THE MODELLING OF RADAR SEA CLUTTER

by

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Abstract

This thesis presents selected research papers and patents written by Simon Watts between 1985 and 2012 on the topic of the modelling of radar sea clutter. This work has been based on the development and exploitation of the compound K distribution model for the amplitude statistics of radar sea clutter. It has covered the development of the model, through the analysis of recorded radar data, to establish its validity over a wide range of conditions and for both coherent and non-coherent radar processing. The work has also developed methods for exploiting the model for improved performance prediction for radar systems, the analysis and development of new detection signal processing schemes and the use of these models for the specification and measurement of radar performance, for the procurement of radar systems. All the work has been undertaken in an industrial environment, motivated by the need to develop improved radar systems to meet customer requirements.

Acknowledgements

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1. Papers presented in the thesis

The papers listed below are the subjects of this thesis. They are referenced by number in the supporting text and the full papers are appended to the thesis, labelled Paper 1, Paper 2 etc.

[1] K D Ward, C J Baker and S Watts, “Maritime Surveillance radar part 1: Radar scattering from the ocean surface” Proc IEE, Vol 137, part F, No.2, April 1990 pp 51-62. (Mountbatten Premium).

[2] S Watts, C J Baker and K D Ward, “Maritime surveillance radar Part 2: Detection performance prediction in sea clutter” Proc IEE, Vol 137, Par F, No.2, April 1990 pp 63-72. (Mountbatten Premium).

[3] S.Watts, K.D.Ward and R.J.A.Tough, Modelling the shape parameter of sea clutter, International Conference Radar 09, Bordeaux, October 2009 (Invited Paper)

[4] S Watts, “Radar detection prediction in sea clutter using the compound K-distribution model”, Proc IEE, Vol 132, Part F, No.7, December 1985, pp 613-620. (J J Thompson Premium).

[5] S Watts, “Radar detection prediction for targets in both K-distributed sea clutter and thermal noise”. IEEE Trans. AES-23, No.1, January 1987, pp 40-45.

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[7] S.Watts, Radar performance in K-distributed sea clutter, SET Panel Symposium on “Low grazing angle clutter: its characterization, measurement and application”, Laurel, Maryland USA, 25-27 April 2000.

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[14] S Watts and K D Ward, “Spatial correlation in K-distributed Sea Clutter”, Proc IEE Part F, Vol 134, No.6, October 1987, pp 526-532.

[15] S.Watts, Modeling and simulation of coherent sea clutter, IEEE Trans AES Vol. 48, No.4, October 2012, pp. 3033-3317

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[18] S.Watts, H.D.Griffiths, J.R.Holloway, A.M.Kinghorn, D.G.Money, D.J.Price, A.M.Whitehead, A.R.Moore, M.A.Wood, D.J.Bannister, The specification and measurement of radar performance – future research challenges, Journal of Defence Science, Volume 8, No.2, May 2003, pp 83-91.

[19] S.Watts, H.D.Griffiths, J.R.Holloway, A.M.Kinghorn, D.G.Money, D.J.Price, A.M.Whitehead, A.R.Moore, M.A.Wood, D.J.Bannister, The specification and measurement of radar performance, IEE International Conference Radar 2002, 14-17 October 2002, IEE Publication No.490, pp 542-546.

[20] K.D.Ward and S.Watts, Use of sea clutter models in radar design and development, IET Radar Sonar Navig.,Vol. 4, Iss. 2, April 2010, pp. 146 – 157 (Special Issue on Radar Clutter)

[21] S.Watts, Radar Sea Clutter Modelling – Recent Progress And Future Challenges, International Conference Radar 08, Adelaide, September 2008 (Invited Paper)

2. Biography of Simon Watts

Simon Watts graduated from the University of Oxford in 1971, obtained an MSc from the University of Birmingham in 1972 and a PhD from the CNAA in 1987. He is currently deputy Scientific Director and Technical Fellow in Thales UK and is also a Visiting Professor in the department of Electronic and Electrical Engineering at University College London. He joined Thales (then EMI Electronics) in 1967 and since then has worked on a wide range of radar and EW projects, with a particular research interest in maritime radar and sea clutter. He is author and co-author of over 50 journal and conference papers, an IET book on sea clutter (with K.D.Ward and R.J.A.Tough) and several patents. He was chairman of the international radar conference RADAR-97 in Edinburgh UK. Simon Watts serves on the IEEE AESS Radar Systems Panel, is an Associate Editor for Radar for the IEEE Transactions AES and a member of the Editorial Board of IET Radar, Sonar & Navigation. He was appointed MBE in 1996 for services to the UK defence industry and is a Fellow of the Royal Academy of Engineering, Fellow of the IET, Fellow of the IMA and Fellow of the IEEE.

3. Background to the Research

The research described here was mainly undertaken in support of the development of airborne maritime surveillance radars, originally by EMI Electronics and subsequently, through the process of industrial acquisitions, by Racal and Thales UK. Much of the work was undertaken in collaboration with researchers at the UK government Radar Research Establishment (RRE) and its successors (RSRE, DRA, DERA, Dstl), either complementing their work or working directly with them. In particular, the research was applied to upgrades to the Searchwater radar, in service in RAF Nimrod MR2 aircraft from 1980 to 2012, and to the design of the Searchwater 2000 family of radars. The Searchwater 2000AEW is currently in service in the RN Sea King Mk7 Airborne Surveillance and Control (ASaC) helicopter and the Searchwater 2000MR was successfully developed and delivered to the RAF for the Nimrod MRA4 aircraft, which was cancelled in 2012. Although this research was motivated to support the development of airborne maritime surveillance radars by the company, it has had application worldwide in the development of all forms of radar operating in a maritime environment. The emphasis of all the work has been to develop models and techniques that have practical application to all aspects of radar design and manufacture. The work spans the period from the early 1980s to the present day.

4. Radar Sea Clutter

A radar operating in a maritime environment will usually observe signals reflected from the sea surface, in addition to reflections from targets of interest, which may vary from large ships to very small targets such as submarine periscopes. The signals reflected from the sea, known as radar sea clutter, are usually unwanted and may significantly interfere with the signals from wanted targets.

A prime example of a military application that encounters problems of this kind is maritime surveillance. Typical examples include the Searchwater radar, which was in service with the UK RAF Nimrod MR2 aircraft, the AN/APS-137 radar fitted in the US Navy P3-C aircraft, and the Blue Kestrel radar in the Royal Navy Merlin helicopter. These radars have many operating modes, but in particular are used for long-range surveillance of surface ships (known as ASuW, anti-surface warfare) and detection of small surface targets, including submarine masts (ASW, anti-submarine warfare). For ASuW operation, the radar must detect, track and classify surface ships at ranges in excess of 100 nautical miles. For ASW operation, the radar must detect submarine masts just above the surface in high sea states, at ranges of many miles. In both these modes, the radar operator and the automatic detection processing must be able to distinguish between returns from wanted targets and those from the sea surface. Unlike satellite radars, the grazing angle at the sea surface for such radars is typically less than 10° and often the area of interest extends out to the radar horizon (i.e. zero grazing angle). Under these conditions, returns from the sea can often have target-like characteristics and may be very difficult to distinguish from real targets. In order to aid discrimination between targets and clutter and, in extreme cases, prevent overload of the radar operator or signal processor, the radar detection processing must attempt to achieve an acceptable and constant false alarm rate from the sea clutter.

The design of such signal processing algorithms requires a detailed understanding of the characteristics of the signals received from both targets and the sea. For this reason, the characteristics of sea clutter have been, and continue to be, extensively studied. The aim of these studies is to improve our understanding of these characteristics, which can vary very widely, dependent on the environmental conditions, viewing geometry and radar parameters. In particular, the desire is to build mathematical models that can capture these characteristics and then be applied to the design and manufacture of better radar systems.

Early work on the development of models of sea clutter concentrated simply on developing models of the mean intensity of the backscatter under different conditions. Subsequently, attempts were made to models the fluctuations about the mean intensity. Early models failed to capture the complex statistics of these fluctuations but a major advance was made by the formulation by K.D. Ward of the compound K distribution model for the non-Gaussian statistics of sea clutter [A]. This was the starting point for the research described here.

The compound K distribution model has been specified for use in defining the required radar performance by defence procurement agencies, incluing those in UK and USA, and is widely accepted as the definitive model for sea clutter amplitude statistics. A search on IEEE Xplore for the terms “K distribution” and “sea clutter” together returns over 4000 results. The model provides the basis for methods for predicting performance of radars detecting targets in sea clutter that are much more accurate, over a wide range of conditions, than previous modelling methods. The model also provides insight into the wider characteristics of sea clutter, supporting the development of improved radar waveforms and detection signal processing algorithms.

5. The development and application of sea clutter models by S.Watts

This Section describes the contributions described in the papers presented in this thesis. The discussion is divided into different aspects of research into the modelling of radar sea clutter. Section 5.1 covers the modelling of the amplitude statistics of the backscatter clutter signals received by a radar. Section 5.2 describes the application of these models to the development of improved radar signal processing algorithms for the detection of small targets against a background of sea clutter returns. Section 5.3 looks at the specific topic of modelling the spatial correlation of clutter returns and Section 5.4 covers work on the Doppler spectra and temporal correlation of sea clutter. An important use of models is to assist in the procurement of advanced radar systems and Section 5.5 reviews work undertaken on the specification and measurement of radar performance. Finally, Section 5.6 considers work that has been done to explain and promote the appropriate use of models of sea clutter and to promote further work in this area.

5.1. Sea clutter amplitude statistics

The returns from a sea clutter may appear in a radar receiver as noise-like returns. This noise is generally modelled as a stochastic process, but unlike the thermal noise also always present at some level in a radar receiver, its statistics are usually non-Gaussian.

The seminal papers that set out the evidence for the validity of the compound K distribution model were Ward, Baker, Watts [1] and Watts, Baker, Ward [2], written in collaboration with K.D. Ward and C.J. Baker, then of RSRE. These papers describe the characteristics observed in radar data that led to the compound form of the model. They demonstrated the good fit to the model consistently achieved with a large amount of real radar data, recorded over a wide range of environmental conditions and radar parameters. A particularly important result was the model reported in the paper that related the shape parameter of the K distribution amplitude PDF to the environmental conditions, the viewing geometry and the radar parameters. This allowed the use of the model for generic radar design applications. Watts collaborated in all this work and in particular was the lead author for [2], which showed results for the exploitation of the models in performance prediction (see also Section 5.2). These two papers were awarded the IET Mountbatten Premium.

Work on the modelling of amplitude statistics has continued over many years, as further data has been collected. More recently, from the late 1990s to the present day, developments in radar data recording techniques have allowed some of these models to be revisited, using data gathered during the development of the Searchwater 2000 radars. Of particular interest is the paper by Watts, Ward and Tough [3], which was presented as an invited paper at the Radar 2006 International Conference. This paper, for which Watts was the lead author, provided greater insight into the variation of amplitude statistics (i.e. the shape parameter and the probability density function of the amplitude) with viewing geometry (particularly the grazing angle), reinforcing the idea of a critical grazing angle, below which clutter statistics become increasingly non-Gaussian. The work contributing to this part of the paper was undertaken by Watts. The paper also reported development in the electromagnetic modelling of the scattering from the sea surface, undertaken by Ward and Tough.

5.2. The application of sea clutter models to target detection techniques

One of the main purposes for the development of statistical models of sea clutter is the design of improved detection algorithms. The compound form of the K distribution model implies two components of the amplitude statistics, that have different spatial and temporal correlations. These must be correctly modelled when predicting performance and will also guide the design of new detection algorithms.

One of the first papers explaining how to predict detection performance of targets in K distributed sea clutter for non-coherent radar systems, particularly those employing pulse-to-pulse frequency agility, was by Watts [4]. This showed how the effects of pulse-to-pulse analogue integration could be modelled and also described the effects of binary integration on detection performance. In this paper, the concept of the "ideal CFAR" (ideal Constant False Alarm Rate) detector was introduced. This showed how performance would be considerably enhanced if the detector were able to follow exactly the underlying mean level component of the clutter. This gave an upper bound to performance and these ideas were developed further in the papers on the Cell-Averaging Constant False Alarm radar (CA CFAR) technique, discussed below. The paper [4] was awarded the IET JJ Thomson Premium.

Thermal noise is always present at some level in a radar receiver due to the inherent noise of the receiver electronics. Although clutter returns may be strongly received in a radar at short or intermediate ranges, towards the radar horizon the clutter returns may be very weak or non-existent and radar performance will be limited by the receiver thermal noise alone. It is very important to be able to model the effects of the changing clutter-to-noise power ratio as the conditions or viewing geometry change. Uniquely, the compound K distribution model allows thermal noise to be accurately incorporated into the modelled sea clutter returns. The method for incorporating noise and the subsequent calculations of detection performance were first described in Watts [5]. This is an important paper in this field and, together with [1] and [2], has been widely cited by subsequent researchers.

A well-known technique for setting an adaptive radar detection threshold is known as the CA CFAR algorithm. This technique predicts the mean level of the radar return of interest at a particular range, by estimating the mean level of the returns from a number of adjacent range cells. The CA CFAR was originally developed for use in thermal noise, but is widely applied for target detection in the presence of sea clutter. As also discussed in Section 5.3, the returns from sea clutter often exhibit a spatial correlation in range, related to the presence of sea swell or waves that modulate the local intensity of the backscattered signal. This spatial correlation can have a very significant effect on the performance of CA CFAR systems, as the cell-under-test is no longer statistically independent of the surrounding cells. The analysis of this performance was initially considered in [2] and then in more detail by Watts [6], showing how performance is affected and how the changes in performance can be quantified. In [6], it was shown that in some real clutter conditions, the performance of the “ideal CFAR” detector, quantified as a “CFAR gain”, could be approached by appropriate selection of the cell-averager length, dependent on the spatial correlation properties of the clutter. It was also shown how the selection of cell-averager length can effect the spatial distribution of false alarms in clutter. A spatially uniform distribution of alarms is very desirable for efficient radar detection. In some conditions, the incorrect selection of cell-averager length can result in a localised bunching of alarms, which can be very deleterious to radar performance.

These areas of performance analysis were further developed and explained in Watts [7] and [8]. In Watts [7], the performance of detectors following pulse-to-pulse integration was further developed, showing how the extremes of pulse-to-pulse correlation of the speckle component of the clutter (for example, such as induced by frequency agile or fixed frequency operation) could be incorporated into performance predictions calculations. In Watts [8], the performance of the CA CFAR was further examined, quantifying the CFAR loss or gain, compared to an "ideal" fixed threshold detector, for different clutter conditions and for different CA CFAR configurations. It is usual to expect a loss in performance when using a CA CFAR detector, but it was shown that there will be an optimum length for the cell-averager, which can result in a CFAR gain in some conditions. This work was further extended in Watts, Ward and Tough [9]. In this paper, the part written by Watts reported the effects of added thermal noise to the results reported in [8]. This showed the interesting result that in some circumstances added thermal noise can reduce the loss of a CA CFAR system compared to a fixed threshold under the same conditions.

A particularly difficult characteristic of sea clutter that is sometimes observed is the presence of discrete target-like "spikes". These spikes may be very large compared with the surrounding clutter returns and may persist for up to a second or more. This behaviour is not modelled by the standard compound K distribution, but can be accommodated in the KA model, first discussed by Middleton [B] and Ward and Tough [C]. Watts developed this model using recorded data and also showed how the additional parameters of the model could be estimated from data measurements, including the effects of added noise. This work was summarised in Watts, Ward and

Tough [10]. Again, this work showed how the model could be applied to practical radar design and discussed the implications of such characteristics to radar detection performance. In that paper, material on the modelling of electromagnetic scattering was contributed by Ward and Tough, whilst the development of the KA model was undertaken by Watts.

One of the aims of this research was always to develop improved detection algorithms. Where these were likely to be exploited in manufactured equipment, patent protection was sought.

Watts [11] was patented in GB and describes a novel technique for improving CA CFAR performance in correlated clutter, by modelling the spatial correlation of the clutter as an autoregressive process and adjusting the weights on the cell-averager FIR filters accordingly. This can provide improvements to detection performance, albeit with added algorithmic complexity.

Watts [12], patented in GB, France and USA, describes improvements to the CA CFAR detector based on exploiting models of the sea clutter characteristics. The clutter characteristics are estimated by observing a high false alarm rate at a low threshold setting. The detector then uses this fit to the model to estimate the required higher threshold to achieve the desired low false alarm rate, which cannot be measured directly. This allowed the CA CFAR threshold to adapt to changing clutter conditions very rapidly, whilst maintaining a good CFAR performance. This circuit has been employed in a number of maritime radar systems sold by the company.

The algorithms used in a modern maritime radar may be very complex, with a number of controls and options available to the radar operator (such as CA CFAR settings, choice of radar antenna polarization, optimum aircraft operating height, and so on). It may not be immediately obvious to a radar operator that the radar and viewing geometry have been set up in manner that are optimum, given the prevailing conditions and targets of interest. The invention described in Watts [13] also exploits the results of clutter modelling to provide a predicted-detection-range display. This uses the radar's own measurements of the conditions, as sensed by its adaptive circuits, such as the CA CFAR threshold circuit described in [12], sensing the clutter amplitude statistics, together with automatic gain control (AGC), which senses the mean level of the clutter, to show the operator on his display what size of target may be detected at different points of the sea surface under surveillance. As the operator adjusts the radar, aircraft height and so on, the radar thresholds adapt and the resulting improvement or degradation of performance is presented to the operator as changing detection contours on the display. This gives the radar operator confidence in his settings and allows intelligent testing of different settings to produce the best performance. Again, the invention has been incorporated in radars manufactured by Thales.

5.3. Spatial Correlation

Spatial correlation of clutter returns is a specific feature that can impact detection performance, as discussed above, and so must also be modelled. The spatial correlation observed by a radar is a function of the prevailing conditions (wind waves and swell), the look direction and the spatial resolution of the radar. An early paper that described the different spatial correlations of clutter and the impact of this on the amplitude statistics with different spatial resolutions was described in Watts and Ward [14]. The work by Watts in this paper showed how spatial correlation could be modelled, including the effects of changing spatial resolution. The paper also reported methods for simulating correlated clutter returns in a computer, which was done by Ward.

5.4. Doppler spectra and temporal correlation

Much of the earlier work discussed above was concerned with the modelling of the statistics of the envelope or intensity of the clutter returns, which is what has been processed by most airborne maritime surveillance radars until recently. There is increasing interest now in exploiting the Doppler shift of maritime targets, to enhance their detectability against sea clutter. One reason for this is that modern radar technology can produce the required high quality coherent radar returns relatively easily compared with the technology available, say, 20 years ago.

Models of Doppler spectra of sea clutter have been much less well developed than those for amplitude statistics. However, they are no less important for the design and assessment of modern radar systems. There is a large body of literature that describes the mathematics of so-called optimum detectors in coherent sea clutter, based around the Generalised Likelihood Ratio Test (GLRT). Such techniques assume that the clutter Doppler characteristics can be defined in terms of a covariance matrix, as a Spherically Invariant Random Process (SIRP). In fact, however, the Doppler characteristics of sea clutter are generally quite non-stationary, as noted many years ago by Ward, Baker and Watts [1], and cannot be described in terms of a simple covariance matrix or an SIRP. Recent observations by Watts of the characteristics of Doppler spectra of sea clutter have led to a new model being proposed, which captures this non-stationary behaviour. This model allows more realistic simulation of clutter returns and also provides the basis for improved detection performance predictions. This work was recently reported by Watts [15].

A rather different analysis of the practical performance of radar detectors was reported in Watts [16]. This related to the statistics of the duration of alarm crossings of a threshold in thermal noise. The duration of false alarms is a function of the frequency response of the radar receiver and the probability of false alarms. The proper understanding of this characteristic, which was not previously correctly reported in the radar literature, is important when interpreting the relationship between the probability of false alarm set by the radar detection threshold, and the number of alarms seen in a given area of a radar display. As the performance of radars is scrutinised in ever greater detail, such understanding is essential to correct assessment of radar performance in practical trials.

5.5. The specification and measurement of radar performance

The procurement of a new advanced radar system by a customer is a complex process, requiring considerable technical insight by the customer if he is to be able to acquire a system that properly meets his needs. Such radars are very rarely supplied “off-the-shelf” with fixed characteristics, but are developed or modified to meet specific customer requirements. Firstly, the customer must specify what is required and the manufacturer must then translate these requirements into a mutually acceptable performance specification. Once the radar is developed, its performance must be demonstrated to the customer so he can accept or reject delivery of the system against the original specified performance. It is often very difficult or impossible to prove radar performance by demonstration in practical trials and often part of any acceptance process must involve modelling. The problem of specifying and then measuring maritime radar performance was highlighted for the first time in the radar literature by Watts [17]. This work looked at what constitutes the performance of radars detecting targets in sea clutter and how such performance can be quantified and measured. This work was further developed when Watts proposed and then chaired a working party for the Defence Scientific Advisory Council (DSAC) of the UK Ministry of Defence. This work involved experts from UK industry, government research laboratories and academia to provide advice to MoD on the specification and measurement of advanced radar systems, from the perspective of the customer procuring such systems. This work was published in Watts et al. [18] and [19]. The topic continues to be of considerable importance.

5.6. The use of sea clutter models

It is appropriate from time to time to revisit the underlying issues associated with why models are used and which models are appropriate to use in different circumstances. The many different uses for models of sea clutter are discussed in Ward and Watts [20]. This work emphasises the role of models in the specification and measurement of radar performance. It also highlights the possible misleading results that can be obtained if the wrong models are used to predict performance in a given situation. A typical example would be the failure to use a compound formulation for the amplitude statistics, and so not properly modelling the effects the correlations of the different components on detection performance.

Finally, to encourage the direction of further research, the occasional tutorial on the state-of-the-art is useful to highlight areas where further research is needed. Such a summary of the current state of research was given by Watts [21], as an invited paper at Radar 2008.

6. Conclusions

The body of research presented here comprises papers published between 1985 and 2012. The work is mainly concerned with the modelling of sea clutter, based on the compound K distribution formulation, and with the exploitation of these models. This exploitation includes improved performance prediction, the design of improved signal processing algorithms for target detection and the role of these models in the specification and measurement of performance for the purposes of radar procurement.

7. References

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Selected Research Papers by S.Watts