

Littoral Sea Clutter Returns at 94GHz

A. G. Stove

DMS

Thales UK

Crawley, England

andy.stove @ uk.thalesgroup.com

D. A. Robertson

D. G. Macfarlane

School of Physics and Astronomy

University of St Andrews

St Andrews, Scotland

{dar, dgm5}@st-and.ac.uk

Abstract—This paper reports and discusses measurements made of the returns from sea clutter in the littoral at 94GHz using the SAFIRE demonstration radar. These measurements add significantly to the limited data which is available on sea clutter at 94GHz as well as showing how a radar developed to assist the public understanding of technology can also be used for research purposes.

Littoral clutter measurements are proportionately more important at 94GHz than at lower frequencies because the short range of radars at these frequencies means that they are much more likely to be operating in this environment than in the open sea.

The measurements show peak backscatter levels of about -22dB (sea state 3, 2° grazing angle), but this is concentrated around the breaking wave crests, and the mean value is close to the -30dB reported by other workers. At the high range resolutions used, the resultant distributions appear very long-tailed.

The data also shows a useful insight into the behaviour of sea clutter when viewed with circular polarisation, for which the peak values are similar to those observed with linear polarisations, but the mean values are much lower.

Keywords—sea clutter, millimetre-wave, circular polarisation

I. INTRODUCTION

There are numerous potential maritime applications for radars operating in the frequency bands around 76 to 94GHz. Radars at these frequencies are very compact by comparison with most radars and can also be very low-cost. Such radars retain the ability of lower-frequency radars to see through fog and water spray much better than optical/infrared sensors [1], although their long-range performance may be limited to a kilometre or less in poor weather by rain attenuation.

These relatively short operating ranges mean that the maritime applications of such radars will be mostly in the littoral, rather than in the open sea.

As with any maritime¹ radar application, the performance may be affected by the level of the returns from the sea itself. This

makes measurement of the sea returns in the littoral an² important step towards being able to design maritime systems using radars at these frequencies.

This paper therefore describes measurements which have been made on the low grazing angle radar return at 94GHz from the sea in the littoral. Most of the data was recorded with linear polarisation (both vertical and horizontal) and is able to add to the limited body of knowledge which was previously available on sea clutter returns at these frequencies. Some measurements have also been made using circular polarisation which provide a further insight into the mechanisms leading to the observed backscatter.

II. REVIEW OF EXISTING DATA

Nathanson's classic source of data on the backscatter from sea clutter [2] does not provide data above Ka-band. Long [3, section 6.3.5] suggests that the second edition of [2] modified some of the Ka-band data, extended its range of sea states and also stated that it would apply at 94GHz, and presumably at intermediate frequencies as well. This suggests that the normalised radar cross section (NRCS or σ^0) would be -34dB for vertical polarisation and -36dB for horizontal polarisation at 1° grazing angle in sea state 3.

The normalised RCS is, of course, the cross section per unit area of sea. It is a ratio of areas and is thus essentially dimensionless, although it may also be expressed in dBm^2/m^2 .

Long [3, p379 but referring back to p82] suggests that the return in circular polarisation will be very low if the receiver uses the same polarisation as the transmitter, as in the case of a common transmit/receive path with a single-polarisation feed i.e. the radar is sensitive to double-bounce, or depolarised, circular polarisation returns. However on p478 he reports some experiments which seem to show that the level of returns seen with this configuration may be only 6dB below that seen with linear polarisation.

Barrett et al [4] report some NRCS values at 89GHz in sea state 1-2 and with horizontal polarisation. Those results are repeated here since their source is not available electronically.

<u>Grazing Angle</u>	<u>NRCS</u>
30°	-27dB
45°	-26dB
55°	-18dB
90°	+13dB

TABLE I. SEA CLUTTER RETURNS AT 89GHZ, SEA STATE 1-2

These measurements were obtained in April 1982 off the Island of Öland in Sweden. Their accuracy is probably of the order of 2dB r.m.s.

A. Unpublished Philips Work

Related to the results described in [4] are some further measurements for low grazing angles made by the same group.

<u>Grazing Angle</u>	<u>Sea State</u>	<u>NRCS</u>
1°	3-4	<-30dB
3°	1-2	-40dB
3°	3-4	-29dB
10°	3-4	-29dB

TABLE II. SEA CLUTTER RETURNS AT 94GHZ, LOW GRAZING ANGLE

These measurements were made at Peacehaven, on the South-East coast of England, in early 1986 and will also have an accuracy of about 2dB r.m.s.

It is worth noting, in view of the paucity of clutter measurements at these frequencies that in this data, large spikes were observed at the higher sea states, although their amplitudes cannot now be quantified. The returns at 30° and 45° at low sea state showed a decorrelation time of the order of 100ms whereas the spikes had a decorrelation time of the order of one second. These were probably associated with the breaking wave crests which, as will be seen below, are associated with regions of high radar cross section.

B. Observation of Wave Crests

Bell et al. [5], in a comparison of littoral waves as seen by an X-band radar and a 77GHz radar observed that the returns from the 77GHz radar were concentrated along the wave crests, where the waves 'broke' and produced spray, and speculated that this may be because the gravity waves on the surface of the sea were of longer wavelength than the radar signals and so did not lead to a reflection from the sea in the way they do at lower radar frequencies.

III. THE SAFIRE RADAR

The SAFIRE radar has been described in reference [6], but its key parameters are noted here for completeness.

The central aim of developing this radar was to illustrate the application of high frequency microwave imaging

technology in modern society to the general public, showing the uses of remote sensing from commonplace everyday experience right through to cutting edge research topics. The variety and wealth of application imagery available from the larger millimetre-wave (MMW) community (passive security imaging, automotive radar, imaging of the cosmic microwave background and so on) provides an excellent basis for stimulating public interest. However, to fully engage with the public and provide an intuitive sense of how MMW imaging works requires an interactive imager that can supply live images of the immediate surroundings. Close range high resolution radar imagery can provide an easily recognisable map of an indoor scene as shown in the figure below (Fig. 1).

For simplicity of implementation, SAFIRE uses Frequency Modulated Continuous Wave (FMCW) waveforms.

A. SAFIRE Design

The design for SAFIRE (Fig. 2) was driven by the requirement for real time display imagery rather than for detection and identification of targets. The scanning mechanism consists of a zenith pointing Gaussian optics lens antenna (GOLA) combined with a 45° angled mirror mounted on a belt driven ring bearing so that the mirror can be continuously rotated through 360° in azimuth. The elevation beam is made somewhat broader than the azimuth by applying a convex curvature to the mirror.

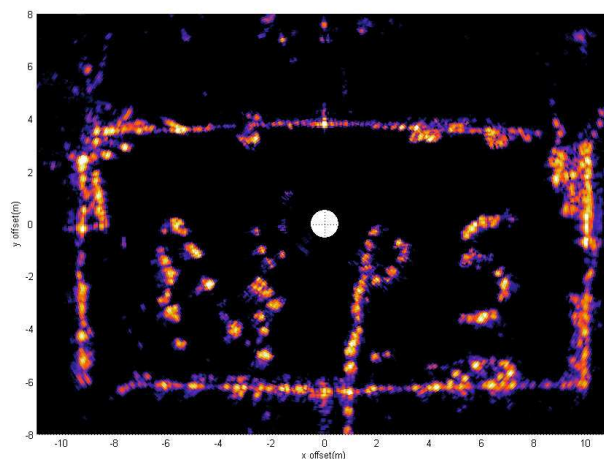


Fig. 1. High resolution SAFIRE image of school sports hall with pupils forming the initials of the school: "NPS"

Circular polarisation for the transmitted signal was chosen to avoid polarisation rotation effects as the mirror rotates. In order to be able to record linearly-polarised measurements the circular polariser was replaced by a section of plain waveguide. In this mode the radar signals were vertically polarised when looking along the long axis of the unit and horizontally polarised when looking along the short axis.

The speed of rotation is controlled via an analogue output from the computer with angular position provided by an optical encoder ring giving two separate logic signals, one indicating every 0.25° of rotation and one to signal completion

of each full revolution. The incremental signal triggers both the transmit modulation ramp and the data acquisition by the analogue to digital converter so that acquisition is synchronised with azimuthal direction.

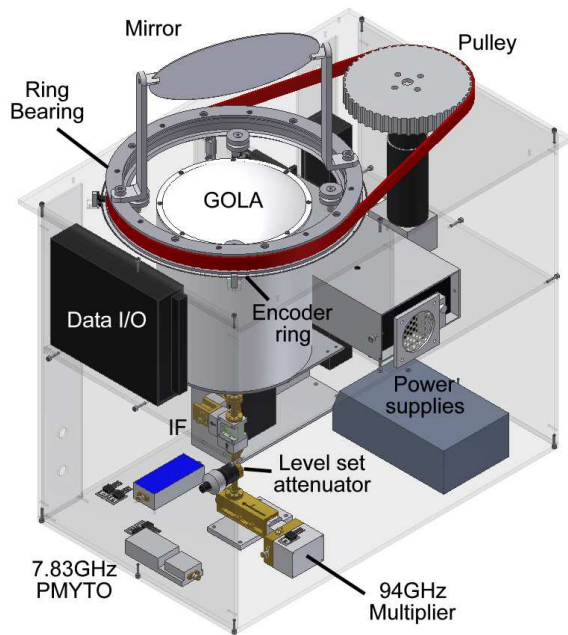


Fig. 2. Design schematic of the SAFIRE radar whilst being used to gather the data.



Fig. 3. The SAFIRE Radar Whilst Gathering Sea Clutter Data

The radar architecture (Fig. 4) is based on earlier successful systems built in St Andrews using a low phase noise frequency multiplied source. The 94GHz signal for SAFIRE is derived from a Permanent Magnet YIG Tuned

Oscillator (PMYTO) source with centre frequency of 7.83GHz and an FM coil bandwidth of up to 167MHz which has excellent sweep linearity and extremely low phase noise. The PMYTO feeds a x12 active multiplier yielding +14dBm at a centre frequency of 94GHz with up to 2GHz of bandwidth, (see Table I) The multiplier feeds the mixer LO whilst a 10dB coupler provides the main transmit signal. The transmit arm consists of a level set attenuator, transmit/receive circulator and transitions from linear to circular sense (both in waveguide and polarisation) to feed the Gaussian optics lens antenna.

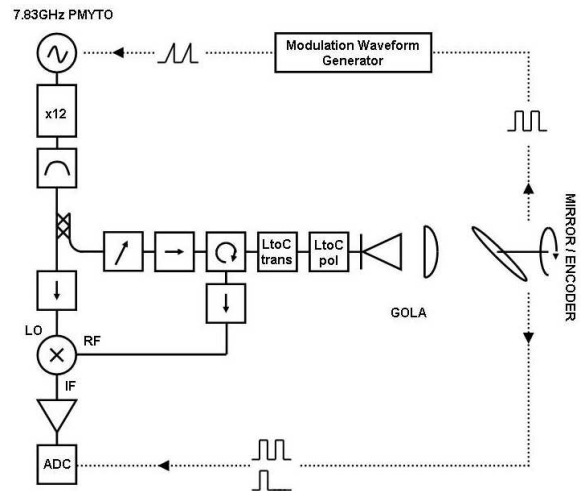


Fig. 4. Design schematic of the SAFIRE radar

SAFIRE has been operational since 2007 has been used at school workshops, science exhibitions and public lectures across the UK since that time. It was available between these exhibitions for the data gathering described here and has proved suitable for that purpose. The fact that it been used successfully for a 'real' radar application may also enhance the 'story' which can be told about it at exhibitions and demonstrations.

The overall design specification for the exhibition requirements are outlined in Table 1 below.

Transmitted power: +2.5dBm
 Azimuth beamwidth: 1.4°
 Elevation beamwidth ≈7°
 Receiver noise figure < 12dB
 4 FM sweeps per degree of azimuth scan
 Scan rate up to >4Hz
 FM Sweep duration: dependent on scan rate,
 typically 200μs

Table 1 Parameters of the SAFIRE radar

The radar was designed to have a high scan rate in order to produce a high update rate of the Plan-Position Indicator display for demonstrations, but this also allows it to provide ‘movie-like’ images of the sea and to simulate what would be seen by a simpler wide-field-of-view staring radar. The range resolution can be as fine as 0.1m, but coarser resolutions are also possible. The maximum indicated range can be up to 2048 range cells.

The radar is controlled by a built in rack-mounted PC. For the trials it could be controlled using an external laptop, which was connected to the internal PC via an Ethernet connection and which could be operated as a remote desktop. The recorded data could be stored internally and then downloaded to the laptop.

IV. ENVIRONMENT

The data were recorded over three days at two sites in Feb. 2013. The first measurements were made using circular polarisation from the Bruce Embankment, a promenade near the beach at St Andrews. The second set was made, also using circular polarisation, at the harbour of Elie on the north shore of the Firth of Forth. At the end of the first day the polarisation was changed to linear and recordings were made at Elie on the second day and back at St Andrews on the third, also using linear polarisation.

Since the radar was placed on the shore, the grazing angles were of the order of 2°.

Data on weather in the open sea in the vicinity of the measurement sites is publically available from weather stations on nearby oil platforms[7]. Over the period of the data gathering the wind speed was in the range 15kt...27kt and the wave heights in the range 10ft...16ft. Both the wind speeds and the wave heights are compatible with sea states in the range 6-7 but, of course, this is only an approximate guide to conditions in the littoral. Figure 5 shows the conditions at St Andrews on the third day, which was very similar to those seen on the other two days. The wave heights can be considered compatible with a sea state 3.



Fig. 5. Waves in the Littoral at St Andrews

V. RESULTS

Figure 6 shows a typical range-cross range image of the waves in linear horizontal polarisation. The range in this image was between about 40 and 65m. The wave fronts comprise a series of waves moving in different directions due to the complexity of the environment in shallow water near the coast. The first thing which is apparent is that this data seems to confirm the observation in [5] that the returns come primarily from the breaking wave crests.

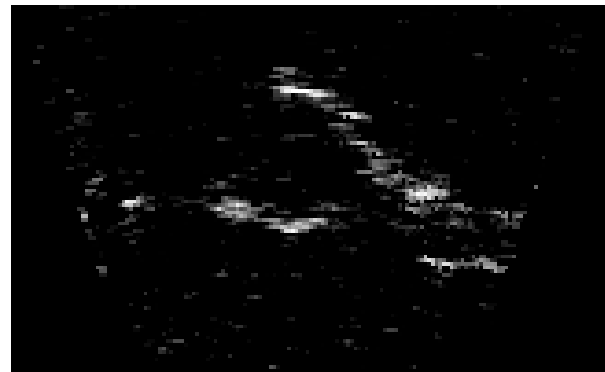


Fig. 6. Typical Wave Returns

The image covers an area about 30m wide and 17m deep and the range increases up the picture. The dynamic range of the image is about 15dB.

The accumulation of similar data from the other measurements further confirmed that the returns come from the breaking wave crests. Between these crests no returns were discernable above the noise level of the radar.

An auxiliary experiment of watching by eye when the wave crests passed a fixed point and observing when the radar return passed the same point confirmed conclusively that the returns were coming from the white caps and not from some other part of the wave. The ‘reference’ point was actually the post supporting the sign on the rock which can be seen on the right hand side of figure 3.

Somewhat similar results were seen with circular polarisation, but detectable returns were much less common. A possible reason for this is discussed below.

VI. ANALYSIS

A. Normalised Radar Cross Section

1) Linear Polarisation

The signal to noise ratio of the wave peaks is about 15dB. The sensitivity of the radar is such that this corresponds to an NRCS of about -22dB. This is actually about 8dB higher than was anticipated, but it should be noted that this only occurs at the peaks of the waves, so the mean NRCS, averaged over the whole wavelength of the waves, will be close to the value of -30dB which would be expected from the data in table 2.

These measurements indicate that the signal levels in the absence of breaking waves is below the receiver noise floor, i.e. at least 15dB below that of the whitecaps or < -37dB.

No significant difference was noted between the levels of backscatter seen between vertical and horizontal polarisation.

2) Circular Polarisation

The strongest clutter returns seen with circular polarisation are very similar in their NRCS to those seen from the breaking wave crests with linear polarisation, but the wavefronts are much less clear because strong returns are much less common than with linear polarisations.

B. Amplitude Distributions

The amplitude distributions of the clutter are important for knowing how high the detection thresholds must be set in order to detect small targets without excessive false alarms from the sea. As such, these distributions are frequently plotted as false alarm rate (i.e. the probability that the signal will exceed a given threshold) against threshold level above the mean value

1) Plots of Amplitude Distributions

Figures 7 to 9 show typical sets of plots of \log_{10} of the false alarm rate versus threshold/mean ratio for vertical, horizontal and circular polarization respectively.

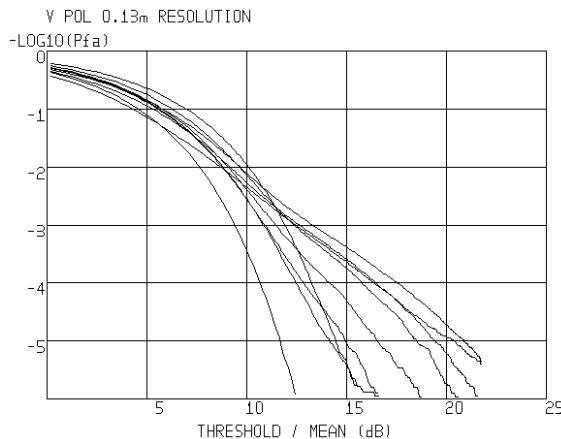


Fig. 7. Typical Amplitude Distributions - Vertical Polarization

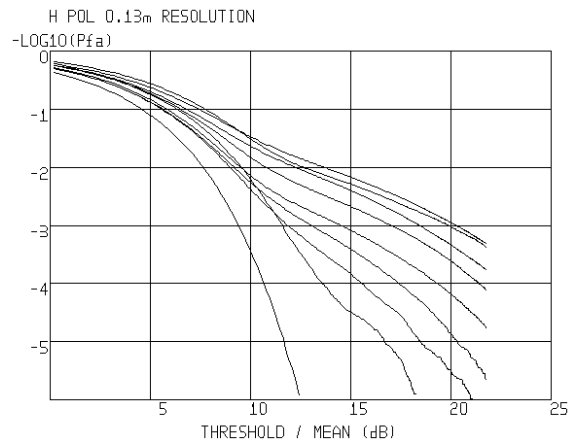


Fig. 8. Typical Amplitude Distributions - Horizontal Polarization

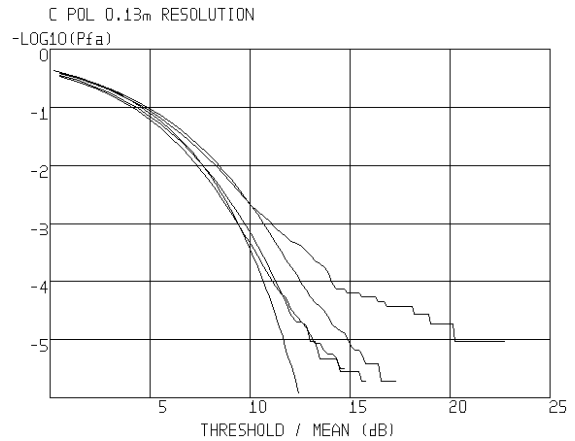


Fig. 9. Amplitude Distributions - Circular Polarization

The left-most curve is the distribution for thermal noise, and it can be seen that all the data is more 'spiky' (shows a longer-tailed distribution) than noise.

The other curves are for various groups of ranges between 30m and 100m from the shore. There is no consistent variation in the shapes of the curves with range, so they need not be distinguished, but they should not really be combined as the clutter-to-noise ratio would be expected to vary as a function of range.

It will be noted that all the data are for a range resolution of about 0.13m. The curves for the linear polarizations were obtained at the Bruce Embankment, and are considered to be typical in that the other curves for different resolutions and for the shore at Elie were not significantly different. It will be observed that the horizontally polarised data seems to have longer tails than the vertical, as is regularly observed at lower frequencies [8]. The circular also becomes spiky, but only at low probabilities, supporting the hypothesis that it has low mean levels but peak values are comparable with those seen with linear polarizations.

2) Fit to a Compound-k distribution

The compound-k model [9] is commonly used to model the amplitude distributions of sea clutter at lower frequencies, and an attempt was made to estimate the shape parameter which such a model would give for this data. The problem was made harder because the noise made a major contribution to the distribution, and harder still because the fact that the mean levels were well below the noise meant that the clutter to noise ratio also had to be estimated as part of the same process.

A method due to Watts [10] was used to estimate both the shape parameter and the clutter to noise ratio. This method gave estimates in the range 0.1..0.2 for the shape parameters (implying it was at the limits of spikiness which is ever observed at lower frequencies) and confirmed that the mean clutter-to-noise ratios were below 0dB and perhaps 5dB lower still with circular polarization, but the extreme values obtained mean that it was judged unwise to put too much weight on the quantitative values obtained.

VII. DISCUSSION

The first point to observe is that these results support the estimate that the low grazing angle normalised RCS at 94GHz in sea state 3 with linear polarisation is $< -30\text{dB}$. Although not an original observation, the paucity of data at these frequencies makes this support for the previous measurements.

The second point is that at low grazing angles the return comes essentially only from breaking wave crests. This confirms the observations by Bell [5] to this effect. The NRCS within the breaking crests is thus of the order of 10dB higher than the average. This may also explain the note in the unpublished Philips work that the structure is very 'spiky.'

A simple, but significant, observation is the confirmation that the returns do come from the crests rather than from another 'phase' of the wave.

The great reduction in NRCS going from sea states 3-4 to 1-2, reported in reference [4] would then be attributable to the absence of breaking waves at the lower sea state.

It must, however, be remembered that reference [4] reported much higher backscatter in low sea states at higher grazing angles. This means that some mechanism in addition to the scattering from the breaking waves must be contributing to the reflections at higher grazing angles. The relationship between this and the shadowing which is seen at lower grazing angles is still to be resolved.

The results with circular polarisation are interesting. They can best be expressed by saying that, most of the time, the circular-polarised returns (sensed for odd-bounce reflections) are much lower than the linear, but that for the strongest peaks of the returns (the biggest accumulations of spray at the breaking crests, which contain foam and bubbles as well as droplets of pure water), the returns are depolarised. This is actually plausible if we consider that the smaller returns come from groups of smaller water droplets, which will be roughly spherical and have very low returns with circular polarisation (odd-bounce reception), but the strongest returns come from

larger droplets whose surface tension can no longer keep spherical such that they give a significant depolarised reflection with circular polarisation. This explanation would also provide a mechanism which could reconcile the different observations in [3] as to the ratio of linear and circularly-polarised returns to be seen at these frequencies.

VIII. CONCLUSIONS

The measurements reported and analysed above help to improve the understanding of the characteristics of the returns from sea clutter in the littoral environment when observed at frequencies of the order of 90-94GHz.

Besides the points this work raises about the mechanisms leading to the backscatter of radar signals from the sea, the availability of this information also helps the community to perform the analyses of the performance of such radars.

ACKNOWLEDGEMENT

This work was supported by the UK MoD through the Centre for Defence Enterprise.

REFERENCES

- [1] Sherman, E. D. R., Hoare, E. G. and Hutton, A., 'Trials of Automotive Radar and Lidar Performance in Road Spray,' IEE Colloq. on Automotive Radar and Navig. Techniques, February 1998, Publication Reference 1998/230, pages 10/1 to 10/7
- [2] Nathanson, F. E., 'Radar Design Principles,' New York, 1969, McGraw-Hill, Chapter 7
- [3] Long, M. W., 'Radar Reflectivity of Land and Sea,' 3rd Ed., 2001, Boston Mass., Artech House, ISBN 1-58053-153-9
- [4] Barrett, M., Booth, P.L. and Stove, A. G., 'FMCW Instrumentation Radar,' Proc. Military Microwave Conf. 1984 pp 579-583.
- [5] Bell, P. S., Williams, J. J., Clark, S., Morris, B. D. and Vila-Concejo, A., 'Nested Radar Systems for Remote Coastal Observations,' J. Coastal Research, Special Issue 39, 2004.
- [6] Macfarlane, D. G. and Robertson, D. A., 'SAFIRE: A Real Time Close Range Millimetre-Wave Exhibition Radar,' 35th Int. Conf. on Infrared Millimeter and Terahertz Waves, 2010, pp1-2.
- [7] http://www.ndbc.noaa.gov/maps/United_Kingdom.shtml
- [8] Ward, K. D., Tough, R. J. and Watts, S., 'Sea Clutter: Scattering, the K Distribution and Radar Performance,' 2nd Ed. London, 2013, ISBN 978-1-84919-589-8, IET Radar Sonar and Navigation, section 3.5.3
- [9] *ibid.*, section 3.5.5
- [10] Watts, S., private communication.