Statistical Measures of S-band Sea Clutter and Targets

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ABSTRACT (U)

An S-band sea clutter trial was conducted in December 2006 at Kangaroo Island of South Australia using a quad-polarised S-band radar developed by DSTO. This report concentrates on radar data processing and analysis. Statistics of sea clutter, including range profiles, sea clutter coefficients, temporal and spatial correlations, temporal and spatial distributions, and as well as Doppler spectra for both the HH and VV sea clutter are measured. Strong and weak target signals are also analysed and classified into Swerling models accordingly. Differences observed by the HH and VV polarisations are explained.

RELEASE LIMITATION

Approved for public release
Statistical Measures of S-band Sea Clutter and Targets

Executive Summary

In support of the ANZAC Anti-Ship Missile Defence (ASMD) upgrade project, a trial of S-band (3.25 GHz) sea clutter data collection, using a DSTO-developed quad-polarised S-band radar, was conducted in November 2006 on Kangaroo Island (KI2006), approximately 110 km south-west of Adelaide. The trial eventually collected a variety of sea clutter in a period of four days. This technical report first outlines the radar system and the trial, and then concentrates on sea clutter data processing and analysis.

Statistics of both the HH and VV sea clutter as well as features of strong and weak target signals measured from the collected data are briefly summarised below.

The low grazing angle (smaller than 0.7°) range profile of sea clutter decays with respect to range faster than what the radar equation indicates. The decaying rate of sea clutter coefficient in far range (corresponding to a grazing angle smaller than 0.35°) is in an order of \(1/R^2\) where \(R\) denotes the range. This observation is consistent with studies reported previously.

The measured VV sea clutter coefficient (mean reflectivity) is in agreement with the values given in the open literature whereas the measured HH sea clutter coefficient in near range is about 5-10 dB below the reported value.

Temporal correlation studies show that for the VV sea clutter, the correlation is independent of range bins. The mean correlation time is 14.5 ms or 9.2 ms depending on whether the complex-value or the intensity of clutter is used in calculation.

The temporal correlation time of the HH sea clutter seems to be correlated to clutter returns. Higher returns from sea spikes are more likely to have longer correlation times, indicating that the HH sea spikes are more persistent than the VV sea spikes. Although the mean correlation time of the HH sea clutter is similar to that of the VV sea clutter, and has a value of 16 ms for the complex-value or 10 ms for the intensity, the correlation time of returns from persistent sea spikes can be as long as 20-60 ms.

Short-term spatial correlations (lagged only a few range bins) of both the HH and VV sea clutter are similar. The radar’s bandwidth used in the trial was 5 MHz or 10 MHz, giving a 15 m or 30 m range resolution. The actual range sample interval, for both the 5 MHz and 10 MHz cases, was 12 m which is an over-sampling rate, so the immediate range bins are not independently identically distributed (iid) samples. To remove the effect of over-sampling, we have calculated spatial correlation using range samples with an interval of 2 range bins for datasets with the 15 m resolution and an interval of 3 range bins for datasets with the 30 m resolution. We have found in such cases that all
range samples become approximately uncorrelated (the correlation coefficient drops below $1/e$). In another words, we have found that the spatial correlation lengths are shorter than 24 m and 36 m for datasets with 15 m and 30 m resolutions, respectively. A radar with higher resolution is needed in order to measure the exact spatial correlation length. We are not aware of any publications about spatial correlation of sea clutter at S-band. The long-term spatial correlation (lagged many range bins), which is not studied in this report, usually contains information of sea wave and swell structures.

The Doppler spectrum of sea clutter has also been briefly studied, and the detailed study to be completed and reported in the future. Though their RCS values are small (typically about $-20 \text{ dBm}^2$), flying birds whose Doppler components differ from that of sea clutter may become detectable as long as the number of integral pulses used is large.

It is found from the data studied that the Rayleigh distribution, i.e., the K-distribution with the shape parameter of infinity fits well with the temporal distribution of the VV sea clutter (30 m resolution, 12 m sampling interval). On the other hand, the K-distribution with the shape parameter approximately in the range of 10 to 20 fits well with the temporal distribution of the HH sea clutter (15 m resolution, 12 m sampling interval). These results are consistent with the two-component K-distributed model of sea clutter. For the former, the slow component, i.e., the underlying mean of sea clutter for the VV polarisation in the observing period changes little results in a Rayleigh distribution. For the latter, the underlying mean of the HH sea clutter in the observing period may also change a little and result in a non but close-to Raleigh distribution. These observations indicate that the HH polarisation is more vulnerable to the effects of shadowing and multi-path scattering.

Finally we have also studied the characteristics of target signals. In the case of the VV polarisation and for a strong stationary target signal (an anchored wave buoy reflector) whose signal-to-clutter ratio (SCR) is greater than 20dB, we have found that both the signal’s amplitude and phase vary very slowly. As a result, its Doppler spectrum concentrates on zero hertz, and its correlation time is 46 ms, much longer than that of its background, the VV sea clutter. According to its amplitude distribution, the target can be approximately classified as a Swerling 1 target, i.e., constant from pulse to pulse (or for a short observing period) and fluctuation following a Rayleigh distribution from scan to scan (or for a long observing period).

The observation of the same target using the HH polarisation is different. Both of the signal’s amplitude and phase vary much faster, possibly because the horizontal polarisation is more sensitive to effects of multipath scattering and shadowing of the sea surface as well as the movement of the target (rolling, pitching and yawing). The correlation time is about 10 ms, similar to that of its background, the HH sea clutter. Its energy spans about 100 Hz in its Doppler spectrum. It has been found that the observed target can be classified as a Swerling 2 target, i.e., fluctuating from pulse to pulse with a Rayleigh distribution.

A weak and unknown target signal with the background of thermal noise has also been studied. Its SNR is about 5dB. Both its amplitude and phase vary very rapidly and its correlation time is as low as 2 ms, and its energy spans about 100 Hz in its Doppler spectrum. The target may be classified as a Swerling 2 target, i.e., fluctuating from pulse to pulse with Rayleigh.
Some problems identified in the current version of the radar are being fixed and functionalities of the radar are being extended. Future trials are planned to collect more extensive data.
Authors

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Dr Yunhan Dong received his Bachelor and Master degrees in the 1980s in China and his PhD in 1995 at UNSW, Australia, all in electrical engineering. He then worked at UNSW from 1995 to 2000, and Optus Telecommunications Inc from 2000 to 2002. He joined DSTO as a Senior Research Scientist in 2002. His research interests are primarily in radar signal and image processing and clutter analysis. Dr Dong was a recipient of both the Postdoctoral Research Fellowships and Research Fellowships from the Australian Research Council.

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**David Merrett**  
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Mr David Merrett graduated from RMIT, Melbourne in 1994 with a B.Eng (Comms). He has since worked in radar hardware and systems engineering on a variety of defence-relevant projects including SAR and OTHR. He currently works for DSTO in the area of maritime phased array radar technology.
1. Introduction

In support of the ANZAC Anti-Ship Missile Defence (ASMD) upgrade project, S-band (3.25 GHz) sea clutter data collection was conducted in November 2006 on Kangaroo Island (KI2006), approximately 110 km south-west of Adelaide. The trial collected a variety of sea clutter in a period of four days. This technical report first outlines the radar system and the trial, and then concentrates on sea clutter data processing and analysis. Finally, characteristics of targets are also presented.

2. Radar System

2.1 Outline

The S-Band radar system used in the trial was designed and developed by DSTO in 2005 by EWRD’s Microwave Radar Branch. It is based on an assembly of mostly commercial off-the-shelf (COTS) items, and housed entirely (except the antenna) in two 19-inch racks. For operation, these are installed and transported in a large courier-type van. Figure 1 shows the radar in operation.

![Figure 1: DSTO developed S-band Radar in operation.](image)

2.2 Design

Table 1 lists parameters of the radar and a simplified block diagram of the radar is shown in Figure 2. The main dish acting as both the transmit antenna and receive antenna 1 can be manually set to either the horizontal or vertical polarisation, whereas the two associated receive horns (on top of the dish, see Figure 1), referred to as receive antennas 2 and 3, are fixed to, respectively, the horizontal and vertical polarisations. Therefore quad-polarised sea clutter data were collected during the trial. This report however mainly concentrates
on analysis of sea clutter received from the main dish which can be either the HH or VV polarisation.

The radar is fully coherent, with a low-noise master oscillator at 10 MHz. All timing and RF signals are synchronised to this clock. A sample of the transmitted pulse is also provided to each receiver channel during transmission, via two directional couplers. The sensitivity time-control (STC) was rarely used during the trial for two main reasons:

1. The highest sea-states (of most interest) were at the greatest range where saturation was not apparent; and
2. Pre-trial schedule did not allow adequate evaluation of the STC feature.

Table 1 Specifications of the S-Band radar system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency range</td>
<td>3.2 to 3.3 GHz</td>
<td>Only 3.25 GHz was used</td>
</tr>
<tr>
<td>Instantaneous TX bandwidth</td>
<td>50 MHz</td>
<td>Chirps of up to 10 MHz were used</td>
</tr>
<tr>
<td>Instantaneous RX bandwidth</td>
<td>10 MHz</td>
<td></td>
</tr>
<tr>
<td>Sensitivity time control</td>
<td>Up to 60 dB</td>
<td>Was used only on selected runs</td>
</tr>
<tr>
<td>Number RX channels</td>
<td>4</td>
<td>Only 3 were used</td>
</tr>
<tr>
<td>Noise figure</td>
<td>~3 dB</td>
<td></td>
</tr>
<tr>
<td>IF centre frequency</td>
<td>125 MHz</td>
<td></td>
</tr>
<tr>
<td>RX Analog sample rate</td>
<td>100 MSPS (AD6645)</td>
<td></td>
</tr>
<tr>
<td>RX sample bits</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>Digital down conversion to baseband</td>
<td>Gray Chip (GC4016)</td>
<td>Generated 16-Bit I &amp; Q outputs</td>
</tr>
<tr>
<td>Baseband output sample rate</td>
<td>12.5 MSPS</td>
<td></td>
</tr>
<tr>
<td>RX memory depth</td>
<td>At least 300 seconds</td>
<td>Records direct to RAID array</td>
</tr>
<tr>
<td>continuous</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power output</td>
<td>1 kW nominal</td>
<td>TWT</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>6.5%</td>
<td></td>
</tr>
<tr>
<td>Waveform generation</td>
<td>Agilent E4438 Vector Signal Generator</td>
<td>Pulse modulation was usually a DC centred complex linear FM chirp</td>
</tr>
<tr>
<td>Number TX channels</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>TX antenna</td>
<td>Horn-fed 33dB parabolic dish</td>
<td></td>
</tr>
<tr>
<td>TX polarisation</td>
<td>Manually selectable H or V</td>
<td>Both H &amp; V were used</td>
</tr>
<tr>
<td>RX antenna 1</td>
<td>33dB parabolic dish</td>
<td>(Also the TX dish)</td>
</tr>
<tr>
<td>RX antenna 1 polarisation</td>
<td>Same as TX</td>
<td>(Also the TX dish)</td>
</tr>
<tr>
<td>RX antenna 2</td>
<td>17dB standard gain horn – always V</td>
<td></td>
</tr>
<tr>
<td>RX antenna 3</td>
<td>17dB standard gain horn – always H</td>
<td></td>
</tr>
</tbody>
</table>
Figure 2 Simplified block diagram of the S-Band radar system used in KI2006.

3. Trial Descriptions

A sea clutter collection trial, KI2006, was conducted in November 2006 in the south-west area of Kangaroo Island, approximately 110 km south-west of Adelaide. Effective data collection was carried out on the four-day period of 27-30 November 2006. The general goals were to obtain sea-clutter data while optimising the following attributes

- the highest sea states possible;
- as many look-angles (azimuth) as possible;
- as many wind directions and strengths as possible.

Four different data collecting sites were selected in the trial together offering look azimuth directions of around 100 to 200 degrees from the true north (i.e., the radar looked approximately in East to South-South-West directions). Their altitudes range approximately from 50 to 90 m above the sea level. Their latitude and longitude readings as well as heights are given in Table 6 and Table 7 in Section 5. Figure 3 shows locations of three of the four data collection sites. A similar variety of data collection parameters were used at all sites, covering

- sampling the extent of azimuth angles (in 5 or 10 degree increments);
- transmissions with horizontal and vertical polarised pulses and
- reception with both polarisations.

Over 90% of transmissions were done with a 20 μs pulse width, a 340 μs PRI and either 5 MHz or 10 MHz linear frequency modulation (LFM) chirps. Different PRIs, STC, continuous wave (CW) and shorter pulse lengths were also used on a small selection of recordings at each site. The receiver mostly used maximum gain settings (No STC), and hence the digitiser system often experienced signal saturation in the first 6 to 8 km of range from the radar. Recording times varied from 1 to 120 seconds, mostly being either 15 or 30 seconds. This was limited by disc space.
In addition to radar data, local weather and wave-buoy data was simultaneously collected. During collection periods, wind speeds were typically 5 to 10 m/s, and maximum wave heights around 3.5 m. The estimated sea state was about 3 to 4.

![Figure 3: Locations of three sites on the Kangaroo Island.](image)

### 4. Data Processing

#### 4.1 General Impression of Data

More than 100 datasets have been collected during the 4-day period. Since the STC function was turned off due to the aforementioned reasons and the most collection was carried out without using attenuators in the receiver before the A/D conversion, the collected data was saturated by the A/D conversion for near range bins. Data in far range bins is noise limited due to radar’s power. Hence only a very small number of range bins for each of these datasets contain valid and usable sea clutter. Some datasets were collected using typical 20 to 26dB attenuators, in these cases, the number of range bins containing valid clutter data increases, but there are still a significant number of saturated range bins. A few datasets were collected with a 34dB attenuator in which only a few range bins are occasionally saturated so that nearly all range bins contain unsaturated clutter data, apart from those noise limited far range bins. The in-phase (real-part) of the raw data collected by the first 100 pulses of ki020 (no attenuation), ki093 (26dB attenuation) and ki048 (34dB attenuation) are plotted in Figure 4, Figure 5 and Figure 6, respectively. The saturated range bins can be easily identified\(^1\) (once the in-phase value reaches either \(-32768\) or \(32767\)).

\(^1\)The A/D converter was 14-bit, but the converted data was stored as 16-bit signed integers.
Figure 4: Signal level of raw data. The data in near range (range bin less than approximate 800) is saturated whereas the data in far range (range bin greater than approximate 1200) is noise limited (data source: ki020, without attenuation).

Figure 5: Signal level of raw data. The number of the saturated range bins is reduced when the receiver was with a 26dB attenuator (data source: ki093).

Figure 6: Signal level of raw data. There seem only a few saturated range bins when the receiver was with a 34dB attenuator (data source: ki048).
4.2 Range Compression

The digitised LFM chirp function used by the signal generator was read out and
decimated by a factor of 8 (the function was sampled at a rate of 100 MHz whereas the
range sampling rate was 12.5 MHz). Its complex conjugate was served as the matched
filter, and convoluted to the baseband raw range data to obtain the range compressed
data.

The range compressed clutter profile, obtained from convoluting the matched filter with
the raw data of ki040 is shown in Figure 7. To evaluate the quality of the range
compression processing, Figure 8 shows the range compression result of the coupled TX
pulse which spans about 250 range cells in the uncompressed range profile. This coupled
TX pulse signal can be considered as the scattering from an ideal point target with a
constant RCS, and the range compression should generate a sinc function like profile for
the pulse, which is seen in Figure 8. Therefore, we can confirm that the quality of the range
compression process is good and acceptable.

The second spike in the profile is believed to be the reflection from the deployed wave
buoy reflector. As the first spike (the TX pulse) can be considered as the radar’s location,
the distance of the wave buoy reflector away from the radar can be determined by
counting the number of range cells between the two spikes. The range cell number for the
first and second spikes are 58 and 1223, respectively, given the range distance of the wave
buoy to be (1223 – 58) * 12 m = 13.98 km. The GPS locations for the sites and the wave
buoy reflector were recorded and are listed in Table 7. The range distance of the wave
buoy reflector measured by the radar generally agrees with the GPS measures.

![Figure 7: One pulse clutter range (range compressed) profile received by channel 1 (data source: ki040, VV polarisation).](image-url)
Figure 8: Detailed view of the quality of range compression: the TX pulse (a span of 250 range cells in the uncompressed range profile) has been compressed to a sinc-function-like profile in range direction.

4.3 Calibration of Receive Absolute Power Level

To calibrate the absolute power level of the receiver, a signal with the centre frequency of the carrier having a power level of $P_{in}$ was injected to the receiving port of the dish. The level of output was measured. The receiving port was then terminated with a matched resistor and the level of output was again measured. Let $\bar{P}_{out}$ be the mean output level corresponding to the input level of $P_{in}$, and $\bar{P}_{term}$ be the mean output level corresponding to the terminated input, the minimum level the system can measure, i.e., the thermal noise level of the receive system is,

$$P_n (\text{dBm}) = P_{in} (\text{dBm}) - [\bar{P}_{out} (\text{dBr}) - \bar{P}_{term} (\text{dBr})]$$

(1)

In the measurement, $P_{in} = -94.55 \text{ dBm}$ and $\bar{P}_{out} (\text{dBr}) - \bar{P}_{term} (\text{dBr}) = 5.7 \text{ dB}$, so the minimum level the system can measure is,

$$P_n = -(94.55 + 5.7) = -100.3 \text{ dBm} = -130.3 \text{ dB}$$

(2)

On the other hand, the noise power level of an ideal receive system is,

$$P_{n0} = kT_0B$$

(3)

where $k$ is the Boltzmann’s constant ($k=1.38 \times 10^{-23}$ Ws/K), $T_0$ the room temperature in Kelvin degrees ($T_0=300K$) and $B$ the bandwidth of the system ($B=10\text{ MHz}$ for our case). We have,

$$P_{n0} = 10\log_{10} (1.38 \times 10^{-23} \times 300 \times 10 \times 10^6) = -133.8 \text{ dB}$$

(4)
Therefore the noise figure of the receive system is 3.5dB. Calculation shows the noise figure of the system is about 3dB, approximately matches the actual measurement. Since the received power of far range reaches the noise level, the noise power level $P_n$ in (2) will be used for the level calibration of the received power. Figure 9 shows the received clutter power range profile (range compressed) and its level in far range has been scaled to the noise power level of the system (data source: ki048, VV polarisation). The impulse-like response in the beginning of the profile is the coupled TX pulse, and its range bin serves as the reference of range, $R = 0$.

![Figure 9: Clutter range profile (after range compression) averaged from data of 500 pulses (data source: ki048, VV polarisation). The noise floor has been calibrated to the noise floor of the system. The range cell 58 containing the TX pulse serves the zero reference of range.](image)

### 4.4 Calculation of Sea Clutter Reflectivity

According to the radar equation, the received power $P_r$, after signal processing, from a target of radar cross section $\sigma$ at a range distance $R$ is (Skolnik, 1990, Chapter 2),

$$P_r = \frac{P_t G_t G_r \lambda^2 \sigma F_t^2 F_r^2}{(4\pi)^3 R^4 L}$$  \hspace{1cm} (5)

where $P_t$ is the transmitted power, $G_t$ and $G_r$ are the radar transmitting and receiving antenna gains, respectively ($G_t = G_r$ for monostatic radar), $\lambda$ is the radar carrier frequency and $L$ is the total system loss, usually including transmission line loss (the loss between the transmitter and the antenna), signal process loss (as the received power is often measured in the baseband and the process from the RF to the baseband may have
undergone some loss) and propagation loss. Finally, $F_t$ and $F_r$ are the transmitting and receiving multipath propagation factors, respectively. For monostatic radar, $F_t = F_r = 1$.

In the case of a radar employing the pulse compression technology, Equation (5) cannot be used directly. The effect of pulse compression may be interpreted from the point of energy. The signal energy in a time-resolution cell (a range bin), after range compression, is $\tau_c P_r$, ($\tau_c = 1/B$, assuming that the bandwidth of the radar system matches all the way, see Lewis et al, 1986, Chapter 2). This received energy $\tau_c P_r$, however, is the result of the transmitted energy $\tau_t P_t$ ($\tau_t$ is the length of pulse). Therefore, for a pulse compressed radar, the single-pulse energy equation is,

$$
\tau_c P_r = \frac{\tau_t P_t G^2 \lambda^2 \sigma F^4}{(4\pi)^3 R^4 L}
$$

or,

$$
P_r = \frac{\rho \tau_t P_t G^2 \lambda^2 \sigma F^4}{(4\pi)^3 R^4 L}
$$

where $\rho = \tau_t / \tau_c$ is the pulse compression ratio. Equation (7) indicates that for a chirped radar, the received power of a range bin, after range compression, increases by a factor of $\rho$, compared to a radar with the same pulse width, but not using pulse compression technology.

Now let us discuss the RCS of sea surface. For distributed scatterers, such as the sea surface, after range compression, we have,

$$
\sigma F^4 = \sigma_0 F^4 A
$$

where $\sigma_0$ is the clutter coefficient (mean clutter reflectivity), defined as the mean RCS per unit of illuminated area for surface distributed scatterers, $A$ is the illuminated area of the range cell, and $A = R\phi c \sec \theta / 2B$ for the pulse length limited (range length limited) case with range compression, $\phi$ is the radar’s azimuth beamwidth, $\theta$ is the grazing angle and $c$ the speed of light. In reality, it is difficult to accurately measure the multipath propagation factor $F$ especially for distributed sea clutter. The common practice is therefore to present the measurement of $\sigma_0 F^4$ together. For simplicity, from now on in this report, $\sigma_0 F^4$ will be simply denote $\sigma_0$, i.e., the value of $\sigma_0$ in this report should be interpreted as the value of $\sigma_0 F^4$.

Inserting (8) into (7) and letting $\sec \theta = 1$, we have,
\[ \sigma_0 = P_r \left( \frac{\rho P_i G^2 \lambda^2 \phi c}{(4\pi)^3 L \ 2B \ R^3} \right) \ \text{(m}^2 / \text{m}^2) \]  \hspace{1cm} (9)

or

\[ \sigma_0 = P_r \text{ (dB)} - 10 \log_{10} \left( \frac{\rho P_i G^2 \lambda^2 \phi c}{(4\pi)^3 L \ 2B \ R^3} \right) + 10 \log_{10}(R^3) \ \text{(dB m}^2 \text{m}^{-2}) \]  \hspace{1cm} (10)

In the actual calculation, we only counted two major contributors for the system loss \( L \). One is the two-way transmission line loss (3dB) and the other the propagation loss, i.e., the two-way atmospheric attenuation. According to Skolnik (1990, Chapter 2), the two way atmospheric attenuation at 3 GHz and zero degree grazing angle is about 0.03dB per nautical mile (for range less than about 125 nautical miles). The value 0.03dB/nmi transfers to 0.0000162dB/m. Therefore, parameter values for our radar system are,

\[
P_i = 1000W = 30dB \]
\[
\rho = 100 = 20dB \]
\[
G^2 = 66dB \]
\[
\lambda^2 = (3e8/3.25e9)^2 = -20.70dB \]
\[
\frac{\phi c}{2B} = \frac{3\pi / 180 \times 3e8}{2 \times 5e6} = \pi / 2 = 1.96dB \]
\[
(4\pi)^3 = 32.98dB \]
\[
L = 3 + 0.0000162R \ \text{(dB)} \]

Finally we have,

\[ \sigma_0 = P_r \text{ (dB)} - 61.3 + 0.0000162R + 10 \log_{10}(R^3) \ \text{(dB m}^2 \text{m}^{-2}) \]  \hspace{1cm} (11)

The VV sea clutter coefficient versus range bin calculated form (11) for dataset ki048 is shown in Figure 10.
4.5 Alignment of Range Profile

It was found that the rising time of the transmitter’s pulses is not exactly the same (after subtraction of the PRI, the cause has now been identified and fixed). The measurement of the rising time of the transmitter’s pulses is shown in Figure 11. It can be seen that the rising time of the transmitter’s pulses was not identical, but rather showed a repetitive pattern of every four pulses. That is, the rising time of pulses 1, 2, 3, and 4 is slightly different, but the rising time of pulses 1, 5, 9, …, or 2, 6, 10, …, or 3, 7, 11, …, or 4, 8, 12, …, is each identical. As a consequence, the compressed range profiles of pulses are slightly misaligned with a repetition of every four pulses. Figure 12 shows the received power levels of the coupled TX pulses for two specific range bins, bins 58 and 59, respectively. It is obvious that the received power level of the coupled TX pulses also shows a repetitive pattern of every four pulses. The phase of the received signal in bins 58 and 59 is shown in Figure 13. This kind of misalignment in range profiles needs to be rectified before any further data analysis.
Figure 11: Measured rising time of transmit pulses with a repetition of every four pulses. The unit of x-axis is 80 ns per increment number.
Figure 12: Misalignment of range profiles of original data. The received power of the coupled TX pulse for pulse sequences of 1, 5, 9,… and 2, 6, 10,… is found to have its peak in range bin 58, whereas the peak is found in range bin 59 for pulse sequences of 3, 7, 11,… and 4, 8, 12,….
Since the coupled TX pulse can be considered as the ideal reflection from a radar target that is stationary and has a constant RCS, the received signal in the baseband should be constant (both amplitude and phase) for all pulses. Therefore we can use this received signal to calibrate data received from different pulses. In this calibration, we used the signals in range bin 58 and its neighbourhood received from the pulse train 1, 5, 9, ..., as a reference signal sequence, signals received from other three pulse trains, 2, 6, 10, ..., or 3, 7, 11, ..., or 4, 8, 12, ..., were calibrated to the reference signal sequence. The Wiener-Hopf filtering technique (adaptive least mean squares) was used for the calibration (Klemm, 2004, p. 867).

Figure 13: The phase of the received signal in bin 58 and bin 59 (before range alignment calibration).
We denote $x_i(k)$ and $y_j(k)$ the input and output signals of the filter, respectively, where $i$ is the pulse number and $k$ the bin number. According to our criteria, for pulse train 1, 5, 9, ..., we have,

$$y_{i+4n}(k) = x_{i+4n}(k) \quad k = M + 1, \Lambda , M_R - M ; \quad n = 0,1,2,...,N-1$$  \hspace{1cm} (12)

where $M_R$ is the total number of range bins, $2M+1$ is the length of the processing window or the order of the filter and $4N$ is the total number of pulses. For pulse train 2, 6, 10, ..., or 3, 7, 11, ..., or 4, 8, 12, ..., the output signal of range bin $k$ is a linear combination of signals of range bins $k-M, \Lambda , k, \Lambda , k+M$ as,

$$y_{i+4n}(k) = \sum_{m=0}^{2M} a_{i,m} x_{i+4n}(k-M+m) \quad k = M + 1, \Lambda , M_R - M ;$$

$$i = 2,3,4; \quad n = 0,1,2,...,N-1$$  \hspace{1cm} (13)

Our goal is to find the optimal parameters $a_{m,i}$, $i = 2,3,4$, $m = 0,1,\Lambda , 2M$ (the order of the filter is $2M+1$), so that the squared residual $|y_{i+4n}(k) - y_{i+4n}(k)|^2$ is minimum. To find the minimum squared residual requires,

$$\frac{\partial}{\partial a_i} [y_{i+4n}(k) - y_{i+4n}(k)]^2 = 0$$  \hspace{1cm} (14)

where

$$a_i = [a_{i,1} \quad \Lambda \quad a_{i,2M+1}]$$  \hspace{1cm} (15)

It is not difficult to find the optimal parameters $a_i$ (Wiener-Hopf weights) to be as,

$$a_i^H = R_i^{-1} z_i \quad i = 2,3,4$$  \hspace{1cm} (16)

where

$$R_i = \frac{1}{2K+1} \sum_{k=-K}^{K} \sum_{n=0}^{N-1} x_{i+4n}(k)x_{i+4n}^H(k) \quad i = 2,3,4$$  \hspace{1cm} (17)
The meaning of (16) is that the optimal parameters are adaptively computed from using data of range bin \( k_0 \) and its neighbourhood, averaged from \( 2K+1 \) range bins and \( N \) pulses. Range bin \( k_0 \) usually contains a signal of a stationary and constant RCS target, so that after calibration, \( y_{i,4n}^*(k) \) approaches \( y_{1,4n}^*(k) \), and the squared residual \( |y_{1,4n}^*(k) - y_{i,4n}^*(k)|^2 \) is statistically to be minimum. If all pulses are identical and so are the received signals, we have,

\[
x_{i,4n}(k) = x_{1,4n}(k)
\]  

(20)

and

\[
\langle x_{i,4n}(k)x_{i,4n}^*(k + m) \rangle = 0 \quad m \neq 0
\]  

(21)

and

\[
\langle x_{i,4n}(k + m)x_{i,4n}^*(k) \rangle = 0 \quad m \neq 0
\]  

(22)

In this case, \( \mathbf{a}_i = [0 \quad 1 \quad 1 \quad 0] \), so that

\[
y_{i,4n}(k) = x_{i,4n}(k) = x_{i,4n}(k)
\]  

(23)

After parameters \( a_{im}, \ i = 2,3,4 \) and \( m = 0,1,2M \) are calculated, the range alignment calibration can be carried out using (13). Shown in Figure 14 are the results after the range alignment calibration of Figure 12. It can be seen that the responses of pulses trains 2, 6, 9, 10, …, and 3, 7, 11, … and 4, 8, 12, …, are all calibrated to the reference response of pulse train 1, 5, 9, … and the differences among them are barely noticeable. The fluctuation of
the response of the pulse train 1, 5, 9, …, itself remains the same, and can be considered as
due to the phase noise of the system, which is generally difficult to be further rectified. The
phase of the calibrated signals is shown in Figure 15. It can be seen again that the phase of
responses of pulses trains 2, 6, 9, 10, …, and 3, 7, 11, … and 4, 8, 12, …, are all calibrated to
the reference response of pulse train 1, 5, 9, …, The random fluctuation of the phase for the
reference signal of the pulse train of 1, 5, 9, …, again remains unchanged and is due to the
phase noise of the system.

\[ \text{Figure 14: Amplitude of the received signals in bins 58 and 59 (after the range alignment calibration).} \]
Figure 15: Phase of the received signals in bins 58 and 59 (after the range alignment calibration).

The effectiveness of the Wiener-Hopf filtering (range alignment) process is further demonstrated in the following two figures. Figure 16 compares power spectra of sea clutter in range bin 448 calculated from 125 successive pulses. Data without the range alignment calibration shows strong harmonic components caused by the periodic pattern of transmitted pulses, which, however, have been successfully eliminated in the spectrum of the data after the range alignment calibration. The inherent Doppler spectrum of sea clutter, however, does not suffer from the process, which is shown in Figure 17, where the inherent Doppler spectra of sea clutter in range bin 448 calculated using the data of the pulse train of 2, 6, 10, ..., 402 (a total of 101 pulses), both before and after the range alignment calibration.
alignment calibration, are plotted. It can be seen that the range alignment process does not destroy or deteriorate the inherent Doppler spectrum of the data.

Figure 16: Spectrum comparison between before and after the range alignment calibration: the harmonic components due to the repetitive pattern of the transmitted pulses have been successfully filtered by the Wiener-Hopf filtering processing (data source: ki048, range bin 488).
Figure 17: Spectrum comparison between before and after the range alignment calibration process: The pulse train of 2, 6, 10, ..., 402, a total 101 pulses, was used in calculation (data source: ki048, range bin 488).

It has further been found, for unknown reasons, even the pulse train, for instance, 1, 5, 9, ..., has the jittering problem itself, if the pulse train is long. Figure 18 shows the signal level received in range bin 58 (the coupled TX pulse) of the pulse train 1, 5, 9, ..., 20000. It can be seen that apart from the phase noise which causes signal level fluctuation, there are also two signal discontinuous points, at pulses 2925 and 14509, respectively, caused by the transmitter jitter. In this case, as the pulse train itself has the jittering problem, one has to eliminate its effect, before using it as the reference signal for calibration of the signals received from other pulse trains. At the moment, we have not found the way to deal with this problem yet, and hence only the data from relatively short pulse trains are analysed in this report.

Figure 18: Signal level received in range bin 58 (the coupled TX pulse) for the pulse train 1, 5, 9, ..., 20000. Apart from signal level fluctuation caused by the system’s phase noise, there are two signal discontinuous points, one at pulse 2925 and the other at pulse 14509 caused by the transmitter jitter.
5. Sea Clutter Profile

5.1 Ground Truth

Among many others, two datasets, ki048 and ki073 are often used for various analyses in this report. For a convenient reference, four tables below list parameters of these two datasets. In particular, Table 2 shows differences between two datasets including polarisation, look angle, LFM bandwidth, date and time of collection. Shown in Table 3 and Table 4 are weather data recorded by the on-situ DSTO weather station and the Bureau of Meteorology (BOM) Cape Borda Weather Station (about 35 km north-north-west of Site D), respectively. Discrepancies exist between the records of two weather stations indicating weather conditions to be of local events. Since the DSTO weather station is on-situ, its records may be more close to the sea surface conditions. Other parameters recorded by both the DSTO and BOM wave buoys are given in Table 5.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Polarisation</th>
<th>Look direction (to)</th>
<th>LFM bandwidth</th>
<th>Collection date</th>
<th>Collection time (local)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ki048</td>
<td>VV</td>
<td>181.5°</td>
<td>5 MHz</td>
<td>29-Nov-06</td>
<td>16:45</td>
</tr>
<tr>
<td>Ki073</td>
<td>HH</td>
<td>221.5°</td>
<td>10 MHz</td>
<td>30-Nov-06</td>
<td>12:11</td>
</tr>
</tbody>
</table>

Table 3: In-situ DSTO weather station data.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Relative humidity</th>
<th>Temperature</th>
<th>Pressure</th>
<th>Wind speed</th>
<th>Wind direction (from)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ki048</td>
<td>68.9%</td>
<td>18.0°C</td>
<td>1001</td>
<td>7.0</td>
<td>73.2°</td>
</tr>
<tr>
<td>Ki073</td>
<td>71.9%</td>
<td>19.7°C</td>
<td>999</td>
<td>5.5</td>
<td>240.6°</td>
</tr>
</tbody>
</table>

Table 4: BOM Cape Borda weather data.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Temperature</th>
<th>Wind direction (from)</th>
<th>Wind speed</th>
<th>Gust speed</th>
<th>Sea level pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ki048</td>
<td>22.9°C</td>
<td>70</td>
<td>8.2 m/s</td>
<td>11.3 m/s</td>
<td>1009</td>
</tr>
<tr>
<td>Ki073</td>
<td>19.6°C</td>
<td>210</td>
<td>8.7 m/s</td>
<td>12.3 m/s</td>
<td>1007</td>
</tr>
</tbody>
</table>

Table 5: Data recorded by the DSTO/BOM Wave buoy.

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Mean wave direction (from)</th>
<th>Spreading width</th>
<th>Rms wave height</th>
<th>1/3 (H_{1/3}) wave height</th>
<th>Max wave height</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ki048</td>
<td>134.5°</td>
<td>25.5°</td>
<td>1.52 m</td>
<td>2.25 m</td>
<td>4.0 m</td>
</tr>
<tr>
<td>Ki073</td>
<td>161.4°</td>
<td>21.2°</td>
<td>1.39 m</td>
<td>1.93 m</td>
<td>3.52 m</td>
</tr>
</tbody>
</table>

Directions are referenced to the true north. However it should be pointed out that the radar’s look direction is defined as ‘to’, so a look direction of 90° means the radar looks from west to east. On the other hand, both the wind’s and wave’s directions are defined as ‘from’, so a wind (wave) direction of 90° indicates the wind (wave) blows (propagates) from east to west.
According to the parameters shown in the above tables, the sea state is estimated at about 3-4 when these two datasets were collected. The radar was looking approximately in the crosswind and upwind directions when collecting ki048 and ki073 datasets, respectively, as shown in Figure 19.

The directional ocean wave spectra, at the time when the sea clutter datasets ki048 and ki073 were taken, recorded by the DSTO wave buoy are shown in Figure 20. It can be seen that the spectrum of ki048 has two dominant components, one with a frequency of 0.08 Hz in the direction of 248° (swell) and the other with a frequency of 0.175 Hz in the direction of 90° (wind wave). On the other hand, the spectrum of ki073 seems to have one dominant cluster whose centre has a frequency of 0.11 Hz in the direction of 156°.
5.2 Sea Clutter versus Range

In order to analyse the sea clutter range profile and link the range to grazing angle, we tabulate the heights of radar sites above the sea level and their corresponding horizon distances using the classical 4/3 Earth’s radius model (the Earth’s radius is 6378 km). The span of range cells (the range sampling rate of 12.5 m/s gives a range sampling interval of 12 m) for each horizon distance is also listed in the table.

Table 6: Heights of radar sites and the corresponding horizon distances.

<table>
<thead>
<tr>
<th>Site</th>
<th>Height (m)</th>
<th>Horizon distance (m)</th>
<th>Span of range cells</th>
</tr>
</thead>
<tbody>
<tr>
<td>A or D</td>
<td>51</td>
<td>29,452</td>
<td>2454</td>
</tr>
<tr>
<td>B</td>
<td>92</td>
<td>39,557</td>
<td>3296</td>
</tr>
<tr>
<td>C</td>
<td>61</td>
<td>32,210</td>
<td>2684</td>
</tr>
</tbody>
</table>

A wave buoy reflector was also deployed during the trial. The GPS readings for Sites A, B, and C as well as the reflector are listed in Table 7. The distances between the reflector and sites thus can be calculated. However, the drift of the wave buoy was possible, so the actual distances between the reflector and radar during the data collection might be different.

Table 7: Locations of the radar sites and the wave buoy reflector.

<table>
<thead>
<tr>
<th>Location</th>
<th>GPS readings</th>
<th>Distance to the wave buoy reflector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site A</td>
<td>-36.061240N, 136.704470E</td>
<td>10,384 m</td>
</tr>
<tr>
<td>Site B</td>
<td>-36.055272N, 136.714316E</td>
<td>11,450 m</td>
</tr>
<tr>
<td>Site C</td>
<td>-36.042198N, 136.715134E</td>
<td>13,633 m</td>
</tr>
<tr>
<td>Site D</td>
<td>No GPS readings recorded</td>
<td></td>
</tr>
<tr>
<td>Wave buoy reflector</td>
<td>-36.147133N, 136.656400E</td>
<td>0 m</td>
</tr>
</tbody>
</table>

Figure 21 is a duplication of Figure 9 with an exception that its x-axis has been replaced by range in metres rather than range bins, and the horizon distance is also marked. It can be seen that the received power approaches the noise level long before reaching the horizon distance in this case.
Figure 21: Received power approaches the noise level long before reaching the horizon distance. The horizon distance is calculated by the use of the classical 4/3 Earth radius model.

It has been found that at low grazing angles the drop of clutter intensity (power) against range is much faster than what radar equation indicates, and can be proportional to $R^{-7}$ instead of $R^{-3}$ (Long, 2001). Figure 22 shows the measured sea clutter power dropping pattern against range, where lines proportional to $R^{-3}$, $R^{-5}$ and $R^{-7}$ are also shown. It seems that the dropping tendency of the received clutter power is consistent with those that have been reported.

Figure 22: Received S-band vertically polarised sea clutter power versus range. Lines proportional to $1/R^3$, $1/R^5$ and $1/R^7$ are also drawn for indications of the decaying tendencies of sea clutter strength against range (data source: ki048).
5.3 Sea Clutter Coefficient versus Grazing Angle

The nominal grazing angle of any range distance can be easily determined using the classical 4/3 Earth radius model. The relationship between the VV sea clutter coefficient and the grazing angle for the valid clutter region is shown in Figure 23. The decrease of sea clutter coefficient with the decrease in grazing angle is obvious. This decrease pattern in a certain region, when $\sigma_0$ is expressed in $dBm^2m^{-2}$, may be described as proportional to $\exp(\theta^\beta)$, where $\theta$ is the grazing angle, and $\beta$ is a constant determining the slope of the line of $\log_{10}[\exp(\theta^\beta)]$ on the log scale of grazing angle as shown in Figure 23 (b). This finding is consistent with a previous study (Dong, 2004). It should be pointed out that since the radar’s antenna was set to the horizontal (e.g., the beam always pointed to zero degrees), measurements with grazing angle higher than 1° may be some decibels lower than they should be, affected by the elevation pattern of the antenna gain.

Figure 23: S-band VV sea clutter coefficient as a function of grazing angle: blue for ki048 and green for ki049a. Values shown in the figure are averaged from using data collected by 2000 pulses (two datasets were collected with 8 minutes in time and 10° in azimuth apart).
The range profiles of the received VV and HH sea clutter power are together shown in Figure 24. Unfortunately two datasets were collected with nearly 20 hours in time and 40 degrees in azimuth apart, the wind direction changed significantly (see Figure 19), hence the sea surface conditions should be different. Nevertheless it shows however, the received HH sea clutter power in near range is lower than the received VV sea clutter power. Besides the HH sea spikes seem to be more persistent as the mean HH profile oscillates larger than the mean VV profile after averaged by 2000 pulses. In addition the HH profile shows an irregular pattern versus the range which may be due to the effects of multipath scattering and shadowing because the HH sea clutter is often more sensitive to these effects (Long, 2001). The HH sea clutter coefficient as a function of the grazing angle, with the comparison of the VV data is shown in Figure 25.

Figure 24: Comparison of the VV (blue) and HH (green) sea clutter range profiles. The HH sea clutter in near range seems to be lower than the VV sea clutter. The effects of multipath scattering and shadowing on the HH data are severer as the mean HH profile shows an irregular pattern against the range (data source: ki048 and ki073).

Since the VV data was collected with a 5 MHz LFM bandwidth and the HH data with a 10 MHz LFM bandwidth, the noise level of the received VV power should be a further 3dB down (see equation (3)) in Figure 24. However, we have adjusted the level of the VV data so that it has the same noise level as the HH data. In this way the received VV clutter power shown in Figure 24 can be considered as if it was collected with a LFM bandwidth of 10 MHz (in terms of the received power level), the same as the HH data.
Sea clutter coefficient in dBm²/m² as a function of grazing angle, at S-band (frequency of 3.0 GHz) V and H polarisations given by Nathanson, et al (1999, Chapter 7) is quoted in Table 8. The estimated sea state when ki048, ki049a.dta1 and ki073 were collected was about 3 to 4. It seems that for the VV polarisation there is a reasonable agreement between the sea clutter coefficients we measured and the values given in the table. However, for the HH polarisation, the coefficients we measured especially at higher grazing angles (1.0°, for instance) are somewhat lower than the values given in the table.
Table 8: Sea clutter coefficient in dBm²/m² at S-band, given by Nathanson, et al (1999).

<table>
<thead>
<tr>
<th>Grazing angle</th>
<th>0.1°</th>
<th>0.3°</th>
<th>1.0°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sea state 2</td>
<td>-75 (VV), -75 (HH)</td>
<td>-62 (VV), -66 (HH)</td>
<td>-53 (VV), -55 (HH)</td>
</tr>
<tr>
<td>Sea state 3</td>
<td>-75 (VV), -68 (HH)</td>
<td>-58 (VV), -60 (HH)</td>
<td>-48 (VV), -48 (HH)</td>
</tr>
<tr>
<td>Sea state 4</td>
<td>-67 (VV), -63 (HH)</td>
<td>-57 (VV), -55 (HH)</td>
<td>-42 (VV), -45 (HH)</td>
</tr>
<tr>
<td>Sea state 5</td>
<td>-63 (VV), -63 (VV)</td>
<td>-52 (VV), -52 (HH)</td>
<td>-38 (VV), -42 (HH)</td>
</tr>
</tbody>
</table>

6. Correlation

6.1 Temporal Correlation

It is well known that the thermal noise intensity is exponentially distributed, so we can denote the thermal noise intensity of a radar to have a mean \( P_\text{n} \) and variance \( P_\text{n}^2 \). As the thermal noise is uncorrelated, the incoherent average of the noise intensity is gamma distributed with a mean \( P_\text{n} \) and variance \( P_\text{n}^2 / N \), where \( N \) is the number of samples used in the average processing. Figure 26 shows received power averaged by 1, 10, 100 and 6000 pulses, respectively. It can be seen that initially the level of fluctuation for both the clutter and noise dominated regions is approximately the same. However, after the incoherent averaging processing, while the reduction in the fluctuation level in the noise dominated region is significantly noticeable as its variance is inversely proportional to the number of samples used in the averaging processing, the reduction in the fluctuation level in the sea clutter dominated region is relatively slow, indicating that sea clutter is temporally correlated.

![Figure 26: Results of incoherent averaging processing indicate temporal correlation of sea clutter.](image-url)
Figure 27 shows a range-time intensity image of the received sea clutter power. In the clutter dominant region, vertical line patterns are very evident, an indication of sea clutter being temporally correlated. In the noise dominant region, however, the image appears textureless, as noise is uncorrelated both temporally and spatially.

![Figure 27: Vertical line patterns in the clutter dominant region of the range-time intensity (dB) image are very evident, indicating sea clutter to be temporally correlated, whereas in the noise dominant region the image appears textureless, as noise is uncorrelated both temporally and spatially (data source: ki048, VV polarisation).](image)

The received power in three different range bins is shown in Figure 28, which illustrates the difference between the temporally correlated clutter profile and the temporally uncorrelated noise profile. Below we will qualitatively study the temporal correlation of the sea clutter.
Figure 28: Received power in three different range bins: bin 500 (blue), bin 700 (green) and bin 2500 (red). Signals in the first two bins are sea clutter dominant and show a strong temporal correlation (a PRI of 340μs) in comparison with the signal in the third bin which is noise dominant and uncorrelated (data source: ki048, VV polarisation).

Assuming a sample series \( \{x(i), i = 1, 2, \ldots, N\} \) is wide sense stationary, the Pearson correlation coefficient \( \rho(k) \) between \( x(i) \) and \( x(i+k) \) is defined as (Proakis and Manolakis, 1996, Stehwien, 1994),

\[
\rho(k) = \frac{\langle x(i)x^*(i+k) \rangle - \langle |x|\rangle^2}{\langle |x|^2 \rangle - \langle |x|\rangle^2} \quad k = 0, 1, \Lambda
\] (24)

where \( \langle \cdot \rangle \) and * denote the ensemble average and complex conjugate, respectively. The ensemble average is estimated by the usual way, for instance,

\[
\langle x \rangle = \frac{1}{N} \sum_{i=1}^{N} x(i)
\] (25)

where \( N \) is the number of samples used in the parameter estimation.

The temporal correlation of the VV data for range bins 301-1200 (sea clutter dominant region) of ki048 is shown in Figure 29 (a) and (b) calculated using the received signals represented by complex values and intensities (square of the amplitude of the complex value), respectively. It can be seen that the correlation patterns are very similar whether the complex values or intensities are used for the calculation. However the former has a slightly longer correlation time. An interesting point we can see from the figure is that the correlation seems to be statistically independent of range bins, that is, whether a range bin
contains VV sea spikes or not, its temporal correlation is statistically the same as others. We will see this point is not valid for the HH sea clutter later.

![Temporal correlation for range bins 301-1200 of ki048. The correlation is statistically independent of range bins.](image)

The corresponding correlation time can be calculated accordingly, using the usual criterion that the correlation coefficient drops from 1 to $1/e$. The correlation time for each range bin is shown in Figure 30. The variation of correlation time seems to be random. The mean temporal correlation time for the VV sea clutter is 14.5 ms or 9.2 ms depending on whether complex values or intensities are used for the calculation.

![Temporal correlation time versus range bin of the VV sea clutter: the top and middle profiles were calculated from using complex values and intensities, respectively. The bottom profile is the received clutter intensity. The variation of the correlation time seems to be random.](image)
The temporal correlation of the HH data, ki073, is shown in Figure 31. Unlike the VV data, the correlation of the HH data does not seem to be random but somehow links to clutter returns. Figure 32 shows the correlation time of each bin, and for the comparison, the mean clutter power is also shown. It demonstrates that in general those persistent sea spikes which have higher clutter returns seem to also have longer temporal correlation time. The mean correlation time of the top and middle profiles is 16 ms and 10 ms, respectively.

Figure 31: Temporal correlation of the HH sea clutter in range bins 301-1200 of ki073. Persistent sea spikes which have higher clutter returns seem to result in longer correlation times.

Figure 32: Temporal correlation time versus range bin for the HH sea clutter ki073: the top and middle profiles are calculated from using complex values and intensities, respectively. The bottom profile is the mean clutter power.
Using a vertically-polarised S-band radar and under typical conditions of sea state 2, Chan (1990) measured the correlation time to be 22 ms in the up-swell direction. It is understood, the lower the sea states, the longer the temporal correlation time. This may explain why the correlation time we measured is shorter than what Chan measured.

6.2 Spatial Correlation

Range or spatial correlation is the correlation among signals in range bins collected from the same pulse. There is a little problem in directly using (24) for calculating range correlation, as the correlation defined by (24) assumes that the data is wide sense stationary. However the received clutter intensity is a function of range (or sea clutter coefficient is a function of grazing angle), and the sample series \( \{x(i), i = 1, 2, \ldots, N\} \) is not wide sense stationary with respect to range, where \( i \) may denote range bins. Therefore strictly speaking, one has to eliminate the range effect from the range data to make it stationary, before calculating the range correlation. However, if we are only interested in the short-term (a small lagging number) range correlation, we can assume that the range effect on nearby range bins are not significant, and therefore, the resultant correlation should not be far away from the correlation of the data in which the range effect has been eliminated. The short-term spatial correlation is shown in Figure 33 and Figure 34 for the VV and HH data, respectively. It is seen that unlike the temporal correlation, the short-term spatial correlation of both the VV and HH data is very similar, and does not show noticeable features of polarisation dependence. We recall that the VV dataset, ki048, has a 30 m range resolution (with a 10 MHz LFM bandwidth) and the HH dataset, ki073, has a 15 m range resolution (with a 5 MHz LFM bandwidth), but both have a range sampling interval of 12 m. Therefore the data were over-sampled and the data in the immediate range bins are not independently identically distributed (iid) samples. The range correlation calculated using the immediate range samples would be affected by the over-sampling rate. To remove the effect of the over-sampling, we re-computed the short-term spatial (range) correlation using an interval of 3 range bins for the VV dataset and 2 range bins for the HH dataset. The corresponding results are shown in Figure 35 and Figure 36, respectively (averaged by 2000 pulses). With the usual criterion that data can be considered as uncorrelated if \( |\rho| < 1/e \), we can conclude that the spatial correlation length for the S-band VV and HH data under our collecting conditions is shorter than 36 m and 24 m, respectively, but the exact correlation lengths are unknown. In order to accurately measure the correlation length, we need a radar with a higher resolution. Since the range correlation length measured by radar is a function of not only the physical conditions of the sea surface itself, but also radar parameters including frequency, polarisation, resolution and illumination geometry. Without specifying these parameters, range correlation length may vary from measurement to measurement, though physical surface conditions may be statistically the same for the measurements.
Figure 33: Short-term spatial (range) correlation of the VV data, ki048.

Figure 34: Short-term spatial (range) correlation of the HH sea clutter, ki073.

Figure 35: Short-term spatial (range) correlation of the VV sea clutter, ki048, with an interval of 3 range bins and averaged by 2000 pulses. The blue and green curves are corresponding to the clutter represented by the complex and intensity values, respectively.
We are not aware of spatial (range) correlation of S-band low grazing angle sea clutter having been reported in the open literature. Nevertheless, one point indicated by Stehwien (1994) is interesting and worth mentioning here. He found that for moderately spiky sea clutter (sea state of 2 to 3) the range correlation remains unchanged regardless the use of the frequency agility when he measured range correlation using an airborne X-band radar at a low grazing angle of about 2.1°.

The long-term spatial correlation (lagged many range bins), not studied in this report, usually contains information of sea wave and swell structures (Dong, 2007).

7. Doppler Analysis

Given a radar (frequency, polarisation and illumination geometry etc) the Doppler property of sea clutter is a function of sea surface conditions, such as directions and scales of wind and swell. Broadly speaking, therefore, the Doppler property of sea clutter is not time stationary as the environmental parameters are not time stationary. However if within the observation time, the wind and swell do not change, then the observation is time stationary. Figure 37 shows typical time-frequency properties of the Doppler spectra of sea clutter calculated from using data in range bin 500, for both the VV and HH polarisations. It can be seen that in general there is no significant frequency shift during the elapsed time window which is less than one second. The results were obtained using the short-time Fourier transform (STFT) with a Hanning window of length 64 (Cohen, 1995).
Figure 37: Time-frequency property of the Doppler frequency spectra of the S-band VV and HH sea clutter calculated using data in range bin 500 (data source: ki048 and ki073). The maximum Doppler spectrum intensity in each plot has been normalised to 0dB.

The following Doppler analysis of sea clutter therefore is based on the assumption of time stationary. Shown in Figure 38 is the VV range-Doppler spectrum map. In order to see its correlation with the sea clutter intensity, the received power profile is also shown in the figure. It is worth noting that (1) the higher Doppler spectrum intensities in near range are due to the higher received power in these bins; (2) bins having higher clutter returns — most likely due to sea spikes — have wider spectra and (3) noise only bins have a higher Doppler component at zero hertz than other Doppler frequencies (thermal noise should have a uniformly distributed Doppler spectrum) indicating that the receiver is slightly biased and contains a DC component in the received signal (The DC component also exists in the HH datasets).

The HH range-Doppler spectrum map is shown in Figure 39. Unfortunately, as aforementioned, the HH dataset ki073 and the VV dataset ki048 were collected about 20 hours in time and 40° in azimuth apart, and the wind direction changed significantly, we cannot make direct comparison between the two. Nevertheless, we make the following observations. The Doppler of the VV data tends to be negative, indicating that radar viewed a sea surface with receding waves (scatterers). It is noted however, the swell propagates in the approaching direction and the wind wave in the almost perpendicular direction (see Figure 20 (a)). On the other hand, the Doppler of the HH data especially in far range bins seems to have two peaks residing on the positive and negative sides, respectively, showing that the radar captured the movement of both receding and approaching waves. Based on these observations, it is understand that the Doppler spectrum of sea clutter is highly correlated to the movement of various wave components from small scale ripples, capillary waves to large scale swells, as well as break waves, white caps and spills. We intend to perform a detailed analysis in the future.
Figure 38: The S-band VV polarised range-Doppler spectrum map (top) and its received power range profile (bottom). It is worth noting that the higher Doppler frequency intensities in the near range are due to the higher received power and sea spikes seem to have wider spectra (data source: ki048).

The VV sea clutter high returns from sea spikes and its adjacent low returns (no-spikes) are shown in Figure 40. The received power of the sea spike dominant bin is more than 10dB higher than that of the non sea spike dominant bin. The Doppler spectrum densities of these two typical bins are shown in Figure 41. It is seen that the spectrum of the non spike dominant bins is narrower, indicating that the surface of continuing waves and swells move slower. On the other hand, the spectrum of the spike dominant bins is much broader, demonstrating breaking waves and whitecaps move differently.
Figure 39: The S-band HH polarised range-Doppler spectrum map (top) and its received power range profile (bottom). This dataset (ki073) was collected about 20 hours in time and 40 degrees in azimuth apart from the collection of ki048.

Figure 40: Received VV intensities of a sea spike dominant bin 473 (blue) and a non-spike dominant bin 457 (green) (data source: ki048).
Figure 41: Doppler spectrum intensity of (a) sea spike dominant clutter in range bin 473 (blue) and (b) non sea spike dominant clutter in range bin 457 (green) (data source: ki048, VV polarisation).

The phenomena observed for the HH sea clutter is different. We again show in Figure 42 the clutter levels of two adjacent bins one with high returns and the other low returns. Their corresponding Doppler spectra are shown in Figure 43. The spectrum of the high return bin (spike dominated) seems to have a single dominant peak. The remaining part of the spectrum is similar to the spectrum of the lower return bin. For far range bins, we can clearly see that they typically have a spectrum pattern with two peaks if we view the Doppler map shown in Figure 39. Such a typical Doppler spectrum is shown in Figure 44. This demonstrates that the scattering mechanisms for the HH polarisation are different from those for the VV polarisation (a well-known phenomenon, for instance see Chan’s 1990 paper, and Plant and Keller’s 1990 paper). The width of the sea clutter spectra for these two datasets is about 200 Hz.

Figure 42: Received HH intensities of a sea spike dominant bin 375 (blue) and a non-spike dominant bin 388 (green) (data source: ki073).
Figure 43: Doppler spectrum intensity of (a) sea spike dominant clutter in range bin 375 (blue) and (b) non sea spike dominant clutter in range bin 388 (green) (data source: ki073, HH polarisation).

Figure 44: Two-peak pattern Doppler spectrum of the HH sea clutter in range bin 882 of ki073.

Viewing the range-Doppler maps shown in Figure 38, we can see some high Doppler frequency components appearing in some bins. The spectrum density of one of such range bins is shown in Figure 45 (ki048, VV polarisation). The Doppler components at frequencies of about $-300$ Hz and $-250$ Hz are believed to be caused by flying birds. These two Doppler frequencies convert to radial velocities of $50$ km/h and $42$ km/h, respectively. Shown in Figure 46 is the Doppler spectrum of the same range bin but collected 8 minutes after and with a $10^\circ$ difference in the looking azimuth (ki049a, VV polarisation). We see a different Doppler component at about $100$ Hz, which converts to a radial velocity of $17$ km/h, also possibly caused by a flying bird. Since these two datasets were collected approximately 8 minutes apart, we might say that there were bird activities in that area at that moment. Such bird activities were not observed in the following day, when the dataset of ki073 was collected as shown in Figure 47.
Figure 45: Doppler spectrum intensity of sea clutter in range bin 1070. In addition to the spectrum of sea clutter, the Doppler components at frequencies of about −300 Hz and −250 Hz seem to be caused by flying birds (data source: ki048, VV polarisation).

Figure 46: Doppler spectrum intensity of sea clutter in range bin 1070. In addition to the spectrum of sea clutter, the Doppler component at the frequency of about 100 Hz seems to be caused by a flying bird (data source: ki049.data1, HH polarisation).
Figure 47: Doppler spectrum intensity of sea clutter in range bin 1070. No bird activities were observed. Instead, we see a typical two-peak pattern spectrum of the HH sea clutter (data source: ki073, HH polarisation).

It might be interesting to further investigate the RCS values of the suspected birds. Since the propagation factor $F$ in (7) is unknown, we can only provide the measured value of $\sigma F^4$ as below.

We assume that in Figure 45 the two Doppler spectral peaks in the region of $[-320 \text{ Hz}, -240 \text{ Hz}]$ was due to two flying birds with the equal RCS. An integral of the spectrum energy in the Doppler frequency region of $[-320 \text{ Hz} - 240 \text{ Hz}]$ minus the sea clutter energy results in an average of $-68.4\text{dB}$ for each flying bird. As this energy is a result of an integral of 500 pulses, so,

$$P_r = -68.4 - 20\log_{10}(500) = -122.4\text{dB}$$

and

$$10\log_{10}(R^4) = 40\log_{10}[(1070 - 58) \times 12)] = 163.4\text{dB}$$

Values of other parameters of (7) can be found from Section 4.4. Finally we calculate $\sigma F^4 = -18.3\text{dB} \text{m}^2$. This value seems to be very close to the commonly suggested value of $-20\text{dB} \text{m}^2$ as a typical RCS value of bird. Similarly, the measured value of $\sigma F^4$ for the supposed flying bird signal in the Doppler frequency region of $[75 \text{ Hz}, 100 \text{ Hz}]$ of Figure 46 is $-23.3\text{dB} \text{m}^2$.

Doppler spectrum of sea clutter is a result of motion of the sea surface, and depends on many parameters. The above analysis is just a preview of this complex issue. We intend to study Doppler properties of sea clutter in a much more detailed way, and report the outcomes accordingly in the near future.
8. Distribution Fit

Another important characteristic of sea clutter is its distribution. Without knowing the clutter distribution, the radar’s performance under such a clutter environment cannot be determined. As radar clutter is a complex random process, and radar detection schemes often require the knowledge of an accurate and precise clutter distribution especially in the upper tail region, it is a common and unashamed practice that clutter distribution models are often obtained from data fitting rather than from rigorous mathematical modelling.

Sea clutter distribution includes the spatial distribution (in the fast-time domain) and the temporal distribution (in the slow-time domain). However, in our case, the spatial distribution study is difficult to proceed because the clutter power or the clutter coefficient is a function of range or grazing angle. Hence a data sequence in range collected by a pulse is not wide-sense stationary.

Broadly speaking sea clutter received in a specific range bin from multiple pulses is a function of time, so it is not temporally stationary either. However, as stated previously, sea clutter data in a specific range bin collected by multiple pulses can be considered as temporally stationary, provided that the observation time is short enough (i.e., the underlying mean of the sea clutter is constant within the time of observation). Naturally, the length of this time window is dependent on radar parameters and sea surface conditions. The rougher the sea surface and the coarser the radar resolution, the longer the time-window is. For instance, if the resolution (in both the range and azimuth) of a radar covers the longest wavelength of swell, and there is no change in wind and swell, then the radar data becomes time independent and can be considered as wide-sense stationary.

To study the temporal distribution, we assume that sea clutter received by a range bin, in the sea clutter dominant range, from multiple pulses is stationary in a time-window of 2000 pulses ($PRI = 340\mu s$). We also assume that it is K-distributed with an unknown shape parameter $\nu$. The probability density function (pdf) of the K-distributed sea clutter intensity is (Ward, at al, 2006),

\[
p_\nu(x) = \frac{2\nu}{\Gamma(\nu)\bar{x}} \left(\frac{\nu x}{\bar{x}}\right)^{(\nu-1)/2} K_{\nu-1}\left(2\sqrt{\nu x/\bar{x}}\right) \tag{26}
\]

where $K_{\nu-1}(\cdot)$ is the modified Bessel function of the second kind with the order of $\nu - 1$, and $\bar{x}$ is the mean of the clutter intensity and is assumed to be equal to its maximum likelihood estimate, as,

\[
\bar{x} = \langle x \rangle = \frac{1}{n} \sum_{i=1}^{n} x_i \tag{27}
\]

To simplify calculation, the data sequence is further normalised, so that $\bar{x} = 1$. If there are sufficient samples, the shape parameter can be estimated accurately using various schemes.
Here we use statistics of data samples (when the number of the samples are not sufficiently large) to evaluate the goodness-of-fit of the pdf (D’Agostino and Stephens, 1986, Chapter 4).

The cumulative distribution function (cdf) of the above K-distribution is,

\[
P_\nu(x) = 1 - \frac{2}{\Gamma(\nu)} \left( \frac{\nu x}{\bar{x}} \right)^{\nu/2} K_\nu \left( 2 \sqrt{\nu x / \bar{x}} \right)
\]

(28)

The empirical cumulative distribution function (Ecdf) \( P_n(x) \) is defined by (D’Agostino and Stephens, 1986, Chapter 4),

\[
P_n(x) = \begin{cases} 
0 & x < x_1 \\
\frac{i}{n} & x_i \leq x < x_{i+1} \\
1 & x_n \leq x 
\end{cases}
\]

(29)

where the data sequence \( \{x_1, x_2, \ldots, x_n\} \) is supposed to have been sorted in the ascending order, i.e., \( x_1 \leq x_2 \leq \ldots \leq x_n \).

The goodness-of-fit can then be examined by evaluating the difference between the Ecdf of data and the cdf of the hypothesised distribution. D’Agostino and Stephens (1986) discussed various techniques of how to test the goodness-of-fit. Figure 48 shows the Ecdf of 2000 pulse samples received by range bin 401 after the normalisation, along with the K-distributed cdfs with the shape parameter \( \nu \) to be 1, 10, and infinity. The K-distribution becomes the Rayleigh (negative exponential distribution) when \( \nu \to \infty \). It can be seen, visually, that in this case the Rayleigh distribution fits best the data’s distribution as the discrepancy between \( P_n(x) \) and \( P_\infty(x) \) appears to be the least.
Figure 48: Cdf comparison indicates that the Rayleigh distribution fits best the sea clutter temporal distribution.

We need more rigorous statistics to evaluate the goodness-of-fit. The most well known statistic is $D$ (distance) defined as (D’Agostino and Stephens, 1986),

$$D = \max_x \left\| P_n(x) - P(x) \right\| = \max_i \left\| i/n - P(x_i) \right\|$$

where $P(x)$ is the hypothesised cdf of the data to be studied.

The second and wide class of the measures of discrepancy is the quadratic statistic given by the Cramer-von Mises family (D’Agostino and Stephens, 1986),

$$Q_0 = n \int_{-\infty}^{\infty} (P_n(x) - P(x))^2 dP(x) = \sum_{i=1}^{n} \left( \frac{i}{n} - P(x_i) \right)^2$$

(31)

If we are interested in the fit in the upper tail region, we may modify the quadratic statistic $Q_0$ as,

$$Q_{1-\alpha} = \sum_{i=k_\alpha}^{n} \left( \frac{i}{n} - P(x_i) \right)^2$$

(32)

where $k_\alpha = \text{int}\{(1-\alpha)n\} + 1$, $\text{int}\{\cdot\}$ is the function which rounds the value to the nearest integer. For instance, if $\alpha = 0.1$, we estimate the quadratic discrepancy only in the upper region of $0.9 < P(x) \leq 1$. It is obvious that $Q_0$ is the special case of $Q_{1-\alpha}$ with $\alpha = 1$.

It is clear that the statistic $D$ measures the maximum distance between the hypothesised cdf and Ecdf of the data, whereas the statistic $Q$ measures the discrepant area (with a penalty weighting factor of the distance).
The statistical measure $D$ for range bins 401-1000 (received power is dominated by sea clutter in these range bins) is shown in Figure 49 with sea clutter assumed to be K-distributed and the shape parameter to be 1, 5, and infinity, respectively. It can be seen that statistically the K-distribution with $\nu = \infty$ matches most the data’s Ecdf as the statistic $D$ for $\nu = \infty$ is minimum. We can draw a similar conclusion when examining the statistical measure $Q_0$ that is shown in Figure 50.

![Figure 49: Statistical measure $D$ for range bins 401-1000 with 2000 data samples for each range bin. The hypothesised distribution is the K-distribution with $\nu = 1$ (blue), $\nu = 5$ (green) and $\nu = \infty$ (red) (data source: ki048, VV polarisation).](image1)

![Figure 50: Statistical measure $Q_0$ for range bins 401-1000 with 2000 data samples for each range bin. The hypothesised distribution is the K-distribution with $\nu = 1$ (blue), $\nu = 5$ (green) and $\nu = \infty$ (red) (data source: ki048, VV polarisation).](image2)

The received power (mean value) and the statistical measure $Q_0$ ($\nu = \infty$) for these range bins are shown in Figure 51. The purpose of showing this figure is to see whether the temporal distributions for high and low clutter bins are different. By viewing the figure, it seems that there is no correlation between the measure $Q_0$ and the clutter power.
Finally we show the statistical measures $D$ and $Q$, averaged from the measures of range bins 401-1000, in Table 9. It can be seen that among the five cases examined the K-distribution with $\nu = \infty$ offers the best fit for the clutter’s temporal distribution, since the $D$ and $Q$ measures achieve the minimum with $\nu = \infty$, except for $Q_{Q_{0.5}}$.

Table 9: Statistical measures $D$ and $Q$, averaged from using the measures of range bins 401-1000 of the VV polarised ki048.

<table>
<thead>
<tr>
<th>Measure</th>
<th>$\nu = 1$</th>
<th>$\nu = 5$</th>
<th>$\nu = 10$</th>
<th>$\nu = 30$</th>
<th>$\nu = \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>0.1889</td>
<td>0.0698</td>
<td>0.0579</td>
<td>0.0530</td>
<td>0.0521</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>30.0756</td>
<td>3.6540</td>
<td>2.3306</td>
<td>1.8983</td>
<td>1.8344</td>
</tr>
<tr>
<td>$Q_{1-0.5}$</td>
<td>4.8582</td>
<td>1.0274</td>
<td>0.7447</td>
<td>0.668</td>
<td>0.6793</td>
</tr>
<tr>
<td>$Q_{1-0.05}$</td>
<td>0.1230</td>
<td>0.0362</td>
<td>0.0253</td>
<td>0.0197</td>
<td>0.0178</td>
</tr>
</tbody>
</table>

If clutter data in each range bin received by multiple pulses is Rayleigh distributed (K-distributed with $\nu = \infty$), after the data of each range bin is normalised to its mean, the data distribution for all range bins should become identical. Therefore, we can combine these normalised data together and study its distribution. This way, we now have a total $2000 \times (1000 - 400) = 1.2 \times 10^6$ samples which should allow us to draw its pdf at a highly precise level. Figure 52 shows the pdf of these 1.2 million samples, together with pdfs of the K-distribution with the shape parameter to be 1, 5, 10, 30 and infinity. Now we can confidently conclude that the short-time temporal distribution of the S-band VV sea clutter collected by our radar is Rayleigh. It is well known that, apart from other parameters, the radar’s resolution plays a key role for sea clutter’s distribution. The finer the resolution,
the spikier the sea clutter (the smaller the shape parameter). The range resolution of our radar is 30 m (in spite of the range sampling resolution to be 12 m) which may be coarse enough for sea clutter to be Rayleigh distributed for the short-time temporal distribution.

![Figure 52: Pdf of the normalised VV clutter intensity in range bins 401-1000 (blue dots) of ki048. Pdfs of the K-distribution are also plotted: from outwards to inwards in the upper tail region are $\nu = 1$, $\nu = 5$, $\nu = 10$, $\nu = 30$ and $\nu = \infty$.](image)

A similar process for another VV dataset ki049a also confirms that the Rayleigh distribution fits best the data’s temporal distribution. The statistical $D$ and $Q$ measures of the dataset are given in Table 10, and the comparison of distributions is shown in Figure 53.

Table 10: Statistical measures $D$ and $Q$, averaged from using the measures of range bins 401-1000 of the VV polarised ki049a.

<table>
<thead>
<tr>
<th>Measure</th>
<th>$\nu = 1$</th>
<th>$\nu = 5$</th>
<th>$\nu = 10$</th>
<th>$\nu = 30$</th>
<th>$\nu = \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>0.1868</td>
<td>0.0689</td>
<td>0.0579</td>
<td>0.0540</td>
<td>0.0535</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>29.4573</td>
<td>3.5228</td>
<td>2.2901</td>
<td>1.9172</td>
<td>1.8816</td>
</tr>
<tr>
<td>$Q_{1-0.5}$</td>
<td>4.8368</td>
<td>1.0279</td>
<td>0.7518</td>
<td>0.6792</td>
<td>0.6921</td>
</tr>
<tr>
<td>$Q_{1-0.05}$</td>
<td>0.1259</td>
<td>0.0370</td>
<td>0.0256</td>
<td>0.0196</td>
<td>0.0175</td>
</tr>
</tbody>
</table>
The statistical measures D and Q for the HH sea clutter are given in Table 11. Unlike the VV data which has the least values for all D and Q measures if the Rayleigh model is used, the measure of $Q_0$ for the HH data has the least value with $\nu = 10$, indicating the K-distribution with $\nu = 10$ provide a globally better fit than others. The distribution of the normalised HH clutter intensity in range bins 401-1000 is shown in Figure 54, which confirms the above analysis using statistical D and Q measures.

Table 11: Statistical measures D and Q of the HH sea clutter, averaged from using the measures of range bins 401-1000.

<table>
<thead>
<tr>
<th>Measure</th>
<th>$\nu = 1$</th>
<th>$\nu = 5$</th>
<th>$\nu = 10$</th>
<th>$\nu = 20$</th>
<th>$\nu = 30$</th>
<th>$\nu = \infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>0.1706</td>
<td>0.0595</td>
<td>0.0521</td>
<td>0.0510</td>
<td>0.0512</td>
<td>0.0522</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>25.0615</td>
<td>2.9757</td>
<td>2.4658</td>
<td>2.5287</td>
<td>2.6007</td>
<td>2.8247</td>
</tr>
<tr>
<td>$Q_{1-0.5}$</td>
<td>3.9852</td>
<td>1.0101</td>
<td>0.9902</td>
<td>1.0777</td>
<td>1.1257</td>
<td>1.2544</td>
</tr>
<tr>
<td>$Q_{1-0.05}$</td>
<td>0.0862</td>
<td>0.0199</td>
<td>0.0139</td>
<td>0.0124</td>
<td>0.0122</td>
<td>0.0124</td>
</tr>
</tbody>
</table>
From the above analysis, we see that the temporal distribution of the VV sea clutter intensity (with a 30 m range resolution) is Rayleigh, a special case of the K-distribution with the shape parameter $\nu = \infty$. The temporal distribution of the HH sea clutter intensity (with a 15 m range resolution) can be fitted with the K-distribution with the shape parameter $\nu$ about 10. In fact if we estimate its shape parameter using the moment method (Blacknell 1994, 2001, Dong 2004), we can obtain $\nu = 11.35$ for this HH dataset. It is well known that the HH sea clutter is inherently spikier than the VV sea clutter. In this case, however, as the datasets have different range resolutions, collected in different times, different observing directions and wind directions, so the direct comparison between two polarisations are inappropriate.

9. Analysis of Target Signal

The characteristics of target signals are another important aspect for radar performance analysis. We study the distribution and correlation properties of target signals in this
section and classify targets accordingly into the well-known target models, such as Swerling models.

Radar targets are often complex objects which produce variety of reflections. The most widely used statistical target models are so-called Swerling models (Swerling, 1960, Ward et al, 2006). Later Swerling (1997) extended his models to the generalised Chi-squared or gamma distribution models which includes the Swerling models as its special cases. The pdf of the Chi-squared or gamma distribution is given as,

$$p(x) = \frac{c^\alpha}{\Gamma(\alpha)} x^{\alpha-1} \exp(-c x)$$  \hspace{1cm} (33)$$

where $c$ is a scale parameter and $c = \alpha / \bar{x}$.

The Rayleigh and Ricean distributions used in the Swerling models are, in fact, the two special cases of the gamma distribution with $\alpha = 1$ and $\alpha = 2$, respectively.

### 9.1 Characteristics of Strong Target Signals

We refer to a target signal with a high signal-to-clutter ratio (SCR) or signal-to-noise ratio (SNR) as a strong target signal and vice versa. Several datasets of the trial seem to have captured the signal of the deployed wave buoy reflector, when the observing azimuth was lined up with the reflector. Unfortunately, the target signal in some datasets was saturated if there was no attenuator in the receiver. One vertically polarised dataset containing unsaturated signals believed to be the echo of the wave buoy reflector are shown in Figure 55. It can be seen that the target signal seems to have abnormal sidelobes. We examined a few other datasets which used the same 10 MHz bandwidth of LFM, and all of them seem to have similar abnormal sidelobes for the target signal. The abnormal sidelobes are however not observed in the datasets which used a 5 MHz LFM bandwidth. Therefore we suspect that the digital down conversion process of the 10 MHz bandwidth LFM might have some problems.

---

3 Definitions of four Swerling models are: model 1 (for a slow-varying target signal) — constant from pulse to pulse but fluctuates from scan to scan with Rayleigh ($\alpha = 1$); model 2 (for a fast-varying target signal) — fluctuates with Rayleigh from pulse to pulse; models 3 and 4 are defined in the similar way as models 1 and 2 but the fluctuation follows Ricean ($\alpha = 2$) rather than Rayleigh.
The VV target (range bin 1241 of ki109) signal's intensity, phase and Doppler spectrum are shown in Figure 56. Both the intensity and phase vary slowly. Its SCR is estimated to be about 25dB, so it can be considered as a strong target.

Figure 56: Target signal received in range bin 1241 of ki109.data1 (VV polarisation). Plots from left to right are the signal's intensity, phase and Doppler spectrum, respectively.

The correlation coefficient of the target signal intensity is shown in Figure 57. The correlation time is 46 ms, much longer than that of the surrounding sea clutter.

Figure 57: Temporal correlation of the VV target signal ((Range bin 1241 of ki109). The correlation time is 46 ms, much longer than that of the surrounding sea clutter.
Figure 58 compares the Ecdf of the signal intensity and cdfs of gamma distribution with different $\alpha$ values. It seems that the Rayleigh distribution (i.e., gamma distribution with $\alpha = 1$) fits best the data distribution. The statistical measures D and Q are given in Table 12 which conform the visual analysis of Figure 58. It is understood that if more samples are used, i.e., the observing time is longer, those statistical measures D and Q would reduce significantly. The above analysis suggests that the target can be approximately considered as a Swerling 1 target, i.e., constant from pulse to pulse (or for a short observing period) and fluctuation following Rayleigh from scan to scan (or for a long observing period).

![Figure 58: Cdf comparison indicates that the Rayleigh distribution (gamma distribution with $\alpha = 1$) fits best the strong target intensity distribution in dataset of ki109, VV polarisation.](image)

Table 12: Statistical measures D and Q of the VV target signal in range bin 1241 with 2000 pulse samples.

<table>
<thead>
<tr>
<th>Measure</th>
<th>Gamma $\alpha = 0.5$</th>
<th>Gamma $\alpha = 1$</th>
<th>Gamma $\alpha = 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D$</td>
<td>0.2672</td>
<td>0.1035</td>
<td>0.1882</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>34.6502</td>
<td>6.4145</td>
<td>20.7825</td>
</tr>
<tr>
<td>$Q_{1-0.5}$</td>
<td>1.4289</td>
<td>3.8671</td>
<td>11.5273</td>
</tr>
<tr>
<td>$Q_{1-0.05}$</td>
<td>0.0496</td>
<td>0.0223</td>
<td>0.0682</td>
</tr>
</tbody>
</table>

Shown in Figure 59 is the signal of the same target but collected in another dataset, ki092, whose collection time was about 40 minutes prior to the collection of the dataset ki109. Its correlation and distribution fit are shown in Figure 60 and Figure 61, respectively. The correlation time is long. The minimum correlation coefficient of $-1$ for the correlation of signal intensity has been reached, demonstrating that the behaviour of the target signal can be quite different from sea clutter, and in some cases is highly negatively correlated. The distribution fit of the signal is shown in Figure 61, either $\alpha = 1$ or $\alpha = 2$ fits the data well but better than others such as $\alpha = 0.5$. As a result, the target may be regarded as either a Swerling 1 or a Swerling 3 target.
Figure 59: Target signal received in range bin 1241 of ki092.data1, VV polarisation. Plots from left to right are signal's intensity, phase and Doppler spectrum, respectively.

Figure 60: Temporal correlation of the VV target signal in range bin 1241 of ki092. The correlation coefficient in (b) reaches -1 indicating that the target signal intensity can be highly negatively correlated (the calculated minimum correlation coefficient is less than -1 due to not sufficient samples used in the numerical calculation).

Figure 61: No distribution fits well the VV target signal (range bin 1241 of ki092, VV polarisation, SCR about 25dB). However the gamma distribution with \( \alpha = 1 \) is the best overall.
Figure 62: Signal in range bin 1140 is believed to be the echo of the wave buoy reflector (data source: ki031, site B, HH polarisation, 5 MHz LFM).

The same target observed with the HH polarisation is shown in Figure 63. This dataset (ki031) was collected about 2 days prior to the collection of ki092 and ki109. The observation site (site B versus site D) and azimuth angle (5 degrees apart) were also different. The SCR is about 20 dB, a few dB lower than the former datasets, possibly due to the target and the main lobe of the radar not being lined up. Both the intensity and the phase of the target signal vary quickly. Its Doppler spectrum therefore is not a single frequency but spreads out about 100 Hz. The fluctuation of the signal (both intensity and phase) may be due to the effect of the environment including multipath scattering and shadowing of the sea surface and also possibly the movement of the atmosphere as well the movement (rolling, pitching and yawing) of the target. According to Long (2001), the effect of multipath and shadowing scattering of sea clutter on target signals is much severer for the HH polarised radar than for the VV polarised radar. Its cdf comparison as shown in Figure 64 indicates the Rayleigh distribution fits well the signal distribution. Its correlation behaviour as shown in Figure 65 is similar to that of its surrounding clutter with correlation time of about 8-10 ms. The above analysis concludes that the observed target can be considered as a Swerling 2 target, i.e., fluctuating from pulse to pulse with Rayleigh.

Figure 63: Target signal received in range bin 1140 of ki039.data1, HH polarisation. Plots from left to right are signal’s intensity, phase and Doppler spectrum, respectively.
Figure 64: Cdf comparison indicates that the gamma distribution with $\alpha = 1$ fits well the Ecdf of a strong HH target signal intensity (bin 1140 of ki031, SCR about 20dB).

Figure 65: Temporal correlation of the HH target signal in range bin 1140 of ki031. The correlation time is about 8-10 ms, comparable to the correlation time of the sea clutter.

9.2 Characteristics of Weak Target Signals

We refer to a low SCR or SNR signal as a weak signal. In dataset ki045 it seems that bin 2450 contains a signal of an unknown target, as the signal is statistically different from its surroundings where otherwise only the thermal noise dominates. The physical size of the target seems to occupy several range bins and its SNR is about 5dB as shown in Figure 66.
The signal’s intensity, phase and Doppler spectrum are shown in Figure 67. As the Doppler spectrum is quite different from that of the thermal noise, we can now be more sure that the echo is definitely from a radar target though we do not know what it was. The correlation time of the signal is short and only about 2 ms which however is possibly biased by the thermal noise as the SNR is low (The correlation time of thermal noise should be 0 second). The correlation of the signal is shown in Figure 68.

The distribution of the signal intensity is shown in Figure 69, indicating that this weak VV target signal intensity obeys the Rayleigh distribution. From the above analysis, we
conclude that the weak VV target signal with the background of thermal noise may be modelled as a Swerling 2 target, i.e., fluctuating from pulse to pulse with Rayleigh.

![Figure 69: Cdf comparison indicates that the gamma distribution with $\alpha = 1$ fits best the Ecdf of the weak VV target signal (SNR about 5dB) in ki045.](image)

10. Summaries

A four-day S-band sea clutter trial was conducted in November 2006 on Kangaroo Island, South Australia, using a DSTO developed S-band quad-polarisation radar. This report primarily concentrates on data processing, clutter and target signal analyses. We reiterate below the features and characteristics of sea clutter as well as target signals based on our studies.

The low grazing angle (smaller than 0.7°) range profile of sea clutter decays with respect to range faster than the radar equation indicates. The decaying rate of the received power versus range (corresponding to a grazing angle smaller than 0.35°) in far range is in an order of $1/R^7$ where $R$ is the range. This observation is consistent with a well-known phenomenon reported previously (e.g., Long, 2001).

The measured VV sea clutter coefficient is in agreement with the values given by Nathanson et al (chapter 7, 1999) whereas the measured HH sea clutter coefficient in near range is about 5-10 dB below the reported.

Temporal correlation studies show that for the VV sea clutter, the correlation is independent of range bins. The mean correlation time is 14.5 ms or 9.2 ms depending on whether the complex-value or the intensity of clutter is used in calculation.

The temporal correlation time of the HH sea clutter seems to be correlated to clutter returns. Higher returns from sea spikes are more likely to have longer correlation times,
indicating that the HH spikes are more persistent than the VV spikes\(^4\). Although the mean correlation time of the HH sea clutter is similar to that of the VV sea clutter, and has a value of 16 ms for the complex-value or 10 ms for the intensity, the correlation time of returns from persistent sea spikes can be as long as 20-60 ms.

Short-term spatial correlations (lagged only a few range bins) of both the HH and VV sea clutter are similar. The radar’s bandwidth used in the trial was 5 MHz or 10 MHz, giving a 15 m or 30 m range resolution. The actual range sample interval, for both the 5 MHz and 10 MHz cases, was 12 m which is an over-sampling rate, so the immediate range bins are not iid samples. To remove the effect of over-sampling, we have calculated spatial correlation using range samples with an interval of 2 range bins for datasets with the 15 m resolution and an interval of 3 range bins for datasets with the 30 m resolution. We have found in such cases that all range samples become approximately uncorrelated (the correlation coefficient drops below \(1/e\)). In another words, we have found that the spatial correlation lengths are shorter than 24 m and 36 m for datasets with 15 m and 30 m resolutions, respectively. A radar with higher resolution is needed in order to measure the exact spatial correlation length. We are not aware of any publications about spatial correlation of sea clutter at S-band. The long-term spatial correlation (lagged many range bins), not studied in this report, usually contains information of sea wave and swell structures (Dong, 2007).

The Doppler spectrum of sea clutter has also been studied. Both the HH and VV sea clutter have a span of approximately 200 Hz in the Doppler spectrum at S-band. The spectrum of the low VV clutter returns (non VV spike bins) is narrower, indicating that the surface of the continuous waves and swells moves slower. On the other hand, the spectrum of the higher returns (the VV spikes) is broader, demonstrating breaking waves and whitecaps move differently.

The observed spectrum of the HH sea clutter contains twin peaks residing on the positive and negative sides, respectively, showing that the horizontally polarised radar captured the movement of both receding and approaching scatterers. The spectrum of high returns generated by the HH sea spikes often has one peak higher than the other. On the other hand, the two peaks in the spectrum of the non-spike returns are about the same. Flying birds can also generate significant Doppler components irrespective of polarisations.

The Rayleigh distribution, i.e., the K-distribution with the shape parameter of infinity fit well with the temporal distribution of the VV sea clutter (30 m resolution, 12 m sampling interval). On the other hand, the K-distribution with the shape parameter approximately in the range of 10 to 20 fits well with the temporal distribution of the HH sea clutter (15 m resolution, 12 m sampling interval).

\(^4\)According to our previous studies (Dong, 2007), correlation between the HH and VV sea clutter is low. A sea spike which generates a high return for one polarisation usually does not do so for the other polarisation. Hence we use VV (HH) spikes to indicate the spikes which generate high VV (HH) returns.
Finally we have also studied the characteristics of target signals. In the case of the VV polarisation and for a strong stationary target (an anchored wave buoy reflector) signal whose SCR is greater than 20dB, we have found that both the signal’s amplitude and phase vary very slowly. As a result, its Doppler component concentrates on the zero hertz, and its correlation time is 46 ms, much longer than that of its background, the VV sea clutter. According to its amplitude distribution, the target can be approximately classified as a Swerling 1 target, i.e., constant from pulse to pulse (or for a short observing period) and fluctuation following Rayleigh from scan to scan (or for a long observing period).

The observation of the same target using the HH polarisation is different. Both of the signal’s amplitude and phase vary rapidly possibly due to the fact that the horizontal wave is more sensitive to effects of multipath scattering and shadowing of the sea surface as well as the movement of atmosphere and the movement of the target (rolling, pitching and yawing). The correlation time is about 10 ms, similar to that of its background, the HH sea clutter. Its energy spans about 100 Hz in its Doppler spectrum. It has been found that the observed target can be classified as a Swerling 2 target, i.e., fluctuating from pulse to pulse with Rayleigh.

A weak and unknown target signal with the background of thermal noise has also been studied. Its SNR is about 5dB. Both its amplitude and phase vary very rapidly and its correlation time is as low as 2 ms, and its energy spans about 100 Hz in its Doppler spectrum. The target may be classified as a Swerling 2 target, i.e., fluctuating from pulse to pulse with Rayleigh.

11. Future Work

We recommend the intermediate future work on this project including:

- To identify and fix the jittering problem of the transmitter to obtain identical and stable pulse trains.

- To investigate and fix the abnormal sidelobe problem which occurred when different bandwidths of LFM rather than 5 MHz was used.

- To evaluate the STC function and enable it during the future data collection to increase and maximise the dynamic range of the radar. The proper use of the STC function enables the A/D device not to be saturated in the near range without sacrifice of the SCR and SNR in far range.

- To consider the possibility of increasing transmit power by increasing the radar’s peak power and/or the length of the pulse and/or the bandwidth of LFM to extend the radar’s maximum range in measuring sea clutter. With the current power level, pulse width and the bandwidth, the clutter profile reaches the noise level long before the range reaches the horizon.
• To consider the possibility of increasing the bandwidth of LFM to allow higher resolution data to be collected.

• In the future trial, to switch between different polarisations as soon as possible while maintaining other parameters unchanged, so that differently polarised sea clutter can be collected under the same environmental conditions to allow more useful comparisons to be made.

• To further explore the relationship between sea surface and environmental conditions and Doppler spectra observed by radar.

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13. References


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19. ABSTRACT

   An S-band sea clutter trial was conducted in December 2006 on Kangaroo Island of South Australia using a quad-polarised S-band radar developed by DSTO. This report concentrates on radar data processing and analysis. Statistics of sea clutter, including range profiles, sea clutter coefficients, temporal and spatial correlations, temporal and spatial distributions, and as well as Doppler spectra for both the HH and VV sea clutter are measured. Strong and weak target signals are also analysed and classified into Swerling models accordingly. Differences observed by the HH and VV polarisations are explained.