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# Remote sensing applications of HF skywave radar: The Australian experience

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**Abstract**

*Australia has conducted research into over-the-horizon radar (OTHR) for almost sixty years. Early programs focused exclusively on military capabilities, such as the detection of aircraft, missiles and ships, but in 1974 a team was formed to design a new OTHR for which a remote sensing mission was proposed. Oceanic wind mapping experiments in 1977-78 yielded promising results so remote sensing became a recognised mission assigned to the new radar, known as Jindalee Stage B. This capability was progressively expanded over the period 1982-87 to include mapping of wave height and other oceanographic variables. A real-time data link to the Australian Bureau of Meteorology was set up in 1985, providing daily wind direction maps covering over one million square kilometres of the NW Indian Ocean, the Timor Sea and the Arafura Sea. In concert with user-focused remote sensing programs, investigations were undertaken to gain a detailed understanding of issues relating to propagation, system calibration, radar resource management and scheduling. Many theoretical studies and radar experiments were conducted to assess the radar's ability to measure ever more ambitious geophysical phenomena, ranging from oil spills and tropical rainfall to cyclogenesis and volcanic activity. Inevitably, as the radar evolved into a facility owned and operated by the Royal Australian Air Force, the remote sensing mission had to compete with surveillance tasks with higher priorities and the quality of the routine service provided to the Bureau of Meteorology deteriorated, eventually being terminated after a decade of activity. Despite this, the knowledge acquired and the practical lessons learned remain valid today and may be of value to other OTHR programs.*

**Key Words:** *HF radar, OTH radar, radio oceanography.*

## 1. Introduction

The Australian Defence Science and Technology Organisation was one of the pioneers of HF skywave 'over-the-horizon' radar (OTHR), tracing its involvement in this technology back some sixty years. Prior to 1974, research programs focused exclusively on military capabilities, such as the detection of aircraft, missiles and ships, but in that year a team was formed to design a new OTHR, the Jindalee Stage B, which was planned as a successor to the prototype radar, the Jindalee Stage A, though at that time the latter was still under construction. As part of the Stage B design guidelines, a remote sensing mission was proposed, inspired by the demonstration of oceanic wind mapping over the North Atlantic reported by OTHR scientists in the US [1].

The Jindalee Stage A radar operated between 1976 and 1978 from sites near Alice Springs in Central Australia, looking over a very narrow arc covering the major air route from Singapore to Australia. Oceanic wind mapping experiments in 1977-78 yielded promising results so the various Stage B radar subsystems were designed to support, or at least not to prevent, future implementation of a routine wind mapping service. This capability was expanded during the Stage B operational era, 1982-87, to include mapping of wave height and other oceanographic variables. A real-time data link to the Australian Bureau of Meteorology was set up in 1985, providing daily wind direction maps covering over one million square kilometres of the NW Indian Ocean, the Timor Sea and the Arafura Sea.

Stage B was subsequently upgraded to military operational status whilst also serving as a scientific test-bed (the Jindalee Facility Alice Springs or JFAS), while a fully-fledged operational national OTHR system, the Jindalee Operational Radar Network (JORN) was being designed and deployed. Today, JFAS and the two JORN radars form an integrated OTHR network with unrivalled regional wide-area surveillance capability. Furthermore, new concepts (or more frequently, concepts which had been identified previously but not realizable with the technology of the day) continue to be explored with the expanded JORN radars, with a view to enhancing their capabilities.

In concert with the user-focused remote sensing programs, many investigations were undertaken to gain a detailed understanding of issues relating to propagation, system calibration, radar resource management and scheduling. Climatologies of propagation conditions relevant to remote sensing date from 1982, highly accurate coordinate registration techniques from 1983, and semi-automated operator advice tools from 1984. Research into the theory of electromagnetic scattering from the sea surface commenced in 1979 and continues today, striving for higher fidelity of both electromagnetic and hydrodynamic models. Where appropriate, the original Fourier-based signal processing techniques were supplemented with high resolution spectrum estimators, time-frequency analysis via bilinear methods and wavelets, higher-order spectrum analysis and adaptive processing in the spatial and temporal domains.

As the Jindalee radar evolved into a facility owned and operated by the Royal Australian Air Force, the remote sensing mission had to compete with surveillance tasks of higher priority and the quality of the service provided to the Bureau of Meteorology deteriorated. This did not impact on the DSTO research program, though, and many theoretical studies and radar experiments were conducted to assess the radar's ability to measure ever more ambitious geophysical parameters. These ranged from oil spills and tropical rainfall to cyclogenesis and volcanic activity. The advantages and disadvantages of alternative HF radar configurations were explored, especially that of HF surface wave radar, bistatic and hybrid radar geometries, and the exploitation of the polarisation domain.

This paper reviews the development of remote sensing capabilities and presents an assessment of the present state of affairs. Rather than pursue a strict chronological order, the discussion has been divided into subject areas within each of which a roughly chronological order is maintained. Some of the milestone achievements are illustrated, along with important lessons that were learned along the way, either by unexpected success or, just as often, by informative failure.

# 2. Impact of the remote sensing mission requirement on radar design

## 2.1. Resolution requirements

The design of the Stage B radar began in 1974 and proceeded on the basis that aircraft detection was the primary radar role, with ship detection a less important mission. In order to model and predict ship detection performance, and hence to influence the radar design, studies of the spectral (Doppler) properties of sea clutter were undertaken based on the theoretical scattering model of Barrick [2] combined with limited information about sea states in the area of interest. One year earlier, Long and Trizna at NRL [1] had revealed the potential of HF skywave radar to measure oceanic wind fields, so as the Jindalee Stage B area spanned an area prone to severe tropical cyclones, the resolution requirements associated with a possible cyclone mapping mission were incorporated in the optimisation criterion. Specifically, statistical distributions of the radius of maximum wind speed and radius of streamline closure were examined to determine the appropriate spatial resolution. The key outcome of these studies was the decision to increase the receiving array aperture quite substantially over that which had been arrived at by a cost-benefit analysis predicated on the aircraft detection mission alone [3]. The resultant 2.8 km array, still in operation, yields cross-range cell dimensions of the order of 10 km at 1200 km range, the distance to the northern coast of Australia, for a typical day-time operating frequency of 15 MHz.

## 2.2. Receiving antenna array design

A crucial aspect of the receiving system antenna design was the decision to adopt an overlapped, subarray architecture, with 32 receivers distributed across the array and digital beamforming of the subarray outputs. Receiver-per-element designs lay beyond prevailing technical capability, not to mention financial limits. The issue of grating lobes was dealt with by careful design of the subarray form factors, while the related issue of array calibration was factorised into stages and implemented around the range-processing and beamforming operations. Calibration was performed across the receiver passband at every change of radar frequency, in part because having cables over 1.5 km long in the hot desert environment meant that phase path length fluctuations were inevitable.

Obviously the subarray parameters were set primarily to meet conventional target detection and tracking needs, but these stringent requirements subsequently proved to be of immense importance to the remote sensing mission. This was evident whenever ionospheric propagation support for a critical remote sensing task, such as responding to a Bureau of Meteorology request for information on possible cyclogenesis, was extremely weak over the area of interest. Had the grating lobes and sidelobes been higher, clutter leaking through from other directions that enjoyed stronger ionospheric support at the selected frequency would have obscured the echoes of interest.

## 2.3. Nonlinearity considerations : IMD effects on sea clutter

The Stage B design called for greater sensitivity than Stage A, placing strict requirements on the linearity and noise figures of the radar subsystems. The transmitters were 'second-hand' units generously provided by the US, and required only modest refinements to enable them to achieve the desired performance. The receivers were to be a new design with substantially greater output bandwidth than that used in Stage A. As a consequence, there was some concern that serious contamination might result from in-band inter-modulation distortion (IMD) of strong clutter echoes. This would likely have marginal impact on aircraft detection, being concentrated at low Doppler, but could degrade ship detection somewhat and largely destroy the remote sensing capability. Accordingly, a computer model of the 11-stage receiver used in Stage A was developed in 1979, incorporating a mathematical representation of the linear and nonlinear transfer functions of all the component elements – amplifiers, mixers and filters. Simulation began by generating a high dynamic range synthetic range-Doppler map incorporating realistic sea clutter features, representing what might be seen at the output of an ideal (perfectly linear) receiver. This was used to generate a time series, which was fed in the time-reversed sense through the receiver, that is, from the receiver output through to the receiving antenna. This simulacrum was then passed in the forward direction through the imperfect (nonlinear) receiver model, yielding a 'realistic' output for each setting of the second- and third-order intercepts for each component. By comparing the range-Doppler map of this output with the original synthetic range-Doppler map used to seed the process, the spectral distribution of nonlinear products could be determined as a function of the intercepts [4]. Using this tool, the specifications of the individual Stage B receiver stages were tightened until the receiver met the specified purity of output, which at the time was in excess of 70 dB spurious free dynamic range.

## 2.4. Signal processing architecture

Flexibility built into the signal processing structure meant that individual subroutines could be accessed in any sensible order to form the processing sequence. For example, beamforming could be carried out before or after Doppler analysis. Moreover, for some steps, inverse operations could be performed. A good example is applying the inverse FFT after an FFT. This meant that there was an option for re-entrant processing schemes, whereby the data would be processed to some stage to yield an output which could be interpreted via rules operating on certain extracted features; based on this interpretation, parameters used in the earlier processing steps would be adjusted and the data passed a second time through the sequence. As an illustration, suppose that it had been established on the first pass, using a minimum 4-sample Blackman-Harris windowing function for FFT Doppler processing selected as a default in case of a sub-clutter visibility (SCV) in excess of 75 dB, that the actual SCV was in fact only 50 dB. The data could be reprocessed using a 50 dB Dolph-Chebyshev window, preserving the achievable SCV but with a finer resolution - the 3.0 dB beamwidth of the Blackman-Harris window is 50% wider than that of the Dolph-Chebyshev window. All but the most basic remote sensing techniques benefit substantially from such an improvement.

Such a scheme was adaptive but deterministic in that the signal flow was still pre-set. Consideration was also given to the possibility of non-deterministic processing sequences. Suppose a diagnosis revealed corruption from meteor echoes or impulsive noise. The processing could then be re-run with previously inactive steps invoked to deal with the problem. With Stage B, though, the processing load and memory constraints meant that strict deterministic timing had to be enforced, with 'event flags' coordinating internal computer task interactions, so any ameliorative processing steps had to be specified at the initialisation of each radar task set-up. The disadvantage of this approach is that applying corrective processing indiscriminately to uncorrupted data can lead to signal degradation, albeit of a different form.

## 2.5. Co-existence of remote sensing with surveillance missions

It was anticipated that, subject to a successful demonstration of the much expanded capabilities of the Stage B radar, the facility would in due course be handed over the Royal Australian Air Force. Not to put too fine a point on it, there was some concern that remote sensing might be seen as a very low priority mission by service operators. This was not at all unreasonable, but it raised questions as to how the remote sensing mission could be carried out with least imposition on the main surveillance missions. The solution which evolved was to embed the basic remote sensing feature extraction algorithms into the standard ship detection signal processing routines, and store the resulting information from every dwell in a dedicated hard disk file, *seamap.dat*. Given the limitations of computing facilities at that time, this was a nontrivial task, but it was successfully implemented. When wind maps or other remote sensing output was required, special tasks were activated to read the data files and generate the processed output for display and dissemination. For high priority observations, the radar could optimise its resources for remote sensing. The merit of the solution is that the radar was producing remote sensing output whenever it was running in ship detection mode. The disadvantage was that the choice of radar frequency would have been made by the operator with a view to maximising performance for the ship detection mission, not matching radar frequency to the particular sea conditions. This turned out to be a less important concern than initially feared – much of the time the conditions for optimum ship detection are suitable for general remote sensing.

## 2.6. Linking remote sensing to surveillance missions

In 1983 the first ship detections were made with the Stage B radar, and it became apparent from the outset that radar parameter selection for this mission is a complicated optimisation task, one which persists today. A key element of radar optimisation is an understanding of the sea conditions that result in the clutter, often masking ship echoes. Therefore, effective parameter selection necessarily involves some knowledge of the ocean directional wave spectrum. In the ocean region of interest to Jindalee, there were no sources of real-time oceanographic data and only four offshore weather stations reporting at 6 hour intervals to provide meteorological information. Clearly the radar would need to generate its own oceanographic information if it wished to adapt to the environment. Unfortunately, the sheer variability of the forms of ionospheric corruption proved to be an insurmountable obstacle to the real-time fully-automated extraction of sufficiently detailed information on a routine basis. Experts familiar with ionospheric physics, oceanography and radar scattering theory could ‘read’ the ocean conditions directly off the clutter maps on the screen and adapt the radar, but regular operators could not. Several approaches were tried in order to get around this problem. Pattern recognition techniques were developed to classify the types of corruption, such as different classes of multimode [5] but, in the absence of effective mitigation techniques, were found to be of limited utility for operators. Expert systems were explored, starting in 1986 with a system called JOSE – the Jindalee Ocean Surveillance Expert [6]. This attempt was abandoned when the designer took up an overseas attachment. (A number of much more sophisticated expert systems were subsequently developed for specific purposes unrelated to remote sensing.) From 1994 onwards, ameliorative processing developed rapidly, and many effective techniques eventually found their way into the evolved Jindalee radar but the computationally expensive goal of automated real-time extraction of detailed ocean wave spectrum information was not achieved.

### 2.7. Algorithm design for remote sensing

The design for the Stage B radar envisaged a block-processing mode wherein a fixed number of time samples - 64, 128 or 256 - would be collected from each spatial cell, then this dwell would be analysed by applying a full-span window and FFT processing. The radar would proceed to the next dwell illumination region (DIR) within its assigned coverage and repeat the process (see [7] for details). Non-coherent integration to reduce the variance of the spectrum estimates was found to be very helpful to the human operators when attempting to detect ship targets against the clutter background – at the time there was no automatic detection and tracking for ships - and this was implemented by averaging several adjacent cells in the range domain. For its intended purpose this worked satisfactorily, but for remote sensing tasks the degradation in range resolution proved unacceptable. Accordingly, the radar was modified in 1984 to enable longer dwells to be collected, typically 384 sweeps, and these were processed as five 50% overlapped 128 sweep dwells. Not only were the spectral estimates thereby stabilised whilst retaining maximum range resolution, but more efficient use was made of the received signal energy and there were the options of processing the data as two 50% overlapped 256-sweep dwells or one 384 sweep dwell. Seen from today, this seems a trivial step but, for a real-time application a quarter of a century ago, it certainly wasn't. From the remote sensing perspective, it was an important development.

The specific algorithms for retrieving remote sensing information in real-time were based on extracting easily computed primary features which could be stored and combined at leisure to yield composite features, which would be mapped onto geophysical parameters. By this approach the computational burden on the real-time processors was kept to a minimum. The primary features were power spectral densities at specific frequencies in the scaled Doppler spectrum, weighted integrals over sub-bands, and some less familiar quantities, such as arc length. What made the scheme efficient was a hierarchical process, which used one feature mapping to select the next, parameterised in accordance with the first to achieve maximum sensitivity for the variable of interest. An example of a feature mapping property chart used for offline remote sensing circa 1989 is shown in Figure 1.

The composite features were used to classify corruption – in essence conducting remote sensing of the ionosphere – as well as the principal task of estimating the ocean surface parameters and inferring surface winds. The mappings were predicated on parametric ocean wave models; at the time this usually meant the Pierson-Moskowitz wavenumber spectrum with a unimodal spreading function. When greater detail was required, a slightly more sophisticated approach was used – parametric model fitting, as illustrated in Figure 2.

### 2.8. Databases, simulation and modelling

As the system converged towards a reasonably stable configuration in late 1985, the utility of databases increased. Nowhere was this more so than with the Frequency Management System (FMS), which provided advice to the operators in regards to selecting an operating frequency and finding clear channels in which to transmit [8]. Furthermore, the synoptic picture of noise and propagation conditions that emerged revealed consistent patterns, which could be used, provisionally, to schedule remote sensing missions. Some of these phenomena were eminently predictable; for example, when the dawn terminator is close to the ionospheric control point for propagation to a particular region, plasma instability corrupts the sea clutter spectrum and often renders it unusable for remote sensing. Other effects came as more of a surprise; identifying and understanding the causes of these effects continue to this day.

With the databases providing a realistic statistical description of the HF environment, it was also possible

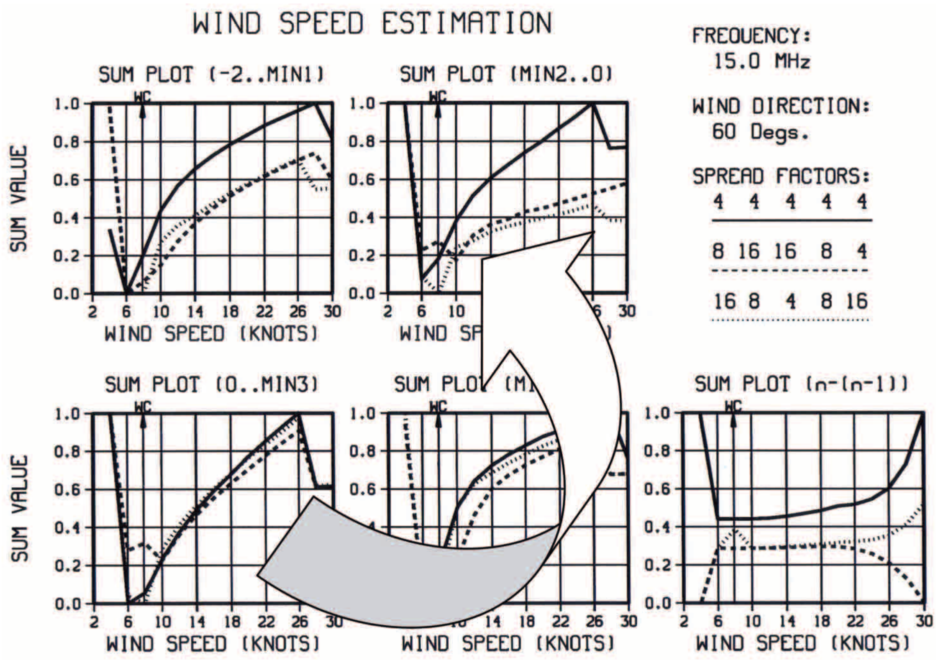


**Figure 1.** Feature mapping chart; at this frequency and for this wind direction, the feature in the lower left is least sensitive to the spreading behaviour of the directional wave spectrum, so it is used first to obtain wind speed. Then, knowing the wind speed, the spreading behaviour is obtained from the chart which shows the greatest sensitivity to spreading for the estimated wind speed.

to simulate remote sensing performance by combining the FMS information with the sea scatter models and compare it with actual radar performance.

## 2.9. Capability for extreme range measurements

The ability of HF radio broadcasts to be heard around the world is familiar to all, so it came as no surprise when signals transmitted from the Jindalee radar were received from the reverse direction via round-the-world paths [9]. After all, the Stage B transmitter power approached 160 kW, comparable with that of major short-wave radio broadcast stations which use 50 – 500 kW. What was marginally more surprising was the reception of substantial levels of backscattered clutter from long ranges, propagated via multi-hop paths in the earth-ionosphere ‘waveguide’. Of course, the cross-range dimension of a resolution cell increases with range, so at 12,000 km, say, a radar cell may be over 100 km across. Further, frequency dispersion over such long paths tends to limit useful signal bandwidths to of the order of 10 kHz, corresponding to a range resolution of 15 km. Multiplying these figures, a resolution cell may have an area exceeding 1500 $km^2$. Thus, for a typical scattering coefficient of the order of $10^{-2}$, the effective RCS of a single resolution cell may exceed 70 dBsm. On occasion, these distant echoes were found to have deleterious effects on radar performance, namely, when they were range-folded onto close-in ranges of interest, where they masked sought-after information. The excellent FMS of Stage B was able to provide warning of this eventuality when it was strong, as its coverage extended to 12,000 km, but the large gap in sensitivity between the radar and the low-power FMS meant that the main radar needed to have the ability to explore the large-scale environment.

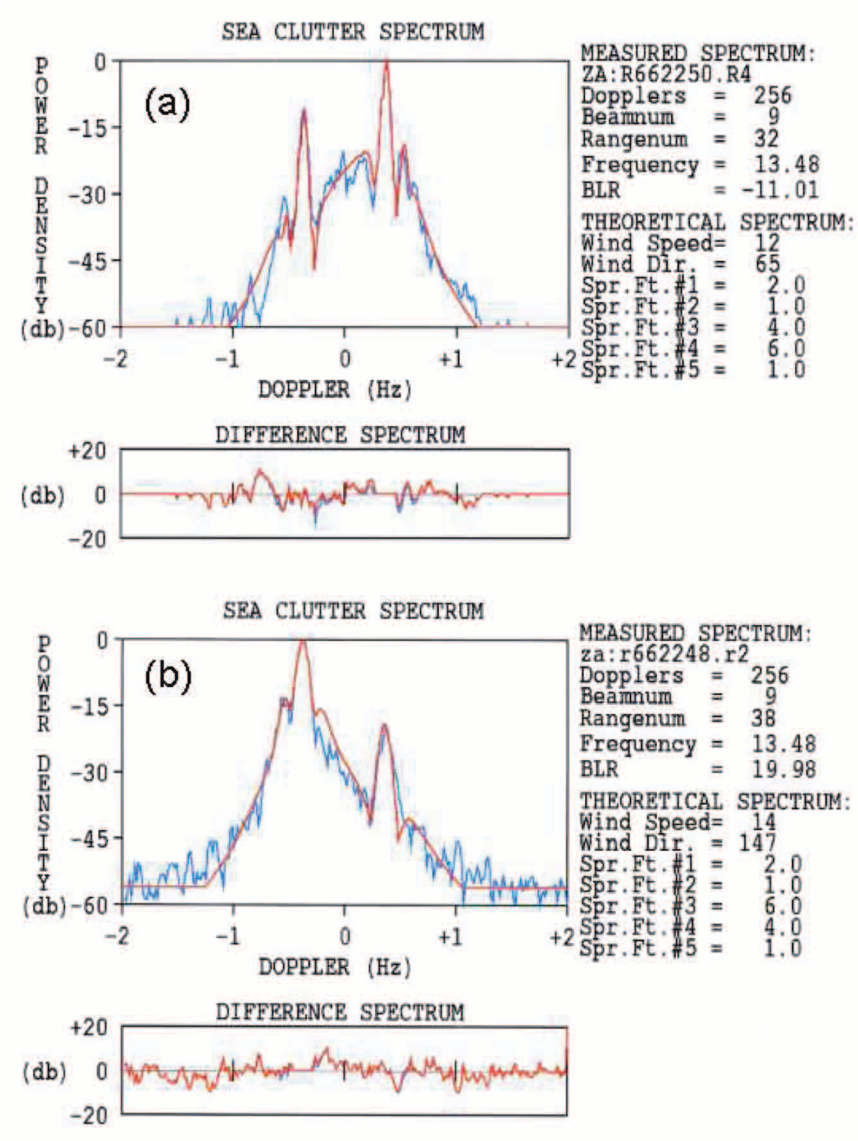


**Figure 2.** Directional wave spectra estimated by fitting clutter spectra via the 1983 JINSCAT code applied to a Pierson-Moskowitz wavenumber spectrum with a spreading function defined by a five-knot spline model of the exponent in a $\cos^{n(k)}\left(\frac{\phi-\phi_{wind}}{2}\right)$ pattern, that is, a fit using seven degrees of freedom.

When the relevance of long range observations became apparent, it was found necessary to make a number of changes to the original radar hardware and software. Some were relatively simple. For example, the synchronisation of the clock used for time-delay matching the receiver-generated replica waveform to the transmitted waveform had been designed for a maximum range offset of about 6000 km. In order to process echoes from longer ranges, or round-the-world signals, two clocks had to be cascaded. Displays and geographic databases had to be modified. More subtle changes included the need to design new waveforms with the requisite ambiguity functions.

The degradation suffered by signals propagating to such extreme ranges usually corrupted the second-order clutter components to the extent that only the Bragg peak ratio could be estimated, yielding an estimate of the prevailing wind direction averaged over the cell.

Despite the crudity of such measurements, and the statistical inhomogeneity and nonstationarity of the earth's land and sea surfaces over such scales, there were times when observations of distant ocean regions showed patterns consistent with large-scale meteorological systems. This long-range remote sensing information was never exploited, and indeed, at the time had restricted distribution. With the plethora of space-based ocean and cloud observing systems nowadays, such coarse oceanic wave field information is probably of no practical value from a weather monitoring perspective. Its value is further reduced in light of recent models of diffuse scattering processes [10, 11], which cast doubt on the accuracy of any derived wind and wave mapping.

## 2.10. Extended instantaneous range depth

The question of instantaneous range depth is a critical one in radar design. It impacts many system characteristics, including choice of antenna elements, computing requirements and mission scheduling. One significant product of the remote sensing database was a statistical analysis of data quality versus instantaneous range depth. The bottom line of this study was that a skywave radar of the Stage B design could profitably illuminate, process and extract information from a footprint of up to 1000 km range depth using a single frequency for a significant fraction of the time, and up to 2000 km on occasion. This conclusion applies to ship detection as well as remote sensing, though it does not apply as convincingly for aircraft detection. It follows that arbitrarily limiting the processed range depth to less than 1000 km could waste a valuable opportunity. A second motivation for providing extended range depth is that it provides the operator with a synoptic view of ionospheric conditions over a greater region, and this information can contribute to understanding the prevailing ionospheric 'weather' and adapting to it.

Two factors limited the number of range cells that could be processed during remote sensing operations. The first, not surprisingly, was processing capacity, but the second was the shortage of an oft-overlooked commodity – display screen real estate. The Stage B design philosophy emphasised presenting the operator with a synoptic picture of the clutter from each dwell, and this was implemented by nesting range and beam dimensions along a single dimension, with Doppler occupying the other. Compatibility with surveillance operations came at the cost of restricted instantaneous range depth.

## 2.11. Networks of OTHRs

By 1986 the many successes of Stage B had given hope to the prospect of a network of three or even more radars, with some degree of overlapping coverage to yield full velocity vectors, not just a single radial component. Accordingly, extensive studies were undertaken to determine the optimum sites for the new radars, so ensure that the overall network performance would be maximised [12]. Australia is fortunate to have such a vast land mass with relatively few constraints on radar site selection, so the possibilities were endless. It was realised that the quality and detail of remote sensing information would be substantially enhanced in a networked system, so some of the figures of merit used to select the radar sites included the predicted benefits to the remote sensing mission. One outcome of these studies was the realisation that effective exploitation of bistatism is a very complex issue but one that can pay a significant dividend in terms of clutter interpretation and control. A more specific lesson was the demonstration that locating the first radar at the best possible location for a single radar system and then deciding to expand to a two radar network and accordingly finding the best supportive location for the second radar yielded a very sub-optimum outcome.

### 2.12. JORN – the Jindalee Operational Radar Network

The decision to build the Jindalee Operational Radar Network, or JORN, was made in 1987, leading to the award of a contract to Telecom Australia, partnered by GEC-Marconi (UK), in June 1991. As part of the requirement, basic wind and wave mapping missions were specified. The unusual contractual scheme imposed by the Australian Government meant that the contractor could not access the advanced techniques and capabilities recently developed within DSTO, so the remote sensing subsystem implemented in the JORN did not achieve the full range of observational capabilities that had been demonstrated. Moreover, whereas the Stage B radar had been designed by scientists and engineers whose personal scientific interests tempted them to preserve every possible degree of freedom in the radar parameter space, the JORN was designed to a specific set of requirements. Under this approach, some combinations of parameters were not permitted, having been ruled unnecessary to meet the specifications. Later some of these constraints were removed during upgrade programs. From the remote sensing standpoint, the inclination is to maximise flexibility and versatility wherever possible. Of course, the calibre of the JORN engineering was first-class, as one would expect for an investment in excess of $\$10^9$.

## 3. Capabilities, validation and performance

### 3.1. Mapping of oceanic wind fields: Stage A

Once the Stage A radar became operational in 1976, experiments were conducted to see whether the echoes from the sea surface did indeed resemble what was predicted by the Barrick theory. The first sea clutter measurements were of rather modest quality because of the limited receiving aperture - 640 m – as well as constraints on waveforms and the absence of a comprehensive real-time frequency management system to provide advice to the operators. Display technology at the time was rudimentary by today's standards and this, coupled with processing load limitations, hampered attempts to understand what might be achievable. It is also pertinent to note that that the operators were venturing into *terra incognita*, so a steep learning curve was only to be expected.

In July 1977 and again in November 1978, remote sensing experiments were conducted in conjunction with ship detection trials. During the latter, contemporaneous wind speed and direction measurements from two offshore weather stations in the Stage A coverage were collected and superimposed on the radar-derived wind maps computed using the Long and Trizna mapping. This was not a real-time procedure – the extraction of Bragg peak ratios was performed laboriously by hand in the laboratory, the mapping applied by computer and the final overlay done manually. Nevertheless, as illustrated in Figure 3, the results were highly encouraging.

### 3.2. Synoptic remote sensing – developing the capabilities of the Stage B radar

Once the surface surveillance mode of operation for the Stage B radar became operational in January 1983, the remote sensing algorithms were refined via frequent comparisons with data from the four offshore stations within the much-expanded Stage B coverage.

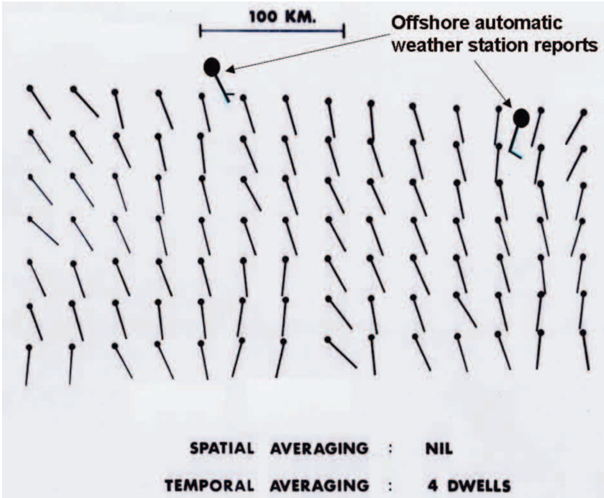


**Figure 3.** Comparison of the second Jindalee Stage A wind map with in situ measurements, recorded in November 1977.

In order to produce a product which could be delivered to clients in near real-time, appropriate geographical displays were developed and installed on the operator consoles. With a single radar, there is a left-right ambiguity in the wind direction estimate at each point in the coverage, so the displays incorporated a switch which selected one or other polarity, which was then applied to every point in the map. The two possible maps thus generated were provided to the users who had to choose which solution they thought more likely at each point. Although in principle there were $2^N$ possible solutions for a map with N points, in practice smoothness and continuity considerations, combined with the offshore weather station readings, meant that ambiguity resolution was seldom an issue. Later, a suite of other methods to guide ambiguity resolution was developed. The wind mapping task was programmed into a template, which could be called up by relatively unskilled operators at any time, to maximise the size of the database which, it was hoped, would accumulate. Accordingly, the radar parameters in this template were pre-programmed so as to minimise the need for specialist decision making and to conform to security guidelines. As originally constructed, this basic template provided coverage over a $64°$ arc, extending from 1200 to 2100 km in range, with a waveform bandwidth of 20 kHz, yielding a primary resolution in range of 7.5 km. The output maps were presented at reduced sampling density, roughly $1°$ in azimuth and 30 km in range, where the latter resulted from the non-coherent summation of spectra from adjacent blocks of 4 range cells.

## 3.3. Accuracy of the remote sensing output

Tests of the accuracy of the radar's wind direction, wind speed and sea state estimates were conducted during the many ship detection trials carried out between 1983 and 1987. Every capital ship in the Royal Australian Navy played a part in these trials at one time or another, as well as over a dozen patrol boats. The vessels would provide hourly position, course and speed information along with their meteorological and oceanographic readings, so correct geographical assignment was ensured. Radar accuracy varied with season and location within the radar coverage, but typically differences between radar estimates and shipboard measurements of wind direction fell within the range $15° - 30°$. Wind speed estimation was crude - the algorithms in use at that time linked wave height to wind speed according to the Pierson-Moskowitz ocean wave spectrum model, so the results were reported in terms of wind speed, despite the fact that the radar was really measuring the ocean surface. The wind speed estimate discrepancies from in situ observations were typically $\pm 2$ ms$^{-1}$ for wind speeds below 10 ms$^{-1}$, with a significant bias towards under-estimation.

In view of the constantly evolving state of the radar and its signal processing, DSTO did not conduct a formal statistical review of remote sensing performance, but an independent quantitative study of the wind direction estimation accuracy was carried out by the Bureau of Meteorology in 1984 as a precursor to a decision to assimilate the Jindalee data into its national weather forecasting system. This study assessed the rms error in wind direction to be 32° [13]. This was rather more than the representative numbers being quoted in the open literature, where claims of ± 15° had been reported, so reasons for the discrepancy were sought. It was concluded that the increased variance arose mainly with comparison data from coastal sites and from shipboard observations. In the former case, orographic effects were almost certainly a factor, while shipboard measurements were inevitably distorted by the ship superstructure. The essential difference between spot measurements and integrals over a resolution cell of more than 100 square kilometres was also a consideration when assessing the comparison. Still, even ± 32° was deemed operationally useful so the Stage B data was integrated into the Bureau's assimilation scheme.

It was later conjectured that the greater variance of the discrepancies with the Jindalee measurements resulted from the low and variable sea states in the test area. As a test of this hypothesis, a large dataset was acquired over several years from two sensors in the Timor Sea – a Datawell directional wave buoy recorded sea state and wave spectra, while a meteorological station measured wind speed, direction, air temperature and other parameters on an offshore oil rig less than 3 km from the buoy. An example of the extent of wind direction fluctuations at low wind speeds is shown in Figure 4.

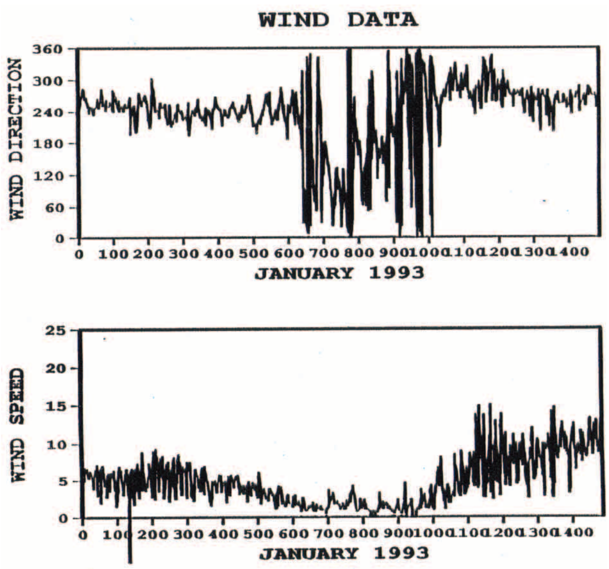


**Figure 4.** Variability of wind direction for low wind speeds in the open ocean.

Correlation analysis of wind speed against wave height confirmed that the assumptions of (i) the wavefield being in equilibrium with the wind, and (ii) the wave spectrum being fully developed at the wavenumber contributing to the radar Bragg peaks, would seldom hold.

## 3.4. Cyclone mapping

One particular issue dominated Bureau interest in Jindalee – the prospect of detecting and tracking tropical cyclones and even of detecting the precursor state of cyclogenesis. A DSTO study conducted in 1977 [14] had noted that errors in cyclone eye position tracks derived from geostationary satellite cloud images could exceed 100 km in the presence of undetectable wind shear, whereas the radar might achieve an accuracy of perhaps 10 − 20 km because it measured phenomena at the surface. Tropical Cyclone Victor in March 1986 provided an opportunity to test this proposition and, indeed, the radar-derived track was found to be superior to the composite 'best track' obtained by assimilating information from all other sources. In fact, it can be asserted that the errors in that 'best track' probably exceed the errors inherent in the radar observations. Figure 5 shows a wind direction map produced during this cyclone, essentially as transmitted to the Bureau in real-time but with streamlines superimposed.

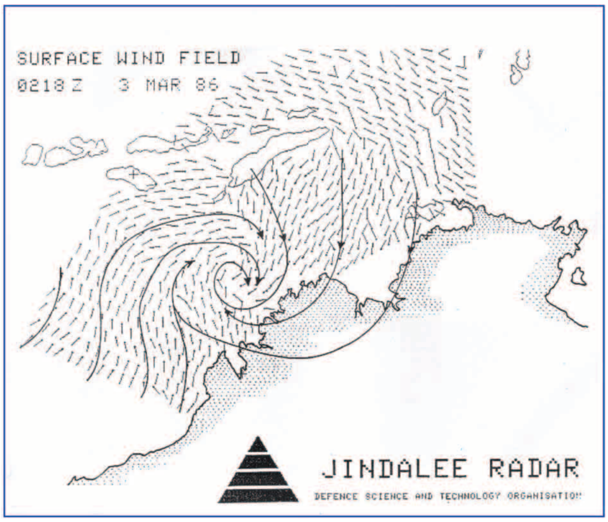


**Figure 5.** Jindalee map of Tropical Cyclone Victor as transmitted to the Bureau of Meteorology within ten minutes of commencing the measurements.

An analysis of wave height around the cyclone was later carried out, more as a test of the algorithm then used for wave height retrieval than as a guide to the actual cyclone severity. The value of this test lay in the fact the wave height around a cyclone shows a particular asymmetry, which should be evident in the radar map if the remote sensing algorithm is working properly. The result, shown in Figure 6, confirmed that the technique was satisfactory in this regard.

The more challenging problem of recognising cyclogenesis was put to the test in March 1985. Bureau analysts had decided that a cloud system in the Indian Ocean was indicative of a low pressure system in the process of evolving into a tropical cyclone, which they named 'Pancho'. The Jindalee radar was called on to provide confirmation of the correctness of this call. The radar measurements established clearly that the circulation at sea level was not closed, and therefore the call had been premature. This was borne out by the subsequent decay of the system.

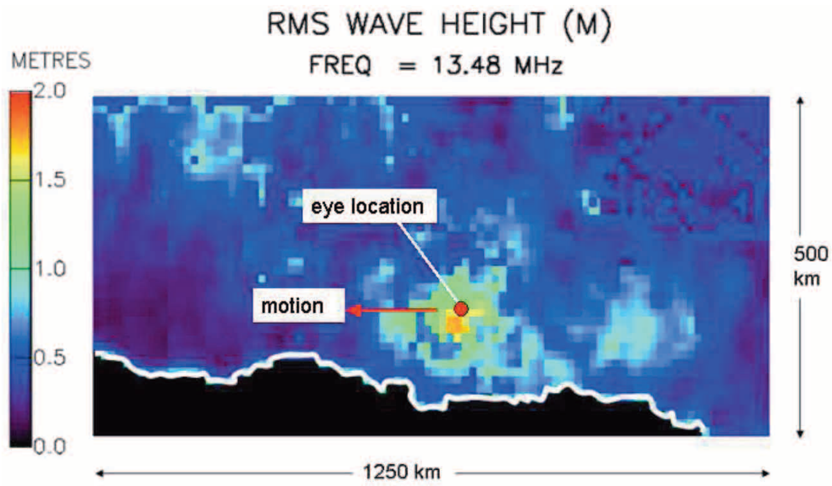


**Figure 6.** Jindalee map of RMS wave height around Tropical Cyclone Victor, March 1986. Note highest seas in advancing left quadrant.

## 3.5. Current mapping

The success of the CODAR SeaSonde HF surface wave radars in the ocean current mapping role motivated some studies of estimating current speeds via skywave, where the Doppler shift imposed by the ionospheric motions would be estimated and subtracted to leave the contribution due to the ocean currents. In practice this did not work well – the currents in the Stage B coverage were generally small, so averaging out the fluctuating ionospherically-induced Doppler shifts proved not to be feasible. On the positive side, current speeds were successfully measured in some near-coastal locations, where land echoes could be used to track and remove the ionospherically-induced Doppler shifts.

## 3.6. Remote sensing capabilities of the JORN

The two new JORN radars are more powerful and more sensitive than the Stage B radar, so they are in principle capable of providing unrivalled remote sensing coverage and detail. Given the heavy demand for strategic surveillance products from the JORN, once it came into operation in 2002, remote sensing found itself relegated to a very subordinate role. Further, the absence of DSTO input to the JORN remote sensing system design meant that it had not addressed some of the issues that years of DSTO experience had established were important. The Stage B radar, or JFAS, initially not formally considered a part of the JORN, became more and more linked to it, with all three radars being controlled from the same facility. The Royal Australian Air Force generously continues to provide DSTO researchers with some access to the radars, enabling some specific experiments, which may have a remote sensing aspect, but of course the flexibility of Stage B experimentation is no more. Today, as the JORN undergoes an upgrade, it seems more likely than not that the remote sensing processing routines and displays will not be retained.

# 4. Exploitation and clientele

## 4.1. Dissemination of remote sensing products

Once the Stage B radar had demonstrated that it could produce maps of wind direction consistent with in situ observations by Royal Australian Navy ships and the offshore weather stations, DSTO approached the Bureau of Meteorology in February 1984 with a proposal to send the maps by fax for assimilation into the Bureau's forecasting system. After the independent trial to assess the accuracy of the radar remote sensing products, the Bureau accepted this offer and, as mentioned earlier, transmission of the synoptic maps of wind direction commenced on 7 February 1985. Initially there were many constraints on release of information concerning radar coverage. When wind maps were delivered to the Bureau of Meteorology in 1985, the azimuthal arc of coverage was declared to be $\pm\ 32°$ and maximum range limited to 2100 km, with degraded resolution, but, by 1987, those limits were largely removed; wind maps could then take the appearance illustrated in Figure 7. The Royal Australian Navy Meteorology and Oceanography Branch sought and received the same maps.

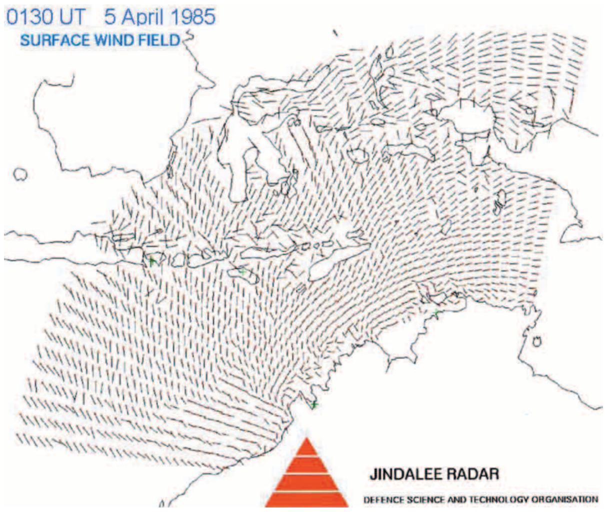


**Figure 7.** Jindalee wind direction map with extended coverage to 3000 km. This map has not been combined with its partner to resolve the ambiguity.

By 1987 the Jindalee wind maps were directly accessible on-line from the Bureau of Meteorology, avoiding the need for human intervention. The Bureau was keen to have wind speed estimates added to the wind direction data stream it received, but DSTO was well aware of the extent to which information derived from second order scattering could be corrupted by ionospheric phenomena. The consensus view was that sending no data was preferable to sending bad data, a decision well supported by subsequent developments, as discussed below.

By and large, both parties were eminently satisfied with the wind maps when they were generated by DSTO experts. Other potential clients began to express interest, including Woodside Petroleum, which operates offshore drilling facilities within the Stage B coverage, and the Tasmanian Hydro-Electric Commission, which wanted information about wave energy distributions to the south of Australia – an area not covered by the existing radar, but one which could easily have been surveyed by adding a single new transmitting antenna and a reversing capability to the receiving array. The idea of charging fees for radar-derived data was raised but discarded – the Bureau belonged to a fellow government department – while other users would benefit far more by receiving the processed output from the Bureau's assimilation scheme, which fused the radar observations with all other sources.

### 4.2. Competition for radar resources – the decline and fall of the remote sensing service

Once the RAAF assumed control of the now-upgraded radar, which happened progressively from 1991, its true potential in its primary missions became apparent. This introduced a serious problem for the remote sensing mission – as a low priority task, it was usually relegated to time slots when propagation was poorest, so as to maximise the radar duty cycle in the surveillance missions. As a consequence, the Bureau analysts noted a substantial degradation in data quality and quantity. Their interest in the radar product waned and late in 1995 the (ir)regular service ceased. Occasional Bureau requests for the JORN to map tropical cyclones near Darwin or the offshore petroleum facilities persisted for a while, but eventually even these stopped.

In retrospect, we can identify several lessons which were learned too late :

1. The DSTO researchers should have realised that once you start supplying the outside world, quality control becomes an important issue. It takes time, effort and money, but it is irresponsible to neglect it.

2. It was evident that radar performance improved dramatically with increased operator understanding of the physics, but how this should be engineered into effective radar practice is not clear. Expert system development for this task was not pursued to operational status so it remains only an idea, and one which has obvious limitations.

3. Setting generalist service operators to master numerous operator functions may have been overly ambitious – perhaps a dedicated remote sensing training scheme should have been implemented.

4. It is not only operator knowledge, but operator skill and dexterity that matters - the rapidity with which the radar operator can detect, interpret and execute system adaptation in response to changes in the propagation environment.

5. In conjunction with the previous point, the otherwise superb engineering that characterised the JORN design paid insufficient attention to the functionality of some time-critical tasks.

While this state of affairs was discouraging to those who had championed the remote sensing mission, there were two fronts on which promising developments were occurring. First, the importance of oceanographic and meteorological information for the planning, scheduling and conduct of naval operations increased substantially in the US as networked warfare concepts began to dominate military thinking. Second, research carried out in DSTO and elsewhere hinted at the prospect of new remote sensing capabilities, which might not be routinely available, but which, on the infrequent occasions when they delivered results, might play a meaningful role in areas such as pollution monitoring and climate change studies. Each of these developments has the potential to rejuvenate the remote sensing role of the Australian skywave radar systems.

# 5. Calibration, registration and scaling

## 5.1. Land-sea mapping

One particularly useful property of the remote sensing capability as implemented in Stage B in 1983 was the ability to discriminate between land and sea echoes. The exploitation of ionospheric reflection brings with it the problem of coordinate registration – establishing a mapping between the radar coordinates of time delay, direction of arrival and Doppler shift to the geographical coordinates of range, bearing and radial velocity. Even for single hop paths, the error in range incurred by wrongly interpreting an echo as having been observed via the E-layer when in fact it had been observed via the F-layer can exceed 150 km. When multiple hop propagation is involved, the error can exceed 400 km. Whether for a target echo or a cyclone map, this magnitude of error renders information virtually useless. By mapping the distribution of land versus sea returns in the processed radar 'footprint' and comparing it with the corresponding geographical map, the ionospheric reflection geometry parameters – height and tilt – can be adjusted until the correlation is maximised. Figure 8 shows an example from 1985; at that time operator intervention was necessary to adjust the assumed virtual height of reflection to achieve a visual best match.

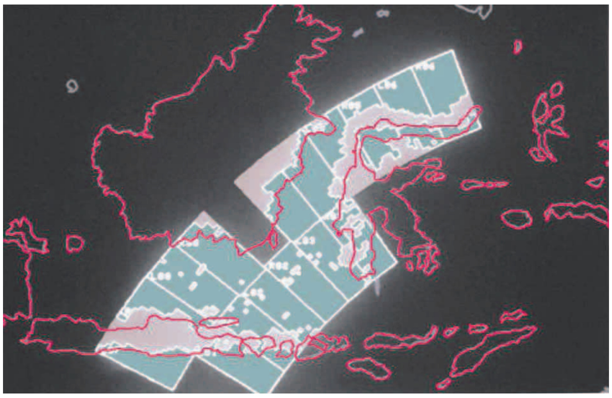

**Figure 8.** Land sea mapping under moderately clement conditions. The land clutter regions are clearly displaced relative to the geographical map, so the assumed ionospheric model parameters need to be adjusted.

In the case pictured, reasonable accuracy could be achieved by a human operator, but higher levels of ionospheric distortion often defied interpretation. Later, an automated procedure was developed, which was generalised to allow for ionospheric tilts, which then could be measured to a fraction of a degree. Depending on the actual distribution of land and sea in the footprint, registration accuracy was improved to better than the dimensions of a single radar resolution cell. The prospective improvement in accuracy for cyclone tracking was not lost on offshore oil well operators within the radar coverage, who pointed out that occasionally they had to decide, based on rough estimates from satellite cloud photographs, whether a cyclone was close enough to warrant separating the riser from the sea floor well head, at a cost of many millions of dollars lost production.

## 5.2. Array calibration

The initial scheme implemented in Stage B in 1982 involved the insertion of a common signal at the subarray centres, behind the array, and the subsequent adjustment of channel gains and phases to yield an ideal plane wave output. This scheme served the radar well until the more rigorous demands of adaptive signal processing confronted designers in the 1990's. It then became necessary to develop more sophisticated techniques, especially methods which could calibrate the entire signal path including the antenna elements. The motivation of this was to enable adaptive signal processing to reject the strong external HF interference, which could degrade the radar performance, including remote sensing products. Several approaches were explored, including the use of meteor trail echoes as sources of opportunity [15]. More recently, interest in MIMO radar at HF has raised the issue of improving calibration at the transmitting array.

## 5.3. Calibration buoys and absolute measurements of scattering coefficients

One of the most significant discoveries during the early remote sensing program was the extent to which seas in the coverage region could be under-developed, that is, have wave power spectral densities below the saturation limit. In 1978, an HF transponder was fitted to a patrol boat, the RCS accurately calibrated, and the vessel tracked for a week through the radar coverage. By using the transponder return as a reference, the scattering coefficient of the sea was measured over a range of sea conditions and related to the wave spectrum via the Bragg scattering model. Selecting only those measurements where the Bragg peak ratio indicated advancing or receding seas, to avoid spreading factor effects, and rejecting data from fetch-limited situations, the absolute power spectral density at the Bragg-resonant wavenumber was determined. Since the theoretical saturation value was known, the discrepancy was calculated and plotted against the local wind speed scaled by the wind speed required to develop the Bragg-resonant waves to saturation.

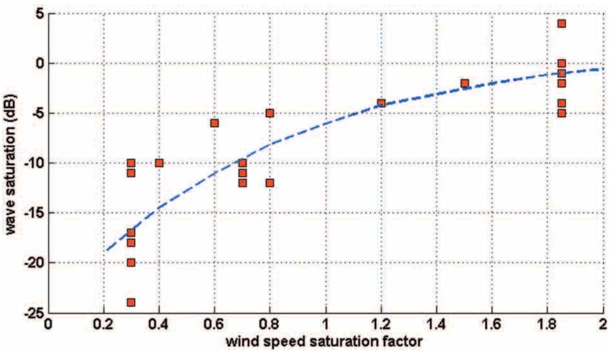


**Figure 9.** Calibrated measurements of the ratio of the measured scattering coefficient to the saturated sea scattering coefficient, plotted as a function of the ratio of wind speed to the phase speed of the Bragg-resonant waves for up-wind / down-wind observations.

The result, presented in Figure 9, illustrated the danger of assuming saturation to linearize the integral equation which arises in some approaches to inversion for directional spectrum estimation. It also highlighted the relevance of ocean remote sensing to radar frequency management for surveillance operations.

Additional experimental measurements of the absolute RCS of the sea surface were conducted in 1998 using an experimental HFSWR system located near Darwin in northern Australia, in conjunction with measurements of various small boats. For some trials a transponder was fitted to the vessel under test, as with the 1976-78 patrol boat experiments in Stage A, but others employed a floating buoy of accurately known RCS as a reference scatterer. Several variants were tested and used collectively to validate the theoretical predictions of buoy RCS. Rather than employ an active antenna with its own internal calibration issues, a passive design was adopted wherein the impedance of a monopole antenna was modulated by rapid switching between open circuit and short circuit near its base. Not only did the resulting signature extend beyond the clutter region in Doppler space, enabling it to be detected without transponder gain, the harmonic spectrum facilitated more accurate measurements of buoy dynamics. Measurements of the coupling between two such devices separated by approximately 1 km were used to discriminate between two different mechanisms, which had been postulated to contribute to surface scattering.

## 6. Clutter modelling and inversion

### 6.1. The forward problem

The clutter modelling carried out for the Stage B design employed the Barrick solution, which did not take into account bistatism, elevation angle effects or polarisation dependence. To support the remote sensing mission, a generalised solution was derived in 1983, still employing the small perturbation theoretic (SPM) approach, to explore the variation with these other parameters [16]. The results indicated that a simple scaling yielded reasonable agreement for low elevation angles or small bistatic angles as were relevant to Stage B but that under extreme conditions, such as observations at close ranges using F-layer propagation, scaling was not an adequate approximation. This is illustrated in Figure 10 which plots the variation of the Doppler spectrum with receiver azimuth for a given sea and fixed transmitter azimuth; here the V-V element of the scattering matrix is presented.

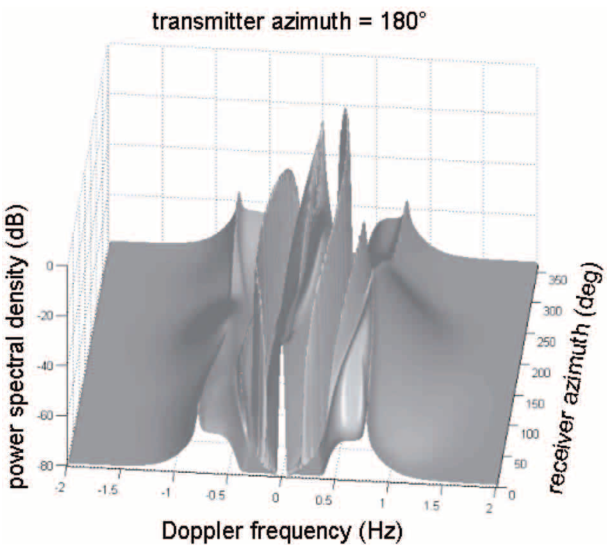


**Figure 10.** Sea clutter Doppler spectrum as a function of bistatic angle (V-V POL).

Figure 11 shows the dependence on polarisation; the important point to note is that bistatic scattering geometry destroys the symmetry of the scattering matrix, though for the modest bistatic angle of 20° used here, the asymmetry is still minor.

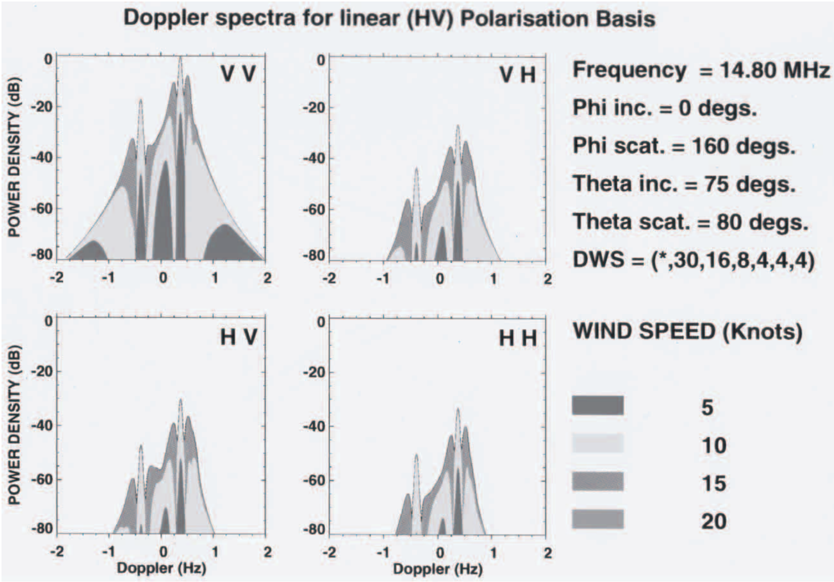


**Figure 11.** The Doppler spectra of the elements of the polarisation scattering matrix for a bistatic angle of 20°. Note the slight asymmetry between the cross-polarised spectra.

The question of polarisation dependence raised more challenging problems – depending on the choice of radar frequency relative to the maximum usable frequency and the direction of propagation relative to the geomagnetic field, differential effects across a radar cell could be handled by averaging or by projection onto a single state. It was often possible to see polarisation fringe effects in the sea echoes if one chose the frequency and propagation mode appropriately.

As the dynamic range of radar systems increased by tens of dB over the Stage A levels, concern grew that the fidelity of the modelling was not commensurate with the quality of the data. In response to this, a long-term program of research into alternative formulations of the scattering problem was set in place.

## 6.2. Representing the sea surface

Although the problem seems to be one of electromagnetics, numerical experimentation revealed that the hydrodynamic problem of correctly modelling the structure and dynamics of the sea surface is even more important. While the basic tenet of a directional wave spectrum remained the starting point, research interest turned to the question of how best to incorporate nonlinearity and coupling effects. This question remains a topic of central importance to HF radar remote sensing. While much remains to be done, a model tuned by Australian radar and wave experimental measurements has undergone a program of continuous refinement since 1992-96, when four years of wind and directional wave information was accumulated from oceanographic and meteorological sensors in the Timor Sea, within the heart of the Stage B radar coverage.

## 6.3. The inverse problem

In order to deliver any remote sensing product, the inverse problem of working from scattered signal to sea surface descriptor must be solved. In fact, there is a second level of inverse problem here – in order to estimate the surface wind field, the nonlocal inverse problem of finding the wind history responsible for an observed ocean wave spectrum which itself is responsible for the observed radar echo. The first Jindalee investigation of the problem in 1983 [17] led to the adoption of a model fitting approach in which nonlinear optimisation techniques were used to obtain the best fit to measured logarithmic power Doppler spectra based on the least squares metric. Sometimes this worked well, more often it was clear that the sea was not well represented by a simple model such as Pierson-Moskowitz. Later, more general models such as the JONSWAP spectrum form were tried, but this too failed to yield uniformly satisfactory results on many occasions. The principal reason appeared to lie in the directional spreading behaviour. In view of the limitations of the parametric approach, a non-parametric approach was developed [18]. It is based on the observation that while ocean surface dynamics in the Stage B coverage region is not accurately described by parametric wave spectrum models for much of the time, this does not contradict the utility of such models for disciplining more general models via regularisation. The scheme is outlined in Figure 12.

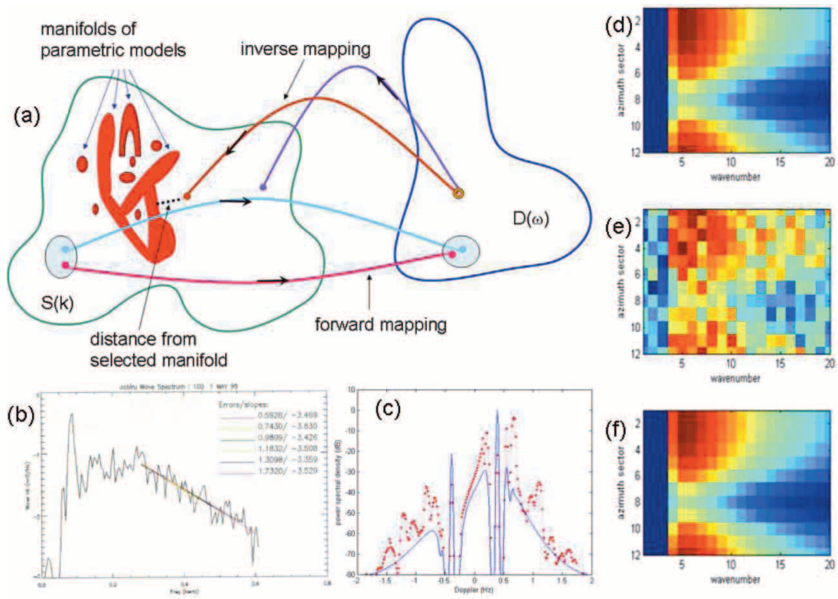


**Figure 12.** (a) Inversion scheme based on a manifold proximity regularisation functional, (b) typical measured wavenumber spectrum used to select model parameters, (c) original Doppler spectrum (continuous line) and Doppler spectrum recovered from unregularized inversion illustrating instability, (d) synthesised directional wave spectrum, (e) retrieved directional wave spectrum (no regularisation), (f) retrieved directional wave spectrum with MP regularisation.

## 6.4. Bimodality

Bimodality arises in three common ways with directional wave spectra. First, there is the case of a new sea evolving from an old sea under changing wind conditions. Second, there is the case of low frequency energy arriving as swell and long waves from a different direction to that representative of the locally generated wave field. Finally, there is bimodality in the short wave spectrum caused by nonlinear wave interactions and perhaps current shear. As a first step, a bimodal spectrum model was developed by parameterizing the Lake George wave directionality measurements of Young et. al. [19]. More recently this has been improved by modelling the behaviour observed in deeper waters. Research into how best to represent these effects so as to be able to retrieve the directional wave spectrum from sea clutter is continuing.

### 6.5. Multifrequency techniques

Having established that equilibrium conditions were the exception, not the rule, in the Stage B coverage area, the idea of exploiting multi-frequency observations to discriminate between different parts of the wavenumber spectrum and indeed, of the directional wave spectrum, was advanced as a potential solution. Measurements conducted to shed light on the actual sea behaviour under multi-frequency illumination were carried out and revealed a very complicated environment. Work on how best to exploit this kind of observation to retrieve the wave spectrum is continuing.

### 6.6. Multistatic techniques

Another 'degree of freedom' potentially available to help solve the inverse problem is the use of multistatic observations. This requires that there be at least two of either receiver or transmitter, suitably located relative to the area of interest. Such a situation was not available prior to the JORN deployment in 2003, but a useful surrogate was the dual transmitter Iluka HFSWR system tested near Darwin in 1997. Sea clutter was collected over an area illuminated by two transmitters, one 15 km from the radar, the other 95 km from the radar. For each cell in the overlapped coverage, two Doppler spectra were recorded. A preliminary analysis of this data yielded some insight into the putative benefits of multistatism [20].

### 6.7. Multiple scattering during wave propagation

The use of HFSWR measurements to study scattering behaviour without incurring the distorting effects of the ionosphere is not really as simple as it seems. The reason is that ground wave propagation experiences its own forms of signal corruption, arising from the temporal variation of the sea surface over which the surface wave progresses. This subject has been explored in considerable detail with some important conclusions about the limitations of such measurements [21]. The modelled clutter spectra show a significant redistribution of energy across the Doppler domain, with the problem exacerbated when the transmitter beam pattern is broad. A similar mechanism occurs with skywave radar, where irregularities in the ionosphere result in 'micro-multipath'. Investigations are underway to elucidate the physics involved so that filtering techniques can be developed to mitigate the signal corruption.

## 7. Propagation and availability issues

### 7.1. Statistical availability of suitable propagation conditions

A key issue with HF skywave radar is the mission duty cycle, namely the fraction of the time for which the ionosphere provides suitable propagation conditions to any given area of interest. With regard to remote sensing, different geophysical parameters have different minimum standards of channel integrity, so a first step in evaluating system performance is to define those lower bounds and then determine their statistical distributions as a function of place and time. The way this was addressed during Stage B was to model the dominant forms of signal degradation and then to apply these to synthetic clutter time series to produce corrupted spectra. The estimates of wind and wave parameters obtained from these corrupted spectra were then compared with the true values used to generate the original uncorrupted data. Based on a moderate amount of modelling, several feature thresholds were set as classification boundaries. The original designated features included sub-clutter visibility, arc length-to-area ratio and modality of the function generated by morphological processing based on grey-scale erosion by an ideal spectrum matched to the Bragg peak ratio. Later, when temporal adaptivity was introduced in 1994-95, a more sophisticated measure of multimode severity was proposed.

## 7.2. Long range propagation

The subject of long range measurements has been mentioned earlier in the context of radar design. Certainly propagation to long ranges is subject to greater variability than to the primary single hop zone. Whether or not remote sensing parameter estimates from long ranges are of value, it is pertinent to note that the patterns in the availability of propagation are still evident. An effective yet inexpensive way of monitoring the characteristics of long range propagation conditions is to record the signal strength of a selection of major short-wave radio stations around the world. Hundreds of these powerful HF transmitters are broadcasting in the HF band, from known locations, with known powers, antenna gains and schedules. In 1999, a study was carried out to assess the utility of such 'signals of opportunity' for diagnosis of ionospheric structure and perhaps even phase stability over extended regions, with a view to establishing guidelines for optimising remote sensing and other missions. *Inter alia*, the study revealed that clear patterns existed in channel transmission loss variations, especially for longer paths. Apart from providing an interesting climatology, such a database can advise real-time frequency selection by comparing prevailing signal strength with the climatological value.

## 7.3. Ionospheric motions and path stability

Most remote sensing tasks require coherent integration times of 20 – 100 s. The ionosphere is subject to a host of dynamical processes, including atmospheric gravity waves, Alfven and fast mode magneto-hydrodynamic waves, meteor trail formation and decay, plasma instabilities on many spatial and temporal scales, and sudden ionospheric disturbances resulting from impulsive solar events. For each of these processes, the propagation path experiences characteristic modulation that is imprinted on the clutter echoes from which the remote sensing information is to be extracted. In addition, long integration times magnify the problem of radio interference and impulsive noise from thunderstorms. A key thrust since 1994 in the Jindalee remote sensing program has been the identification of the physical mechanisms responsible for the observed signal distortion and contamination, and the development of ameliorative signal processing. Although some distortion mechanisms are now essentially curable, others remain debilitating, if not fatal to the remote sensing mission.

## 7.4. Polarisation transformation

Propagation via the ionosphere inevitably leads to a transformation of the polarisation state of the signal, often simplistically described as Faraday rotation though the reality is far more complex. This raises a number of questions when high dynamic range measurements of sea clutter are involved. Between 1984 and 1986 experiments were conducted using collocated transponders with orthogonal polarisation scattering matrices. Time series of the returns were acquired and used to establish the temporal scales of the variations in channel polarisation transformation [22]. This information was then combined with the polarisation dependence of the scattering from the sea surface predicted by the JINSCAT code to estimate the extent of signal degradation due to polarisation shifting during coherent integration. It was found to depend on the level of ionospheric activity – during the passage of atmospheric gravity waves, appreciable smearing could result. A second investigation examined the prospect of measuring the full scattering matrix through an intervening ionosphere with unknown parameters. A solution in the affirmative was found for the simplest geometry. Finally, an experiment was set up to study the detailed structure of one-way ionospheric propagation as a function of radar frequency, polarisation, angles of arrival (elevation and azimuth), time delay, Doppler and slow time. Various obstacles delayed the commencement of this experiment, which has only recently been completed. The goal of this investigation is to support a cost-benefit analysis of investing in fully polarimetric HF skywave radar configurations.

### 7.5. Wavefront analysis

The wavefronts that reach the receiving array after propagating via the ionosphere are seldom, if ever smooth, let alone planar. This impacts adversely the performance of most spatial processing techniques; for instance, it uses up valuable degrees of freedom in adaptive algorithms. On the positive side, it has recently been discovered that the statistics of the 'crinkles' may afford a means of identifying specific propagation modes and thereby improve coordinate registration [23].

### 7.6. Diffuse scatter

In the case of multi-hop propagation, it had been assumed in all previous models that one need consider only the forward scattered signal at the intermediate ground bounces. In a detailed study conducted in two parts, the diffuse scattering occurring from the rough sea surface at the intermediate bounces was modelled and the resultant contributions arriving at the receiver from the same direction as the notional signal, with the same time delay, were obtained by integration. The first analysis [10] revealed that the power densities were indeed significant, the second showed that the spectral structure of the contamination could significantly impact remote sensing parameter estimation [11].

## 8. Signal processing techniques

### 8.1. Spectrum analysis

The computational efficiency of the FFT saw it used for range processing (in conjunction with a linear FMCW waveform) and Doppler analysis in both the Stage A and Stage B radars. In Stage B, with multiple receiver channels, it was also used for digital beamforming. The push to step beyond the FFT paradigm for the remote sensing mission came from several directions:

1. The high Doppler resolution needed for ocean wave spectrum estimation conflicted with the increasing demands on the radar timeline. Spending 50 or 100 seconds to measure the waves in a single dwell interrogation region came to be viewed as an unaffordable luxury.

2. Even if that time were available, the ionospheric channel was seldom stable enough to support such high coherent processing gain. Phase modulation of the sea echo over such long integration times destroyed the very information that was being sought. In addition, noise and interference from other sources was much more likely to contaminate a long dwell than a short dwell of about 1 second, as employed for aircraft detection.

3. The ocean surface itself is characterised by nonstationarity associated with nonlinearity and coupling; the use of techniques geared to the spectral decomposition of a weakly stationary stochastic process would make little sense if the spectral structure evolved appreciably during the coherent integration.

To address these issues, advances were needed in several areas. First, it was clear that alternative spectrum analysis tools would be needed, able to extract the desired information from shorter time series. Second, it was essential to quantify the spatial and temporal scales of nonstationarity of the ionosphere and the ocean surface so that the point of diminishing returns for conventional processing could be identified. Third, there was an obvious role here for remedial techniques able to identify nonstationarity and transform the clutter time series into a stationary process whose spectral structure was representative of the geophysical conditions. Fourth, the likelihood of encountering noise and interference would remain high for even somewhat abbreviated remote sensing dwells, so a means of dealing with these additive phenomena without compromising the treatment of the 'multiplicative' effects would be required. Fortuitously, at the time when these issues began to receive serious attention, from the mid 1980's, the signal processing research community was brimming with developments matched to these problems.

## 8.2. High resolution spectrum estimators

The earliest investigations of high resolution techniques for clutter analysis examined parametric estimators, focussing on the maximum entropy method. This was found to be suitable for estimation of first-order clutter terms but not second order. Subsequently a number of comparative analyses were carried out, leading to the conclusion that, of a dozen or so methods tested, the modified covariance AR estimator yielded the best results for wind speed estimation and wave height analysis [24]. Later, in 1994, Thomson's multi-taper technique [25] was applied to HFSWR data and found to yield excellent results for remote sensing parameters. In particular, the reduced variance of the spectrum estimates facilitates the application of pattern recognition techniques for the extraction of remote sensing parameters. This can clearly be seen in Figure 13.

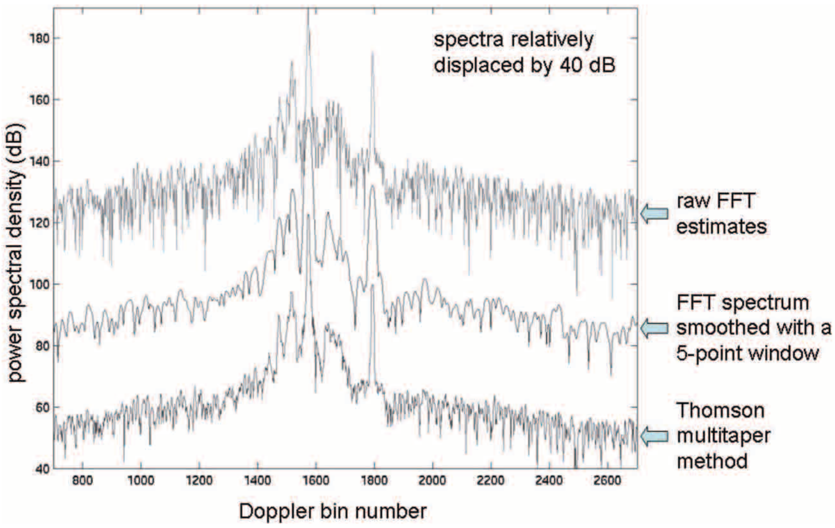


**Figure 13.** Comparison of FFT, smoothed FFT and multi-taper estimates of the sea clutter Doppler spectrum from the same time series.

A related, but much simpler approach to higher resolution involves data extrapolation to reduce the efficiency penalty associated with tapering. The fidelity of the predicted sequences is not so critical as the purpose of extrapolation here is to generate the data segments that will be tapered in accordance with the standard approach. This technique can profitably be used to double the resolution relative to that of the standard FFT [26].

## 8.3. Techniques for characterising and correcting for nonstationarity

The question of how to deal with temporal nonstationarity was addressed first from the practical perspective of how to remove it. As early as 1983 it had been proposed to apply a focusing technique based on perfect (delta function) concentration of the dominant Bragg peak energy. This approach was not implemented in the operational code because there was no sound physical basis for the implied ionospheric modulation mechanism. In 1988, the well-known Parent-Bourdillon phase demodulation method was published [27], with an explanation of the phase modulation mechanism, and this was promptly implemented in the Stage B signal processing suite. Two enhanced versions were developed: first, one that allows slow amplitude modulation, and second, one that employs two 'pilot tones' for estimating the demodulation sequence. Finally, in 1995, an entirely new technique exploiting the invariance of the rank of the clutter covariance matrix was proposed and found to yield excellent results [28]. This technique was introduced into the operational radar processing suite in 1996, but it was soon observed that the radar operators seldom invoked it. The explanation appeared to draw on four considerations. First, the remote sensing missions, and hence the long dwells, which might require nonlinear phase correction sequences, were seldom scheduled. Second, the use of high resolution spectrum estimators reduced the severity of the smearing effects by shortening the dwells. Third, the radar displays accommodated a very high dynamic range, with grey scale shading, so the broadening/focusing effects were barely discernible to the human eye. Fourth, the amplitude of the magnetic disturbances responsible for the smearing was small at the low latitudes sampled with the Stage B radar.

While these techniques were effective, they made no attempt to exploit any physical content contained in the smearing sequences. In 1991-92, bilinear time-frequency analysis was used to map the time development of the signal spectrum within the coherent integration time. Scientifically, this was rewarding. For instance, some examples suggested the presence of coupling between the amplitude variations and the rate of change of the phase modulation; polarisation effects were hypothesised to explain this. Also, the primary attribution of the phase modulation to magneto-hydrodynamic waves associated with field line resonances gained support when the spatial correlation length was estimated and found to correspond to low azimuthal wavenumbers. Operationally, though, time-frequency distributions found no role in the radar real-time processing system.

An alternative approach altogether emerged in 1994 when wavelet analysis was applied to Jindalee radar data. The computational efficiency of wavelet decomposition and filtering made real-time implementation feasible, so considerable effort was devoted to comparing wavelet methods for transient echo filtering with the heuristic techniques that were already in service. The results were certainly not overwhelming, and wavelets remained a tool for post-trial data exploration, not real-time processing.

## 8.4. Techniques for characterising nonlinearity

HF skywave radars operate with high average powers and high directive gain so, throughout the radar process, from power amplifier and transmitter, through propagation, scattering, return propagation, reception and A/D conversion, nonlinearity is present to some degree. Recognition that this should be examined led to a program during the period 1991 – 95 wherein bi-spectrum and tri-spectrum analysis was performed on time series recorded at various stages in the radar signal time-line, to see where nonlinearity might be an issue of importance to remote sensing [29]. The only domain where it was undeniably present at significant levels was in the ocean surface hydrodynamics, which one might expect would eventually manifest itself in the clutter echoes. The path to unravelling this connection is a long and tortuous one, yet to be navigated to a convincing conclusion.

## 8.5. Ameliorative processing for multimode

One of the curses of skywave radar is ionospheric multimode, that is, echoes arriving at the receiver via different propagation paths, with different Doppler shifts, possibly different spectral content, but from the same direction and with the same group delay. As early as 1984, cepstrum analysis had been considered as a possible solution, but it proved ineffective because the differential ground range between the respective clutter sources exceeded the correlation length. In 1995, an optimization approach using linear programming was implemented, but while this performed well on simulated data and handled some real situations, it was not robust enough for operational use. Thus, it was concluded that, from a remote sensing perspective, full deconvolution was not feasible. Instead, it would be necessary to characterise the multimode and try to select those parts of the spectrum which were dominated by energy from a single mode; these portions of the Doppler spectrum would then be passed on for interpretation. To do this, the land-sea mapping technique mentioned earlier was recruited. By employing the erosion-dilation operators of mathematical morphology, and knowing the true distribution of land and sea, it was shown how the relative displacements of multimode contributions could be estimated and used to guide analysis. Despite its efficacy, the technique relied on complex geographical data requiring real-time scaling to account for propagation geometry, and, hence, it did not enter the ranks of operational real-time tools.

## 8.6. Space-time adaptive processing and its generalisations

Although some recognition of the relevance of adaptive signal processing had emerged during the 1980's, it wasn't until 1994 that the serious attention of the Jindalee remote sensing practitioners became focussed on this domain. Given the now-proven efficacy of these techniques, this tardiness seems almost inexplicable, as the fact that the HF radars are almost always external noise limited had been known for decades, the anisotropy of the HF signal environment was obvious to all, and the limitations of DFT/FFT-based spatial processing were familiar to the signal processing community.

The first applications of adaptive processing in OTHR remote sensing dealt with the time domain – desmearing and impulsive noise rejection – but spatial adaptivity soon followed, to counter HF interference and as part of new array calibration schemes. An example of the impressive gains achievable with spatial adaptive processing can be seen in Figure 14, which overlays two clutter spectra, scaled to a common 'noise' floor.

The adaptive method yields a spectrum with $\sim$ 60 dB dynamic range, enough for detailed remote sensing; the conventional FFT-based method barely manages 20 dB dynamic range and is of marginal utility, even for wind mapping. Similar improvements can be delivered by joint space-time adaptive processing (STAP) when the environment is time-varying, but in this case the computational burden forced compromises in the algorithm design [30]. A particularly important development was the incorporation of the method of stochastic constraints, which enabled the temporal adaptation of the spatial response to achieve high efficiency for rejection of time-varying interference whilst preserving the phase structure of the clutter returns [31-34]. The availability of high dynamic range data from HFSWR systems provided opportunities to test and refine the algorithms, including extension to a two-dimensional array. A step towards even higher dimensional processing came with experiments carried out with a polarimetric receiving array, which showed that improved noise rejection could be obtained by adaptive filtering in the polarisation domain [35].

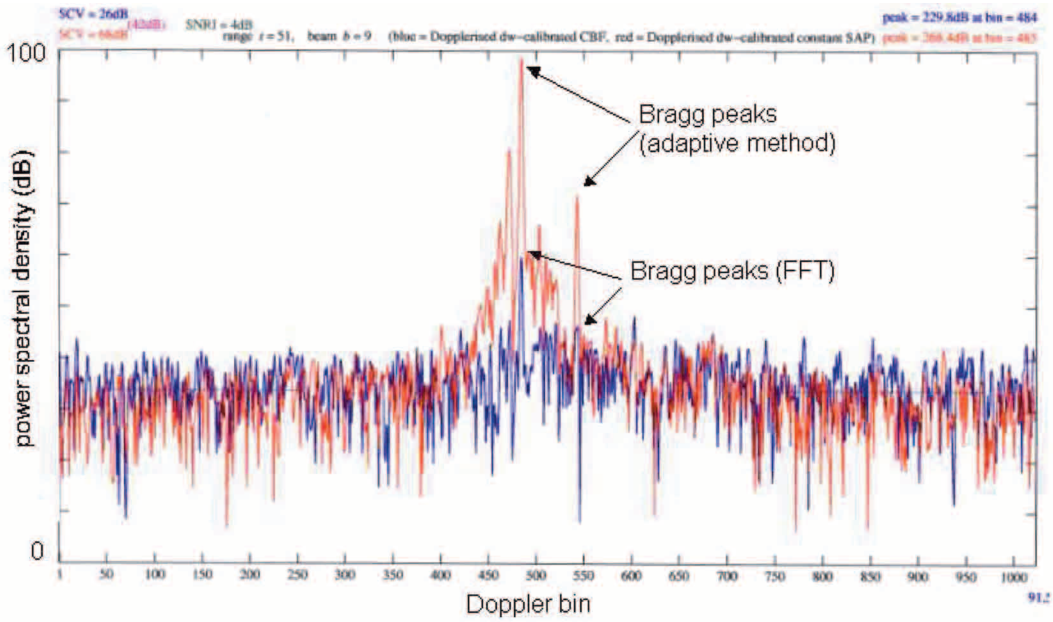


**Figure 14.** Comparison of spatially adaptive processing with conventional beamforming.

### 8.7. Dealing with multiple simultaneous forms of contamination

The diversity of sources and forms of signal distortion and contamination in OTHR means that it is often necessary to deal with multiple types of corruption occurring simultaneously. This raises some quite fundamental issues in ameliorative signal processing, such as the interaction between algorithms, non-commutativity, convergence, and so on. A study of this problem in 1998 [36] resulted in an algorithmic structure based on multiple recursive estimation of distortion parameters, which showed substantial gains over traditional processing sequences.

## 9. Other HF radar configurations

### 9.1. HF surface wave radar

In 1993, DSTO deployed an experimental HF surface wave radar (HFSWR) at Port Wakefield in Gulf St. Vincent, South Australia. Remote sensing measurements carried out with this facility provided an outstanding baseline or reference as to what could be achieved with HF radar when the ionospheric contamination effects were absent. Not only did this motivate new signal processing techniques to clean up the skywave radar data, it revealed additional ocean surface phenomena that would never have been recognised from the skywave echoes alone, including the modulation of the surface wave field by atmospheric waves. This symbiosis of skywave and surface wave radar was pursued in later research programs involving the Iluka and SECAR HFSWR systems deployed in northern Australia in 1997 and 2000 [37]. In retrospect, the HFSWR program would not have been nearly so successful without prior HF skywave radar experience, but in return, the HFSWR programs significantly enhanced the verisimilitude of the physical models of the sea surface and the scattering processes invoked by remote sensing algorithms in the skywave context.

### 9.2. Bistatic and stereoscopic radar configurations

Building on earlier investigations (e.g. [38]), an assessment of the advantages of bistatic skywave radar for remote sensing missions was explored in 1989-90 using the JINSCAT code together with a global climatological database of ocean wave spectra. It was found that in many locations where wave information could be of high importance, bistatic observations could yield superior results under conditions of high wind speeds, especially when combined with monostatic data.

There are many anisotropies in the geophysical environment, including the geomagnetic field, prevailing winds, wave climates, ocean currents and large-scale ionospheric structures, such as the equatorial anomaly, so it would seem self-evident that the performance of an HF radar interrogating a given patch of the ocean surface will depend in a very complex way on the direction from which the viewing takes place. With bistatic radars, the problem is even more complicated. Experience has shown that the consequences of overly simplistic modelling for site selection can be serious, so a site optimisation method based on a genetic algorithm was developed in 2006 and applied to a particular HFSWR system. In the skywave radar context, the question as to which environmental phenomena need to be included has been investigated recently for the case of OTHR deployments at equatorial latitudes [39] ,

### 9.3. Ship-borne SAR at HF

Another subject of perennial inquiry concerning HF radar is the potential for ship-based systems to measure whilst underway, achieving the necessary azimuthal resolution by means of aperture synthesis. An investigation was conducted with the assistance of the Commonwealth Scientific and Industrial Research Organization(CSIRO), who provided ship pitch, roll and heave time series for a survey ship in transit in the Southern Ocean. By estimating the phase modulation imposed on the radar signals by the random ship motions, the extent of degradation of sampled sea clutter Doppler spectra was estimated. The results suggest that in a typically directional sea, optimum courses could be designed with the property that the clutter smearing could be reversed with reasonable efficacy.

### 9.4. PCL techniques

In recent years there has been a resurgence of interest in exploiting transmissions of opportunity not merely as indicators of ionospheric structure, but as the actual probing signals which are collected and analysed to extract information about the objects and surfaces from which they have been scattered. This technique – usually termed passive coherent location – has been applied at HF for various configurations, including skywave radar. A theoretical study carried out in 2005 demonstrated that this form of radar might support a few niche applications, but that it was unlikely to approach the levels of performance which are needed to yield worthwhile information in a remote sensing role. The key problem is the fact that most transmissions in this band have narrow effective bandwidths and, worse, poor ambiguity functions.

### 9.5. MIMO techniques at HF

Another form of OTHR that has received attention recently adopts the multiple input, multiple output (MIMO) paradigm. In the Australian HF radar context this has taken two forms: (i) experiments and associated signal processing research with the JORN Laverton skywave radar, and (ii) computer modelling of the consequences of multiple scattering in HFSWR systems and the potential of MIMO techniques to overcome the resultant contamination of remote sensing information caused by inappropriate transmit antenna illumination patterns. From a remote sensing viewpoint, MIMO appears to be a particularly relevant concept to exploit because the signal of interest, that is, the clutter, is strong, so sensitivity can be traded for the ability to discriminate between echoes arriving at the receiver from the same direction, with the same time delay and Doppler support, but having been scattered from different patches of the ocean. Whether MIMO will fulfill its apparent promise is still an open question.

## 10. Exotica

A surprising number of investigations into the remote sensing possibilities latent in HF radar came as responses to natural disasters or other singular natural events. In each case the procedure was more or less the same – a theoretical study of the physics involved was followed by a simulation in which Jindalee radar parameters were used to assess the viability of predicting, detecting, measuring or monitoring the event. In some instances the outcome of the investigation could be estimated with some confidence from a back-of-the-envelope analysis, but often the need for a formal report to relevant authorities dictated that a more rigorous study be undertaken.

The first such study followed an incident where a British Airways Boeing 747 jet en route from Jakarta to Perth suffered engine failure in three of its four engines after flying through an elevated cloud of dust ejected during a volcanic eruption on Java. This was followed by studies of oil spill detection, algal blooms ('red tides'), soil moisture fluctuations, internal waves, large industrial (or other) explosions, intense rainfall over the ocean, solar eclipses, tropical cyclones, earthquake precursors, convective cells, and tsunami detection.

It is rather obvious that, for most of these phenomena, sensors other than OTHR would be far better suited to the task, but, if the only sensor available at the time is an OTHR, then the question of capability is a valid one. Still, the majority of the studies concluded that the event of interest might be observable by HF skywave radar only under the most favourable conditions, with optimum site selection and radar design. For HF surface wave radar, the conclusions were generally more positive.

## 11. Where are we now?

The present low priority accorded the remote sensing capabilities of the JORN radars is indicative of one prospective future of operational skywave remote sensing with the Australian military radars. A more positive development may be in the offing with the proposal to construct a civilian radar of the SuperDARN type in Northern Australia to complement the South-looking TIGER radar in Tasmania. While the remote sensing capabilities of these radars are rather limited when compared with the high sensitivity, high resolution JORN radars, the freedom to task the SuperDARN radars with remote sensing missions more or less at will is a powerful argument in their favour.

Notwithstanding the somewhat gloomy prognosis for operational remote sensing, there are reasons for optimism:

1. The JORN radars are immensely capable sensors, with a program of continuous upgrades driven by DSTO scientific and technological input.

2. DSTO continues to support a team of roughly fifty people conducting research and development related to OTHR.

3. The scientists have limited, but generally adequate access to the radars to test ideas emerging from the laboratory.

4. As this paper has attempted to show, a substantial body of knowledge and experience has been accumulated over some 35 years of OTHR remote sensing research, spanning the modelling of geophysical phenomena, the design and implementation of radar techniques, and the formulation and solution of the resulting inverse problems.

### 11.1. Conclusion

The Australian OTHR remote sensing program has pursued its scientific goals with considerable success. Many of its achievements have not been matched elsewhere. Moreover, the substantial body of experimental and theoretical research surveyed in this paper has added enormously to our understanding of the capabilities and limitations of OTHR. True, in terms of national utilization of the remote sensing products, it has yielded surprisingly little return on the investment after the original collaboration with the Bureau of Meteorology between 1984 and 1995. To some extent this is because of the emergence of space-based meteorological and oceanographic observing systems, whose performance is often more reliable than that of OTHR, and for which standardized data assimilation tools are available. Yet, discussions with practising meteorologists reaffirm that OTHR could still make an important contribution in some domains.

It would appear that, in Australia, remote sensing with OTHR has been the victim of the success of the three major radars in their primary roles of air and surface surveillance. A decade of successful delivery of synoptic wind maps was a unique demonstration of OTHR's remote sensing potential but, in the absence of strong support from all the agencies involved, this achievement is unlikely to be followed by an ongoing operational remote sensing service.

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## References

[1] A.E. Long, D.B. Trizna. "Mapping of North Atlantic winds by HF radar sea backscatter interpretation." *IEEE Trans. Antennas and Propagation*, Vol. AP-21 (5), pp.680-685, 1973.

[2] D.E. Barrick. "Chapter 12: Remote sensing of sea state by radar." in *Remote Sensing of the Trosphere*, V.E. Derr, Boulder, CO: NOAA/Environmental Research Laboratories, pp. 12.1 – 12.6

[3] S.J. Anderson. “Design implications of a ship detection requirement for JINDALEE Stage B.” Weapons Research Establishment Technical Memorandum WRE-TM-B95 (AP), July 1976.

[4] S.J. Anderson. “Simulation and modelling for the JINDALEE skywave radar.” *Mathematics and Computation in Simulation*, Vol. 27, pp. 241-247, April 1985.

[5] S.J. Anderson. “Adaptive remote sensing with HF skywave radar.” *Proceedings of the IEE*, Part F, Vol.139, No.2, pp.182-192, April 1992.

[6] S.J. Anderson. “Remote sensing with the JINDALEE skywave radar.”, *IEEE Journal of Oceanic Engineering*, Vol. OE-11, pp.158-163, April 1986.

[7] G.F. Earl, B.D. Ward. “Frequency management support for remote sea-state sensing using the JINDALEE skywave radar.” *IEEE J. of Oceanic Engr.*, Vol. OE-11, pp. 164-173, April 1986.

[8] J.M. Headrick, S.J. Anderson. “Chapter 20: HF vver-the-horizon radar.” in *Radar Handbook*, Merrill Skolnik, (Ed.), $3^{rd}$ edition, McGraw-Hill, 2008.

[9] M.A. Tyler. “Round-the-world high frequency propagation: A synoptic study.” *DSTO Research Report DSTO-RR-0059*, 1995.

[10] S.J. Anderson. “Limitations to the extraction of information from multi-hop skywave radar signals.” *Proceedings of IEEE International Conference on Radar*, RADAR 2003, Adelaide, September 2003.

[11] S.J. Anderson. “The Doppler structure of diffusely-scattered multi-hop skywave radar echoes.” *Proceedings of the International Conference on Radar*, RADAR 2004, Toulouse, October 2004.

[12] S.P. Tucker, S.J. Anderson. “Site evaluation for a network of multi-role OTH-B radars.” *Electronic Research Laboratory Technical Memorandum ERL-0389-TM*, November 1986.

[13] T.D. Keenan, S.J. Anderson. “JINDALEE skywave radar sensing of oceanic wind fields.” in *Windows on Australian Meteorology*, E.K.Webb (ed.), Australian Meteorological and Oceanographic Society, 1997.

[14] S.J. Anderson. “Over-the horizon radar meteorology.” *Weapons Research Establishment Technical Report WRE-TR-1752 (A)*, April 1977.

[15] I.S.D. Solomon, D.A. Gray, Y.I. Abramovich, S.J. Anderson. “Over-the-horizon radar array calibration using echoes from ionised meteor trails.” *IEE Proceedings F - Radar, Sonar and Navigation*, Vol. 145, No. 3, pp.173-180, June 1998.

[16] S.J. Anderson, W.C. Anderson. “Bistatic HF scattering from the ocean surface and its application to remote sensing of seastate.”in *Proc. IEEE APS International Symposium*, Blacksburg, VA, USA, June 1987.

[17] S.J. Anderson. “The extraction of wind and sea state parameters from HF skywave radar echoes.” *IREECON International Digest*, IREECON-83, Sydney, Australia, pp.654-656, September 1983.

[18] S.J. Anderson. “Regularisation functionals for a class of nonlinear inverse problems in rough surface scattering.” in *Computational Techniques and Applications Conference (CTAC 04),* Melbourne, September 2004.

[19] I.R. Young, L. A. Verhagen, M. L. Banner. “A note on the bimodal directional spreading of fetch-limited waves.” *J. Geophys. Res.*, Vol.100, pp. 773–778, 1995.

[20] S.J. Anderson. "Directional wave spectrum measurement with multistatic HF surface wave radar." in *Proceedings of the IEEE International Geophysics and Remote Sensing Symposium*, IGARSS 2000, Honolulu, July 2000.

[21] S.J. Anderson. "Multiple scattering of HF surface waves: Implications for radar design and sea clutter interpretation." Invited paper submitted to *IET Radar, Sonar & Navigation*, September 2009.

[22] S.J. Anderson. "Ionospheric Faraday rotation signatures in the space-time-frequency domain." in *Proceedings of the IEE International HF Radio Conference*, Edinburgh, Scotland, pp. 167 - 172, July 1991.

[23] S.J. Anderson. "Multiple scattering of HF skywave radar signals - Physics, interpretation and exploitation."in *Proceedings of the IEEE Radar Conference*, RADARCON 2008, Rome, May 2008.

[24] S.J. Anderson, A.R. Mahoney. "Spectral estimation techniques for HF sea clutter analysis." *International Symposium on Signal Processing and its Applications*, Gold Coast, Australia, pp.123 – 128, August 1990.

[25] D.J. Thomson. "Spectrum estimation and harmonic analysis."in *Proc. IEEE*, Vol. 70, No. 9, pp. 1055-1096, 1982.

[26] D.N. Swingler, R.S. Walker. "Line-array beamforming using linear prediction for aperture interpolation and extrapolation." *IEEE Trans. Acoust. Speech Signal Processing*, Vol. 37, pp. 16-30, 1989.

[27] J. Parent, A. Bourdillon. "A method to correct HF skywave backscattered signals for ionospheric frequency modulation." *IEEE Trans. Antennas and Propagation*, Vol. AP-36, No.1, pp.127-135, 1988.

[28] S.J. Anderson. "Inverse problems in HF radar." in *Coupling of Fluids, Structures and Waves in Aeronautics*, Springer Book Series Notes on Numerical Fluid Mechanics, Vol. 85, October 2003.

[29] S.J. Anderson, A.R. Mahoney, A.O. Zollo. "Applications of higher-order statistical signal processing to radar." in *Higher-Order Statistical Signal Processing*, B. Boashash, E.J. Powers and A.M. Zoubir, Longman Australia and Halstead Press, 1995, pp. 405-446.

[30] G.A. Fabrizio, Y.I. Abramovich, S.J. Anderson, D.A. Gray, M.D.E. Turley. "Adaptive cancellation of nonstationary interference in HF antenna arrays." in *IEE Proceedings - Radar, Sonar and Navigation*, Vol. 145, No.1, pp.19-24, February 1998.

[31] S.J. Anderson, Y.I. Abramovich, G.A. Fabrizio. "Stochastic constraints in nonstationary hot clutter cancellation." in *Proceedings of the International Conference on Acoustics, Speech and Signal Processing*, ICASSP'97, Vol. 5, pp. 3753-3756, Munich, Germany, May 1997.

[32] Y.I. Abramovich, S.J. Anderson, A.Y. Gorokhov, N.K. Spencer. "Stochastic constraints method in nonstationary hot clutter cancellation, Part I : Fundamentals and supervised training applications." *IEEE Transactions on Aerospace and Electronic Systems*, Vol. 34, No. 4, pp. 1271-1292, October 1998.

[33] Y.I. Abramovich, S.J. Anderson, A.Y. Gorokhov, N.K. Spencer. "Stochastic constraints method in nonstationary hot clutter cancellation, Part II : Unsupervised training applications.' *IEEE Transactions on Aerospace and Electronic Systems*, Vol 36, No.1, pp. 132 – 149, January 2000.

[34] Y.I. Abramovich, S.J. Anderson, A.Y. Gorokhov, N.K. Spencer. "Stochastically constrained spatial and spatio-temporal adaptive processing for nonstationary hot-clutter cancellation." in *Applications of Space-time Adaptive Processing*, R.K. Klemm, Springer, 2004.

[35] Y.I. Abramovich, N.K. Spencer, S. Tarnavskii, S.J. Anderson. "Experimental trials on environmental noise rejection by adaptive spatio-polarimetric processing for HF surface wave radar."in *Proceedings of the German Radar Symposium*, GRS 2000, Berlin, October 2000.

[36] S.J. Anderson, Y.I. Abramovich. "A unified approach to detection, classification and correction of ionospheric distortion in HF skywave radar systems." *Radio Science*, Vol.33, No.4, pp.1055–1067, July-August 1998.

[37] S.J. Anderson, P.J. Edwards, P. Marrone, Y.I. Abramovich. "Investigations with SECAR - a bistatic HF surface wave radar."in *Proceedings of IEEE International Conference on Radar*, RADAR 2003, Adelaide, September 2003.

[38] S.J. Anderson. "Stereoscopic and bistatic skywave radars: Assessment of capabilities and limitations."in *Proceedings of Radarcon-90*, Adelaide, Australia, pp.305-313, April 1990.

[39] S.J. Anderson. "Geophysical considerations in the design of equatorial OTH radar systems." submitted to *Radio Science*, October 2009.