Improved Sea Surface Reflectances for Remote Sensing

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The Problem
Removal of sea-surface sun glint and sky reflectance is a critical step in converting measured top-of-the-atmosphere (TOA) radiances to remote-sensing reflectances as used for retrieval of oceanic environmental properties. This is normally done by modeling the surface reflectance as a function of solar zenith angle and viewing direction, for a given wind speed and sky conditions.

There are three requirements for accurate computation of surface reflectances: (1) The sea surface itself must be modeled in a way that accounts for both wave elevations and slopes; (2) The simulated light rays must account for polarization; and (3) The ray tracing must account for multiple scattering between light rays and waves. The first requirement is met by generating random sea surfaces using wave variance spectra and Fourier transforms formulated in a way that guarantees conservation of wave energy and fully resolves wave height and slope variances. Monte Carlo polarized ray tracing, which accounts for multiple scattering between light rays and wave facets, is then used to compute effective Mueller matrices for reflection and transmission of air- or water-incident polarized radiance.

Sea Surface Generation

Wave elevation variance spectral densities in spatial frequency space,

$$\Phi(k_x,k_y) = 1 \over 2 \pi^2 \rho(k_x,k_y)$$

are used to generate Hermitian Fourier amplitudes via

$$\rho(k_x,k_y) = \sqrt{\rho(k_x,k_y) + i \rho(k_y,k_x)}$$

Based on Tessendorf (2004), modified to conserve wave variance, $k_x, k_y$ are discrete spatial frequencies, and $\rho$ is a non-Gaussian random variable.

These amplitudes conserve wave elevation variance (wave energy):

$$\rho(k_x,k_y) = \sqrt{\rho(k_x,k_y) + i \rho(k_y,k_x)}$$

The omnidirectional spectrum $S(\theta)$ is modified so that the surface is a bit too rough, in order to fully resolve the optimally important sea surface slope variance with a limited number of spatial frequencies.

The inverse FFT then gives surface elevations that fully resolve the surface slope statistics. See Mobley (2014, 2015) for more details on this calculation.

Example Sea Surface Reflectances

Sky radiance Stokes vector times the surface Mueller reflection matrix gives the surface-reflected radiance Stokes vector.

The radiance reflectance factor

$$\rho(\theta, \varphi) \equiv \frac{I_S(\theta, \varphi)}{I_S(\theta, \varphi) + I_T(\theta, \varphi)}$$

can be used to remove sun glint and background sky reflectance from above-water radiance measurements in order to estimate the water-leaving radiance (Mobley, 1999).

Previous available tables of $\rho(\theta, \varphi)$ were computed using Cox-Munk surfaces and unpolarized ray tracing. Computations using FFT surfaces and polarized ray tracing give $\rho(\theta, \varphi)$ values that are even more accurate, depending on the viewing direction and sky polarization.

Conclusions

- The FFT surface generation techniques developed here are extremely fast; 10^5 surfaces generated in 36x10^5 Stokes vectors traced to completion require less than 8 hours on a PC. This enables accurate reflection and transmission calculations to be incorporated into coupled ocean-atmosphere vector RT codes.

Detailed calculations show that

- Irradiance reflectances (not shown here; see Mobley, 2015) differ by 18 to 32% for various combinations of polarized vs unpolarized ray tracing, Cox-Munk vs FFT surfaces, multiple vs single scattering, and wave age.

- Radiance reflectance factors $\rho$ differ by much more, typically tens of percent, for various combinations of how the factors are computed. Moreover, the $\rho$ factors depend not just on wind speed and sun-view viewing geometry, but also on sky polarization condition (i.e., on spectral type and concentration). This makes $\rho$ more variable and more difficult to estimate in practice.

References


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