Remote Sensing of Sea State by the Brewster's Angle Technique

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ABSTRACT

The extent of plane polarised light resulting from Brewster's reflection from a wide-roughened sea surface is studied for various sea states on the assumption that the incident light on the air-sea interface is unpolarised. The sea states associated with different wind speeds are simulated using the Cox and Munk 'wind speed-wave slope' law and the Gaussian distribution of wave-slopes. The spatial distribution of plane polarised component of diffuse reflected light is also studied with a view to exploring possibilities of using this parameter for remote sensing of sea state from a sensor viewing the sea surface through an appropriate polaroid. The results show that the plane polarised fraction of reflected light as received in a given look angle can be directly related to the prevailing sea state and can be used as a convenient parameter for remote sensing of sea state. The scope and limitations of the method proposed are discussed.

1. INTRODUCTION

Polarisation of visible radiation, though one of the precisely measurable phenomena in pure physics, has found little direct application in ocean remote sensing. The change in the polarisation status of visible radiation resulting from its reflection at the sea surface is not measured by sensors presently operating in the visible region as they are primarily designed to detect the spectral characteristics of upwelling light. It is well-known that the completely diffise light which is reflected upwards from a wide-roughened sea surface shows a variety of polarisation characteristics, as each incident ray encounters a diierent instantaneous. wave-slope during its reflection', thus imparting a stochastic nature to the process. Polarisation characteristics of an individual reflected ray of light which depend upon its original angle of incidence and

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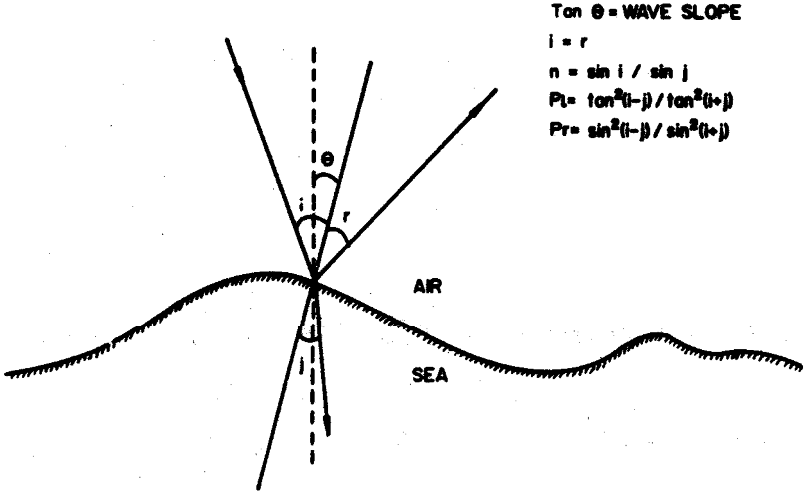

Figure 1. Interaction of an individual ray with the air-sea interface. *Pl* is the parallel component and *Pr* is the perpendicular component of polarisation of reflected beam.

the instantaneous wave-slope encountered by the incident ray can be completely described by Fresnel's law of reflectance[2], as shown in Fig 1. In marine optics, however, the polarisation characteristics of surface-reflected light are often computed to mainly serve as intermediary parameters required for estimation of other optical properties of ocean-atmosphere system such as radiance, reflectance, albedo, etc. Burt[3] used polarisation characteristics of reflected light to estimate near-accurate results of albedo over wind-roughened sea surface as a function of wind speed. Takashima and Masuda[4] computed the extent of total upwelling light emerging from top of an atmosphere-ocean model from the degree of polarisation at several layers by the 'adding method' for wind speeds of 2, 5 and 8 m/s. For an atmosphere-ocean model where the ocean is assumed to be flat and lying beneath a standard Rayleigh atmosphere, Fraser and Walker[5] estimated intensity and degree of polarisation at the top of the atmosphere, while Kattawar et *al.*[6] reported similar properties at various levels in the atmosphere where ocean was assumed flat. The assumption of a flat ocean lying below an atmosphere rules out any possibility of relating the polarisation of reflected radiation to wave-slope distribution at the sea surface. Results of these studies, therefore, do not provide an adequate framework for an algorithm by which a relationship may be established between the polarisation characteristics of reflected light being received in a certain specific look angle and the wave-slope distribution of the sea surface which is responsible for imparting these characteristics.

It is well-known that when light is reflected from a semitransparent medium, the component of vibration perpendicular to the plane of incidence *Pr* has more reflectance than the one parallel to the plane *PI* and the opposite holds true in the case of transmittance'. When the angle of incidence in this case equals the Brewster's angle*, the parallel component *Pl* is totally absent in reflected light and in the case of transmittance the perpendicular component *Pr* is absent. This leads to a plane polarised light being reflected upwards from the sea surface whenever light is incident at

Brewster's angle. Austin' suggested use of this peculiar phenomenon to eliminate the reflected light which is considered as 'noise' in the context of remote sensing of the radiance coming from within the sea by viewing the sea surface at Brewster's angle through a suitable polaroid. Gower[10] has used this technique to minimise the surface-reflected light in remote sensing of chlorophyll from an aircraft. Sathe and Sathyendranath[11] examined the. efficiency of this technique for sea states other than zero by simulating wind-roughened sea surface for wind speeds up to 60 knots and concluded that this technique may be employed only in the case of remote sensing calm sea with practically flat surface. A wind-roughened sea has a dynamic surface with its slope fluctuating in time and space. This imparts to'the reflected beam of light, a continuously varying polarisation status. As long as the source of upwelling radiation is reflection, Fresnel's law of reflectance require that the perpendicular component of polarisation *Pr* will always exceed the parallel component *Pl*, regardless of direction of upwelling flux, and the absence of the parallel component *Pl* in the upwelling flux 'is a peculiar probability occurring whenever the effective incidence angle equals Brewster's angle. Assuming the wave-slope distribution to be Gaussian", the unique probability of certain rays hitting the sea surface at Brewster's angle can be determined, once the look angle of the sensor is specified. This in turn becomes the probability that a plane polarised light will be received by the Sensor viewing the sea surface in a specified look angle.

Thus an optical sensor on board a satellite, aircraft or an observation tower, viewing the sea surface in a certain look angle and which can uncode the polarisation status of the light received by it, collects sufficient information over a period of time to estimate the wave-slope (and consequently the wind speed) distribution. This paper describes such an algorithm for a sensor viewing the sea surface through a Polaroid.

2. ALGORITHM

The algorithm of the method proposed consists of the following four stages :

(i) To simulate a wave-slope distribution associated with a certain wind speed;

(ii) To identify the wave-slope θ on the sea surface which will reflect the incident light in Brewster's angle with respect to a given look angle of the sensor;

(iii) To determine the probability of occurrence of that wave-slope θ in a given wave-slope distribution (as simulated in stage i) which is the same as the probability for a plane polarised light to be reflected upwards in a given look angle; and

(iv) To estimate the sea state by relating this probability function to the wind speed.

3. METHOD

The linear relationship between wind speed and wave-slope proposed by Cox and Munk[13] as discussed extensively by Preisendorfer[12] was used in the present work to arrive at the mean square wave-slope $\tan^2\phi$ for a given wind speed. This relation is commonly used elsewhere[4,11,14]. This expression is

$$\tan^2\phi = 0.003 + 0.00512 \times W \qquad (1)$$

Where $\tan^2\phi$ is the mean square wave-slope and W is the wind speed in meters per second. Cox and Munk[13] believe the first term of Eqn.(1) to be due to the swell, i.e. mean square wave-slope generated due to wind blowing elsewhere. Assuming the wave-slope distribution to be Gaussian, the probability function $P\theta$ of occurrence of wave-slope tan θ was computed from the expression

$$P\theta = \exp(0.5 \times \tan^2\theta)/\tan^2\phi \qquad (2)$$

It is important to note that this Gaussian probability function has a validity in both space and time[12]. This is to say that if a large area of the sea surface with the mean wave-slow tan ϕ is considered at the same time (as in aerial photography), the probability $P\theta$ will refer to the fraction of area photographed having the slope tan θ. On the other hand, if only one point of the sea surface having the mean slope tan ϕ is being observed over a period of time, the piobability $P\theta$ will refer to the fraction of time that the observer will notice the'wave-slope of that point to be tan θ.

If the sea surface is flat, a plane polarised light can get reflected only at 52.13 degrees (Brewster's angle) and hence the sensor also must view the sea surface with the same tilt. This situation is reduced to a case in which Austin's suggestion of eliminating the surface-reflected light (for remote sensing of sub-surface radiance) through polaroid viewing, becomes valid. When the sea surface gets roughened by wind, it is possible to get Brewster's reflection in any direction depending upon the wave-slope. If B is the Brewster's angle and L is the look angle of the sensor, then there can be two possible cases of the wave-slope θ as shown in Fig. 2. In both the angles of incidence (and hence the angles of reflection) will equal the Brewster's angle. These cases are :

Case (i) $\theta = L-B$ if look angle is more than the Brewster's angle (Fig. 2(a)), and

Case (ii) $\theta = B-L$ if look angle is less than the Brewster's angle (Fig. 2(b)).

The second case has arisen because the wave-slope θ in Fig. 2(b) which is in anticlockwise direction, is ndt considered negative for reasons of simplicity. The results are not affected by the sign of the wave-slope θ as tan (-6) is the same as -tan θ and the term is squared and used in Eqn.(2).

It is clear from the aforesaid equations that the required value of the wave-slope θ, which is to be found on the sea surface for Brewster's reflection (for generation of plane polarised light), varies with every look angle. This would imply that its probability of occurrence $P\theta$ under a given mean wave-slope (or in other words, under a given wind speed prevailing over the surface) also varies with every look angle. In this work, the probabilities $P\theta$ have been computed for 31 cases of wind speeds varying from 0 to 60 knots at intervals of 2 knots. For each case of wind speed, look angle were varied from 0 to 90 degrees at intervals of 5 degrees to compute these probabilities. The results are shown in Figs. 3 and 4.

4. RESULTS AND DISCUSSION

Detection of a plane polarised light coming from the top of the sea surface can be best done by a sensor by viewing the sea surface through a polaroid with its axis orthogonal to the plane of polarisation of the incoming light. The intensity of the

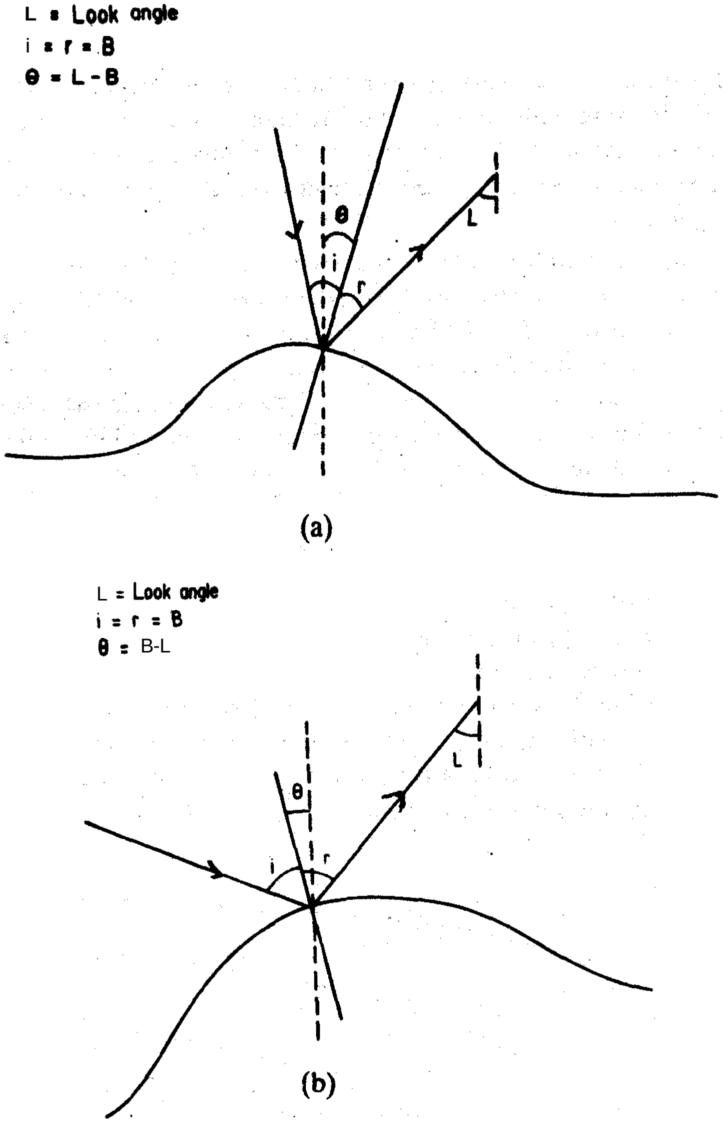

Figure 2. Two possible viewing geometries of receiving a reflected beam from a non-flat sea surface (the diagram is only symbolic and not drawn to scale).

light recorded by such a sensor will drop to zero whenever it receives plane polarised light. All other forms of light will pass through this sensor and get recorded (though at reduced intensity). A similar sensor was earlier suggested by Austin’ and later used by Gower[10] for detection of sub-surface radiance on the assumption that the surface-reflected light is completely cut off by viewing the sea surface at Brewster’s angle. The sensor to be used in the present context would work on the same principle except for the fact that the sensor recommended by Austin views the sea surface only at Brewster’s angle while the one to be used in this context may view the sea surface in any angle including the Brewster’s angle. The main purpose of Austin’s sensor was to cut off the surface-reflected light, while in the present case, the sensor analyses the surface-reflected light for remote sensing of sea state. The sensor is expected to view a fixed point on the sea surface over a period of time from a satellite, aircraft or an observation tower and estimate the fraction of time that it received plane polarised light, i.e., intensity of light recorded by it dropped to zero. This information may be directly related to the sea state through the probability functions *P0* for the corresponding look angle.

Figures 3 and 4 show plot. of these probability functions for plane polarised light being reflected upwards from a wind-roughened sea surface against wind speeds varying from 0 to 60 knots at intervals of 2 knots. Figure 3 covers look angles varying from 5 to 45 degrees at intervals of 5 degrees each, while Fig. 4 shows the same information for look angles varying from 50 to 90 degrees. Thus each plot in these figures refers to one look angle. The plot for look angle 0 degrees is not shown here as the computed values for the probability function *P0* are too small in this case to be meaningfully plotted to scale. These values are shown separately in Table 1. It is seen that all plots are smooth, monotonic and non-intersecting. Although a certain positive probability of plane polarised light upwelling from the sea surface always exists in every possible direction (by virtue of diffuse incident light encountering a multitude of wave-slopes), Figs. 3 and 4 show that this probability appreciably increases and tends. to unity as the look angle approaches Brewster's angle (52.13 degrees) from either extremity, viz. from look angle in the vicinity of 0 as well as 90 degrees. The general pattern of curves displayed for look angles greater than Brewster's angle (55 to 90 degrees in the increasing order) seems to be a rough replica of the pattern displayed for look angles smaller than Brewster's angle (50 to 5 degrees in decreasing order).

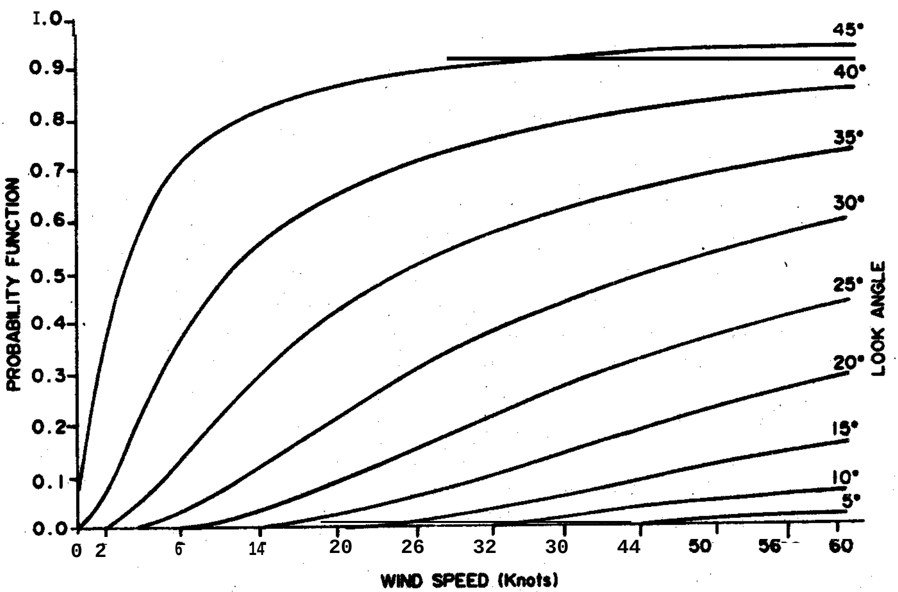

Figure 3. Probability functions of receiving plane polarised light from a wind-roughened sea (wind speeds from 0 to 60 knots) for different look angles varying from 5 to 45 degrees.

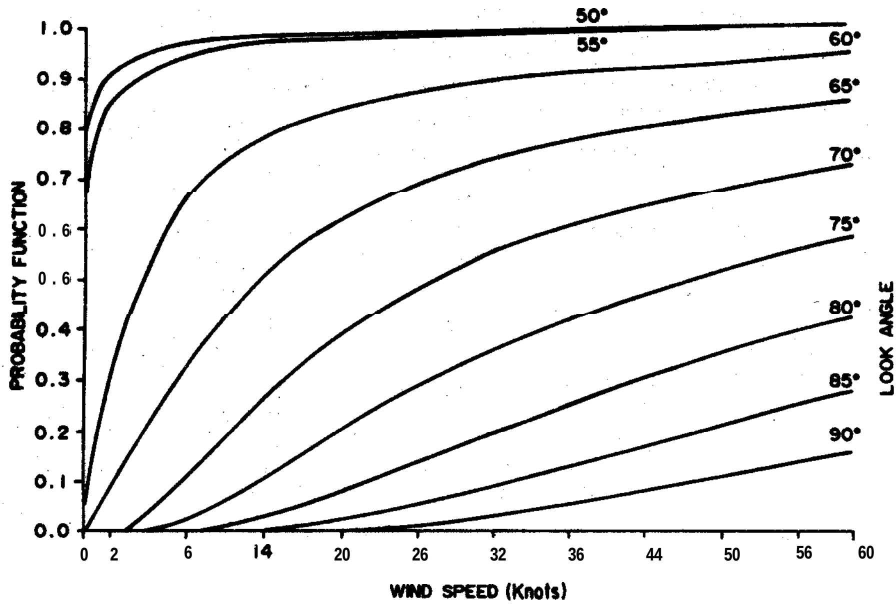

Figure 4. Probability functions of receiving plane polarised light from a wind-roughened sea (wind speeds from 0 to 60 knots) for different look angles varying from 50 to 90 degrees.

For any of these plots to be considered as a reference curve for relating the information collected from the sensor to the wind speed over the region of observation, it is necessary that its domain over the probability range be wide and its slope at the point of observation be significantly high for better resolution. Table 2 shows the probability domains and average slopes for all plots representing look angles from 5 to 90 degrees. Though Fig. 4 shows a remarkably high probability of receiving plane polarised light under all wind speeds for look angles in the vicinity of Brewster's angle (see plots for look angles 50 to 55 degrees), these look angles are unsuitable as viewing angles for remote sensing the sea states by the method proposed, as they cover a small range on the probability domain as seen in Table 2. It may be noted here that what is important is not whether certain look angles can receive a high percentage of plane polarised light from the sea surface but how well can the variation of this percentage be linked to the-variation in the wind speed blowing over the sea surface. It can be seen from Fig. 4 and Table 2 that slopes of the curves for 50 and 55 degrees have a very low value making them nearly straight lines along the wind speed axis (except in the region of low wind speeds up to 4 knots), thus rendering them unsuitable as viewing angles despite their receiving highest quanta of plane polarised light from the sea surface.

Viewing angles in the vicinity of 0 and 90 degrees also occupy a small range on the probability domain and have small values for their probability function $P\theta$ which reduces to zero for lower wind speeds. Even for a look angle as high as 25 degrees, probability function is zero for wind speeds up to 8 knots. Their low values for slopes (see Table 2) also indicate small variation in probability function with wind speeds as seen in Figs. 3 and 4. These look angles are clearly unsuitable for viewing the sea surface for remote sensing of the sea state by the method proposed. Considering the look angle at 90 degrees is out of question as it, refers to an absurd condition of keeping the sensor on the horizon to view the sea surface. For the viewing angles 45 and 60 degrees, the slope and probability domain show highest values. These viewing

Tabk 1. Probability function values for different wind speeds for the look angle zero degrees

Wind speeds (knots)	Probability function
0	0.0000000E+00
2	0.0000000E+00
4	1.9752598E–27
6	5.8447639E–20
8	9.3618624E–16
10	4.6494633E–13
12	3.4935936E–11
14	8.3911 122E–10
1 6	9.6017096E–09
18	6.6032726E–08
20	3.1534373E–07
22	1.1494143E–06
24	3.4105910E–06
2 6	8.6215941E–06
28	1.9190038E–05
30	3.8542585E–05
3 2	7.1163915E–05
34	1.2253808E–04
36	1.9900748E–04
38	3.0757458E–04
40	4.5567038E–04
42	6.5091904E–04
44	9.0091018E–04
46	1.2130005E–03
48	1.5941436E–03
50	2.0507525E–03
52	2.5886104E–03
54	3.2127984E–03
56	3.9276578E–03
58	4.736781x-03
60	5.6430208E–03

Table 2. Range in the probability domain and the average slopes of probability function plots for different look angles

Look angle (degrees)	Range in the probability domain	Average slope
5	2.643	0.044
10	7.719	0.129
15	16.618	0.277
20	29.087	0.485
25	43.956	0.733
30	59.585	0.993
35	74.274	1.238
40	86.489	1.441
45	87.850	1.464
50	20.158	0.336
55	33.438	0.577
60	90.053	1.501
65	84.905	1.415
70	72.220	1.204
75	57.291	0.955
80	41.666	0.694
85	27.055	0.451
90	15.058	0.251

angles, however, cannot be recommended in this context because their suitability is restricted to remote sensing low wind speeds (up to 12 knots) only. For wind speeds higher than 12 knots, their probability function shows little variation (see Figs. 3 and 4).

The results show that the most appropriate viewing angles for remote sensing the sea state (i.e., wind speed over the region of observation) by the method proposed by authors are in the range 30 to 40 and 65 to 75 degrees as they have higher average slope and comparatively high values for the probability function $P\theta$. Besides, they also occupy a wide range on their probability domains which is the most important consideration in this context. The range 30 to 40 degrees is preferable to the range 65 to 70 degrees for viewing the sea surface as the former shortens the path that reflected light travels from the sea surface to the sensor, thereby reducing atmospheric effects. The results also show that look angles in the neighbourhood of 40 degrees give better resolution for remote sensing winds up to 15 knots while those in the neighbourhood of 30 degrees give better resolution for higher wind speeds, as their probability function rapidly drops to zero at low wind speeds. A similar situation prevails for look angles in the range 65 to 75 degrees where viewing around 65 degrees effectively resolves winds up to 15 knots and for higher wind speeds, viewing around 75 degreeswould give better results.

5. SCOPE AND LIMITATIONS OF THE TECHNIQUE

The technique proposed in this paper requires the sensor to estimate the fraction of time that a plane polarised light is recorded while viewing a fixed point on the sea surface in a certain look angle and relate this information to the wind speed prevailing over the area of observation. This is based on the assumption that Brewster's reflection at the sea surface is the only process responsible for generation of plane polarised light with its plane perpendicular to the plane of incidence. Any other natural process of sending a plane polarised light towards the sensor will invalidate the technique. Figure 5 shows the three sources from which a sensor can receive light, viz. the atmospheric scattering towards the direction of sensor, the surface-reflected light from the sea and the sub-surface radiance emerging out from within the sea. Polarisation is associated with all forms of scattering, both in the atmosphere as well as underwater. However, the net effect of multiple scattering by aerosols and other atmospheric particles eliminates the possibility of light acquiring any preferential polarisation characteristics by its mere passage through the atmosphere. The marginal polarisation characteristics acquired (if any) by light due to its multiple scattering in the atmosphere would be in innumerably varying planes and such a light would become indistinguishable from ordinary unpolarised light. Burt" had estimated near accurate results for albedo over wind-roughened sea as a function of wind speed and concluded that all light incident on sea, both direct and that coming from the clouds can be considered unpolarised. The same holds true for sub-surface radiance emerging out from within the sea water. Rays of light once having entered the sea and interacted with water and other constituents in the sea, having been multi-scattered and eventually back-scattered up and out of the sea are not expected to show any bias in their polarisation status. Generation of a plane polarised light in the direction of the sensor by such random multiple scatterings is even less probable. Hence we assume that any plane polarised light received by a sensor must bear its origin to Brewster's reflection at the sea surface. The sensor designed by Austin, as referred earlier, was also based on the same assumption.

Multiple reflection of light at the sea surface is ignored in the present work. It is assumed that every ray of light has undergone just one reflection at the sea surface before being received by the sensor. Total contribution to the degree of polarisation by multi-scattered light is not expected to be significant. Ahmed and Fraser" also ignored multiple reflection in their interactive radiative transfer code for computing intensity and degree of polarisation of diffuse reflected light in models of ocean-atmosphere system and showed that their results were in excellent agreement with those of Mullamaa's atlas of optical characteristics of disturbed sea surface[16] for a rough ocean and no atmosphere. Sathe and Sathyendranath[11] while reporting ratios of polarisation components of diffuse upwelling light from a wind-roughened sea also ignored the multiple reflection. Similarly, the sensor used by Gower[10] for remote sensing of chlorophyll from an aircraft was also designed on the assumption that the , surface-reflected light undergoes just one reflection at the air-sea interface.

The foam present on the sea surface at high wind velocities alters the surface slope distribution at microscopic level. The foam is composed of very small particles of water which scatter light in all directions. Although the foam does not invalidate the basic ‘wind speed-wave-slope law’, and the wave-slope distribution associated with each wind speed does exist under the foam cover, the foam splits the uppermost layer of water into fine particles. This process generates another finer slope distribution superimposing the original Gaussian distribution pertaining to prevailing wind speed. The foam will thus contribute to the ‘noise’ in remote sensing the sea state by the method proposed. The exact amount of this noise cannot be estimated as reflectance of foam is not well-established. The reported values on foam-reflectance vary from as low as 0.45 (Quenzel and Kaestner[17]) to as high as 0.90 (Gordon and Jacobs’*). Noise due to foam is not a special limitation exclusive to the new remote sensing technique being proposed in this paper. All passive sensors operating in the visible region are handicapped by the noise received by them from the foam-covered sea surface. In case of sensors that record spectral emission of sea water such as CZCS (bands 1 to 4), TM (bands 1 to 3), SPOT (bands 1 and 2), etc., foam is a major source of noise as it alters the spectral signature of the surface. In the present context, foam is expected only to weaken the signal by continuously adding scattered light of uniform polarisation characteristics to the signal. Removal of noise due to foam will be similar to the removal of noise due to the light scattered from the atmosphere as discussed in the following paragraphs.

The main source of noise interfering with the signal received by sensor is the intervening atmosphere between the sensor and the sea surface. Though the atmosphere is not known to have any depolarising effect on the light leaving the sea surface, the multiple scattering of incident light field by aerosol and other particles in the atmosphere results into back-scattering of a fraction of light by the atmosphere before it may reach the sea surface. The sensor thus receives this back-scattered light from the atmosphere which carries no information of the sea surface (Fig. 5). On account of this constant ‘airlight’ received by the sensor, the intensity of light will never fall to zero even when a plane polarised light is received by the sensor. This constraint may be overcome by a technique commonly known as ‘haze removal”‘,

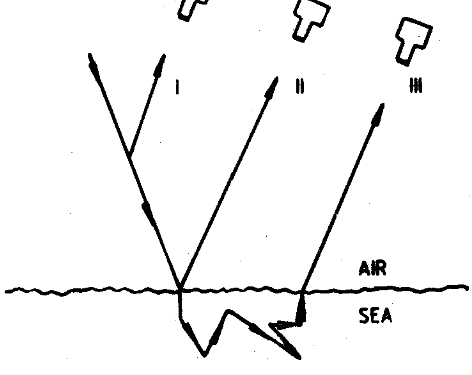

Figure 5. The three sources from which a sensor viewing the sea may receive radiation, viz. the atmospheric back-scattered radiation (I), the surface reflected radiation (II) and the radiation emerging from within the sea (III).

applied to other passive sensors (such as MSS and TM on board LANDSAT series of satellites) in which one of the methods used is to subtract the smallest radiance value recorded by a sensor from all other measurements. This atmospheric component being unpolarised[3], will have little effect on the reliability of the technique.

6. CONCLUSION

A wind-roughened sea surface imparts to the diffuse reflected light specific polarisation characteristics which a suitable sensor, viewing the sea surface through a polaroid, can decode. The plane polarised light resulting from Brewster's reflection at the sea surface can be used for the purpose of remote sensing of wind speed as the plane polarised component in diffuse reflected light can be shown to be directly related to the sea state. Viewing angles in the range of 30 to 40 degrees are most suited for this purpose.

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