The atmospheric correction techniques described in Level 2 of this chapter remove most of the effects of atmospheric scattering and absorption and sea surface reflectance from a measured TOA radiance. The end result is an estimate of the water-leaving radiance, which can be converted to a normalized reflectance as shown on the Normalized Reflectances page. However, neither the sensor radiometric calibration nor the atmospheric correction are perfect, so a satellite-derived water-leaving radiance usually will not exactly match a water-leaving radiance measured at the sea surface. It is therefore necessary to make comparisons between satellite-derived radiances and radiances measured at the sea surface in order to determine the gain or correction factor needed to convert a best estimate of a radiance into one that agrees with the radiance measured at the sea surface. This process is called *vicarious calibration.*

The vicarious calibration methodology employed by the NASA Ocean Biology Processing Group (OBPG) is described in Franz et al. (2007). Their procedure simultaneously corrects for residual errors in both sensor radiometric calibration and in atmospheric correction. The correction factors are therefore specific to a particular sensor and atmospheric correction procedure, but they are independent of the how the water-leaving radiance is obtained. It is assumed that the sensor has been calibrated as well as possible, so that only residual calibration errors need be corrected by the vicarious calibration process.

Operational data processing starts with a measured TOA total radiance $L_{\rm t}$ and derives the corresponding water-leaving radiance $L_{\rm w}$. The process is based on Eq. 4 of the Problem Formulation page:

$$L_{\rm t} = \Big(L_{\rm r} + L_{\rm A} + t_{\rm dv} L_{\rm wc} + t_{\rm dv} L_{\rm w}\Big)\, t_{\rm gv} t_{\rm gs} f_{\rm p}\,, \tag{1}$$

where (recall the table on that page and the associated discussion)

- $L_{\rm t}$ is the TOA radiance measured by the sensor,
- $L_{\rm r}$ is the Rayleigh radiance, which is due to scattering by atmospheric molecules,
- $L_{\rm A}$ is the radiance due to scattering by aerosol particles and aerosol-molecule multiple scattering,
- $L_{\rm wc}$ is the radiance due to whitecaps and foam,
- $L_{\rm w}$ is the water-leaving radiance,
- $t_{\rm dv}$ is the diffuse transmittance along the viewing path of the sensor,
- $t_{\rm gv}$ and $t_{\rm gs}$ are the transmittances by atmospheric gases in the viewing and solar directions respectively, and
- $f_{\rm p}$ is a known sensor-specific polarization-correction factor.

These quantities are all functions of wavelength. No specular-reflection term is included in Eq. (1) because it is assumed that pixels containing a detectable amount of specular reflection are omitted from consideration. In this equation, the aerosol radiance $L_{\rm A}$ and the water-leaving radiance $L_{\rm w}$ are the two primary unknowns. The aerosol-dependent diffuse transmittance t_{dv} can be computed for a given aerosol type as described on the Atmospheric Transmittances page. The Rayleigh and whitecap radiances and the gaseous transmittances can be computed for given atmospheric conditions as described on the pages on Non-absorbing Gases, Absorbing Gases, and Whitecaps. The determination of the aerosol contribution is the crux of the atmospheric correction process and is described on the Aerosols page. These computations constitute the atmospheric correction process. Once these terms have been computed, Eq. (1) can be solved for a measured L_{t} to obtain the corresponding L_{w}.

To develop the correction factors, this process is reversed. Let $L_{\mathrm{w}}^{\mathrm{t}}$ denote the known or "target" water-leaving radiance that is to be matched by the satellite-derived value. In most instances, the target water-leaving radiance is obtained from in-situ measurement, but can in principle be the value retrieved by another satellite sensor or predicted by a model. In any case, this value can be propagated to the TOA under various assumptions about the atmospheric conditions to obtain the corresponding target TOA radiance $L_{\mathrm{t}}^{\mathrm{t}}$ which, ideally, would match the satellite-measured TOA radiance. The ratio

$$g(\lambda) = \frac{L_{\mathrm{t}}^{\mathrm{t}}(\lambda)}{L_{\mathrm{t}}(\lambda)} \tag{2}$$

is then the correction or gain factor that, when multipled by a measured L_{t} gives an adjusted TOA radiance $L_{\mathrm{t}}^{\mathrm{t}}$ that, when atmospherically corrected, yields the correct water-leaving radiance $L_{\mathrm{w}}^{\mathrm{t}}$. Note that the gain factor is different for each wavelength. The gain factors are created via a series of "match-up" comparisons of satellite and in situ data and then, once determined, are routinely applied as part of the operational reduction of satellite-measured TOA radiances to water-leaving radiances.

Now consider the details of the computation of the gain factors. A satellite-derived L_{w} is converted to an exact normalized water-leaving radiance as described on the Normalized Reflectances page. This process can be summarized as

$$[L_{\mathrm{w}}]_{\mathrm{N}}^{\mathrm{ex}} = \frac{L_{\mathrm{w}}}{\mu_{\mathrm{s}}\, f_{\mathrm{s}}\, t_{\mathrm{ds}}\, f_{\mathrm{b}}\, f_{\lambda}}\,, \tag{3}$$

where

- μ_{s} is the cosine of the solar zenith angle,
- f_{s} is the Earth-Sun distance correction factor,
- t_{ds} is the Rayleigh-aerosol diffuse transmittance in the Sun's direction,
- f_{b} is the BRDF correction factor, and
- f_{λ} is a band-pass adjustment factor.

A target water-leaving radiance is converted to an exact normalized water-leaving radiance in the same manner:

$$[L_{\mathrm{w}}^{\mathrm{t}}]_{\mathrm{N}}^{\mathrm{ex}} = \frac{L_{\mathrm{w}}^{\mathrm{t}}}{\mu_{\mathrm{s}}^{\mathrm{t}}\, f_{\mathrm{s}}^{\mathrm{t}}\, t_{\mathrm{ds}}^{\mathrm{t}}\, t_{\mathrm{gs}}^{\mathrm{t}}\, f_{\mathrm{b}}^{\mathrm{t}}\, f_{\lambda}^{\mathrm{t}}}\,, \tag{4}$$

where now the superscript t on the terms in Eq. (4) indicates that these terms are evaluated for the Sun and viewing geometry at the time of the measurement of $L_{\rm w}^{\rm t}$, which may be different from the geometry at the time of the satellite observation leading to $L_{\rm w}$. A factor of $t_{\rm gs}$ is included in Eq. (4) to account for the diffuse transmittance due to absorption by gases in the Sun's direction at the time of measurement of $L_{\rm w}^{\rm t}$. This factor does not appear in Eq. (3) because that correction to the total measured radiance $L_{\rm t}^{\rm t}$ is accounted for in Eq. (1). The radiances in Eq. (1) are computed for the full spectral response of each sensor band. The f_λ factor converts these full-band values to nominal band-center wavelengths to remove residual out-of-band response effects. Since the satellite and in situ instruments usually have different spectral responses, this factor adjusts the satellite and in situ values to a common wavelength dependence.

Writing $L_{\rm w}$ in terms of $[L_{\rm w}]_{\rm N}^{\rm ex}$ via Eq. (3) and then replacing $[L_{\rm w}]_{\rm N}^{\rm ex}$ by the target value $[L_{\rm w}^{\rm t}]_{\rm N}^{\rm ex}$ gives an equation for the target value of the TOA radiance:

$$L_{\rm t}^{\rm t} = \Big(t_{\rm dv}[L_{\rm w}^{\rm t}]_{\rm N}^{\rm ex}(\mu_{\rm s}\, f_{\rm s}\, t_{\rm ds}\, f_{\rm b}\, f_\lambda) + L_{\rm r} + L_{\rm A}^{\rm t} + t_{\rm dv}L_{\rm wc}\Big)\, t_{\rm gv}t_{\rm gs}f_{\rm p}\,. \tag{5}$$

The total transmittance along the Sun's path is the product of the diffuse transmittance for the Rayleigh and aerosol scattering and the diffuse transmittance for gaseous absorption. The $t_{\rm ds}^{\rm t}$ term depends on the aerosols and is thus an unknown for the calibration target. The total transmittance for the target could be obtained from auxillary measurements (e.g., from a Sun photometer) made at the time of the target radiance measurement. However, such measurements are not generally available and, even if available, any error in those measurements would be an additional source of error in the the target radiance. Therefore, the satellite-retrieved atmospheric and aerosol properties are used to evaluate the total transmittance for the target measurement via

$$t_{\rm ds}^{\rm t}t_{\rm gs}^{\rm t} = \exp\left[\ln(t_{\rm ds}t_{\rm gs})\frac{\mu_{\rm s}}{\mu_{\rm s}^{\rm t}}\right]\,. \tag{6}$$

The total transmittance for the target is therefore the total transmittance for the satellite with a correction for the difference in the solar zenith angles. Other terms in Eq. (5) such as the Rayleigh radiance and gaseous transmittances along the viewing direction are evaluated for the atmospheric conditions of the satellite retrieval as described on pages Non-absorbing Gases and Absorbing Gases. Thus the $t_{\rm dv}$ that multiplies $L_{\rm wc}$ is determined by Rayleigh-scattering calculations based on the sea-level pressure. The whitecap radiance is modeled as a function of wavelength and wind speed as described on page Whitecaps. These choices reference both the target and the satellite radiances to a common atmosphere, which is desirable for the development of the gain factors.

Finally, the BRDF correction factors $f_{\rm b}$ and $f_{\rm b}^{\rm t}$ must be evaluated. As discussed in the BRDF Effect section of the Normalized Reflectances page, the IOPs needed for evaluation of the BRDF correction are parameterized in terms of the chlorophyll concentration Chl. If a measurement of Chl is made in conjunction with the target measurement, then that value of Chl can be used to evaluate the BRDF correction. However, chlorophyll measurements are not usually available. Operationally, the chlorophyll concentration is obtained via insertion of the satellite-derived $[L_{\rm w}]_{\rm N}^{\rm ex}$ (or the corresponding reflectance $[\rho_{\rm w}]_{\rm N}^{\rm ex}$) into a chlorophyll-retrieval algorithm. That is an iterative process because $[L_{\rm w}]_{\rm N}^{\rm ex}$ is required to determine

Chl, and Chl is required to determine $[L_{\rm w}]_{\rm N}^{\rm ex}$. During the determination of gain factors, the target radiance can be used as input to the operational chlorophyll-retrieval algorithm and no iteration is required.

The final issue is the determination of the aerosol properties. This is a two-step process based on the "black-pixel" assumption to be described in the Black Pixels section of the Aerosols page. As seen in the table on that page, satellite sensors have two NIR wavelengths used for aerosol retrievals. Call the longer of these wavelengths $\lambda_{\rm L}$ and the shorter $\lambda_{\rm S}$. (For VIIRS, the NIR bands are at the nominal wavelengths $\lambda_{\rm L} = 862$ nm and $\lambda_{\rm S} = 745$ nm.) During determination of the gain factors, it is first assumed that the water-leaving radiance at these two wavelengths is zero (the black-pixel assumption). This is usually a good approximation for the mid-ocean, oligotrophic waters used for vicarious calibration. It is further assumed that the instrument calibration is perfect for the $\lambda_{\rm L}$ band, in which case the gain factor for the longer NIR band is $g(\lambda_{\rm L}) = 1$. The black-pixel assumption means that Eqs. (1) and (5) reduce to

$$L_{\rm t}(NIR) = \&\Big(L_{\rm r} + L_{\rm A} + t_{\rm dv}L_{\rm wc}\Big)\, t_{\rm gv}t_{\rm gs}f_{\rm p} \quad (7)$$

$$L_{\rm t}^{\rm t}(NIR) = \&\Big(L_{\rm r} + L_{\rm A}^{\rm t} + t_{\rm dv}L_{\rm wc}\Big)\, t_{\rm gv}t_{\rm gs}f_{\rm p}\,, \quad (8)$$

respectively, at the two NIR bands. Given the satellite-measured TOA radiances at the two NIR bands, Eq. (7) can be solved for $L_{\rm A}$ at the two NIR bands. The assumption that $g(\lambda_{\rm L}) = 1$ means that $L_{\rm A}^{\rm t}(\lambda_{\rm L}) = L_{\rm A}(\lambda_{\rm L})$. Thus $L_{\rm t}^{\rm t}(\lambda_{\rm L})$ is determined via Eq. (8) evaluated at $\lambda_{\rm L}$. The locations for match-ups are purposely chosen at times and locations where it is reasonable to assume that the aerosol type in stable and predictable over the image area, e.g. mid-ocean areas where the aerosols are predominately sea salt and water droplets. The aerosol model derived from the satellite measurements as described in the Black Pixels section of the Aerosols page can then be used along with the value of $L_{\rm t}^{\rm t}(\lambda_{\rm L})$ to determine $L_{\rm t}^{\rm t}(\lambda_{\rm S})$. Both $L_{\rm t}$ and $L_{\rm t}^{\rm t}$ are then known at the two NIR wavelengths, and the NIR gain factor at $g(\lambda_{\rm S})$ can be determined by Eq. (2).

Values of $g(\lambda_{\rm S})$ are computed for various times and locations during the lifetime of the mission. These values are averaged to determine the mean gain $\bar{g}(\lambda_{\rm S})$. The selection of suitable images for gain determination is quite strenuous and most candidate pixels are eliminated from consideration because of glint, inhomogeneous water at the target location, or non-ideal atmospheric conditions. The details of the selection criteria and statistical determination of the mean gain factors are given in Franz et al. (2007). Experience shows that 20 to 40 match-ups are required for the determination of $\bar{g}(\lambda_{\rm S})$ values that are stable to within 0.1% of their long-term values. Once the NIR gains $g(\lambda_{\rm L}) = 1$ and $\bar{g}(\lambda_{\rm S})$ have been determined for the given sensor, the extrapolation algorithm described in the Black Pixels section of the Aerosols page can be used to determine $L_{\rm A}^{\rm t}(\lambda)$ at all wavelengths. Equation (8) then gives $L_{\rm t}^{\rm t}(\lambda)$, and the gains at the remaining visible wavelengths are obtained from Eq. (2). Once determined, the gains are held fixed and applied as part of the operational atmospheric correction process.

For the SeaWiFS sensor the gains ranged from 1.0377 at 412 nm to 0.972 at 765 nm. A correction of 3 or 4% to the TOA radiance can correspond to a 30 or 40% correction to the water-leaving radiance because the water-leaving radiance is typically about 10% of the TOA radiance. Thus the determination of accurate gain factors is critical to the overall retrieval process. It must be remembered that a set of gains must be determined for each sensor and atmospheric correction algorithm. As improvements are made to the atmospheric correction algorithms described in Level 2 of this chapter, the gains must be recomputed. However, these recomputations can be made using the original target radiances. Gain recalculation is a part of the standard reprocessing of data sets.