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Spectral Transmission Studies of Ocean Water Under Different Sea Conditions

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Abstract. Propagation of electro-magnetic radiation through the atmosphere and the sea depends upon different physical processes. The atmosphere is primarily a scattering medium. In the case of sea water, however, both absorption and scattering account for its spectral attenuation characteristics. The sea surface determines the transition of radiation at the air-water boundary. The spatial and temporal variations in the sea conditions make it a very complex medium for theoretical predictions. The paper reports various parameters relevant to the study of spectral transmission of ocean water under different sea conditions.

1. Introduction

Radiative transfer of energy from atmosphere to sea and propagation of electro-magnetic (EM) radiation thrcugh the sea water are physical in nature and have wide applications in oceanography and related fields. The atmosphere is primarily a scattering medium though absorption bands corresponding to water vapour, carbon dioxideand oxygen are present in the IR region of the solar spectrum[1]. The sea water is however a complex medium. The electro-magnetic radiation traversing the ocean can interact with the water and the material dissolved and suspended in it. The interaction takes the form of absorption and scattering. The absorption process changes the radiation in other forms of energy. The scattering results in deviating the direction of propagation of radiation through reflection, refraction and diffraction.

The sea has two transmission windows in the electro-magnetic spectrum, one at frequencies less than 10Hz and the other in the visible range between 400 to 600 nm. Since the quantum energy of photons of 10Hz frequency is very low, the visible window provides the only probing wavelength region. The study of ocean from an optical point of view is a special branch of oceanography and is often referred to as optical oceanography.

Spectral transmission characteristics of the sea water are dependent upon the various dissolved and suspended particulate organic and inorganic substances present in the water. The sea is a mysterious medium with different constituents at different places and even at the same place, at different points in time. It is not a homogeneous medium but is made up of layers of warm and cold waters and waters of different density and refractive index. The whole sea is always in constant motion from the surface winds, the spinning of the earth, the change in density and tides. This makes modelling of real time propagation of radiation under different sea conditions extremely difficult.

2. Electromagnetic Radiation at Air-Sea Boundary

Radiation incident on the atmosphere-sea boundary could be from natural sources like sun and sky radiation and sources designed and deployed for a specific task such as tungsten quartz iodide light, mercury vapour lamps and quantum emitters of various types like copper vapour, Argon, Bismuth, Nd glass (X2) and turned dye etc. The natural sources support and sustain marine life. The man-made sources are used for various different applications like photography, ranging, detection, command, control, communication; etc. The global radiation consists of collimated solar radiation and diffused sky radiation. The sky radiation is rich in short wavelength radiation especially for solar elevation less than 30° (Fig 1). The sea water has maximum transmission window in the blue green region and the global radiation, penetrates to considerable depths in the sea water. The sun energy has been detected up to a depth of 600m with photoelectric detectors[2].

When EM radiation is incident on the atmosphere-sea boundary both reflection and refraction take place. The specular reflectivity for unpolarised light is given by.

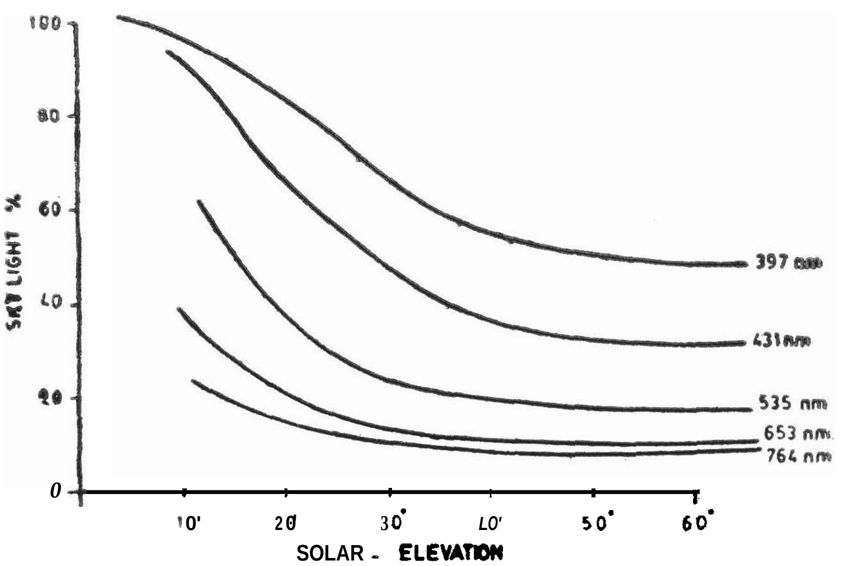

Figure 1. Spectral characteristics of sky light.

$$\rho_s = \frac{1}{2}\left[\frac{\tan^2(i-j)}{\tan^2(i+j)} + \frac{\sin^2(i-j)}{\sin^2(i+j)}\right] \quad (1)$$

where *i* and j are the angles of incidence and refraction respectively. Since the refactive index of water is **4/3,** the reflectivity of sea surface remains less than **3** per cent for $i \leqslant 45°$. This is quite an important result in sea instrumentation when either the transmitting or receiving or both the terminals are located in the air. The source beam may be at an angle with the air-water boundary surface without excessively increasing the reflection losses. **For** diffused radiation like sky radiation, the reflectivity is given by the relation[5],

$$\rho_d = \int_0^{\pi/2} \rho_s\,(i) \sin 2i\, di \quad (2)$$

For sky radiation, the value of this integral has been evaluated as **6.6** per cent.

The sea surface is wind roughened, it can no more be presumed to be a plane surface. The reflectivity is considerably reduced for low solar elevations (less than 20°) because the angle of incidence i is reduced. The effect is not very significant for high solar elevations. However the measurement of return signal fromair borne laser systems could be used to measure the parameters of the surface waves[4,5]. Measurement of reflected light under rough sea conditions is quite difficult to distinguish between the true reflection and the back scattered light from the sea.

Refraction at the atmosphere-sea boundary takes place according to the well known **Snell's** law. The critical angle for a water-air interface is 48.5° which means that the radiant flux which may be incident within 2π sterdians at a point on the interface in the air would get confined to a cone of **97** sterdians. Radiations from an underwater source if incident at an angle of more than 48.5" at the water-eir boundary suffer total internal reflection. The light scattered by the sea water, back scattered light in the case of over water surface source and forward scattered light in the case of underwater source, reaching an in-the-air detector is, therefore, confined to a narrow cone of semi-angle **48.5°** in the water and spreads out 2π sterdians after emerging out of the water. This reduces considerably the noise due to the back scattered radiation.

In case the sea surface is not calm and has surface waves, the incidence angle continuously varies and the refracted beam wanders. There may be as much as ± 15% change in the beam direction. The surface waves also have a lensatic effect and the refracted beam may become dangerously intense at times. Since each point on the randomly ruffled ocean surface deviates the beam from its original direction independently of the points in the near vicinity, the surface wave slope statistics can be derived by measuring time-averaged radiance of sun radiation at solar elevation near zenith[e].

3. Propagation of Radiation in Sea Water

Reflection and refraction are boundary surface phenomenon in a homogeneous medium and last till the radiation enters the medium. Thereafter, it is propagation of radiation in that medium. In the case of sea water, the radiant flux attenuation is due to absorption and scattering by the constituents of the sea water.

The sea water contains 77 different elements in different concentrations[7] dissolved or suspended in pure water. Out of these 7 compounds namely $NaCl$, $MgSO_4$, $MgCl_2$, $NaHCO_3$ $CaCl_2$, KCl & KB_2 are very important because of their industrial potential. The sea water also consists of yellow matter, phytoplanktons, zoo plank-tons and many marine oraganism and plants. The yellow substance consists of humic acids, melanoidins and other compounds which result from the decomposition of plants and animal materials. It has been a subject of considerable research and study[8,9] in optical oceanography. Jerlov[8] has attempted to link the physical factors to the biological factors of the sea and offered a model for the origin of the yellow substance. The yellow substance, however, still remains a mysterious substance as far as its origin and exact optical properties are concerned.

The phytoplanktons, another sea constituent, are biological optically active substances. These are transparent to visible radiation and act as scattering centres. These vary in size from a few microns to a few millimetres. Phytoplanktons are found as big colonies at different depths according to the available sun light, probably due to the requirement of certain specific level of sun energy by them for photosynthesis. They form deep scattering layers and are very important from defence point of view because the submarines can evade sonar detection if they sneak under them.

The optical properties of pure sea water of a given temperature and salinity are more or less invariant. . The ions of dissolved salts scatter the radiation. The suspended particulate matter, present in highly variable concentrations in the sea, alter the attenuation characteristics of the sea water.

4. Attenuation Parameters

The attenuation parameters which describe the behaviour of propagation of mono-chromatic unpolarised. radiation in a medium are the absorption coefficient, the scattering coefficient and the volume scattering function. The definitions and the notations adopted by International Association of Physical Sciences of Ocean for these coefficients and related parameters are given[10]

Radiant Flux ϕ is the rate of transport of radiant energy

$$\phi = \frac{d\,(\text{Energy Transported})}{d\,(\text{Time})}$$

Radiant Intensity **I** is the radiant flux emitted from an element of surface per unit solid angle

$$\mathbf{I} = \frac{d\phi}{d\omega} \text{ Watt Sterdian}^{-1}$$

Trradiance E is the total radiant power falling on a detector of area dA, divided by the area

$$E = \frac{d\phi}{dA} \text{ Watt } m^{-2}$$

Absorption coefficient a is the fraction of the energy absorbed from a collimated beam per unit distance traversed in the medium

$$a = -\frac{d\phi_{abs}}{\phi . dx} \quad m^{-1}$$

Total scattering coefficient b is the fraction of the energy scattered out of a collimated beam per unit distance traversed by the beam,

$$b = -\frac{d\,\phi_{scatt}}{\phi\,.\,dx} \quad m^{-1}$$

Beam Attenuation Coefficient is the fraction of energy in a beam removed by both absorption and scattering per unit distance traversed by the beam.

$$c = -\frac{[d\,\phi_{abs} + d\,\phi_{scatt}]}{\phi\,.\,dx}$$

and

$$c = a + b$$

The definition of Beam Attenuation Coefficient precludes the possibility of any of the scattered photons to reach the detector. Diffuse Attenuation Coefficient K is the fraction of energy removed by both scattering and absorption per unit distance traversed by the beam but the photons once scattered out of the beam can reach the detector after suffering multiple scattering. Evidently $K \leqslant c$

$$K = a + \frac{b}{n}$$

where n is a constant. Based upon the analysis of available relevant data, **a** value of $n \simeq 6$ has been suggested.[12] Volume scattering function is the scattered radiant intensity in a direction θ per unit. Volume divided by the incident irradiance E as shown in Fig. (2)

$$\beta(\theta) = \frac{I(\theta)}{E\,dV} \quad m^{-1} \text{ sterdian}^{-1}$$

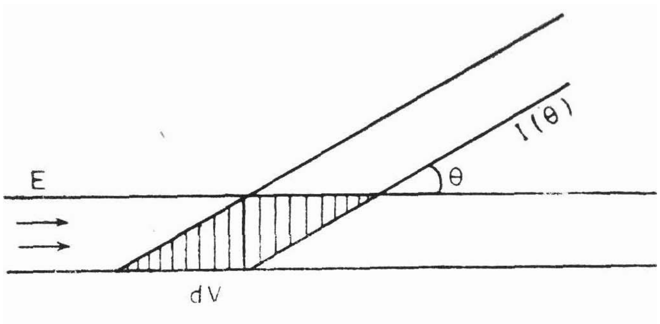

Figure 2. **Volume scattering by medium.**

The total scattering coefficient b is given by

$$b = 2\pi \int_0^{\pi} \beta(\theta) \sin\theta \, d\theta$$

The forward scattering coefficient is b_f given by

$$b_f = 2\pi \int_0^{\pi/2} \beta(\theta) \sin\theta \, d\theta$$

and the backward scattering coefficient b_b is given by

$$b_b = 2\pi \int_{\pi/2}^{\pi} \beta(\theta) \sin\theta \, d\theta$$

and

$$b = b_b + b_f$$

The constituents of the sea water influence individually and collectively the different propagation parameters. It is, therefore, necessary to discuss the effect of the constituents of the sea on the propagation parameters individually and as a whole.

5. Sea Constituents and Propagation Parameters

The spectral attenuation of radiation depends upon the constituents and their concentration in a particular volume of sea water. In turbid coastal waters, the attenuation is minimum in the spectral region 510 to 550 nm. For cold water the wave band is 470 to 500 nm and for clear water, the minimum attenuation **wave** band shifts to still lower wavelength region i.e. **430** to 470 nm. For pure water,

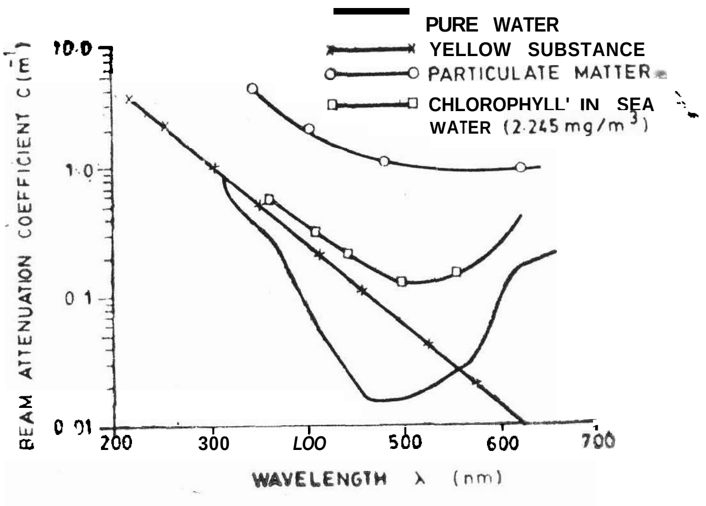

Figure 3. Spectral attenuation characteristics of (a) water (b) yellow substance (c) particulate matter (d) Chlorophyll.

the maximum transmission window is from 430 nm to 530 nm. The shift in the spectral region is probably due to selective absorption by inorganic sea salts, yellow matter and suspended particulate matter, all of which tend to have increased absorption towards the short wavelength region (Fig. 3). The phytoplanktons have been found to have attenuation characteristics like chlorophyll a+; the extent of attenuation being dependent upon their concentration and size distribution in unit volume[t3]. The spectral absorption and scattering coefficients of phytoplanktons are closely inter-related and appear to counteract each other to produce the attenuation spectra. Chlorophyll shifts the wavelength of maximum transmittance from blue to green region of the spectrum. Colour of the ocean as observed from an aircraft or space craft may be used to estimate the chlorophyll concentration in surface waters.

In the visible region, the sea salts do not appear to contribute towards absorption[10,11]. They, however, have a very weak scattering function which tends to increase scattering in the short wavelength region. Pure water has strong IR absorption characteristics. On account of highly selective absorption characteristics, water acts as a monochromator of blue light. It has long been known that half the radiant energy of the global radiation i.e. sun plus sky radiation, is attenuated within half a metre depth in the sea. The water molecules act as scatterers, the scattering being more prominent at 90° to the radiation propagation direction. The scattering occurs according to Rayleigh's λ^{-4} Law and is, therefore, highly spectrally selective.

Dissolved organic compounds like yellow matter can be highly variable in the sea but are generally associated with continental run-off. Yellow matter has very strong absorption towards the shorter wavelengths and the presence of yellow matter tends to shift the peak of maximum transmission to longer wavelength region.

Scattering due to Suspended Particulate Matter (SPM) occurs due to diffraction, refraction, and reflection. In the case of transparent SPM, reflection and refraction are the main causes whereas in the case of opaque SPM, diffraction is responsible for the forward small angle scattering, and reflection for scattering at all other angles. Scattering by reflection and refraction depends upon the refractive index and the particle size. For forward scattering particle size alone is important. In sea water, the volume scattering function is dominant in the forward direction and as such the particle size distribution is more important than the shape and the refractive index[14]. The concentration of SPM can vary from a few microgram per litre in clear ocean waters to tens of milligram per litre in the very turbid coastal waters[11]. When the nature of particulate matter does not change in a given volume but the concentration does, the particle attenuation coefficient is proportional to the particle concentration. Optical measurements are ideal for the determination of particle concentration ***in situ.*** The main sources of suspended particles are humus like matter brought into the sea by river run-offs, the biomass resulting from phyto plankton growth and sediment transportation in the sea.

The effect of temperature and salinity on the refractive index has been studied extensively by Sagar[15]. The refractive index increases both with temperature and, salinity, the change with temperature being smaller than the change with salinity. The effect of temperature and refractive index on scattering by liquids has been investigated by Smoluchowski and Einstein[1%] According to this theory, the volume scattering function is given. by

$$\beta(\theta) = \frac{2\pi^2}{\lambda^4} \cdot KT.\, n^2 \left(\frac{\partial n}{\partial p}\right) \cdot \frac{1}{\eta} \cdot \left[\frac{6(1+\delta)}{6-7\delta}\right]\left(1 + \frac{1-\delta}{1+\delta}\cos^2\theta\right)$$

where ***n*** is refractive index

$\frac{\partial n}{\partial p}$ is the change in refractive index with pressure, δ is degree of polarisation, T is temperature, and η is thermal compressibility.

Table 1. Summary of spectral propagation of visible radiation through seawater

Constituent	***Effect***	
	Absorption	**Scattering**
Water	**Strong variable dependence on λ**	**Weak effect, strong dependence on λ varies as λ^{-4}**
Dissolved Sea salts	**Insignificant effect**	**Weak scattering which tends to increase towards short wavelength**
Yellow Substance	**Significant effect, Increases towards short wavelength**	
Suspended Particulate Matter	**Significant effect, Increases towards short wavelength**	
Phytoplanktons	**Variable effect Attenuation minimum in blue-green region**	**Strong scattering, varies with λ**

This equation clearly shows that volume scattering by sea water increases both with the temperature and salinity and varies as λ^{-4} with the wavelength.

The spectral attenuation of radiation by the sea water is the net resultant effect of all the constituents of the sea which are summarised in Table 1.

6. Conclusion

The propagation and distribution of radiant energy in the sea waters depends upon the optical properties of the sea constituents. The spatial variation of optical properties in the sea is closely related to the concentration of its constituents especially the suspended particulate matter and the yellow matter. The physical, chemical and the dynamic conditions of the sea determine the state of the sea at a particular place at a given time. 'The sea is a living medium that allows itself to be neither systematized nor brutalized[17]. It is necessary to study it in place and patiently'.

7. Discussion

The following areas in optical oceanography are identified for further study and investigation.

(a) Solutions of problems related to underwater visibility and communication require information regarding the optical properties of ocean waters for different geographical areas and water depths. The present state of knowledge of these properties is restricted by the type and capability of the instrumentation available. There is a need to improve capability and standardise the instrumentation so that the results of different investigators could be correlated and tangible conclusions drawn.

(b) Very few reports have been made on light penetration characteristics of Indian coastal waters[1*]. There is a requirement for preparing and optical profile of the Indian waters to help the study of marine vegetation, marine organism and the phenomenon taking place at the sea bottom like sediment transportation and under currents[19]. This study could also be of tactical use to Navy.

(c) Investigation into the relationship between the sea surface roughness and the return signal from an airborne source could be useful in development of Airborne Laser Systems for different applications.

(d) Relationship between beam attenuation coefficient C, diffuse attenuation coefficient K, the scattering coefficient h, and the absorption coefficient a for different wavelengths may be investigated for different water types. This could permit estimation of unknown propagation parameters by measuring one or more of them for a particular water type.

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