# Coherent Microwave Marine Radars for Deterministic Wave Profile Mapping, Decameter-Scale Coastal Current Mapping and Ocean Wave Spectra Measurements

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*Abstract-* **Two different approaches in development of a coherent marine radar for ocean remote sensing applications have been designed, assembled, and tested: a fully coherent radar (COHrad) and a coherent-on-receive radar (CORrad). These radars operate similar to standard marine radars, with rotation revisit rates of either 0.4 or 0.8 Hz, suitable for measuring ocean wave frequencies of half these values. They allow repetitive maps of radial velocity, primarily orbital wave velocity of ocean waves, and thus can provide a map of ocean wave height directly, without the need for a modulation transfer function as is used with non-coherent radars. When averaging of a large set of consecutive images, slower time scale phenomena can be mapped, such as mean area currents and localized rip current features. Two radars illuminating a common area could thus provide the vector current field for all such processes in that area. A string of such radars along a coast with overlapping coverage could provide continuous coastal maps of ocean currents. A description of both radars is provided, the signal processing involved, and some preliminary examples of displays that are available for data from these systems.**

## I. Introduction

Marine radars are useful tools for coastal ocean remote sensing. The maximum echo occurs due to a combination of roughness distribution over an ocean wave profile, and the tilt angle of the local surface normal in the scattering patch. Thus, long ocean waves are imaged with sufficient spatial modulation to allow ocean wave imaging over a few square kilometer areas. A rotating radar can provide a plan view of the ocean wave system in a surrounding area typically 0.5 to 1.5 km for modest antenna heights of 12 m or so, typical of coastal operations. Used aboard ship, with 25 – 50 m mast height radar location, the range coverage can extend out to 3 to 6 km with similar results. Non-coherent standard marine radars can be used to develop ocean wave spectrum estimates by 3-D FFT processing of a time series of a modest 64 x 64 pixel window covering roughly 192-m x 192-m box within the area of coverage. The output of the resulting $\Omega,K_x,K_y$ image spectrum in radar cross section (RCS) per Hz is then scaled to a surface truth directional wave spectrum in $m^2/Hz$ to develop the scale factor, or the modulation transfer function (MTF), for each ocean wave frequency component. For a 64-rotation time series of 64 windows, this results in 32 positive frequencies and 32 values of the MTF, one for each frequency. This MTF will be sensitive to radar grazing angle, determined by the range location of the window chosen for FFT processing. It will also vary with azimuthal intensity of the echo, relative wind direction to the propagating waves, and atmospheric stability which is modifies scatter roughness depending on air-sea temperature differences [Ref. 1].

Coherent radars offer an alternative approach to measuring ocean wave spectra that do not depend on the complexities of the behavior of the MTF approach. Coherent radar differs from a standard non-coherent marine radar by the fact that the pulse transmitted always has the same start phase from one pulse to the next. This allows one to compare phases between pulses to measure radial velocity, typically in one of two ways. Using two pulses, one takes their phase difference to get a value $d\phi$. Dividing by the time between pulses, dt, one gets the rate of change of phase between pulses, $d\phi/dt$. This is related to the radial velocity of the target being measured though the Doppler shift equation for the radial velocity, dv: $dv = (\lambda/2)* d\phi/dt$, where $\lambda$ is the wavelength of the radar, typically 0.016 m for a 9.4 GHz X-band radar. This works for very strong echoes, such as large targets and generally the ocean surface echo. For very weak echoes in the presence of strong echoes for the same time delay, one must use many pulses from a sequence and do Doppler processing using the Fast Fourier Transform (FFT). This provides an additional dimension now, Doppler shift, and allows a weaker target signal to be seen in the presence of a stronger echo due to the sea surface. This type of processing is typical of HF radars, where approach and recede echoes from waves traveling away from and toward the radar can be separated and their measurement used to determine ocean surface currents. Either two-pulse Doppler or FFT Doppler processing can be applied to either the COHrad or CORrad systems.

II. Coherent-on-Receive Radar

Non-coherent marine radar produces a random phase from one pulse to the next and each echo reflects the same phase as that transmitted. If one could record the transmitted pulse, then one could realign the phase of the echo waveform to create a coherent-like waveform. This approach is often referred to as Coherent-On-Receive radar. The phase difference in an echo sample between two consecutive pulses represents the distance the echo source has moved radially to or away from the radar. Fig. 1 below shows an example of the randomness of the transmitted pulse phase in the upper right panel for three consecutive pulses.

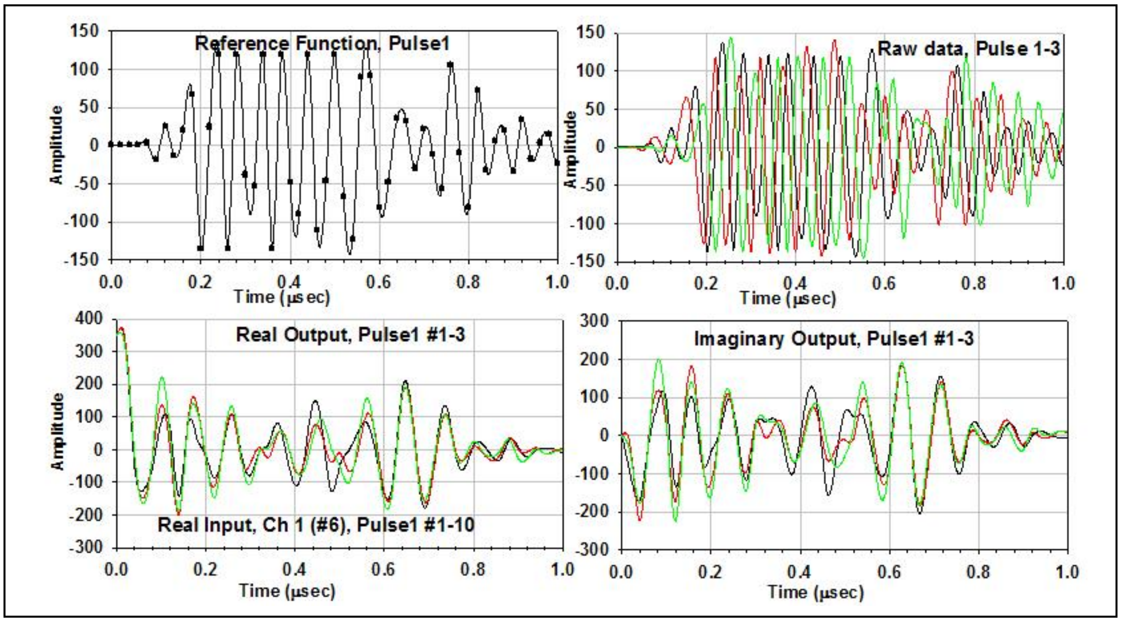


**Fig. 1 Single transmitted pulse (upper left), three consecutive pulses (upper right) with random phases, and Real and Imaginary (I and Q) outputs show the alignment of phases using coherent-on-receive processing.**

The CORrad approach is limited in one sense to the range resolution of the pulse transmitted, while coherent radars can use pulse compression methods to generate similar echo strengths using much less transmit power. A typical transmitter for a non-coherent radar used in the CORrad approach uses 12 to 25 kilowatts peak power. A fully coherent radar can get by with just 5 to 10 watts of average power, or peak power when pulsed, by operating at a much higher pulse repetition frequency. This can be 25 to 50 KHz, vs. 1 to 2 KHz for a marine radar.

*Physical differences between CORrad and COHrad*

The photos below in Fig. 2 show the components of a CORrad (left) and COHrad (right), mounted on the top and bottom, respectively, on the plate that slides into a standard marine radar pedestal.

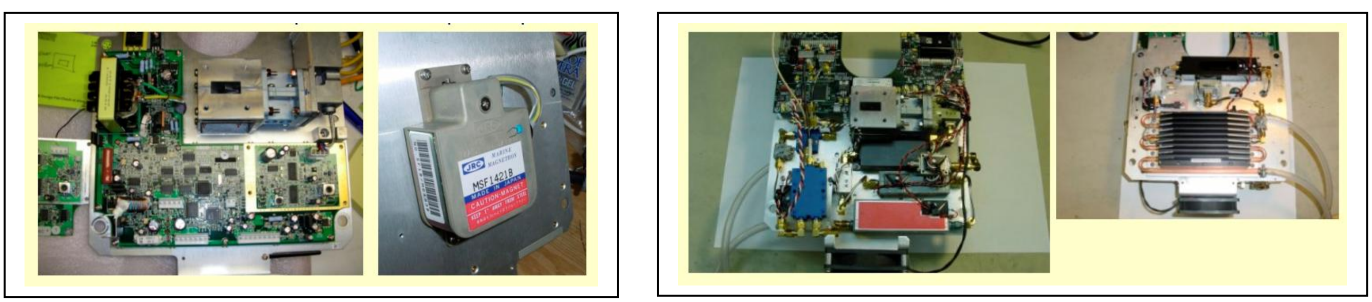

**Fig. 2 The upper and lower halves of a CORrad and COHrad are shown on the left and right, respectively. The upper plate on each contain receiver microwave elements, with the rectangular opening in the waveguide in the upper center of each showing the microwave path to the antenna over the tope of the pedestal. The echo signal is returned via the same path and exits into the waveguide to coax line transition to the right. It continues into 9.4-GHz filters and the low noise amplifier chain, then is mixed down to an intermediate frequency centered about 30 MHz which allows it to be digitized, producing the signal shown in the upper right of Figure 1.**

*Coherent Radar Description*

The fully coherent radar requires a more sophisticated signal input than does the CORrad, which needs only an impulse function to excite the incoherent RF modulation source. ISR has developed for HF radar applications a transceiver card that has phase locked transmit-receive capability, with a pulse-modulation signal developed within the card. A number of waveforms can be programmed, including a variety of chirped FM signals, as well as Barker codes and user defined codes. For HF radar applications, the card has 8 receive channels, and has been named the Octopus transceiver. For this microwave COHrad use, we use a scaled down version with just four receive channels, and use just one receive channel, named a Quadrapus card. The transmission signal used for this application is a frequency-modulated (FM) linear chirp pulse, swept from 50 to 80 MHz, or a 30-MHz bandwidth, corresponding to 5-m range resolution using a rectangular envelope. Higher range resolution can be achieved using a cosine-squared envelope, also available to the user. The compression gain one achieves is related to the ratio of the pulse length over which the waveform is chirped, 1 μs in this case, to the compressed pulse length. The latter is proportional to the reciprocal of the bandwidth of the chirp, 0.033 μs, resulting in a 30-1 compression in field strength, or 900-1 in received power. This amounts to 29.5 dB of compression gain, a factor of a thousand, so that 5 watts coherent is equivalent to approximately 5 kilowatts non-coherent. Additional processing gain is achieved by summing waveforms on board the transceiver card before transforming to the computer for storage by Direct Memory Access (DMA). A 50-kHz pulse repetition frequency (PRF) using 25 onboard sums will generate a 2 KHz record PRF, the same as the standard marine radar. Adding 25 coherent waveforms generates 28 dB processing gain. This combination of processing gain and earlier pulse compression gain results in a total of 58.5 dB total gain under most efficient conditions, more than enough to offset the lower power of the coherent power amplifier used.

An example of a transmitted pulse with pulse compression is shown in Fig. 3 below. On the top left is a pulse chirped from 50 to 80 MHz, which is used as the reference function for pulse compression processing. Below it, at lower left, shows the result of compression of the transmitted pulse against itself, re-normalized, so that the amplitude scaling is relative. One the right is a typical echo over a little less than a 5-μs delay, or 750 m. Local echoes for a sequence of consecutive waveforms are shown, with the leakage of the main pulse through the microwave circulator and near range pier echoes maximizing. The panel at lower right represents the real part of the same data pulse-compressed, and is now symmetric in range, and the actual time period shown is 10-μs, so the first half is the unambiguous data. As we use only real input data at 100 MHz sample rate, the output pulse compressed data is now complex and at 50 MHz, or 3-m range resolution. Phase is determined from the arctan of I/Q in Fig.1. Adjacent pulse-pair phase differences are then calculated and divided by the period between pulses to determine $d\phi/dt$ defined earlier. The radial velocity of the echo is then just one half the wavelength times this time derivative of phase.

Next we show some examples of radial velocity imagery obtained by a customer in a field experiment aboard ship.

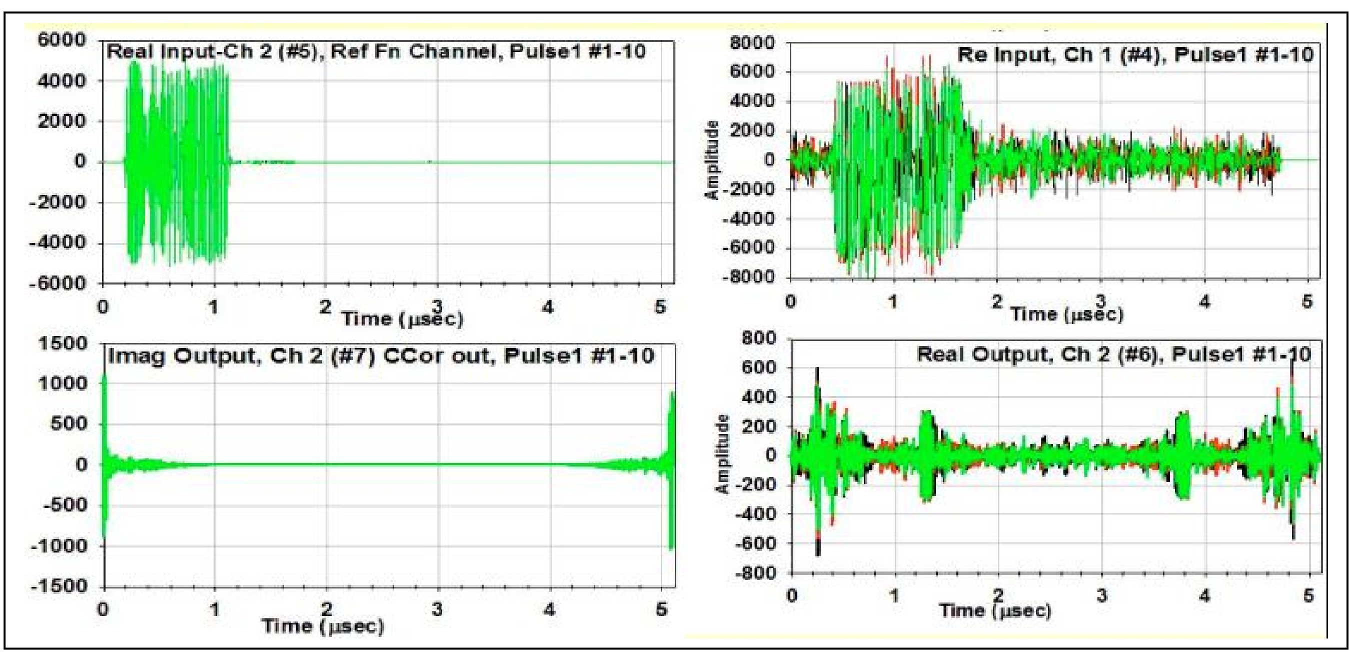


**Fig. 3. FM chirped radar pulse and same, compressed, shown on left. Right side shows uncompressed and pulse-compressed radar echoes for the fully coherent radar, with time scales discussed in the text.**

*Coherent-On-Receive Example*

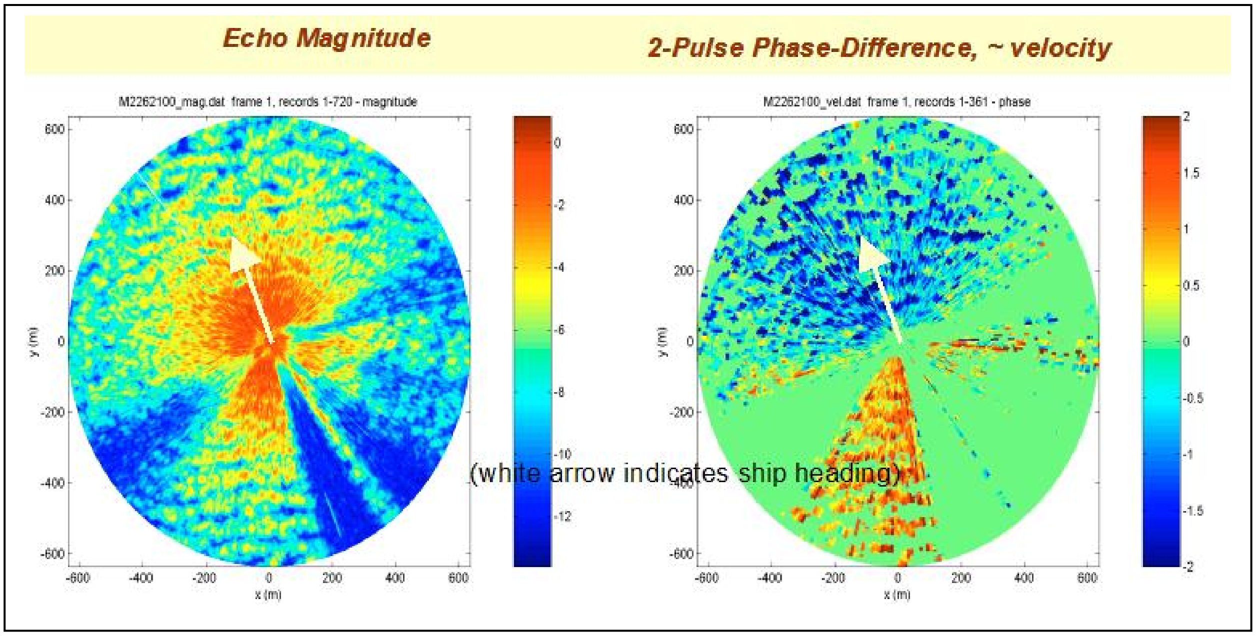


**Fig. 4. Ocean surface radar echo from a shipboard radar developed by Dr. David Lyzenga is shown on left, and radial velocity map shown on the right. The velocity scale maximizes at $\pm$2 m/s magnitude. Gaps in data reflect shadowing by ship elements.**

The phase difference derived from the CORrad system shown on the right shows an imaging advantage of the coherent radar approach to the measurement of wave height. First, note the change in color intensity of the echo on the left, reflecting the grazing angle dependence of the radar scatter from the sea surface, as well as the $R^{-3}$ range loss as the beam spreads at longer ranges. It is clear that use of a MTF using this image will depend on the range of the window chosen, and may have to be varied with changing sea state depending on echo strength variation. Also, there is a change in the modulation within the window one chooses without some empirical damping function to smooth the range variation. On the right, the change in phase difference across the scene is very modest to non-existent. It reflects only the grazing angle dependence of the radial velocity of the scatterer, varying as cosine of grazing angle, changing from a few degrees to just less than a degree over ranges shown. Thus, there is virtually no difference in the orbital wave radial velocity measured at long range compared to the shortest ranges.

The wave height profile was developed by Lyzenga using a simple tilt-modulation model to derive wave height. We will be developing a method based on spectral representation similar to that discussed earlier using the RCS MTF approach. This will be described in more detail in a companion paper at these proceedings.

*Comparison of Coherent Radar with Coherent-on-Receive*

There are no simultaneous data from both radars currently, there were some collected made under similar conditions a few days apart, but with very low sea state conditions. Fig.5 below shows examples of received power from both radars. Wave patterns were not present with either radar, so the sum of 128 rotations is shown to define the mean echo signal with azimuth. The COHrad system appears to have better behaved range dependencies, so that longer-range capability may be available from this system. There is a slight range offset in the COHrad data relative to CORrad, which has not been accounted for in the range labeling, due to the 1-µs pulse (100-m) pulse that was transmitted. The range-time plots each start at an azimuth corresponding to just left of the pier from the radar location at the end of the pier in each case, and the waveform number count on the vertical axis corresponds to azimuth. The darkened shadow left to right in each image, approximately midway on the left and at azimuth count #700 on the right, each corresponds to a radar shadow due to a tower at the southeast corner of the pier, just beyond 180 deg in azimuth. The COHrad had closer to a 360-deg azimuthal coverage, as the pair of curves at lower right represents the mean location of wave breaking at the shore and hard echoes from the berm landward of the shoreline.

The CORrad used a vertically polarized antenna, so that the more spatially uniform echo is a result of distributed roughness, whereas the horizontally polarized antenna used with COHrad is dominated by localized small scale breaking features. (See Ref. 3 for a detailed consideration of polarization differences under these conditions.)

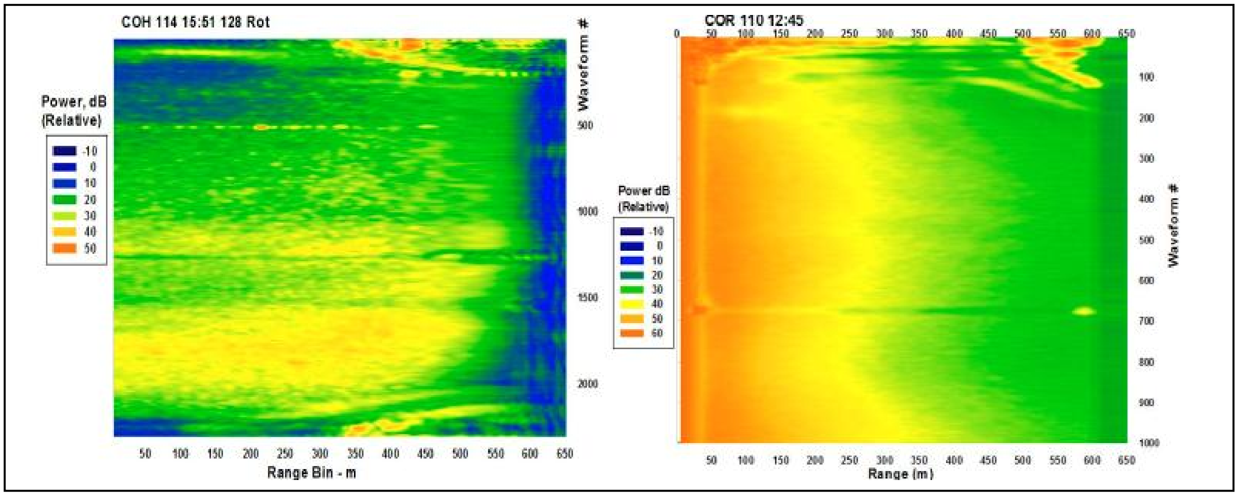


**Fig. 5. Mean radar echoes from a COHrad and CORrad on the left and right, respectively. The higher resolution achieved using pulse compression with COHrad shows up markedly in the comparison.**

## III. Future Plans

Both radars are now operational at the FRF pier and are run hourly. Data collected during higher wave conditions expected in the fall months prior to the conference will be presented at the conference. More details on application of signal processing methods being developed will be presented in a companion paper in these proceedings [3].


## IV. Acknowledgment

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## V. References


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