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INTERNAL DOCUMENT 208

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THE POTENTIAL OF REMOTE SENSING FOR THE MEASUREMENT OF WAVES AND CURRENTS IN UK WATE

by

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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This report was commissioned by the Department of Energy, Petroleum Engineering Division.

Institute of Oceanographic Sciences
Crossway
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Somerset

June 1984

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1. GENERAL INTRODUCTION

This report was requested by the Petroleum Engineering Division of the Department of Energy to help guide their thinking on future trends in the measurement of the environment related to the design of offshore structures. It was specified that it should cover the measurement of waves and currents in UK waters.

There has been a great deal of talk over many years about the potential of remote sensing as a tool in oceanography: both with respect to satellite and to ground-based HF radar. Many extravagant claims have been made, and in the former case in particular a great deal of money has been spent. Yet the ability to use remote sensing of oceanographic phenomena as a reliable practical tool is still not with us except in the restricted case of fixed microwave radar. How much longer shall we have to wait?

This question is particularly relevant when planning programmes to determine the environmental climate. Such a programme necessarily involves long-term routine measurements over a number of years, and quite long lead times in some cases.

IOS has been putting considerable effort in recent years into assessing remote sensing techniques.

In the present report we summarise our views in relation to the measurement of waves and currents.

2. SATELLITE-BORNE MICROWAVE SENSORS

2.1 Background

The potential benefits of synoptic measurements of sea surface conditions afforded by orbiting satellites have been self-evident since the launch of the first spacecraft, but until comparatively recently the great majority of satellite sensors operated in the visible part of the electromagnetic spectrum so that their usefulness, especially around UK latitudes, was limited by impenetrable cloud cover. Lacking the ability to collect reliable information at regular, predictable intervals satellites produced little of real value to marine forecasting centres. It was the performance of Seasat in 1978 which demonstrated that all-weather microwave instrumentation had been developed to the point where operationally useful accuracies and resolution could be obtained.

Seasat was the first satellite dedicated to a study of the sea surface. It was an experimental craft designed as a 'proof-of-concept' mission and when it failed, due to a severe short-circuit in its power supply after no more than 100 days of operation, there was no back-up satellite to replace it. As the spacecraft's data were analysed and compared with 'in situ' surface observations it became increasingly clear that the stringent objectives placed on sensor accuracy had largely been achieved and, in some cases, surpassed.

The impact of the satellite's performance on the marine research community has led both Europe (ESA) and the USA (NASA) to plan the launch of pre-operational satellites with payloads very similar to that of Seasat. The European satellite is ERS-1, the American is NROSS and they are both scheduled for launch around 1988/89. This report will focus more particularly on the proposed ERS-1 satellite which will carry the following sensors:

- Radar altimeter for measuring the precise height of the satellite above the mean sea surface as well as significant wave height and wind speed at nadir.
- Scatterometer for measuring wind speed and direction across a 400 km swath.
- Synthetic aperture radar (SAR) for imaging ocean surface waves to provide information on wavelength and direction.
- Scanning radiometer operating in the infra-red for the measurement of sea-surface temperature.

Since the payload proposed for ERS-1 owes much to the Seasat experience, the potential effectiveness of Europe's first remote sensing satellite can be reasonably assessed by examining the performance of Seasat's sensors during the satellite's brief operation.

Although some satellite-borne sensors can detect phenomena associated with currents, none has a proven capability to measure them. Nor does there seem to be much prospect of such a capability being developed in the foreseeable future so far as currents on the continental shelf are concerned. Thus, this section is concerned only with the measurement of waves, and the sensors concerned are the altimeter and SAR.

It should, however, be mentioned that satellite-borne microwave sensors can measure winds. The altimeter can measure wind speeds at nadir (vertically below the satellite) to an accuracy of about 2 m/s by using the amplitude of the returned echo, and a specially designed wind scatterometer can measure wind speed and direction over a swath 400 km wide (in the case of ERS-1) by measuring the directional characteristics of the backscatter at oblique angles.

2.2 The precision altimeter

The one planned for ERS-1 is virtually identical to that on SEASAT. A detailed description of this is given by Townsend (1980). Brief details of ERS-1 are given in Haskell (1983). The principle in outline is as follows (see figure 1).

The SEASAT altimeter consisted of a 13.25 GHz (Ku band) narrow beam (1.59^{o}) radar with an effective pulse length of 90 cm looking vertically down at the sea. When the pulse is reflected by a completely calm sea, the rise time of the echo received by the satellite is extremely short. However, in the presence of sizeable waves, echoes are received from the crests, the troughs and suitable facets in between and the rise-time of the echo is slowed. This slowing is a measure of the wave height.

Echoes from a rough surface such as the sea are extremely and randomly variable in amplitude. Thus, one can only make sense of this by averaging many returns. SEASAT transmitted 1020 pulses per second, and the returns were initially averaged 50 at a time. Ten such averages are shown in Figure 2. It will be seen that there is still a great deal of random variability left. Thus, it is necessary to average H_s estimates over 1 second to get 10% confidence limits, and since the satellite travels nearly 7 km over the surface in this period, this limits the along-track resolution of the instrument to about 10 km (which includes the radar beam width). Higher accuracy can only be obtained at the cost of degrading the along-track resolution.

This spatial resolution limits the application of the satellite in coastal waters and areas of shallow topography. In addition, when the satellite flies off land over the sea, it takes the altimeter some 20 km of track to settle down and give usable data.

The specification for the altimeter proposed for ERS-1 in its wave measuring mode is (from Haskell 1983):

Measurement range (H_s)	1 to 20 m
Accuracy	$\pm$ 0.5 m or 10%, whichever is worse

Several comparisons of the Seasat altimeter wave heights against surface measurements have been made. An example is given in figure 3 (from Webb 1981). To reduce the random error, Webb averaged over 21 s intervals (equivalent to a ground track of approximately 140 km). In general the accuracy goals appear to have been achieved, but only over a limited range of waveheights since few comparisons could be made against well-calibrated, reliable 'in situ' observations. Further checks will therefore be required in the early days of the next satellite altimeter mission.

2.3 Synthetic Aperture Radar (SAR)

The principles of SAR are described by Tomiyasu (1978). The details of the seasat SAR are given by Jordan (1980), and outline details of the ERS-1 SAR by Haskell (1983).

The synthetic aperture radar operates on a moving platform and transmits a series of short coherent pulses to the earth's surface in a direction perpendicular to the flight path. The image resolution in the range (cross-track) direction is determined by the effective pulse length while resolution in the azimuthal (along-track) direction is achieved by synthesising a long antenna. The echoes received from a target while the radar travels a distance L are coherently summed to provide in effect the signal which would have been recieved from a real array of length L. For maximum resolution L equals the width of the actual antenna footprint on the sea surface (about 16 km from Seasat). However, to reduce the speckle (due to the random variability of the echo mentioned in section 2.2) this full resolution is not used so that in the case of Seasat for example, L was approximately 4 km. Since the speed in orbit was 7.5 km/s, the aperture synthesis time ("integration time") was approximately 0.6 s. This is a "4-look" system (effectively averaging speckle over 4 independent echoes) and it gave an along-track (azimuthal) resolution of approximately 25 m, equal to the cross-track (range) resolution. This explanation is slightly simplified so that the reader may find that he cannot reproduce the same numbers. However, it gives the correct physical feel for the problem.

This resolution is capable in principle of imaging the longer sea waves, and waves are in fact seen on many images of the sea (figure 5).

This imaging relies on the modulation of the microwave backscatter by the longer waves, a process which is not understood well enough to allow useful estimates of the wave height tobe made. However, estimates of the wave modulation/speckle ratio (effectively a signal/noise ratio) indicate that waves with lengths shorter than about 100 m cannot be resolved above the background level.

A further important effect is as follows. The principle of aperture synthesis depends on the target field being constant during the integration time. However, this is not the case for the sea surface which in moderate or rough seas can move several radar wavelengths during the aperture-synthesis period. This degrades the along-track resolution. The full effect is surprisingly difficult to calculate theoretically and this has not yet been done. However, Tucker (in press) shows that the degradation is quite large, reducing the along-track resolution of Seasat to a wavelength of at least 250 m (6 db cut-off) in all but the calmest seas.

Thus, we are still not sure of the ability of a satellite-borne SAR to measure the wavelength and direction of travel of sea waves or, more generally, their directional spectrum. It is to be hoped that by the time the next satellite-borne SAR is flying our understanding will have advanced far enough to enable SAR images of waves to be interpreted with confidence.

2.4 ERS-1 as presently configured

Although ERS-1 is presently configured to carry a suite of microwave sensors similar to Seasat, plus a scanning infra-red radiometer for the measurement of sea-surface temperature, some important differences have been introduced into the ERS-1 concept. Whereas the altimeter will be equivalent in precision to the Seasat model and will operate at the same frequency (13.5 GHz), the scatterometer and synthetic aperture radar are combined in the ERS-1 mission to form the Active Microwave Instrumention (AMI) operating at C-band (5 GHz) in place of the Ku-band (14.6 GHz) of the Seasat scatterometer and the L-band (1.4 GHz) of the SAR. And while the swath of the ERS-1 SAR will be comparable to Seasat (80 km as opposed to Seasat's 100 km) the swath of the scatterometer will be considerably reduced from the 1000 km (500 km each side) for Seasat to 400 km in ERS-1. The SAR is also designed to operate in a special 'wave scatterometer' mode whereby 7 x 7 km^2 areas of ocean will be sampled every 100 km. The reason for such a mode is that the normal SAR operation requires such a high data rate ($\sim$ 100 mbits/s) that on-board recording is not possible and SAR is limited to a few minutes operation per orbit over areas within transmitting distance from a ground station. By restricting the areas sampled to 7 x 7 km squares every 100 km data can be stored on the satellite allowing wave statistics to be gathered at global ocean scales.

The advantage of the functions of synthetic aperture radar and wind scatterometer in a single unit operating at a single frequency is a reduction in the required weight, volume and cost by sharing common hardware. The disadvantage may be that whereas L-band and Ku-band are known to give good results for the SAR and scatterometer on the basis of the Seasat experience, there is considerably less data available on the performance characteristics of a C-band system.

2.5 Sampling regime related to the orbit

The most serious limitation on the utilisation of a single, polar-orbiting, earth-observing satellite for environmental monitoring is the comparatively long sampling period of observations for narrow-swath sensors. Satellites used for meteorological or oceanographic monitoring usually fly at heights in the range 600-1000 km. Seasat's altitude was 800 km, its inclination 108 degrees (ie it reached latitude 72 degrees) and it circled the earth in 100 minutes. As presently configured ERS-1 will fly at a height of 777 km, will reach latitude 82 degrees and will have a nodal period of 98 minutes. This means that successive orbit crossings of the equator will be separated by 2700 km and by about half that distance at UK latitudes. The satellite's ground tracks completed over the North Atlantic in three days are shown in figure 6 while the coverage achieved by the 400 km swath scatterometer over the same area is shown in figure 7. The time and space scales of wind and wave variability clearly do not allow adequate resolution by a single orbiting satellite. As shown in figure 8, where nodal separation is plotted against sampling frequency for 1-4 satellites orbiting at a height of 800 km, an operational system of satellites would require a multi-satellite mission.

An important consideration in planning the sampling strategy of a satellite mission is the trade-off between frequency of sampling and spatial coverage. Conflicts may also arise between the different requirements of the sensors making up the payload. Synthetic aperture radar imagery over land, for example, may demand an orbit pattern which ensures that swaths are laid down sequentially to provide complete coverage over a wide area rather than (say) a pattern which ensures frequent sampling of the same scene. For oceanographers interested in monitoring surface currents and tides, geoidal variations must be eliminated from the altimeter's signal and the easiest way of doing this (in the absence of the detailed knowledge required) is to make repeat measurements along the same track and subtract out the average, time-invariant geoidal profile. For example a random error of $\pm$ 2 m in geoidal height would reduce to $\pm$ 0.2 m in less than a year if sampled every three days Thus compromises must be made and the selected repeat pattern for ERS-1 is likely to be in the range 8-12 days with a 3-day repeat during calibration periods. A plot of a 10-day coverage of the area around the UK is shown in figure 9. This represents in effect the grid over which measurements of significant wave height would be made since the altimeter's footprint of the sea surface is no more than a few kilometres wide. The same is true of the wave mode of SAR which is limited to 8 km squares.

3. AIRBORNE REMOTE SENSING AND FIXED MICROWAVE RADARS

3.1 Airborne remote sensing

As in the case of satellites, there is no established or even prospective technique for measuring currents from aircraft so far as we are aware.

With regard to waves there are 3 relevant techniques: stereo photography, radar altimeters, and SAR.

One or two studies have been made using stereo photography. An early and rather famous one was that by Cote et al (1960), which gave one of the first measured directional wave spectra. They used cameras mounted in the wing-tips of a conventional aircraft. This was a technique used in the early days of airborne stereo photogrammetry, but has since been superseded by time-lapse photography using a single camera. The latter technique would not work over the sea, of course, because it is in motion.

More recently, Holthuijsen (1982) has reported measurements using two cameras mounted on separate helicopters and synchronised by radio (to get a bigger inter-optical separation). He analysed 40 stereo pairs by conventional techniques to give 4 directional spectra. Unfortunately he gives few details of the analysis procedure.

The main problem with stereo-photography is the labour required in analysis. To get reasonable statistics, an area covering several wavelengths of the longest wave of interest must be analysed (and a 20 s wave has a wavelength of approximately 600 m). At present this has to be done by hand, though it might be possible to develop computerised image-analysis systems. Thus, while it appears to be a useful technique for special investigations, it is not a practicable routine tool, even apart from weather and cost limitations.

The principle of the satellite-borne radar altimeter in its wave measuring mode cannot be used from aircraft. The attainable altitude is two orders of magnitude less, and thus if an attempt were made to cover enough area of sea surface to average over many wavelengths, the radius of curvature of the radar wavefront would be such as to introduce time delays in the edges of the beam which would swamp those due to waveheight. An airborne radar altimeter for measuring waves has to go to the opposite extreme and try for a high resolution in relation to the sea wavelength: this requires low flying. With a reasonably fast aircraft this gives a quasi-instantaneous cross-section of the sea, and doing this in different directions can in principle yield a directional spectrum.

Quite a few attempts have been made over the years to use such a system, including the use of optical altimeters. Two by IOS are described by Pitt, Driver and Ewing (1978) and Crabb (1980). The problems have, however, always proved prohibitive. The main ones are (1) the great variability of the echo amplitude, requiring a dynamic range in the receiver of at least 60 db if drop-outs and other effects are to be avoided (2) it has proved very difficult to subtract fluctuations in the altitude of the aircraft or towed-body (3) even if the measurement could be perfected, the inherent sampling variability of the wave spectrum makes interpretation very difficult.

It is possible that a major development programme could overcome these problems, but the general cost and difficulty experienced with operating aircraft do not make this an attractive proposition.

Airborne SAR's have been developed for military purposes, and one of these has been adapted by the Canadian Centre for Remote Sensing for imaging the sea surface, primarily to detect ice as a threat to offshore platforms in the Canadian arctic. This was hired by the European Space Agency about 3 years ago to gain experience in interpreting SAR images over both the land and the sea. IOS took part in this exercise with attempts to image waves and sandbanks. The aircraft managed to produce no usable images in either exercise. The reasons were complex. Some were fundamental, such as the inability of the aircraft to keep on a straight enough course, but it was partly the problem of keeping an extremely complex piece of equipment fully operational in the environment of an aircraft.

Another general experience has been that it is difficult and unsatisfactory to attempt to use aircraft of convenience, such as maritime patrol aircraft. It is very expensive to fly suitable dedicated aircraft (of the order of £1000 per hour).

To sum up, while various techniques for wave measurement are possible in principle from aircraft, none has proved satisfactory in practice, and the cost and problems of routine operation seem prohibitive.

3.2 Fixed microwave radars

A simple mass-produced X-band PPI radar has been used successfully by IOS for routine measurement of predominant wave direction near a coast in connection with a beach stability study (Heathershaw, Blackley and Hardcastle 1980). In practice this technique highlights the wave crests and operates in an extremely non-linear mode so far as the relationship between wave elevation and echo strength is concerned. It therefore cannot be used to measure waveheight or any precisely definable property of the directional spectrum, but the analysis of predominant directions obtained by Heathershaw, Blackley and Hardcastle made sense in their context and gave useful information from a comparatively cheap and simple instrument.

Other, more sophisticated techniques have been proposed. In particular two microwave frequencies have been used to produce beats with a wavelength equal to a component of the sea-wave spectrum, and the envelope of the backscatter then has a modulation dependent on the amplitude of this component and with the corresponding Doppler Shift, as in HF radar (see Section 4). It seems unlikely to become a useful tool for wave measurements, but is being developed by a/s Informasjonskontroll in Norway (under the name of MIROS) as a current measuring tool. However, this instrument has a maximum range of about 1 km and is conceived as a tool for measuring the local current, whereas HF radar measure the current pattern over a wide area.

4. HF RADAR

4.1 Introduction and general principles

The term HF radar is used to describe a technique in which information about sea surface waves and currents is obtained remotely by the use of radio waves whose wavelengths are comparable with those of the energetic part of the gravity wave spectrum. Radio energy is transmitted from a shore-based installation and the energy backscattered from the sea-surface is received and analysed. Generally speaking the upper end of the HF band (about 30 M Hz) is used for current measurement, while lower frequencies, down to perhaps 3 M Hz, are better for wave measurement.

Since the sea-surface is moving, the backscattered radio waves have Doppler shifts. The spectrum of these Doppler shifts, which is confined to frequencies within about $\pm$ 1 Hz of the radio carrier is measured for a resolution cell whose size depends on the effective pulse length and beam-width of the radar. A coherent radar is required, and the hardware and software are very sophisticated: they will not be described here. (See Shearman 1980 for a general description of the techniques.) The more resolution cells which need to be analysed simultaneously on-line, the more expensive and complex the system.

A good example of a Doppler spectrum is shown in figure 11: note the logarithmic spectral density scale. The most striking features are the first order Bragg lines. These are produced by interaction of the radio waves with sea waves of exactly half the wavelength: these waves act as a kind of diffraction grating, and backscatter the energy coherently. The physics and the mathematics are reasonably straightforward first-order theory and have been worked out by Barrick 1971. His solution is as follows.
The first order return is given by:

$$\sigma^{(1)}(\omega) = 2^6 \pi k_o^4 \; S(-2\, m\, \bar{k}_o) \quad \delta(\omega - m\omega_B)$$

$$m = \pm 1$$

where $\sigma^{(1)}(\omega)$ is the intensity of backscatter given as a dimensionless number called the backscattering cross section. ω is the radian frequency of the backscatter with respect to the transmission frequency - ie the Doppler frequency. S is the directional wave spectrum expressed as a function of $\bar{k}$, the vector wavenumber. $\bar{k}_o$ is the radar wavenumber defined in the same sense as $\bar{k}$.

Thus the first order spectrum consists of just the two peaks at $\pm\, \omega_B$. One peak is due to waves approaching the radar (positive Doppler) and the other due to receding waves. In the absence of currents the Doppler frequency is the same as the sea wave frequency. Currents shift these frequencies, which is the basis of current measurement by HF radar (see 4.2 below).

As well as the first order lines, there is a continuum with various peaks. This continuum is due to a complex set of second-order interactions. There are, in fact, three separate effects. The first is due to the hydrodynamic non-linearity of the waves. For example, if we were dealing with regular waves generated in a tank, their profile would not be sinusoidal but would contain a second harmonic. Thus, waves of twice the Bragg resonant wavelength (half the wave number) also backscatter the radio waves from their second harmonic, but because they travel at the higher phase velocity corresponding to the wavelength of the fundamental they give a higher Doppler frequency ($\sqrt{2}\, \omega_B$ in fact). In spite of the complexity of a real sea, there is usually an identifiable peak at this frequency.

The second effect arises from the non-linearity of the electromagnetic interaction of radar waves with sea waves of finite amplitude, and the third from multiple reflections from two wave trains of different wavelengths travelling in different directions.

The exact second-order theory of these interactions has been worked out by Barrick (1972) and Barrick and Weber (1977). The resulting equations are complex, but handleable. To illustrate this the basic equation will now be quoted, but the reader need not try to understand it in detail.

The second order backscatter is given by:

$$\sigma^{(2)}(\omega) = 2^6\pi\ k_o^{\ 4} \iint |\Gamma|^2\ S(m\bar{k})\ S(m^1\bar{k}^1)\quad (\omega - m\sqrt{gk} - m^1\sqrt{gk^1})\ k\ d\ k\ \theta$$

$m,\ m^1 = \pm 1$

where $\bar{k}$ and $\bar{k}^1$ are the wavenumbers of two interacting waves for which $m\bar{k} + m^1\bar{k}^1 = 2\ \bar{k}_o$ (the second order Bragg resonance condition), $\bar{k} = (k,\theta)$ the vector wavenumber; $|\bar{k}| = 2\ \pi$/wavelength; θ = direction of propagation. Γ is a (complex) coupling coefficient which is available as a function of $\bar{k}$ and $\bar{k}^1$ from the second order analysis.

This second order Doppler spectrum is produced by interactions over the whole range of wavelengths and directions of travel in the sea wave spectrum, and therefore contains information on this. The basis of wave measurement by HF radar is to extract this information from the second order spectrum. It turns out that while it is comparatively easy to calculate the expected Doppler spectrum from a given sea-wave spectrum using Barrick's equations, it is a very difficult and complex matter to calculate the wave spectrum from a measured Doppler spectrum.

However, one problem which does not appear is the requirement to know all the terms in the radar equation, and in particular the propagation loss. This is because the equation is the same for the first order Bragg lines, whose energy can therefore be used to normalise the second order spectrum.

4.2 Current measurement

If there is a current flowing towards the radar, then the approaching waves will approach more quickly while the receding waves will recede less quickly. The result is that the observed Doppler frequencies are all increased; if the current had been flowing away from the radar they would all have decreased. Thus the whole of the Doppler spectrum and in particular the first order lines are shifted with respect to the transmission frequency (zero Doppler) by an amount which is directly proportional to the component of the current which lies along the radar beam. Two radar systems looking at the area from different directions are required to measure the total current vector.

The measurement made is an average in space and time rather than a point measurement. The horizontal averaging area is given by $R.\Delta R.\Delta\theta$ where R is the range, ΔR the range resolution, and $\Delta\theta$ the beam width. Typically, it would amount to a few square kilometres. The measurement also represents an average current over a surface layer of the ocean to the depth which affects the velocity of the waves, and this can be taken as about one sixth of the Bragg wavelength. To achieve acceptable accuracy the measurement must be made over a finite time which is of the order of 5 to 10 minutes, so the measurement represents an average over this time.

Because only the position (ie frequency) and not the intensity of the first order lines is of interest in the measurement of currents, the signal to noise ratio of these lines required for an accurate current measurement can be as low as 5 dB. The demands on the performance of the radar system are therefore much less than is the case for wave measurements where 45 dB signal to noise is considered essential.

There are two highly developed current measuring radars in existence. Chronologically the first was the American CODAR (Coastal Ocean Dynamics Applications Radar) being marketed by CODAR Inc. Barrick and Lipa (1979) describe the principles of this. Instead of forming radar beams in the usual way, this uses a compact loop aerial and forms beams by using the Doppler spectrum in a rather subtle way. To do this it has to assume that the current speed and direction are homogeneous over the antenna beam (at each range).

The Rutherford Appleton Laboratory's OSCR (Ocean Surface Current Radar) represents a straightforward application of the technique and is now close to being produced as a commercial instrument.

The radar is conceived as essentially a transportable instrument of modest capability in terms of range. It operates in the 27 M Hz (Citizen's) band, and using a mean transmitted power of 100 W can achieve ranges of up to 40 km. The use of a comparatively high operating frequency means that the transmitting and receiving aerials can be made reasonably small. Thus the receiving aerial array need only be 90 m long to achieve a beamwidth of 6^{o}. Another advantage of using a high radar frequency is that the Bragg frequency is high, so that adequate current speed resolution is achievable with short data lengths. Dr King of RAL believes that the accuracy of the radar is $\pm$ 1 or 2 cm/sec using 4.5 minute data series. He bases the claim on (a) the fact that the calibration is fundamental, (b) his theoretical calculation of the accuracy to which the equipment can determine the frequencies of the first order Bragg lines, (c) the results being internally consistent to this accuracy. While this figure may be over-optimistic, we see no reason to disbelieve that OSCR can produce results as accurate as any other current meter: that is, about $\pm$ 5 cm/s in vector velocity.

If the radar is required to be used offshore it will be necessary to mount it on a platform or ship, and this raises a number of development problems:

1. Will it be possible to achieve a narrow well-forward beam with an aerial array mounted on a ship or structure?
2. Will it be possible to compensate for the motion of the aerial system due to platform/ship motion?

The answer to both of these if probably 'Yes, up to a point', but it will require a development programme of perhaps 2 years to come up with practical working solutions.

4.3 Wave measurement

One might suppose that a full picture of the directional wave spectrum could be built up by pointing the radar in a series of directions, and determining $\sigma^{(1)}(\omega)$ for a series of radar frequencies each with its unique ω_B. However, for a number of reasons this is not practicable. Firstly, the method requires an assumption of spatial homogeniety since each direction of look would be seeing a different piece of sea. In a coastal area this assumption is unlikely to be true. Secondly, the method requires the radar operating and in particular the propagation characteristics to be stable and accurately known over a wide range of frequencies and directions. This cannot be done in the present state of knowledge of radio surface wave propagation over the sea. Thirdly, it would be difficult to find a useful number of radio frequencies in the required band which were not already allocated for broadcast use.

For these reasons it is more promising to study the Doppler spectrum as a whole, and in particular the second order structure.

The Doppler frequency of the backscatter is a combination of the frequencies of the two interacting waves and falls into one of four bands, known as sidebands, one on either side of each of the first order lines.

If ω_B is the Doppler frequency of the first order Bragg wave, then for $1.2\omega_B > \omega > 0.8\omega_B$ energy at ω is contributed by sea waves with a frequency $|\omega - \omega_B|$. For a given sea wave frequency the Doppler spectrum therefore gives four values of Doppler spectral density, and this contains all the available information about the directional properties of the waves at that frequency. It is clear that information about the directional properties is severely limited. In effect, it is possible to derive only a predominant direction and a measure of directional spread.

The situation gets more complicated for higher frequency sea waves, and although there may be some scope for numerical inversion of the spectrum here this is by no means certain yet.

Because of the complicated way in which the Doppler spectrum depends on the directional wave spectrum, it has proved impossible so far to devise satisfactory means for direct computation of the wave spectrum from the Doppler spectrum. Dr Wyatt of Birmingham University has therefore devised a procedure for starting with an assumed wave spectrum, computing its corresponding Doppler spectrum, and then varying the parameters of the wave spectrum in a systematic way until a best fit is obtained. This has been tested on simulated spectra, but trials with measured wave and the corresponding measured Doppler spectra have become possible only recently because of the previous lack of measured directional wave spectra. The joint Birmingham University/Rijkswaterstaat/IOS project NURWEC was undertaken to remedy this situation but only preliminary results are available at the time of writing.

It is clear, however, that the techniques for extracting directional and spectral information from the Doppler spectra are not yet adequate, and more research is required.

In these circumstances, efforts have been made to develop simpler, more empirical techniques, which will give useful information on a limited number of parameters of the wave spectrum.

Although the second order structure has a very complex relationship with the directional spectrum of the sea waves, it has been observed that the ratio, R, of the energy in the second order continuum to that in the first order lines increases with increasing sea states. A number of attempts (Maresca and Georges (1980)) have been made to correlate R with measured sea state parameters, or, where there are insufficient data to establish a correlation, the relationship can be investigated using the simulation procedures discussed earlier, see Wyatt et al (1983).

Since, as has been mentioned, the frequency of the Doppler spectrum bears a relatonship to the wave frequency causing it, at least for Dopplers fairly close to ω_B, an empirical relationship has been sought between the moments of the Doppler spectrum and period parameters such as zero-crossing wave period T_Z or "mean" wave period T_1 which depend on the moments of the wave spectrum: see Wyatt et al (1983) for this also. The accuracy obtained seems to be at present limited by the statistics described below. The accuracies achievable have to await full analysis of the data from the NURWEC experiment but seem to be of the order of $\pm$ 30% in H_S and 20% in T_1. It is clear that these figures can be improved upon by a better appreciation of the statistical problems, but it is not clear at the moment how far this improvement can be taken.

Statistical aspects:

All of the techniques so far developed for the recovery of wave information from the Doppler spectrum require that the second order spectrum is normalised by the first order lines. Now, the first order lines are very narrow - their 'intrinsic' width is probably of the order of 10^{-4} Hz. In practice they are considerably broadened by currents and to some extent third order effects (although unfortunately the high resolution analyses required to quantify this have not been carried out). Thus we are faced with the problem of estimating the variance in a narrow band random signal, and it can be shown that the random variability in such estimates is very large unless long data sequences are used. Curiously, the broadening effects referred to above mitigate the problem to some extent, but at the expense of poorer resolution in the spectrum as a whole.

Barrick (1977) has written a useful paper on these problems.

4.4 Summary of operational status of HF radar

4.4.1 As a tool for measuring currents

There is now a good deal of experience of operating the RAL OSCR as a single station system and there is every indication that it will become a practical commercial tool. It should be noted, however, that it is essentially a short-range instrument (maximum range 40 km) and was conceived as a shore-based system. For use in offshore areas the radar will have to be mounted on a ship or platform in the area of interest, and this will require a number of new developments in the radar. In particular the radar will have to be compensated for Doppler errors introduced by the motion of the platform, and the antenna design will require modification in order to give an acceptable performance in the ship/platform environment. While these matters can no doubt be attended to, the development time required should not be underestimated.

4.4.2 As a tool for measuring waves

1. The Birmingham radar is now quite adequate to demonstrate the feasibility or otherwise of using the HF technique to measure waves.

2. In operational use a multifrequency radar would be essential, and the Birmingham radar would allow the best use of the available frequencies. Experience during NURWEC suggests that usable observations would be available for more than half the time.

3. Work on the interpretational aspects has not yet reached the point where the viability of the technique as an operational tool for measuring waves is proven.

4. Increased effort should be directed to the interpretational work and should include attention to the following:

(i) Theoretical and (particularly) empirical work on the characteristics of the first order lines - their width, variability, decorrelation time etc.

(ii) Work on the statistics of wave height estimates from the spectra.

(iii) The present inversion strategy, even if refined, uses essentially a two scale model of the directional spectrum which is too restrictive.

Substantial effort should be applied to investigating alternative strategies.

5. COSTS AND TIMESCALES

5.1 General

Costs and timescales can be difficult to predict. For example, for the past few years the expected launch date for ERS-1 has always been about 5 years from the present. The cost to the end-user of data depends enormously on policy decisions. For example, if the "full economic cost" of satellite remotely-sensed data were charged to the user it would be prohibitive, but if (as has happened so far) only the "marginal cost" were charged it would be cheap. None of the systems discussed in this report is really "off the shelf", so even for the reasonably well-established systems, only order of magnitude costs can be quoted.

5.2 Satellite Systems

No satellite observations of surface waves are likely to be available before 1989/90, although there is a possibility that data on significant wave height obtained by the radar altimeter of the US Military Satellite GEOSAT, due for launch at the end of 1984, may be released to selected wave forecasting centres on a trial basis.

Satellites are comparatively expensive, and the trend in the last few years has been to seek payment from the end-user of the data to offset costs. However, recent attempts to privatise US meteorological satellites came to nothing - and it now seems likely that, in the foreseeable future, national governments will carry the burden of investment. At present the UK investment in ERS-1 is made through the Department of Trade and Industry. The present DTI/RAE plan is to receive ERS-1 data at a station in this country, thus ensuring that sensor data over UK-designated waters would be immediately available for processing and analysis. A definition of the 'products' required from ERS-1 is currently under study by a group represented by the Meteorological Office, DTS, RAE plus a number of research council organisations such as IOS, RAL, SPRI etc.

5.3 Airborne and fixed microwave radars

As discussed above, we do not consider any existing airborne systems to be practicable for wave or current measurement.

The cost of buying, modifying and installing a fixed conventional microwave radar and its associated camera for wave direction measurements should be in the region of £5,000 to £10,000, depending on the site. The cost of routine operation should be modest, so long as someone is available on the site to change film cassettes at regular intervals. However, data analysis is rather laborious, depending greatly on the accuracy and detail required.

We consider the two-frequency microwave radar to be still unproven as a practical tool, though its role as a short-range current meter looks promising. Its costs would not be very different from those of the HF radar equivalent (see below) since the data processing requirement is similar and this is where the bulk of the costs lies.

5.4 HF Radars

So far as we are aware no HF radar is available "off the shelf" or has been in routine operation for long periods. However, current-measuring radars are likely to be in this position before long. If a definite customer appeared at the moment, an operational system could probably be produced within about 1 year based on the RAL system, and probably about the same based on the CODAR (though we have not enquired about this from CODAR Inc).

The capital cost would depend on how much of the development costs were included. Without these, RAL estimate the cost to be about £100,000 for a two-component radar of their type. The operational costs will depend in the end on whether the system proves to be capable of unattended operation, and on how much servicing is required. At the moment, it would be wise to assume that full time attendance by a trained and qualified technician is required.

The wave measuring radar is more sophisticated but only one is required. The present system is an experimental one and a transportable version would have to be built for practical use. This would probably take about 2 years. Birmingham University estimate the hardware costs to be in the region of £160,000, but this includes no development costs or commercial overheads. Once again, in operation it would probably require the full time attendance of a technician.

It is perhaps worth remarking that in both cases large quantities of data would be produced in operation, and the cost of banking this data in a form convenient for further analysis would be considerable: we have not attempted to estimate this.

6. CONCLUSIONS

6.1 Current measurement

1. There is little prospect of a technique for measuring currents on the continental shelf from satellites.

2. There is a reasonable prospect of the two-frequency fixed microwave radar measuring currents over a comparatively short range. This technique needs to be kept under review.

3. It is established beyond reasonable doubt that HF radar working at about 27 M Hz can measure surface currents to an accuracy equal to that of the best current meters, over a wide range of environmental conditions, to ranges of up to about 40 km. However, its range deteriorates under severe conditions and it is not yet known how it behaves in exceptionally severe conditions.

The RAL version is at present only suitable for use from land because of its aerial length. The CODAR Inc version can in principle be used from a fixed offshore platform because of its compact aerial.

4. Commercial versions of this type of equipment could probably be produced within about a year if the financial resources were available.

6.2 Wave measurement

1. The precision radar altimeter carried on an orbiting satellite has been demonstrated as being capable of measuring wave height to useful accuracy. However, the only ones likely to fly in the next 5 years will be aboard military satellites and it is not known if the data will be made available to civilians.

2. Studies are under way to see if a useful measure of wave steepness (and hence a period parameter) can be derived, but this is not yet proved.

3. A satellite-borne SAR can image waves and hence give a measure of wave length and direction. Hoeever, there are still important question marks over the interpretation of these.

4. A simple land-based microwave radar can image waves out to a range of a few kilometres, and from its images the predominant direction of travel can be measured. This has proved to be a useful tool for coastal engineers when combined with one-dimensional wave measurements.

5. HF radar for measuring waves remains something of an unknown quantity. A combination of the very complex relationship between the wave field and the radar Doppler data and a lack of appreciation of the severe statistical problems inherent in the technique have so far prevented a convincing demonstration of its capabilities.

However, further research into the interpretational aspects will certainly bring improvements. This is where effort is more urgently required rather than on the engineering aspects which are adequate for proving the technique.

6. As far as coverage is concerned, the satellite altimeters cover the whole globe rather sparsely in both space and time (though it is possible to interchange geographical and temporal coverage within limits), whereas if they become operational, HF radars can cover a limited area comparatively densely in both space and time.

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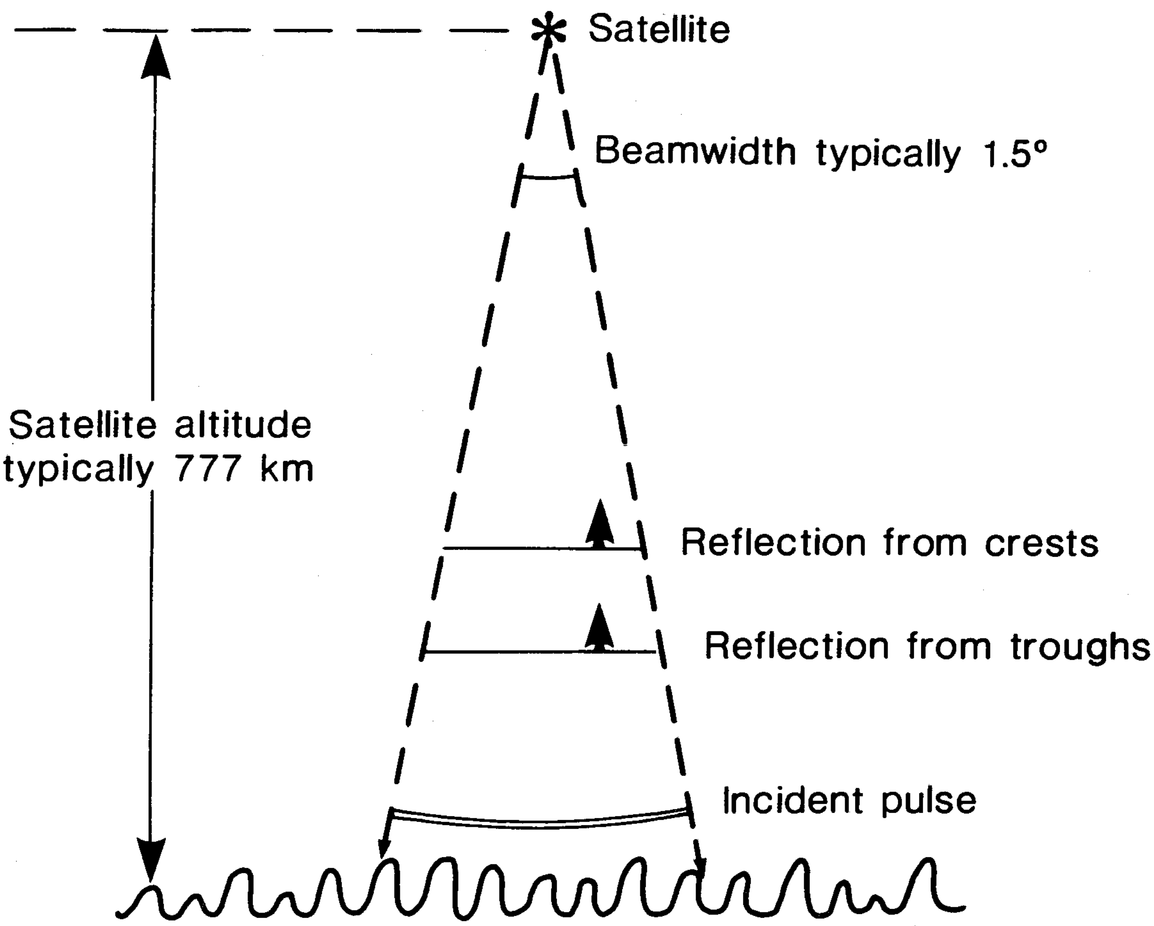
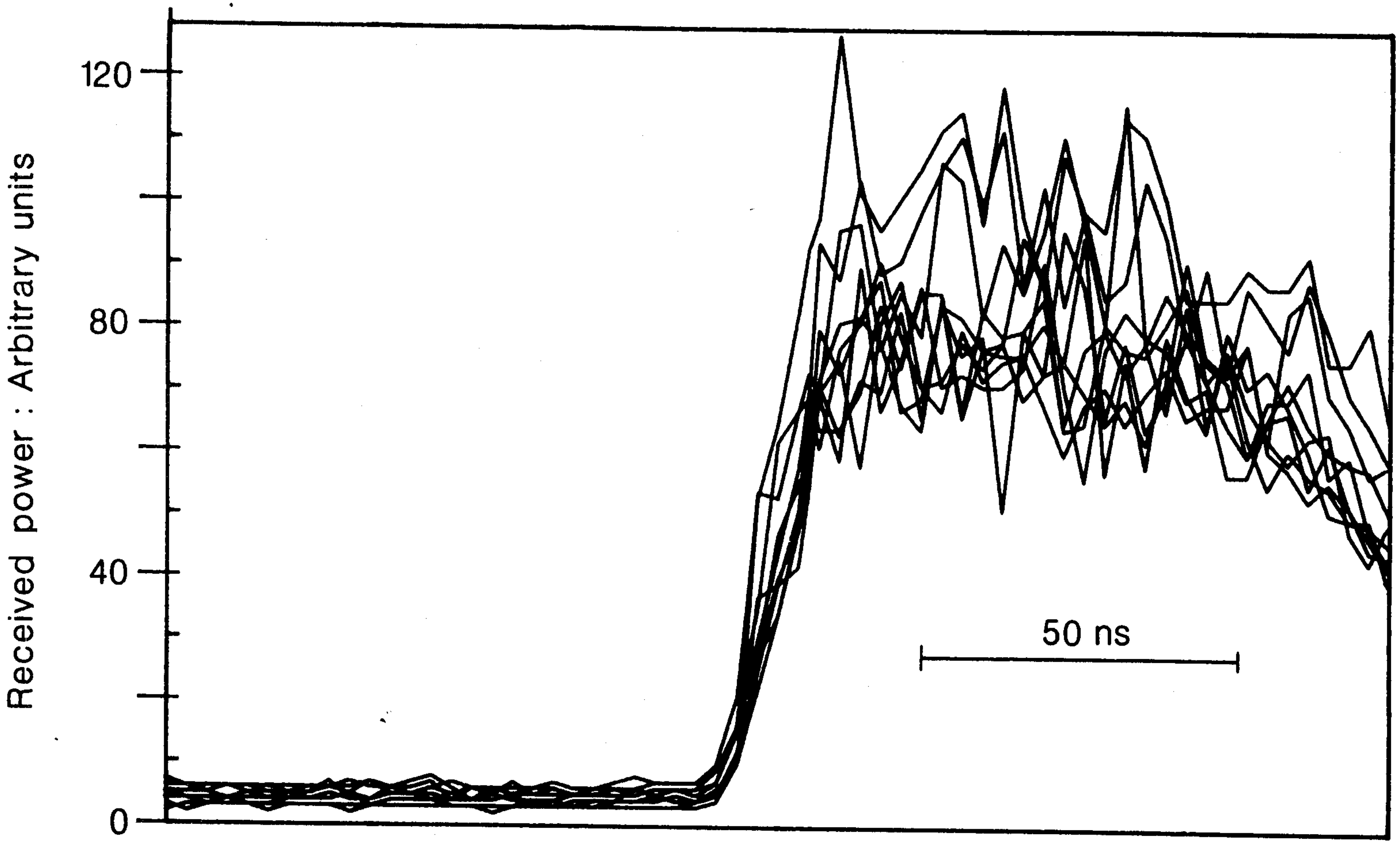
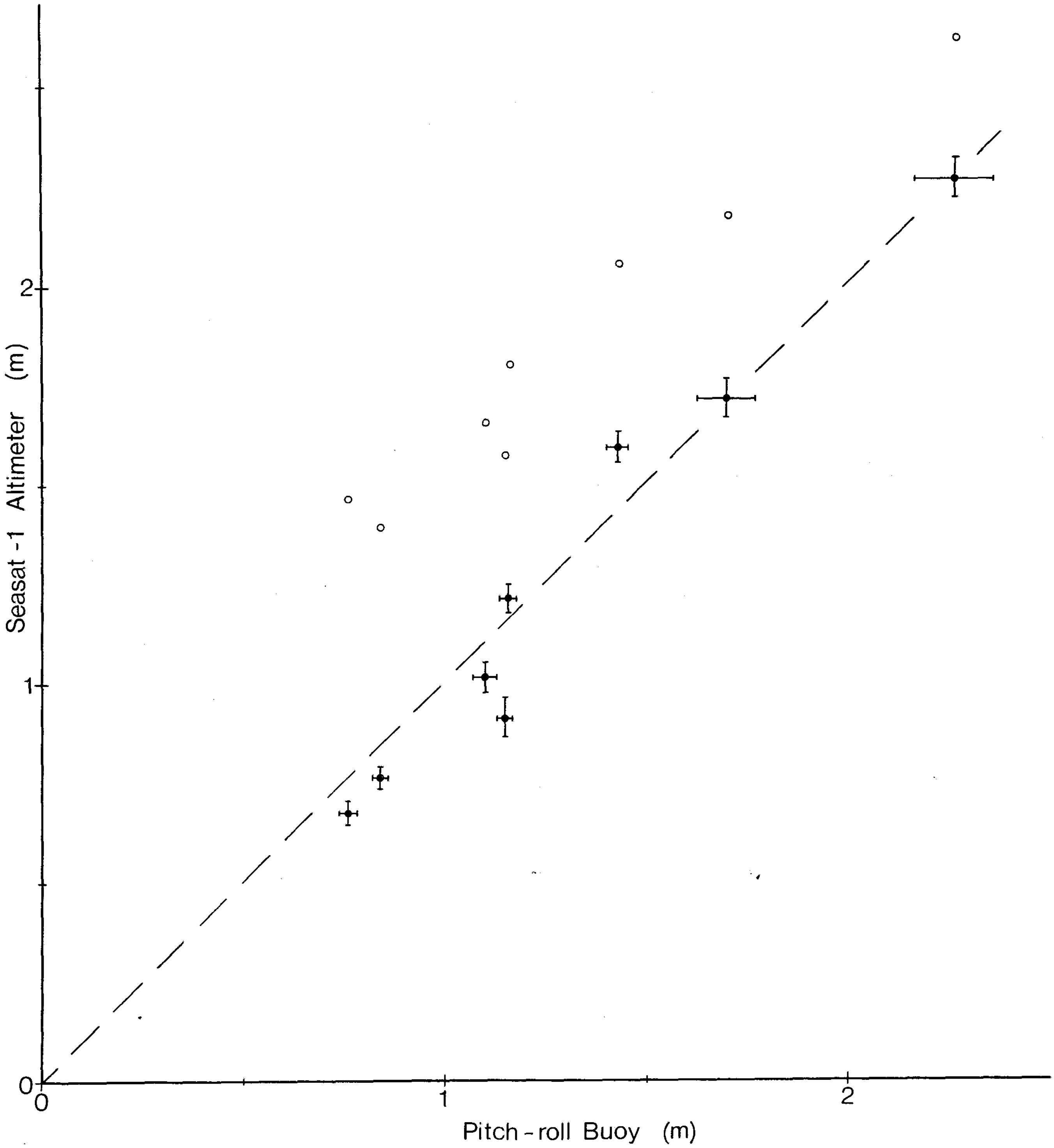


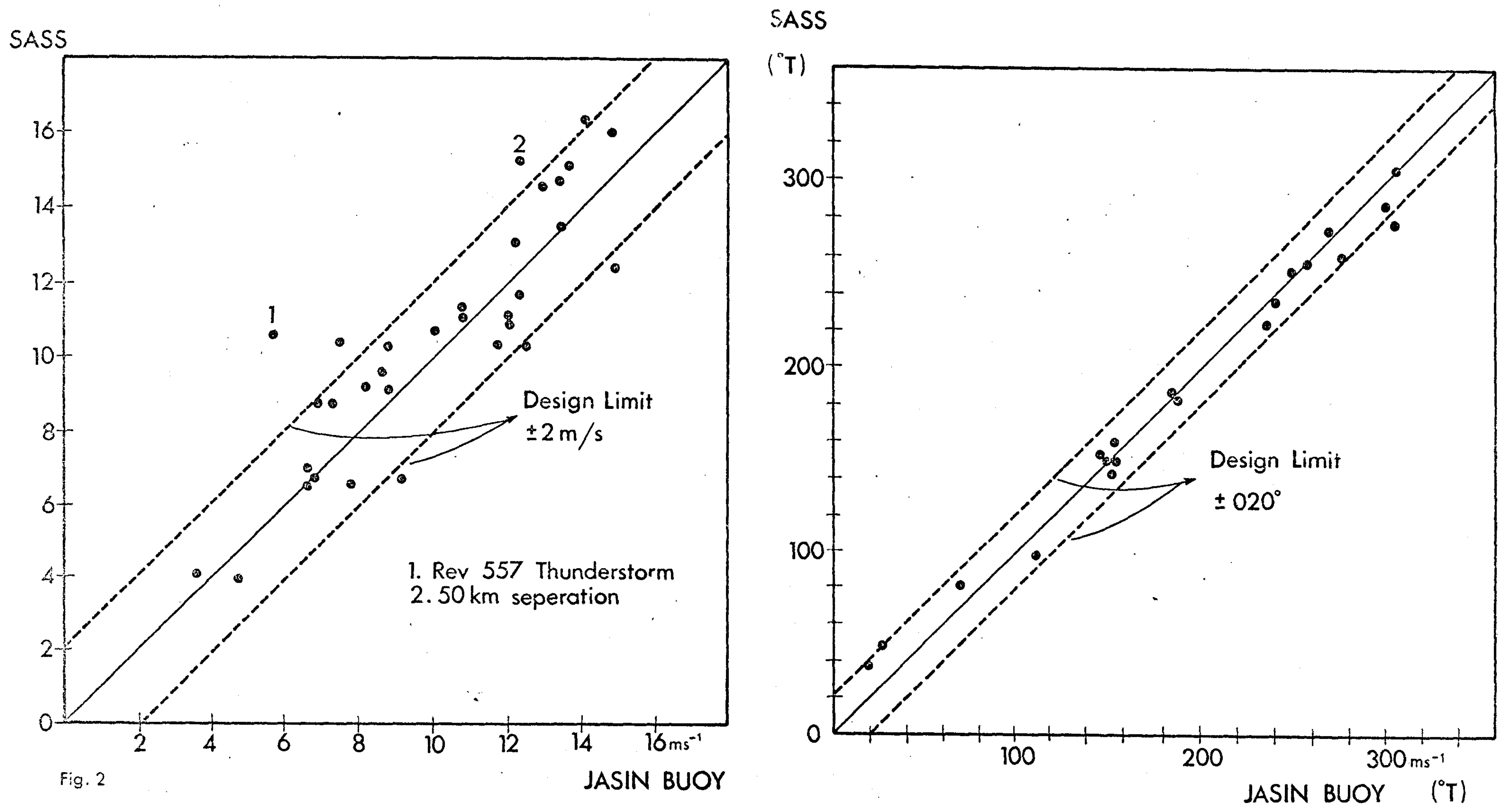
1. The principle of operation of the radar altimeter as a wave measuring device.



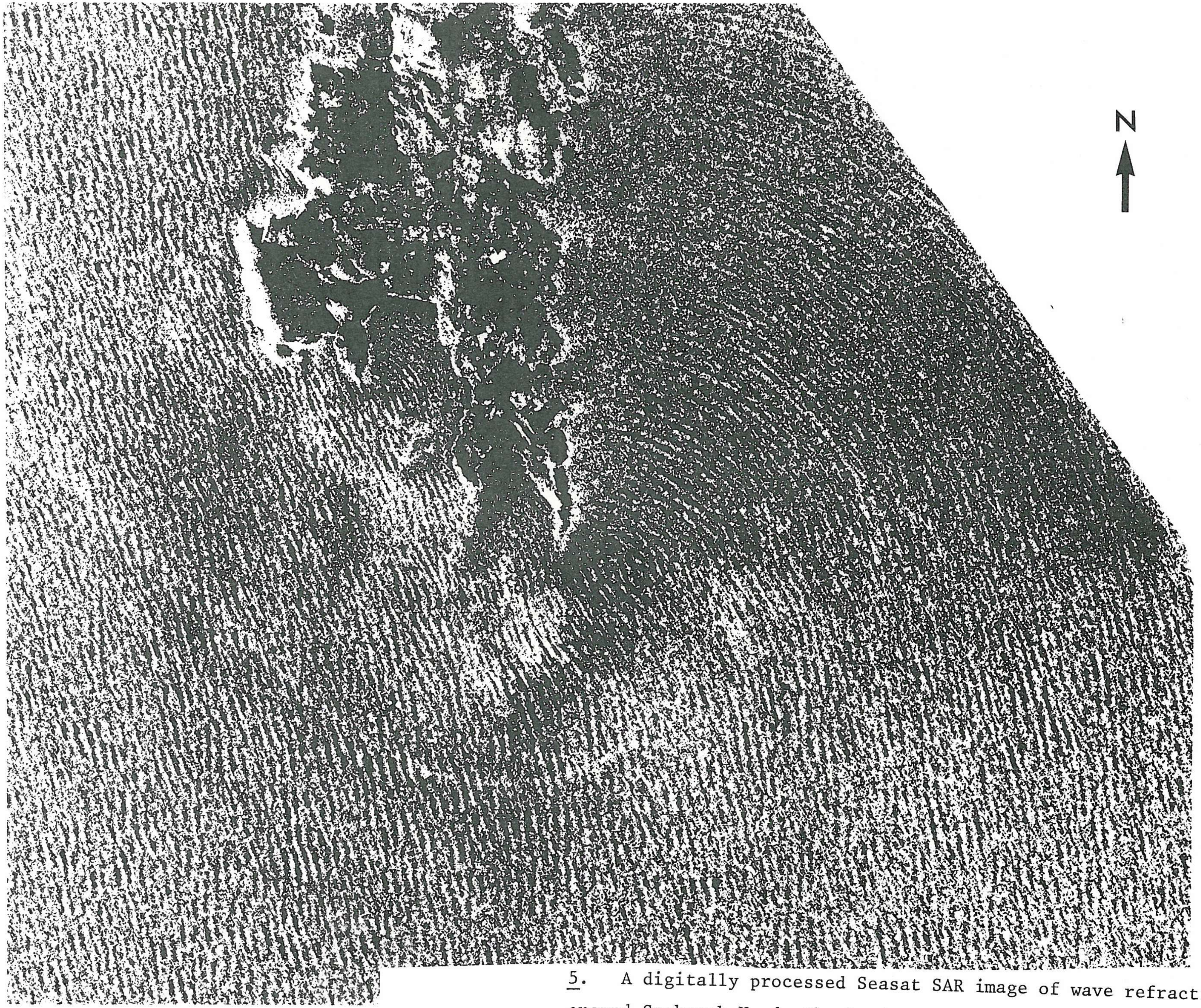
2. The radar altimeter. Each line is an average of the returns from 50 pulses, and the figure demonstrates the large variability still remaining.



3. A comparison of the radar altimeter and pitch-roll buoy estimates of significant wave height. The solid circles correspond to altimeter data that has been averaged and corrected by the JPL algorithms. The open circles represent averaged but otherwise uncorrected data from the altimeter. (From Webb 1981)

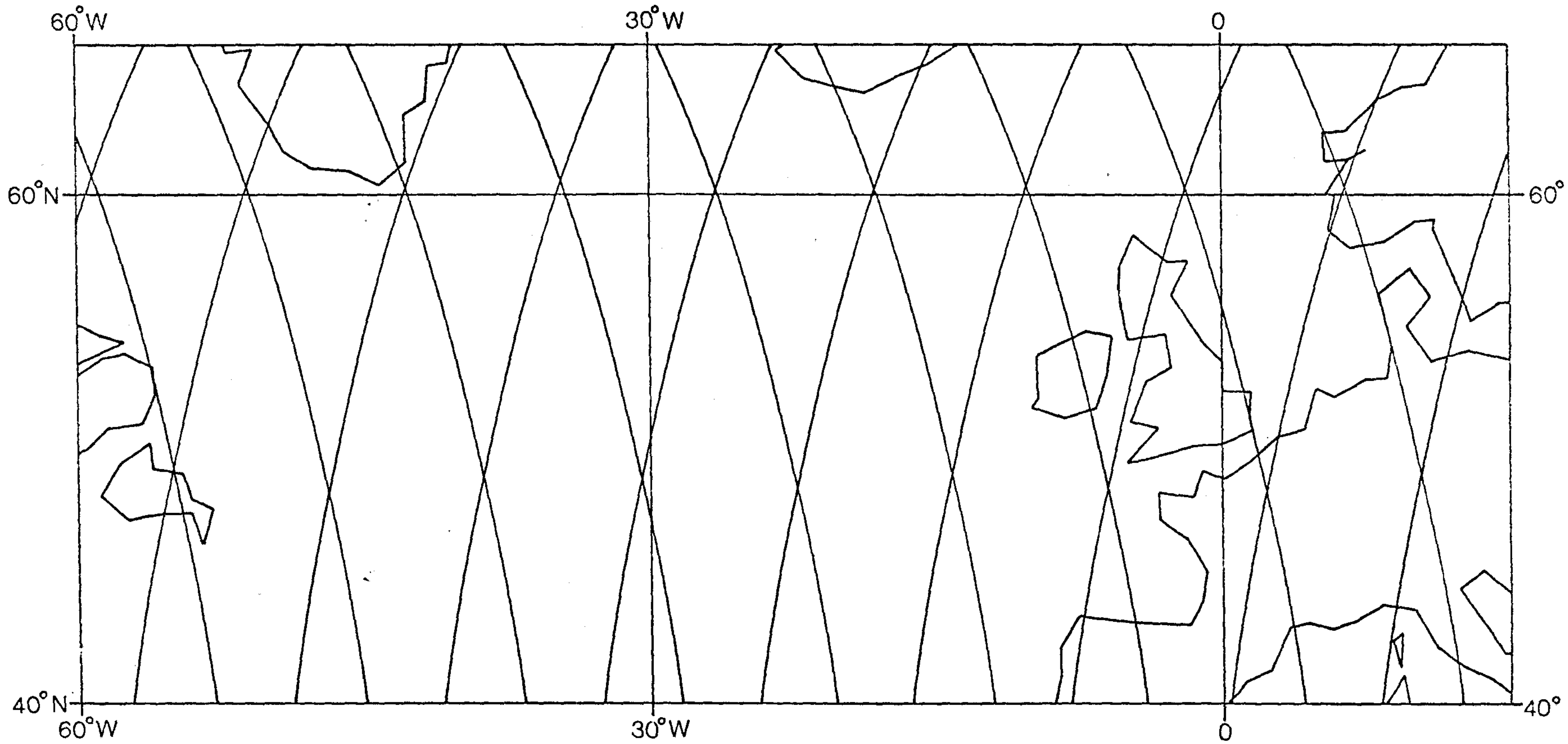


4. A comparison of JASIN wind speeds and wind direction measured simultaneously by a calibrated surface buoy and the Seasat scatterometer on several passes over the area.



5. A digitally processed Seasat SAR image of wave refraction patterns around Sumburgh Head, Shetlands.

44 ORBITS (3 DAY REPEAT)



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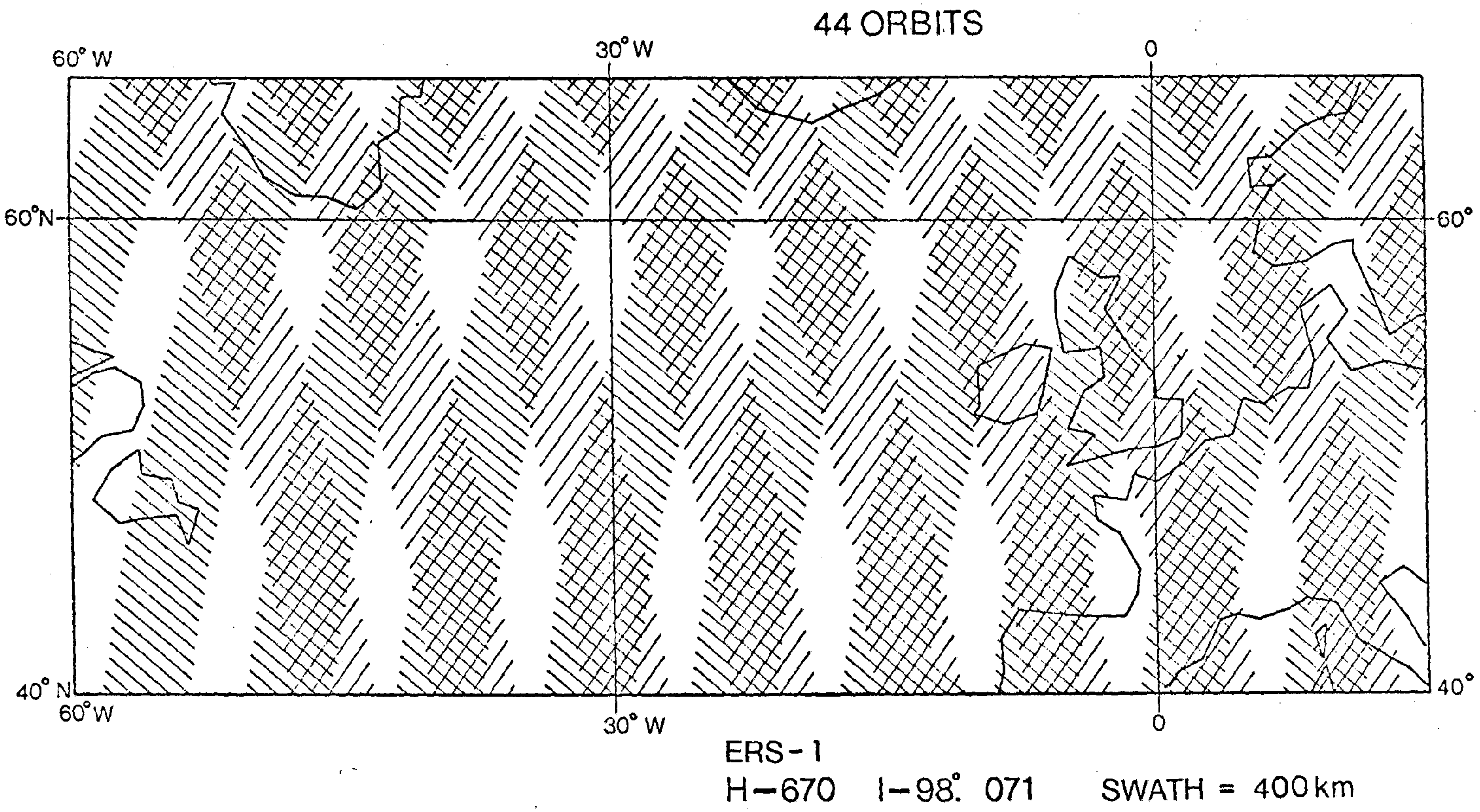
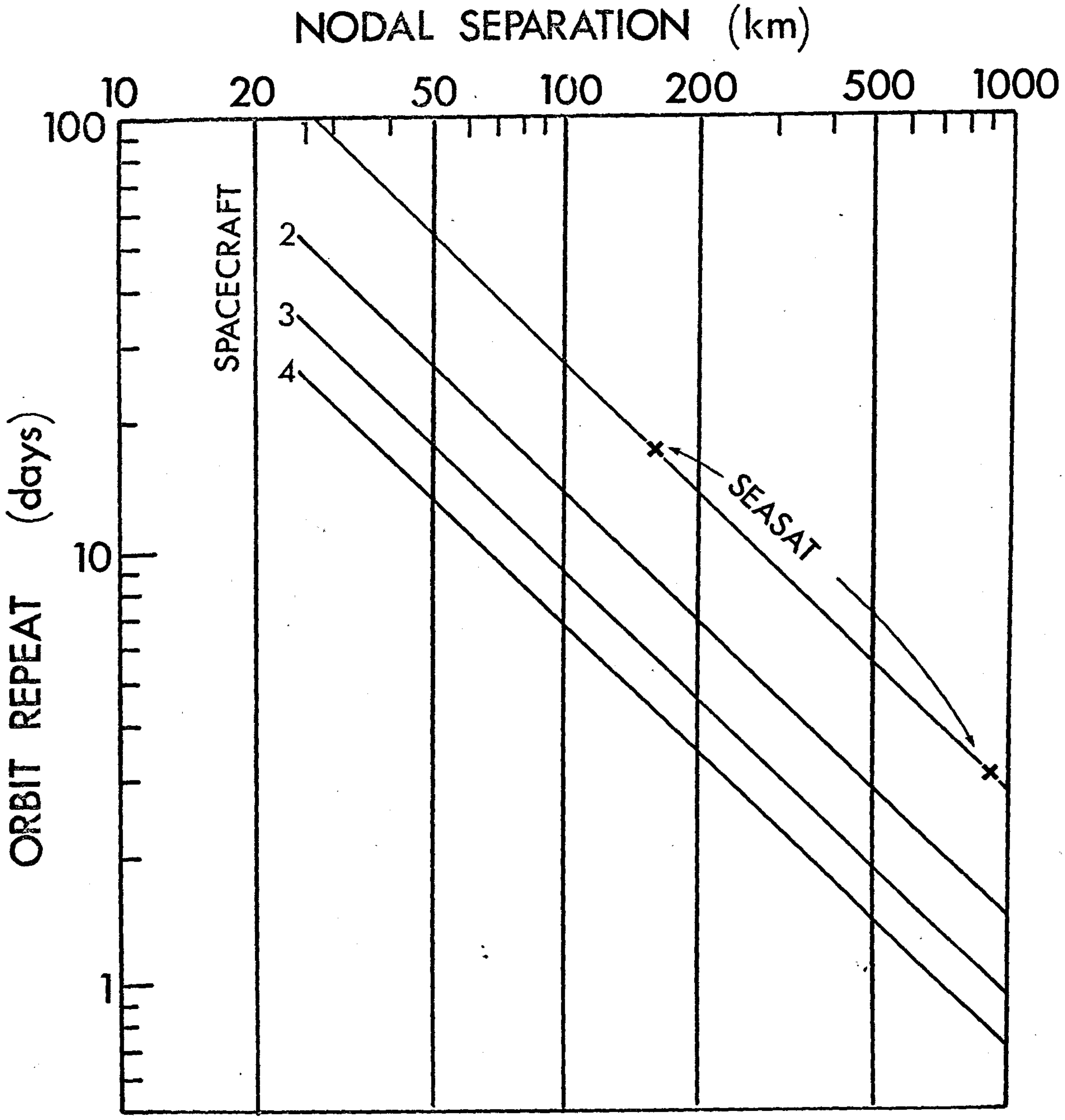
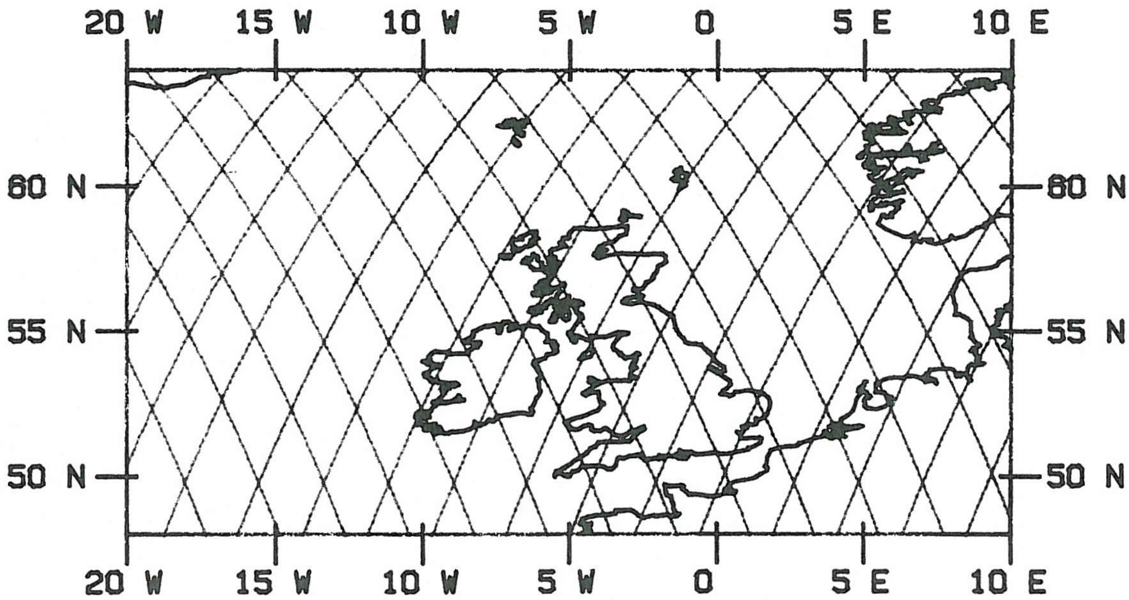
6. The ground track of the proposed ERS-1 orbit for a 3-day repeat period over the North Atlantic.



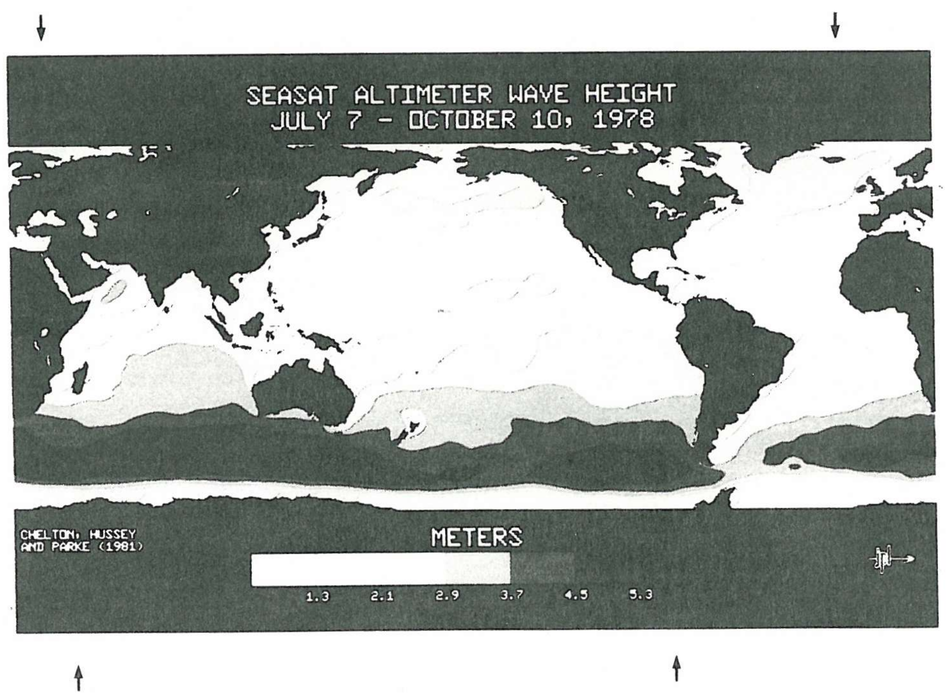
7. The 3-day scatterometer coverage of wind measurements for ERS-1.



8. Plot of equatorial separation between adjacent orbits and repeat period days for 1 to 4 satellites.



9. A 10-day repeat orbit coverage around the UK.



10. A plot of global wave height derived solely from the Seasat altimeter.

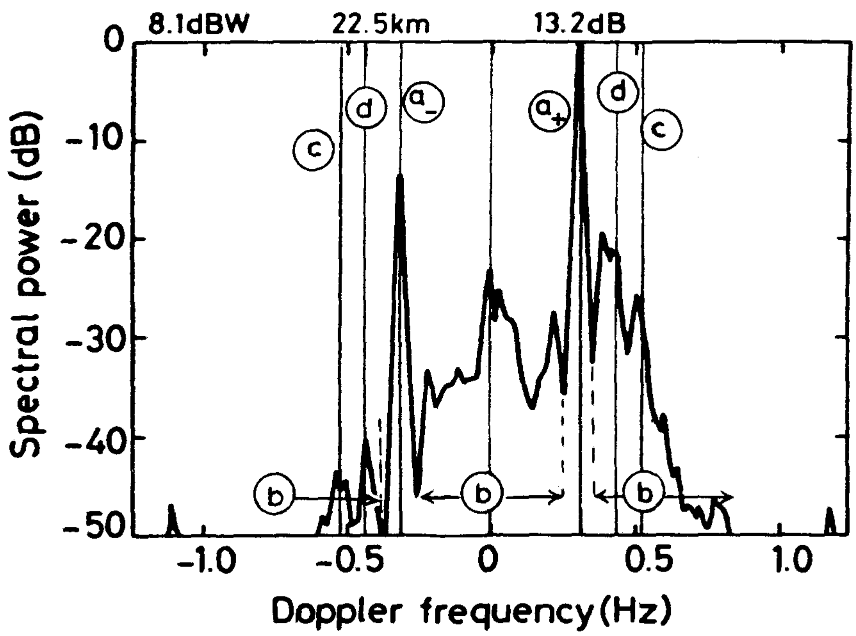


Figure 11. A typical ground-wave Doppler spectrum.

(a+) - approaching first order Bragg line at $\omega_B = \sqrt{2gk_o}$ where $\underline{k}_o$ is the radar wavenumber.

(a-) - receding first order Bragg line at $-\omega_B$.

(b) - second order continuum.

(c) - corner reflector at $\pm 2^{3/4} \times \omega_B$.

(d) - 2nd harmonic of ocean waves of wavenumber $\underline{k}_o$ at $\pm \sqrt{2} \times \omega_B$.