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AVIRIS CALIBRATION USING THE CLOUD-SHADOW METHOD

K.L. Carder, P. Reinersman, R.F. Chen

University of South Florida St. Petersburg
Marine Science Department
140 Seventh Avenue South
St. Petersburg, FL 33701-5016

More than 90% of the signal at an ocean-viewing, satellite sensor is due to the atmosphere (Gordon, 1987), so a 5% sensor-calibration error when viewing a target that contributes but 10% of the signal received at the sensor may result in a target-reflectance error of more than 50%. Since prelaunch calibration accuracies of 5% are typical of space-sensor requirements, recalibration of the sensor using ground-based methods (e.g. Gordon, 1987; Carder et al. 1993) is required for low-signal targets. Known target reflectance or water-leaving radiance spectra and atmospheric-correction parameters are required.

In this article we describe an atmospheric-correction method that uses cloud-shadowed pixels in combination with pixels in a neighboring region of similar optical properties to remove atmospheric effects from ocean scenes. These neighboring pixels can then be used as known reflectance targets for validation of the sensor calibration and atmospheric correction. The method uses the difference between water-leaving radiance values for these two regions. This allows nearly identical optical contributions to the two signals (e.g. path radiance and Fresnel-reflected skylight) to be removed, leaving mostly solar photons backscattered from beneath the sea to dominate the residual signal. Normalization by incident solar irradiance reaching the sea surface provides the remote-sensing reflectance of the ocean at the location of the neighbor region.

Errors result from this method if corrections are not made for the following: 1) reduction of the path radiance over the shadowed pixels resulting from partial shadowing of the overlying atmospheric column; and 2) adjacency effects resulting from solar-derived photons leaving the water from the bright, surrounding waters that are scattered into the field of view for the shadowed pixels.

The initial application of the shadow-neighbor method was made assuming that the sensor calibration is correct. For illustrative purposes, assume that the solar zenith angle θ_0 is 45°, and that the angle from the pixel to the sensor θ is 0°. A small cumulus cloud (about 1 km diameter) at 1.2 km altitude removes direct solar photons and shades a region. The water-leaving radiance from this shady region directed toward the sensor is designated L_{ws}. The wavelength dependence of terms in this article have been left out for brevity. This radiance results from skylight photons which have been scattered from beneath the ocean surface.

Adjacent to the shadowed region is a neighboring patch of water with identical inherent optical properties to those of the shadowed region, differing only in the fact that direct, solar photons as well as skylight irradiate it. The water-leaving radiance from the neighbor region is designated L_{wn}. Since the cloud is quite small, it occludes a similar fraction of the sky for both shadow and neighbor patches, and contributes a similar amount of diffusely scattered light to each. Furthermore, the atmospheric columns over each are considered to be identical. Therefore, both the path radiance contributed to the total signals and the diffuse attenuation t of the L_w signals are nearly equal. Later, we will investigate the differences induced by the fact that a short column of the atmosphere over the shadow is shaded from solar photons by the cloud.

To second order, the path radiance consists of a portion due to molecular or Rayleigh scattering, L_r, one due to aerosol scattering, L_a, and one due to multiple scattering, L_{ra}. Let the radiance measured at the sensor when viewing an area in unshadowed water be given by (Wang and Gordon, 1992).

1) $$L_{tn} = L_a + L_r + L_{ra} + t\, L_{wn}$$

where

L_{tn} = measured radiance when viewing an unshadowed (neighbor) pixel
L_a = path radiance due to aerosol scattering
L_r = path radiance due to Rayleigh scattering
L_{ra} = path radiance due to Rayleigh-aerosol interaction
t = diffuse transmittance of the atmosphere for water-leaving radiance
L_{wn} = water-leaving radiance of neighbor pixel
L_{ws} = water-leaving radiance of shadowed pixel.

The apparent path transmittance of the water-leaving radiance from the shadowed pixel may not be equivalent to the term used in Eq. 1. Use of the "diffuse transmittance" is justified when viewing a large homogeneous area where the radiance scattered out of the viewing path is balanced by the radiance scattered into it from adjacent areas of the scene. In the case of the shadowed pixel, the adjacent areas of the scene are generally brighter, and so the apparent transmittance may be increased.

If Δ terms express perturbations due to non-homogeneity in the scene illumination, the total radiance at the sensor when viewing a shadowed pixel may be written

(2) $$L_{ts} = L_a - \Delta L_a + L_r - \Delta L_r + L_{ra} - \Delta L_{ra} + (t + \Delta t)\, L_{ws}.$$

In general, the water-leaving radiance may be expressed as the sum of two parts: one part caused by backscattering of incident, diffuse skylight, and the other by backscattering of the direct solar beam by water and hydrosols. For the neighbor and shadowed pixels, respectively,

(3) $$L_{wn} = {}_{sky}L_{wn} + {}_{sol}L_{wn}; \quad L_{ws} = {}_{sky}L_{ws} + {}_{sol}L_{ws}.$$

Under the assumptions that the shadowed pixel receives no direct sun and that the incident sky light at both pixels is the same, that is

(4) $$L_{ws} = {}_{sky}L_{ws} = {}_{sky}L_{wn},$$

(5) $$L_{tn} - L_{ts} = \Delta L_a + \Delta L_r + \Delta L_{ra} + t\, {}_{sol}L_{wn} - \Delta t\, {}_{sky}L_{wn}.$$

The first three terms on the right of Eq. 5 depend on the length of the shadowed portion of viewing path to the shadowed pixel. The height of the intersection of the viewing path and the upper edge of the cylinder of atmosphere shaded by the cloud can be determined from scene geometry. The layer of atmosphere below this intersection would normally be the source of less than 20% of the Raleigh scattering, so we will assume that the Raleigh-aerosol correction term, ΔL_{ra}, must be negligible. Then, following Gordon et al. (1987), for the aerosol and Rayleigh corrections we may write

(6) $\Delta L_x = \{\omega_x \tau_x' F_o'' P_x(\theta,\theta_o,\lambda)\} t'/4\pi, \quad x = a, r$

where

τ_x' = optical thickness of shaded viewing path (vertical)

ω_x = single-scattering albedo

F_o'' = $F_o e^{-(\tau-\tau')/\cos\theta o}$

F_o = extra-terrestrial solar irradiance

$P_x(\theta,\theta_o)$ = $\{P_x(\theta_-) + [\rho(\theta) + \rho(\theta_o)] P_x(\theta_+)\}/\cos\theta$

$\cos\theta_\pm$ = $\pm \cos\theta_o \cos\theta + \sin\theta_o \sin\theta \cos(\phi-\phi_o)$

$\rho(\theta)$ = Fresnel reflectance (θ)

$P_x(\theta)$ = scattering phase function

t' = diffuse transmittance from top of layer to top of atmosphere

t' = $\exp\{-(\tau_r/2 - \tau_r'/2 + \tau_{oz} - \tau_{oz}')/\cos\theta\}$.

The term involving Δt in equation (2) represents the apparent increase in diffuse transmittance of water-leaving radiance when viewing a shadowed pixel. The work of Tanre et al. (1979) indicates that this term is proportional to the difference in water-leaving radiances from the shadowed and neighbor pixels and is dependent on the geometry of the particular case. We will express Δt as

(7) $\Delta t = t * \sigma\,(L_{wn} - L_{ws})/L_{ws} = t * \sigma\,({}_{sol}L_{wn}/{}_{sky}L_{wn})$.

Preliminary Monte Carlo simulations indicate that σ(550 nm) is of the order of 0.1 for circular shadows of radius equal to 1 km for moderately turbid atmospheres (τ_a = 0.2). Thorough investigation of the dependence of σ on wavelength and geometry is pending. Using equation (7) and equation (5) we obtain

(8) ${}_{sol}L_{wn} = \{L_{tn} - L_{ts} - \Delta L_a - \Delta L_r\}/t(1-\sigma)$.

Now define (Gordon et al. 1987)

(9) $$\epsilon(\lambda_i,\lambda_j) = \frac{\omega_a(\lambda_i)\tau_a'(\lambda_i)P_a(\theta,\theta_o,\lambda_i)}{\omega_a(\lambda_j)\tau_a'(\lambda_j)P_a(\theta,\theta_o,\lambda_j)}$$

then

(10) $$\frac{\Delta L_a(\lambda_i)}{\Delta L_a(\lambda_j)} = \epsilon(\lambda_i,\lambda_j)\,\frac{F_o''(\lambda_i)}{F_o''(\lambda_j)}\,\frac{t'(\lambda_i)}{t'(\lambda_j)} = S(\lambda_i, \lambda_j)$$

then

(11) $$t(\lambda_i)[1-\sigma(\lambda_i)]_{sol}L_{wn}(\lambda_i) = L_{tn}(\lambda_i) - L_{ts}(\lambda_i) - \Delta L_r(\lambda_i) - S(\lambda_i,\lambda_j)\{L_{tn}(\lambda_j) - L_{ts}(\lambda_j) - \Delta L_r(\lambda_j) - t(\lambda_j)[1-\sigma(\lambda_j)]_{sol}L_{wn}(\lambda_j)\}$$

If λ_j is a wavelength such as 780 nm where the water-leaving radiance is essentially zero, then ${}_{sol}L_{wn}(\lambda_j) = 0$, and

(12) $\Delta L_a(780) = L_{tn}(780) - L_{ts}(780) - \Delta L_r(780)$

and

(13) $$t(\lambda_i)(1-\sigma(\lambda_i))_{sol}L_{wn}(\lambda_i) = L_{tn}(\lambda_i) - L_{ts}(\lambda_i) - \Delta L_r(\lambda_i) - S(\lambda_i,780)[L_{tn}(780) - L_{ts}(780) - \Delta L_r(780)].$$

From scene geometry, the cloud height H and height of the shadowed viewing path can be calculated. Then, $\Delta L_r(\lambda)$ can be determined for all λ by differencing Lowtran 7 results for the entire air column and the air column down to height H. The aerosol correction term, $\Delta L_a(780)$, is then determined by Eq.12. Knowledge of wind speed allows estimation of $\epsilon(\lambda_i,780)$ (Gregg and Carder, 1990), and thus $S(\lambda_i,780)$. The $\sigma(\lambda_i)$ term involved in the transmissivity correction has been estimated by Monte Carlo simulations to be described later. Thus, Eq.13 allows ${}_{sol}(L_{wn}(\lambda_i)$ to be calculated.

The results for an AVIRIS scene, 19 November, 1992 seaward of Key Biscayne, Florida are shown in Figure 1, where terms from Eq. 5 are normalized by the incoming solar irradiance ${}_{sol}E_d$ (no skylight) to form remote-sensing reflectance spectra. Note that the spectrum resulting from the cloud-shadow method differs from that using conventional atmospheric correction methodology (see Carder et al., 1993) by only about 3.5%. This derived reflectance spectrum can in principle serve as a calibrated ground target to help with model parameterization for atmospheric correction of the entire scene, or in validation of the calibration of a sensor for scenes where conventional methods were unavailable.

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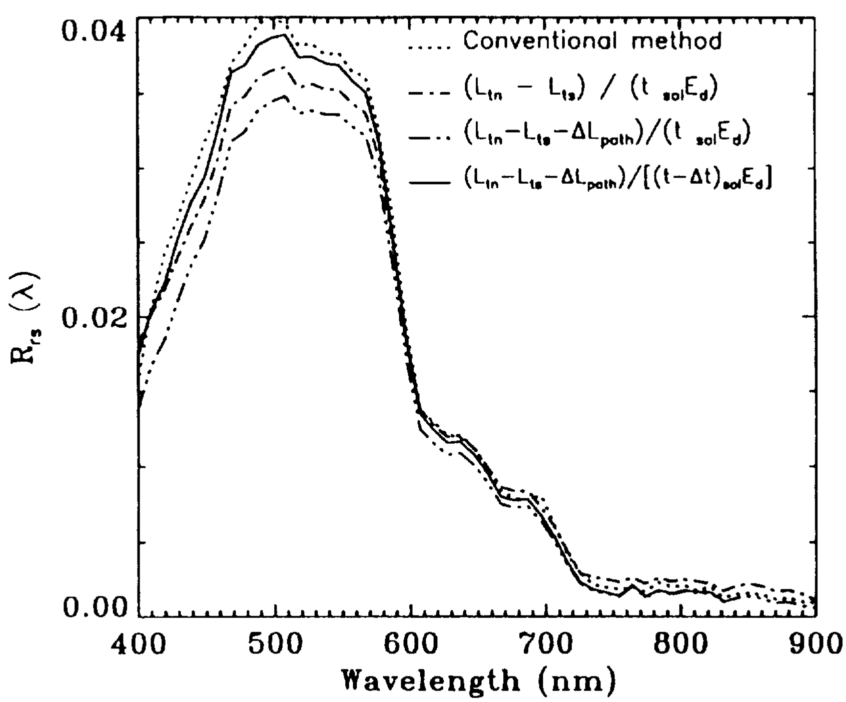

Fig. 1: Remote-sensing reflectance spectra using conventional atmospheric-correction methods and the cloud-shadow method where path-shadow and transmittance perturbations are sequentially removed.