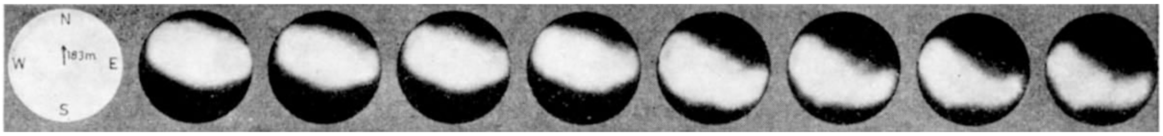

a *b* *c* *d* *e* *f* *g* *h* *i*

Fig. 5. Photographs taken at intervals of 0·25 s of a pattern moving towards the south. *b* to *e* show a movement of approximately 50 m. Between *e* and *f* the transmitting aerial was displaced as indicated in *a* and the pattern is displaced a similar distance to the south. *f* to *i* again show the normal pattern drift.

half-power) is $\pm 4°$ at 1·98 MHz and $\pm 1·3°$ at 5·94 MHz.

There are spurious "diffraction grating orders" at the higher frequency, however, and these may be troublesome in some experiments. The beam can be directed away from the zenith by inserting phase shifts between rows of elements.

An important application will be the study of meteor echoes at lower frequencies than have previously been used. At the frequencies normally used, meteor trails are not observed above about 110 km because at greater heights diffusion is so rapid that the trail quickly expands to a diameter greater than the radio wavelength. For a frequency near 2 MHz, however, theory suggests that trails should be observable up to 140 km. The results may therefore give new information about the total influx of meteoric material into the atmosphere. Doppler studies will provide drift velocities of meteor trails over the height range 70 to 140 km, to be compared with simultaneous observations with the 27 MHz Adelaide meteor system[21]. In the height range 70 to 100 km, drift velocities determined from the weak echoes returned from the *D*-region[22] are already being compared with drifts of meteor trails observed simultaneously with the 27 MHz system.

Electron densities in the *D*-region will be studied by the differential absorption method[23,24]. There have been some uncertainties about the effects of off-vertical echoes when using this method; these should be removed by the use of a narrow beam directed towards the zenith.

For the study of many ionospheric phenomena, it would be valuable to observe the instantaneous angular distribution of downcoming waves. Such observations should throw much light on the phenomena involved in normal ionospheric reflexions, scatter from the E_s-layer and from the *D*-region, scatter of the "spread *F*" type, and in reflexions from travelling ionospheric disturbances. There are several possible ways in which a large aerial array can be used to make such observations, but the most promising seems to be the use of image-forming techniques similar to those proposed for use with radio telescopes[25].

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Power Spectra from Ocean Movements measured remotely by Ionospheric Radio Backscatter

by

J. F. WARD

Department of Physics,
Townsville University College,
Townsville, Queensland

Ocean wave movements can be detected at great distances using high frequency radio waves propagated by the ionosphere.

RADIO backscatter at high frequency from land and sea regions via an ionospheric propagation mode has been used widely in studies of the *E* and *F* regions of the ionosphere (see, for example, Shearman[1,2]). Crombie[3] in New Zealand, followed by Dowden[4] and Haubert[5], detected experimentally Doppler frequency changes imposed on HF radio signals by moving sea scatterers in the vicinity of their observation stations. Sofaer[6] investigated the same phenomena at VHF for the case of television signals scattered from Plymouth Sound. The present work demonstrates that it is possible to detect ocean wave movements at great ranges by probing the sea surfaces with high frequency radio waves which have been propagated ionospherically.

The experimental requirements to do this successfully are exacting because the Doppler shifts generated by the movements in the scattering regions are both extremely small, and also barely an order of magnitude different in value from the unavoidable variations impressed by instability in the ionosphere itself. Power spectra analyses of the radio frequency echoes received, however, can resolve the main contributory components and provide a substantial body of what, as yet, is chiefly phenomenological data for scientific use. The experimental sophistication necessary is outweighed by the potential usefulness of this radio probing method, for vast ocean areas could be surveyed in a few hours from a single observing station. Data can be obtained, moreover, from remote regions of the ocean not previously contributing information to the world-wide meteorological prediction programme.

In 1965 studies commenced in Townsville, Queensland (lat. 19·25° S, long. 146·7° E), of the backscatter behaviour of the ocean regions to the south and south-east of Victoria and Tasmania—some 1,500 miles nearly due south of the probing location. This experiment was planned to allow an examination of large tracts of ocean over which extensive, quasi-coherent, wave patterns might be expected to develop. The region, in addition, is important meteorologically to Australia yet remains largely devoid of fixed observing stations.

At present data are obtained from an HF radar operating at a frequency of 21·840 MHz, with a peak effective radiated power greater than 1 MW, and operating in the bistatic mode. The receiving station, 5 miles from the transmitter site, uses a circularly polarized aerial array feeding a Racal HF receiver followed by extensive signal processing equipment using time domain circuitry and active filters to achieve the overall phase coherence which in turn enables the Doppler frequency shifts—actually phase shifts with time—to be extracted from the echo signals. The resultant analogue data are stored magnetically and subsequently analysed in a Fenlow *SA*2, narrow band spectrum analyser of range 0·30–1·60 Hz associated with a bandwidth of 0·06 Hz. The transmitting array can be slewed electronically in azimuth from 170° to 185° E of N, while for either of these bearings, time gating of the received echoes can give different, effective range samples for observation. This time selection in increments of less than 1 ms, when related to the combined polar patterns of the transmitting aerial array (+20 dB with respect to dipole in free space) and receiving aerial array (+10 dB with respect to dipole in free space), allows boxes of illumination on the sea surface of approximate side length 70 miles to be examined successively, or at will. Four sets of data are available for any selected target region: the fluctuating characteristics of the A scan echo; an amplitude–time record; the sense and magnitude of the phase variation with time; and the relative power density spectrum derived from the phase–time record. Changes in phase of 10 electrical degrees in a 21·840 MHz radio wave can be read from the analogue record (see Fig. 1) while the resultant power spectra exhibit lines for which the resolution in frequency corresponds to about one order of magnitude better than this. In good conditions spectral lines may be determined with a frequency error limited by the calibration accuracy of the search oscillator of the spectrum analyser, say, ±0·01 Hz, which represents a limit of approximately 1 part in 10^9. Although high, this is found to be a necessary order of resolution for an error of this magnitude in frequency introduces an uncertainty of several degrees of angle in the computed direction of movement of the distant ocean wave front.

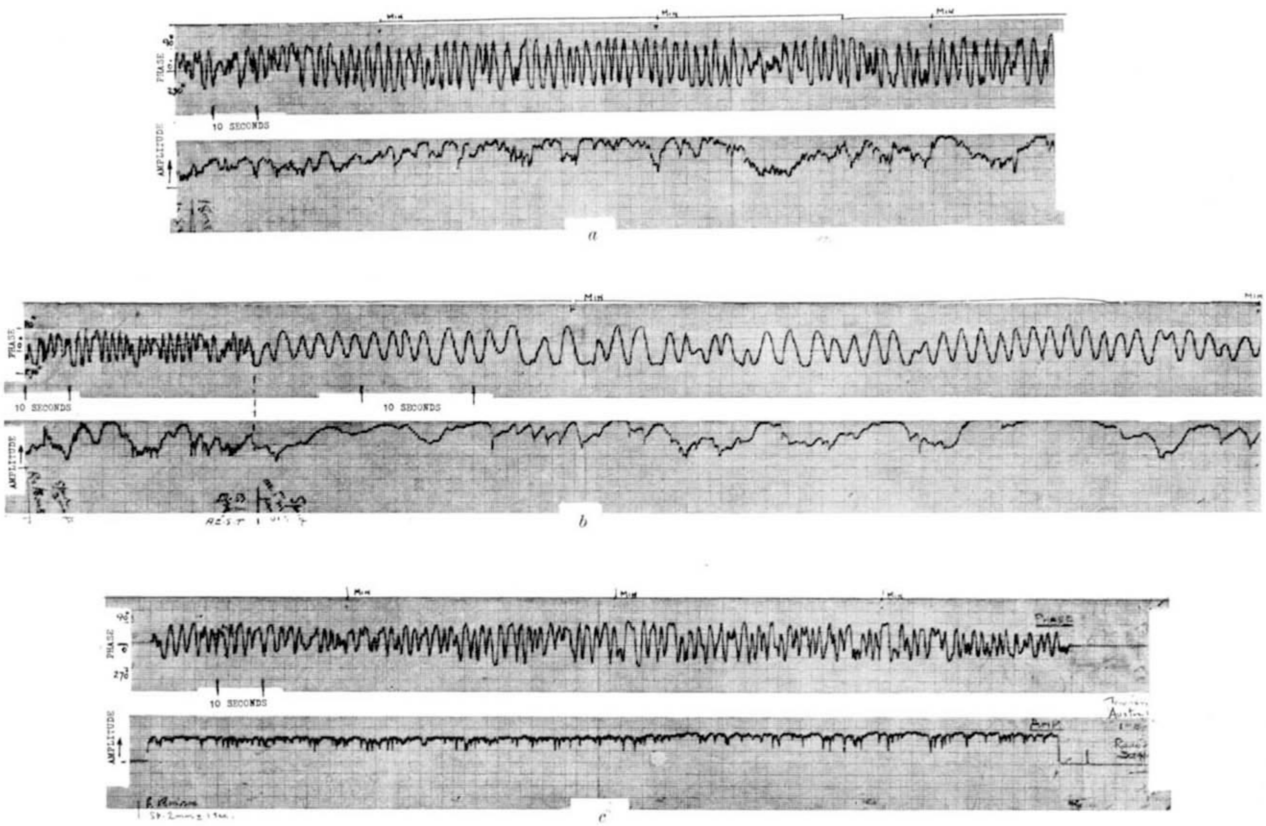

Fig. 1. Phase-time and amplitude-time records exhibiting coherence in echo signals. *a*, April 10, 1968, 0252 GMT, range 18 ms; *b*, April 11, 1968, 0251 GMT, range 18 ms; *c*, August 1, 1968, 0255 GMT, range 18 ms.

An example is given in Fig. 1*a* for April 10, 1968, at 0252 GMT of a progressive variation in phase—equivalent to a frequency shift—of an echo signal from a range of approximately 2,700 km, corresponding to a total time of flight of 18 ms on bearing 170° true from Townsville. (The phase detector gives maximum voltage output for phase differences of 90° and 270° and minimum for 0° and 180°.) Such records must be corrected for cycle slipping due to the ray interference fades, examples of which are apparent in the amplitude record of Fig. 1*b*, before manual scaling can be attempted. The Doppler frequency deduced subsequently from this second record by a process of cycle counting is found to be 0·58 ($\pm$0·02) Hz. The sense of this frequency shift with respect to the transmitted wave is determined directly, and simultaneously, by an ancillary observation based on electronic gating techniques. The Doppler frequency thus computed arises from the resolved component of the sea wave front velocity with the result that an ambiguity still exists as to the true direction straddling the great circle radio path.

In Fig. 2*a*–*f* a series of amplitude–time and phase–time records to a common time base are given for February 26, 1969, between 0217 GMT and 0250 GMT on true bearing 170° from Townsville. The various radar ranges—shown as total times of flight in milliseconds—are indicated in the caption. Although all the scattering regions concerned are various surfaces of the same stretch of ocean, considerable variation can be noted in both the amplitude and the phase of the echoes received in Townsville. In the examples displayed in Fig. 1*a* significant measure of phase coherence can easily be recognized, with several other instances apparent in Fig. 2.

The power density spectra corresponding to Fig. 2*a*–*f* are shown in Fig. 3*a*–*f* respectively, where the ordinate gives the true relative power of the various spectral lines. Samples of record of about 60 s duration were selected for analysis, each spectrum taking approximately 1 h to produce—using a bandwidth of 0·06 Hz associated with a smoothing time of 15 s. Analysis was carried out from a magnetic tape loop, the joint in which introduced a step function in the recorded analogue signal which in turn produced the near continuum of spectral lines with a periodicity related to the tape loop circulating time. The spectral structure of interest, however, is the envelope of the detailed record and this reveals several discrete major lines associated with a number of weaker, although still significant, components. Ionospheric drifts must contribute to the ensembles displayed, but the evidence indicates that for the daily time of observation, chosen to be that for maximum ionospheric stability, these result in minor and recognizable components[2,8]. The spectra given refer to sea areas from east of Gabo Island, Victoria (lat. 38° S)—13 ms—out to the maximum for a single hop, F2 propagation, mode for the aerial system available, that is, to about 3,200 km southward from Townsville, say, 21 ms. The best results in the overall set of observations will be seen to occur at radar ranges of 18 ms to 20 ms which correspond broadly to the single hop, F2, modes associated with the lobe peak to be expected at approximately 12° in the vertical plane of the transmitting array.

In general, the power spectra tend to exhibit two or three predominant lines which can be interpreted to relate to stable orders of equivalent diffraction grating such as $n=1$, 2 and 3 or $n=2$, 3 and 4. It can be claimed, however, on oceanographic evidence, that the $n=1$ geometry—postulating a roughness given by a wave height of the order of 4 feet ($\lambda_r/10$), in a wavelength of 22 feet ($\lambda_n=\lambda_r/2$), ratio 1/5—is an unstable condition for a gravity wave in a liquid. At frequencies above the dominant lines there is reasonable evidence for contributions from higher order wave components as indicated in Fig. 3*c* and typified in Fig. 3*h*.

On the other hand, following Crombie[3] for the results he discussed, these enhancements might represent principal maxima of a series of ill-formed sea wave systems of slightly varying geometries spread about the most significant configuration. Below the first dominant line considerable fine detail exists and Fig. 3*g* is included to accentuate this by a decrease from 15 s to 2 s in the smoothing time used in the analyser. Cycle slipping, which can be almost periodic for short intervals, must introduce some coherence into a power spectrum and it is intended to minimize this aberration by means of an electronic logic operation. For the present, therefore, the pattern in the lowest spectral region seems best regarded as due to complex beat frequency components the existence of which is indicated by the slow envelope modulation apparent on many of the analogue signal records (see, for example, Fig. 1*a* and Fig. 2*b*). The spectrum envelope of Fig. 3*h* will be discussed in more detail below.

Interpretation of the Results

Since the distinctive observation by Crombie[3] of sea echoes at close range, it is usually assumed that the backscattered radio energy arises chiefly from a crude resonant phenomenon which exists when the sea wave profile behaves as an equivalent diffraction grating possessing wavelength components "λ_n" for which $\lambda_n=n(\lambda_r)/2$, the radio wavelength, where $n=1$, 2, 3 and so on. Wind generated sea waves are regarded as non-linear perturbations with the result that components of all (but the shortest) wavelengths can be assumed to exist and so, being gravity waves, give a dispersion of corresponding phase velocities which by definition will be proportional to the square root of sea wavelength. The resolved parts of these movements in the direction of the radio signal provide the Doppler phase shifts which generate the power spectra. As higher orders, n, of the resonant scattering process seem permissible, in fact, experimentally evident, the complexity of the resultant spectra rises rapidly and some oceanographic experience must be sought to decide what reasonable upper limit to impose on n for interpretation purposes.

Investigation of the envelope of the dominant spectral region centred at 0·37 Hz in Fig. 2*c* and the corresponding relative power spectrum of Fig. 3*c* shows that the most probable spectral peak can be scaled to within $\pm$0·01 Hz. If this is related to the probing frequency of $21{\cdot}840\times10^6$ Hz a detectability of Doppler shift of about 1 part in 10^9 is indicated. With longer phase–time data samples for analysis this resolution might be improved by half an order of magnitude, at which stage the calibration accuracy of the experimental equipment is the limiting factor.

In the probable envelope pattern for Fig. 3*c* as depicted in Fig. 3*h*, clear spectral lines can be read at (0·37$\pm$0·1); (0·54$\pm$0·01) and (0·66$\pm$0·01) Hz with some evidence of others at (0·75$\pm$0·01), (0·83$\pm$0·01), (0·90$\pm$0·01) and (1·01$\pm$0·01) Hz. For $n=1$ and a radio wavelength λ_r of 44·5 feet the characteristic Doppler shift would be 0·475 Hz–0·478 Hz. If the trigonometric allowance to resolve the wave normal direction, as discussed later, is applied to identify this theoretical maximum with the experimentally determined peak of (0·37$\pm$0·01) Hz, then the higher order spectral lines based on 0·37 would be sought as follows: for $n=2$, $\sqrt{2}(0{\cdot}37)=0{\cdot}52$; $n=3$, $\sqrt{3}(0{\cdot}37)=0{\cdot}64$, $n=4$, $\sqrt{4}(0{\cdot}37)=0{\cdot}74$; $n=5$, $\sqrt{5}(0{\cdot}37)=0{\cdot}82$; $n=6$, $\sqrt{6}(0{\cdot}37)=0{\cdot}905$; and $n=7$, $\sqrt{7}(0{\cdot}37)=0{\cdot}98$. These predicted values have been superimposed on the spectrum of Fig. 3*h* to indicate that the measure of agreement holds to within 4 per cent out to the seventh diffraction order. A simple calculation, using either the $n=1$ or $n=2$ dominant line frequency, gives the azimuthal angle defining the direction of the wave normal as (31°$\pm$2°) with respect to the great circle radio wave direction (170° E of N from Townsville). A similar type of fit may be traced out for the more complicated spectrum of Fig. 3*a* in which, if the $n=1$ line is chosen as 0·38 Hz, the $n=2$ order compares

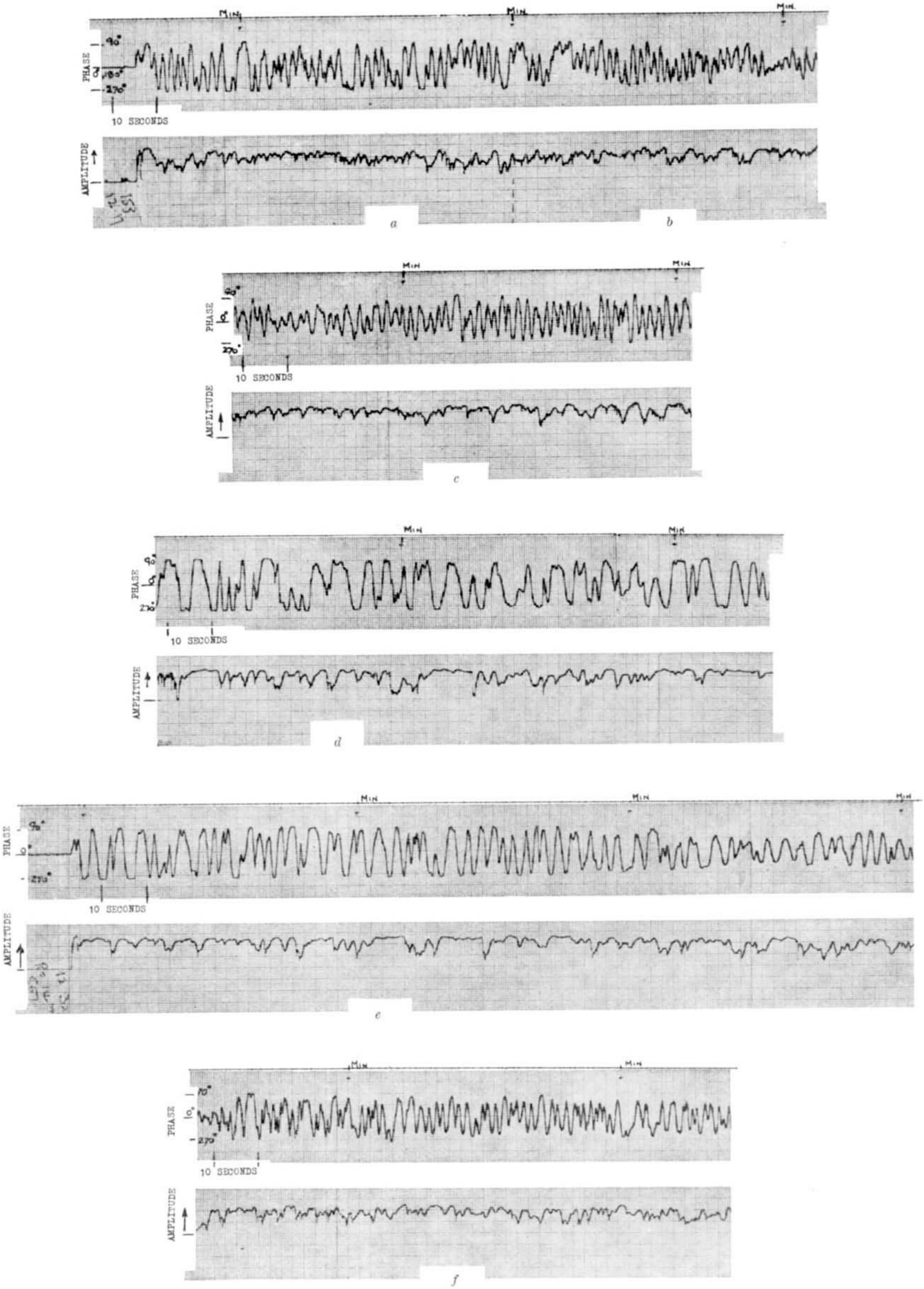

Fig. 2. Records for February 26, 1969, at long range on true bearing 170°. *a*, 0217 GMT, range 20 ms; *d*, 0219 GMT, range 20 ms; *c*, 0220 GMT, range 18 ms; *d*, 0223 GMT, range 16 ms; *e*, 0232 GMT, range 14 ms; *f*, 0242 GMT, range 13 ms.

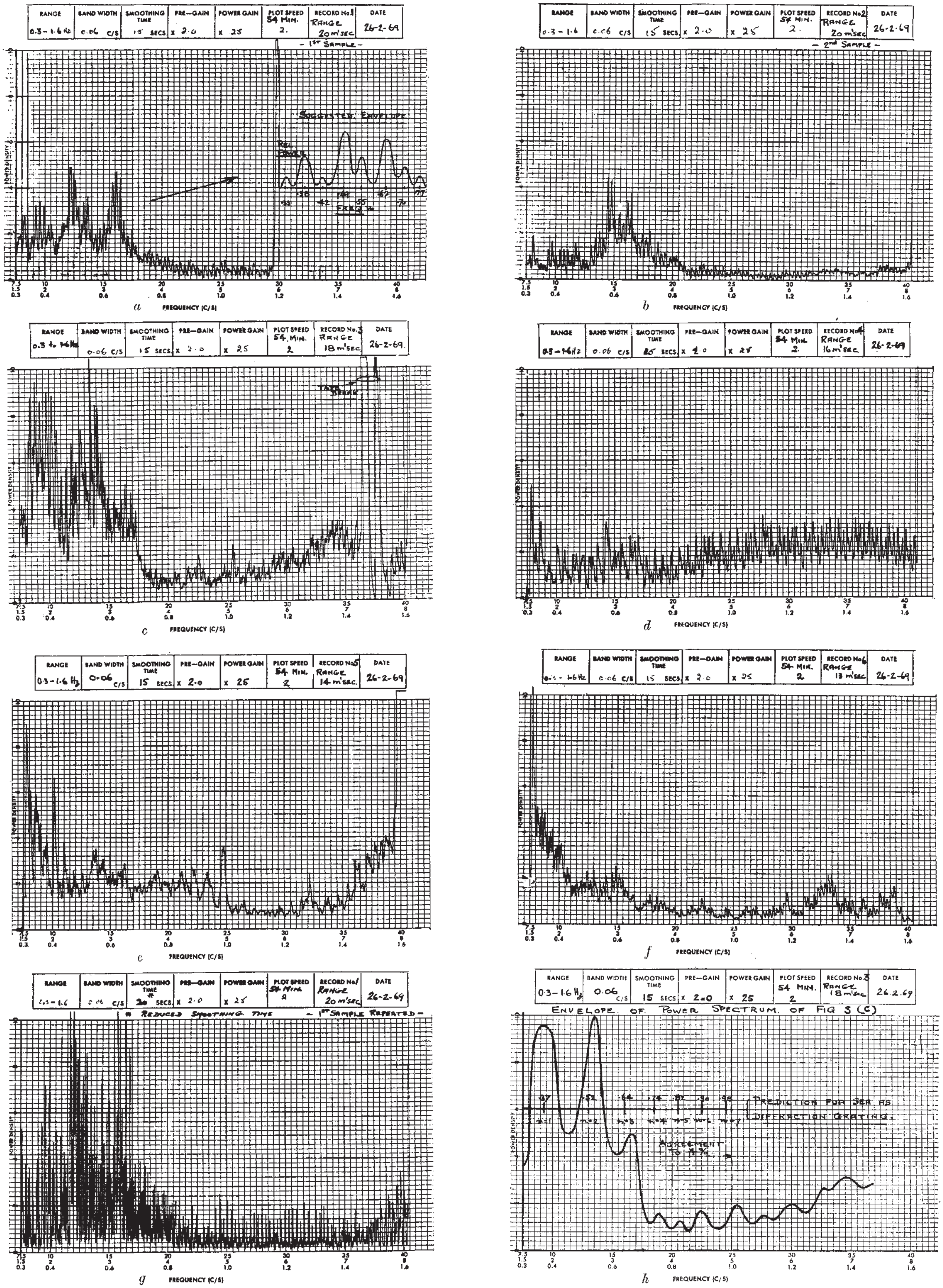

Fig. 3. Power spectra from an analysis of the data of Fig. 2. *a–f* relate to Fig. 2 *a–f* respectively; *g*, range 20 ms, corresponds to Fig. 2*a*, but smoothing time reduced to 2 s; *h*, envelope derived from Fig. 3*c*.

with the measured 0·49 Hz, the $n=3$ with 0·65 and the $n=4$ with 0·77 Hz.

It is considered that there is experimental evidence that the actual radio frequencies corresponding to the various diffraction components representing the spectral lines discussed here beat among themselves to yield fine structure evident chiefly in the power spectrum region below the $n=1$ line of principal resonance. This class of detail can be noted in Fig. 3*a* and holds promise as a phenomenological indicator of the degree of roughness and coherence of the sea scattering region. In other examples displayed (see Fig. 3*b* and *c*) there is some evidence that the general power density rises in a broad continuum as the Doppler frequency shift increases. This could be interpreted as the contribution of the water waves of higher surface velocity, and so of greater wavelength, which are known to arise from, or contain, relatively, the greater energy components within the non-linear sea perturbation. There is some evidence in Fig. 3*c*, for example, that spectral lines out to $n=10$, that is, $\lambda_n=$ 222 feet, are detectable and the suggestion arises that an examination of the broad energy enhancements in measured spectra could indicate something of the swell energy in addition to the more discrete wind generated components.

It will be noted that the wave velocity component which yields the Doppler shift as measured electrically is the resolved part of the sea wave velocity in both azimuth and vertical angle to align with the direction of propagation of the radio wave. For a single probing station observing one scattering region, the true velocity of motion cannot be determined directly although the magnitude of the azimuthal direction angle can be computed despite an ambiguity in angle about the path of the radio beam. A series, however, of such observations of contiguous scatter regions provides a crude matrix from which the true direction of movement of the wave front may be deduced. On the basic assumption of resonant scattering, with a series of n values, and a given radio frequency, the possible direction angle, θ, of the sea wave front normal to the great circle direction of the radio wave can be derived by trigonometric resolution with allowance for the square root dependence of sea wave velocity on wavelength. It is given by

$$\delta f_0 = \delta f_n (\cos \theta)^{3/2} \cos \Delta$$

where δf_0 is the observed Doppler frequency shift, δf_n the theoretical Doppler shift for order n ($n=1$, 2, 3 and so on), and angle Δ the downcoming angle in the vertical plane of the radio wave. The latter can be predicted for a stable ionosphere of given height from a knowledge of the slant range as given by radar timing and generally will lie in the range 0° to 30°.

The experimental work in progress aims at building up crude sector maps of wave directions along the two main regions illuminated by the radio beams. An initial attempt at a correlation between the wind directions measured from Townsville and those deduced from rather scant synoptic data by the Commonwealth Bureau of Meteorology was carried out for April 9, 1968, and April 11, 1968. Radio ranges between 16 ms and 24 ms on azimuths of 170° E of N and 185° E of N were selected for the two days to provide four groups of data with a total of twenty-five separate predictions of wind directions. The average of the angular difference between the two methods of derivation of surface wind direction was 22°. Further attempts at correlation are in progress for the sea regions east of Tasmania and extending southwards to Macquarie Island (lat. 54·5° S) and this will be extended during 1969 when an Antarctic survey vessel is in the region.

Ocean Scanning Service

The experimental evidence indicates that meaningful data resulting from the moving sea surface can be collected by radio sounding using the ionosphere as the transmission medium. Power spectra sufficiently reliable to allow estimates of probable directions of the surface waves have been derived and considerable scope now appears to exist for experimental and theoretical interpretation. It is obvious that the introduction of analogue to digital procedures associated with quite a modest on-line computer would be advantageous because a conservative estimate, projected from experience with the spectral density programme applicable to a slow (IBM 1620) computer, indicates that power spectra might be produced at the rate of one per minute. There is therefore no experimental and analytical reason which would prevent the observation by one station of an annular sweep of ocean throughout the full azimuth and for radio range limited by the HF skip distance on one hand, and by the maximum distance for a single hop, F2, propagation mode on the other, representing an area in excess of a million square miles. This region could be surveyed, the Doppler shift data analysed and the wind vectors prevailing throughout plotted in a few hours.

A significant step forward would be to observe simultaneously from two stations located about a transcontinental baseline, to measure the various Dopplers separately, then collate the resultant wave direction maps, and from these deduce the true wave front directional movements—a form of Doppler frequency triangulation. An even more effective procedure, in addition, would be to make swept frequency observations, but because the instrumentation complexities, the variation in range with frequency changes, and the problems associated with frequency allocation would be extensive, the sounding by a single frequency must be relied on until the experimental method can be shown to be attractive synoptically. The immediate plan for the Townsville installation is to adopt monostatic radar operation associated with an advanced design of continuously rotatable, low delta aerial array[11], using vertically polarized radiation launched over the sea surface. Effective propagation at angles down to three degrees in the vertical plane is expected and this should yield useful probing ranges at least out to 3,500 km in any azimuthal direction. The ray geometry appropriate for these longer ranges should ensure that the resolved part of the Doppler shift due to the undesired ionospheric movement will decrease with respect to the shifts of ocean origin.

The most general form of the problem raised by these experiments is to measure and interpret Doppler shifts from a systematically moving, rough scatterer[12,13], as observed via a distorting ionosphere. Because the components of the complex sea waves compatible with the radio wavelengths adopted in these measurements are expected to yield a significant correlation between the wave profile and the surface wind generator, a method of surface wind observation of potential interest in meteorology and oceanography has been presented.

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