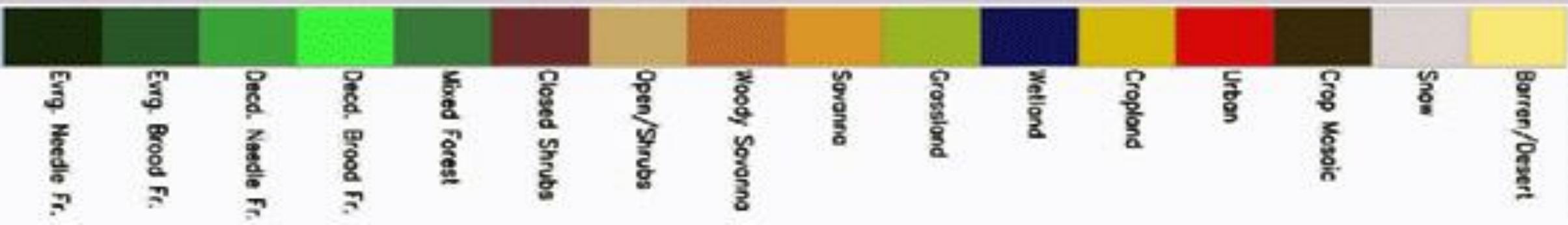
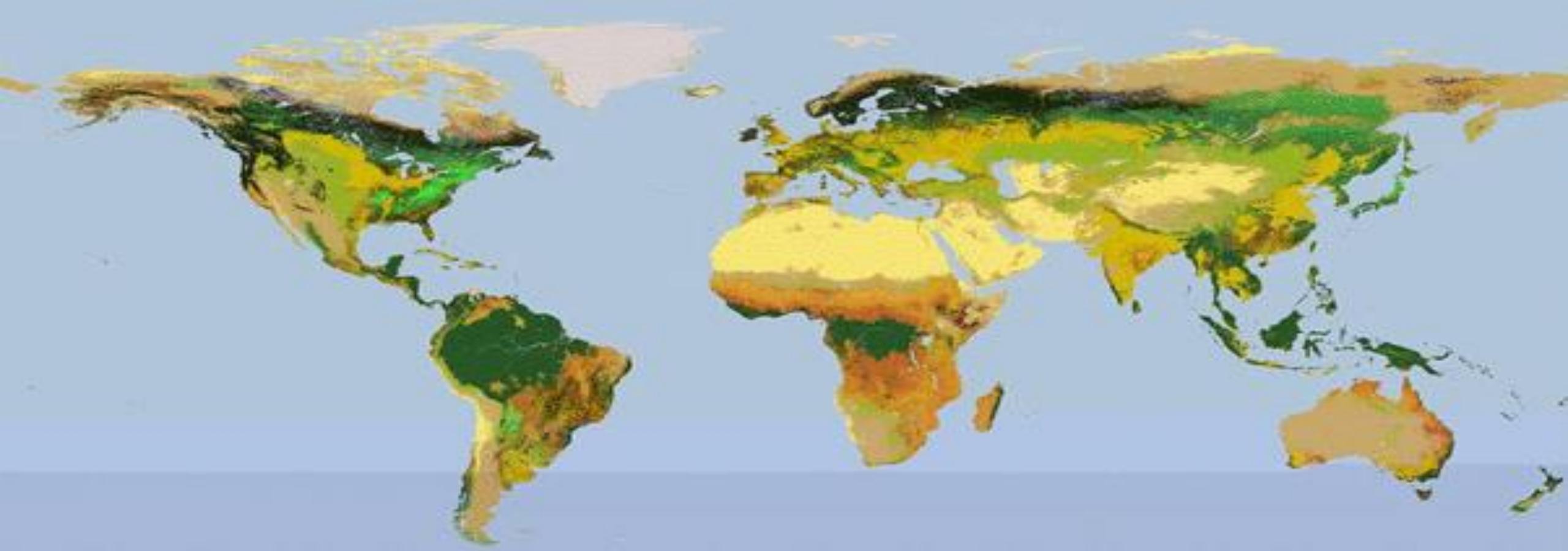


# Modeling Polarization Properties of Reflected Solar Spectra from Evergreen Needle-Leaf Trees

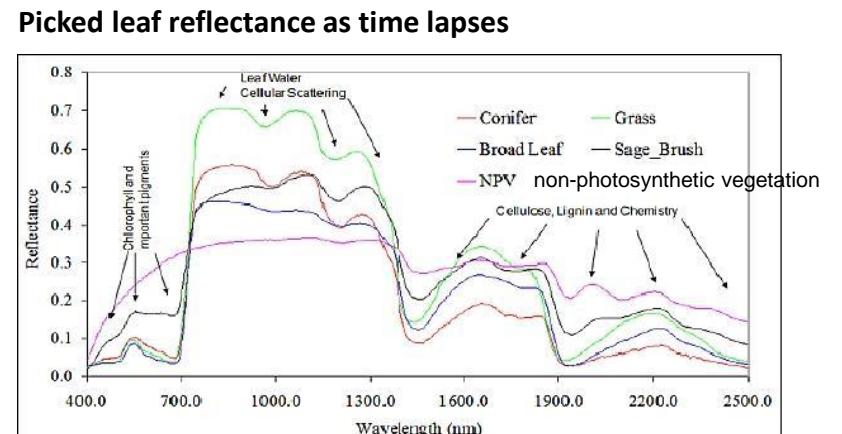
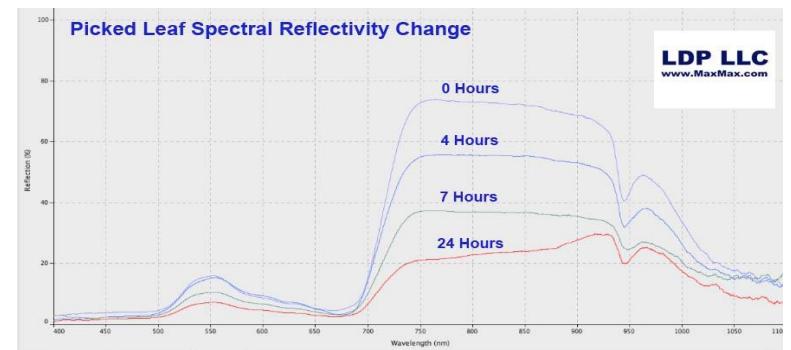
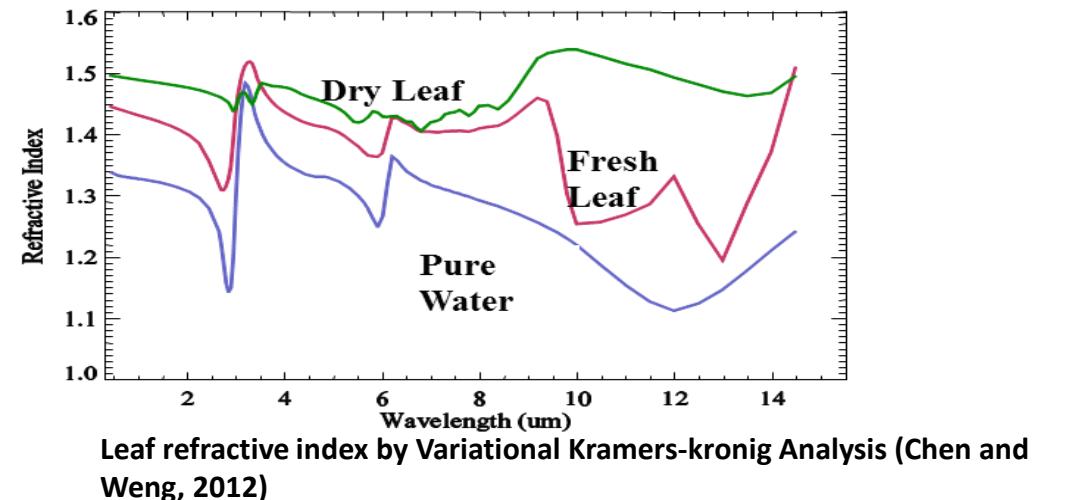
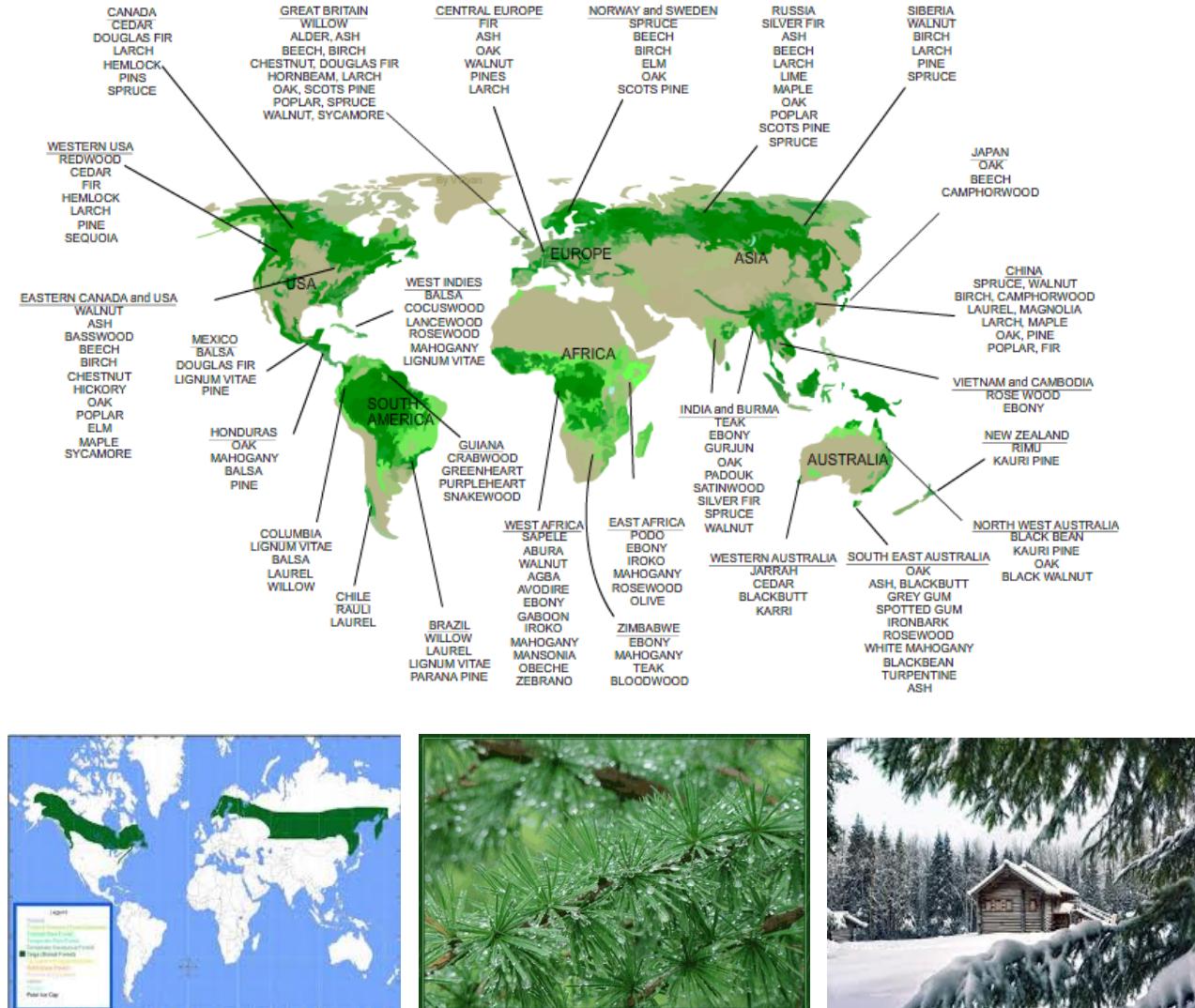
Wenbo Sun, Rosemary R. Baize, and Constantine Lukashin

## Introduction

- As a function of leaf types, forest-reflected solar radiation's degree of polarization (DOP) can be as large as ~70%.
- Empirical PDMs from PARASOL data can be obtained only at 3 wavelengths, which cannot be applied to whole solar spectrum.
- To correct polarization-induced error in satellite data, polarization state of solar spectra from various leaf types must be obtained.
- Polarization properties of solar spectra from evergreen needle-leaf trees are modeled with ADRTM and PARASOL data.



# Why modeling polarization of light reflected by tree leaves is challenging?



Rock minerals and vegetation reflectance spectral from 400 to 2500 nm in the solar reflected light spectrum (NASA/JPL AVIRIS)

## Theory for modeling polarized RS from tree leaves

$$\mathbf{R}(\theta_s, \theta_v, \phi) = c_1[R_{leaf} - c_2\left(\frac{1}{\pi} \int_0^{2\pi} \int_0^{\pi/2} R_{specular} \sin \theta d\theta d\phi\right) + c_2 \mathbf{R}_{specular}] + c_3 R_{soil}$$

$$R_{specular} = 0.5\left[\frac{\pi\rho_{specular}(n)}{4\cos^4\beta \cos\theta_s \cos\theta_v} P_1(Z_x, Z_y) + \frac{\pi\rho_{specular}(n)}{4\cos^4(\beta - \pi/2) \cos\theta_s \cos\theta_v} P_2(Z_x, Z_y)\right]$$

$$P_1(Z_x, Z_y) = \frac{1}{\pi\sigma^2} \exp\left(-\frac{Z_x^2 + Z_y^2}{\sigma^2}\right) = \frac{1}{\pi\sigma^2} \exp\left(-\frac{\tan^2 \beta}{\sigma^2}\right)$$

$$P_2(Z_x, Z_y) = \frac{1}{\pi\sigma^2} \exp\left(-\frac{Z_x^2 + Z_y^2}{\sigma^2}\right) = \frac{1}{\pi\sigma^2} \exp\left[-\frac{\tan^2(\beta - \pi/2)}{\sigma^2}\right]$$

$$Z_x = \frac{\sin\theta_v \cos\varphi - \sin\theta_s}{\cos\theta_v + \cos\theta_s} \quad Z_y = \frac{\sin\theta_v \sin\varphi}{\cos\theta_v + \cos\theta_s} \quad \tan\beta = \sqrt{Z_x^2 + Z_y^2}$$

Once we know  $c_1$   $c_2$   $c_3$   $\sigma$   $n$   $R_{leaf}$   $R_{soil}$ , we can calculate land surface reflection matrix elements.

$n$   $R_{leaf}$   $R_{soil}$  are from PROSAIL model for leaves spectra.  $c_1$   $c_2$   $c_3$   $\sigma$  are from fitting the modeling results to PARASOL data at 490, 670, and 865 nm. When soil is covered by snow,  $R_{soil}$  is replaced by snow reflectance from LandSat-4 thematic mapper (Dozier 1983).

## Leaf and soil spectral reflectance from PROSAIL (Jacquemoud et al. 2009)

with parameters:

Erectophile leaves

Cab	=	5.0	Chlorophyll content ( $\mu\text{g.cm}^{-2}$ )
Car	=	1.0	Carotenoid content ( $\mu\text{g.cm}^{-2}$ )
Cbrown	=	0.0	Brown pigment content (arbitrary units)
Cw	=	0.025	EWT (cm)
Cm	=	0.015	LMA ( $\text{g.cm}^{-2}$ )
N	=	1.0	Structure coefficient
Psoil	=	1	Dry soil (For large SZA, we set 50% snow coverage for annual mean. Snow spectra are from Dozier (1983))
LAI	=	8.0	Leaf area index ( $\text{m}^2/\text{m}^2$ )

$c_1$  = tree fraction

$c_2$  = specular reflection leaf fraction

$c_3$  = soil reflection fraction (see next page)

$$c_1 = 0.3 \quad c_2 = 0.3$$

$$\sigma = 0.256$$

$$\tau^a(\lambda) = \beta \cdot \lambda^{-\alpha}$$

Aerosol turbidity number  $\beta = 0.045$  and Angstrom number  $\alpha = 1.55$  for forest in Western Siberia (Sakerin and Kabanov, 2006)



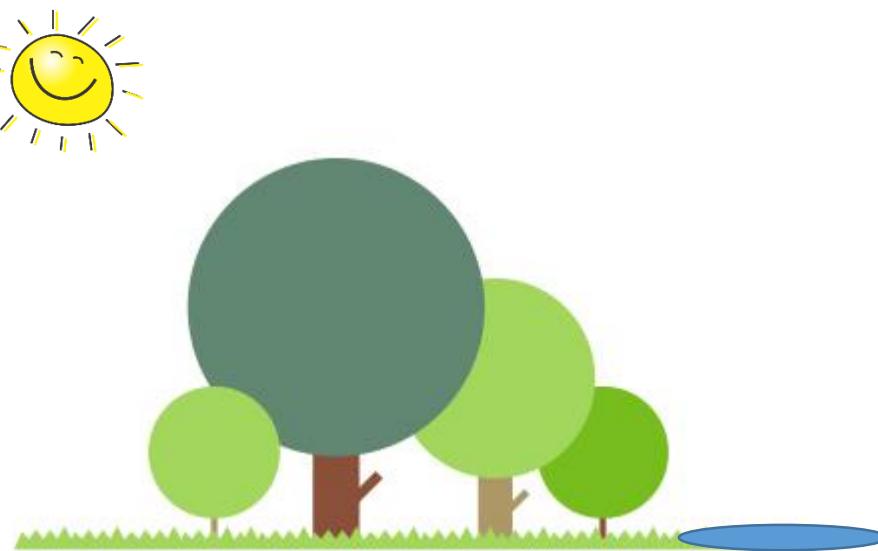
$$c_3 = 1 - c_4$$

$c_4$  is tree shadow fraction. Reflection by shadowed area to indirect solar radiation is neglected.

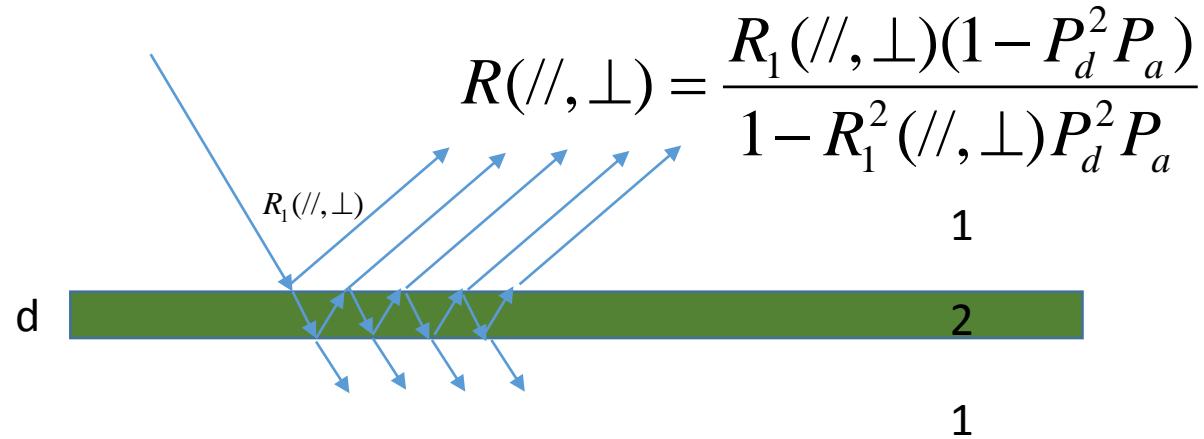
**Shadow of tree is approximated by assuming as spherical tree shape**

$$\text{ShadowArea} / \text{TreeArea} \sim \tan \theta_s$$

$$c_4 = c_1 \tan \theta_s$$



**Specular reflection matrix of leaves is calculated from a lossless dielectric slab**

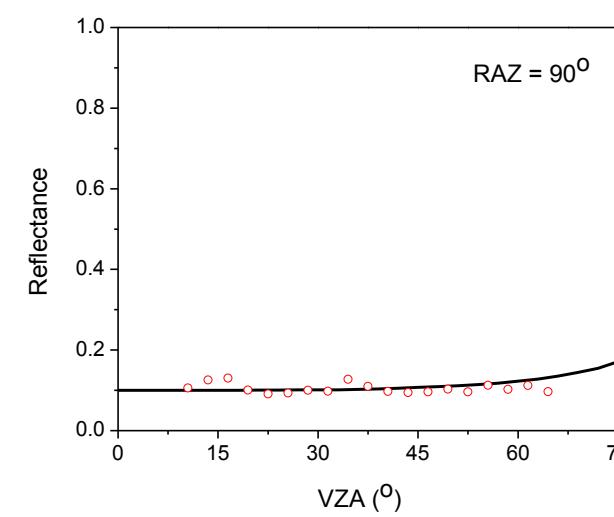
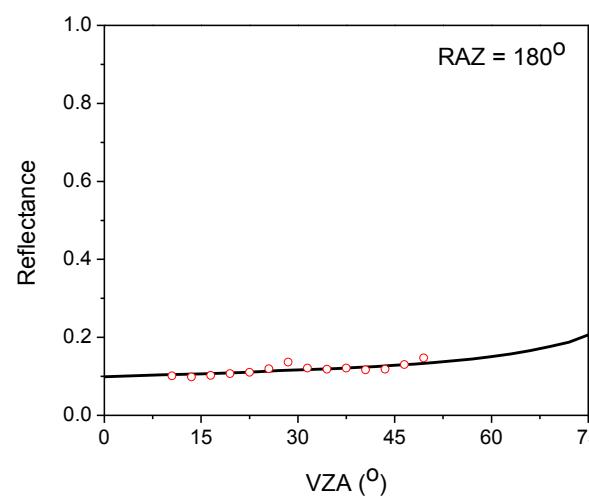
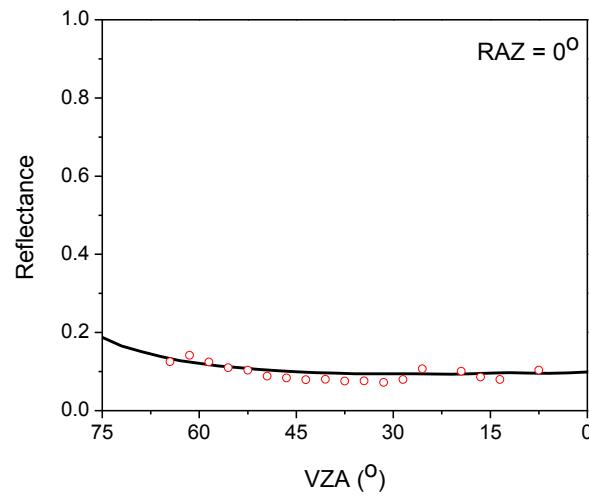
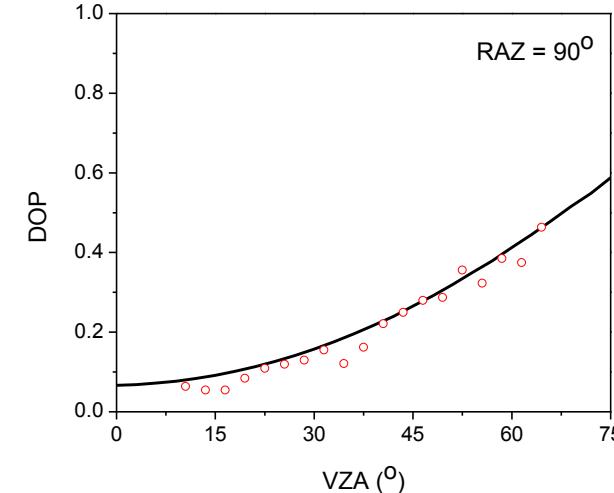
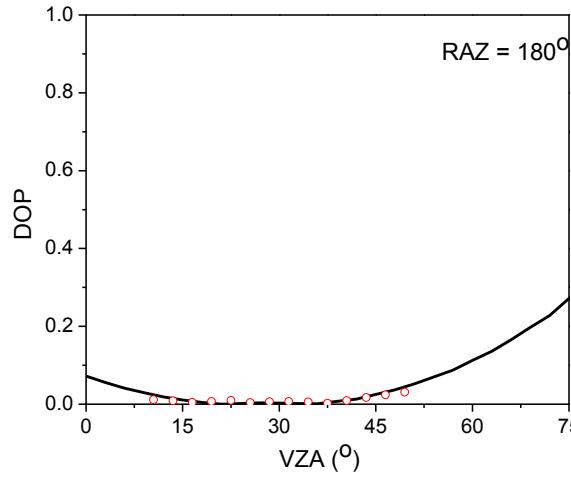
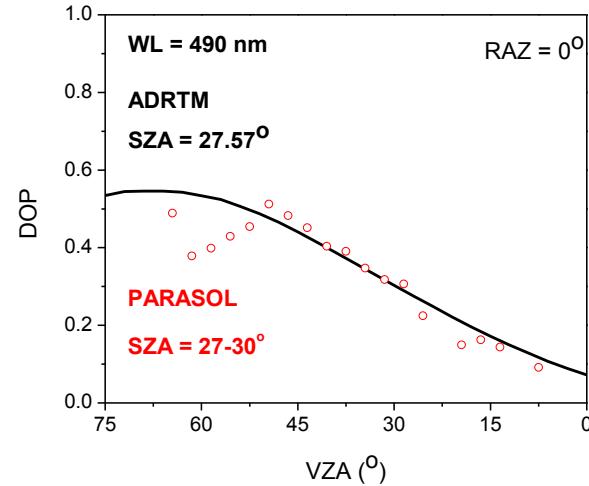


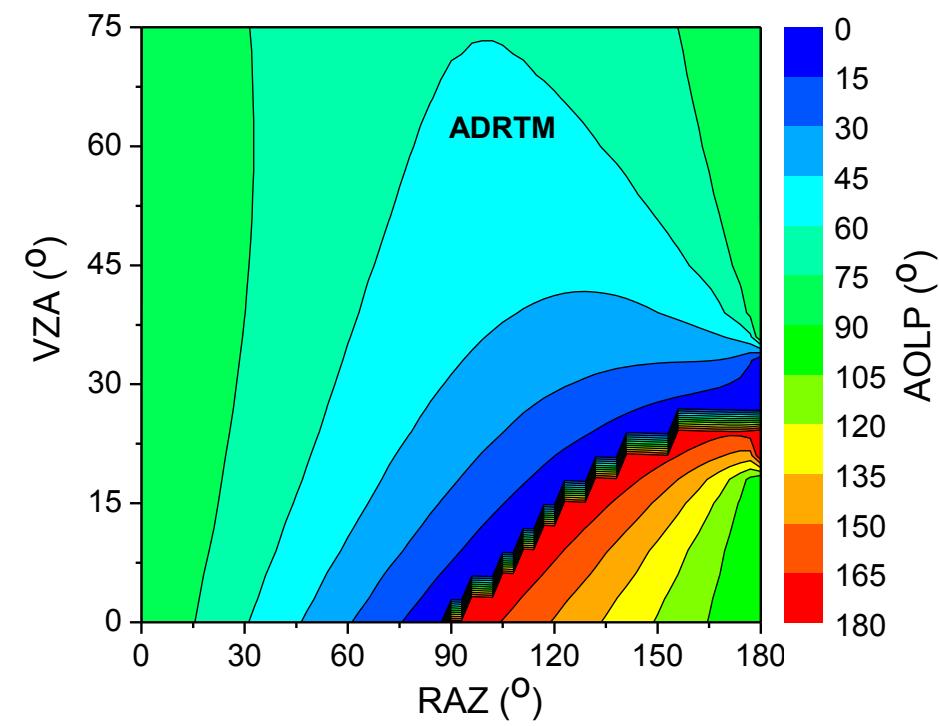
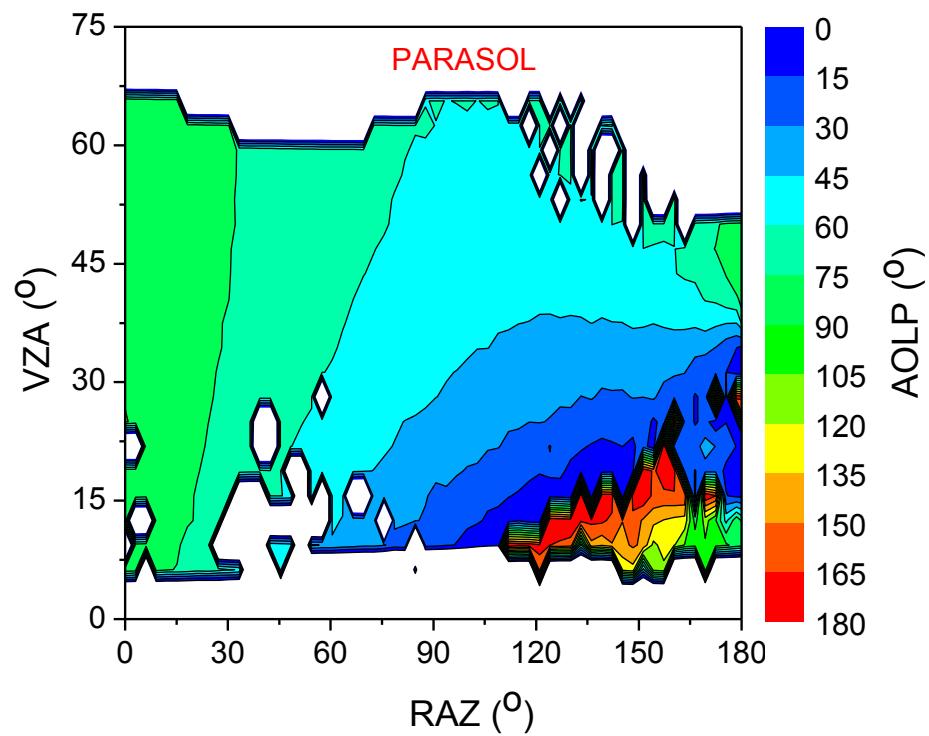
$$P_a = \exp(i2k_1 d \tan \theta_t \sin \theta_i)$$

$$P_d = \exp(ik_2 d / \cos \theta_t)$$

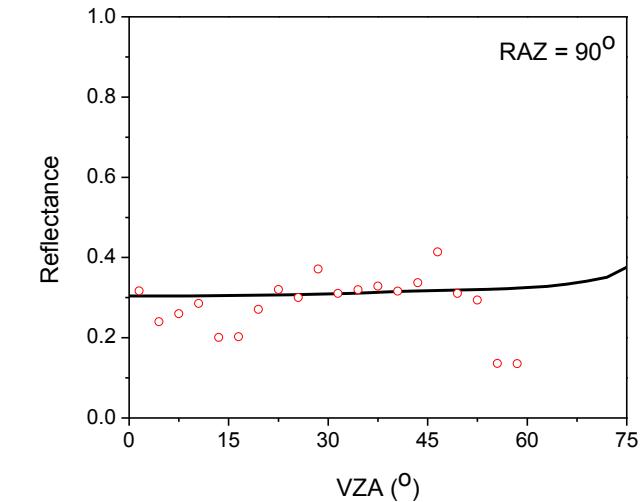
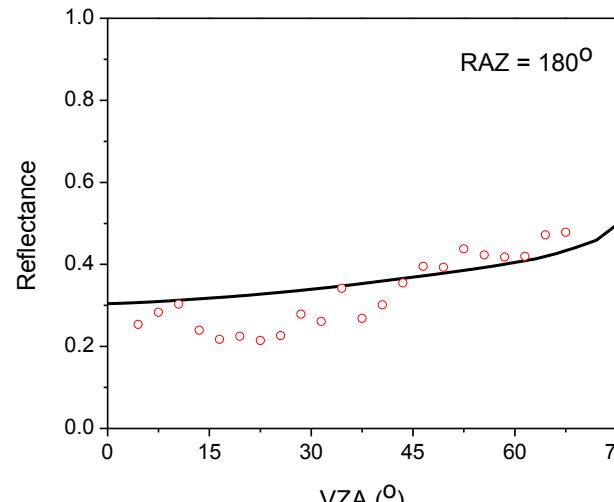
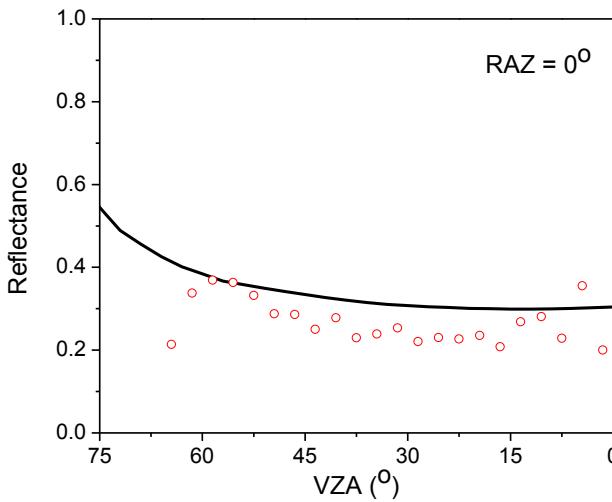
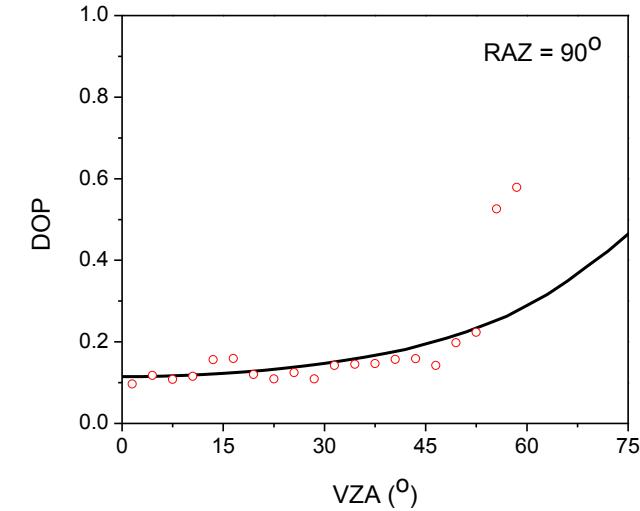
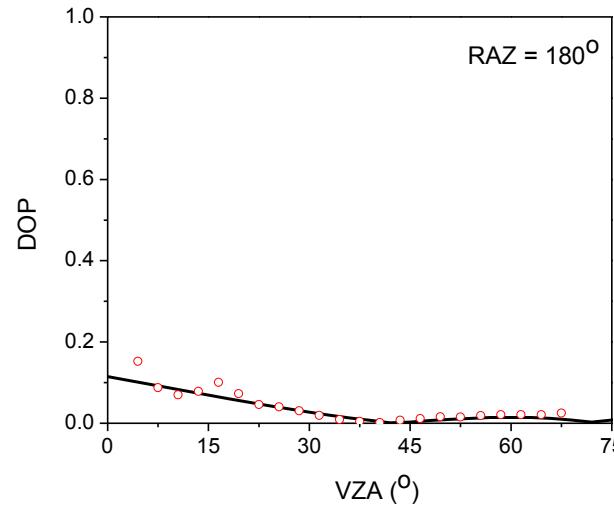
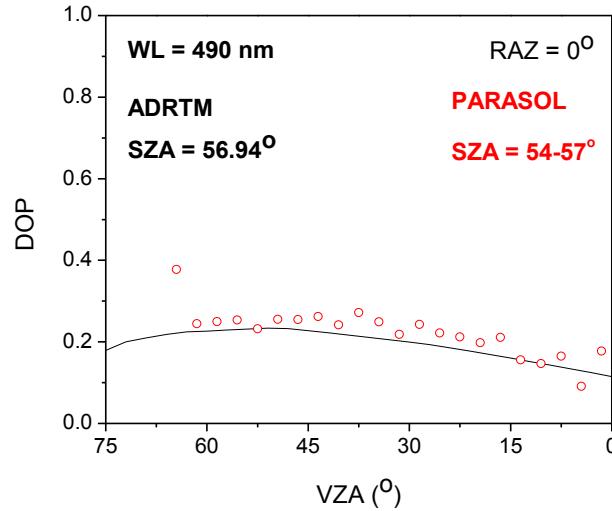
With  $R(\parallel, \perp)$  we can calculate the reflection matrix of the leaf slabs  $R_s$ .

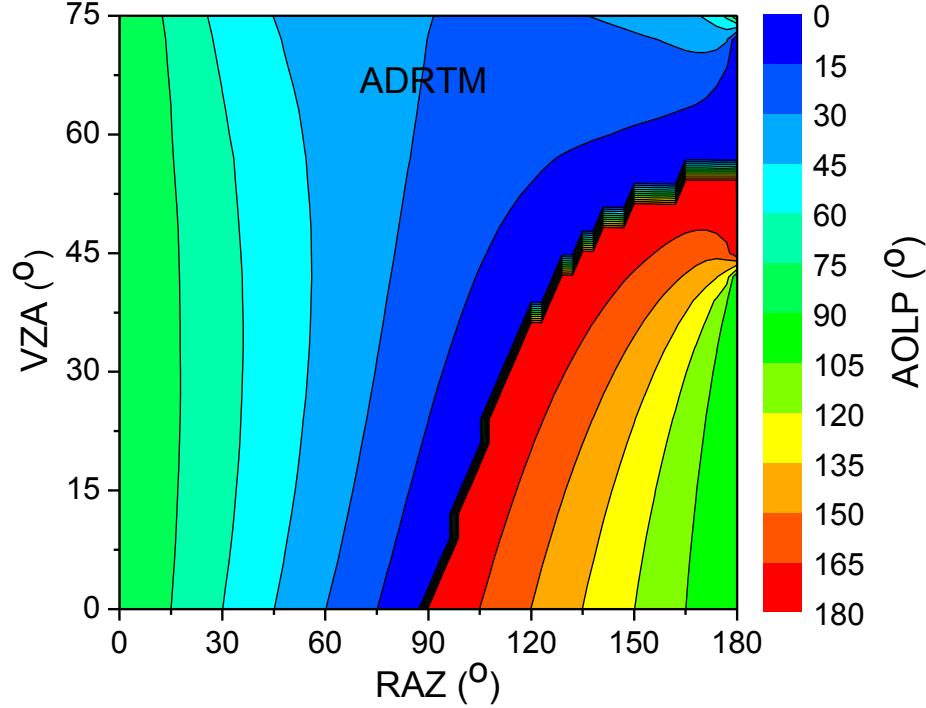
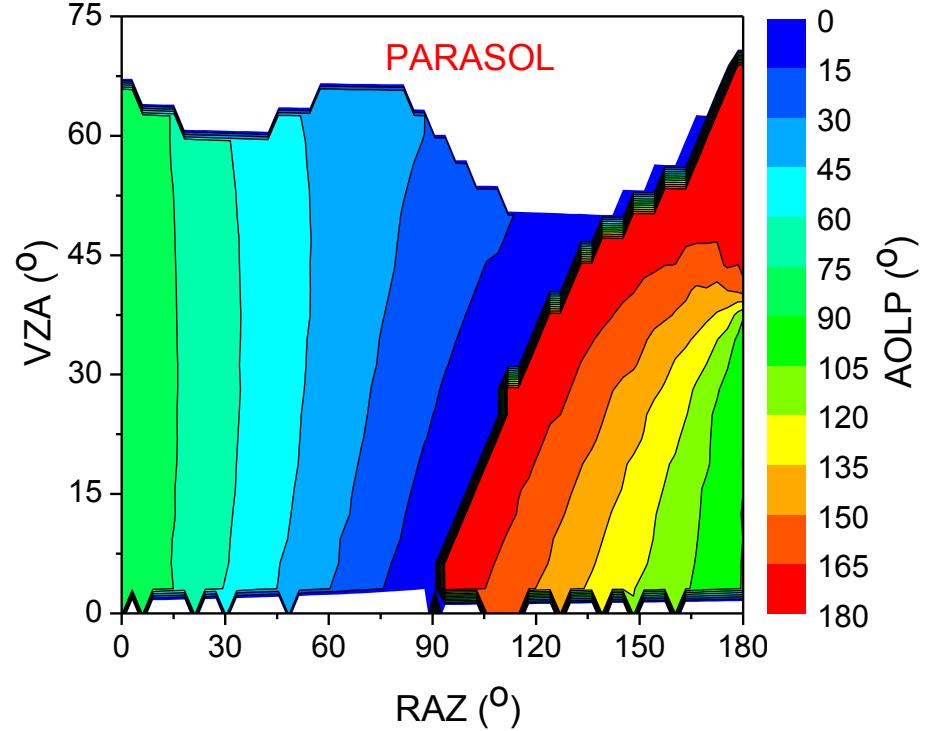
# Comparing model results with satellite data at a wavelength of 490 nm and a SZA of 27.57 deg



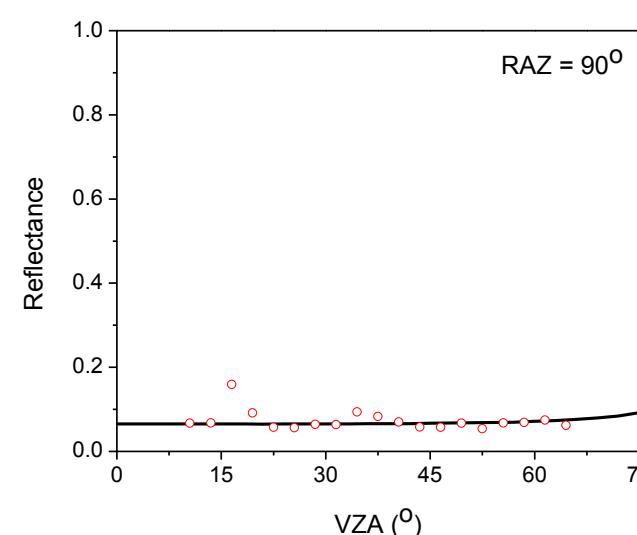
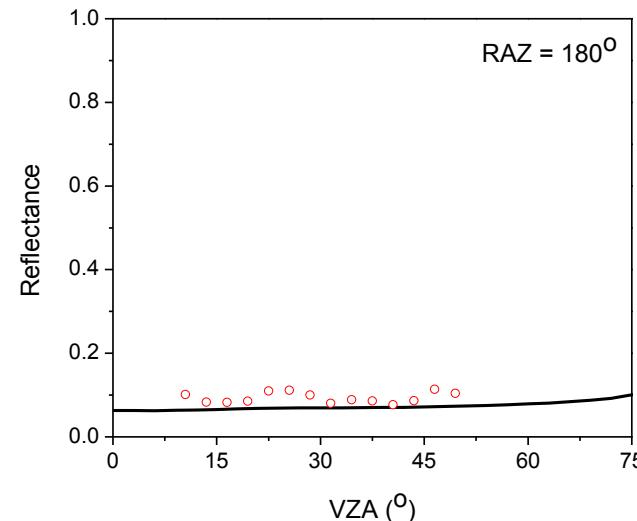
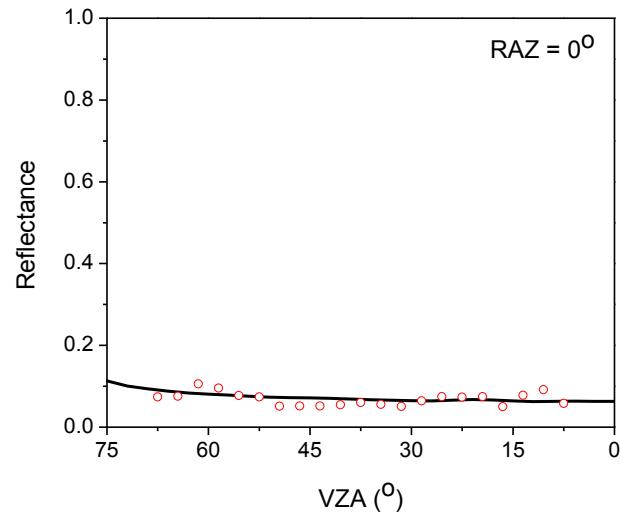
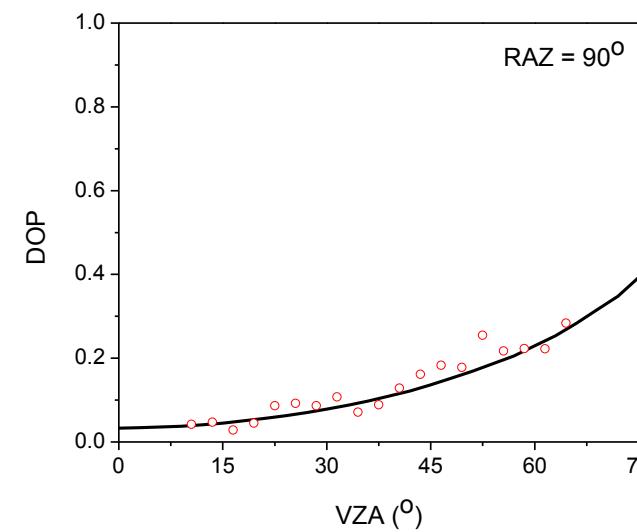
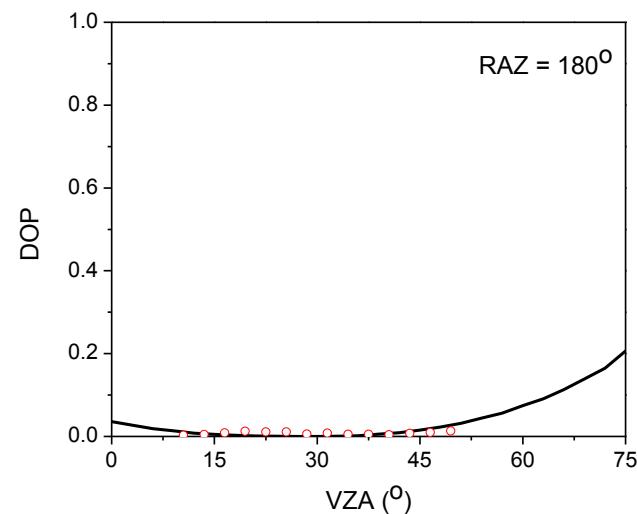
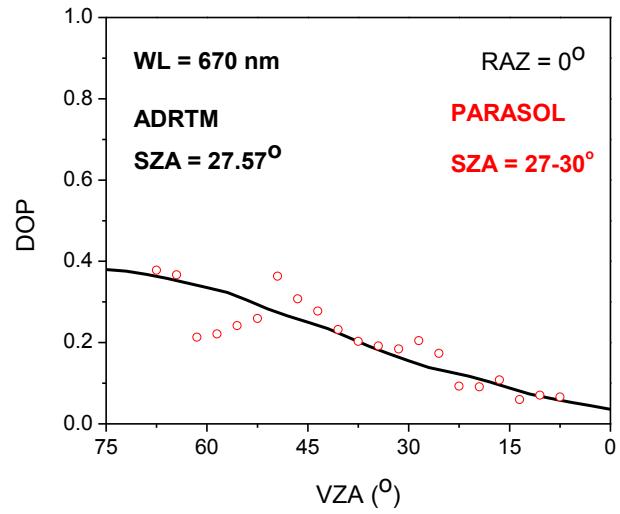


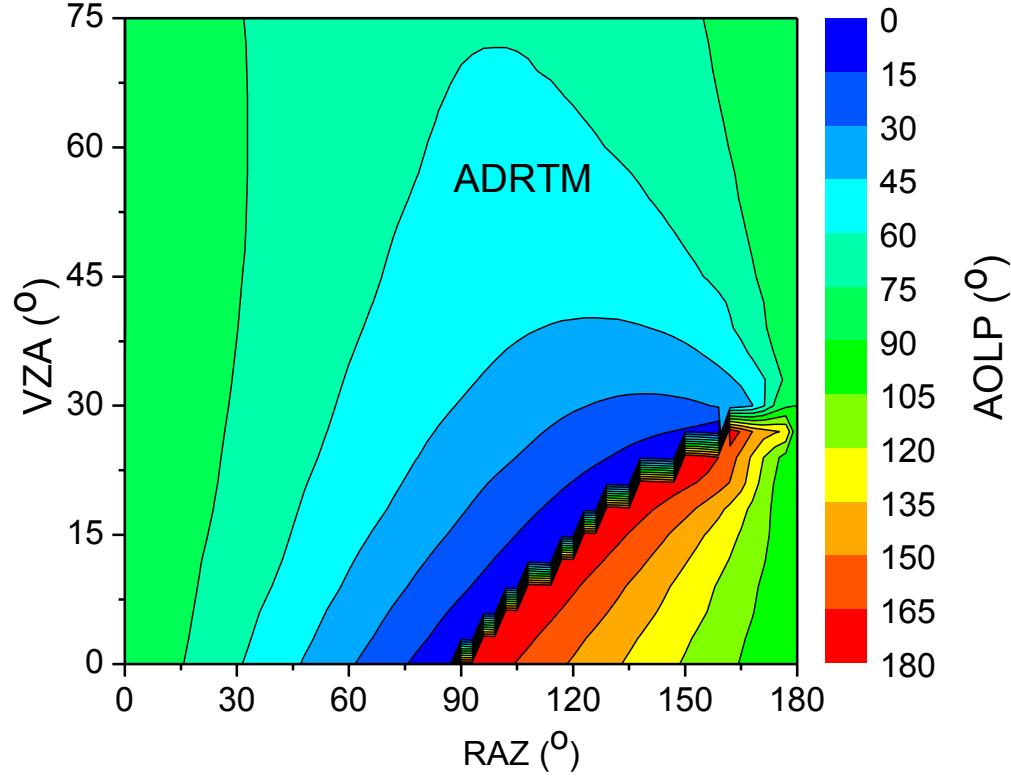
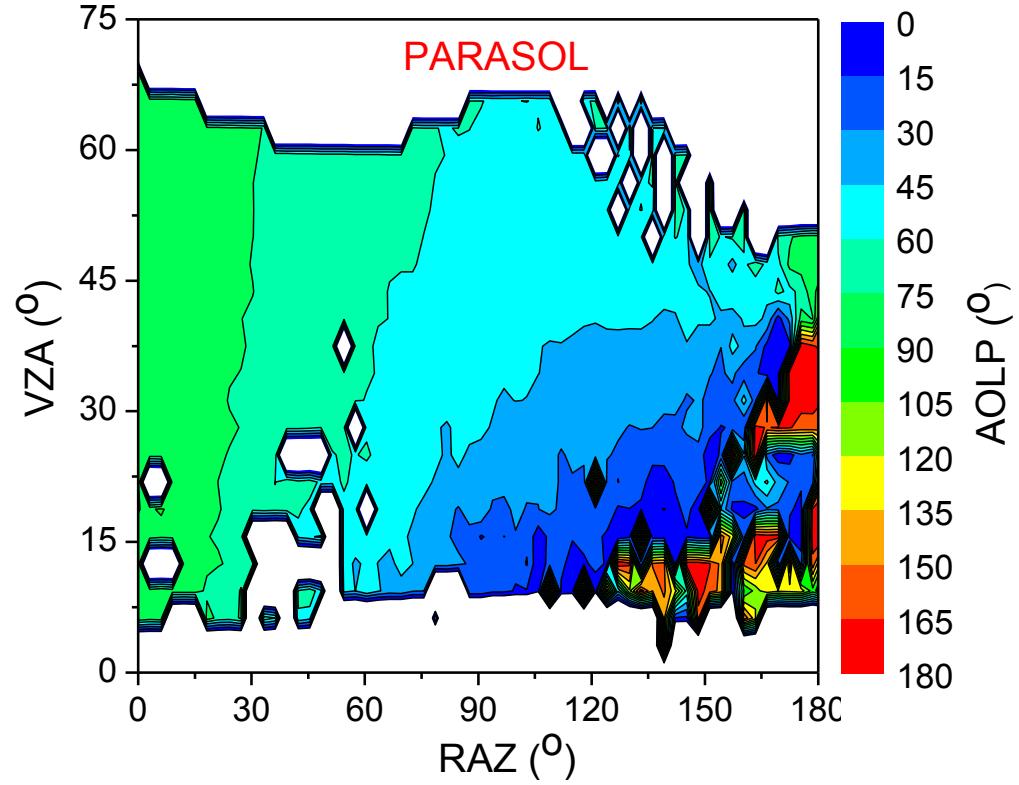
# Comparing model results with satellite data at a wavelength of 490 nm and a SZA of 56.94 deg



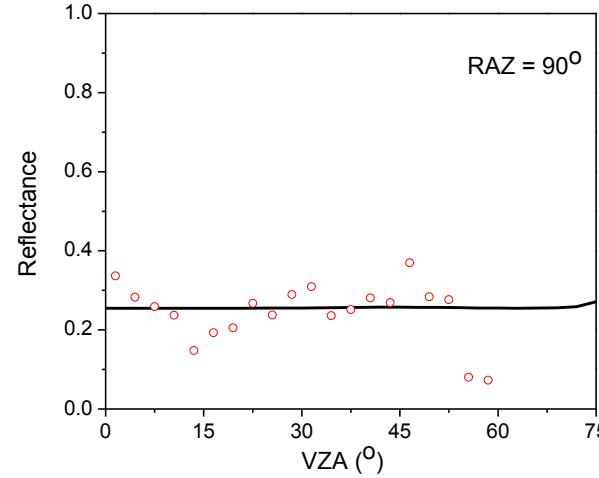
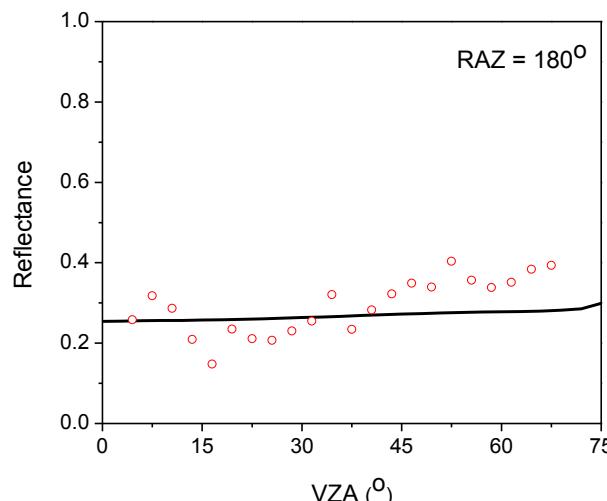
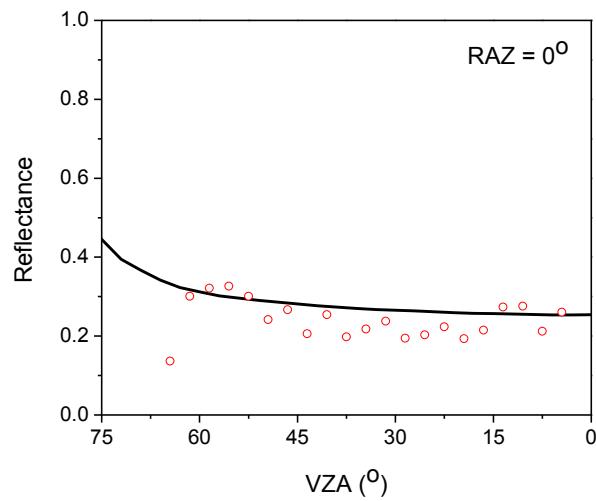
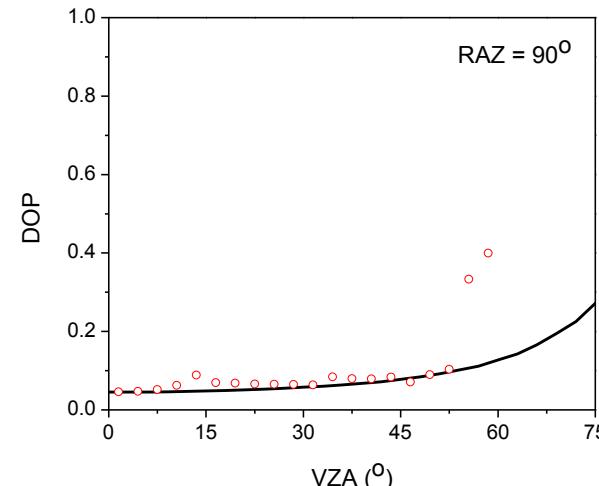
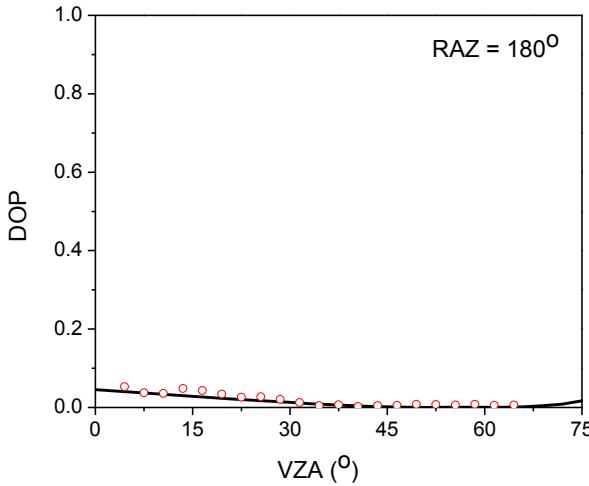
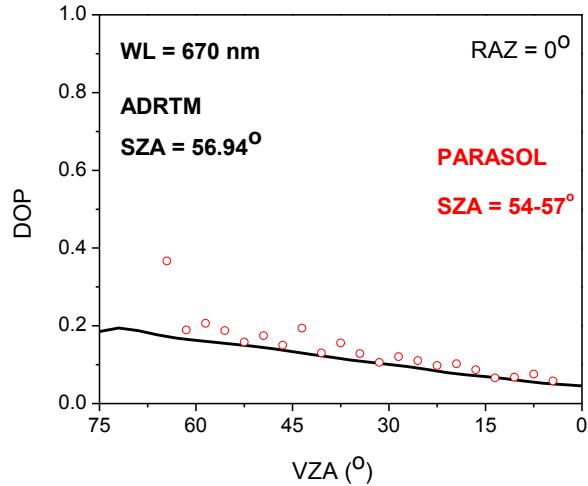


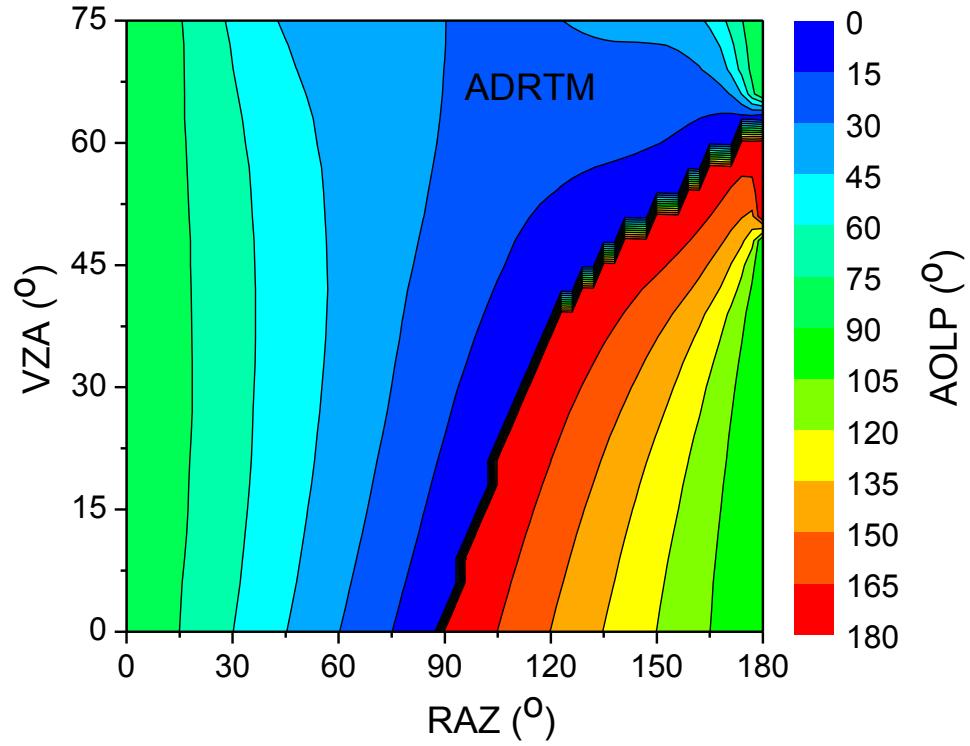
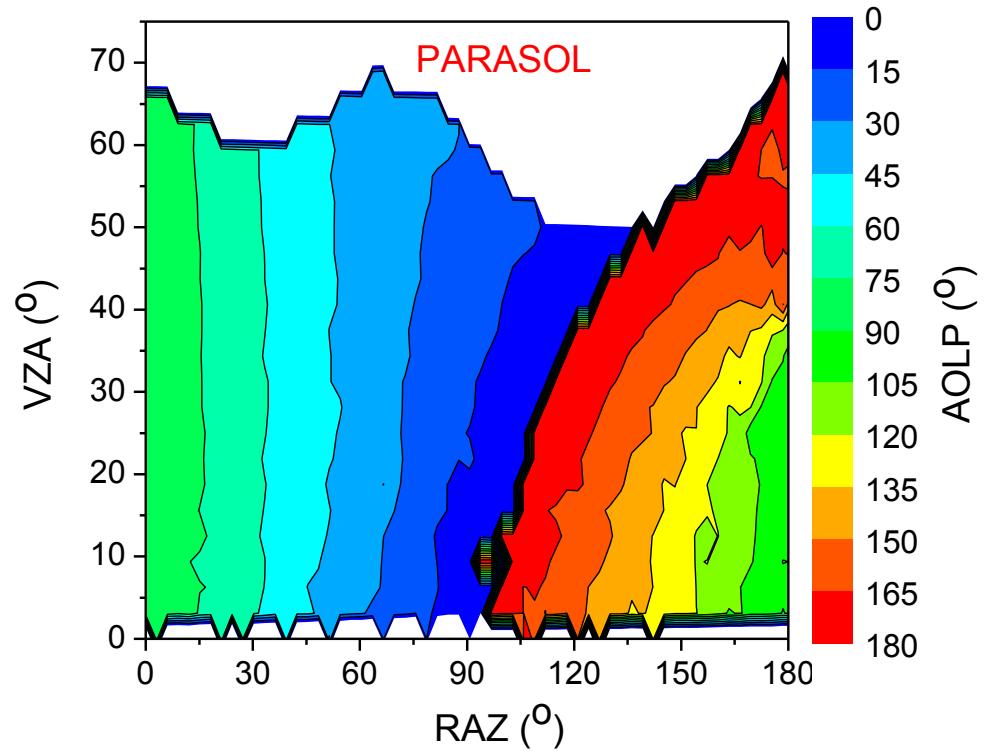
# Comparing model results with satellite data at a wavelength of 670 nm and a SZA of 27.57 deg



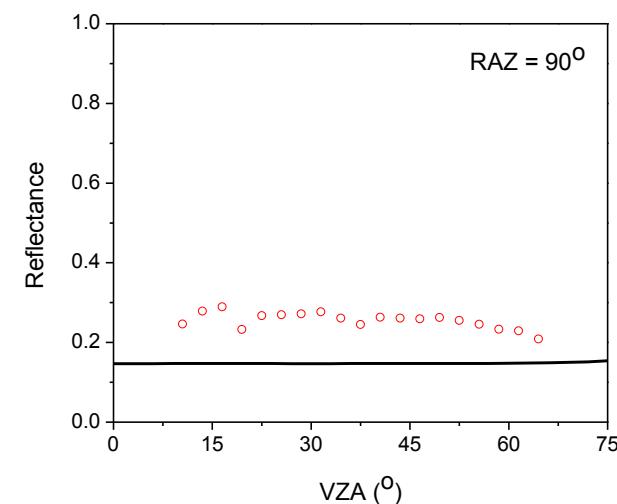
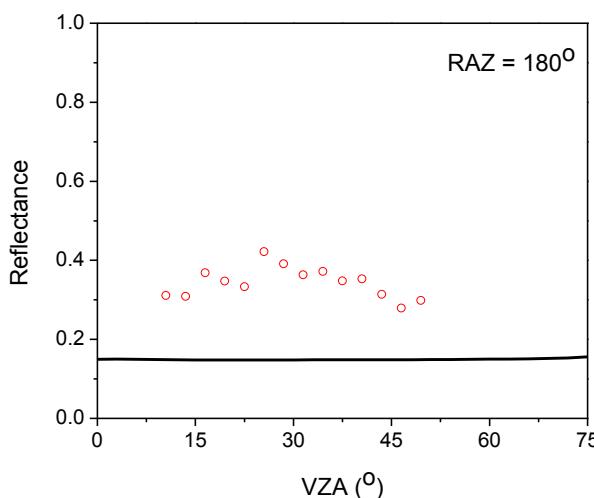
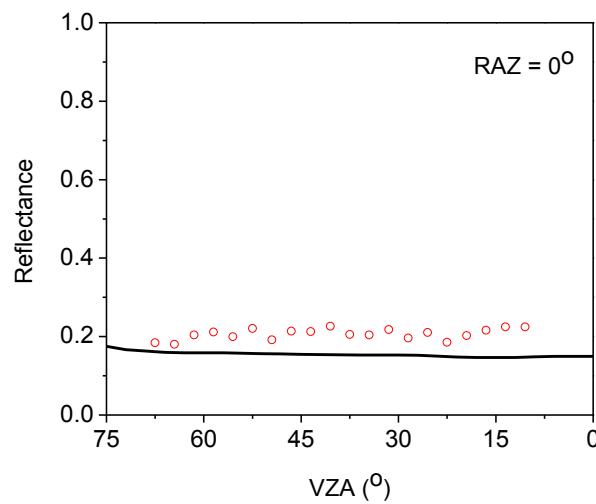
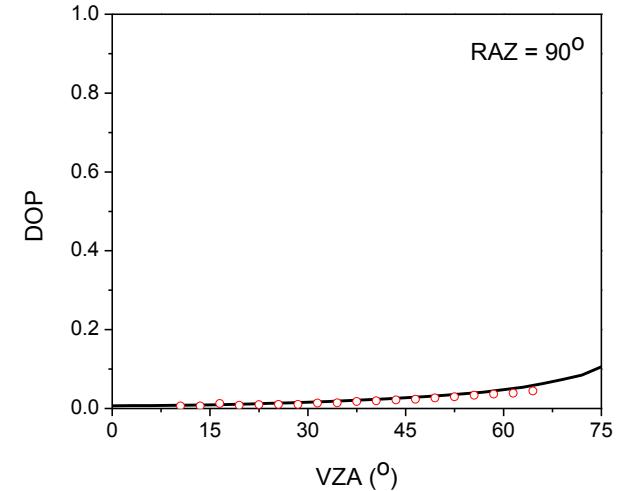
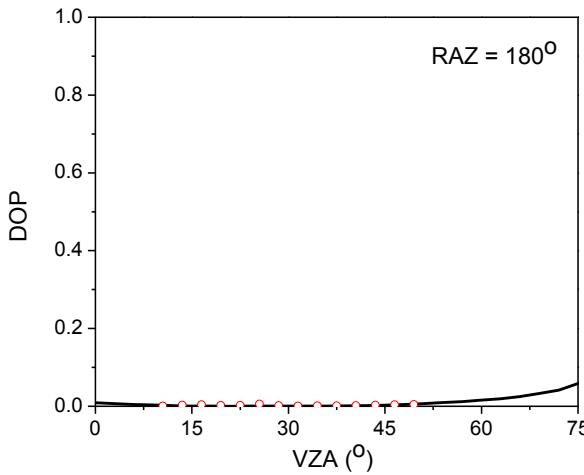
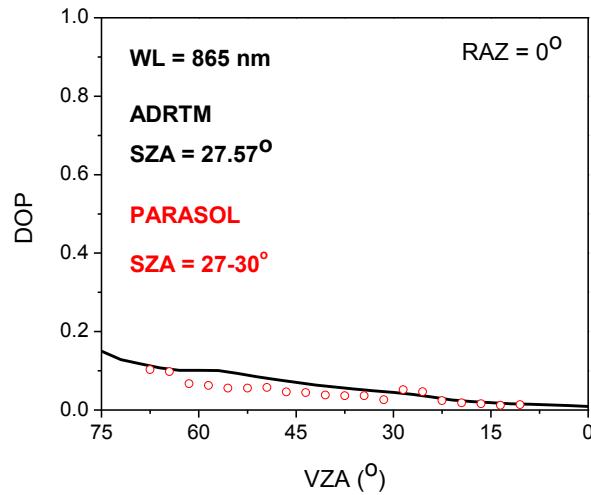


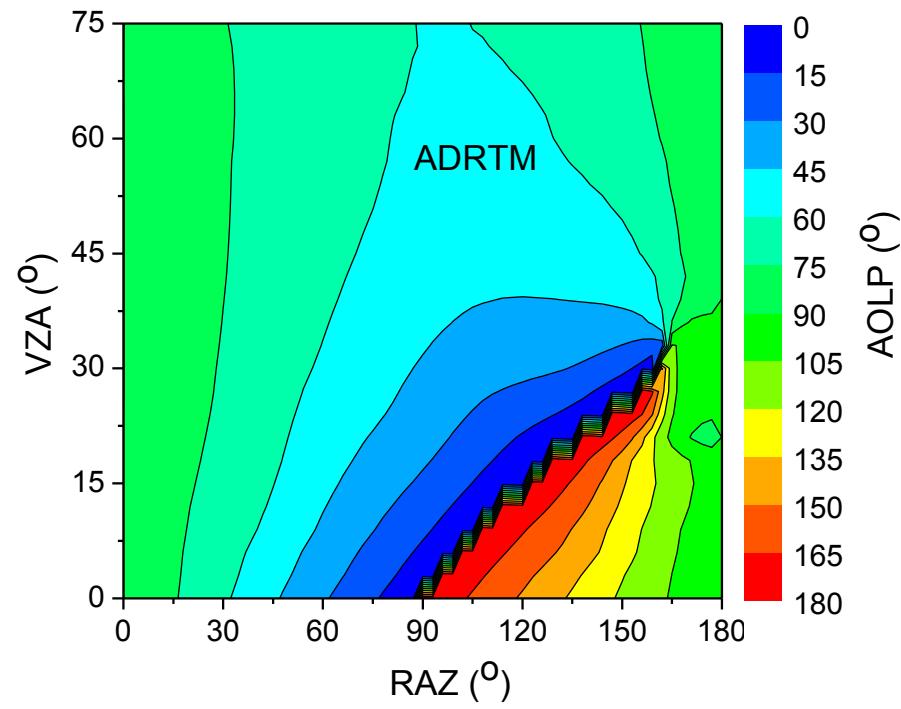
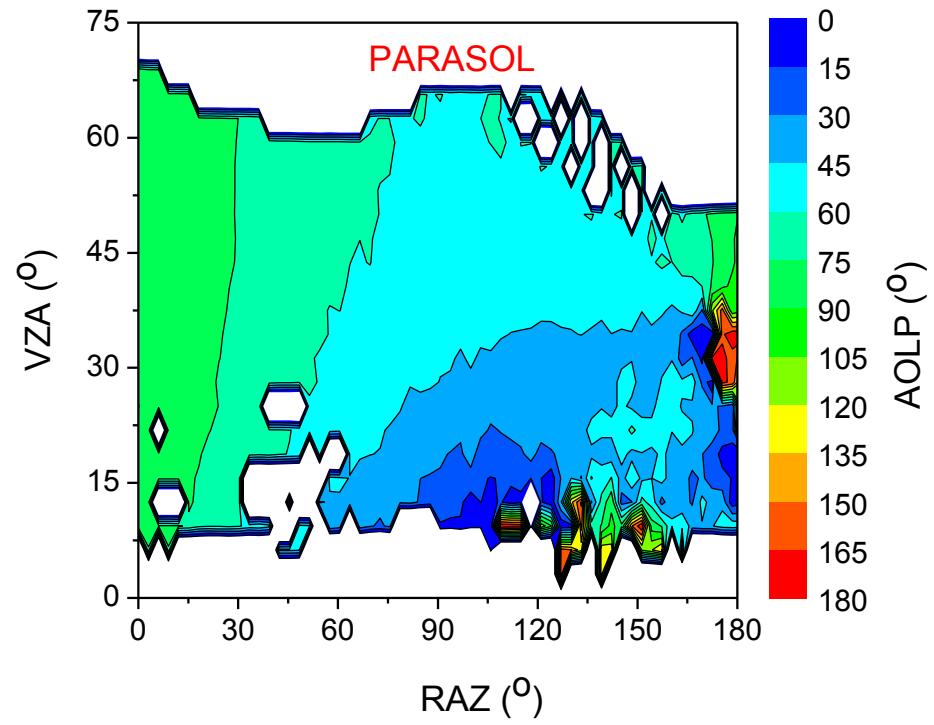
# Comparing model results with satellite data at a wavelength of 670 nm and a SZA of 56.94 deg



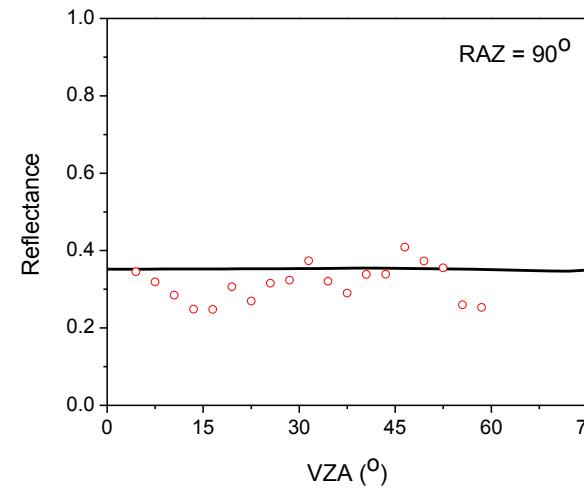
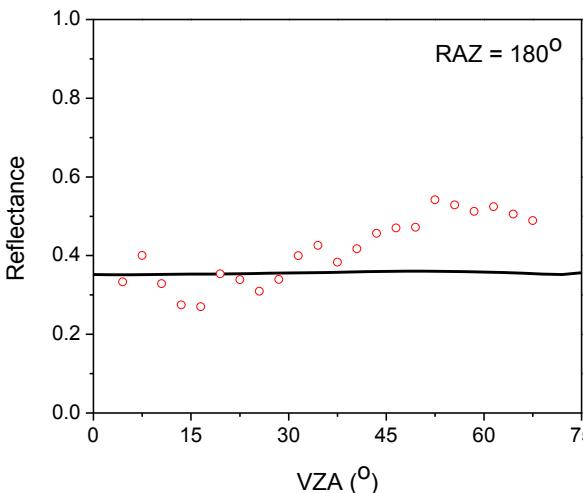
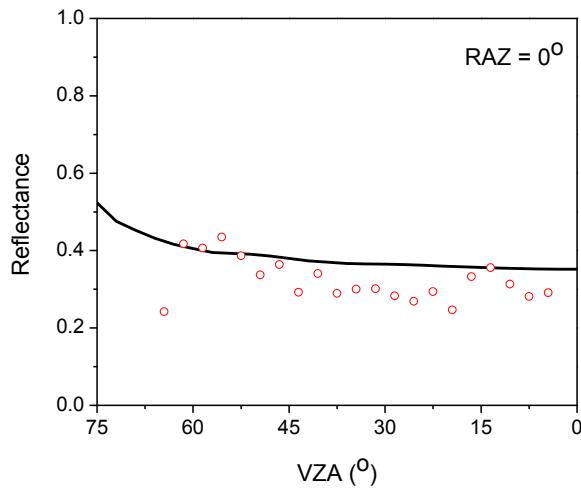
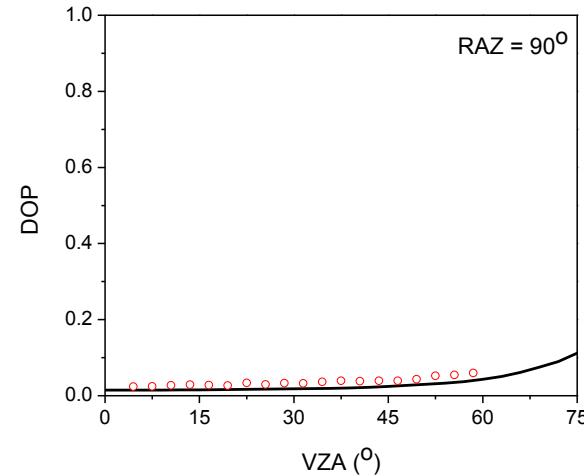
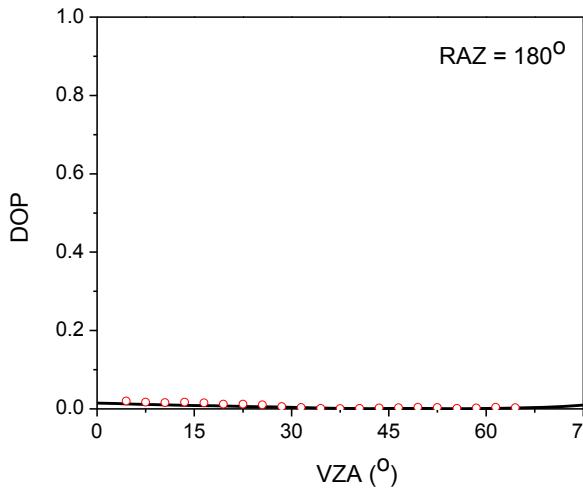
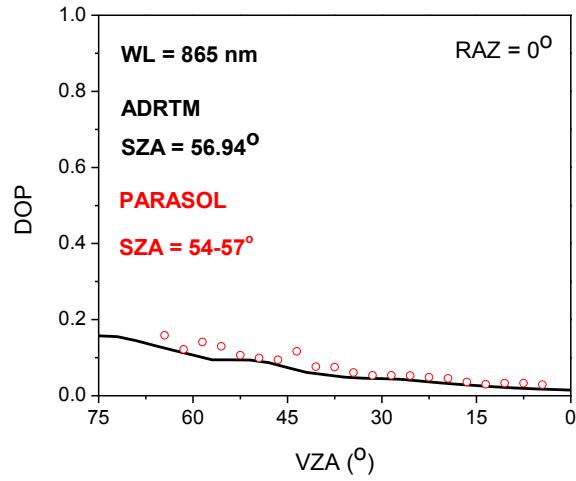


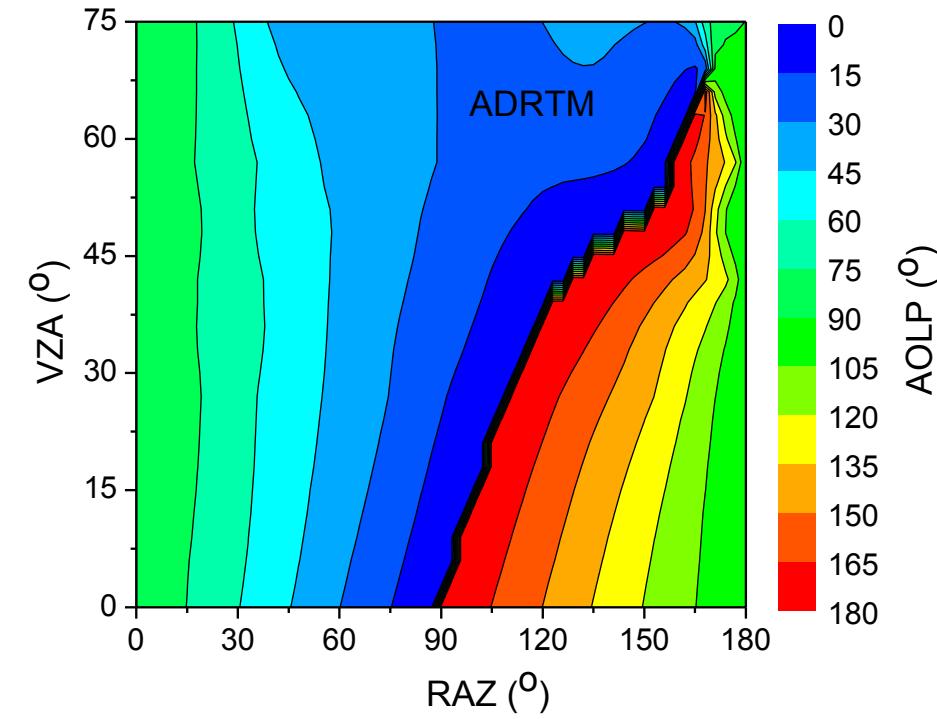
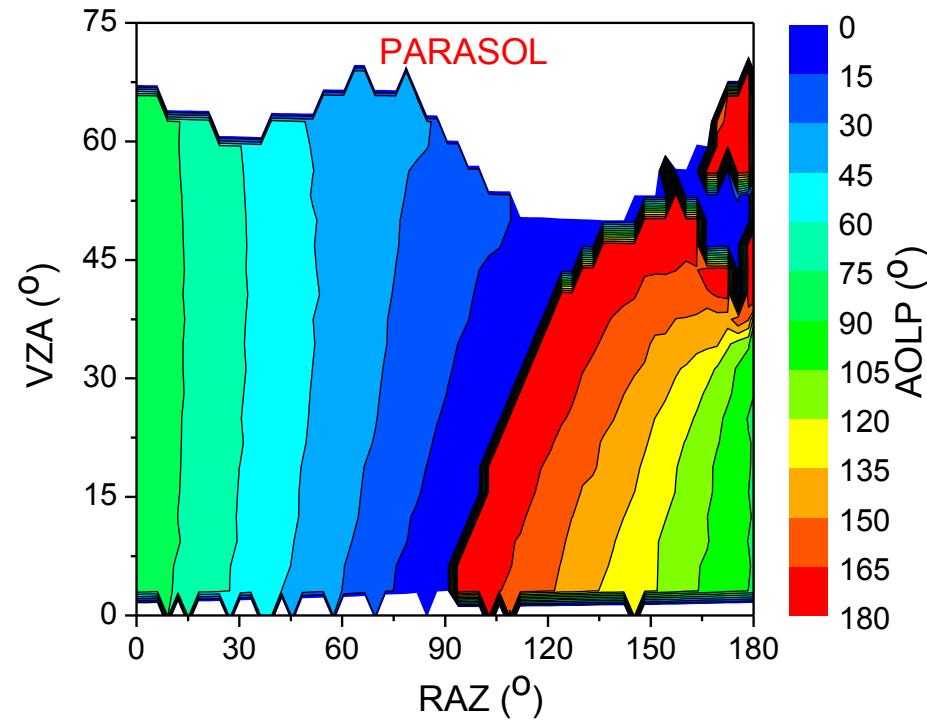
# Comparing model results with satellite data at a wavelength of 865 nm and a SZA of 27.57 deg



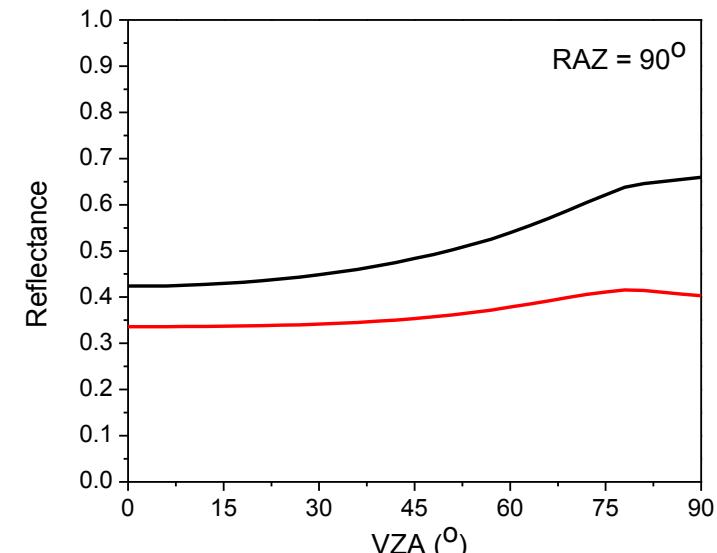
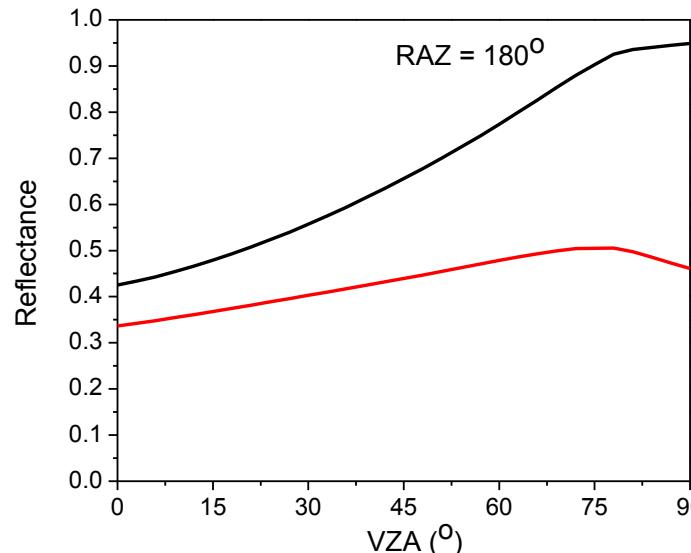
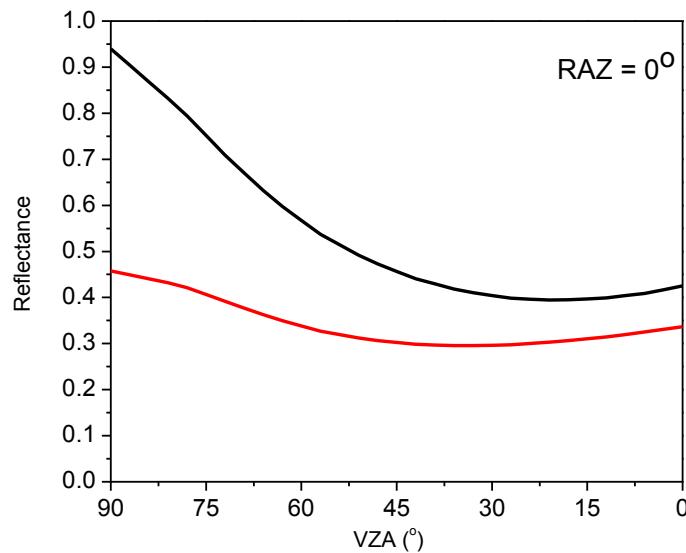
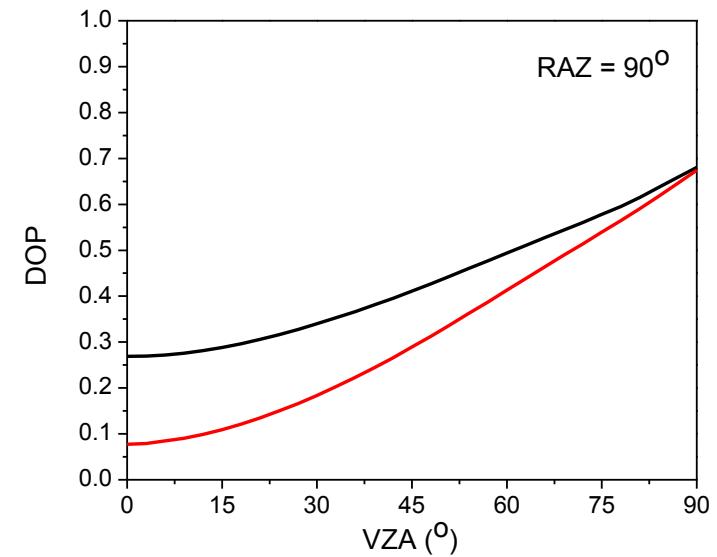
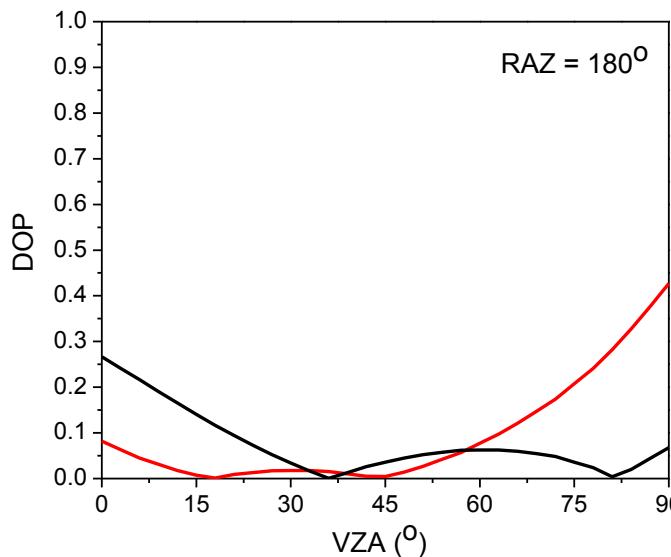
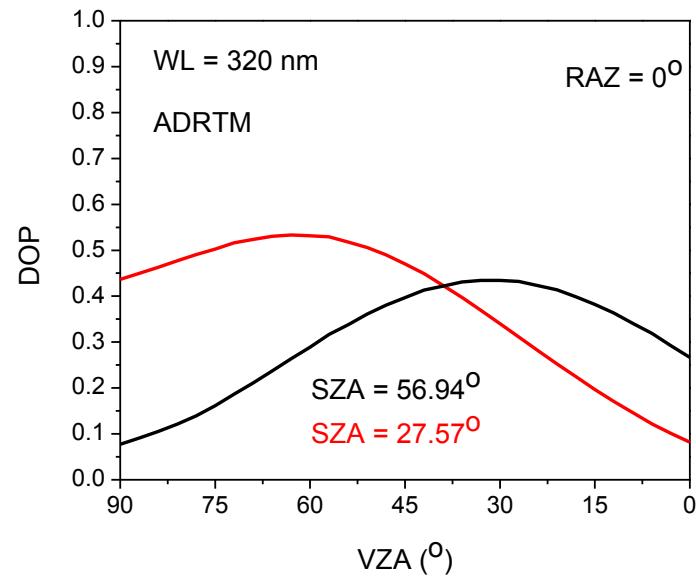


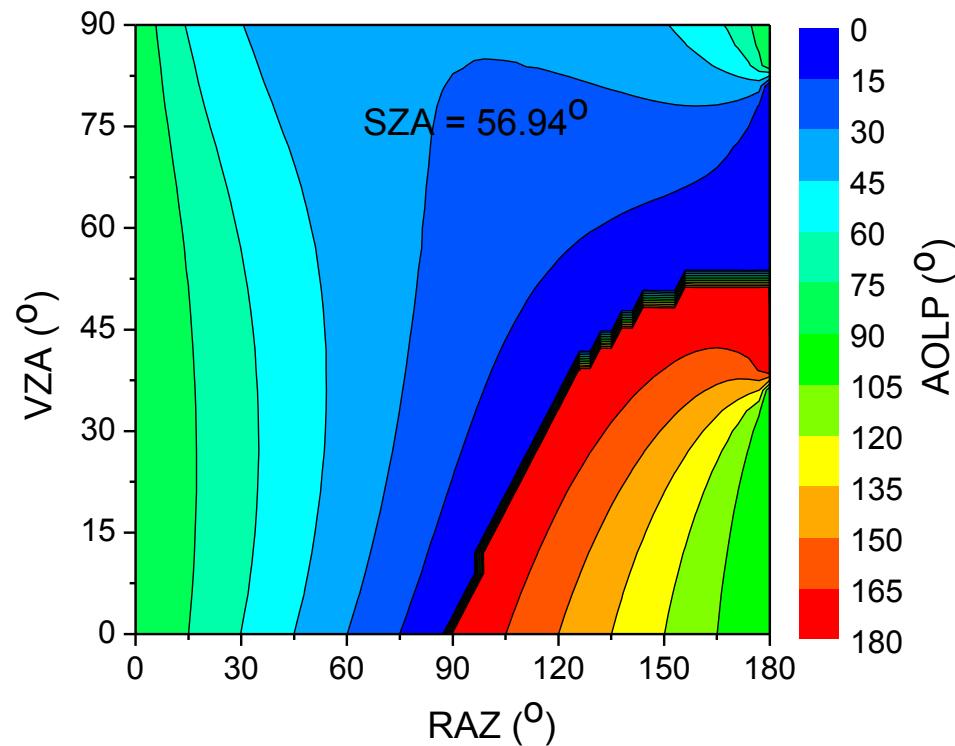
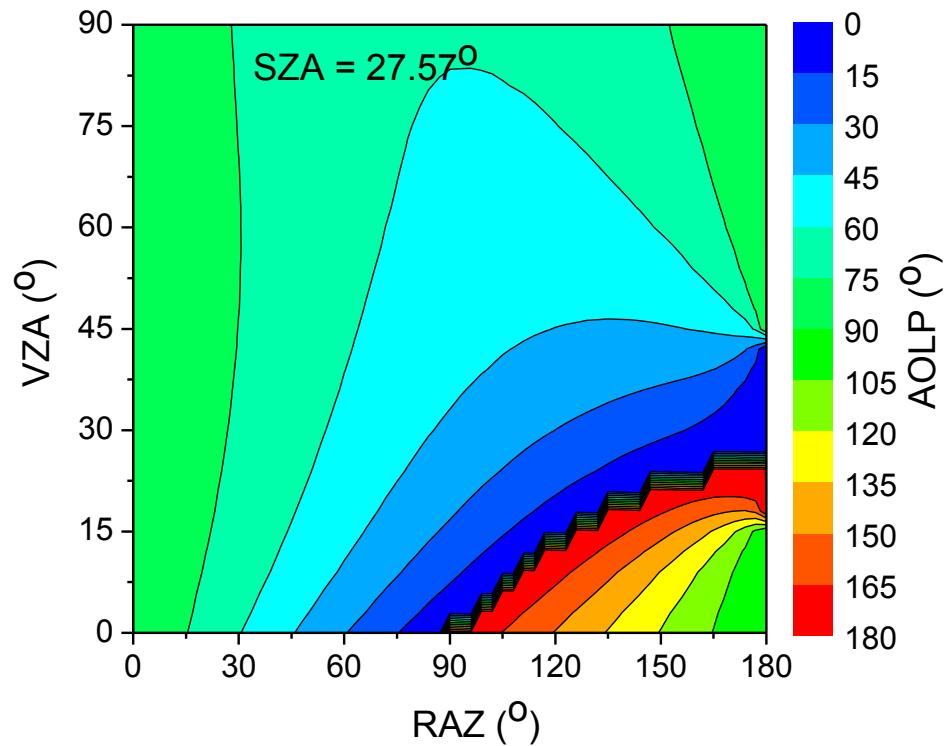
# Comparing model results with satellite data at a wavelength of 865 nm and a SZA of 56.94 deg



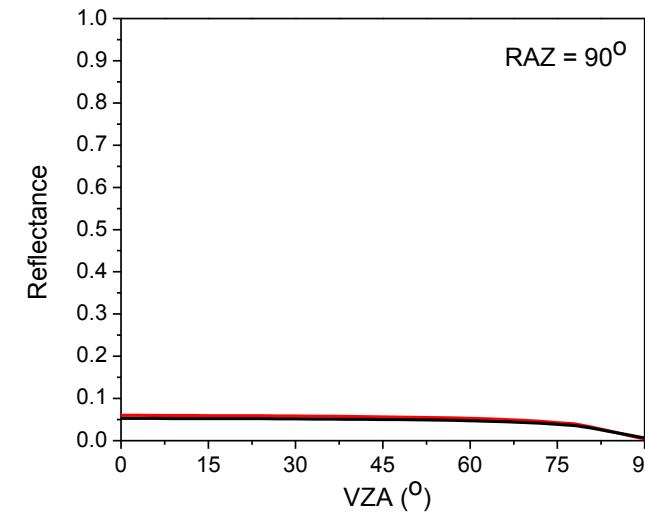
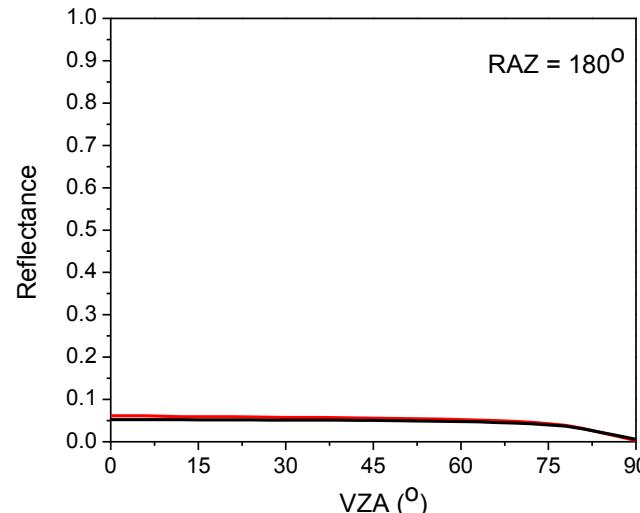
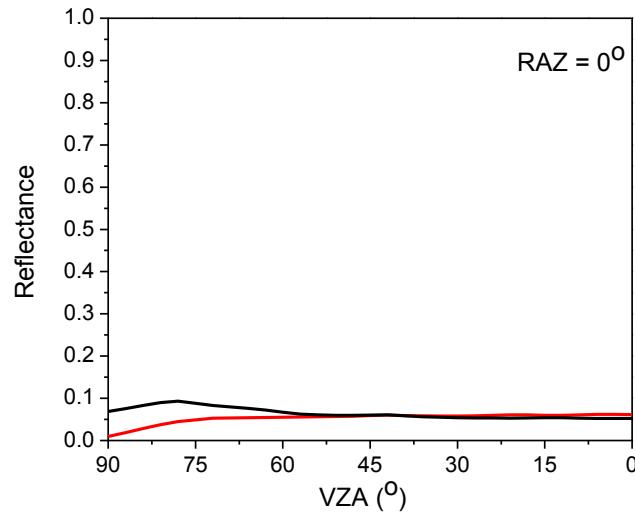
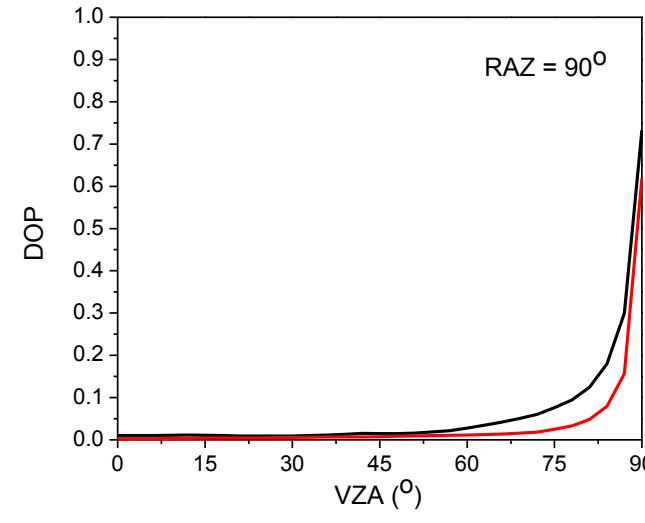
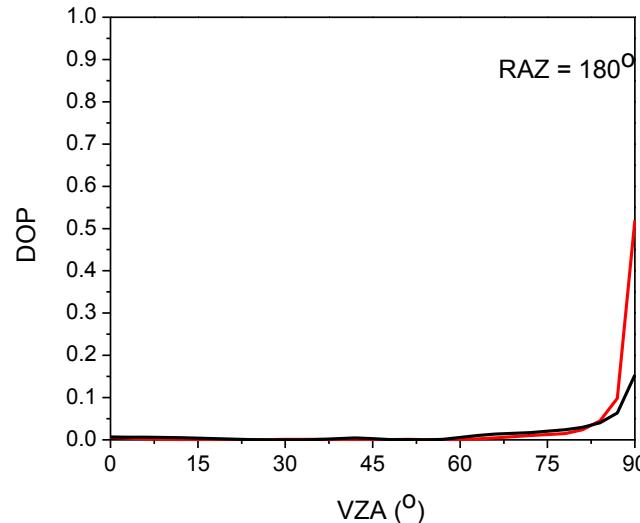
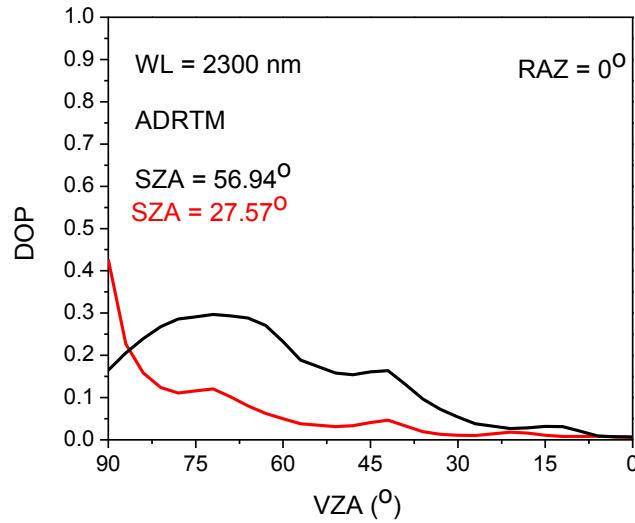


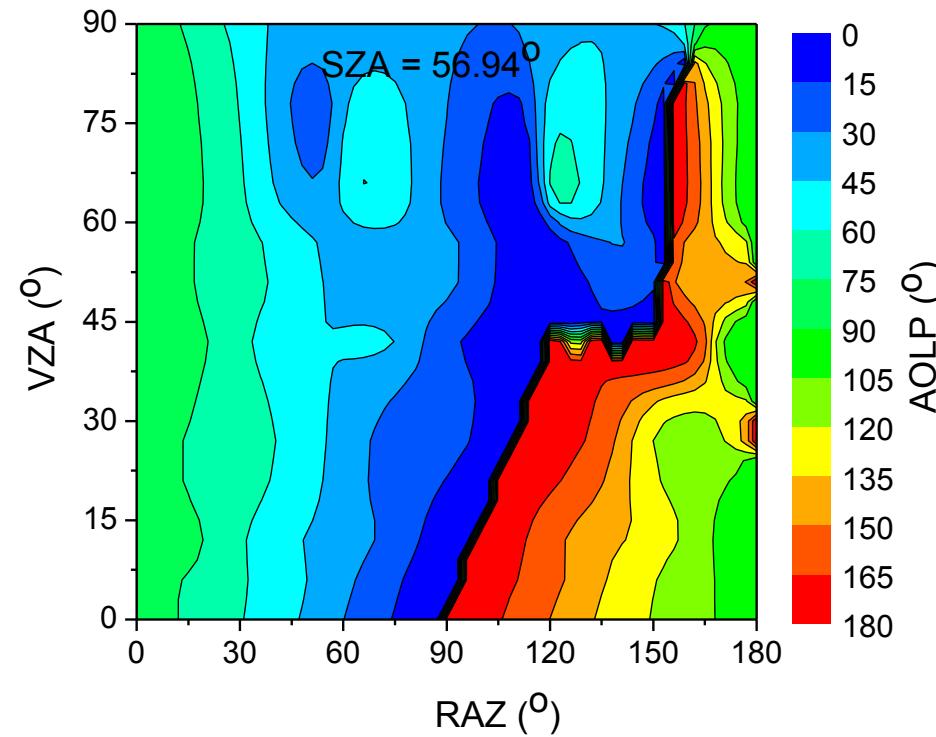
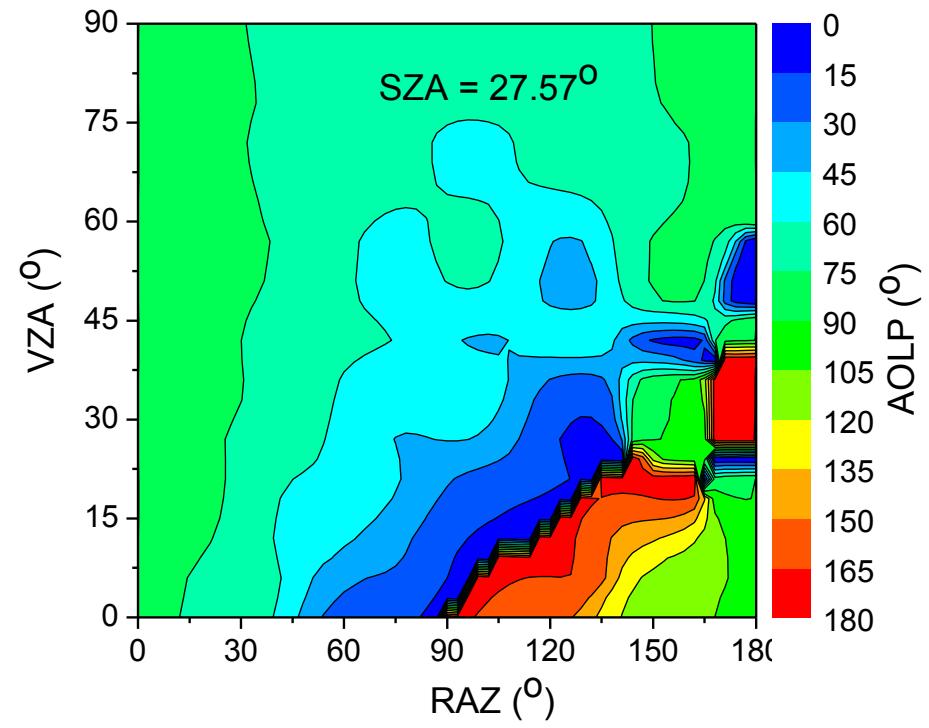
## Model results at a wavelength of 320 nm





## Model results at a wavelength of 2300 nm





## Summary

1. Spectral polarization states of reflected solar radiation from evergreen needle-leaf trees are modeled.
2. The PROSAIL leaf optical spectra model is used to obtain the total reflectance.
3. Light polarization is approximated with uppermost leaves' scattering of solar spectra.
4. Polarization state of solar spectra reflected from needle-leaf trees can be accurately calculated.

**Next: Broad-Leaf Trees**



## Journal publications with CLARREO and Glory supports since 2011:

1. **Wenbo Sun**, Rosemary R. Baize, Gorden Videen, Yongxiang Hu, and Qiang Fu, "A method to retrieve super-thin cloud optical depth over ocean background with polarized sunlight", *Atmos. Chem. Phys.*, 15, 11909-11918, doi: 10.5194/acp-15-11909-2015 (2015).
2. **Wenbo Sun**, Rosemary R. Baize, Constantine Lukashin, and Yongxiang Hu, "Deriving polarization properties of desert-reflected solar spectra with PARASOL data", *Atmos. Chem. Phys.* 15, 7725-7734, doi: 10.5194/acp-15-7725-2015 (2015).
3. **Wenbo Sun**, Constantine Lukashin, Rosemary R. Baize, and Daniel Goldin, "Modeling polarized solar radiation for CLARREO inter-calibration applications: Validation with PARASOL data," *J. Quant. Spectrosc. Radiat. Transfer* 150, 121-133 (2015).
4. **Wenbo Sun**, Bing Lin, Rosemary R. Baize, Gorden Videen, and Yongxiang Hu, "Sensing Hadley cell with space-borne lidar," *J. Quant. Spectrosc. Radiat. Transfer* 148, 38-41 (2014).
5. **Wenbo Sun**, Gorden Videen, and Michael I. Mishchenko, "Detecting super-thin clouds with polarized sunlight," *Geophys. Res. Lett.* 41, 688-693, doi: 10.1002/2013GL058840 (2014).
6. **Wenbo Sun** and Constantine Lukashin, "Modeling polarized solar radiation from ocean-atmosphere system for CLARREO inter-calibration applications," *Atmos. Chem. Phys.* 13, 10303-10324, doi: 10.5194/acp-13-10303-2013 (2013).
7. **Wenbo Sun**, Gorden Videen, Qiang Fu, and Yongxiang Hu, "Scattered-field FDTD and PSTD algorithms with CPML absorbing boundary conditions for light scattering by aerosols," *J. Quant. Spectrosc. Radiat. Transfer* 131, 166-174 (2013).
8. **Wenbo Sun**, Zhaoyan Liu, Gorden Videen, Qiang Fu, Karri Muinonen, David M. Winker, Constantine Lukashin, Zhonghai Jin, Bing Lin, and Jianping Huang, "For the depolarization of linearly polarized light by smoke particles," *J. Quant. Spectrosc. Radiat. Transfer*, 122, 233-237 (2013).
9. **Wenbo Sun**, Gorden Videen, Seiji Kato, Bing Lin, Constantine Lukashin, and Yongxiang Hu, "A study of subvisual clouds and their radiation effect with a synergy of CERES, MODIS, CALIPSO and AIRS data," *J. Geophys. Res.*, 116, doi: 10.1029/2011JD016422 (2011).
10. **Wenbo Sun**, Bing Lin, Yongxiang Hu, Constantine Lukashin, Seiji Kato, and Zhaoyan Liu, "On the consistency of CERES longwave flux and AIRS temperature and humidity profiles," *J. Geophys. Res.*, 116, D17101, doi: 10.1029/2011JD016153(2011).