The Use of SPOT Data for Wave Analysis

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After recalling the various techniques used for wave measurement, this paper concentrates on the possibilities of using SPOT data for large scale wave analysis. Conditions for good wave pattern visibility are discussed from a theoretical point of view. In order to check the theory, examination of a large number of SPOT images was performed concerning the relation between viewing conditions and image quality. Using spectral analysis, a comparison is achieved using available simultaneous in situ directional data and SPOT images of an off-shore area in Brittany, France. Major conclusions are that both types of data compare rather well and that SPOT data could be used effectively in the coastal zone, provided that a proper software is designed to process small spatial windows. Recommendations are given for image acquisition procedure.

INTRODUCTION

The wave climate of a coastal reach refers to different wave directions, wave heights, and their distribution in time and space. The wave climate affects a number of natural processes in the coastal zone but is also important for different uses of the zone such as

- —Littoral transport at erodible coasts—both along-shore and on–off-shore—depends on the waves. The possibilities of understanding and predicting coastline changes of a natural reach or a reach subjected to constructions (breakwaters, coastal defences, etc.) is primarily linked to a knowledge of the wave characteristics at wave breaking —especially wave direction, height, and period.
- —Harbor localization and design is affected by the degree of wave motion in the harbor entrance and the amount of wave energy reaching the harbor basin.

Field observations of at least some aspects of the wave climate along coastal reaches are generally rare in the developed parts of the world and even more so in other areas. Comprehensive and systematic observations for extended periods comprising heights, lengths, and directions are consequently even rarer. Thus, if wave data is needed for a specific coastal reach, one has to launch a special measurement program or resort to calcula-

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tions. The former method usually consists of point measurements by means of wave riders, for instance. Such measurements are rather expensive and of limited duration but could provide detailed information on the wave climate at one point. One main drawback is, of course, that point measurements do not provide an overall view of the wave characteristics in a coastal area. Calculations rely on empirical relations between (supposedly) known wind data and deep water waves. The propagation of these waves into shallow water is then calculated using models. It is obvious that this method contains a lot of uncertainties—input wind data, transfer functions, wave propagation behavior.

BACKGROUND IN REMOTE SENSING OF WAVE CHARACTERISTICS

The brief discussion above indicates a need for better availability of field data on wave climates. The right way to collect wave data is to install directional wave measuring buoys. It would, however, be very expensive to build a large network of *in situ* wave gauges to be established around the coasts of the world. Other ways of obtaining wave information have thus to be considered. Airborne or space remote sensing of the water surface could provide some wave data in itself and be valuable in complementing *in situ* measurements. For coastal areas it could provide large scale, synoptic information on wave characteristics (wavelengths and directions) and their changes when the waves propagate from deep to shallow water and eventually break.

Aerial photography of waves is a more or less established technique which is discussed by McClellan and Harris (1975). The basic idea is to take a picture of the instantaneous wave pattern in a coastal water area, usually from an airplane, assuming that the grey-tone variations of the photo reflect the wave characteristics. Wave visibility is enhanced in sunny conditions looking close to the specular reflection direction.

Wave studies using satellite data are mainly based on active microwave technology. Unfortunately, no radar instrument is operational now on a regular basis. The potential of wave imaging was however demonstrated by the shortlived SEASAT and the SIR missions. The european ERS-1 is planned to be equipped with both SAR facilities and an altimeter.

The best possibility of studying wave characteristics (length and direction) right now on the basis of satellite data is provided by the operational SPOT using CCT data from the panchromatic channel having a spatial resolution of 10 m and a single scene coverage of 60 km×60 km. Such data have a strong resemblance to ordinary aerial photography. The detected light wave spectrum is approximately the same and the spatial resolution is such that waves are directly visible on satellite images. There are some nice features with SPOT data, making it useful for wave analysis:

- —Data exist in digital format, that is, no need for digitizing photos for image processing purposes.
- —Very good spatial resolution makes it possible to study smaller wave lengths than with SAR technique.
- —Data are delivered in a geometrically corrected format (level 1b) which is important for accurate wave analysis (CNES and SPOT IMAGE, 1988).
- —The satellite can be programmed for a very frequent and also a quite spatially exact coverage of a specific water area.

A drawback with SPOT data is, of course, the dependence—as with all visible light detectors—on the atmospheric conditions. Another issue is the price—that is, of the order of 10,000–15,000 French francs for a single scene. This might, however, compare favorably to using airplanes. In order to illustrate wave features that could be detected in a SPOT scene, an example from Cap Vert, Dakar (12 March 1986) is shown in Figure 1. This image reveals several features:

a. Two different wave systems can be distinguished in the left-hand side of the image.
b. Waves originating from the northwest are clearly diffracted around Cap Vert.
c. Waves propagating from deep to shallow water are affected by the bottom topography (refraction) in two ways: Waves crests tend to get aligned with isodepth lines and wavelength is shortened.
d. Zones of breaking waves can be located.

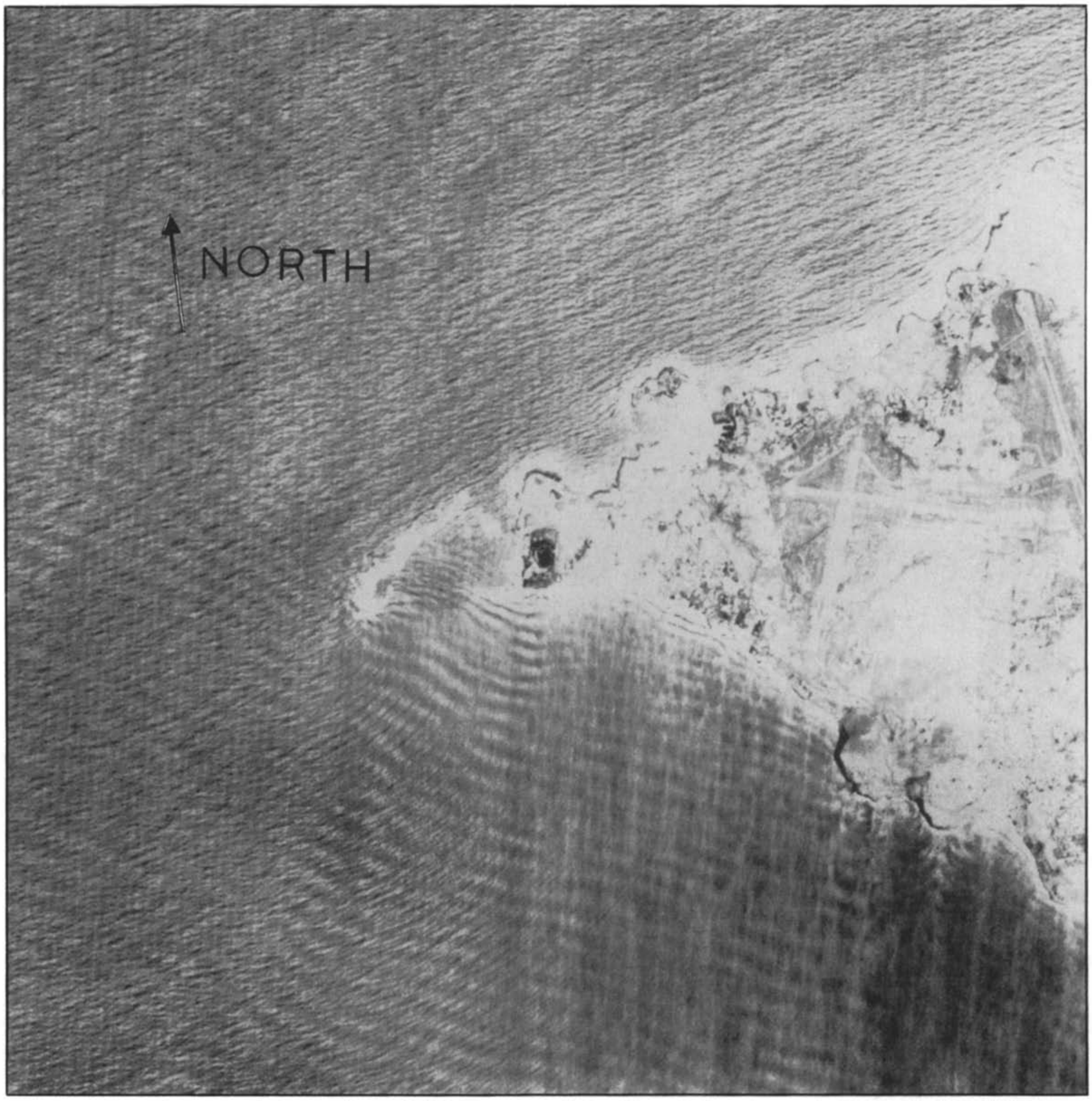


Figure 1. Panchromatic (10m resolution) SPOT image off Cap Vert, Dakar, Senegal, 12 March 1986 (5 km × 5 km).

LIGHT REFLECTION ON SEA SURFACE

In order to get proper images of the sea surface, it is important to understand its interaction with light. Let us consider a flat sea surface. Sun reflection is composed of two components: a) the specular component (glitter), symmetrical to the incident light with respect to the surface normal; b) the diffuse component, proportional to the scalar product between incident light and surface normal (i.e., stronger when the sun is high in the sky). Of course, glitter is much more energetic per unit of solid angle (Cox and Munk, 1954).

When the sea surface is modulated by sinusoidal movement (Fig. 2), the specular vector is no longer unidirectional, but varies with the wave slope symmetrically around the still-water specular reflection direction. These variations remain small, as typical wave slopes only reach a few degrees. E is the sun elevation angle (measured from horizon) and I the viewing incidence (with respect to the vertical), specular reflection is expressed as $E + I = 90°$. To get proper surface illumination (according to the aerial photography in Fig. 3), the condition to be fulfilled is

$$60° < E + I < 120°. \qquad (1)$$

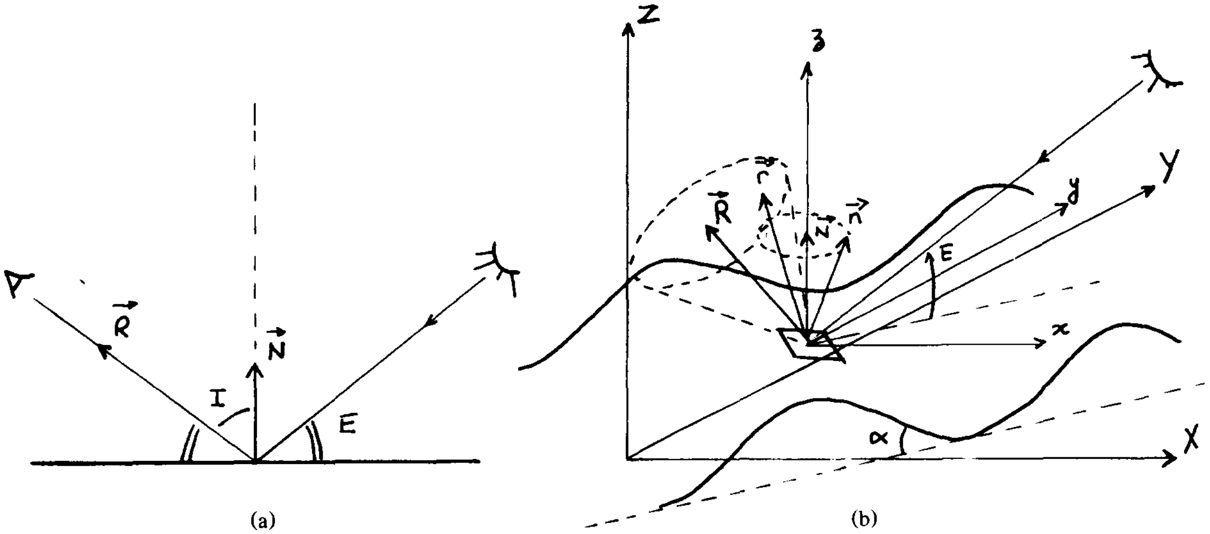


Figure 2. Sun reflection on sea surface: (a) still water $E + I = 90°$; $\vec{R}$: specular direction for still water; (b) wave modulation, $\vec{r}$ and $\vec{n}$ oscillate in planes limited by half-angle α cones; α = wave slope.

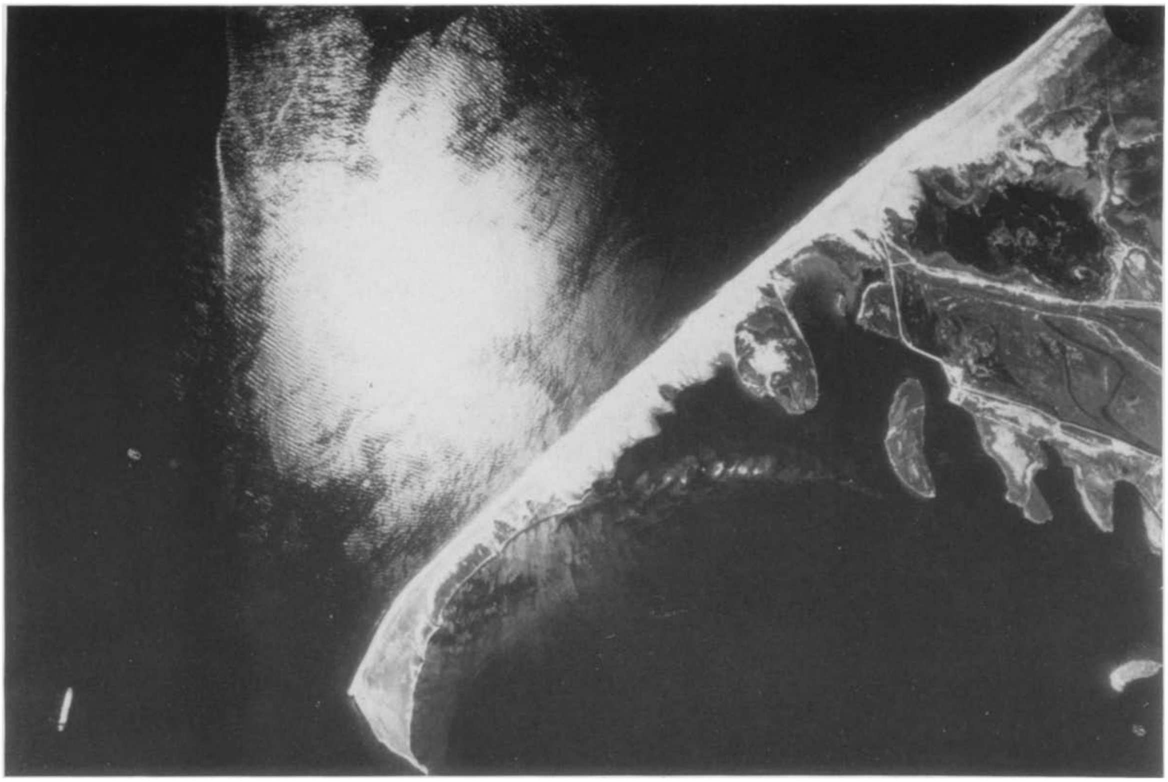


Figure 3. Aerial photography of coastal water with waves visible around the "hot spot," that is, the point for specular reflection.

This range is compatible with data quoted by Wadsworth and Piau (1987). Let us now consider the case of SPOT imaging conditions.

Its field of view being only about 4°, we can assume a fairly constant incidence angle over a whole SPOT scene. As a matter of fact, at scene center, I can vary from 32° eastward to 32° westward. In order to satisfy relation (1), the minimum E required is around 35° for sun elevation, together with strong eastward tilting (around 30°). Eastward viewing will be required in most cases; only very high solar elevations will allow slight westward viewing.

To confirm or invalidate these recommendations about viewing parameters, statistics have been established on a number of scenes (see the Methodology section further on).

STATISTICS ON VIEWING CONDITIONS

This study consists in reviewing all the existing images of the French coast. Visual examination is only possible when the image has been processed to level 1b by the Spot Image Co. This unfortunately limits the total number to 180. Among them, only those for which a) reliable wave data issued from coastal buoys were available (period measurements performed by ships were discarded as being too inaccurate) and b) swell amplitude was over 0.5 m were considered. This latter cutoff value is the threshold above which real swell may be no longer mistaken for "wind sea."

Among the 50 situations with swell higher than 0.5 m, swell is clearly visible in 12 and not visible in 38. The parameters which seem to influence the image quality are:

—$(E+I)$ value (see the previous section).
—Angular dispersion, wavelength, and wave height.
—Weather conditions: cloud cover, visibility.

The small sample size does not allow the probability of observing swell to be defined.

However, it appears that, by choosing $E+I$ above 60°, one gets a 50% chance of seeing the swell, whereas this probability decreases to 20% below 60°. Although the small size of some samples does not allow straightforward conclusions, the recommendation is to make provision for a high sensor tilting value, that is, a high I value. Nevertheless, one cannot eliminate all images with $E+I$ below 60°, which is quite a new fact.

Below 1 m height, the swell is hard to detect visually, and above 2 m very few good images are available, certainly because of cloud cover. As expected, the number of positive cases increases with wave height.

Few favorable cases are expected at either end of the period range. Short period values (for instance, 5 s or 40 m wavelength) are representative of "wind sea," with strong angular dispersion. For long period values (about 15 s, i.e., 350 m), the ratio height over wavelength gets very small and so does the swell slope. Therefore, the decrease in the signal to noise ratio makes it difficult to detect the swell.

METHODOLOGY FOR IMAGE PROCESSING AND DATA COMPARISON

Analysis of Wave Parameters by Means of Fourier Transform Techniques

A satellite image is a two-dimensional sampling of the wave field and thus a two-dimensional discrete Fourier transform (DFT) has to be used. Let $x(m_1, m_2)$ be the digital levels attached to the pixels within an $N \times N$ subarea of the digitized image with m_1, m_2 representing the pixel location. Suppose that the pixels are equally sized with a side length Δx. The two-dimensional DFT is defined by

$$F(n_1 \cdot k_0, n_2 \cdot k_0) = \frac{1}{N^2} \sum_{m_2=0}^{N-1} \left[\sum_{m_1=0}^{N-1} x(m_1, m_2) \cdot e^{-i2\pi n_1 \cdot k_0 \cdot m_1 \cdot \Delta x} \right] \cdot e^{-i2\pi n_2 \cdot k_0 \cdot m_2 \cdot \Delta x}, \tag{2}$$

where

$$k_0 = 1/L,$$
$$L = N \cdot \Delta x.$$

Computations are performed using algorithms for Fast Fourier transforms (FFTs), limiting the choice of N:

$$N = 2n \quad (n = 1, 2, \dots).$$

The coordinate axes of the squared amplitude spectrum correspond to the wave numbers in the X and Y directions, respectively. The peak of the spectrum (n_1, n_2) is representative of the wave characteristics:

$$\frac{1}{\lambda} = K_v = \sqrt{K_{vx^2} + K_{vy^2}} \tag{3}$$

$$\tau_g \alpha = \frac{K_{vy}}{K_{vx}} = \frac{n_2}{n_1} \tag{4}$$

where

λ = wavelength of real wave,

K_v = wave number of real wave,

$K_{vx} = K_0 \cdot n_1$ = wave number of X direction,

$K_{vy} = K_0 \cdot n_2$ = wave number of Y direction,

α = propagation direction.

Comparison of Image and Buoy Spectra

In order to compare image and buoy spectra, we have to consider that they were obtained in two different ways. Image data represent the specular properties of the sea surface. They are then dependent on the slope distribution and on other phenomena such as sea-ripples (wind action), white capping, etc. So it seems of interest to investigate whether the sea surface roughness has a large effect or if the image spectrum is actually representative of the directional slope spectrum of the sea surface (SS). On the other hand, buoy spectrum is a true directional water surface displacement spectrum (S). There is a relation between these two kinds of spectra stated by Klemas et al. (1974):

$$S_s(K_x, K_y) = K^2 S(K_x, K_y). \tag{5}$$

K is the wave number: $K^2 = K_x^2 + K_y^2$.

The K^2 factor appears when calculating the slope energy spectrum after deriving, for x and y, the expression of the superposition of N sine waves:

$$W(x, y) = \sum_{i=0}^{m} ai \cos(K_{ix} x + K_{iy} y) \tag{6}$$

Assuming a) deep water waves and b) homogeneity in space and time of the wave characteristics, one can use the following relation,

$$K = \frac{2\pi}{g} f^2, \tag{7}$$

where K is the wave number equal to $1/\lambda$ and f the frequency equal to $1/T$, to compare the slope spectrum (spatial domain) with the displacement spectrum (time domain). Before plotting the energy as a function of the period, the image spectrum is divided by $4\pi^2/g^2T^4$, according to (5) and (7).

Prior to comparing image and buoy data, noise has to be eliminated. Since it is white noise, a simple subtraction of the minimum energy value to the whole spectrum is performed, as a first approximation. Only then can the SS (image) be divided by the $4\pi^2/g^2T^4$ factor.

APPLICATION TO AN OFFSHORE AREA IN BRITTANY

The major reason that led us to choose the Ouessant area as a test site in the presence of an open sea directional wave measuring buoy, so that image data could be compared with *in situ* data. Also, waves are quite common in that area, making image acquisition easier.

Buoy Beatrice Data Description

This buoy is moored 30 miles off the isle of Ouessant, at a depth of about 110 m. The instruments installed on board are:

—a magnetometric compass giving buoy orientation,
—a heave gauge based on acceleration measurement,
—pitch and roll gauges which create alternating magnetic fields.

The system records on five analog channels: pitch, roll, heave, sine, and cosine of the bearing. After filtering, sampling is performed (2 Hz for heave, roll and pitch, 1/3 Hz for bearing) and then 12 bits encoding, multiplexing, and storage.

Processing starts when 4096 values have been recorded, that is, 34 min 8 s of sea state record. It is based on a statistical model of the sea surface which describes its displacement as the sum of a great number of monochromatic waves with various frequencies and directions. The phases are independent and cover the $[0, 2\pi]$ interval. In each frequency band, the calculation yields a value of energy and the direction for which the energy is the highest. Figure 4 shows a typical energy spectrum (Racape and Ezraty, 1987).

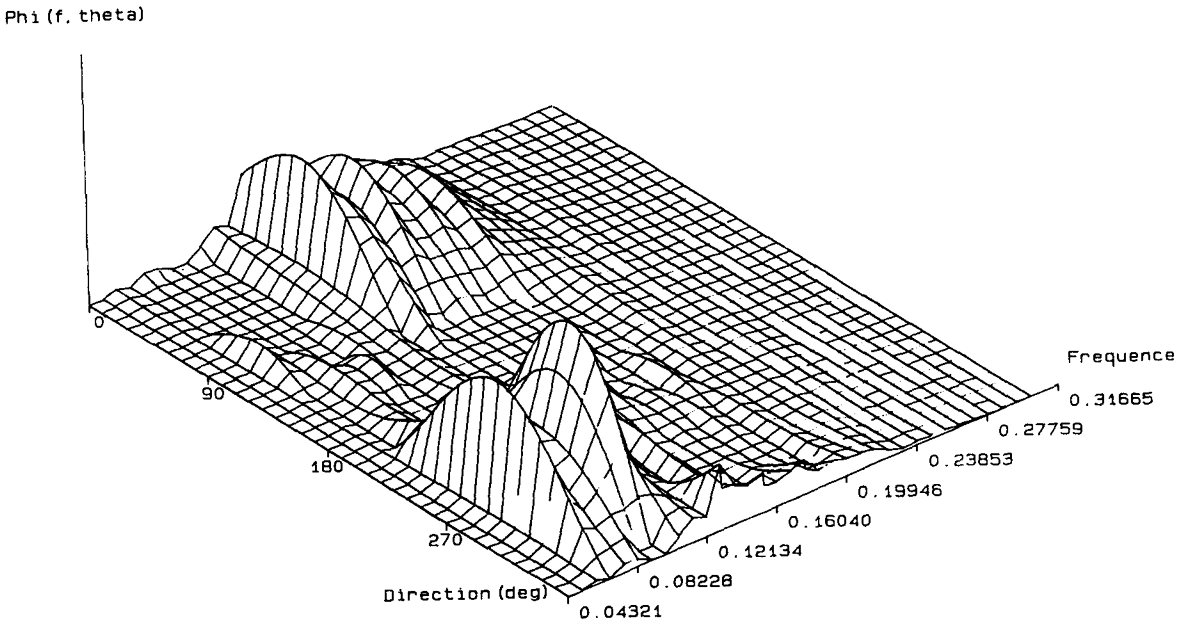


Figure 4. Directional wave buoy spectrum Phi (dir, freq) obtained off Ouessant on 25 April 1988 (12.00 h Hm0 = 2.52 m).

SPOT Images Acquisition Campaign

We have had little experience with the possibility of getting the right SPOT images at the right time. To put it another way: how to choose the best period of the year, over a determined area, which will provide the highest probability of a good wave situation, together with the right sun elevation. It appears that in Western Europe, springtime will generally be the best period with regards to these conditions. Sun elevation after the equinox will currently reach 45° at 45° latitude, while the prevailing weather conditions will generate waves most of the time. Of course, the choice of the period will have to be adapted to each study location with chances varying accordingly.

In order to test the strategy, an acquisition campaign was carried out in Spring 1988 at the Beatrice buoy location. It resulted in 13 scenes recorded by the satellite between 31 March and

Table 1. Panchromatic Spot Scenes Acquired by the Satellite from 31 March to 16 May, 1988, on Grid Node 23/252 (Off-Shore Ouessant, Brittany)

				In Situ Wave Data			
Date	*Incidence Angle*	*E + I*	*Cloud Cover*	*Azimuth to North*	*Period (s)*	*Height (m)*	*Purchased for Study*
880331	6.1 W	39	1122	N.A.			No
880404	21.1 E	67	2222	N.A.			No
880410	2.8 E	52	2221	63°	7.0	1.5	No
880415	8.2 E	59	2222	N.A.			No
880420	13.0 E	67	0001	268°	10.0	2.2	Yes
880425	17.2 E	73	1111	a/40°	6.5	2.5	Yes
				b/275°	15.0		
880426	5.5 W	49	0202	296°	11.0	1.6	No
880430	21.1 E	77	2222	N.A.			No
880501	1.3 W	55	2222	N.A.			No
880505	24.1 E	81	2221	241°	9.0	0.7	No
880506	3.4 E	61	0000	314°	11.5	1.2	Yes
880511	8.2 E	67	1222	300°	12.0	2.3	No
880516	12.4 E	74	1212	a/262°	8.0		Yes
				b/340°	5.0	0.7	

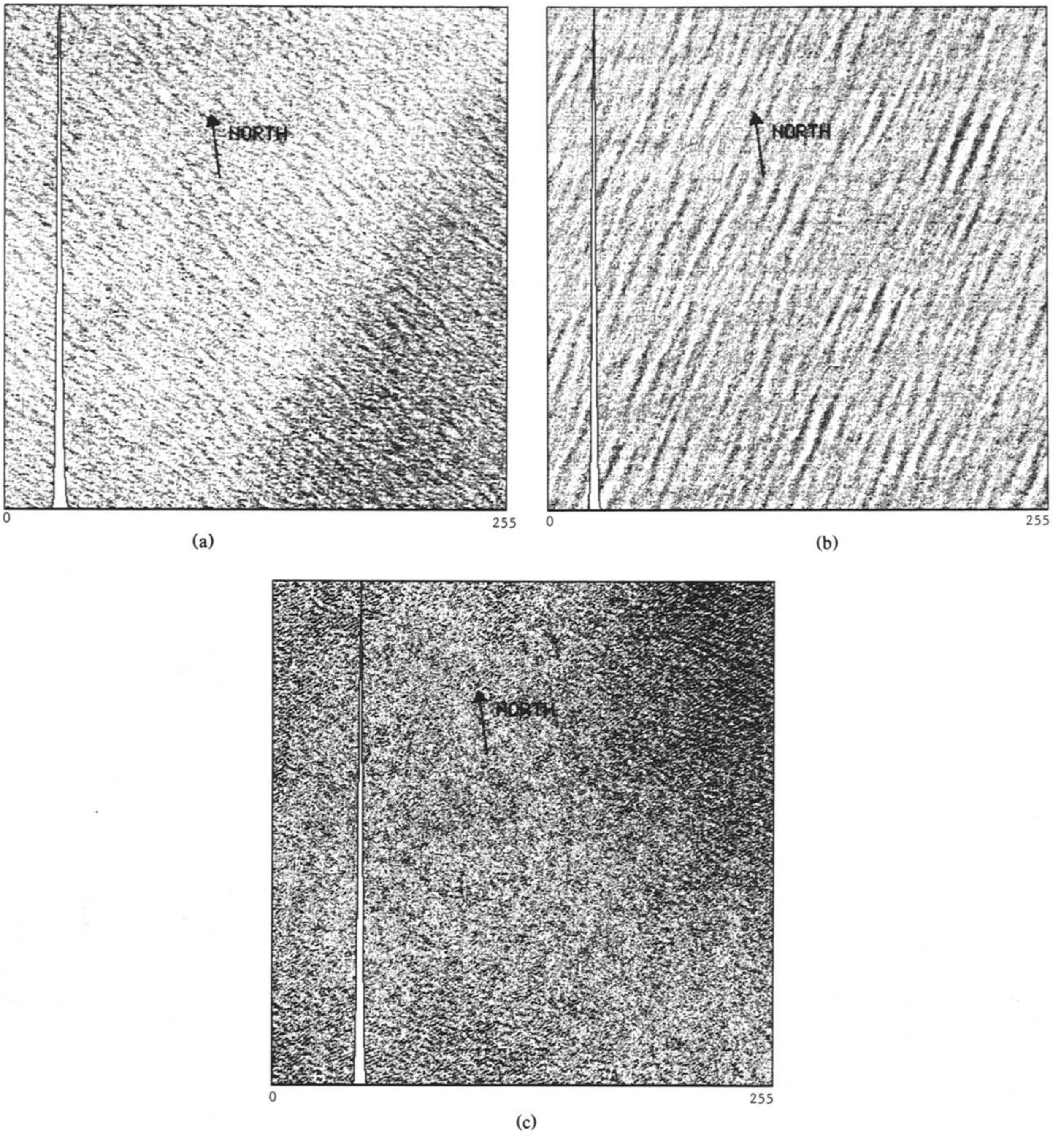


Figure 5. Panchromatic (10 m resolution) SPOT images off Ouessant, Brittany; 5 km×5 km images and grey level histograms (a) 20 April 1988, (b) May 6, 1988, and (c) May 16, 1988.

16 May. Image characteristics are shown in Table 1 with cloud cover scaled from 0 to 2 per scene quadrant. Among the 13 images, four were totally cloudy. The cloud cover on the remaining nine varies from (0000) to (2221), with viewing angles varying from 24° E to 6° W. These nine images are all, if not totally, at least partially exploitable. This can be checked by ordering quick-look images from the company.

When the acquisition campaign was over, preliminary wave data were obtained from Beatrice buoy[1]. Cloud cover, viewing angle, and wave fea-

[1]Note: In the general case, when no buoy data is available, rough wave data can be obtained from coastal stations or ships.

tures were then examined together in order to choose the right images for purchase. For financial reasons, only four of them were purchased (Table 1).

Figures 5a, b, and c show three SPOT panchromatic images for various wave conditions. Their grey level histograms are superimposed and they are contrast enhanced in the same way by simple linear transform, which allows visual comparison. A number of parameters influence the image quality. For these three situations, the values of $(E + I)$, wave height and direction to north (obtained from ship data) are respectively a) 67°, 2.2 m, 45°, b) 61°, 1.2 m, 134°, c) 74°, 0.7 m, 45° and 165°. For all these images, the sun azimuth is around 165°. Comparing a) and b), the wave height alone does not account for image quality. The propagation direction with respect to the sun azimuth also seems to influence it.

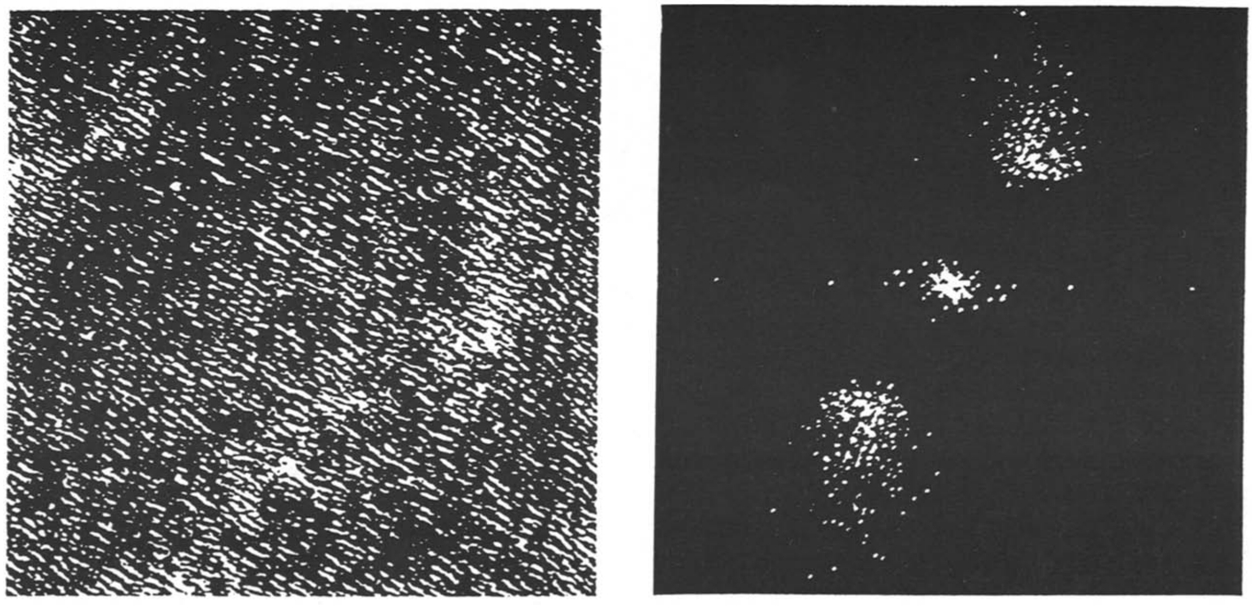
Some recommendations can be made concerning the right time for image acquisition. In order to fulfill condition 1, at 45° latitude, image acquisition can start at the beginning of March, with sun elevation around 35° at 10:30 a.m. solar time. SPOT viewing angle should then be no lower than 25°, which only allows a couple of acquisition over the 26 days cycle. As spring time moves forward, sun elevation will increase, allowing lower incidence angle and consequently higher data acquisition frequency.

Results

It should be noted that, being for off-shore (depth of 110 m), homogeneous wave conditions can be expected over a whole SPOT image. Visual examination of the 25 April enhanced image (Fig. 6) reveals two wave systems, one clearly visible propagating in the SW to NE axis, the other one rather difficult to distinguish with longer wavelength running roughly west to east.

The buoy detects two wave systems. The first one comes from 40° with a 6–7-s period (70 m), the other one, coming from 275° with a 15-s period (350 ms). The average height is 2.5 m. The enhanced image hardly shows the latter system except for a very faint signal in some parts. The spectrum displays some points eastward and westward of the central component, at close distance, but their energy value is low.

Comparing both spectra as a function of T (Fig. 7b), one can see that both curves remain very close up to 8 s. Then a faint energy peak appears at 10.5 s on the image curve, while from 14 s upwards noise prevails. On the buoy curve, the two strong peaks at 15 s (350 m) and 10.5 s (172 m) belong to the same wave system.



(a) (b)

Figure 6. Image off Ouessant, (a) 25 April 1988, (5 km × 5 km) $E + I = 73°$, wave height is 2.5 m, wave direction 40°; (b) spectrum.

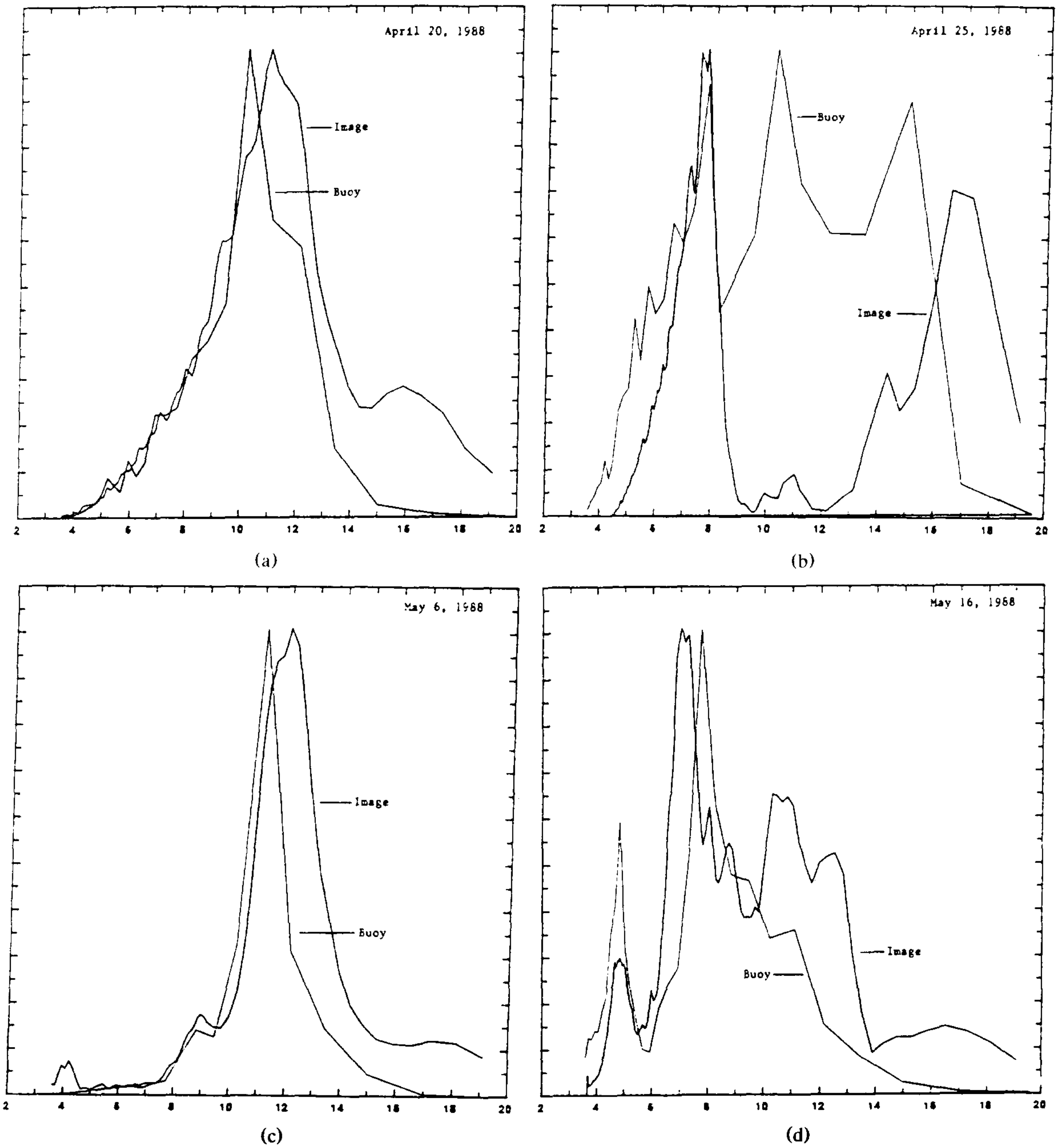


Figure 7. Energy versus period (seconds): (a) 20 April 1988; (b) 25 April 1988; (c) 6 May 1988; (d) 16 May 1988.

There might be three reasons accounting for the discrepancy between the two curves above 8 s. a) If noise reduction is not performed in the best way, the T^4 scaling factor may have a too severe effect on the image spectrum for long T. This increases the noise influence and thus explains the 17 s peak on the image spectrum. b) The 15 s wave train has very low slope angles, inducing little specular effect. c) Sea roughness: The wind speed was 20 knots and the direction was obviously that of the "wind sea."

The other purchased images (Fig. 5) show rather good agreement between spectra (Fig. 7a, c, d). Main peaks differ by no more than 1 s. On Figs. 7a, b, c, d, two wave systems are fairly well separated (periods of 5 and 7 s).

CONCLUSION

Provided that the adequate sensor viewing conditions are carefully sought for and local conditions taken into account, it does not seem illusory to use SPOT data for wave studies. Although not perfect, the comparison between buoy and image data has proven trustworthy in the usual range of coastal swell (5–13 s). Indeed, synoptic visible images such as those of SPOT may be a very useful complement to point-type measurements made by fixed assets, mainly in order to illustrate the spatial behaviour of the waves.

Simple examination of enhanced images not being sufficient, ways of extracting wavelength and wave direction should be further studied. As waves reach the coastal zone, smaller subimages have to be used in order to reduce dispersion. Then Fourier techniques become quite limited in terms of wavelength and direction computation accuracy. Other methods such as the 2-D linear prediction (Cariou et al., 1988) seems more appropriate in dealing with small subimages. After assessing its capabilities, user-friendly software should be written for automatic calculation of the wave parameters on a regular grid.

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