Measured forward-scatter sea clutter at near-zero grazing angle: analysis of spectral and statistical properties

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Abstract: To develop forward-scatter radar (FSR) systems for use in maritime applications, a fundamental understanding of the operating environment is required. Currently, there is a lack of published experimental FSR sea clutter data at very low (near-zero) grazing angle over the sea. This data is necessary for the development of FSR systems for maritime applications. Therefore to facilitate further investigation, clutter data for such a system has been recorded at frequencies of 7.5 and 24 GHz with static, medium gain antennas for low sea states 1–3 on the Douglas scale. Analysis of forward scatter propagation phenomena is presented, and spectral and statistical analysis of forward-scatter clutter is performed.

1 Introduction

The forward-scatter (FS) mode of bistatic radar operation offers significant benefits in target radar cross section (RCS) enhancement over backscatter radar, and provides a relatively simple, reliable and low cost solution for perimeter protection [1, 2]. An important additional benefit is the ability to measure very low Doppler frequencies (~1 Hz) by utilising the self-mixing properties of the FS approach [3], which involves the mixing of the direct path signal and those scattered from targets through the use of non-linear or parametric circuits. Thus, in the maritime environment, the FS approach allows detection of low speed, low mono/bistatic RCS (‘difficult’) seaborne targets in the presence of significant sea clutter.

Forward-scatter radar (FSR) has been used in fence applications since the early 1900s [4], but advances in modern digital signal processing techniques now allow for significant improvement in capability and performance, including the ability to measure target baseline crossing velocity, crossing angle and crossing range as well as automatic target detection and classification [2, 5–8].

In this paper, we present the results of clutter studies for a FSR. Fundamentally, this type of radar does not have range/angular resolution [3, 5], so clutter is picked up from the large surface area illuminated by Tx/Rx antennas, such that any practical system is clutter-limited rather than noise-limited [9] and therefore the characteristics of sea clutter in the forward scattering direction at near-zero grazing angle must be understood.

Forward scattering of microwaves above the sea surface at low grazing angles requires special attention due to the specific scattering conditions. In general, three main scattering mechanisms can be distinguished:

- Dominant coherent scattering: For a relatively calm sea, the reflections from the smooth surface are assumed to be specular and typically represent coherent scattering; the presence of ripples on the surface will partly reduce the amount of signal energy reflected in the forward direction due to diffuse scattering. For low-grazing angles we can expect that coherent scattering, representing large-scale signal trends, will be dominant even at higher sea states, as shadowing will reduce the amount of diffuse scattering reaching the receiver, while specular reflections from illuminated tops of waves (which are predominantly the only parts visible by both Tx and Rx) contribute into the received power at Rx. Breaking waves and whitecaps, which are normally present above sea state 3 may however change the situation, but such scenarios are beyond the scope of this paper and are subject for further research.

- Dominant diffuse scattering: For high sea states with line-of-sight still present, dominant coherent scattering may give way to diffuse scattering. This is mainly true for large grazing angles, as stressed in [10, 11]. For high wind speeds, the rough sea surface profile causes a reduction in the specular reflection, so the coherent power vanishes for large grazing angles. Whereas for low-grazing angles, there is little or no reduction in the Fresnel reflection coefficient [11].

- Shadowing with intermittent loss of signal: For very high sea states, the shadowing of direct and reflected forward
waves may result in intermittent loss of signal, of which the duration may also be reduced by diffractive effects.

With regards to the detection of the aforementioned ‘difficult’ seaborne targets, the scenario actually only exists for the first two situations in which the condition of the sea will still allow small target vessels to be safely at sea. Small low-altitude airborne targets, such as UAV, may represent a threat even in very high sea states. Results of current research are however restricted to relatively low sea states and the detection of low profile seaborne targets such as small inflatable boats and jet-skis with low mono/bistatic RCS. A more quantitative analysis of these targets of interest can be found in [3].

Analytical approaches and computer simulation of the time-spatial scattering processes have been widely used for estimation of radio propagation characteristics [10–18]. However, there is rather limited amount of research on experimental observation of radar scattering at low grazing angles [13, 19–23]. During the mid-1950s, several propagation experiments were conducted across the Golden Gate in San Francisco [13, 19, 20] where sea wave spectral analysis and radio spectra in X-band were estimated for different grazing angles starting as small as 0.6°.

In the experimental study in [21], the propagation characteristics of X-band continuous wave (CW) over a surface of artificially generated gravity waves in an indoor wave tank were thoroughly investigated. In this study, the waves were scaled to be 1/10th of the actual significant wave height for a given sea state and due to the generation method (no wind effects), no capillary waves were generated on the surface. Gradual increase of the sea state led to a smearing out of the typical two-ray path interference pattern, clearly indicating the transition from dominant coherent to rather diffuse reflection even in the absence of capillary waves. At sea state 0, a clear coherent reflection for the glassy sea surface was observed; at sea state 3 with larger than 5° grazing angle, the time averaged power/mean interference pattern demonstrates typical constructive–destructive behaviour with frequency and, finally, sea state 5 produced entirely diffuse scattering at the same grazing angle. A shift in the mean interference pattern for higher sea states was also observed, with the most pronounced shifts at smallest grazing angles due to the height of the illuminated water surface responsible for specular reflections being higher than the mean water surface level.

A majority of papers on forward scattering have been published in the context of shipboard and coastal communications to estimate the received power reduction due to the presence of the rough dynamic surface. Therefore the main focus was on average characteristics, such as the average power scattered per unit area of sea surface, or average specular reflection coefficient [11, 16, 23–26]. In the two fundamental models of Ament [24] and Miller–Brown–Vegh (MBV) [26], the procedure of coherent equivalent reflection coefficient estimation was suggested based on an ensemble average over the illuminated height of the waves obeying some specific statistics. Later discussion of Ament and MBV models [16, 23] analysed the suitability of the suggested statistics and estimates to describe coherent equivalent propagation.

Direct numerical simulations of near-zero grazing angle FS have been performed in [10] where in addition to coherent and incoherent power estimations at various angles, the spectral and statistical properties of clutter were discussed. Although this study has been performed for shipboard communication systems at a different frequency band (1 GHz) compared to our own experimental studies, they suggested quite useful qualitative and quantitative explanations of expected phenomena, which agree with our observations, and are discussed in the following sections.

In contrast to the main goal in the modelling of communications systems, which aims to give accurate estimation of average received power, we focus on the statistical and spectral properties of the measured sea clutter. FS sea clutter is a time-varying modulation of the average coherent power due to the presence of incoherent diffuse reflections and shadowing, where interference of the direct signal and multipath arriving from all areas of the illuminated surface footprint produce random deviations from the coherent received power. Clutter may mask the signal scattered by a target no matter how greatly the target cross section is enhanced by the FS effect [5] and therefore the ability to eliminate clutter in either time or frequency domain largely governs radar target detection performance. Thus, an intensive measurement campaign has been conducted in diverse sea conditions, over a range of frequencies and parameters of the FSR system. The results discussed here are obtained at frequencies 7.5/24 GHz with grazing angles between 0.05° and 0.7° at different test sites and sea states 1–3 (hereinafter referred to as SS 1–3). Comparison with published results at 1, 9.3 and 37.5 GHz will also be shown.

The reminder of the paper is structured as follows: First, FS scattering mechanisms in the maritime environment will be described. Then, coherent and incoherent power estimations for a few experimental scenarios will be presented. Next, the clutter measurement set-up will be briefly described, then clutter spectral and statistical properties under different conditions will be compared and discussed and their effect on radar performance will be demonstrated followed by the conclusion.

**Fig. 1** Geometry of ray paths over the sea surface

Figures illustrate the direct path signal and a specular reflection where scattering occurs from an area of the smooth surface forming one main reflected wave front. b Diffuse scattering where reflections occur from many individual scatterers in all directions. Both for the case of a relatively rough sea, which is not mirror like, but where line of sight is always maintained between antennas.
2 Scattering mechanisms in FSR

In FSR, clutter is received from a large area of the sea surface illuminated by the Rx and Tx antennas, which face each other. Spatially distributed dynamic sea waves may be generally considered as obstacles forming backscatter, bistatic and FS signal interference with the direct signal. Indeed, it has been confirmed experimentally that the average values and amplitude fluctuation characteristics of signals scattered over a sea surface path at centimetre and millimetre wavelengths can be satisfactorily described by the model of the interference of direct and scattered beams [10, 11, 17, 18, 27, 28] as illustrated in Fig. 1. Such a model describes the electromagnetic field at the reception point as the superposition of the coherent component (the sum of the direct beam and the specular reflected beam) and the incoherent component that corresponds to the diffuse scattered field.

A propagation gain [10] can be used for analysis of the received signal

$$F = \frac{E_{\text{dir}} + E_{\text{scat}}}{E_{\text{dir}}}$$

where $E_{\text{dir}}$ is the line-of-sight direct wave; $E_{\text{scat}} = E_{\text{spec}} + \sum E_n$, where $E_{\text{spec}}$ corresponds to the specular reflected wave and represents the coherent contribution to the total field, the sum represents the diffuse scattered field from a vast number of independent individual scatterers.

For our convenience and to adopt communications terminology, we will completely redefine (1) in terms of coherent and incoherent fields

$$F = \frac{E_{\text{coherent}} + E_{\text{incoherent}}}{E_{\text{coherent}}}$$

where

$$E_{\text{coherent}} = E_{\text{dir}} + E_{\text{spec}}$$

$$E_{\text{incoherent}} = \sum E_n$$

According to [11], the magnitude of the coherent field is

$$|E_{\text{coherent}}| = |E_{\text{dir}}| \left[1 - |R|^2 + 4|R|^2 \cos^2(\Phi/2)\right]^{1/2}$$

where $R$ is the complex Fresnel coefficient and $\Phi = kd + \phi$ is the phase shift of the reflected wave due to path difference $d$ and the phase of the reflection coefficient $\phi$; $k$ is the wavenumber.

In general, coherent and incoherent power can be expressed in the form [10]

$$P_{\text{coherent}} = \langle |E|^2 \rangle$$

$$P_{\text{incoherent}} = \langle |E - \langle E \rangle|^2 \rangle$$

where the $\langle \cdot \rangle$ operator denotes the ensemble average (or mean value) and therefore, $P_{\text{coherent}}$ represents the mean value of the received signal, while $P_{\text{incoherent}}$ is the mean signal variance.

For a rough sea, when the coherence between the direct and reflected field is reduced, the reduction factor $\rho$ for the average reflection coefficient is introduced and the effective reflection coefficient is

$$R_{\text{eff}} = \rho R$$

Different approximations for the roughness reduction factor $\rho$ according to Ament [24] and MBV [26] were obtained

$$\rho_{\text{Ament}} = e^{-1/2(2kh_{\text{rms}} \sin \alpha)^2}$$

$$\rho_{\text{MBV}} = \rho_{\text{Ament}} I_0\left(-\frac{1}{2}(2kh_{\text{rms}} \sin \alpha)^2\right)$$

where $h_{\text{rms}}$ and $\alpha$ are the rms deviation of surface height and grazing angle, respectively, $I_0$ is a modified Bessel function of the first kind of zero order. Grazing angle is defined by geometry and the mean surface level. It is important to stress here that whatever the deviation of the surface $h_{\text{rms}}$ is, if grazing angles tend to zero both reduction factors tend to 1, and there is no reduction due to the roughness of the sea. Indeed, the reflection in the forward direction will take place from the tops of the waves (bottoms and slopes of the wave troughs are not ‘visible’ from Tx/Rx), defining coherence of the reflected waves for the ensemble average sea surface. Moreover as pointed out in [11], reflection from the wave tops decreases the reflected wave path length relative to that from points at mean sea level and, therefore, the interference pattern of the received power from the coherent component is shifted down. This conclusion was confirmed by both measurements [21] and simulations [10, 11, 16].

2.1 Coherent and incoherent power at low grazing angles

The coherent power depends mainly on the large-scale geometry of the FS radar link, while incoherent reflects randomness of the deviations from the coherent component due to time-varying deviation of the surface from its mean level. In this paper we focus on the discussion of clutter, or in other terms – time variation of power from its mean level as defined by the coherent power, so rather illustrative examples of coherent and incoherent power observations will be presented here.

Radar links at 7.5 and 24 GHz have been set at five baselines: 300, 820, 975, 1600 and 2300 m. Sea state conditions, roughly estimated as sea state 1–2 on Douglas scale, were slightly changing within the experimentation period on 30th April 2013 in the Portland area, UK. The purpose of the experiment was to test the sensitivity of the radar on its ability to track tidal changes of sea level. First, we have used the log-distance model to calculate of the expected received average power level and has proved to be quite accurate for our large database of measurements, such that

$$P_{\text{coherent}} = P_t G_t G_r \frac{h_t^2 h_r^2}{d^4}$$

where $P_t$ is the transmitted power, $G_t/G_r$ are gains of transmit and receive antennas, respectively, $h_t/h_r$ are heights of transmit/receive antennas and $d$ is the baseline distance. According to this model, we can then analyse the effect of geometry change on the received power.
Fig. 2  Dependence of the average power on propagation distance

a at 7.5 GHz  
b at 24 GHz. Lines show the log-distance model for different values of $n$ (3, 4 and 5), where $n$ is the power of distance. Markers indicate experimental measurement results.

Fig. 3  Dependence of the received power on the change of the sea surface height due to tide

a Illustration of tidal change of sea surface height in Portland on 30th April 2013 [29]  
b Time variation of received power corresponding to period 1 in (a), at 7.5 and 24 GHz  
c Time variation of received power corresponding to period 2 in (a), at 7.5 and 24 GHz.
Fig. 3 illustrates the change of average signal level, due to the tide falling (b) and rising (c). Records 1 and 2 in (a) – about 30 min each – were made at baselines of 820 m (b) and 975 m (c) (about 3 dB difference in path loss), where the time-average sea-level was the same. The change of received power (in dB) for the same initial heights of Tx/Rx antennas $h_A$ can be calculated by

$$\delta P_r(dB) = P_{\text{stop}}^r - P_{\text{start}}^r = 40 \log \left(1 + \frac{\delta}{h_A}\right)$$  \hspace{1cm} (8)

where $\delta$ is a shift of the sea height in the period between the start and end of signal recording. $\delta > 0$ corresponds to the tide falling and $\delta < 0$ if tide is rising. Superscripts 'start' and 'stop' relate to the start and stop times of the signal records.

The initial height of antennas for both records 1 and 2 were kept the same at about 1 m. During the first record the approximate sea level change was +7 cm, while for the second record it was −10 cm. Measured and calculated coherent power level differences presented in Table 1 demonstrate an overall reasonable agreement which emphasises an independence of frequency, inherent for two-ray propagation model.

Some discrepancy can be explained by the inaccuracy of antenna height estimation above the mean sea surface level and sea level change itself [29]. In addition to the monotonic change in the mean level of received power, we also observe larger scale temporal fluctuations, which replicate the wind strength fluctuations over the period of the records. As was mentioned in the introduction, the increase of sea roughness at low grazing angles changes the path of specular reflected waves as the height of the reflective sea footprint increases and antennas appear to be lower with regards to this level.

Figs. 4a and 4b show coherent and incoherent powers as functions of the baseline distance, measured at 7.5 GHz. Sea conditions were similar for all records used, corresponding to sea state 2 on the Douglas scale. If coherent power (Fig. 4a) falls off with distance to the fourth power, incoherent power (Fig. 4b) decreases with faster rate of approximately sixth power of distance, so that

$$P_{\text{coherent}} = O(1/d^4)$$

Thus, we can expect that incoherent-to-coherent power will decrease 20 dB per decade with distance. This effect is yet to be explained and further measurements are planned to confirm this conclusion.

### 3 FS clutter

Time variation of the scattering geometry (sea surface) modulates the propagating signal. The power spectrum of the received signal indicates such a modulation, where the frequency of a coherent component change is very much smaller than that of an incoherent component change. Thus, the output of the Doppler receiver used in our measurements represents a modulation of the propagation gain (2) due to the presence of incoherent power on the top of the DC level corresponding to coherent component, then the time varying propagation gain

$$F(t) = DC + \text{Re}(A(t)e^{i\phi(t)})$$ \hspace{1cm} (9)

where $A(t)$ and $\phi(t)$ are the time varying amplitude and phase of the modulated signal.

This formulation of problem allows subtraction of the DC component and, therefore, the analysis of only incoherent component of the propagation gain, which hereinafter will be referred to as the FS clutter.

Time-variation of the sea surface defines the spectral and statistical properties of the clutter. In modelling and simulation approaches, the illuminated surface elevation profiles were described as variates with known statistics, where the majority of ocean profile statistics in forward propagation are assumed to be Gaussian [10, 16, 24] and,

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Power change due to tide</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Power change $\delta P_r$, dB</td>
</tr>
<tr>
<td></td>
<td>7.5 GHz</td>
</tr>
<tr>
<td></td>
<td>Calculated</td>
</tr>
<tr>
<td>record 1</td>
<td>1.2</td>
</tr>
<tr>
<td>record 2</td>
<td>−1.8</td>
</tr>
</tbody>
</table>

Fig. 4 Coherent and incoherent received powers against range, measured at 7.5 GHz

a Coherent
b Incoherent
in particular, in [10] it was shown that both \( I \) and \( Q \) channels are independent Gaussian distributed variates, so the propagation channel is Gaussian. This agrees well with our conclusions which will be discussed in Section 5.2.

The presence of the diffuse field due to the large number of randomly distributed, incoherently contributing surface/volume sources within the illuminated area defines the clutter distribution. If the propagation channel is Gaussian, then the presence of the coherent component would result in signal magnitudes (or intensities) being Rician distributed. However, removing the DC level in (9) we would expect to have a Rayleigh distribution of the clutter magnitude for the Gaussian channel.

Intensity of clutter depends on the wind speed. Sea surface motion activated by the wind requires some time to reach to a steady state and become what is termed a ‘developed’ sea state. Although such conditions are not necessarily attainable and indeed sea state itself may change, over the short time scales we are considering for target observation (max. 10s of seconds), we can consider clutter as a stationary process and therefore again converging towards being Gaussian distributed.

### 4 Measurement program

A program of measurement has been undertaken at sea to establish a comprehensive database of sea clutter measurements at almost zero grazing angles, to understand the mechanism of clutter generation and to validate on-going modelling and simulation work. The topology of the radar assumes relatively short baselines and, therefore, atmospheric effects and ducting are assumed negligible over the radar operational area. Laboratory measurements have been made to establish the sensitivity of Doppler FSR and, therefore, its ability to measure low frequency clutter. To perform the measurements in real sea conditions, an FSR system has been deployed at different sites providing a wide set of environmental conditions ranging from an almost perfect mirror surface (Lake Coniston) to rough, long range, deep water sea states (Bulgaria) – Table 2. For a more detailed description of the test site topologies, see [5].

CW-FS measurements were accompanied by simultaneous weather and sea condition recordings, including wind speed and direction. Video records and GPS positioning provided data truth. Received clutter signals are recorded at the output of the received signal strength indicator (RSSI) channel, which represents a composition of the dc component due to coherent propagation and the Doppler shifted scattered components, and more information about the receiver output can be found in [3, 5]. The system hardware includes stationary directional antennas with both vertical and horizontal polarisation and differing azimuth beam widths (6°, 20° and 60°) operating at 7.5 and 24 GHz. Results shown relate to VV polarisation, although our observation over hundreds of records showed no significant difference in clutter characteristics, which could be attributed to polarisation or illuminated footprint due to difference in antenna beam widths.

The calibration procedures included two major steps: First, the calibration of the non-linear detector used inside the

<table>
<thead>
<tr>
<th>Site</th>
<th>Experiment location</th>
<th>Water</th>
<th>Depth, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Portsmouth area, UK</td>
<td>Littoral water, across Langstone harbour</td>
<td>10–15</td>
</tr>
<tr>
<td>B</td>
<td>Portsmouth, Hampshire, UK</td>
<td>Littoral water, off coast</td>
<td>10–15</td>
</tr>
<tr>
<td>C</td>
<td>Sozopol, Bulgaria</td>
<td>Deep water</td>
<td>25–35</td>
</tr>
<tr>
<td>D</td>
<td>Coniston Water, Cumbria, UK</td>
<td>Fresh water</td>
<td>10–20</td>
</tr>
<tr>
<td>E</td>
<td>Weymouth, Portland, UK</td>
<td>Littoral water</td>
<td>10–15</td>
</tr>
</tbody>
</table>

This experiment was performed in collaboration with Prof. Hristo Kabakchiev’s group from Sofia University, St. Kliment Ohridski, Bulgaria.

Fig. 5 **PSDs of FSR sea clutter**

\( a \) Normalised PSDs of FSR sea clutter measurements from Langstone Harbour, Bulgaria and Lake Coniston
\( b \) PSDs of FSR sea clutter data recorded from SS 1 to SS 3
\( c \) Normalised PSDs of FSR sea clutter recorded at varying frequencies, ranges, sea states and test sites

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receiver and secondly, the calibration of the signal at the output of RSSI receiver by a reference target. Calibration of the received signal has been performed by comparison of the result of EM modelling of the FS response from a sphere above the sea surface with the actual measurement of this sphere. The FSCS of the sphere has been simulated in CST and also estimated by analytical modelling as well. The agreement between results for the sphere allow us to calibrate the signal from target/clutter. This procedure is outlined in [8].

5 Clutter analysis

Owing to the specifics of FSR, there is fundamentally no range/angular resolution and clutter is picked up from the whole area defined by the antenna beam footprints on the surface. Measurements in the Portsmouth area (sites A, B in Table 2) were made at baseline ranges from 300 m up to 2 km at SS 1–3. At Lake Coniston (site D) the range varied from 500 m to 1300 m with a relatively calm state, similar to a SS of 1–2. Deep sea measurements were made on the Black Sea with 1 km baseline between Sozopol and St Ivan Island (site C) and up to 700 m baselines in the open sea – sea states varied from 1 to 4. In all results presented, long clutter records have been used, the length of each acquisition is not less than 20.

5.1 Clutter spectrum

Fig. 5a shows a sample of representative clutter spectra from three measurement sites overlaid and normalised for comparison. The data was recorded at 7.5 GHz with vertical polarisation at Langstone Harbour (SS 2), Lake Coniston (SS 1) and Bulgaria (SS 1). The power spectral density (PSD) of the clutter signals and analysis of all recorded data clearly demonstrate that PSD slopes correspond to approximately 35–40 dB per decade and, therefore, to the maximum inverse fourth power of the Doppler frequency. This result is in good agreement with [10], where the fitted power spectrum model that decays as $O(1/f^4)$ was suggested.

The spectrum as defined by a 10 dB power drop is limited to a maximum width of 0.5–0.8 Hz and is practically invariant of the sea state. Clutter power however increases by about 30 dB for SS 3 as shown in Fig. 5b.

It was also found that clutter spectrum is independent of the transmit/receive baseline distance and radar frequencies within 1–3 GHz. Fig. 5c shows the spectra from seven completely separate measurements at differing frequencies, ranges and sea states. Clutter was recorded at 7.5 GHz at SS 1 with baseline range 600 m and 2.3 km, 9.3 GHz at SS 3 with range 14.5 km [17, 18], 24 GHz at SS 1–2 with baseline range 600 m and 2.3 km and at 37.5 GHz at SS 3 with baseline range 14.5 km [17, 18]. The PSD of a 1 GHz signal numerically simulated for shipboard communication system with baseline 2.45 km is also reconstructed as in [10] for comparison. The results have been normalised to stress that FS clutter spectrum is reasonably invariant of range, operating frequency and sea state. It also shows good agreement between the numerical calculations and actual maritime measurements.

This conclusion has an immediate practical application. If the clutter spectrum is invariant to radar parameters and sea
conditions, while the target signature spectrum depends on radar and motion (speed, trajectory) parameters and is significantly wider; it is clear that an essential part of the clutter can be removed by use of a whitening filter, or even, in the simplest case, by a high pass filter with a cut-off frequency corresponding to the clutter spectrum width. To illustrate this, Fig. 6a shows the recorded time domain Doppler signal of a small inflatable boat target in sea clutter. The target signature is selected and PSDs are formed by both this and the remaining clutter, Fig. 6b. The signal from Fig. 6a is then passed through a 1 Hz HPF and the resultant clutter filtered signal is shown in Fig. 6c – the target signal to clutter ratio improvement is apparent.

### 5.2 Clutter statistical properties

The clutter amplitude distribution is the most determinative characteristic to enable theoretical estimation of radar detection performance in terms of false alarm rate and probability of detection. Figs. 7a and b show the probability density functions (PDFs) and the cumulative distribution functions (CDFs) of clutter data in Fig. 5a. The Rayleigh fit has been used as a reference in both plots. We found it useful to present the CDF on Weibull paper [30] (on which the Rayleigh fit is a straight line) where y-axis shows log(ln(1/1 – CDF(a))) whereas the x-axis corresponds to log(a), where a is the intensity of the signal.

The data has been normalised by taking the ratio of the signal power (after subtraction of the DC level) to the standard deviation of the clutter signal power, to demonstrate the similarity between clutters in terms of the distribution of their amplitude probabilities.

Figs. 8a and b show the comparison of the PDFs and CDFs for different sea states with their corresponding analytic Rayleigh fits and Figs. 8c and d show the PDFs and CDFs of normalised clutter measured at both 7.5 and 24 GHz with Rayleigh analytic fit.

It follows from the analysis of the results shown in Figs. 7 and 8 that the clutter distribution in FSR is close to Rayleigh for the considered sea states and frequency ranges, especially for the main body of the clutter distribution. It is worth to stress here that this conclusion may only be true for relatively low sea states. Significantly rougher seas may demonstrate different effects on propagation at low grazing angles, however such a study is still to be performed.

These conclusions about the spectrum and distribution of the clutter are different from traditional high/medium resolution backscatter radar observations, where the K-distribution or similar [28, 30] are more appropriate models to describe sea clutter with varying spectra. This difference can be explained by the physical nature of the clutter obtained at near zero grazing angle illumination in FSR. In our case, the transmitted signal is scattered from a large number of independent waves over the long propagation path, which provides clutter contribution randomisation, while the oscillating nature of the wave on the sea surface corresponds to the previously developed model of clutter as a composition of independent oscillators with one (largest wave) dominating the spectrum [9]. Thus, we conclude that, at least at the initial stage of maritime FSR performance analysis, the assumption of the normal distribution of the sea clutter and constancy of the clutter spectrum can be used.

To note, practically all records consist of infrequent Doppler signatures from small targets of opportunity (e.g. seagulls), some high amplitude targets were removed (cut), however inevitably not all could be removed. This will contribute to some deviations/discrepancies from analytical fits.

### 6 Conclusions

In FSR, the system is inherently clutter-limited and the analysis of spectrum and statistics of the FS sea clutter is of crucial importance for maximisation of target signal-to-clutter ratio. This paper has focused on the analysis of the experimentally measured sea clutter over a range of microwave frequencies, at different sea states and different locations.

Experimental results for the time–frequency structure of microwaves scattered by a sea surface are presented for near-zero grazing angles. Coherent and incoherent power trends have been discussed and quantitative estimations of received power with changing scattering geometry were presented.

FSR sea clutter measured at very low grazing angles (less than 0.5°) exhibits, to a first approximation, a near constant frequency centred below 1 Hz, with a roll off of approximately 25–40 dB per decade in the frequency
conditions. In practical applications, significant target signal to clutter level improvement is possible by the simple application of a whitening filter with a cut off frequency defined by the clutter spectrum. Additional sea trials are planned to provide long-term measurements to extend the clutter database over a wide variation of sea states and diverse conditions.

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8 References


25 Brown, R.M., Miller, A.R.: Geometric-optics theory for coherent scattering of microwaves from the ocean surface, 1974


29 http://www.tides4fishing.com/uk/england/weymouth