The advantage of dual-frequency operation in ship tracking by HF surface wave radar

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Abstract: In this paper we demonstrate the advantage of operating HF Surface Wave Radar (HFSWR) in a dual-frequency mode. This includes improved performance in ship tracking through sea clutter and ionospheric clutter as well as through target radar-cross-section aspect-angle-dependent nulls. These advantages demonstrate the necessity of dual-frequency (or multiple-frequency) operation in a HFSWR used for maritime surveillance.

Keywords: *Maritime Surveillance, HF surface wave radar, HFSWR, dual-frequency operation, sea clutter, ionospheric clutter, and target radar-cross-section nulls.*

1. Introduction

HF Surface Wave Radar (HFSWR) takes advantage of the low attenuation experienced by the vertically polarized High Frequency surface waves (3-30 MHz) when propagated over sea water. This allows the radar to detect and track ships and low-flying aircraft to distances well beyond that achievable by a co-located microwave radar. A land-based HFSWR is a cost-effective sensor for maritime surveillance. A HFSWR system used for maritime surveillance typically operates at the lower end of HF band. In collaboration with Defence R&D Canada (DRDC), Raytheon Canada Limited (RCL) developed and installed a coastal surveillance HFSWR system at Cape Race, Newfoundland, Canada. The radar operates simultaneously at two radio frequencies (RF) within the 3 to 5 MHz band [1].

A 16 kW peak-envelope-power transmitter generates interleaved pulses centred at two selected carrier frequencies. The output of the transmitter feeds a log-periodic monopole antenna array. A uniform linear array of 16 doublet antennas is used on receive. Each doublet consists of two kite-shaped monopoles phased to receive backscatter from the sea. The receive antennas feed two sets of receivers, each tuned to one of the two carrier frequencies. The data stream from each set of receivers is processed separately. This includes pulse compression, impulse excision, data decimation, Doppler processing, beamforming, external interference cancellation, and target detection. The detected targets from the two data streams are associated in a common tracker. Because of the difference in speed (and therefore in Doppler), the radar operation at each carrier frequency is optimized for ship or aircraft detection and tracking. The radar operation can be programmed to detect and track ships or aircraft only at both carrier frequencies, or ships at one RF and aircraft at the other simultaneously.

When used for ship detection only, the HFSWR operates at two well-spaced RFs. This offers the advantages of improved target tracking through sea clutter and ionospheric clutter. It also improves the consistency of tracking through target radar-cross-section (RCS) nulls associated with the aspect angle of the target to the radar's look direction. In 2002, the Canadian Department of National Defence undertook a technical evaluation (TECHVAL) of the HFSWR at Cape Race for both ship and aircraft detection and tracking. During the ship-tracking trials, the radar operated simultaneously at 3.1 and 4.1 MHz. In this paper, a subset of the TECHVAL report [2] is presented that illustrates the advantages of dual frequency operation when tracking ships.

2. Tracking ships through sea clutter

The sea clutter spectrum from a HFSWR can be divided into two dominant components: first and second order sea clutter. The first-order sea clutter consists of two, strong, spectral lines known as Bragg lines, and the second-order sea clutter consists of a continuum encompassing a few, relatively strong, discrete components. The Bragg lines and second-order discrete components can result in blind velocities allowing surface targets to go undetected.

The Bragg lines are the result of a resonant scattering of the transmitted radar signal from ocean waves that have a wavelength equal to one half of the radar wavelength along the radar's look direction [3]. If the radial velocity of the ocean currents is zero, then the Bragg lines have Doppler frequencies at

$$f_B = \pm\sqrt{\frac{g}{\pi\lambda}} \tag{1}$$

where g is the gravitational acceleration ($g=9.81\ m/s^2$) and λ is the radar wavelength.

This inverse square-root relationship between the Bragg frequency and the radar wavelength is different from the standard inverse linear relationship between the target Doppler frequency and the radar wavelength, given as

$$f_t = \frac{2v}{\lambda} \quad (2)$$

where v is the radial velocity of the target (v is positive when the target moves away from the radar).

Hence, the relative separation between the target and Bragg lines is a function of the frequency of operation. If a target return is masked by a Bragg line at one radar frequency, the target return and Bragg line will be separated at another radar frequency. This enables the radar to detect a target continuously regardless of its radial velocity relationship with the Bragg lines. Figure 1 presents an example where a ship masked by a Bragg line at 3.1 MHz is clearly separated from the Bragg line at 4.1 MHz, and thus remains detectable by the radar.

The second-order sea clutter also contains identifiable discrete components, at Doppler frequencies of $2^{1/2}$, $3^{1/2}$, $4^{1/2}$, $5^{1/2}$, …, and $2^{3/4}$ times the Bragg frequencies [4]. The $2^{1/2}$, $3^{1/2}$, $4^{1/2}$, $5^{1/2}$,…, spectral lines are due to higher-order Bragg scatters from ocean waves of length $L=\lambda$, $3\lambda/2$, 2λ, $5\lambda/2$, etc. (rather than $L=\lambda/2$). These ocean waves have velocities of $2^{1/2}$, $3^{1/2}$, $4^{1/2}$, $5^{1/2}$, …, times the velocity of those waves that give rise to the Bragg lines, thus resulting in $2^{1/2}$, $3^{1/2}$, $4^{1/2}$, $5^{1/2}$, …, times the Doppler shifts of the Bragg lines. The $2^{3/4}$ spectral lines are due to a double scattering of the radar signal in a manner similar to the “corner-reflector” electromagnetic effect. In reality, because of the long wavelengths in the lower end of HF, only the $2^{1/2}$ and $2^{3/4}$ spectral lines are likely observable in the Doppler spectrum. All these discrete components have Doppler shifts that follow the same inverse square-root relationship as the Bragg lines (except a scaling constant). Figure 2 presents an example where the return from a ship is masked by one of these discrete components at 4.1 MHz but is readily detectable at 3.1 MHz.

3. Tracking ships through ionospheric clutter

Since Marconi's 1901 demonstration of communications across the Atlantic, the frequency spectrum from 3-30 MHz has been used for long-distance communications. Propagation is via reflecting layers that make up the ionosphere. The region below an altitude of 90 km is referred to as the D-region, the region between 90 km and approximately 160 km is the E-region, and the region above 160 km is known as the F-region. The D-region exists only during daylight hours and, at the lower end of the frequency band, is responsible for attenuating these waves through partial absorption. Skywave propagation, at HF, depends primarily on ionospheric reflections from the E and F-regions.

HFSWR utilizes the surface wave mode of propagation. Unfortunately, not all the energy emitted by the HFSWR propagates along the sea surface. Some of this energy is unavoidably directed upwards and may be reflected from either the E or F-layers. The energy may be reflected vertically from the ionosphere, or at an angle below vertical causing it to travel outwards whereupon reflecting from the sea surface, it returns to the radar either along the original path as skywave or along the sea surface as surface wave [5].

The first option for combatting ionospheric clutter is frequency agility. The radar is preferably operated at the very low end of the HF band (i.e. 3 MHz) to benefit from lower surface wave attenuation rates and higher rates of D-layer absorption. However, the radar signal is reflected from the E-layer during daylight hours. The layer-critical frequency is defined as the highest frequency below which the radio signal is reflected if vertically incident on the layer. Above this frequency the radar signal penetrates the layer instead of being reflected from it. It is shown that operating at two radar frequencies alleviates the effect of ionospheric clutter during daytime operation. During mid-day the E-layer critical frequency is typically between 3 and 4 MHz. When operated below this critical frequency, HFSWR may observe clutter reflected back from the E-layer, but not from the F-layer. Above the critical frequency, the radar signal penetrates through the E-layer, but not the F-layer, and the radar signal is reflected back by the F-layer, resulting in a band of clutter being observed beyond a distance of about 220 km.

Figures 3 and 4 illustrate the frequency dependency of ionospheric clutter and its effect on ship detection. In Figure 3, it can be observed that the target return is obscured between 14:45z and 15:30z by the E-layer at 3.1 MHz but is clearly detectable at 4.1 MHz. In Figure 4, a second ship return is obscured between 14:00z and 15:00z by F-layer clutter at 4.1 MHz but clearly detectible at 3.1 MHz. This illustrates how frequency diversity improves the performance of the radar when tracking ships through the daytime ionospheric clutter.

However, this advantage of improved performance disappears at night when the absorptive D-layer disappears and both the transmitted signals at 3.1 and 4.1 MHz penetrate through the E-layer and are refracted back from the F-layer. The radar observes the F-layer clutter in both frequencies, at ranges corresponding to the height of the layer and beyond.

4. Tracking ships through RCS nulls

The behaviours of the radar-cross-sections (RCS) of several surface vessels at the lower end of HF band have been previously studied [6]. The results show that large ships typically have a maximum RCS at broadside, and local RCS peaks and nulls at various other aspect angles.

A surface vessel has multiple scattering centres, and its RCS is a function of the coherent sum of the echoes from these centres. At HF, the separation of these scattering centres is comparable to the radar wavelength. Depending on the aspect angle, constructive or destructive scattering may result from these centres, causing the RCS to peak or dip. When the RCS peaks, the target signal is enhanced. However, when the RCS is in a null, the target signal weakens. The latter may lead to missed detection and broken tracks. Fortunately, the RCS peaks and nulls occur at different aspect angles at different radar frequencies. Operating at two well-spaced radar frequencies can separate the RCS nulls so that they do not appear at both frequencies at the same time.

Figure 5 presents an example of a ship track that was terminated prematurely at a range of 167 km in the 3.1 MHz data stream but was tracked to a range of greater than 250 km at 4.1 MHz. Towards the end of the track, the outbound ship was travelling at 91° True, relative to the radar. Figure 6 presents the clutter-plus-noise intensity plots from a fixed beam in the target direction, for the radar frequencies of 3.1 and 4.1 MHz. These plots were obtained from averaging the power from a small Doppler interval encompassing the signal of the ship. Figure 6 shows that the target was initially detectable at both frequencies. However, at 3.1 MHz the target signal was last detected at a range of 167 km at approximately 08:00z, but was detectible at 4.1 MHz to 12:30z when it had reached 315 km.

Figure 7 illustrates the observed signal variations of the outbound track as functions of range at the two radar frequencies. It can be observed that between 120 and 160 km range, the ship's RCS at 4.1 MHz dropped by 5 dB, while the RCS at 3.1 MHz remained unchanged. At approximately 160 km, the ship's aspect angle changed, resulting in the RCS at 3.1 MHz to drop by 15 dB while the RCS at 4.1 MHz increased by almost 10 dB. It can be concluded that the RCS at 3.1 MHz reached a null while the RCS at 4.1 MHz reached a peak.

The above example illustrates the detrimental effects of RCS nulls on target detection. However, it also illustrates that dual-frequency operation can be complementary in ship tracking: a ship that is not detected at one frequency, due to a null in its RCS, may be detected at the second frequency, therefore maintaining the track.

5. Conclusions and recommendations

This paper presents examples where a ship was detectable at one radar frequency but not the other because of differences in (i) the sea clutter spectrum, (ii) the ionospheric clutter, and (iii) the radar cross sections at the two frequencies. All examples illustrate situations where ship detections would have been missed or tracks would have been broken or terminated if the HFSWR were operated in a single frequency mode. We conclude that the HFSWR performance in ship tracking is significantly improved when operated at two (or more) well-separated, radar frequencies.

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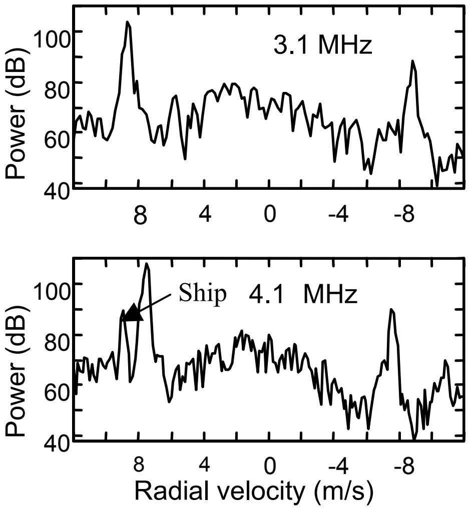

Figure 1. A ship travelling at 9 m/s outbound was obscured by the receding Bragg line at 3.1 MHz but visible at 4.1 MHz. Data were recorded on Feb 9, 2002 at 05:23z.

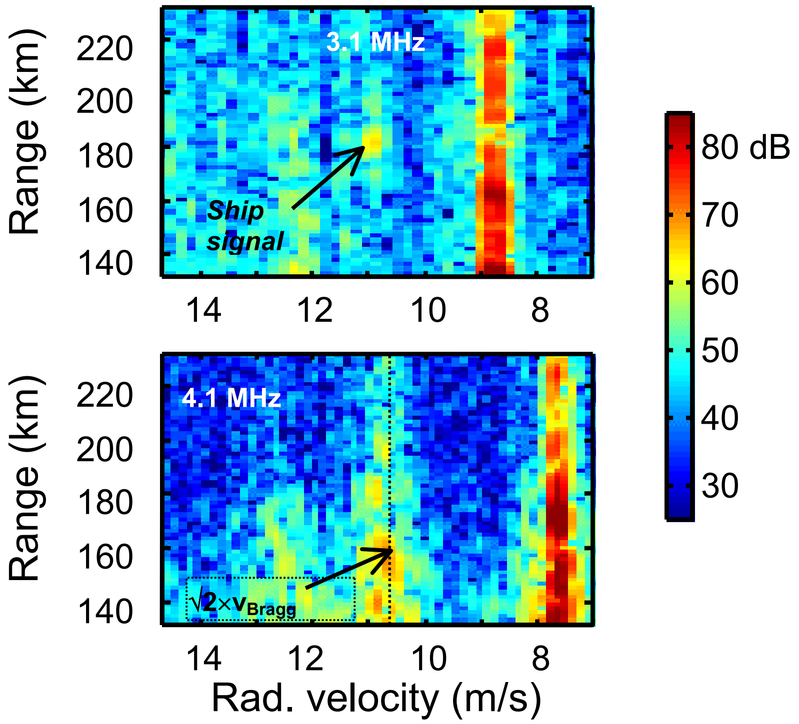

Figure 2. Range/Doppler plots of dual-frequency data at Azimuth=89°T. At 3.1 MHz, the ship signal appeared at a Doppler shift with low clutter. At 4.1 MHz, the ship signal could not be separated from the discrete component of the 2nd-order sea clutter at $\sqrt{2}\times v_{Bragg}$, where v_{Bragg} is the radial velocity at Bragg frequency. Data were recorded on Feb 15, 2002 at 00:54z.

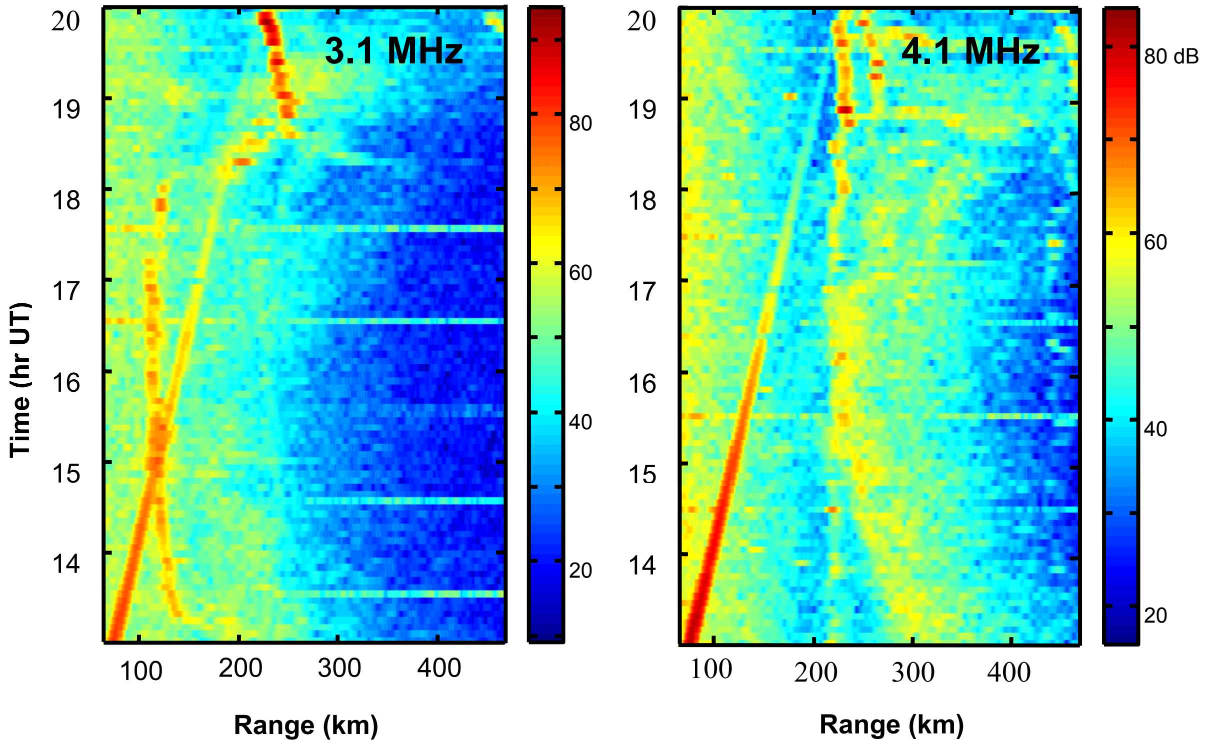

Figure 3. A ship obscured by ionospheric clutter at 3.1 MHz but visible at 4.1 MHz. At 3.1 MHz the ship was undetectable from 14:45z to 15:30z and after 18:10z. The data were recorded on Feb 9, 2002. Track ID: 12366.

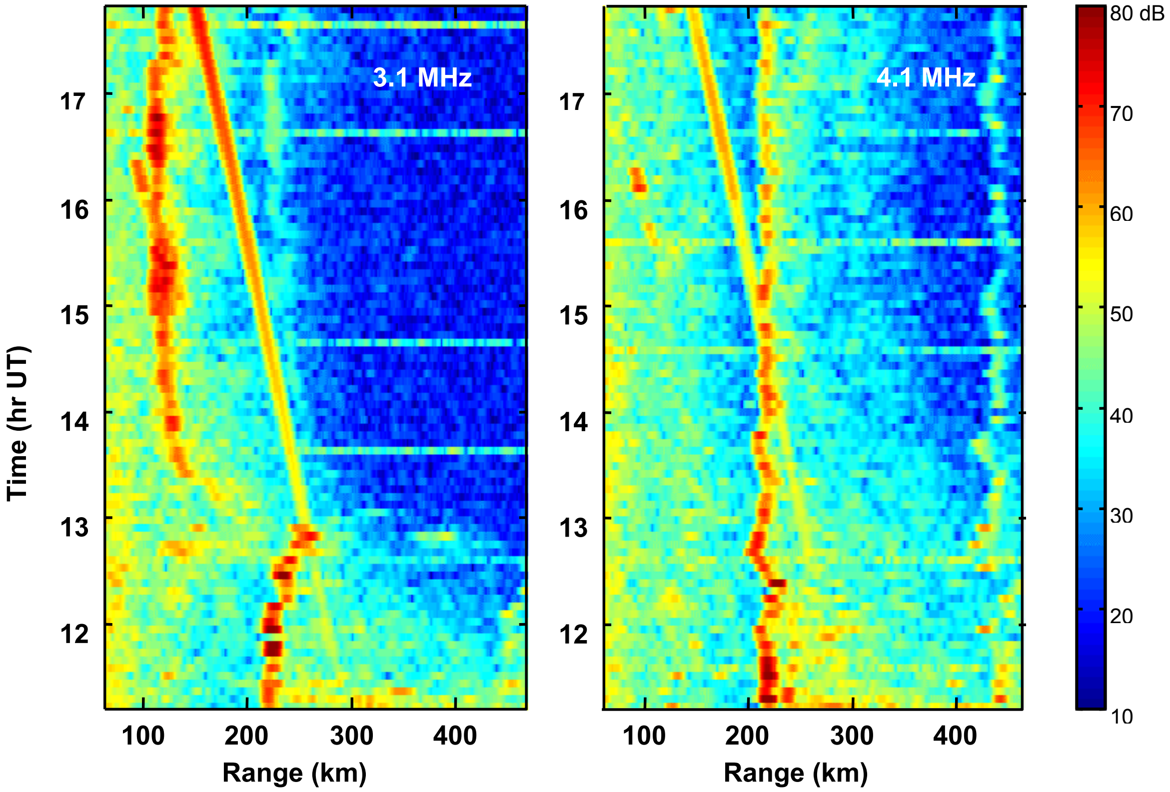

Figure 4. Dual-frequency operation. At 3.1 MHz the ship was detectable at 270 km range at 12:00z and could be followed for 6 hours. At 4.1 MHz it was obscured by F-layer clutter until 12:45z and from 14:00z to 15:00z. Data were recorded on Feb 9, 2002. Track ID: 12367.

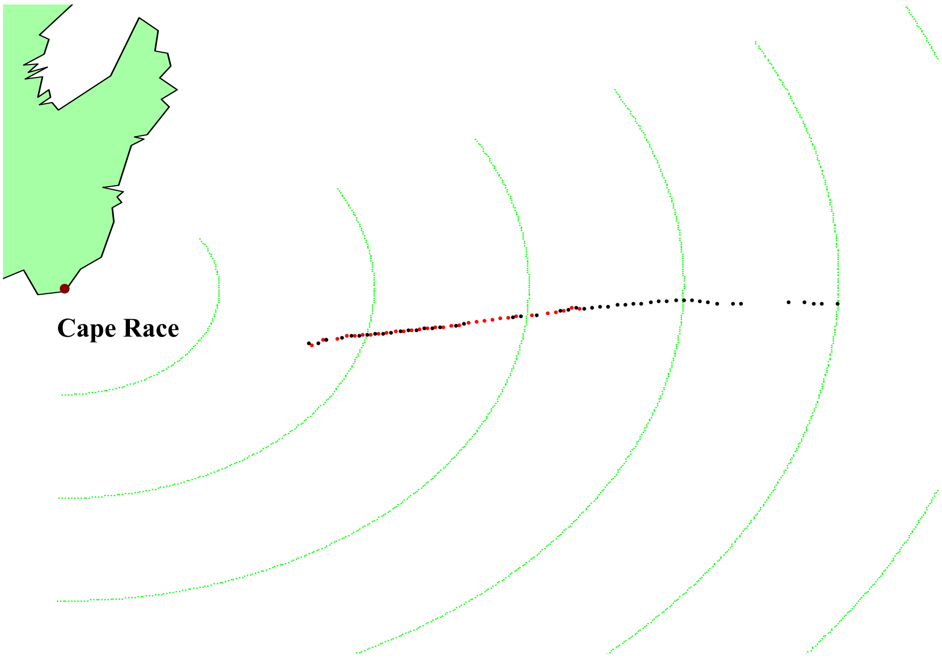

Figure 5. Outbound track 12363 on Feb 9, 2002. The rings are in steps of every 50 km. The ship track was terminated at ~167 km at 3.1 MHz (red) but extended out to 250 km at 4.1 MHz (black). Note that the missing gap between 220 and 235 km was due to a stoppage in radar operation.

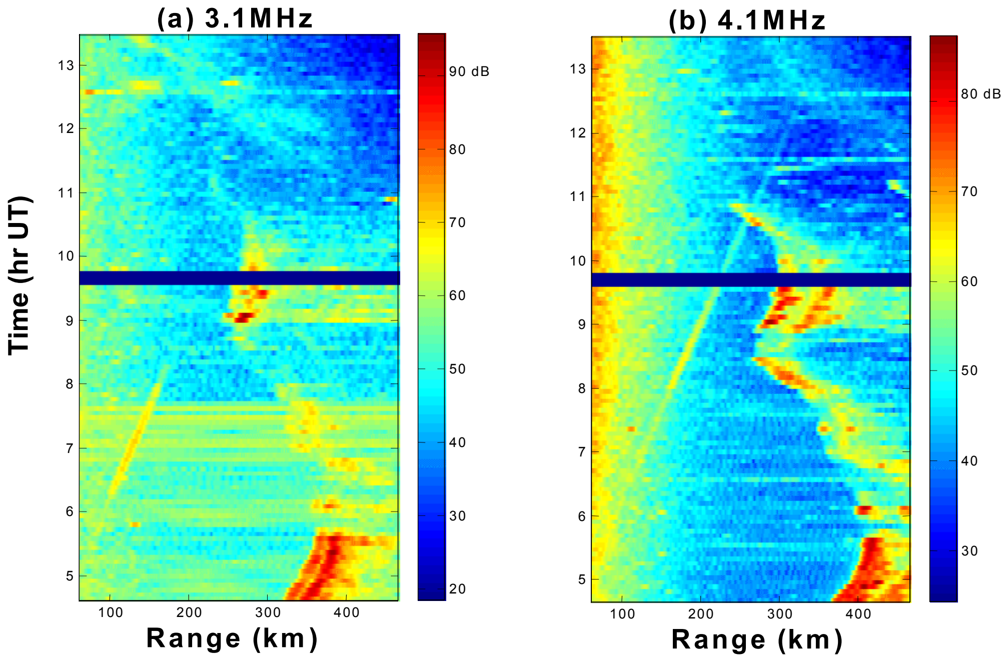

Figure 6. Clutter intensity plots from the beam along the direction of ~91° from the true North, at the radar frequencies of 3.1 and 4.1 MHz. The clutter-plus-noise intensity in each plot was obtained from a small Doppler interval encompassing the signal of a large ship. Data were recorded on Feb 9, 2002. Track ID: 12363. Note that the radar stopped recording for ~15 minutes at 09:45z. The horizontal stripes prior to 07:45z (more obvious at 3.1 MHz) were due to external interference, which was not cancelled in this set of data.

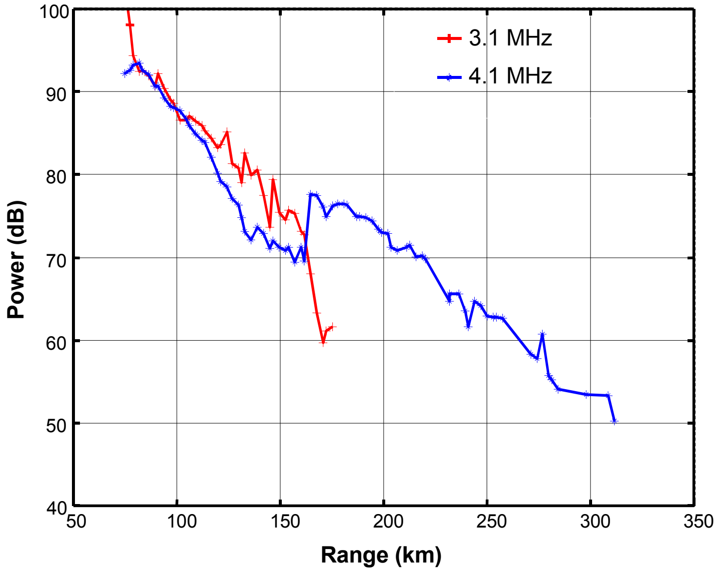

Figure 7. The 3.1 and 4.1 MHz signals of a large vessel sailing away from the HFSWR at Cape Race. Between 120 and 160 km range, the ship's RCS at 4.1 MHz dropped ~5 dB. At 160 km, the ship's aspect angle changed so the RCS at 3.1 MHz dropped nearly 15 dB and it became undetectable, while at 4.1 MHz the RCS rose ~10 dB and the ship was detected to 315 km. Data were recorded on Feb 9 2002 at 05:00 – 12:00z. Track ID: 12363.