processing purpose, the raw data stream coming out of the receiver is sampled with a 16-bit ADC. A Fourier transform (FFT) over 1024 samples is computed to give the range dependent amplitudes and phases. This processing step is called *range FFT*.

For a target of interest, we repeatedly perform the range FFT so many times, usually a multiple of power of 2 [2]. For the demonstration purpose we choose the number of sweep repetition to be 512. After completing 512 sweeps, for each range cell found we do a second-level FFT called *Doppler FFT*. The result of this Doppler FFT is a two dimensional (2D) complex valued spectrum, whose amplitude corresponds to the Doppler shift of the moving target. In the computation, the phase information is dropped and only the amplitude is maintained [2]. The processing steps of the Doppler FFT are shown in Fig. 3.
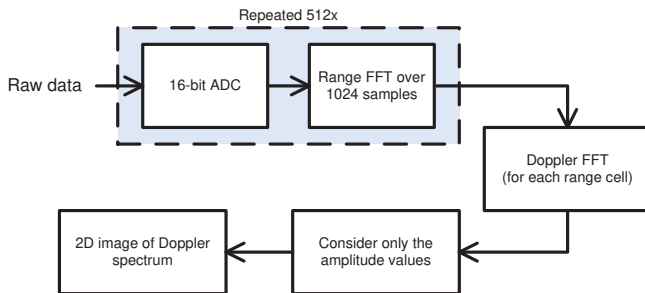

Figure 3: Schematic diagram of Doppler FFT.

III.   SIMULATION OF DOPPLER FFT

For the simulation purpose we first generate the beat signal received by the Rx antenna. Then we perform the Fourier transform on the generated beat signal to obtain the range FFT. As a result we can detect an object located at the 100th range cell, as shown in Fig. 4.
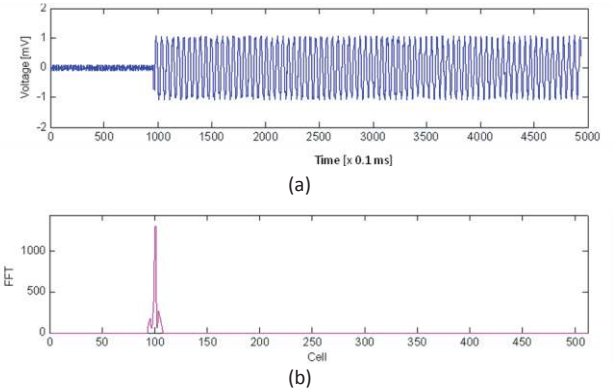

Figure 4: Radar beat signal (a) and its range FFT (b).

For the above target of interest, we repeat the sweep as many as 512 times. The resulting amplitude and phase spectrum are shown in Fig. 5.

As depicted, the amplitude and phase spectrum values are displayed as color dots that are placed on top of two-dimensional region with the number of sweep as horizontal axis and the range cell as vertical axis. Red color represents the maximum, and deep blue color represents the minimum value of the corresponding spectrum. In our simulation we divide the maximum range into 512 cells.
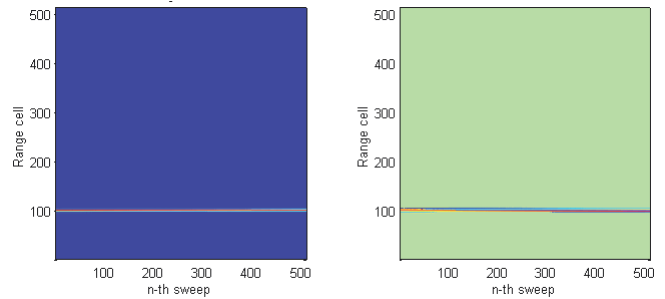

Figure 5: Amplitude (left) and phase (right) spectrum resulting from 512 sweep repetitions.

Starting from this point, we continue the processing by performing Doppler FFT to determine the Doppler shift of a target located at the 100th range cell. Fig. 6 and 7 display the result of Doppler FFT. As shown, only the amplitude spectrum is used to determine the Doppler shift.

As depicted in Fig. 6, the spectrum peak is found to be in the right half plane of the 2D Doppler spectrum. This result indicates that the target of interest is actually moving towards the radar location. By incorporating the information about the maximum unambiguous Doppler speed detectable using the FMCW radar, we can determine the current radial speed of the moving target. In our simulation, the detected target's radial speed is about 5 knots.

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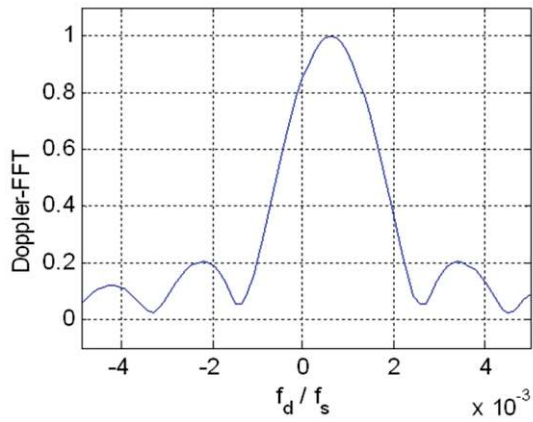**2013 IEEE International Conference on Teaching, Assessment and Learning for Engineering (TALE)**

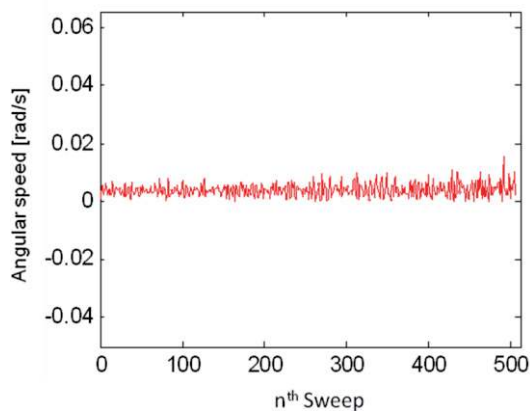Figure 6: Result of Doppler FFT calculation at the 100th range cell.

Figure 7: Phase information obtained from the calculation of Doppler FFT at the 100th range cell.
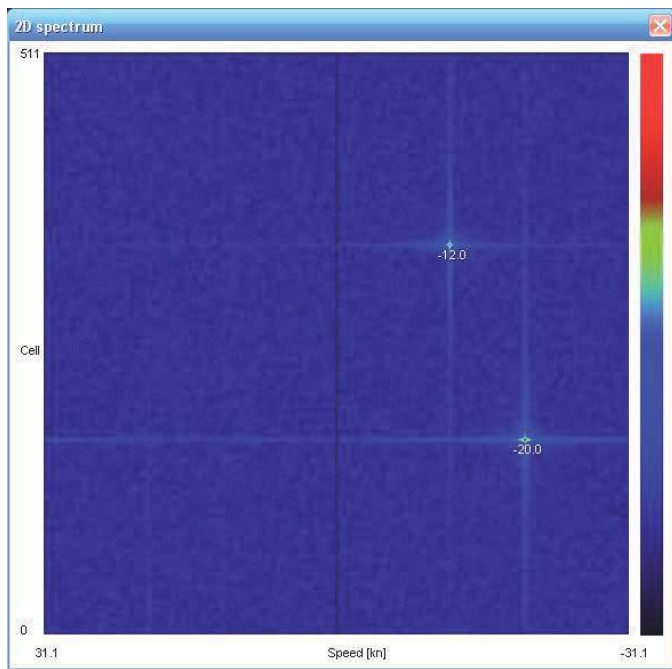

Figure 8: Doppler spectrum of two moving targets.

After determining the first target's speed we can continue the processing steps by repeating the same procedure for each range cell. By doing this, we can measure the radial speed of each target detected by the FMCW radar. Fig. 8 shows 2D Doppler spectrum of two targets moving away from the origin of radar, each with the speed of 12 knots and 20 knots respectively.

IV. RESULTS AND DISCUSSION

To verify our method we have carried out a series of field tests using INDERA radar. INDERA is the first Indonesian FMCW maritime radar developed jointly by RCS and IRCTR – TU Delft [3,4]. INDERA was built with an ability to detect and measure the distance of a vessel using very low transmit power.

During the test procedure we have carried out two types of measurements. In the first type of measurement, our radar was installed on top of a 12m high tower in the coastal area. From there the radar starts to scan the surrounding area. Once the radar found moving targets, in order to perform the Doppler FFT, the radar antenna is directed to the targets. In the second type of measurement, we installed our radar on a vessel. In order to perform the Doppler FFT, we always directed the radar antenna to a certain point in the coastal area, whereas the vessel is required to move away from that point with a specified speed. The results of the field tests are shown in Fig. 9 and 10.
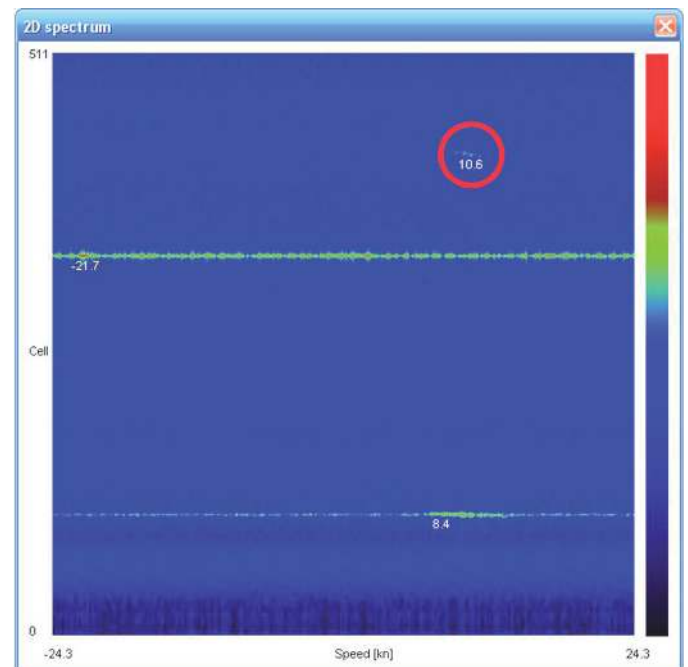

Figure 9: Doppler spectrum of multi targets resulting from the first type of measurements.

Fig. 9 shows two moving targets detected at the time of measurement. Here we can see that the nearer target is located in the lower part, and the farther target is in the upper part of the 2D image of Doppler spectrum respectively. By looking at the horizontal axis scale, we can see that the nearest target was moving towards the radar position with the speed of 8.4 knots.

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The farthest target (in red circle) was detected with the speed of 10.6 knots, also moving towards the radar position. If the signal peak in the Doppler spectrum is very low, we can always adjust the threshold level, so that the actual radial speed of target can be clearly recognized in the 2D image of Doppler spectrum.

Unfortunately there was an artifact caused by frequency leakage in the middle range cells that occurred during the first type of measurements. The artifact can be seen clearly as a horizontal bright line across the Doppler spectrum. As a result, we were unable to determine whether there was a third moving object at the corresponding range cell.
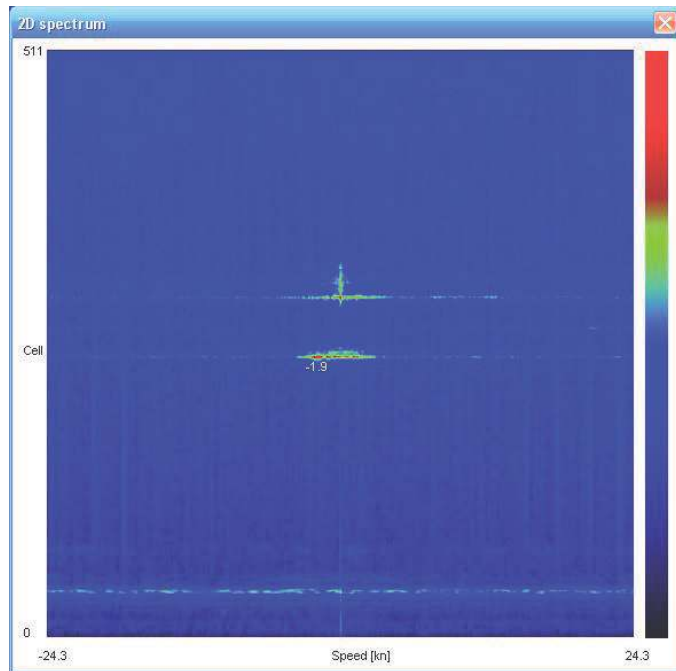

Figure 10: Doppler spectrum of moving targets obtained from the second type of measurements.

Fig. 10 shows two-dimensional Doppler spectrum of multi targets resulting from the second type of measurements. As shown, there are two targets detected at the time of measurement. We can see that the first target which was located a little bit farther from the origin of radar was not moving. This is indicated by the red dots in the spectrum found nearly in the middle, or zero position, of Doppler spectral width. The second target, which is located at the middle range cell, was detected as a moving target with the radial speed of 1.9 knots away from the origin of the radar.

The results obtained from measurements during the field test show that the Doppler shift can be used to determine the radial speed of moving targets. In order to calculate the real direction and speed of the moving targets, we can perform the vector addition operation to the actual speed of the vessel, in which the FMCW radar is installed.

V. CONCLUSIONS

This paper presented a method to measure the Doppler shift of a moving target using FMCW radar. The determination of Doppler shift is obtained after performing the range FFT. For a target of interest, the range FFT is repeated 512 times, so that there are enough data available to perform the second level of FFT (Doppler FFT). The final result is a two dimensional complex valued matrix, whose amplitude corresponds to the Doppler shift of moving target. This method has been implemented in a computer simulation, and verified through a series of measurements using radar INDERA. The measurement results show that this Doppler shift can be used to determine the radial speed of moving targets found in the actual radar range.

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