Toward modeling for efficient PDMs

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Status of the adding-doubling radiative transfer model (ADRTM)

1. ADRTM:
   This can calculate full Stokes parameters (I, Q, U, V).
2. Atmospheric profiles:
   Any atmosphere profile.
3. Spectral gas absorption:
   Line-by-Line and $k$-distribution plus ozone cross-section table.
4. Molecular scattering:
   Rayleigh with depolarization factor.
5. Particulate absorption and scattering:
   Mie for water clouds (Gamma size distribution);
   PML FDTD for fine-mode aerosols;
   CPML PSTD code is developed for coarse-mode aerosols;
   FDTD, PSTD, GOM for ice clouds.
6. Surface reflection model:
   Lambert surface for land;
   More practical model for land is being considered...
   Cox & Munk without Gram-Charlier expansion plus foam for ocean;
   Cox & Munk with Gram-Charlier expansion plus foam for ocean;
   Wave shadowing effect is integrated in the ocean surface model;
   Lambert model for water-leaving radiance from ocean water volume.
   More practical model for water-leaving radiance is being considered...
7. Output:
   polarization parameters are mapped to uniform angular grids.
Employing symmetry of Stokes parameters in simplifying the PDMs

\[
R_0(\theta_s, \theta_v, \varphi) = f R_{WC} + (1 - f) R_{WL} + (1 - f) \frac{\pi M(\theta_s, \theta_v, \varphi)}{4 \cos^4 \beta \cos \theta_s \cos \theta_v} P(Z_x, Z_y)
\]

If wind direction is NOT accounted for

\[
P(Z_x, Z_y) = \frac{1}{\pi \sigma^2} \exp\left(-\frac{Z_x^2 + Z_y^2}{\sigma^2}\right)
\]

(Cox and Munk, 1956)

If wind direction is accounted for

\[
P(Z_c, Z_u) = \frac{1}{2 \pi \sigma_c \sigma_u} \exp\left(-\frac{\xi^2 + \eta^2}{2}\right) [1 - \frac{C_{21}}{2} (\xi^2 - 1) \eta - \frac{C_{03}}{6} (\eta^3 - 3 \eta) + \frac{C_{40}}{24} (\xi^4 - 6 \xi^2 + 3) + \frac{C_{04}}{24} (\eta^4 - 6 \eta^2 + 3) + \frac{C_{22}}{4} (\xi^2 - 1)(\eta^2 - 1) + \cdots]
\]

\[
\xi = \frac{Z_c}{\sigma_c}, \quad \eta = \frac{Z_u}{\sigma_u}
\]

(Cox and Munk, 1954)
Reflectance and DOP on the principal plane at a wavelength of 670 nm from Cox-and-Munk models with and without wind-direction dependence.
AOLPs from the ocean wave slope probability distribution model with wind direction (a) 0°, (b) 90°, and (c) 180°, and for (d) the ocean wave slope probability distribution model without wind direction dependence.
• Wind direction and wave slope distribution models have little effect on the polarization state of reflected light at TOA.

• We will use the Cox-and-Munk model without wind direction dependence [Cox and Munk 1956] in the future modeling for operational PDMs.

• Using the Cox-and-Munk model without wind direction dependence, we only need to calculate DOP and AOLP over the RAZ of 0° to 180°. These quantities will be obtained by symmetry for the RAZ of 180° to 360° with noting that

\[
\begin{align*}
I(VZA,360^\circ - RAZ) &= I(VZA, RAZ) \\
Q(VZA,360^\circ - RAZ) &= Q(VZA, RAZ) \\
U(VZA,360^\circ - RAZ) &= -U(VZA, RAZ) \\
V(VZA,360^\circ - RAZ) &= -V(VZA, RAZ)
\end{align*}
\]

\[
DOP(VZA,360^\circ - RAZ) = DOP(VZA, RAZ)
\]

\[
AOLP(VZA,360^\circ - RAZ) = 180^\circ - AOLP(VZA, RAZ)
\]
Mapping ADRTM output polarization parameters to uniform VZA

ADRTM’s outputs are at Gaussian Quadrature points of VZA.

• For each RAZ, linear extrapolation is done to obtain I, Q, U, and V at VZA = 0 deg and 90 deg.

• For each RAZ, linear interpolation is done to obtain I, Q, U, and V at uniform VZA grid point from 0 to 90 deg.

• At each grid point of the uniform VZA and RZA, DOP and AOLP are derived from the I, Q, U, and V at these uniform points

This simple treatment greatly reduces the stream number of the ADRTM required for the PDM modeling, makes the modeling times faster.
Reflectance and DOP on the principal plane calculated with the ADRTM at the Gaussian quadrature points (black dots) and after the mapping to uniform VZA grids (solid curve)
AOLPs before (left panel) and after (right panel) the mapping to uniform VZA grids
Effect of ocean wave shadow on the polarization of reflected light

Ocean wave shadowing effect is calculated by multiplying the reflection matrix by a bidirectional shadowing function

\[ S(\theta_s, \theta_v) = \frac{1}{1 + \Lambda(\theta_s) + \Lambda(\theta_v)} \]

\[ \Lambda(\theta) = \frac{1}{2} \left\{ \frac{\sigma}{\cos \theta} \left[ \frac{2(1 - \cos^2 \theta)}{\pi} \right]^{1/2} \exp \left[ - \frac{\cos^2 \theta}{2\sigma^2(1 - \cos^2 \theta)} \right] - \text{erfc} \left[ \frac{\cos \theta}{\sigma \sqrt{2(1 - \cos^2 \theta)}} \right] \right\} \]

where \text{erfc}(x) is the complementary error function [Tsang et al., 1985].
Reflectance and DOP on the principal plane from ocean surface model with shadowing and without shadowing factor
AOLPs from ocean surface model with shadowing (left panel) and without shadowing (right panel) factor
Effect of ice cloud particle size distributions on the polarization of reflected light

Two in-situ-measured ice particle size distributions used in the modeling for ice clouds
Phase matrix elements of ice clouds with hexagonal column particle shape and HP (1984) and FIRE II (1991) size distributions
Reflectance and DOP on the principal plane from thin cirrus with HP (1984) and FIRE II (1991) size distributions
Summary

1. Wind direction and wave slope distribution models have little effect on the polarization state of reflected light at TOA.

2. Based on Cox-and-Munk model without wind direction dependence, DOP is symmetric and AOLP is supplementary to the principal plane.

3. Mapping the ADRTM results to uniform VZA grids makes the modeling and the PDM more efficient.

4. Ocean wave shadowing slightly reduces the total reflectance and DOP at large VZA, but affects the AOLP insignificantly.

5. Ice cloud particle size distribution affects the polarization insignificantly.

6. Future work is to compare model results with Parasol/RSP data and to derive land surface reflection matrix from these data with the model.