PARASOL EMPIRICAL POLARIZATION DISTRIBUTION MODELS (PDM’S) FOR CLARREO

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MOTIVATION

- CLARREO (Climate Absolute Radiance and Refractivity Observatory) is a NASA Decadal Survey Mission recommended by NRC
- CLARREO’s objectives:
  - make highly accurate spectral reflectance observations
  - serve as an on-orbit intercalibration standard for other instruments (MODIS, VIIRS)
- In order to achieve climate accuracy radiometric measurements need to be corrected for polarization effects
- CLARREO’s accuracy goal: 0.3% (k = 2), including all uncertainty contributions
PDM’S: FROM PARASOL TO CLARREO

• Degree of polarization $P$, angle of linear polarization $\chi$ and total radiance $I$ completely specify the polarization state

• PDMs are $P$ and $\chi$ distributions (or tables) in spherical coordinates over given surface type

• **OBJECTIVE 1**: Construct Polarization Distribution Models (PDMs) as a function of physical parameters and viewed scene type (e.g. clear-sky surface, clouds) using 2006 PARASOL dataset
  • Why use PARASOL data? The only instrument on orbit that provided multi-angle polarization measurements

• **OBJECTIVE 2**: Apply PDM uncertainties to find the effect on intercalibration accuracy with CLARREO

CLARREO: OVERVIEW

• **Double-Module Reflectance Spectrometer**
  - solar reflected spectra to infer cloud feedbacks, snow/ice albedo feedbacks, and decadal change of clouds, radiative fluxes, aerosols, snow cover, sea ice
  - 320-2300 nm spectral coverage
  - polarization sensitivity: $< 0.5\%$ (k=2) for $\lambda < 1000$ nm, $< 0.75\%$ (k=2) for $\lambda > 1000$ nm
  - reflectance uncertainty of $0.3\%$ (k = 2)

• **2 Infrared Spectrometers**
  - temperature, water vapor and cloud feedbacks and decadal change of temperature, water vapor, clouds, and greenhouse gas radiative effects
  - measurement uncertainty of $0.1 \text{ K}$ (k = 3)

• **2 Global Navigational Satellite System Radio Occultation instruments**
  - decadal change of temperature profiles
  - measurement uncertainty of $0.1 \text{ K}$ (k = 3)
PARASOL: OVERVIEW

- Part of A-Train, 705 km altitude
- 274×242 pixel CCD detector array, wide view optics
- 9 spectral channels from blue (443 nm) to infrared (1020 nm)
  - 3 polarization bands: 490 nm, 670 nm, 865 nm
- Pixel resolution for Level-1B data: 5.3×6.2 km (at nadir)
- Absolute accuracy: 2-3% [Riédi et al., EarthCare Mtg, 2007]
- Up to 14 views per pixel (collected off-line): multi-angular sampling improves PDMs’ precision
- Current status: after ~9 years in orbit PARASOL was shut off on Dec. 18, 2013
**PDM’S DEFINITIONS**

- **PDM**: 2D map of time-averaged (1 yr here) degree of polarization $P$ or angle of linear polarization $\chi$
  - $x$ axis: Viewing Zenith Angle
  - $y$ axis: Relative Azimuth
- **Start with $P$.** It describes (in our case) the degree of polarization of the light reflected from Earth’s surface

Polarized reflectance:

$$\rho_P = \frac{\pi I_p}{E \cos(\theta_s)}$$

Total reflectance:

$$\rho = \frac{\pi I}{E \cos(\theta_s)}$$

Stokes parameters

- $I = I_{0^\circ} + I_{90^\circ}$
- $Q = I_{0^\circ} - I_{90^\circ}$
- $U = I_{45^\circ} - I_{135^\circ}$

$$P = \rho_P / \rho = I_p / I = \frac{\sqrt{Q^2 + U^2}}{I}$$
### SAMPLE PDM FOR DEGREE OF POLARIZATION FOR CLEAR SKY OVER WATER BODIES (PARASOL 2006)

Asymmetry due to aerosols

**Cuts on Data**

<table>
<thead>
<tr>
<th>Cut</th>
<th>VALUE</th>
</tr>
</thead>
<tbody>
<tr>
<td>IGBP index</td>
<td>17</td>
</tr>
<tr>
<td>(\theta_s)</td>
<td>(40^\circ &lt; \theta_s &lt; 50^\circ)</td>
</tr>
<tr>
<td>Cloud fraction</td>
<td>&lt; 0.01</td>
</tr>
<tr>
<td>Cloud phase</td>
<td>240</td>
</tr>
<tr>
<td>Wind speed</td>
<td>&lt; 2.5 m/s</td>
</tr>
<tr>
<td>(\lambda)</td>
<td>670 nm</td>
</tr>
</tbody>
</table>

**\(P_{max} \approx 0.9\)**

**Clear Sky bitmask (PARASOL-specific)**

**P Mean for Scene Type 17**
PDM’S FOR ANGLE OF LINEAR POLARIZATION

Angle of Linear Polarization relative to principal plane (PARASOL)

\[ \chi = \frac{1}{2} \arctan(U/Q). \]

Angle of Linear Polarization relative to scattering plane

\[ \psi = \chi - \alpha. \]

where:

\[ \tan \alpha = \frac{\sin \phi}{\sin \theta_v \tan \theta_s - \cos \theta_v \cos \Delta \phi}. \]

Expect \( \psi \approx 90^\circ \)
Principal and scattering planes coincide $\Rightarrow \chi = \psi = 90^\circ$

At $VZA = 0$, 1 degree in $VZA \iff 1$ degree in $\chi$

High std deviations: low polarization region
RELATIVE INTERCALIBRATION (RI) UNCERTAINTY

Reference intercalibration (RI) relative uncertainty \( \left( \delta_{RI} \equiv \sigma_{RI}/\rho_{RI} \right) \):

\[ \delta_{RI} = \sqrt{\delta_0^2 + \left( \frac{mP}{1+mP} \right)^2 \left( \delta_m^2 + \delta_P^2 \right)} \]

Relative uncertainties:
- \( \delta_0 = \sigma_0/\rho_0 \): CLARREO's own uncertainty + intercalibration auto-correlation unc. + imager unc.
- \( \delta_m = \sigma_m/m \): unc. in imager sensitivity to polarization
- \( \delta_P = \sigma_P/P \): polarization unc. from PDMs

Next steps:
1. Fix some variables at reasonable values, let others vary:
   - \( \delta_0 = 0.2\% \) (k = 1)
   - \( m \) and \( \delta_m \) will vary
2. Plot \( \delta_P \) vs \( P \) and parametrize it
3. Plot \( \delta_{RI} \) vs \( P \) using the values in step 1 and 2.

Imager sensitivity to polarization

\[ \rho_{\text{imager}} = \frac{\rho_0}{1+mP} \]

Error propagation

C. Lukashin et al.
δ_p VS P FIT FOR WATER BODIES

\[ \delta_p \text{ vs } P \]

\[ \text{Fit: } p_0 + p_1/x + p_2x \]

\[ \chi^2 / \text{ndf} \rightarrow 46.12 / 84 \]

\[ p_0 \rightarrow 0.1492 \pm 0.0090 \]

\[ p_1 \rightarrow 0.01287 \pm 0.00135 \]

\[ p_2 \rightarrow -0.08362 \pm 0.01053 \]

Error bars from PDM uncertainties

\(\delta_p\) behaves as we’d like it to behave: gets smaller as \(P\) increases

Fraction (not percent!)
RI IMAGER UNCERTAINTY FOR WATER BODIES FROM $\delta P$ vs $P$ FITS

\[ \delta_{RI} = \sqrt{\delta_0^2 + \left( \frac{mP}{1+mP} \right)^2 (\delta_m^2 + \delta_P^2)} \]

$\delta_0 = 0.2\%$

$\delta_m = 3\%$

$\delta_m = 10\%$

$m = 0.10$

$m = 0.05$

$m = 0.03$

roughly, MODIS accuracy

- Degradation in imager’s sensitivity ($m$ or $\delta m$) leads to greater error in imager’s reflectance measurements
CONCLUSIONS AND PLANS

• **Done:** Produced PDMs for clear sky over water bodies using 2006 PARASOL data

• **Done:** Applied PDM results to estimate intercalibration uncertainties dependence on degree of polarization

• **In progress:** Looking at suitability of PDMs for clear-sky land surfaces and cloudy scene types

• **Future:** PARASOL has only 3 bands (490, 670 and 865 nm). Will extend PDMs over entire spectrum

• **Future:** Considering PDM parametrization with multivariate analysis, e.g. Artificial Neural Networks

• **Future:** Compare 2006 PARASOL PDMs with Radiative Transfer Models (RTM)

• **Future:** Merge PARASOL Level-1 with MODIS Level-2 data. Develop PDMs for new data product. Validate it
DOES PDM FOR THE DEGREE OF POLARIZATION MAKE SENSE?

PARASOL data (12 days) (C. Lukashin et. al)

Pick $P_{\text{max}}$ region
$\theta > 30, 170 < \phi < 190$
and plot scattering angle

Max polarization occurs for the scatt angle $> 140$ (rainbow region) as expected
SAMPLE PDM FOR CLEAR SKY OVER WATER BODIES: AEROSOL EFFECTS

Aerosol Optical Depth ($\tau$)

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$\lambda$ 670 nm
(II) SAMPLE PDM FOR CLEAR SKY OVER WATER BODIES: AEROSOL EFFECTS

PDM from Slide 7, but with aerosol optical depth cut (previous slide)

More symmetric

$\sigma(P) \sim 0.1$

$\sigma(P)/P \sim 10-30%$

Low $P$ regions: $Q$ and $U$ close to noise
DO $\chi$ PDMS MAKE SENSE?
LOOK AT $\psi$

From $\chi$, angle relative to principal plane, calculate $\psi$, angle relative to scattering plane.

Expect mean $\psi \approx 90^\circ$.

Angle of Linear Polarization relative to scattering plane

$$\psi = \chi - \alpha.$$ 

where:

$$\tan \alpha = \frac{\sin \phi}{\frac{\sin \theta_v}{\tan \theta_s} - \cos \theta_v \cos \Delta \phi}.$$ 

$\psi \approx 90^\circ$, slightly lower (?)

Constant $= 1.209e+06$

Mean $= 87.69$

Sigma $= 1.889$