PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Observation of Ocean Waves [and Discussion]

M. J. Tucker, E. D. R. Shearman and D. E. Cartwright

Phil. Trans. R. Soc. Lond. A 1983 **309**, 371-380
doi: 10.1098/rsta.1983.0048

Phil. Trans. R. Soc. Lond. A **309**, 371–380 (1983)
Printed in Great Britain

Observation of ocean waves

By M. J. Tucker
Institute of Oceanographic Sciences, Crossway, Taunton, Somerset TA1 2DW, U.K.

[Plate 1]

The European Space Agency plans to launch an Earth Resources Satellite (ERS-1) in a few years' time with a view to establishing an operational system of such satellites. It will carry two microwave devices giving information on waves: a precision altimeter and a synthetic aperture radar (SAR). Careful assessment of the potential performances of these instruments is therefore being carried out.

In the precision altimeter, the leading edge of the returned radar pulse is smeared by the rough sea surface. The degree of smearing is highly correlated with the significant waveheight and appears to be independent of other parameters. The main fundamental limitation to operational use comes from the sampling variability, which necessitates long averaging times. The SAR gives pictures of the sea surface that often show wave patterns, but their precise interpretation is an exceedingly complex problem, which is still not properly understood.

Even with three satellites in orbit, coverage in U.K. latitudes would be only once a day along the sides of a diamond-shaped grid with a side of approximately 500 km. An initial assessment indicates that this coverage is probably enough to be very useful in the open ocean, but that this limitation and the size of the altimeter 'footprint' become increasingly serious as a coast is approached.

1. Introduction

At present we can measure waves satisfactorily only by using sensors at the sea surface, and it is impracticable to put out large numbers of these to cover a wide area. Remote sensing provides the promise of covering large areas with one instrument.

There are at present only two types of wave sensor that are serious candidates for use in satellites, and both were tested on Seasat during 1978. They are the precision radar altimeter and the synthetic aperture radar. Both work at microwave frequencies. Optical sensors, even if practicable in principle, would not be acceptable operationally because of the loss of data due to cloud cover, and radio wavelengths would not be practicable because of the need to use large directional aerials to achieve adequate signal:noise ratios, and possibly also because of the interference they would cause.

The orbits of Earth-observing satellites are designed to be at approximately constant altitude, so that they can be described by two main parameters: this altitude and the inclination to the Earth's axis. The altitude of the sort of satellite with which we are concerned is fixed fairly tightly between two constraints: it must be outside the drag of the atmosphere, but it must not be too high because the sensors are close to their signal:noise limits and the higher the orbit the worse these get. At higher altitudes the attainable spatial resolution is also less. Thus the range of practicable altitudes is about 650–800 km. A satellite at 668 km does precisely $14\frac{2}{3}$ orbits per day, and one at 770 km does $14\frac{1}{3}$ orbits per day. In each case, therefore, they will cover the same track after 3 days. Such an orbit is termed 'Sun-synchronous', and a typical track of the former is shown in figure 6. The speed of such a satellite in its orbit is approximately 7.5 km s^{-1}, and the speed over the ground approximately 6.8 km s^{-1}. Seasat had an altitude of approximately 800 km. It was not Sun-synchronous during the first part of its life, but was moved to a 3-day Sun-synchronous orbit 24 days before it failed.

2. The radar altimeter

The more straightforward of the two wave sensors is the precision radar altimeter, and a detailed description of the one mounted on Seasat is given by Townsend (1980). The carrier frequency was 13.5 GHz, the effective pulse length was just over 3 ns in time or approximately 10 cm in space, and the pulse repetition frequency was 1020 Hz. The echo from a rough sea shows a sharp initial rise due to the echo from immediately below the satellite, followed by a decaying tail from the rest of the patch of sea illuminated by the pulse (figure 1). The steepness of the rise depends on the waveheight. The precise mechanism is still being researched, but qualitatively one can think of echoes coming from crests and troughs of waves over an area a few kilometres in diameter immediately below the satellite. The important point is that the mechanism is sufficiently clear for us to be certain that the steepness of the rise of the echo pulse depends primarily on waveheight and not significantly on wavelength or any other wave parameter.

The steepness of the rise is measured by sampling the echo at three points. The system causes the centre one to follow the mid-point of the rise, and the separation of the other two is switched automatically to give optimum sampling as the waveheight varies. A number of corrections have to be applied, for example, to take account of the tilt of the beam from vertical.

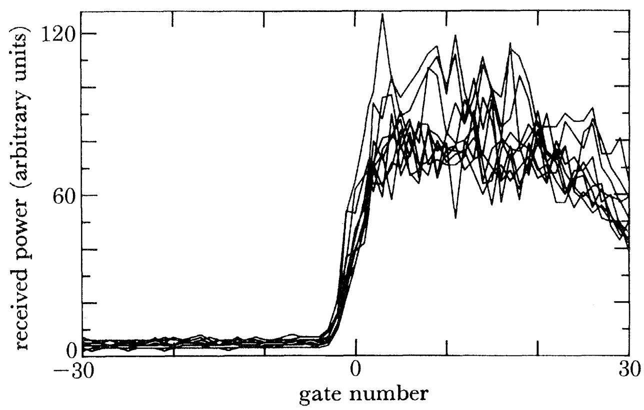

Figure 1. Ten of the smoothed returns from the radar altimeter on Seasat. Each return results from the averaging of 50 raw pulses and all the ten shown were taken within a flight time of 1 s. Each gate on the horizontal axis has a width of 3.124 ns.

As in nearly all wave-measuring devices, one of the main limits to accuracy is the inherent sampling variability. In the present case this appears as a random variability in the radar echo strength. When an echo is being received from a random surface such as that of the sea, the echo strength in any range gate is randomly chosen from a probability distribution whose mean (or 'expected value') is the information we require. The departure from the expected value is random on two timescales: these can be seen in figure 1 as the 'wiggles' within a single return, and the changes between successive returns.

Within the return from a single transmitted pulse, the amplitude randomizes after a time equal to the pulse length. Thus the random components of the returns within our three gates are uncorrelated. If the whole system were stationary, the returns from successive transmissions would be identical. However, the satellite is moving and looks at the sea from a different position for each transmission: the sea surface also moves, but this has less effect. The precise time it takes for this movement to produce an independent new 'look' at the sea surface depends on various factors including the waveheight, but the systems are designed so that with moderate or rough seas, each transmission produces an effectively independent look. In these circumstances, when smoothing over N echoes that have been through a square-law detector (as in Seasat), the proportional standard deviation σ of the smoothed values about their mean is simply $1/\sqrt{N}$. When $N = 50$, $\sigma \approx 14\%$: the scatter in figure 1 appears to be approximately this value. Estimates of waveheight derived from the differences between three gates on the rise are obviously going to have considerably more proportional scatter. Thus further smoothing is necessary if meaningful estimates of waveheight are to be obtained.

The relevant part of the Seasat specification was that when computed waveheights are averaged over 1 s, their standard deviation should be less than 10% of the mean. Webb (1981, amplified by personal communication) found that in practice he had to take 21 s averages to reduce the variability to 2%. This corresponds to a track length of approximately 140 km. The significance of this will be discussed later.

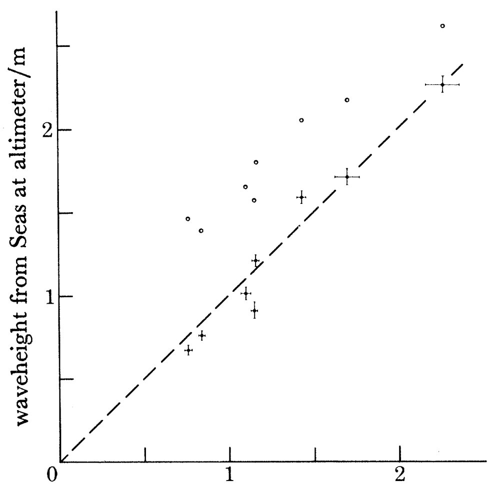

FIGURE 2. Comparison of estimates of significant waveheight from the Seasat altimeter with those from surface buoys. The solid circles with confidence bars show altimeter data that have been averaged and corrected by the J.P.L. algorithms. The open circles represent averaged but otherwise uncorrected data from the altimeter (from Webb 1981).

Webb (1981) compared the altimeter measurements of significant waveheights with measurements taken by surface buoys during the JASIN experiment and after all corrections had been made, the agreement was excellent considering that the measurements were not made at exactly the same place (figure 2). Chelton *et al.* (1981) report comparisons with 87 buoy measurements and get indications that the altimeter gave waveheights approximately 50 cm higher that they should have been for significant waveheights greater than 2 m. The reason for this discrepancy does not appear to be known. However, with more research we can expect that such an altimeter can achieve a 10% accuracy in waveheight measurement.

3. Synthetic aperture radar

The second wave sensor is the synthetic aperture radar, or SAR. A good description of the principles is given by Tomiyasu (1978), and the characteristics of the one on Seasat are described by Jordan (1980).

A satellite-borne SAR consists basically of a coherent radar looking at right angles to the flight path. In Seasat, the swath examined covered from 240 to 340 km to the right of the point beneath the spacecraft, the radar wavelength used was 23.5 cm, and the along-track resolution obtained (at a range of approximately 880 km) was 25 m. To obtain this resolution, a real aerial would have to be approximately 4 km long. The resolution in range is governed by the pulse length and in Seasat this was also 25 m on the sea surface.

The beam width of an ordinary radar is governed by the aperture of its aerial. Simply speaking, at a given point within the beam the phases of the signals coming from each part of the aperture have to be effectively the same so that they add constructively, whereas outside the beam they are different and add destructively. If we had a small aerial moved progressively across a large aperture, transmitting a signal each time it moved its own length, and measured the phase (relative to the transmission) of the received signal at a given target point, then when the large aperture had been filled one could add the received signals vectorially and get the same result as from a single transmission from the large aperture. With a little thought it will be seen that the same is true for the echo received by the radar from a fixed point target. This is the basic concept of synthetic aperture radar.

The time taken for Seasat to travel 4 km was approximately 0.6 s. This is long enough for the sea surface to have moved by considerably more than one radar wavelength. The principle of the SAR depends, of course, on the target field's being constant during the period of aperture synthesis, and the complex motions of the sea surface therefore degrade the along-track, or azimuthal, resolution. In rather special circumstances these motion effects can actually increase the visibility of long low waves, but more generally they act as a filter removing short-wavelength azimuthally travelling components. It is clear from figure 3, plate 1, which shows waves refracting round an island, and figure 4, plate 1, which shows a rather larger-scale image of waves on the deep ocean, that the SAR is capable of seeing waves, and it is believed that at least three and possibly four modulation mechanisms are at work at the same time. In all cases it is generally assumed that the basic physical process producing backscattering is 'Bragg resonance', in which the incident radar waves are backscattered by that short-wave component of the surface roughness whose wavelength matches that of the radar waves on the sea surface and therefore gives a coherent return ($\lambda_{\text{water}} = \lambda_{\text{radar}}/2 \sin \theta$, where θ is the angle of incidence). One of the easiest modulation mechanisms to understand in concept is the change in tilt of the sea surface towards or away from the satellite. Another is the way that the short Bragg resonant waves are

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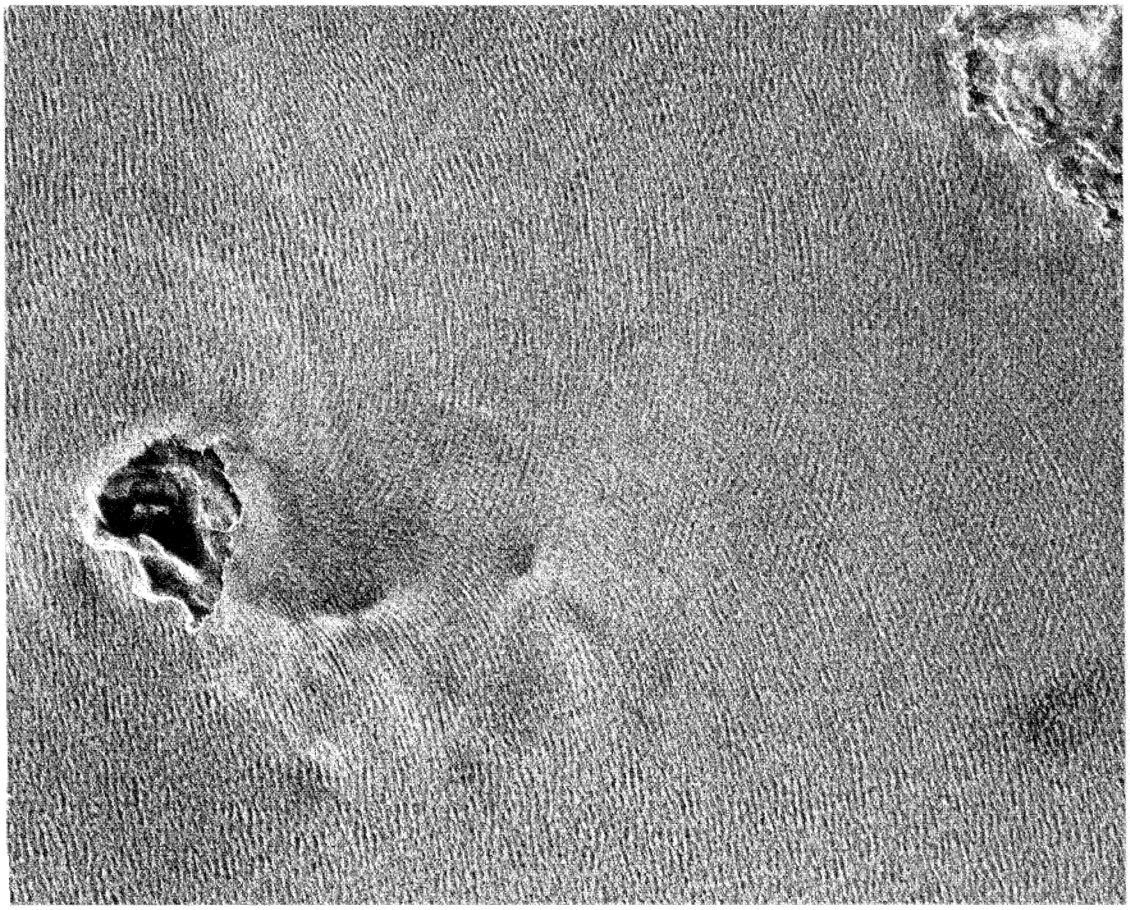
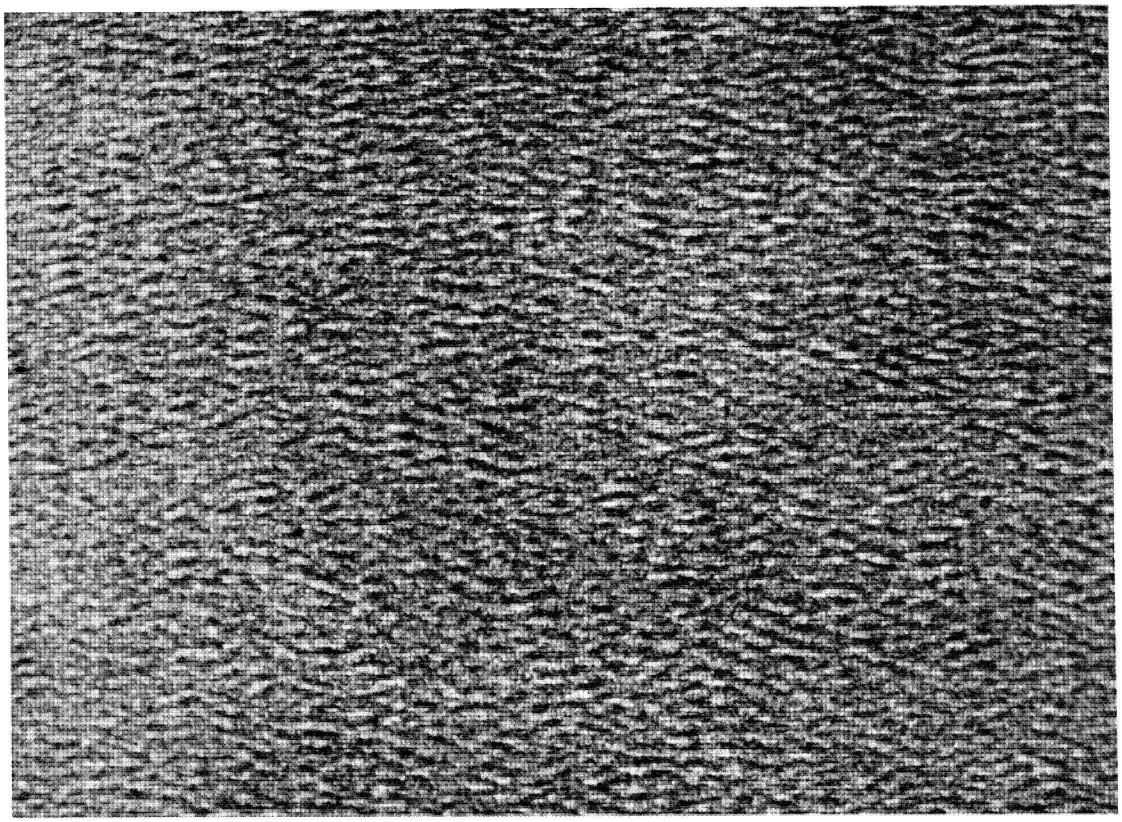
Description of plate 1

Figure 3. Waves refracting round the Island of Foula, west of the Shetland Isles. Seasat SAR; orbit 1149; image 30 km × 24 km; y axis true north; SAR range direction is 56° east of north. (Image made by Space Department, Royal Aircraft Establishment.)

Figure 4. An image of waves from Seasat orbit 0762 at 60° 11′ N, 6° 41′ W; image 12.8 km × 9.4 km; y axis is SAR incremental range direction, and is 56° east of north. (Image made by Marconi Research Centre, Chelmsford.)





FIGURES 3 AND 4. For description see opposite.

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stretched and compressed by the much longer waves that are being imaged. There is some indication that the variation of wind speed over the wave profile plays a part. Finally, as has been mentioned, in some circumstances the interaction of the surface motion due to long low waves with the aperture synthesis process can produce an imaging mechanism: however, this is a subtle process not readily explained in a short paper.

Figure 5 is the directional spectrum of the image in figure 4 (calculated digitally via Fourier transforms), and shows that apart from the longest waves (i.e. the lowest wavenumber waves), the spectrum of the image is symmetrical about the range axis and has a fairly constant width in the azimuthal direction. In this particular case we have wind speed and waveheight (but not a directional spectrum) measured nearby on the sea surface, and we can deduce that the true

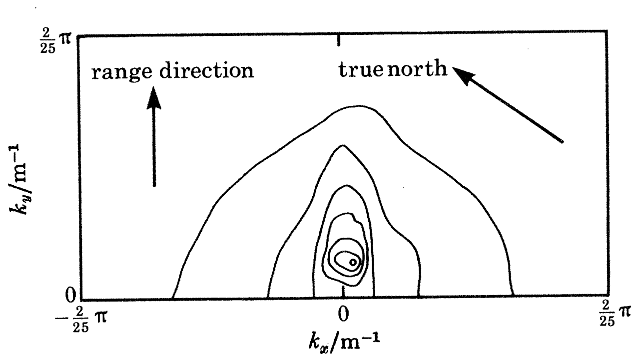

FIGURE 5. The two-dimensional spectrum of the image in figure 4 obtained digitally via Fourier transforms. Contours are at 2:1 intervals of spectral density. Note that apart from the low-wavenumber swell peak, contours are approximately symmetrical about the $k_x = 0$ axis, and that in the middle ranges of wave number the 3 dB azimuthal width is approximately constant. The omnidirectional background is due to speckle, which is not discussed in this paper.

wave spectrum is likely to be much broader in its range of directions at medium and higher wavenumbers than the image spectrum. Thus there appears to be a filter operating that removes the components with higher azimuthal wavenumbers, and this is due to the interaction of the sea surface motions with the aperture synthesis process. In the case under discussion the oceanographic situation is fairly simple and we can calculate the approximate characteristics of this filter (Tucker 1983), and its bandwidth agrees with that of the measured spectrum at medium wavenumbers (assuming that the azimuthal bandwidth of the real waves is much broader).

However, the way in which sea waves are imaged by a SAR is a complex matter, which is still far from being properly understood. Thus we are at present unable to extract waveheight information from the images to any useful precision, and are even unsure to what extent we can extract useful information on wavelengths and directions. This is an area of very active research at the present time.

Of course, the wave-measuring role should not be considered as the only justification for flying a SAR over the seas, as will be clear from Dr Raney's contribution to this symposium. There is also a fascinating report by Fu & Holt (1982) showing examples of all the identifiable oceanographic phenomena that were seen on Seasat SAR images.

4. Operational considerations

In this context there are two types of requirement for wave data: real-time data for use in the execution of marine operations, and statistical or 'climate' data for use in the design of structures and for the planning of marine operations. In fact, the first application really requires forecast data. A number of wave forecasting systems are in operation, including one run by the U.K. Meteorological Office using, as input, data from their meteorological forecasting model (Golding 1980). However, it is helpful to have real-time data to supplement and check the predictions of these models.

A single satellite gives rather sparse coverage in space and time, as will be seen from figure 6. Consecutive 'up' tracks on the Earth's surface are separated by approximately 2700 km in latitude at the Equator, and by 1350 km at 60° N. Twelve hours later the same area will be crossed by 'down' tracks. Approximately 24 h later the area will be crossed by tracks 900 km to the west at the equator, or 450 km to the west at 60° N.

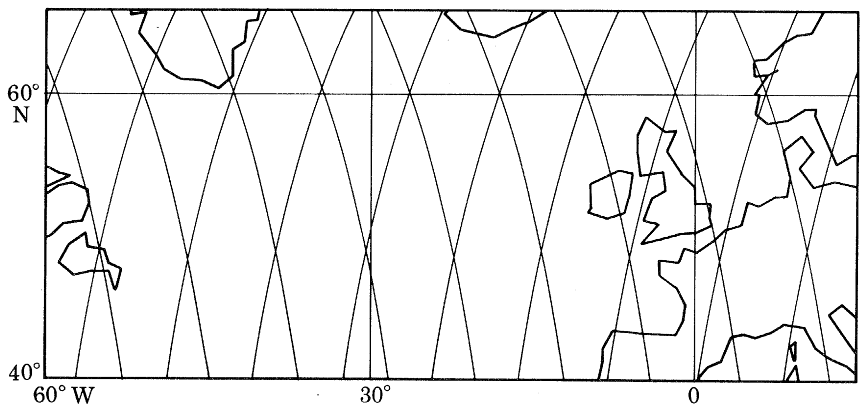

Figure 6. The tracks of a single satellite over the North Atlantic during a period of 3 days. Height 668 km, orbit inclination 98°.

A system of three satellites arranged to cover the same tracks at daily intervals would give better coverage, but at U.K. latitudes one would still only get daily readings along the sides of a roughly diamond-shaped grid of about 500 km sides.

This raises the two related questions: 'How local are short-term wave conditions?' and 'How local is the long-term wave climate?' Near coasts, the conditions vary on a scale roughly equal to the distance from the nearest coast (this is a gross oversimplification but good enough as an order of magnitude for present purposes), so in this case the answer to both questions is 'very local'. However, the situation is not so clear over the open ocean far from land. Challenor (1983) has made a preliminary study of this problem by using eight successive passes of the Seasat altimeter over the same track over a period of 24 days (all that was available owing to the short life of Seasat). The track chosen was a 'down' track passing from approximately NE to SW and close to O.W.S. *Lima* (57° N, 20° W). Data on significant waveheight (H_s) from the altimeter were plotted and are shown in figure 7. Variation along the tracks (each approximately 2000 km long), is remarkably slow, even in the vicinity of storms, and the few bumps, which are probably due to fronts, are comparatively insignificant. The average of these eight tracks is shown in figure 8 and shows only a slow and modest drop towards the southern end of the track studied. Challenor compares these space scales with the time variation of waveheight at O.W.S. *Lima*, using the group velocity of the waves, and gets general agreement. Some idea of the sort of climatic information that could be available is given by Chelton *et al.* (1981), who have analysed all the data from Seasat.

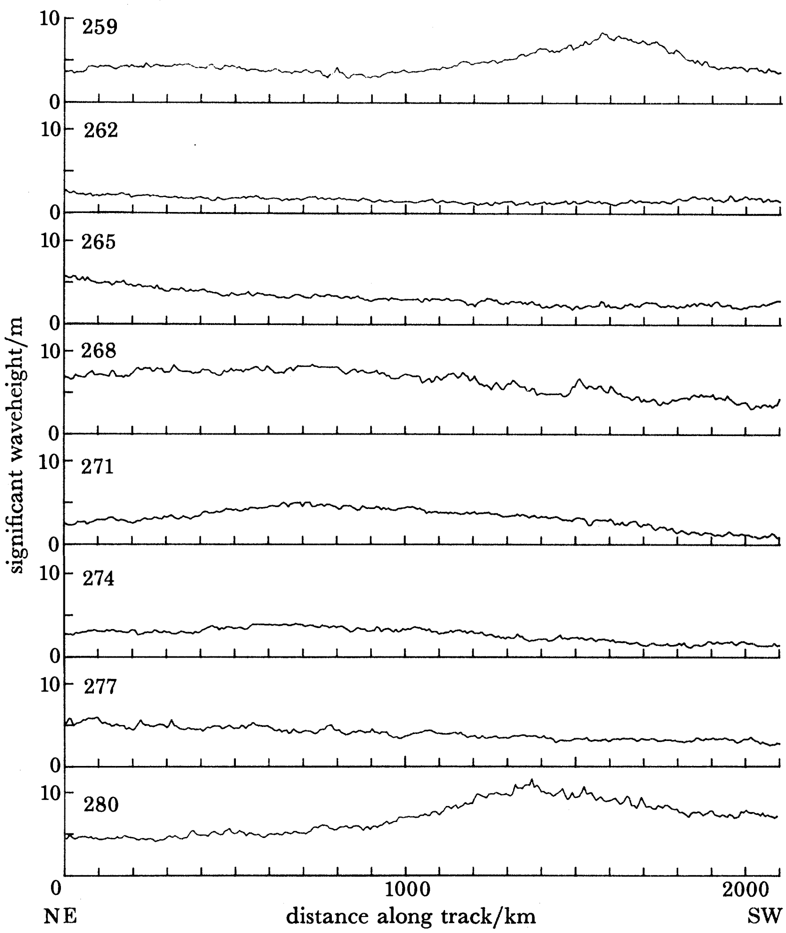

FIGURE 7. Significant waveheight from the Seasat altimeter during eight passes over the same track at 3-day intervals. The tracks passed over O.W.S. *Lima* (57° N, 20° W) and went approximately from NE to SW (from Challenor 1983).

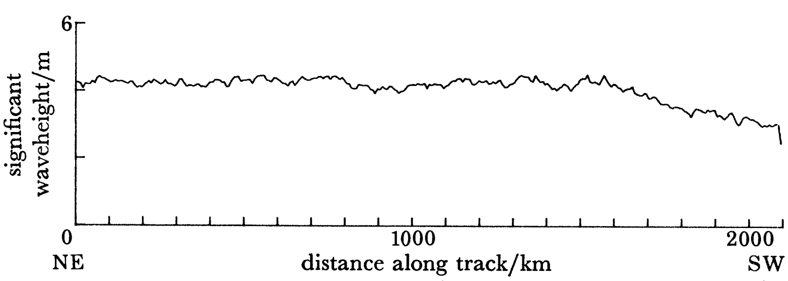

FIGURE 8. The average of the eight tracks in figure 7.

This evidence is, of course, very limited, but as far as it goes it agrees with what one might expect. Thus the coverage of the deep oceans away from the coast by the altimeter may well be adequate for the determination of waveheight climate (given a long enough duration of

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observation), and with three satellites the frequency–spacing combination will give a reasonable, though not ideal, short-term coverage of the same areas for operational use. If detailed wind maps could be made available by a satellite scatterometer system, for example, then these would supplement the pattern by showing where there were high winds producing locally rough seas.

At present we are looking to the SAR only for data on wavelength and direction, and it is unfortunate that the SAR swath falls about midway between the altimeter tracks. However, the altimeter on up tracks crosses with the SAR swath on down tracks and vice versa, so that the data can be correlated at these crossing points with some time delay, which would in fact be comparatively short if three satellites were operating.

The European Space Agency's planned ERS-1 satellite uses some hardware common to both the SAR and Wind Scatterometer (together they are termed the Active Microwave Instrument, or AMI). Thus the SAR and scatterometer cannot be operated simultaneously, but a reasonably satisfactory pattern of interleaved measurement can be achieved. The SAR wave measurements will be in the swath of the wind scatterometer, which measures the distribution of surface wind by measuring the microwave backscatter, and the two measurements should supplement one another in many circumstances.

We can now return briefly to the subject of accuracy. It must be emphasized that as established at present, the altimeter gives information only on height, and none on wavelength or direction of travel. With waveheight readings averaged over 1 s, the satellite 'footprint' is approximately 10 km long and the accuracy about $\pm 10\%$. Such information would be useful for many operational uses as long as the observations are not too close to shore. For wave climate purposes higher accuracies are desirable, and it looks as though they may be obtainable by longer averaging. Thus good climatic information is probably only obtainable in the open ocean away from coasts, but this is just where such information is most difficult and expensive to get by using surface sensors.

Finally, one must not forget that even a single satellite produces a huge amount of data. When the SAR is working in its full imaging mode it produces approximately 10^8 bits of data per second! Even the radar altimeter will generate one value of significant waveheight every second. If this data is to be available in either near real time, or from historical archives, a major system has to be set up to process it and bank it.

5. Conclusions

A precise radar altimeter on a satellite can measure waveheight to useful accuracy for operational purposes over oceans and to within perhaps 10 km of the coast. However, the time and spatial coverage is rather sparse for applications near the coast.

The altimeter can possibly give an accuracy adequate for wave climate work but with a poorer spatial resolution, which means that it can only be used much further from coasts than the 10 km quoted above.

The degree to which synthetic aperture radar can give useful information on wavelength and direction is not yet established. This poses a complicated problem requiring further research. The mechanisms of modulation are not yet well enough understood to extract waveheight information from it.

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References

Challenor, P. G. 1983 In *Seaset over Europe* (*Proceedings of a conference in London*, 14–16 April 1982) (ed. T. D. Allan). Chichester: Horwood. (In the press.)
Chelton, D. B., Hussey, K. J. & Parke, M. E. 1981 *Nature, Lond.* **294**, 529–532.
Fu, L. L. & Holt, B. 1982 *Seasat views oceans and sea ice with synthetic aperture radar*. N.A.S.A. Jet Propulsion Laboratory Publication no. 81-120.
Golding, B. W. 1980 In *Power from sea waves* (ed. B. Count), pp. 115–134. Academic Press.
Jordan, R. L. 1980 *IEEE Jl ocean. Engng* **OE-5**, 154–164.
Townsend, W. F. 1980 *IEEE Jl ocean. Engng* **OE-5**, 80–92.
Tomiyasu, K. 1978 *Proc. IEEE* **66**, 563–583.
Tucker, M. J. 1983 In *Seasat over Europe* (*Proceedings of a conference in London*, 14–16 April 1982) (ed. T. D. Allan). Chichester: Horwood. (In the press.)
Webb, D. J. 1981 *J. geophys. Res.* **86**, 6394–6398.

Discussion

E. D. R. Shearman (*Department of Electronic and Electrical Engineering, University of Birmingham, U.K.*). In discussing the observation of gravity waves by a SAR, Mr Tucker mentioned various mechanisms by which gravity waves modulate the capillary waves, which are the primary scatterers detected by a microwave radar. One mechanism, which he did not mention, is roughness modulation, the variation of the amplitude of the capillary waves from one part of a gravity wave to another, a phenomenon that one can observe visually on waves in a tank or at sea. Would Mr Tucker comment on the contribution that this mechanism makes to the overall process of gravity-wave detection by SAR?

As a comment, rather than a question, I should like to point out another technique for area surveillance of gravity waves, namely high-frequency (h.f.) radar, of which the ground-wave version should permit continuous observation of wave development over an area extending some 100–200 km out from the sea coast. In the 6–8 years between now and the launch of the next generation of radar satellites for ocean surveillance, there is time for a network of h.f. radars to be installed and to be generating invaluable sea-truth for the satellites. Of the two techniques, satellites give world coverage but on a time and space sampled scheme, whereas h.f. radar gives continuous coverage over a limited area, the two thus being truly complementary. (Sky-wave radar gives poorer quality data over a considerably greater area.)

I suggest that it behoves those planning the satellite experiments to ensure good coordination of the two types of measurements.

M. J. Tucker. The mechanisms of modulation are discussed briefly in the published paper. Detailed analyses of the 'hydrodynamic modulation' effect referred to by Professor Shearman, and of the mechanisms of modulation by tilt and by the interaction of sea-surface velocities with the aperture synthesis process, are given in the following review paper: W. R. Alpers, D. B. Ross & C. L. Rufenach (*J. geophys. Res.* **86** (C7), 6481–6498 (1981)).

However, these three mechanisms do not adequately explain recent experimental results from radars mounted on towers in the sea, and it seems likely that one or more other mechanisms play a part. Table D1 is instructive: it shows the attenuation times and distances of water waves due to viscosity alone. There are additional mechanisms for dissipating energy from steep waves, so the decay times and distances quoted are maximum possible values. (Typical values of the relevant parameters are used in these computations.)

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TABLE D1

wavelength/m	phase velocity	group velocity	radian frequency	amplitude decay to 1/e (s)	amplitude decay to 1/e (m)
1.0	1.249	0.6252	7.85	8332.0	1.07×10^4
0.25	0.626	0.3160	15.74	520.7	3.40×10^3
0.10	0.401	0.2119	25.19	83.3	3.64×10^1
0.04	0.272	0.1780	42.70	13.3	4.88
0.02	0.233	0.2146	73.07	3.33	1.48
0.01	0.248	0.3086	155.6	0.83	0.53

These figures show that for the longest wavelength radars (for example, L-band), the energy of the Bragg resonant ripples persists for many cycles of the predominant sea waves, and travels slowly compared with the phase velocity of these. Thus the compression of the sea surface in the crests of the long waves compresses the ripple energy there, and the reverse happens in the troughs. However, for the shortest wavelength radars (for example, Ku band) the energy of the Bragg resonant ripples decays quickly and an approximate local equilibrium is achieved between generation and decay as they ride over the long-wave profile. In this case it is plausible, for example, that variation in surface wind speed over the wave profile can modulate the backscatter.

It is perhaps worth commenting on the common use of the term 'capillary wave' in this context, because I believe it to be misleading. By using a typical value for the surface tension of clean water, the contribution of this to the restoring force equals that of gravity for waves with a wavelength λ of approximately 1.7 cm. For longer waves, the effect of surface tension rapidly diminishes, and is 5% for $\lambda \approx 5.2$ cm. For the Seasat SAR, the Bragg resonant wavelength was approximately 34 cm, and for the proposed SAR on ERS-1 it is approximately 7.2 cm. Thus these are both firmly in the gravity-wave part of the wave spectrum. Even for X-band, the Bragg resonant waves will usually be on the gravity-wave side of the dividing line, depending on the angle of incidence. The term 'ripple' would be better to distinguish these short waves from longer ones.

D. E. CARTWRIGHT (*I.O.S. Bidston, Birkenhead, U.K.*). I wonder if too many people are assuming that ERS-1 will necessarily have a 3 day repeat? I am not in touch with the latest decisions by E.S.A., but those concerned with using the altimeter data for currents and tides would certainly prefer an exact repeat period in the region of 6–10 days, to produce a grid of smaller mesh in a somewhat longer time. This would make negligible difference in the spacing between Earth-tracks beneath consecutive revolutions, which is most relevant to Mr Tucker's problem of defining the global wave field. For example, altering the 'Seasat' orbit from a repeat period of 3 days to one of 10 days would only entail the difference between $14\frac{1}{3}$ and $14\frac{3}{10}$ revolutions per day.

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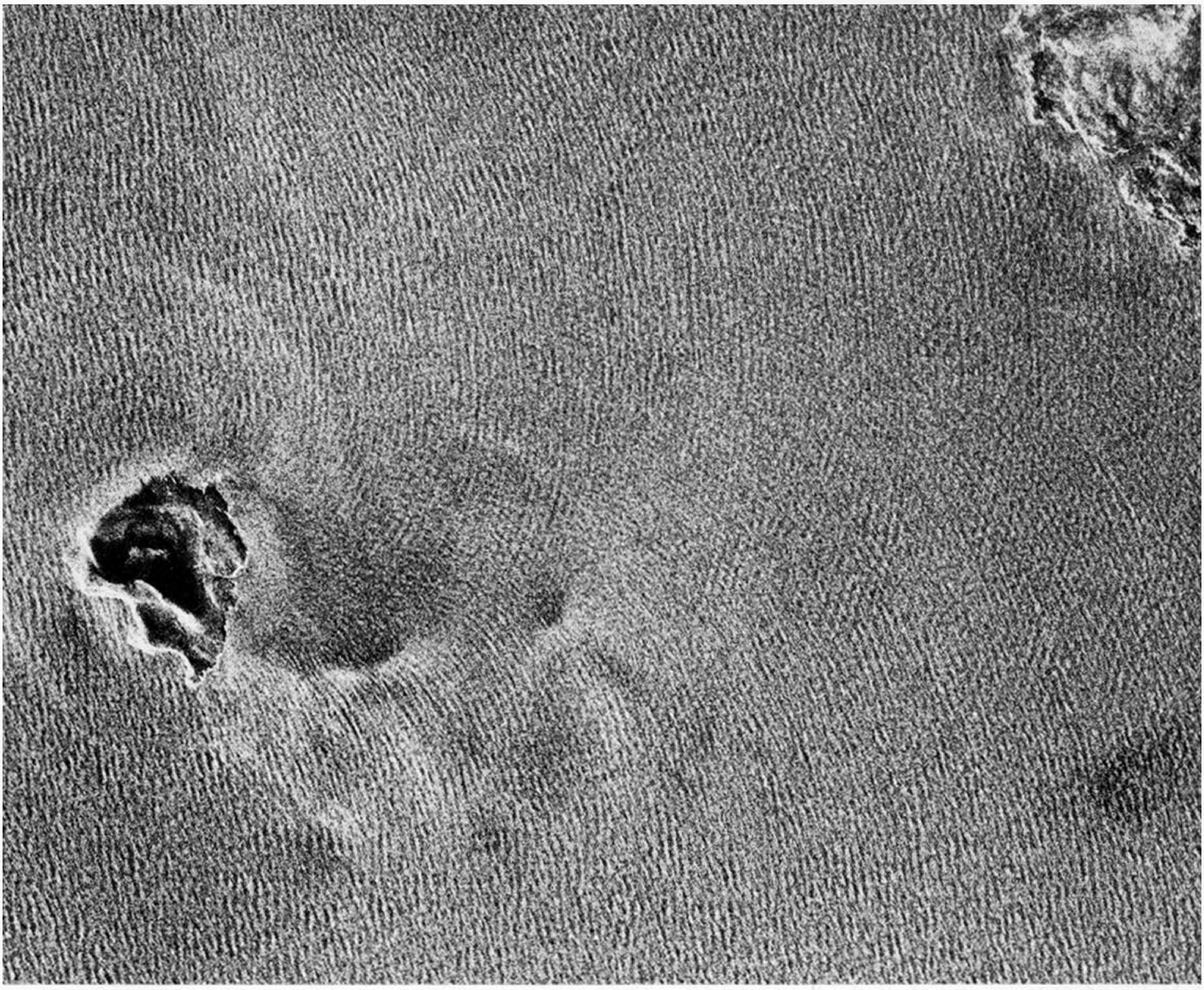

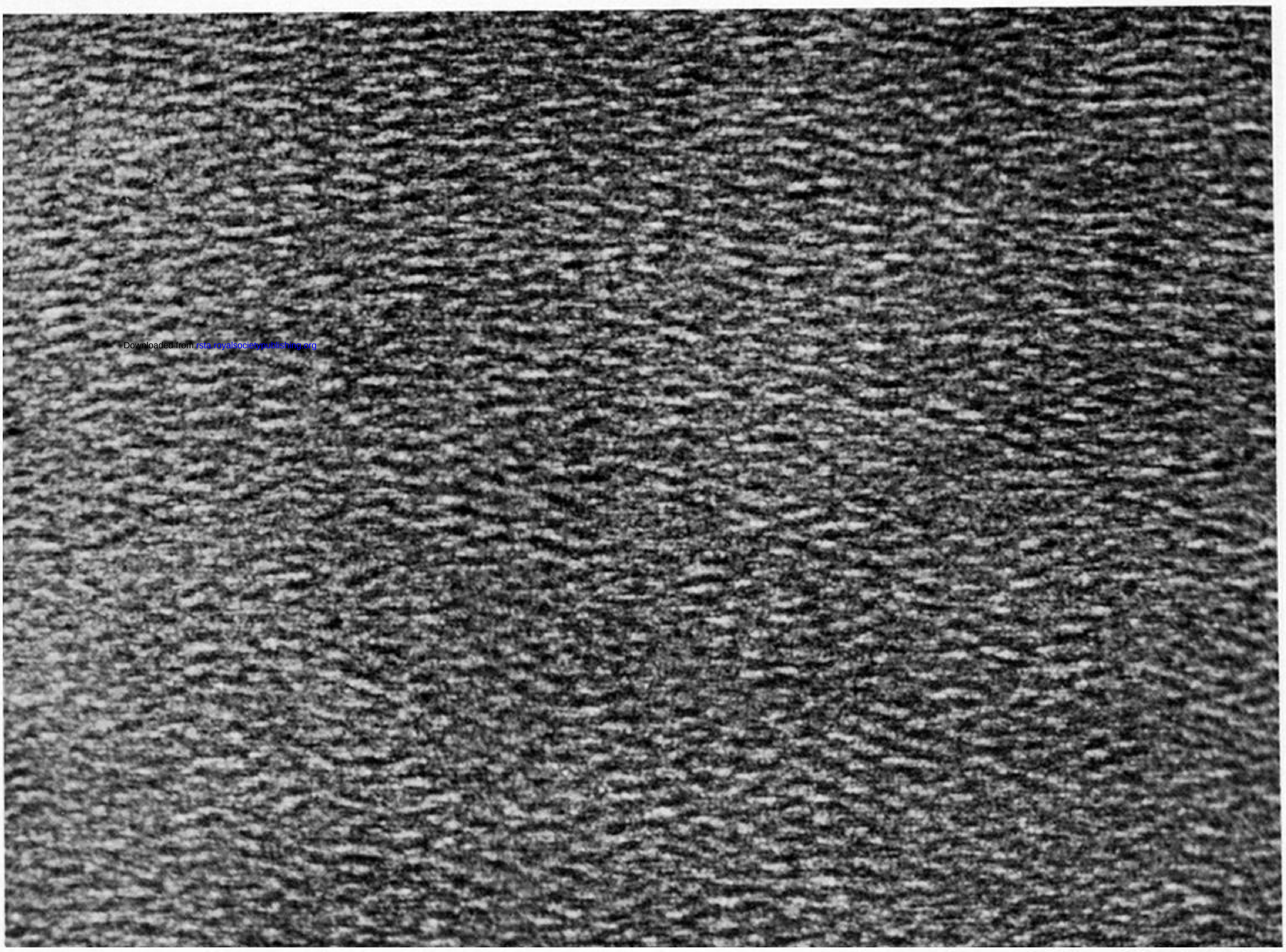

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