If we could always measure or model the complete BRDF of a surface our radiative transfer problems would be solved. However, measuring even a partial BRDF for a few values of $\theta_i, \phi_i, \theta_r, \phi_r, \lambda$ is a difficult and tedious task in the laboratory and is almost never attempted in the ocean. Of course, everyone wants to have some easily made (compared to a BRDF) measure of surface reflectance that, with appropriate assumptions, can be used to describe the optical properties of the surface. This leads us to various other reflectances and quantities derived from the BRDF.

Albedos

There are many definitions of "albedo." Hapke (1993) defines bolometric, Bond, geometric, hemispherical, normal, physical, plane, single-scattering, and spherical albedos, as well as an albedo factor. Not a single one of these albedos corresponds to how albedo is defined in Light and Water (1994) (page 193). Fortunately, oceanographers do not have to deal with all of these albedos, but we should clarify a point that can cause confusion when reading papers on reflectance (which sometimes just say, "...and the albedos is..." without telling you which one they are using).

Optical oceanographers generally think of the albedo as being the ratio of the upwelling plane irradiance to the downwelling plane irradiance, *for whatever conditions of incident lighting you have in nature at the time of measurement.* (This is how the albedo is defined in *Light and Water.*) This is what you need to know to compute an energy balance in the ocean, for example. Thus the oceanographers' albedo is the same as the irradiance reflectance $R = E_u/E_d$.

Many surface-reflectance scientists (e.g., in the paint industry) like to define their albedos and reflectances in terms of *isotropic illumination of the surface*, i.e., the incident radiance $L_i(\theta_i, \phi_i)$ is a constant independent of (θ_i, ϕ_i). For isotropic incident radiance, the general equation for the irradiance reflectance R (see the page on Lambertian BRDFs)

$$R \ = \& \ \frac{E_u}{E_d} \ = \ \frac{\iint_{2\pi_r} L_r(\theta_r, \phi_r)\,|\cos\theta_r|\,d\Omega_r}{\iint_{2\pi_i} L_i(\theta_i, \phi_i)\,|\cos\theta_i|\,d\Omega_i}$$

$$= \& \ \frac{\iint_{2\pi_r} \left[\iint_{2\pi_i} L_i(\theta_i, \phi_i)\, BRDF(\theta_i, \phi_i, \theta_r, \phi_r)\,|\cos\theta_i|\,d\Omega_i \right] |\cos\theta_r|\,d\Omega_r}{\int \int_{2\pi_i} L_i(\theta_i, \phi_i)\,|\cos\theta_i|\,d\Omega_i} \tag{1}$$

reduces to just

$$A \ \equiv \frac{1}{\pi} \iint_{2\pi_r} \left[\iint_{2\pi_i} BRDF(\theta_i, \phi_i, \theta_r, \phi_r)\ |\cos\theta_i|\,d\Omega_i \right] |\cos\theta_r|\,d\Omega_r \ . \tag{2}$$

This quantity is called the Bond or spherical albedo, or the spherical or bi-hemispherical reflectance, or just the albedo, depending on the author's preference. Note that this A is not equal to $R = E_u/E_d$ unless the incident lighting is isotropic (which never occurs in nature) or unless the surface is Lambertian (which never occurs in nature). For a Lambertian surface, $A = \rho$, where ρ is the reflectivity of the surface.

The same convention of assuming isotropic illumination of the surface is often used when defining other reflectances, e.g., the hemispherical-directional reflectance. Note that the convention of using isotropic illumination when defining albedos and reflectances is not necessarily bad: it removes a complicating factor—variable incident lighting—from the discussion of surface properties. However, oceanographers cannot control their incident lighting; they have to live with whatever incident radiance nature gives them.

The Irradiance Reflectance vs. The Bi-Hemispherical Reflectance

As already noted, the oceanographers' albedo or irradiance reflectance $R = E_u/E_d$ as given by Eq. (1) is a bi-hemispherical reflectance, but it is not the bi-hemispherical reflectance as defined in books such as Hapke's, because the oceanographer's R uses the actual incident radiance distribution in Eq. (1), rather than an isotropic incident radiance.

The Remote-Sensing Reflectance

The oceanographers' remote-sensing reflectance

$$R_{rs}(\theta_r, \phi_r) \equiv \frac{L_r(\theta_r, \phi_r)}{E_d} \qquad (\mathrm{sr}^{-1}) \, , \tag{3}$$

has the same units as the BRDF, but they are not the same thing. Note in particular that R_{rs} uses the downwelling radiance from all directions (as contained in E_d), whereas the incident radiance in the definition of the BRDF is in a collimated beam. [Also, some people call this ratio the "remote-sensing reflectance" only if the measurement is being made just above the sea surface and L_r is the water-leaving radiance (the total upward radiance minus the surface-reflected sky radiance). If measured in water, the ratio of upwelling radiance to downwelling irradiance is then called the "remote-sensing ratio."]

The Reflectance Factor and the Radiance Factor

The *reflectance factor REFF* (also called the *reflectance coefficient*) is defined as the ratio of the BRDF of a surface to that of a perfectly diffuse surface under the same conditions of illumination and observation. "Perfectly diffuse" means a Lambertian surface with $\rho = 1$. Thus

$$REFF(\theta_i, \phi_i, \theta_r, \phi_r) \equiv \frac{BRDF(\theta_i, \phi_i, \theta_r, \phi_r)}{BRDF_{\mathrm{Lamb}}(with\ \rho = 1)} = \pi\, BRDF(\theta_i, \phi_i, \theta_r, \phi_r) \, . \tag{4}$$

The *radiance factor RADF* is defined as the reflectance factor for normal illumination, i.e., for $\theta_i = 0$. Thus

$$RADF(\theta_r, \phi_r) \equiv \pi\ BRDF(0, 0, \theta_r, \phi_r) \, . \tag{5}$$

The Fresnel Reflectance

The Fresnel reflectance R_{F} is the reflectance of a perfectly smooth surface between two media of different indices of refraction n. Formulas for R_{F} are given in almost any optics text, and in Light and Water (1994, page 157). Figure 1 gives R_{F} for unpolarized light incident onto either side of an air-water surface; the water has a real index of refraction (relative to the air) of $n = 1.34$.

Note that the Fresnel reflectance describes the reflectance of the surface itself. The irradiance and remote-sensing reflectances, R and R_{rs}, when measured just above the sea surface describe the reflectance of the sea surface plus the water beneath the surface.

R_{F} can be combined with Dirac delta functions to create a BRDF. Consider the BRDF

$$BRDF(\theta_{\mathrm{i}}, \phi_{\mathrm{i}}, \theta_{\mathrm{r}}, \phi_{\mathrm{r}}) = 2R_{\mathrm{F}}\, \delta(\sin^2\theta_{\mathrm{r}} - \sin^2\theta_{\mathrm{i}})\, \delta(\phi_{\mathrm{r}} - \phi_{\mathrm{i}} \pm \pi) \, .$$

Inserting Eq. (1) into the general equation for reflected radiance (Eq. (4) of the BRDF page),

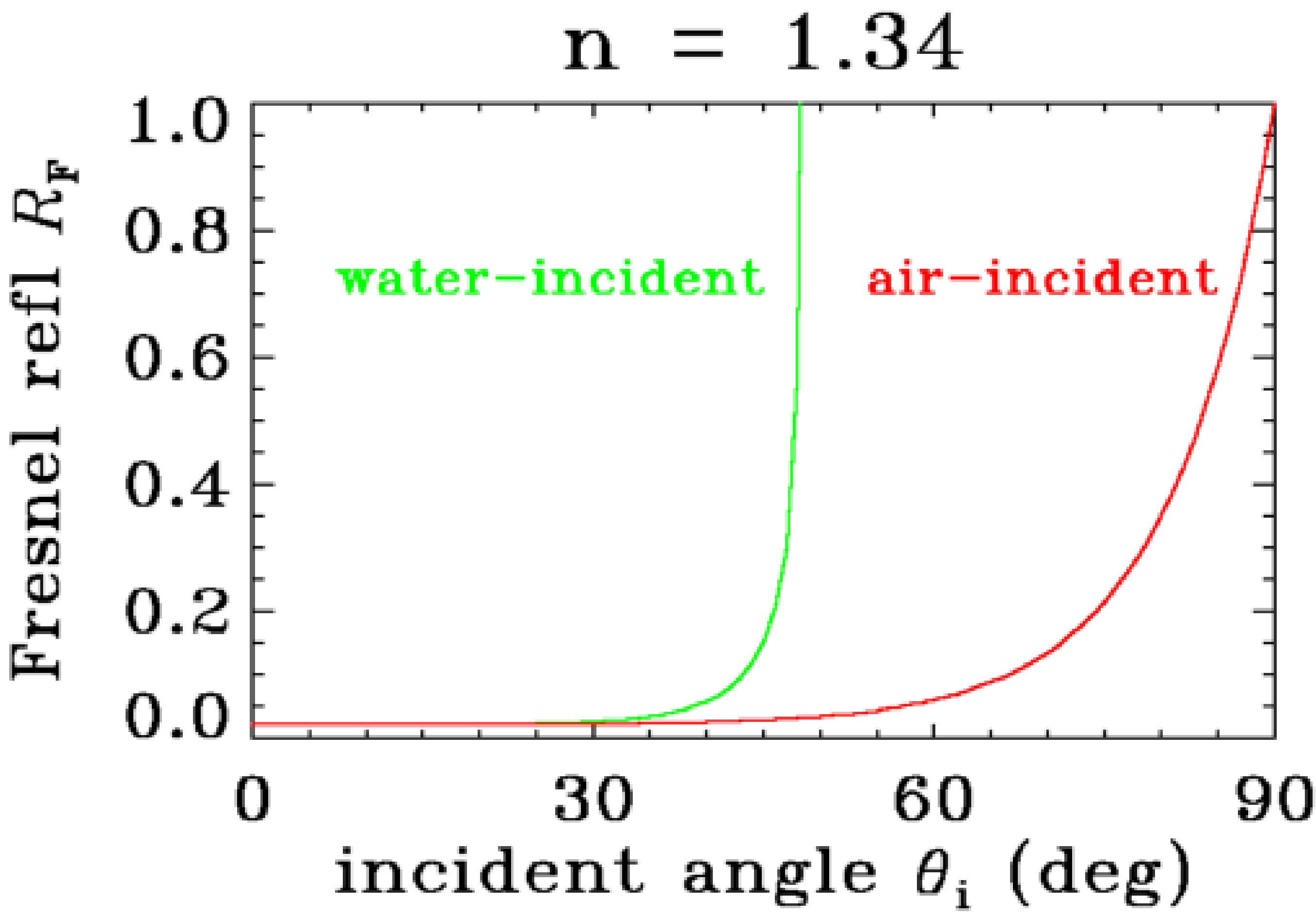

Figure 1: Fig. 1. Fresnel reflectance of an air-water surface for unpolarized incident light.

$$L_r(\theta_r, \phi_r) \;=\; \iint_{2\pi_i} L_i(\theta_i, \phi_i)\, BRDF(\theta_i, \phi_i, \theta_r, \phi_r)\, \cos\theta_i\, d\Omega_i \;,$$

gives

$$\begin{aligned} L_r(\theta_r, \phi_r) \;=\& \; R_F \iint_{2\pi_i} L_i(\theta_i, \phi_i)\, \delta(\sin^2\theta_r - \sin^2\theta_i)\, \delta(\phi_r - \phi_i \pm \pi)\, 2\cos\theta_i\, \sin\theta_i\, d\theta_i\, d\phi_i \\ =\& \; R_F \int_0^1 L_i(\theta_i, \phi_i = \phi_{\mathrm{r}} \pm \pi)\, \delta(\sin^2\theta_r - \sin^2\theta_i)\, d\sin^2\theta_i \\ =\& \; R_F\, L_i(\theta_i = \theta_r,\, \phi_i = \phi_r \pm \pi) \;. \end{aligned}$$

This last equation is the form usually seen in the definition of the Fresnel reflectance as being the ratio of reflected to incident (ir)radiances for angles related by the law of reflection.