

Determination of Phase difference of Backscatter Signals from Coherent-on-Receive Microwave Marine Radar for Wave Measurement

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Abstract—In present study, a X-band marine radar was installed at the northwestern coast of Taiwan. The IF signal from the super-heterodyne receiver of the marine radar was retrieved, amplified, band-pass filtered and digitized to be the raw dataset, from which the phase of transmitted and echo radar EM wave could be determined. Based on Doppler theory, the time rate change of the phases between succeeding pulses could be used for estimating the water particle velocity of wave orbital motion. Due to the fact that the magnetron in the marine radar produces random frequency jump, and leading to mis-estimate of the phase differences. We adopted the Ensemble Empirical Mode Decomposition method as a filter to exclude the effects of frequency jump. The results demonstrated the improved capability of coherent-on-receive marine radar for surface wave measurement.

Keywords—coherent-on-receive radar; microwave marine radar; Empirical mode decomposition

I. INTRODUCTION

Civil marine radar (CMR), which was originally designed and built for ship detection and tracking at sea or on navigable waterways, and for vessel surveillance from land-based authorities, is the largest radar market. For the past decades, the business competition in the CMR market has forced the CMR to evolved and become a low-cost, easily maintained system. It is usually an HH polarization microwave radar used in low-grazing angles. The use of CMR for ocean surface wave and current remote sensing has been developed (Young et al., 1985; Seemann et al., 1997; Nieto Borge et al., 1999; Nieto Borge and Soares, 2000). Algorithms applied to the processing of the radar sea-clutter image sequence demonstrated its capability of retrieving information about sea-surface height, directional wave spectrum, surface current, shallow water bathymetry, and wind stress field (Nieto-Borge et al. 1998, 2000; Dankert & Horstmann, 2004; Dankert et. al., 2003, 2005; Bell, 1999). This category of ocean remote sensing radar can be referred as the traditional image radar.

Recent studies by Trizna (2010) further improved the marine radar performance by replacing the non-coherent

magnetron with a solid-state power amplifier, allowing it to detect the phases of transmitted and received EM waves. In the detection, a stable reference oscillator wave, which is locked in phase with the transmitter during each transmitted pulse, is mixed with the echo signal to produce a beat or difference signal. As the reference oscillator and the transmitter are locked in phase, the backscatter of sea clutter can be determined. Such radar, referred to as fully coherent radar (COHrad), can provide spatial-temporal data with higher resolution and accuracy over the coastal area. However, the export/import of the associated key components are prohibited to certain countries/areas and thus the fully coherent marine radar can hardly become alternative to the traditional image radar.

The Coherent-on-Receive radar (CORrad), or Pseudo-coherent Radar, which still uses magnetron and requires little modification of the CMR, seems to play a role. One of the shortcomings in technical aspect is of CORrad is that the incoherent RF excited from the magnetron would produce random frequency jump from one pulse to the next and thus leads to mis-estimation of the phase difference and so are the wave heights. As the network of CMRs has been setup at more than 200 fishery ports for vessel surveillance around the 1300 km coast of Taiwan, the aim of present project is to develop a toolkit that can upgrade the existing CMRs to become coastal remote sensing CORrad at comparatively low cost. The present paper focuses on proposing a method for reducing the effects of frequency random jump.

II. EXPERIMENT SETUP

The field test of radar operation was carried out from March 1 to March 15, 2013, at the National Central University coastal observatory. The experiment site was located on the north-western coast of Taiwan (24.966°N, 121.0086° E), as shown in Figure 1. Instrumentation included an ISR X-band CORrad and a traditional X-band image radar remote sensing system, eddy covariance systems for air-sea flux, and coastal meteorological factors measurements, as well as an array of bottom-mount ADCPs. The integrated parameters that describe

the atmospheric boundary layer, surface waves, and ocean currents were simultaneously recorded. The ISR CORrad system used in present study was Koden MDS X-band (9.41GHz) radar with antenna lengths of 4 ft, azimuth resolution of 1.8°, and pulse repetition rate of 2,000Hz. The rotating speed of both antennas was 48 rpm (rounds per minute). The IF signal from the super-heterodyne receiver was first amplified with gain about 30 dB and band-pass filtered. The signal was then digitized using NI data acquisition card at sampling rate of 1GHz.

In this experiment, upward looking ADCPs, deployed at various water depths, were used for providing sea-truth wave and current data. The ADCPs used in this study were RDI Sentinel 1200KHz. Three functions of RDI ADCP can be used for surface wave measurement: the surface-tracking function, the pressure sensor for water elevation measurement, and the velocity profile measurement for wave orbital-motion estimation. In extremely shallow water depths, as in the present study, the surface tracking method has the preferred wave frequency range. The footprints of acoustic beams on the sea surface ranged from 0.22 m² to 0.33 m², which was sufficiently small, compared to the typical wavelength (approximately 70m) during the experiment. The surface tracking of the wave mode setting was adopted to retrieve surface wave data, with a sampling rate of 2Hz.

The deployed locations of ADCPs are shown in Figure 1, denoted as Station A, to Station E, with mean water depth ranges from 7m to 13m. The ADCPs collected the temporal variation of ocean surface elevations with four acoustic beams. The altitudes of ADCPs, e.g. the pitch, roll, and heading angle were also recorded and used, together with the tidal elevation, to determine the positions of the footprints from the projection of the four acoustic beams on the ocean surface. The temporal series of water elevations from the 4 beams, and the footprint shapes were then used as inputs to DIWASP, a directional wave spectra toolbox for MATLAB® (Johnson, 2008), in which the Extended Maximum Likelihood Method (EMLM) was chosen for directional wave-spectrum estimation.

A flux tower was equipped with two eddy covariance systems for the measurements of heat, moisture, CO₂ fluxes, and sea surface roughness. The 3-D ultrasonic wind sensors were installed at 10m and 15m above mean sea level. Other basic coastal meteorological factors, such as air-temperature, humidity, rainfall intensity, barometric pressure and solar radiation were also observed. The data collected by the flux tower provided the background condition of the atmospheric duct for the estimation of the atmospheric refractive index for further discussion.

III. METHOD

In order to overcome the difficulty of nonlinear and non-stationary nature in amplified IF signal, a novel multi-timescale analysis method, ensemble empirical mode decomposition (EEMD) (Wu & Huang, 2009) is adopted in present study. EEMD is an improved version of EMD (Empirical mode decomposition, Huang et al. 1998, Huang et al. 2008). It decomposes original signals into multiple intrinsic mode functions (IMF); it acts essentially as a dyadic filter bank

resembling the IMFs that represent the characteristics on different temporal scales (Flandrin et al. 2004). The remainders are residuals, which can be viewed as trends in the changes of original signals.

To define the IMFs, the original EMD uses the envelope calculations to determine the local maxima and minima separately (Huang et al. 1998). Once the extrema are identified, all the local maxima and minima are connected by a cubic spline curve as the upper and lower envelopes. Their mean is designated as m_1 , and the difference between the data and m_1 is the first component, h_1 , i.e.

$$h_1 = x(t) - m_1 \quad (1)$$

By repeating the process, with h_1 replace by $x(t)$, m_2 is the mean envelope of h_1 ,

$$h_2 = h_1 - m_2 \quad (2)$$

Each IMF h_i , represents simple oscillatory mode will be resulted by continue the sifting process till the following conditions are met: the number of extrema is identical to the number of zero-crossings or, at most, differ by one.

$$x(t) = \sum_{i=1}^n h_i + r_n \quad (3)$$

where r_n is the residue, which can be either the monotonic trend or a constant.

EMD method sometimes has mode mixing problem, which is defined as a single IMF including oscillations of dramatically disparate scales. Wu and Huang (2009) proposed EEMD to overcome the drawback by adding finite white noise to the data. They used the advantage of the statistical characteristics of white noise to perturb the signal and then cancel itself out after serving its purpose. The implementation steps for EEMD are as follows (Wu and Huang 2009).

- (1) Add white noise to the data and apply EMD.
- (2) Subtract the same white noise used by step (1) from the data, and apply EMD.
- (3) Stack the results of steps (1) and (2).
- (4) Repeat steps (1)–(3) several times with different white noise added each time.
- (5) Stack all the IMFs of the same level and calculate the average.

It is noted that the IMFs of different levels sometimes are needed to be combined to obtain the result with their physical meaning. In present study, the IMF or combined IMFs representing an oscillatory mode, is considered to correspond to the Doppler effects from orbital wave motion. The amplitude of oscillation and frequency can change with time,

but the mode does not produce riding waves and will not be limited to narrowband signals

IV. DATA PROCESSING AND RESULTS

The major processing steps of the IF signal are:

1. Calculate the Quadratic signal and the corresponding phase by applying the Hilbert Transform to the I signal that recorded with sampling rate 1GHz.
2. Alignment of the waveforms between the 1st pulse envelop and the succeeding pulse envelop using the cross spectral analysis of the 1st and 2nd I and Q channel, as shown in Fig.2.
3. Assume the transmitted signals in the 1st pulse and 2nd pulse have the same frequency; calculate the phase difference of the echo between pulses at every radial grid.
4. Transfer the phase difference to radial velocity using Doppler Theory. After the text edit has been completed, the paper is ready for the template. Duplicate the template file by using the Save As command, and use the naming convention prescribed by your conference for the name of your paper. In this newly created file, highlight all of the contents and import your prepared text file. You are now ready to style your paper; use the scroll down window on the left of the MS Word Formatting toolbar.

Applying the above-mentioned steps to every pulse envelope and echo that obtained as the antenna rotationally scans over the entire domain, the spatial radial velocity can be gridded and mapped. It is noted that the Doppler frequency shift induced by wave orbital motion and surface current is too little to be detected using current spectral resolution. Therefore instead of frequency shift, we actually measure the temporal phase variation. In the condition of constant frequency, the phase should vary from $-\pi \sim \pi$ along with time, and repeat the cycle steadily. If there exist the Doppler frequency shift, the phase change will deviate from the steady cycle. The phase difference was calculated by the subtraction of the phases between pulse signal. However, if the civil marine radar RF excited from magnetron exhibits frequency jump from one pulse to the next, the phase difference between succeeding signals will be significantly mis-estimated. This effect would degrade the performance and therefore impeded the use of Cohere-on-Receive marine radar. In present study, we use EEMD to identify the phase deviation.

In order to discern the time rate change of phase that deviates from steady $-\pi \sim \pi$ cycle, the EEMD is applied to each phase signal, as shown in Fig. 3. Using a single pulse as an example, as illustrated in the blue line. Twelve IMFs can be obtained accordingly. The linear superposition of IMF6, IMF7 and IMF8 is shown in figure 4; while other IMFs are treated as unrelated information. The curve in figure 4 can be regarded as the phase change of echo signal that induced by wave orbital motion. By applying EEMD to every pulse signal, the velocity field can be obtained.

Figure 5 demonstrates the result of present proposed method (right panel) and the comparisons if the effects of frequency jump were not removed (left panel). The Fig.5b is the velocity field obtained from the phase, which is independent to the measurement of the backscatter strength; still, it is found to exhibit consistent wave crest pattern with the backscattering PPI plot, shown in Fig. 6.

ACKNOWLEDGMENT

Authors gratefully thank Taiwan Ocean Research Institute and Typhoon and Flood Research Institute of National Applied Research Labs for the supports of instrumentation. Authors also thank Dr. Lai, Jian-Wu and SINO Instrumentnt company for their assistance of radar installation.

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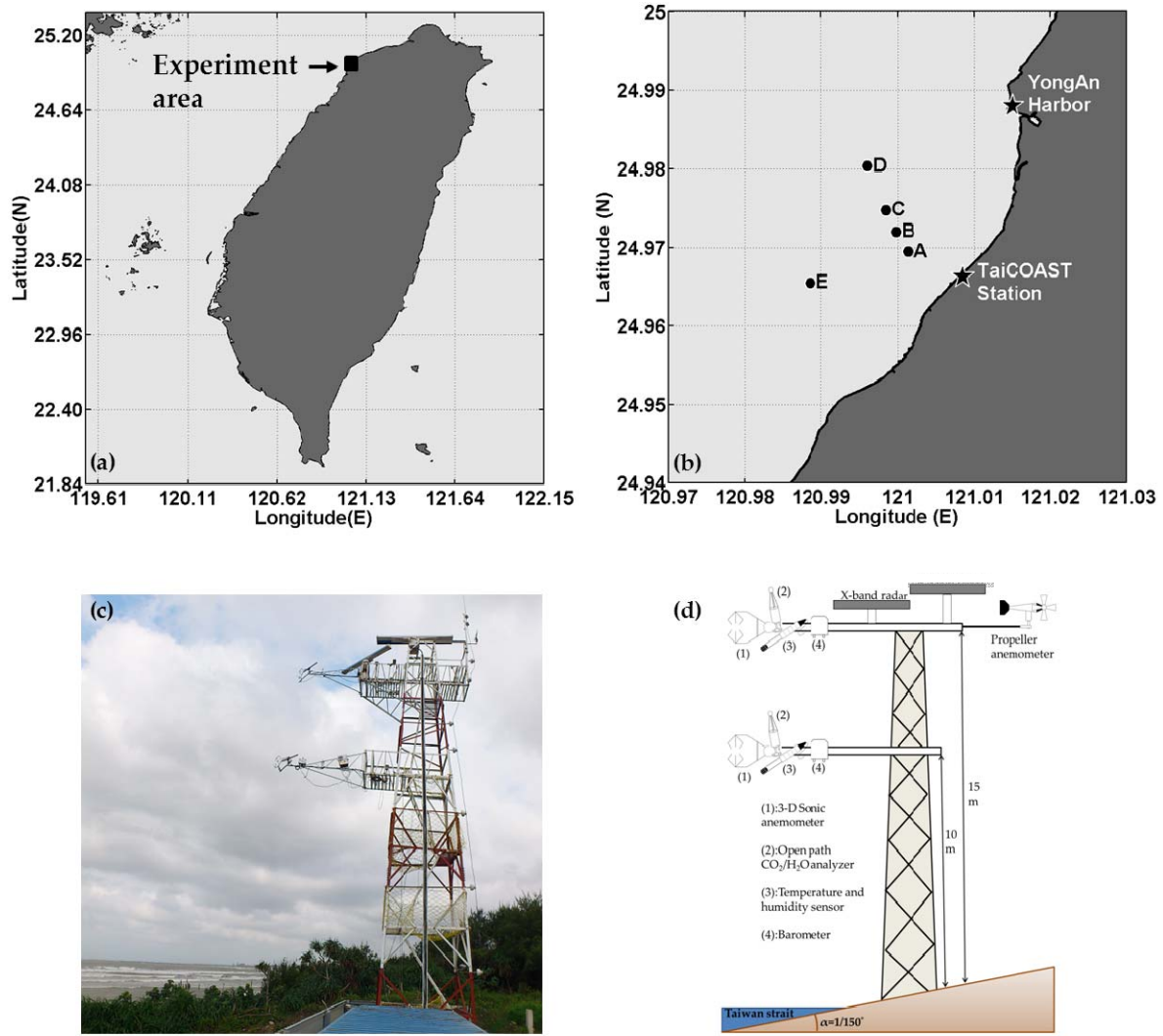


Fig. 1. Location, layout and instruments of the field experiment. (a) The experiment site, denoted as the black box, locates at the north-western coast of Taiwan. (b) The enlargement of the black box on panel (a) shows the layout of ADCP array, in dots, and the NCU coastal observatory. (c) A flux tower and dual bands microwave radars were installed in the station by the waterline. (d) the sketch of the instrumentations on the flux tower.

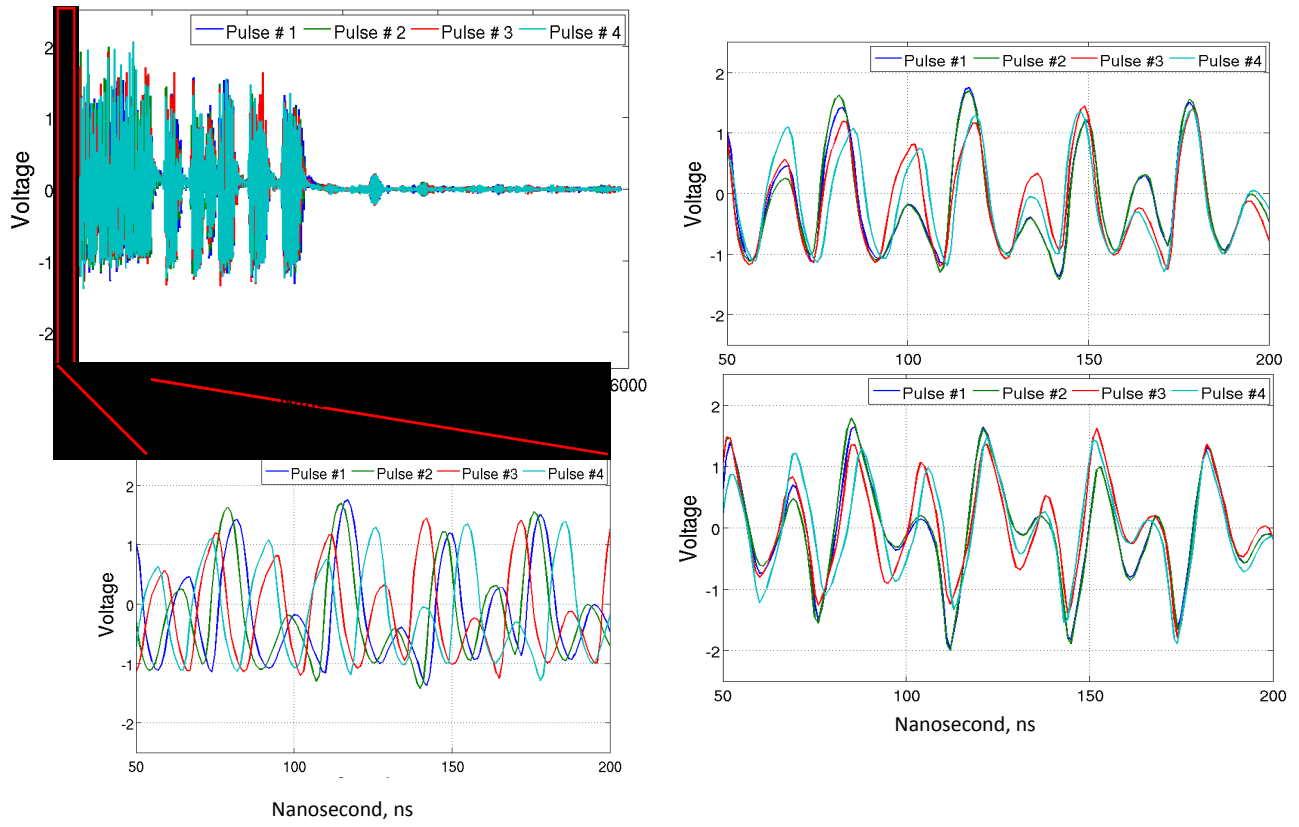


Fig. 2. The left panels show the original measured temporal variations of 4 succeeding transmitted and echo signals. Be noted the random phases of the pulse envelop inherited from Coherent-on-Receive radar. Using Hilbert Transform, and alignment of the random phases, the I & Q signals can be obtained as illustrated in right two panels, respectively.

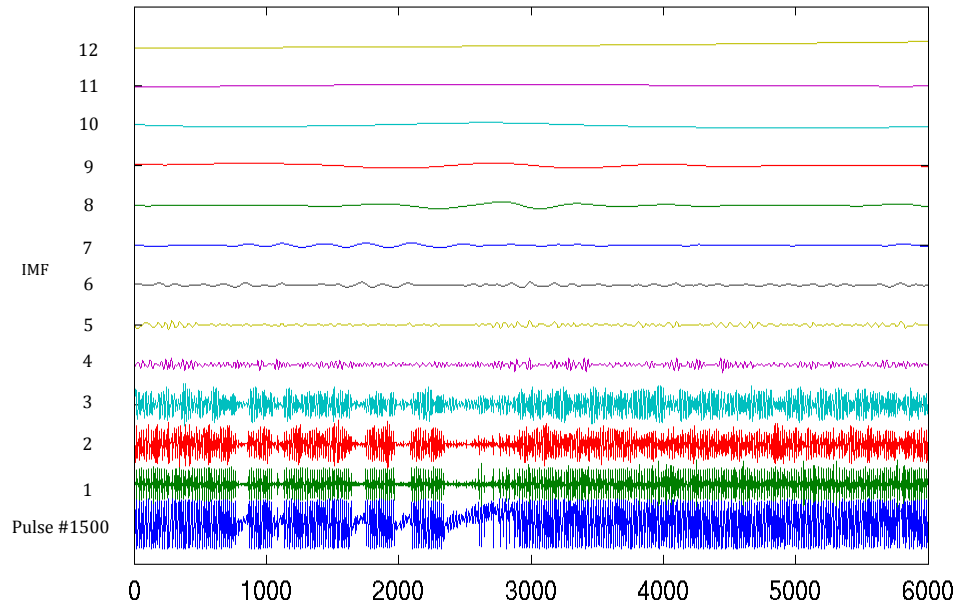


Fig. 3. The IMFs of the phase on a single pulse signal.

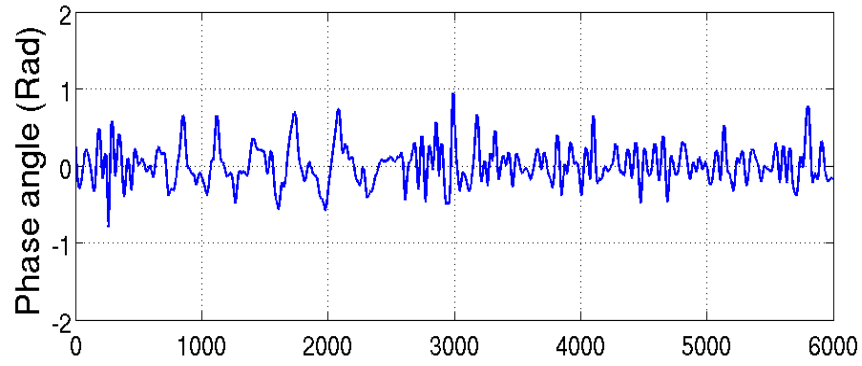


Fig. 4. The curve represents the linear superposition of IMF6+IMF7+IMF8, which is the phase that deviates from the steady cycle; and can be regarded as incurred by the Doppler effects of wave orbital motion.

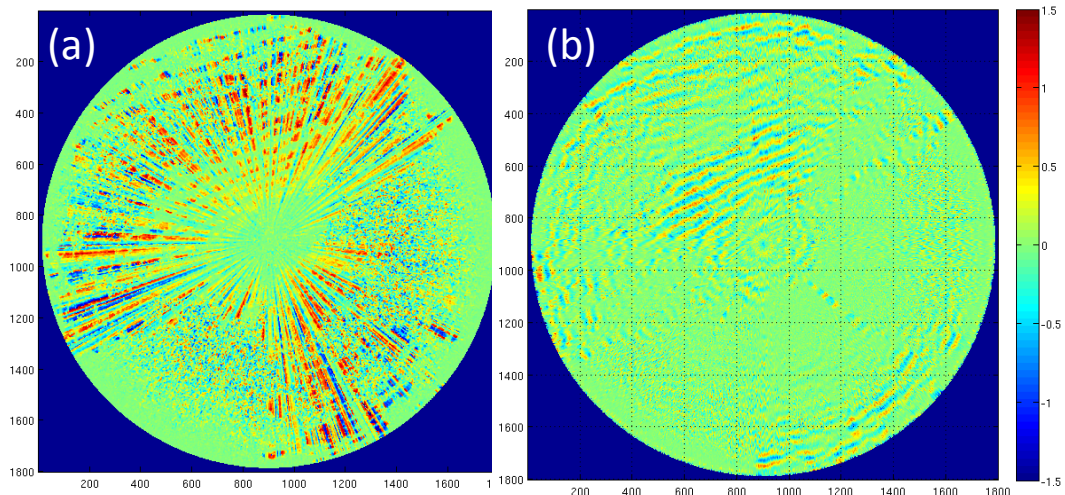


Fig. 5. By applying EEMD to the phase of echo signal from individual pulse, the frequency jump can be corrected by removing the Intrinsic Mode Functions (IMFs) that exhibit much greater temporal scale than those of phase shift induced by orbital motion. (a) & (b) are the comparison of radius velocity fields of previous method (a) and present proposed method (b). (a) shows the invalid velocity frequency incurred jumps between pulses, and (b) shows the improved result. The unit of colorbar is m/s.

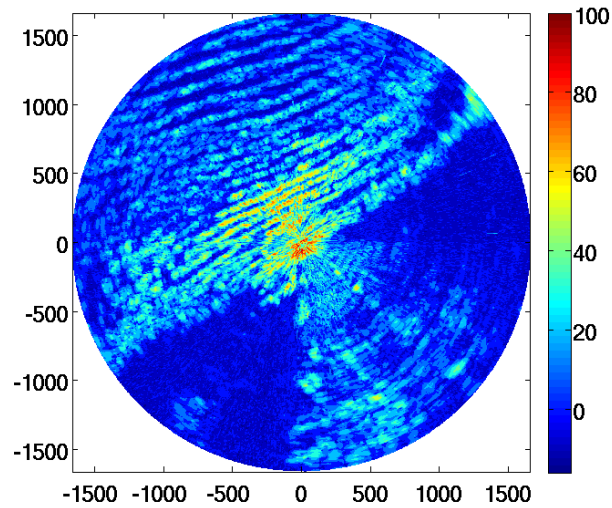


Fig. 6. The intensity of backscatter of sea clutter.