CHAPTER 21

HF-RADAR MAPPING OF EXTENSIVE OCEAN WINDFIELDS

by

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1 INTRODUCTION

The possibility of deriving parameters of sea wave spectra remotely from characteristics of radio waves at high frequency (HF) scattered from the sea surface was first raised when Crombie (1955) correctly deduced that Doppler frequency shifts in the signal returned from short range in his HF radar resulted uniquely from components of the sea wave spectrum having wavelengths exactly one-half the radio wavelength, and travelling radially with respect to the radar. Since then the technique has been expanded in two directions:

(a) The use of ionospherically propagated HF radio waves ('Skywave' HF radar) to examine extensive ocean areas out to some 4000 km from the observing site, to obtain oceanographic and meteorological data suitable for input to synoptic observation systems. This approach has been developed through the experimental work of Tveten (1967) and Ward (1969), and the empirical technique proposed by Long and Trizna (1973) to allow the simple extraction of sea surface wind vectors from Doppler spectra of the backscattered radio signals.

(b) The determination of directional sea wave spectra and sea surface currents at short ranges with HF radars operating in the ground-wave propagation mode, based on theoretical analyses of the scattering process such as those of Barrick (1972).

The HF Skywave radar constructed and operated at Townsville by the Physics Department of James Cook University has been employed for some years now on research into the possibilities for mapping sea states and sea surface winds over ocean areas surrounding Australia (Ward, 1969; Ward and Dexter, 1976; Dexter and Casey, 1978).

While the high spatial resolution necessary for the accurate mapping of such meteorological systems as tropical cyclones with a Skywave radar (Maresca and Carlson, 1979) can be achieved with extensive aerial arrays, these arrays are necessarily fixed, and the spatial coverage which may be obtained is thus limited. The James Cook University radar employs a fully rotatable aerial array, thus enabling a full 360° azimuthal cov-

erage of the sea surface, out to ranges approaching 4000 km from the coastline. The limited physical size of the array in this case in turn limits spatial resolution, although the resolution obtainable is sufficient to delineate most large-scale meteorological systems (Dexter and Casey, 1978).

The present paper will describe briefly the James Cook University radar, and discuss recent results involving the mapping of sea surface wind vectors over extensive ocean areas to the east and south of Australia. It will also examine some of the limitations imposed on data collection and analysis by a moving ionosphere, and will argue that the resolution and coverage of the James Cook University radar are well suited to the input data requirements of numerical meteorological analysis and forecast systems currently in use for the southern hemisphere.

2 RADIO THEORY

The backscatter of HF radio waves from the sea sumface is interpreted, to first order, as a Bragg resonant interaction between the incident radio waves and ocean waves of one half the radio wavelength propagating along the radar radial. The backscattered radio wave has a Doppler frequency shift imposed by the moving ocean waves, and its frequency spectrum contains discrete components at

$$\omega = \omega_o \pm (2gk_o)^{\frac{1}{2}} = \omega_o \pm \omega_B \qquad (1)$$

where k_o and ω_o are the wave number and frequency of the incident radiation (wavelength g_o) and g is gravitational acceleration. These components, the Bragg lines, correspond to advancing and receding ocean waves, respectively. The ratio r of the amplitudes of the two Bragg lines is directly related to the relative proportions of advancing to receding waves and, through a directional model of the sea wave spectrum, may be interpreted in terms of surface wind direction. For the James Cook University radar, operating at 21.84 MHz, Bragg scatter occurs from ocean waves of 6.9 m wave length. These waves will be in equilibrium with the local wind for all wind speeds above about 4 m/s.

Unfortunately, this saturation of the resonant ocean wave components means that the Bragg lines can supply no information on state of development of the sea (in simple terms, wave heights or ultimately surface wind speeds). For this information recourse must be made to second and higher order scattering, which produces lower-level sidebands in the frequency spectrum of the backscattered signal. Various empirical and theoretical techniques have been developed to extract relevant information from the second order Doppler spectrum. For a full discussion of radio scatter theory, to both first and second order, see Barrick (1972, 1977, 1978), Johnstone (1975) and Lipa (1977).

3 RADAR FACILITY

The James Cook University HF skywave radar has been described in detail by Ward and Dexter (1976), Dexter and Casey (1978) and Dexter (1979). Some of the characteristics of the facility are summarised in Table 1.

TABLE I

JAMES COOK UNIVERSITY HF SKYWAVE RADAR

Transmitter	
Operating frequency	21.840 MHz
Peak power	20 kW
Pulse repetition frequency	25 Hz
Pulse length	0.5-1.0 ms
Receiver	
Bandwidth	1-4 kHz
Antenna (monostatic)	
Gain	+13 dB over free space dipole
Front/back ratio	+20 dB
Beamwidth	24^{o} (-3 dB points)
Sidelobes	-15 dB
Targets	
Range coverage	1000-4000 km
Range resolution	0.5 ms group delay ≡ 75 km
Angle coverage	360^{o} of azimuth
Angle resolution	Of the order of $\pm 7^{o}$ (700 km at 3000 km range)
Expected Bragg Doppler	±0.475 Hz
Doppler resolution	0.04 Hz system, 0.14 Hz due to ionosphere
Range accuracy - relative	30-40 km
- absolute	around 50 km
Angle accuracy	$\pm 0.5^{o}$

4 OBSERVATIONS, ANALYSIS AND INTERPRETATION

A quasi-operational test of system performance was conducted on 26 October 1978. Observations were made during the 3 hour period 0130Z to 0430Z (the optimum time as determined by Ward (1972) and Heron and Rose (1978(a)) to minimise mean ionospheric Doppler shifts), with 102.4s data blocks being obtained from scattering areas selected at group delays of from 9 ms to 25 ms (ground ranges approximately 1200 to 3700 km) on azimuths from true bearing 050^{o} from Townsville to true bearing 190^{o}. Radar coverage was thus fairly uniform over a total sea area of some 2×10^{7} km^{2} in the Coral Sea, Tasman Sea and Southern Ocean (Fig 2).

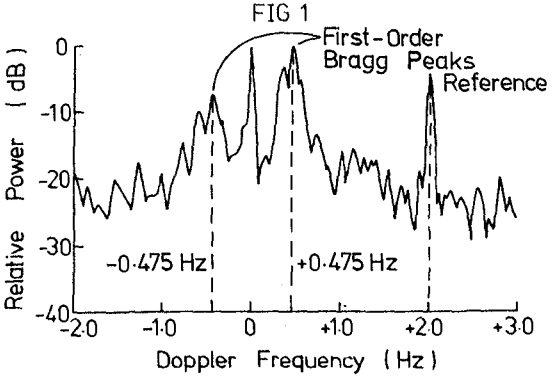

Figure 1 Doppler spectrum from 102.4s of data recorded near 0230Z on 26 October 1978. Scattering area located on true bearing 070° from Townsville, at a ground range of 2800 km. Bragg peaks (exhibiting multipath) occur at ±0.475 Hz. Peaks at Doppler frequency shifts of 0 Hz and 2 Hz represent transmitter frequency leakage and a reference signal, respectively.

The 102.4s data blocks for each scattering cell were digitised at 10/s. The resulting 1024 data points were divided into four sets of 256 points, spectral analysis performed on each with an FFT, and the resulting raw spectral estimates incoherently averaged to give spectral resolution of 0.04Hz and approximate 90 per cent confidence limits of +2.0 and -3.1 dB (Dexter and Casey, 1978; Dexter 1979).

An example of the resulting Doppler spectrum for a single scattering cell (true bearing 070°, range 2800 km from Townsville) is shown in Fig 1. There was some leakage of transmitter frequency into the processor circuitry during this experiment, and this has resulted in the peak at zero Doppler frequency. The spectral line near +2Hz is a locally injected reference.

The frequency spectrum exhibits both positive and negative first-order lines, with the dominant positive line indicating approaching waves (and winds). Wind direction analyses were performed on this and similar spectra for all scattering cells using the technique of Stewart and Barnum (1975). Briefly, this assumes a wave directional spectrum of the form

$$g(\theta) = \cos^{s} (\theta/2) \qquad (2)$$

where θ is the angle between mean wind and radio propagation direction, and s is a parameter related to wind speed (Tyler et al., 1974). The ratio of advancing to receding waves is thus $\tan^{s} (\theta/2)$. However, this is also the ratio of the advance to recede Bragg line amplitudes, A^{+} and A^{-} respectively. Thus

$$\theta = 2 \arctan \left(\frac{A^{+}}{A^{-}}\right)^{\frac{1}{s}} \qquad (3)$$

In practice, for reasons discussed by Dexter and Casey (1978), a uniform wind speed of 10 m/s was adopted in this analysis. Full results of the direction analysis are shown in Fig 2. The fit to the meteorological mean sea level (MSL) pressure analysis for 0300 Z (1300 h local time) on 26 October is obviously good, particularly when allowance is made for cross-isobar flow. A similar direction analysis using the technique of Long and Trizna (1973) was also performed, with inferior results (although this technique has been used with success in the North Atlantic by Shearman et al. (1977)).

Most of the Doppler spectra obtained in this experiment (including that shown in Fig 1), display features characteristic of an unstable ionospheric propagation mode. Of most significance are:

(a) ionospheric multipath, manifest as a splitting of the Bragg lines into three or more distinct peaks;

(b) broadening of the Bragg lines due to small scale and random ionospheric movements, imposing a spectral resolution limit of the order of 0.14 Hz (at 21.840 MHz), as found by Heron and Rose (1978(b)).

Neither of these phenomena affects wind direction determinations, but both interfere substantially with wind speed computations. The approach employed in this case was again that of Stewart and Barnum (1975), in which the width (B) of the principal Bragg line, at a level 10 dB below the peak, is related empirically to surface wind speed. The approach can only be applied to spectra which do not exhibit multipath, and the particular empirical relationship employed has been that derived by Dexter and Casey (1978). The few wind speeds which could be computed in this way are also displayed in Fig 2. Comparison with available surface observations is reasonable.

Absolute ground ranges have been computed for all scattering cells using ionospheric data supplied by the Australian Ionospheric Prediction Service for Brisbane, applied to a technique devised by Dexter (1979). These ranges could only be confirmed where identifiable land features occurred in a scattering cell, but errors are unlikely to be greater than system range resolution.

5 DISCUSSION

While the low spatial resolution (average scattering cell for 'almost independent' observations of the order of 150 km × 470 km) of the James Cook University radar makes it unsuitable for the detailed observations of such small-scale atmospheric features as fronts and tropical cyclones as have been attained with the high resolution radar of Barnum et al. (1977) and Maresca et al. (1978), its flexibility of operation and large scanning area do afford other advantages. In particular, a total potential sea area coverage of some 5×10^7 km^2 makes this radar an attractive possibility for the observation of surface wind vectors over a significant portion of the data sparse southern hemisphere oceans. An illustration of the areal coverage for the radar when sited at Townsville and near Alice Springs is shown in Fig. 3. It remains to be seen whether such data is compatible with required meteorological synoptic analyses.

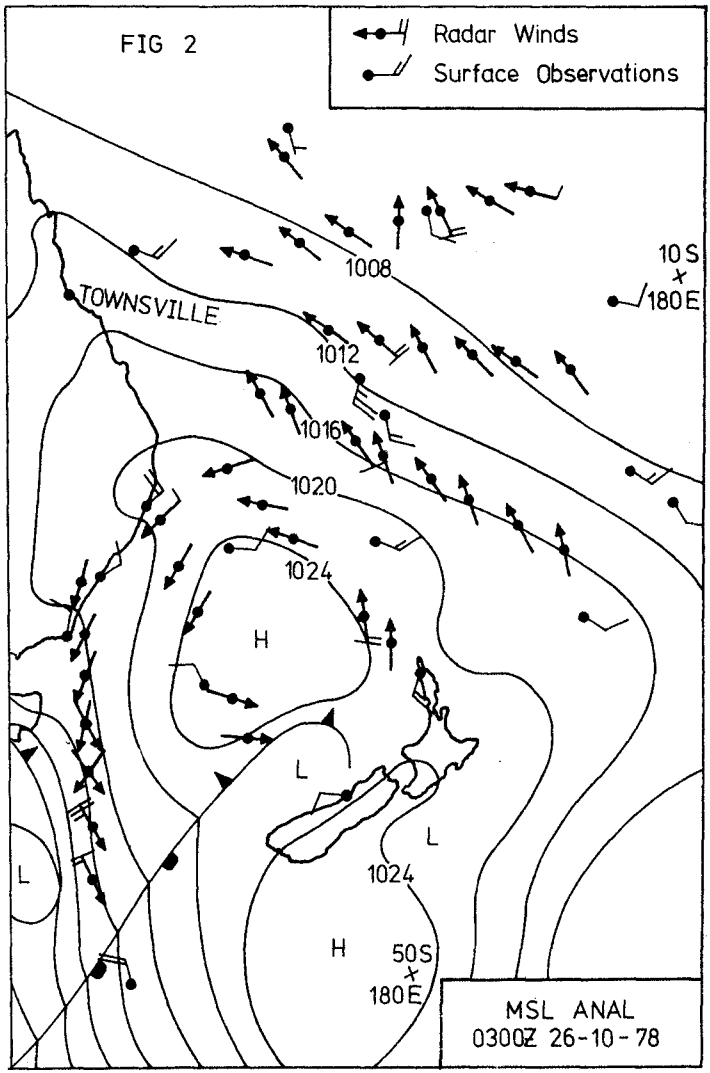

Figure 2 Surface meteorological analysis for 0300Z on 26 October 1978, with radar-derived winds superimposed. Solid arrows are radar wind directions, with feathers in wind speed intervals of 2.5 m/s. Measured surface winds are also shown, where available.

FIG 3

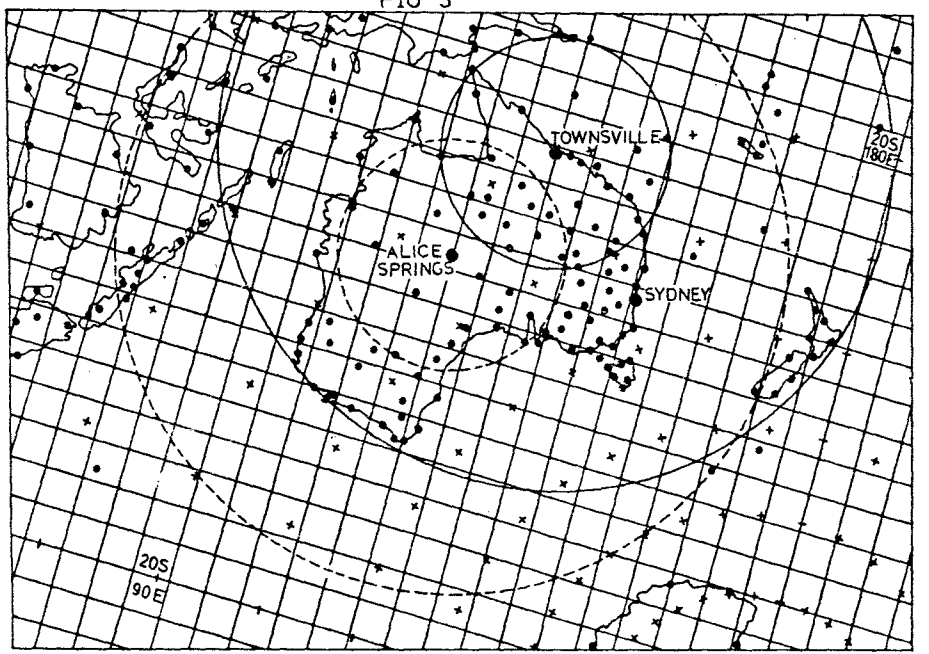

Figure 3 Standard meteorological chart for Australian region, polar stereographic projection (true at 60°S), with relevant portion of 47 x 47 grid superimposed. Also shown is approximate areal coverage of the James Cook University radar in its present site, and when more conveniently sited near Alice Springs. Dots represent meteorological synoptic observing station.

Numerical meteorological analysis and prognosis models currently in use with the Australian Bureau of Meteorology are hemispheric in scope and based on a rectangular grid, either 61 × 61 (grid spacing approximately 330 km at 60°S), or 47 × 47 (grid spacing approximately 490 km at 60°S (Fig. 3)). Both grid spacing are comparable with the average spacing between observations for the radar winds, of around 300-400 km. Seaman (1977) has analysed the optimum density of an observational network in terms of such observational parameters as spatial correlation of observational errors, observational error variance, and the scale size of particular meteorological systems required to be observed and forecast. If it is assumed that this latter scale size is approximately twice the numerical grid spacing, this analysis shows that the point of diminishing return for the rms analysis error in the absolute value of a particular meteorological element is reached for an observational network spacing between 1.0 and 1.4 of the grid spacing. Thus the density of 'almost independent' observations attainable by the radar is well matched to the operational numerical grid, and the maximum system resolution.

In addition, a complete Australian region coverage can be made by the radar in a 2 to 3 hour period at least once per day. While this is not ideal, it is at least similar to the observational frequency in the Australian region from orbiting meteorological satellites.

Similar considerations apply to numerical wave forecast models for southern hemisphere oceans with the additional factors: (a) in the absence of extensive sea state observations, initial wave fields must be computed from analysed surface wind fields. Thus direct observations of these wind fields over the ocean assume even greater significance. (b) The low success rate for wind speed extraction (around 15% of all observations) to date could limit utility in this regard. While the problems of multipath and peak broadening are always likely to be present for a skywave radar of this configuration, work is currently underway to develop a more reliable technique for wind speed determination from observed Doppler spectra, and hopefully this will raise the success rate to better than 60%. This work is to be reported on separately at a later date.

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