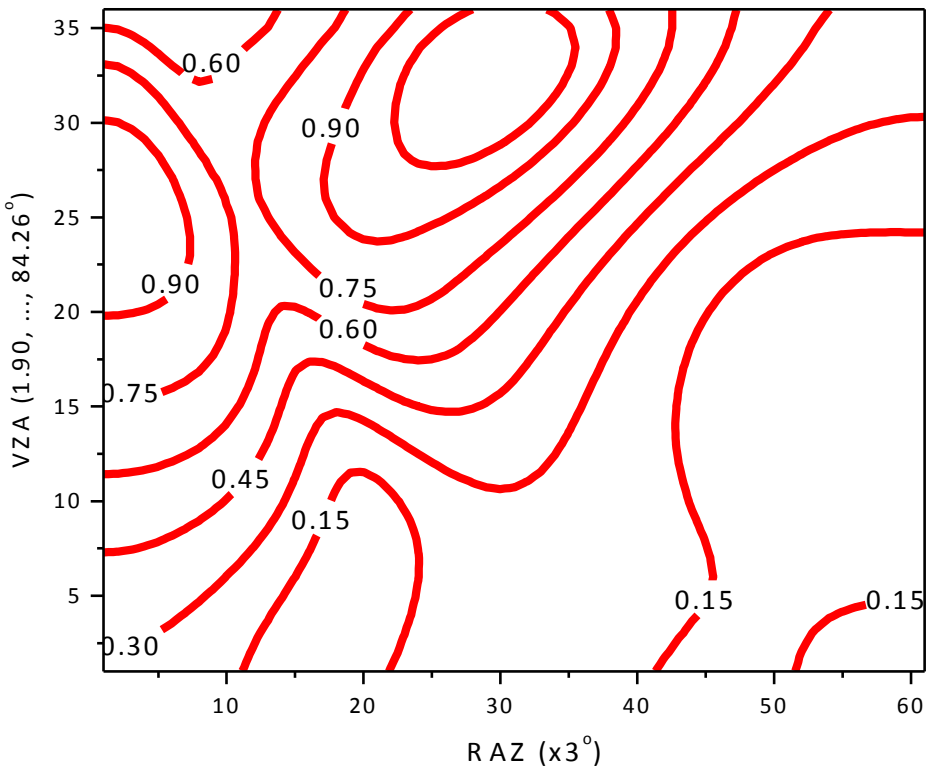
Progresses in modeling polarized solar radiation from ocean surface

Wenbo Sun, Bruce Wielicki, David Young, and Constantine Lukashin

- **Introduction: Why polarization correction is needed for RS?**
- **Status of the adding-doubling radiation transfer model (ADRTM)**
- **Sensitivity of ADRTM accuracy to Fourier expansion terms**
- **Comparison of ADRTM with DISORT**
- **Sensitivity of polarized radiation from ocean to wind direction**
- **Pseudo-spectral time domain (PSTD) light scattering model for coarse mode aerosols**
- **On modeling polarized RS from land surface**
- **Summary**

Introduction: Why polarization correction is needed for RS?



RS DOP at 670 nm over ocean, SZA = 41.58 deg

- DOP over ocean can easily exceed 30%, even if at nadir.
- 1% polarization dependence of a sensor (CLARREO goal is 0.75%) means a measurement uncertainty of 30% x 1% = 0.3% , simply due to polarization. CLARREO RS accuracy is required to be 0.3%.

Status of the adding-doubling radiation 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;
   Lambert model for water-leaving radiance from ocean water volume.

Sensitivity of ADRTM accuracy to Fourier expansion terms

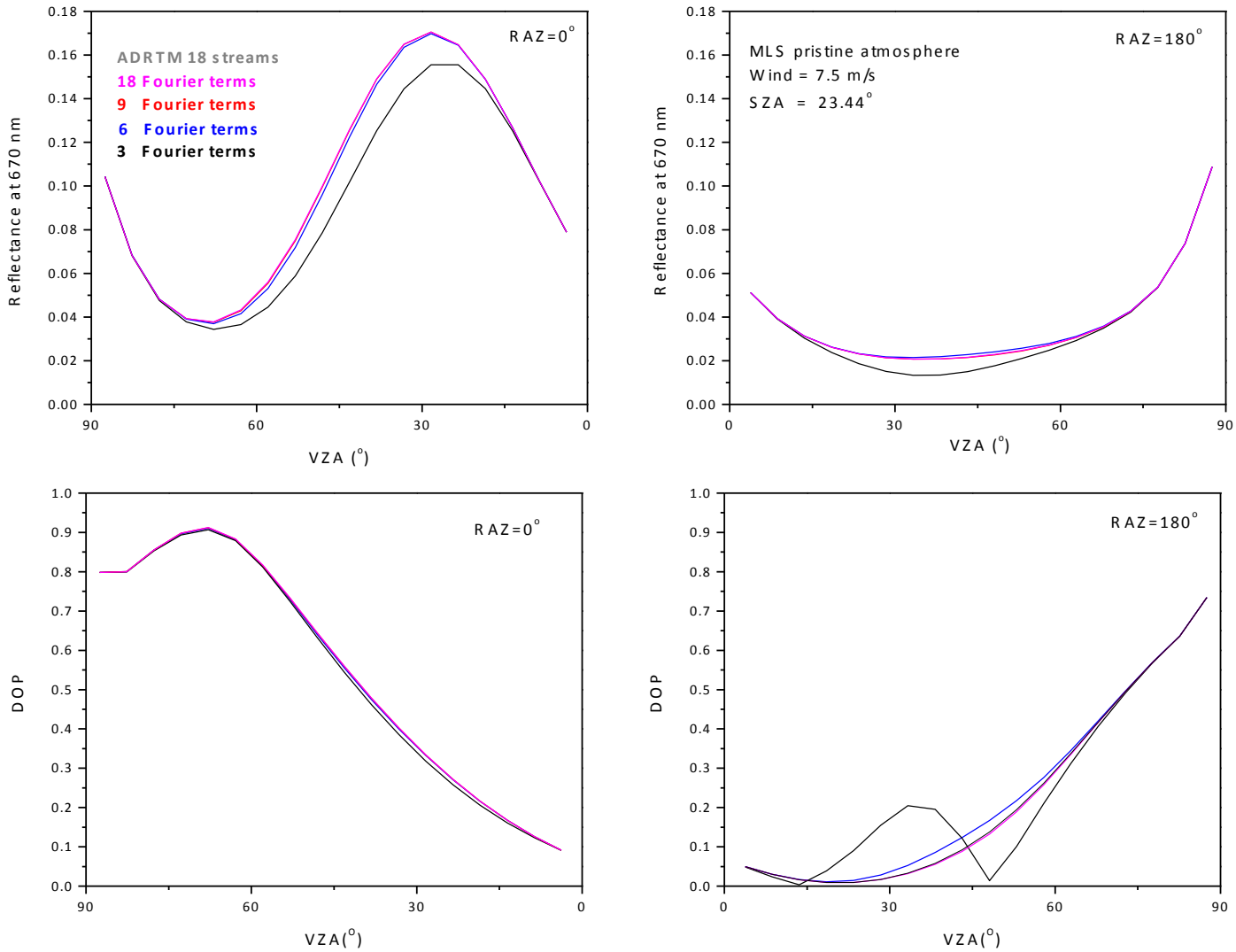
$$I(\theta) = \sum_{m=0}^{M} \cos(m\varphi) I_m(\theta)$$

$$Q(\theta) = \sum_{m=0}^{M} \cos(m\varphi) Q_m(\theta)$$

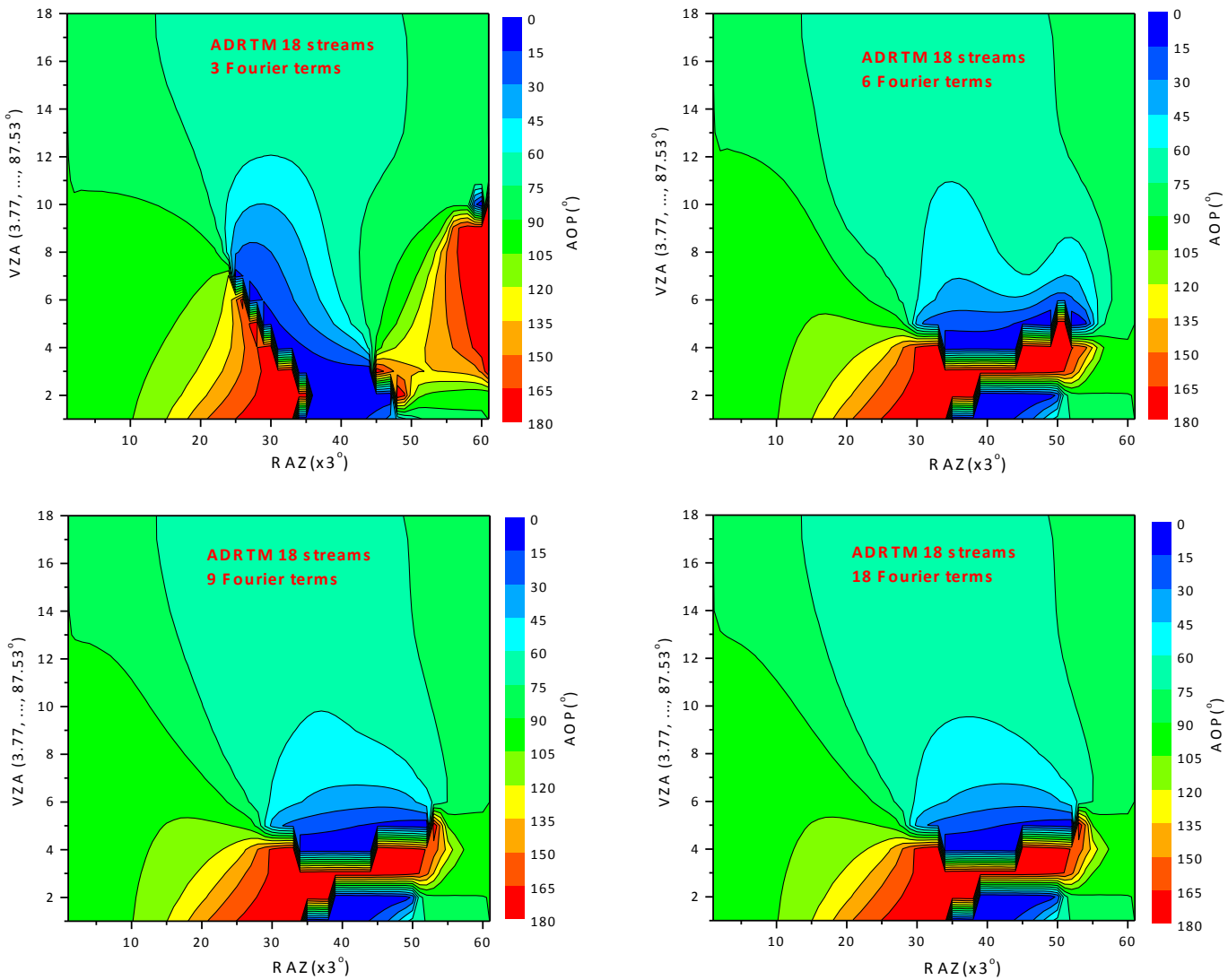
$$U(\theta) = \sum_{m=0}^{M} \sin(m\varphi) U_m(\theta)$$

where I_m, Q_m, U_m are Fourier expansion components of *I, Q*, and *U*.

Accuracy of the modeling depends on Fourier expansion term number *M.*

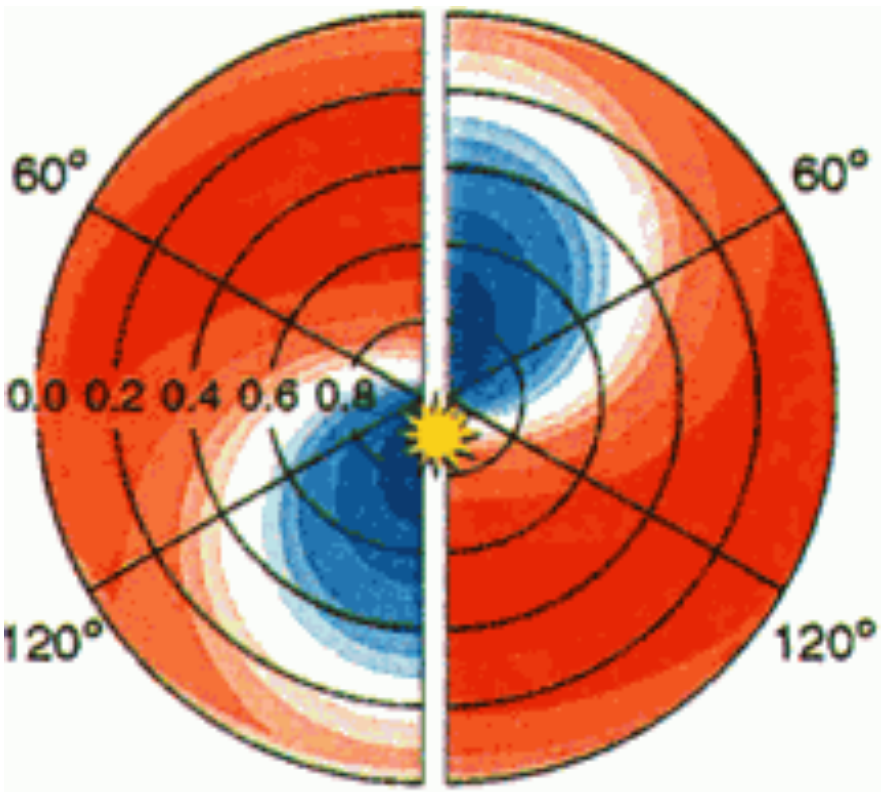


Fourier term truncation does NOT affect total reflectance and DOP when enough number of Fourier terms are used



Fourier term truncation does NOT affect AOP when enough number of Fourier terms are used

Comparison of ADRTM with DISORT



REFLECTION / TRANSMISSION
(WITH LAMBERT OCEAN)

-10 -9 -7 -5 -3 -2 -1 1 2 3 5 7 9 10

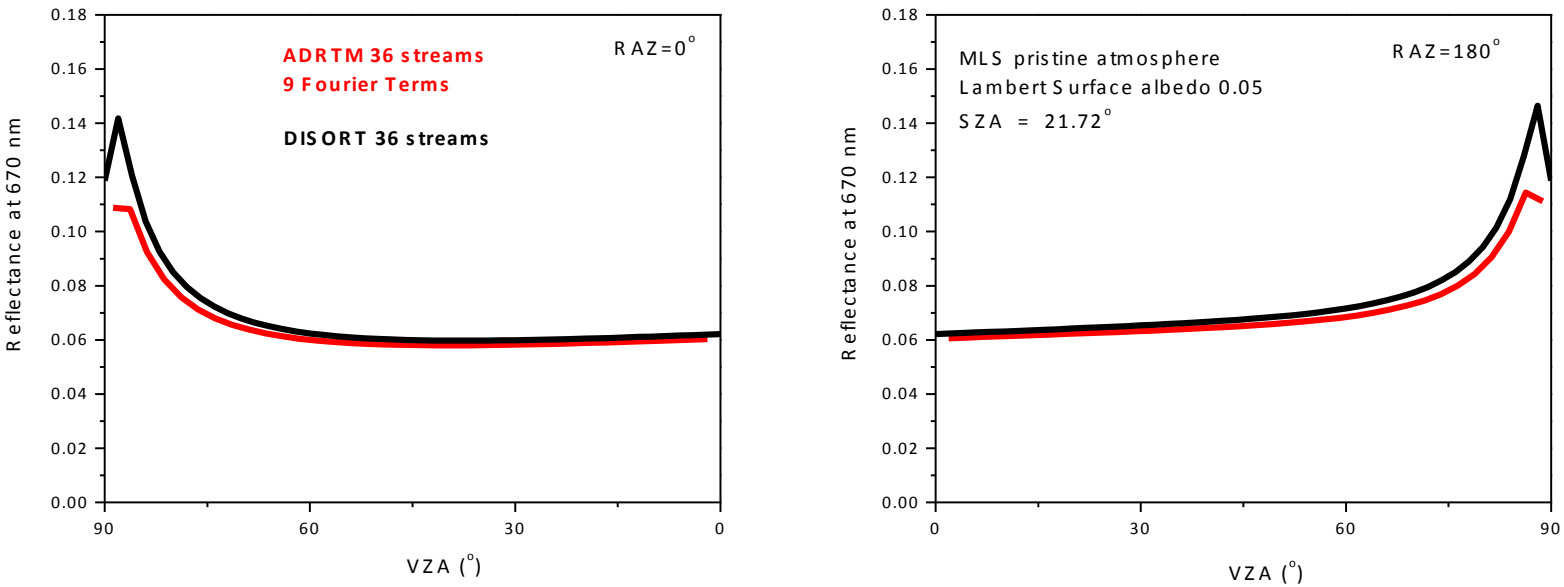
100x(Scalar- Vector) / Vector

Lambert Surface

Scalar approximation intensity errors in Rayleigh scattering atmosphere, SZA = 25 deg, WL = 455 nm

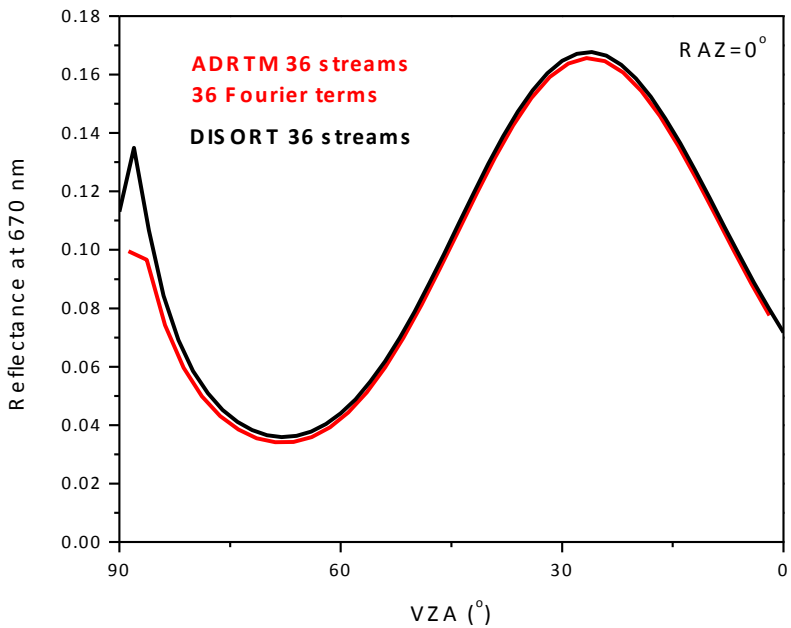
Lacis et al 1998

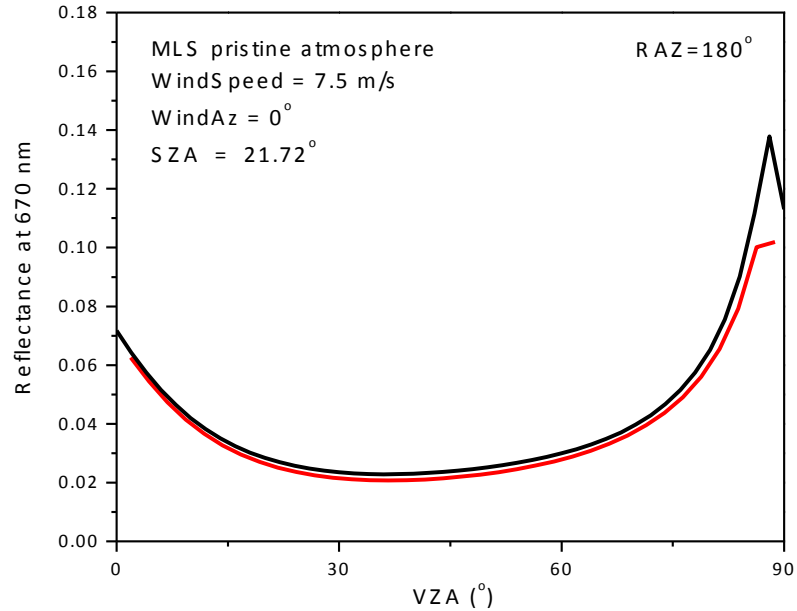
Lambert surface with albedo = 0.05



Modeled total reflectance from DISORT and ADRTM, SZA = 21.72 deg

Ocean surface with specular reflection





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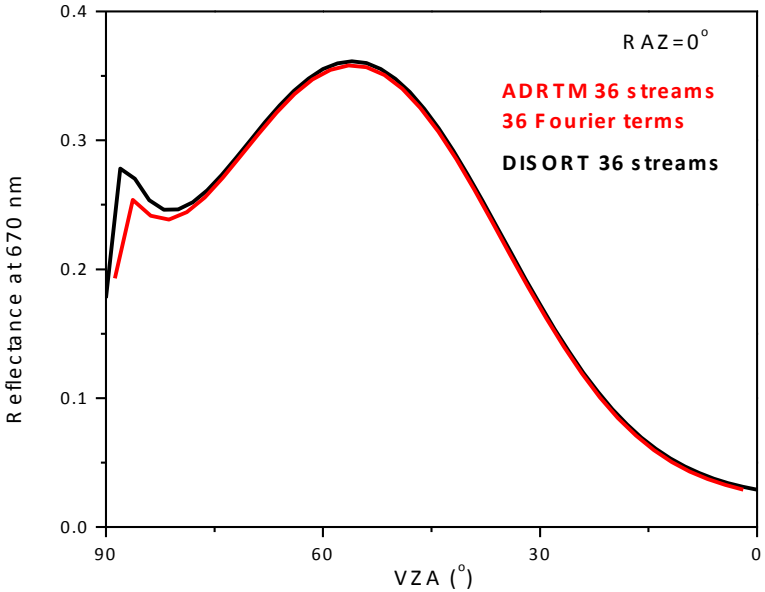
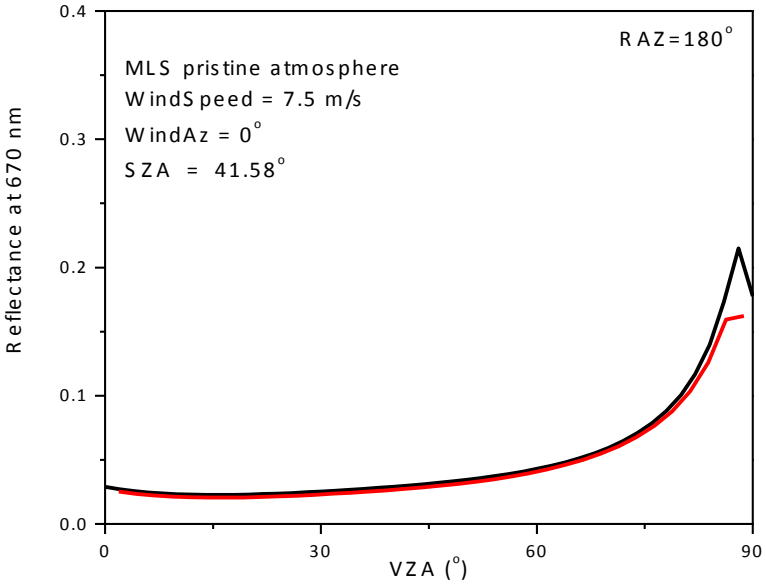
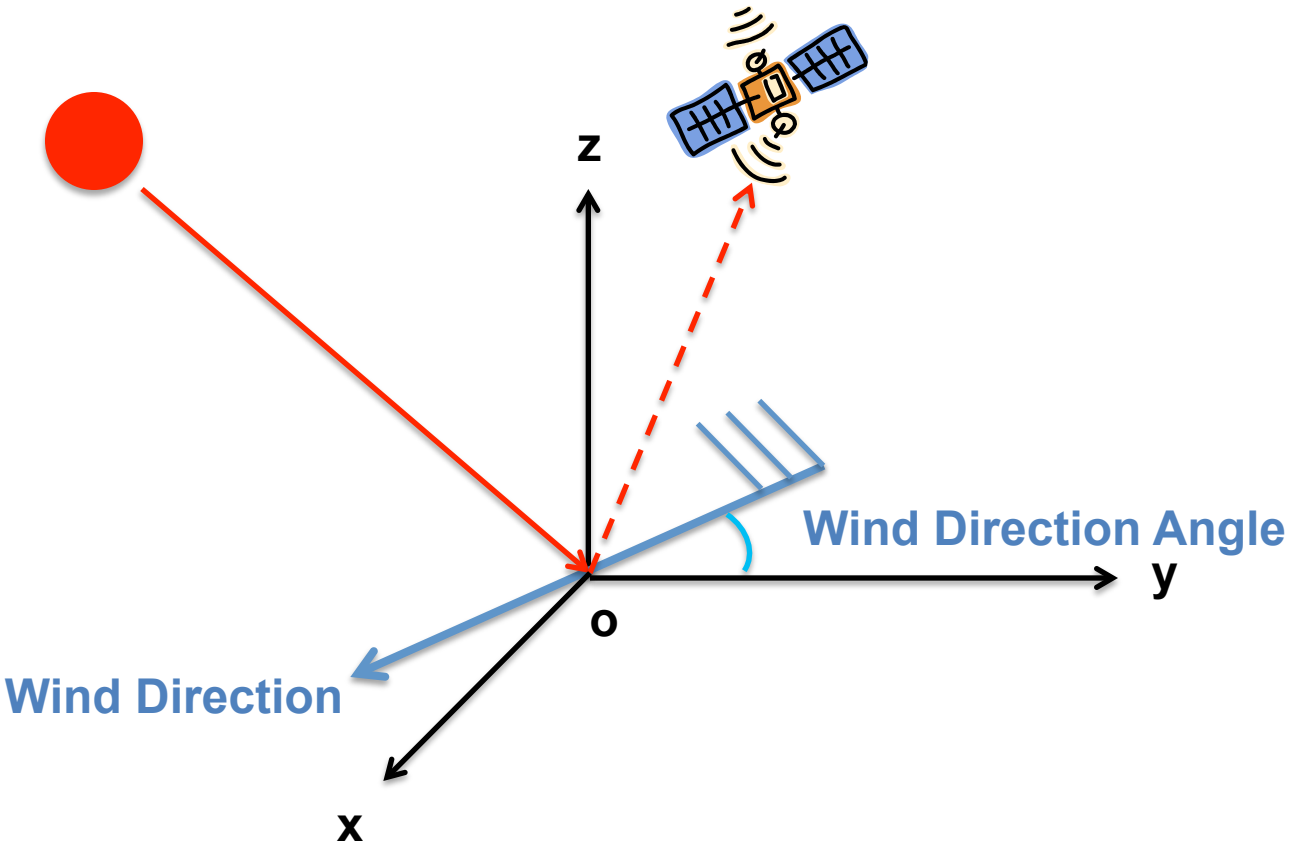


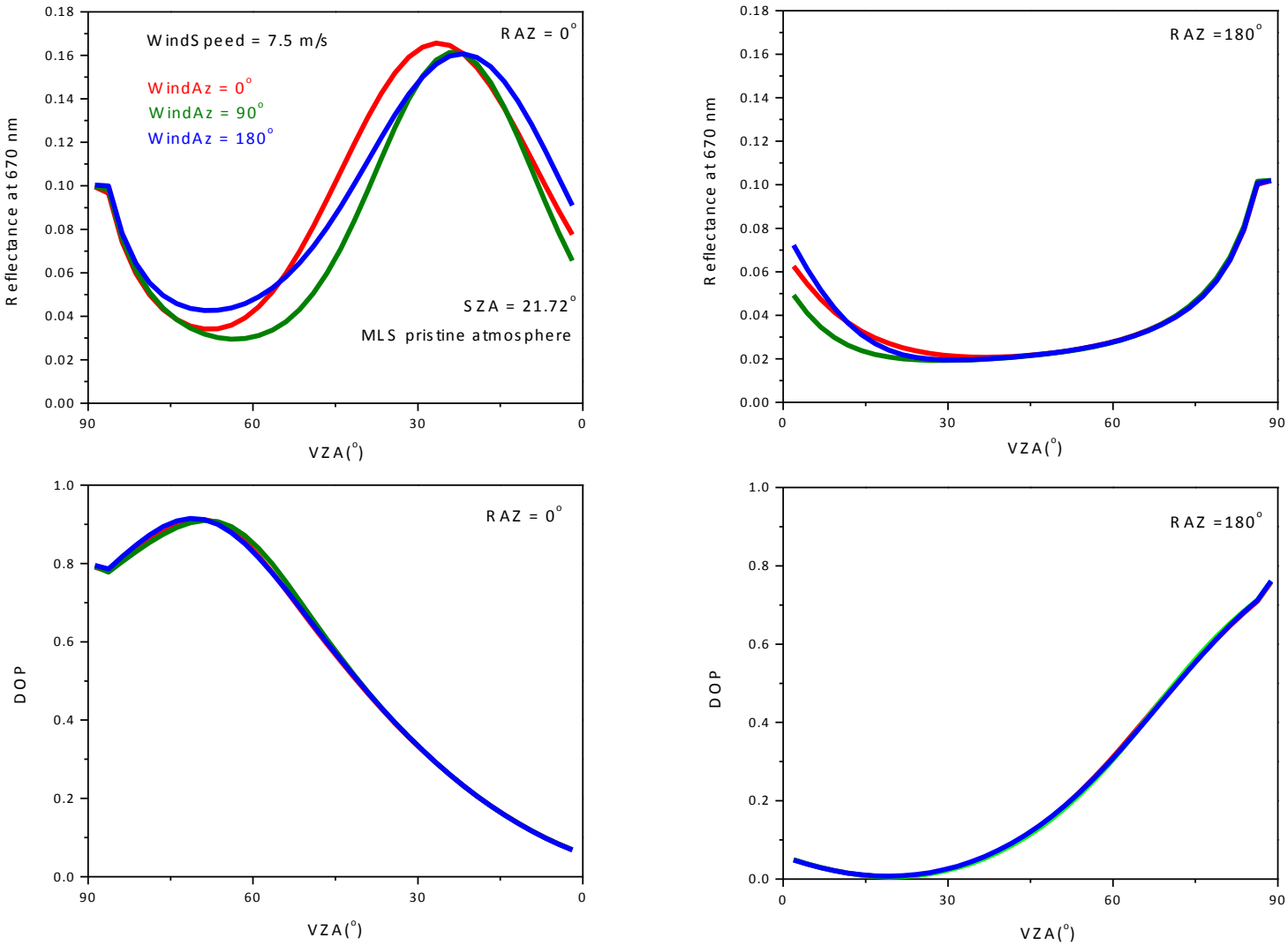


Modeled total reflectance from DISORT and ADRTM, SZA = 41.58 deg

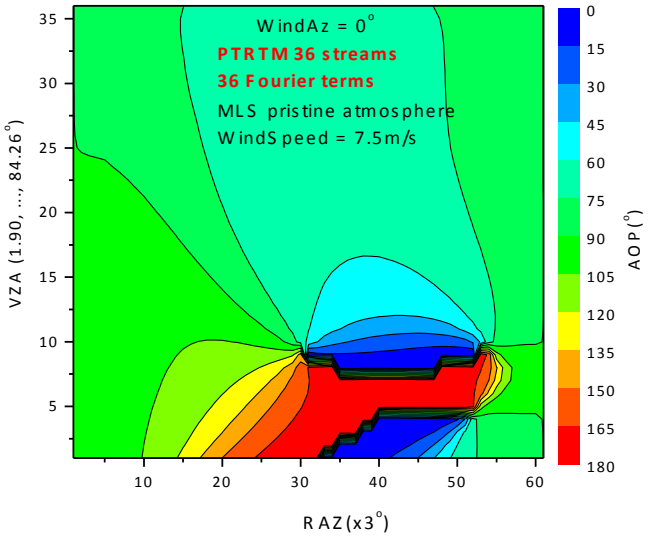
Sensitivity of polarized radiation from ocean to wind direction

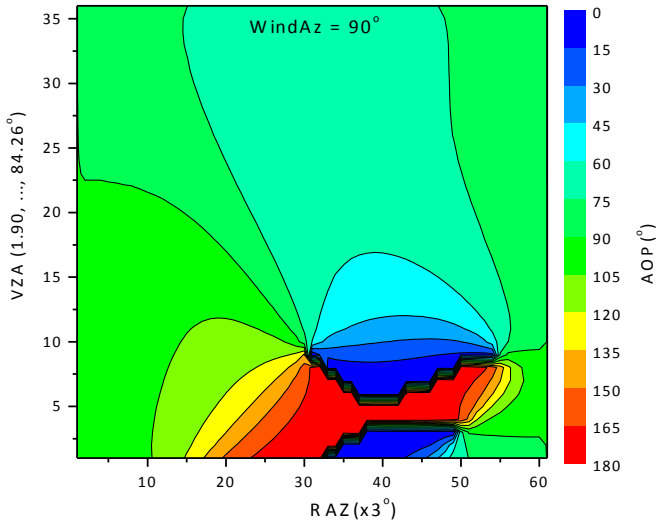


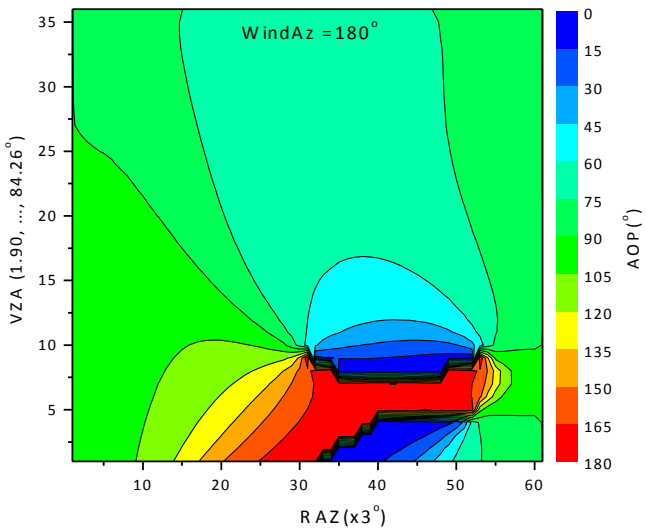
Geometry of light reflection and wind direction at sea surface



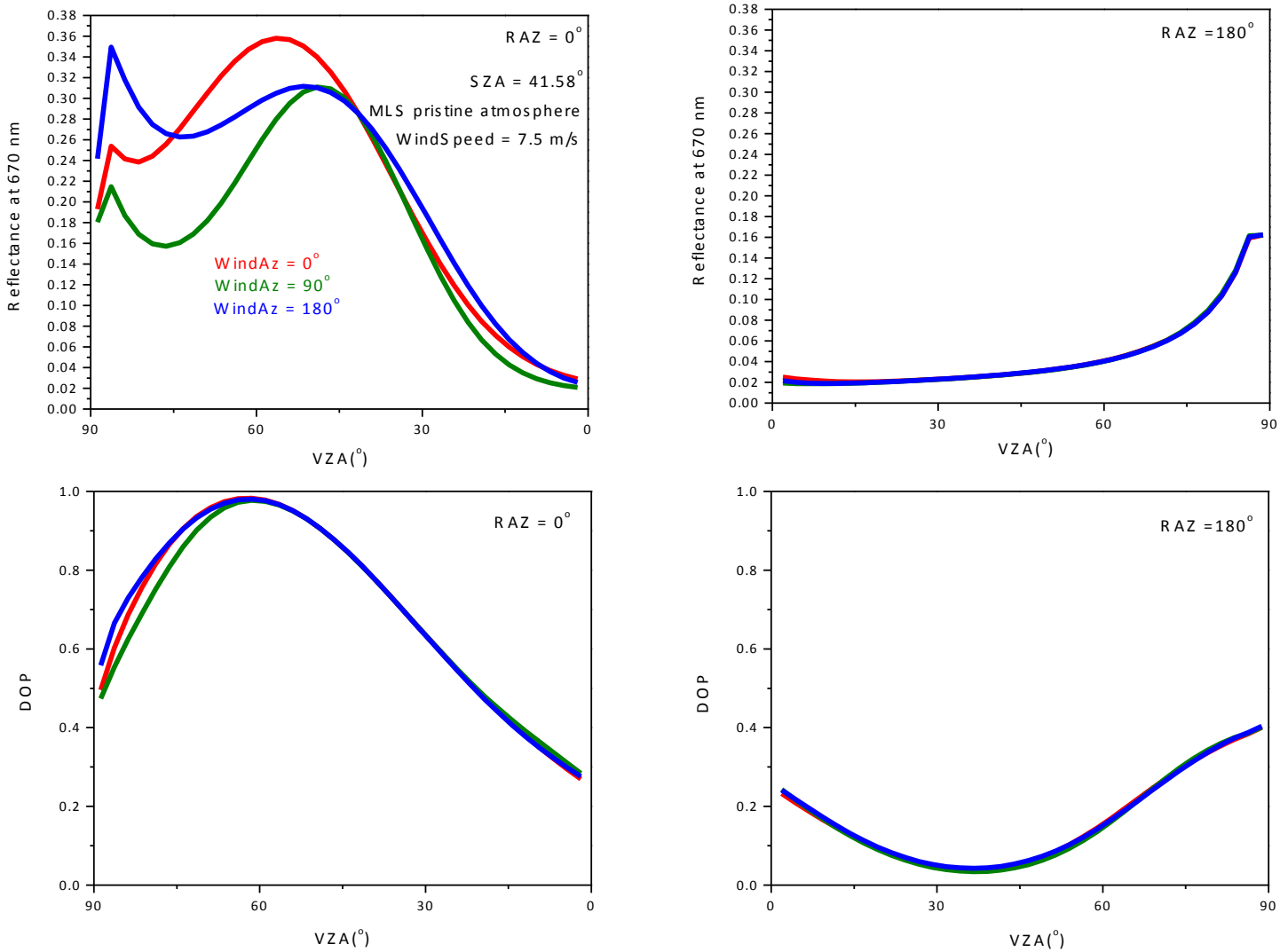
Sensitivity of reflectance and DOP to wind direction (SZA = 21.72 degree)







Sensitivity of AOP to wind direction (SZA = 21.72 degree)



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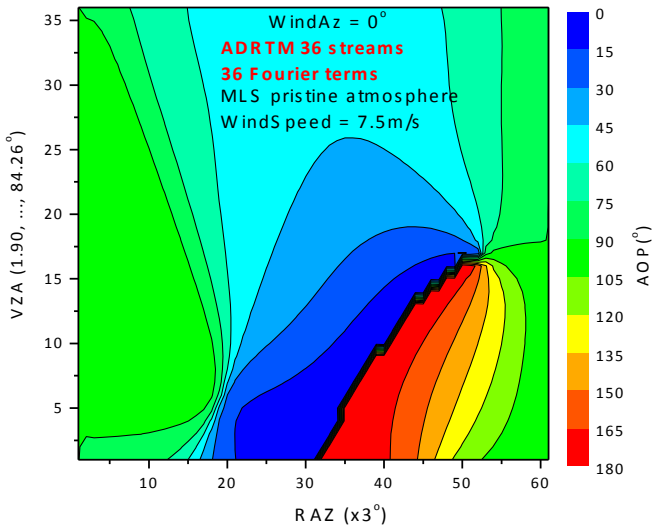
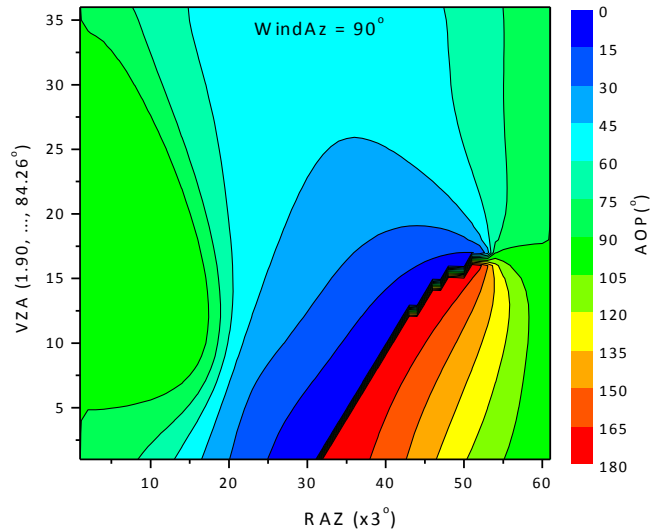
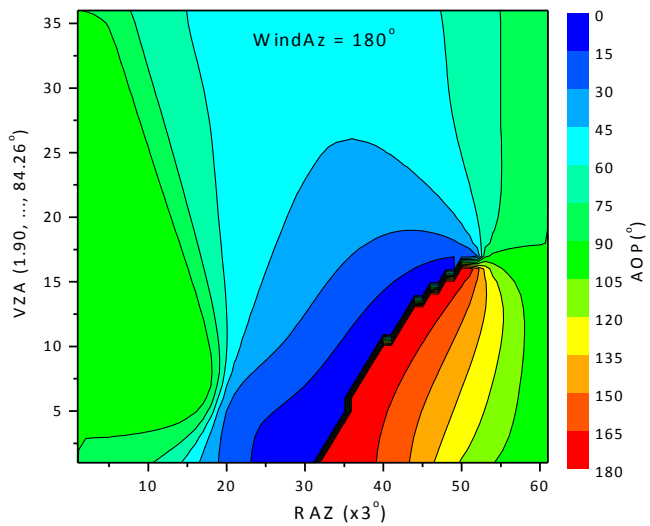
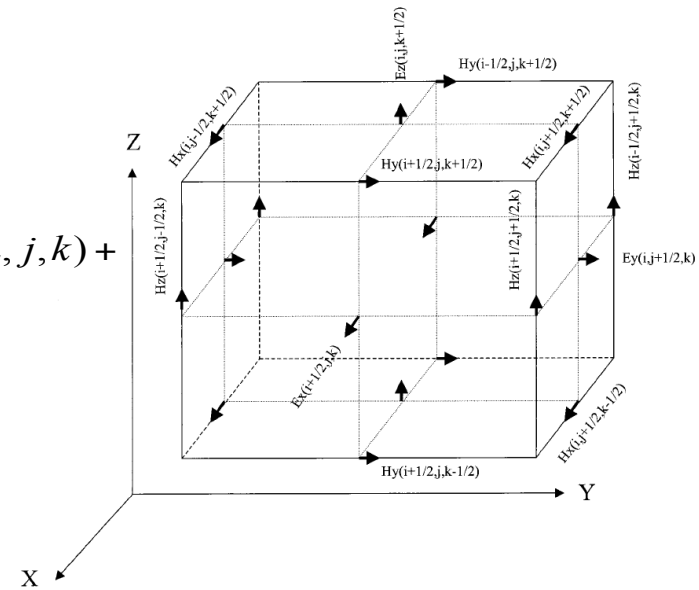






Sensitivity of AOP to wind direction (SZA = 41.58 degree)

Pseudo-spectral time domain (PSTD) light scattering model for coarse mode aerosols



FDTD Technique

$$E_x^{n+1}(i+1/2,j,k) = \exp[-\frac{\varepsilon_i(i+1/2,j,k)}{\varepsilon_r(i+1/2,j,k)}\omega\Delta t]E_x^n(i+1/2,j,k) +$$

$$\exp[-\frac{\varepsilon_i(i+1/2,j,k)}{\varepsilon_r(i+1/2,j,k)}\omega\Delta t/2]\frac{\Delta t}{\varepsilon_0\varepsilon_r(i+1/2,j,k)\Delta s}$$

$$\times[H_y^{n+1/2}(i+1/2,j,k-1/2) - H_y^{n+1/2}(i+1/2,j,k+1/2)$$

$$+ H_z^{n+1/2}(i+1/2,j+1/2,k) - H_z^{n+1/2}(i+1/2,j-1/2,k)],$$

PSTD Technique

$$\nabla\times\mathbf{H} = \varepsilon_0\varepsilon\frac{\partial\mathbf{E}}{\partial t}$$

$$\nabla\times\mathbf{E} = -\mu_0\frac{\partial\mathbf{H}}{\partial t}$$

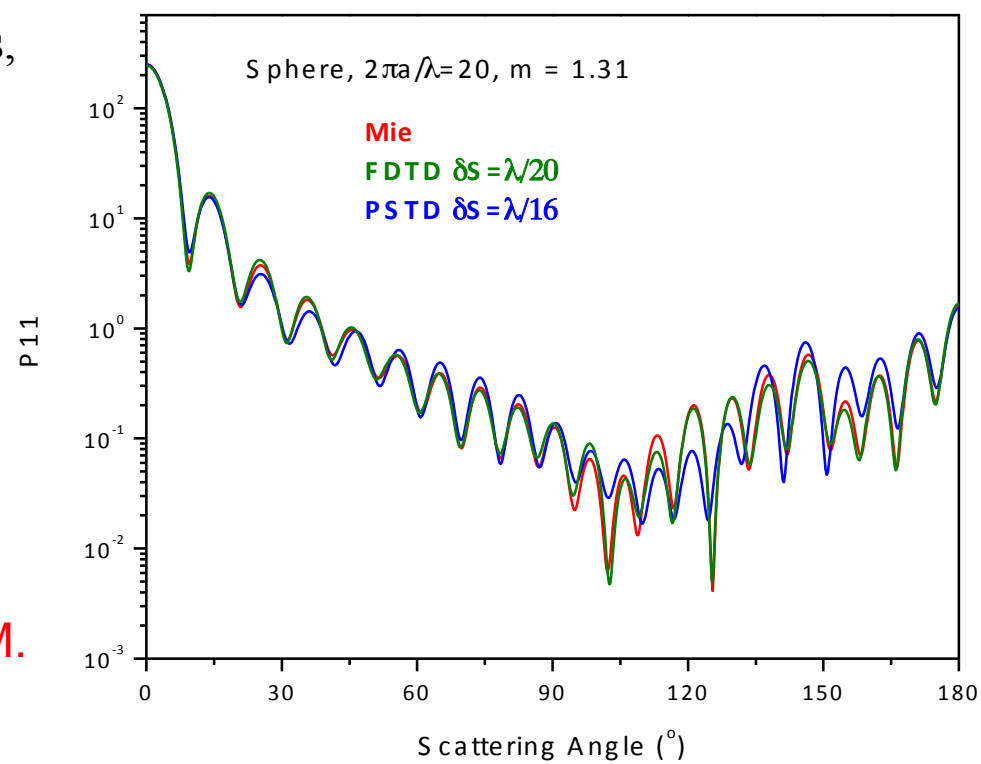
$$\frac{\Delta F(x)}{\Delta x} \approx \frac{\partial F(x)}{\partial x} = \frac{\partial[\int_{-\infty}^{\infty}F(k)e^{-ikx}dk]}{\partial x} = -\int_{-\infty}^{\infty}ikF(k)e^{-ikx}dk$$

All field components are calculated at the center of the spatial cubic cell. Replacing spatial differential of field components in the FDTD updating Eqs with *FFT* and FFT^{-1}

FDTD has numerical dispersion errors and requires $\Delta S \approx \lambda_d / 16$

PSTD has Gibbs effect errors but requires $\Delta S \approx \lambda_d / 8$

In 3D cases PSTD only needs 1/8 of the memory which the FDTD uses, but requires significantly more CPU time for each spatial difference calculation, and involves larger numerical errors due to Gibbs effect.



A 3D scattered-field PSTD light scattering model with CPML ABC is developed for coarse mode aerosol parameters in the ADRTM.

On modeling polarized RS from land surface

"Cox and Munk" for land surface reflection matrix: A long way to go …

$$R(\theta_s,\theta_v,\varphi) = fR_L + (1-f)\frac{\pi\rho_{specular}(n)}{4\cos^4\beta\cos\theta_s\cos\theta_v}P(Z_x,Z_y)$$

$$P(Z_x,Z_y) = \frac{1}{\pi\sigma^2}\exp(-\frac{Z_x^2+Z_y^2}{\sigma^2})$$

$$\tan\beta = \sqrt{Z_x^2+Z_y^2}$$

$$Z_x = \frac{\sin\theta_v\cos\varphi - \sin\theta_s}{\cos\theta_v + \cos\theta_s}$$

$$Z_y = \frac{\sin\theta_v\sin\varphi}{\cos\theta_v + \cos\theta_s}$$

f R_L σ n **vary for different scene types, they will be estimated with data from Parasol and RSP**

Summary

1. RS reflectance from ocean surface is sensitive to solar/viewing angles, cloud/aerosols, wind speed/direction, and gas absorption.

2. DOP and AOP of RS is not sensitive to wind direction and gas absorption. They can be modeled very accurately.

3. ADRTM reflectance is very close to that of DISORT. This demonstrates the numerical excellence of this polarized radiative transfer model.

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