CHAPTER 12

OPTICAL PROPERTIES OF THE AIR-WATER SURFACE

12.0 Introduction

The study of the penetration of light into, and the reflection of light from natural hydrosols at some point must consider the geometric and physical properties of the air-water surface. In this chapter we shall study the salient geometric and radiometric features of the air-water surface in both its static and dynamic states. We shall be guided in these studies, especially as regards the selection of auxiliary material outside the discipline of radiative transfer, by fixing at the outset two main goals for the present chapter. These are the complete description of the transmission and reflection properties of the air-water surface, *in both its static and dynamic states*, taking into account the optical interactions of the surface with the atmosphere above and the hydrosphere below. In order to achieve these goals, and still keep the discussion essentially self contained, we shall draw on the fields of physical optics, hydrodynamics, and harmonic analysis, in addition to the principles of radiative transfer theory.

Our first goal, then, is the description of the general radiative transfer process across a static air-water surface. Were there never a breath of air, nor tidal, seismic, or other agents to disturb the air-water surfaces on the natural hydrosols of the earth, our task in the present chapter need not extend past sections 12.1 and 12.2 below. In those sections we describe and solve completely the main optical problems of the static air-water surface as they arise in the study of radiative transfer across such surfaces. For all that is currently needed in such a case is knowledge of three laws of physical optics and the interaction principle of radiative transfer. The three laws from physical optics are the geometric reflection and refraction laws and Fresnel's reflectance formula.

Such an ideal static state of the air-water surface is rarely found in nature and consequently, in our quest for the second main goal, we must face a complex, dynamic air-water film which during each second and at each point reflects light from many different portions of the sky and transmits light from many different portions of the underwater domain to the eye of the beholder. Ordinarily, when one looks at a wind-blown sea with its underriding phalanxes of swells and gravity waves and with its crinkly skin of capillary waves, one absorbs the sensation as an unanalyzed whole and uncritically accepts the external reality of the dynamic surface in all its complexity. However, under the direction of aroused scientific curiosity or under the necessity of solving some problem in which the successful description of the dynamic surface plays an essential role, the analytical and critical faculties of the observer come into play and soon a conceptual webwork begins to join the previously loose-knit visual sensations together. For example, in the radiative transfer context, the dynamic surface could be conceptually frozen into a state of immobility, as one would stop a high speed movie film of the surface, and the mental image then could be scrutinized for patterns and possible orderings of data. Each visualized brilliant highlight of reflected sunlight becomes a static tiny patch of light with a geometrically precise relation between four further constructs envisioned by the observer: the position of the sun, the observer, and the position and orientation of the reflecting facet of the air-water surface. Furthermore it is possible, and this must be taken into account in any complete theory of radiative transfer across a dynamic air-water surface, to envision and describe in detail the radiometric interaction of the complex curved surface with itself: Virtually infinite numbers of multiple interreflections within the frozen concavities of the surface are possible before the resultant flux is once again moving free in the atmosphere above the surface or towards the observer. The conceptual webwork in which the dynamic air-water surface is being envisioned thickens as further knowledge is introduced concerning the orderly and lawful motions the seemingly chaotic jumble of waves must in reality obey: So that when the conceptually frozen motion of the air-water surface is allowed to take its natural course into the next frame of the film, its movement is inexorably prescribed by the laws of hydrodynamics. Once again, when the various parts of light field of this new configuration are examined, they are found to obey the same general type of radiative equations as in the preceding frame, and so the conceived order increases, and conceptual chaos decreases. However, conceptual order on both the radiative transfer and hydrodynamic levels notwithstanding, the growing number of frames in the conceptual film as second succeeds second makes it impossible to succinctly and completely describe numerically the radiometric relations from frame to frame. For this reason the concepts of harmonic analysis and statistics are called into service to succinctly summarize the averaged or statistical features of the radiative and hydrodynamic processes extant in the dynamic air-water surface.

The requisite amount of hydrodynamic theory for constructing the present optical theory of the air-water surface is given in section 12.3, and those parts of harmonic analysis required for the present task are developed in section 12.4. In order to give depth to the present statistical theory and to prepare for useful applications of the theory to air-water radiative transfer phenomena, there follows in sections 12.5 to 12.8 a review of some recent experimental studies of wave generation and decay and of certain statistical properties of wind-generated seas in equilibrium with the generating wind. Section 12.9 contains an attempt to understand the reviewed empirical data from a unifying statistical-theoretical vantage point. Then in sections 12.10

to 12.14 a statistical theory of radiative transfer across a dynamic air-water surface is developed and applied to some illustrative examples. The chapter concludes with a brief study of possible devices which may be used in the laboratory to simulate the optical properties of randomly moving surfaces of natural hydrosols.

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12.1 Reflectance and Transmittance Properties of the Static Surface

We begin the discussions of the reflectance and transmittance properties of the static surface with the simplest and most useful of the laws of geometric optics for our present purposes, namely:

The Geometric Law of Reflection

Figure 12.1(a) depicts a portion Y of an optical medium near a plane boundary interface S which separates Y into parts X' and X in which the indices of refraction are respectively n' and n. The surface S is a *mathematical* surface, i.e., one which has no thickness and serves merely to separate X' from X. A narrow beam of radiant flux in X' is incident along a direction ξ' at point x on the interface S. If $\mathbf{n}$ $(= \mathbf{k})$ is the unit normal to the surface S and is directed, as shown in (a) of Fig. 12.1, from X to X', then the part of the incident beam that is reflected at x back into X' is directed along ξ where ξ', ξ and $\mathbf{n}$ are related by the *law of reflection*:

$$\boxed{\frac{\xi - \xi'}{|\xi - \xi'|} = \mathbf{n}} \qquad (1)$$

where "$|\xi - \xi'|$" denotes the magnitude of the difference $\xi - \xi'$ of the two unit vectors ξ' and ξ. From (1) we find (since $\xi + \xi'$ is perpendicular to $\xi - \xi'$) on dotting $(\xi + \xi')$ into each side:

$$\xi \cdot \mathbf{n} = -\xi' \cdot \mathbf{n} \quad , \qquad (2)$$

which shows that the angles between the reflection direction ξ and $\mathbf{n}$, and between the incident direction ξ' and $\mathbf{n}$ are equal. Suppose we write:

"θ'" for $\arccos(-\xi' \cdot \mathbf{n})$

and

"θ" for $\arccos(\xi \cdot \mathbf{n})$

then (2) implies that:

$$\theta = \theta' \quad . \qquad (3)$$

In addition, (1) summarizes the fact that ξ', ξ and $\mathbf{n}$ lie in a common plane, the *plane of incidence*. The significance