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

DANIEL GOLDIN (SSAI), CONSTANTINE LUKASHIN (NASA-LARC), WENBO SUN (SSAI)

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**

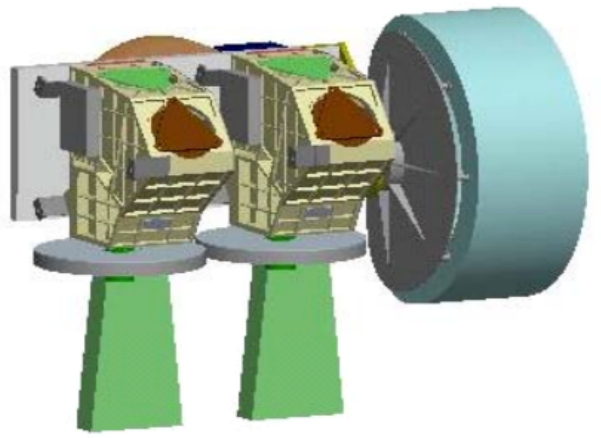
PDM'S: FROM PARASOL TO CLARREO

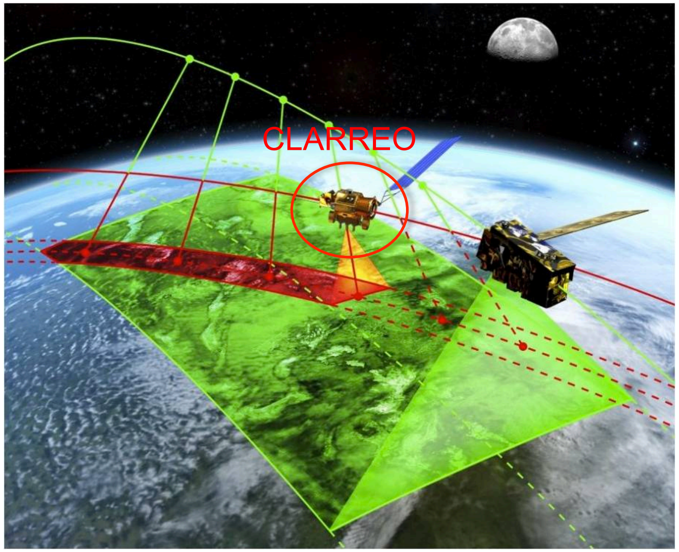
- **Degree of of polarization *P*, angle of linear polarization χ and total radiance I completely specify the polarization state**
- **PDMs are *P* and χ distributions (or tables) in spherical coordinates over given suface type**
- **OBJECTIVE 1: Construct Polarization Distribution Models (PDMs) as a 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**
- **Extending the work done by C. Lukashin et al. (IEEE Trans. Geosci. Remote Sens. V. 51, No.3, 2013)**

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 λ < 1000 nm, < 0.75% (k=2) for λ > 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 K (k = 3)
- **2 Global Navigational Satellite System Radio Occultation instruments**
  - decadal change of temperature profiles
  - measurement uncertainty of 0.1K (k =3)

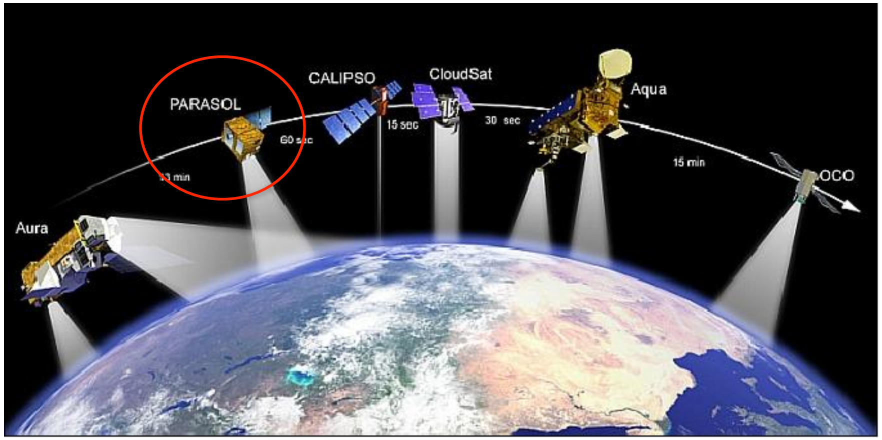
Reflectance Spectrometer

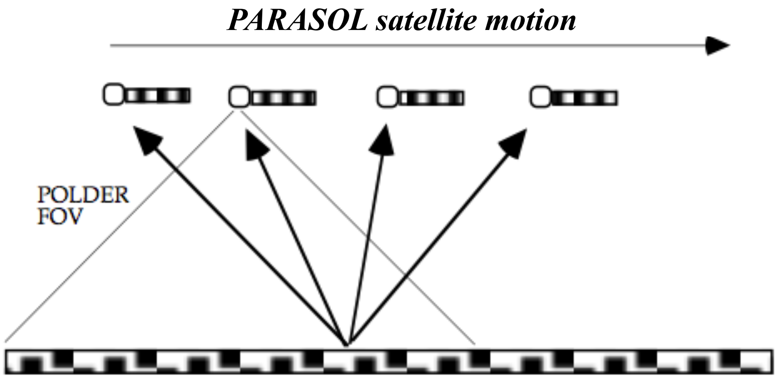




PARASOL: OVERVIEW

- **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 <u>polarization</u> 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**

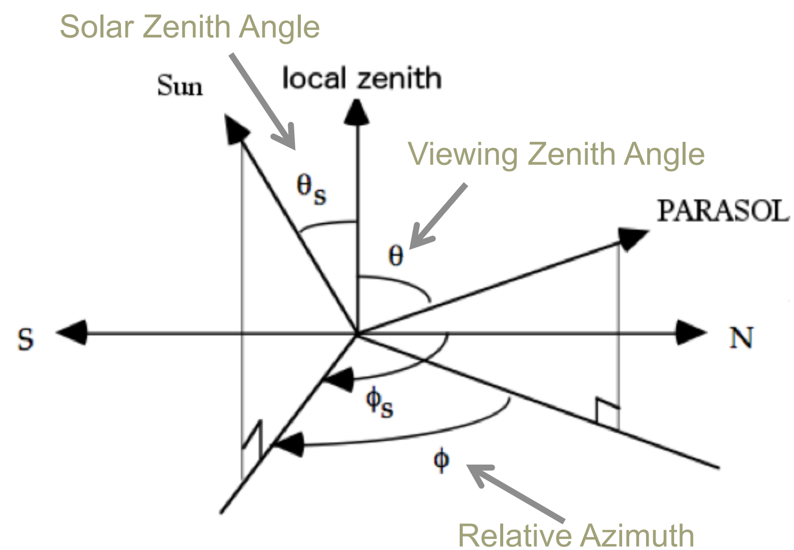




PDM'S DEFINITIONS

P

- **PDM: 2D map of time-averaged (1 yr here) degree of polarization *P* or angle of linear polarization χ**
  - 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

$$I = I_{0^\circ} + I_{90^\circ}$$

$$Q = I_{0^\circ} - I_{90^\circ}$$

$$U = I_{45^\circ} - I_{135^\circ}$$

$$P = \rho_p / \rho = I_p / I = \frac{\sqrt{Q^2 + U^2}}{I},$$

Polarized radiance

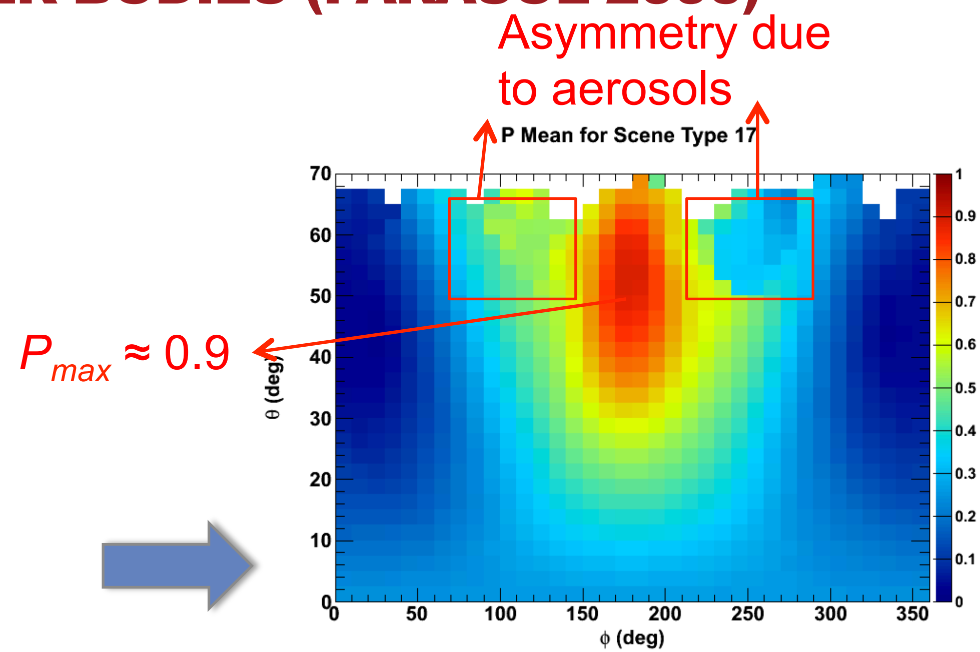
Total radiance

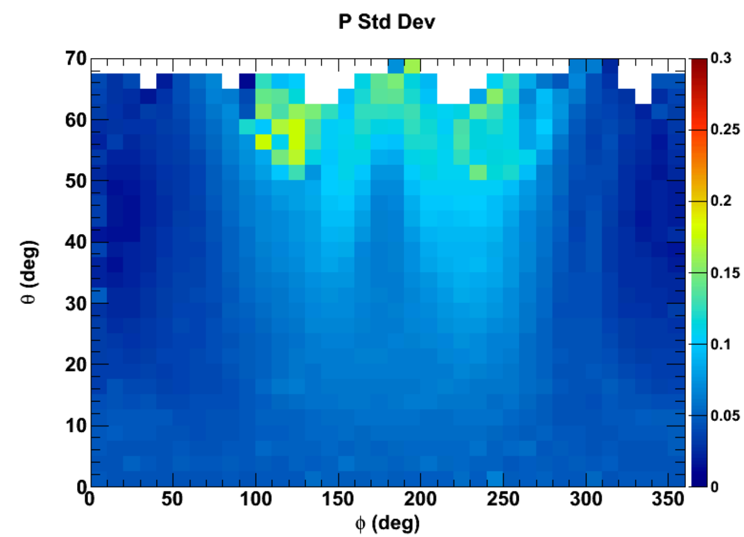
SAMPLE PDM FOR DEGREE OF POLARIZATION FOR CLEAR SKY OVER WATER BODIES (PARASOL 2006)

Cuts on Data

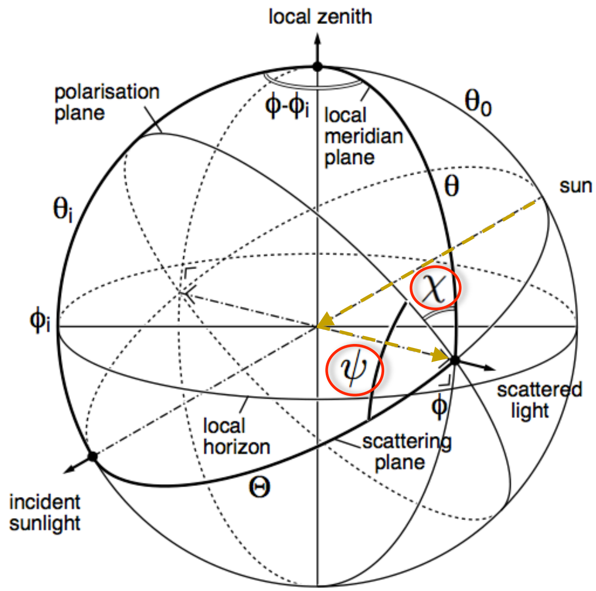
Cut	VALUE
IGBP index	17
θ_s	$40° < \theta_s < 50°$
Cloud fraction	< 0.01
Cloud phase	240
Wind speed	< 2.5 m/s
λ	670 nm

Clear Sky bitmask (PARASOL-specific)





PDM'S FOR ANGLE OF LINEAR POLARIZATION χ



Expect ψ ≈ 90°

Angle of Linear Polarization relative to principal plane (PARASOL)

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

Angle of Linear Polarization relative to scattering plane

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

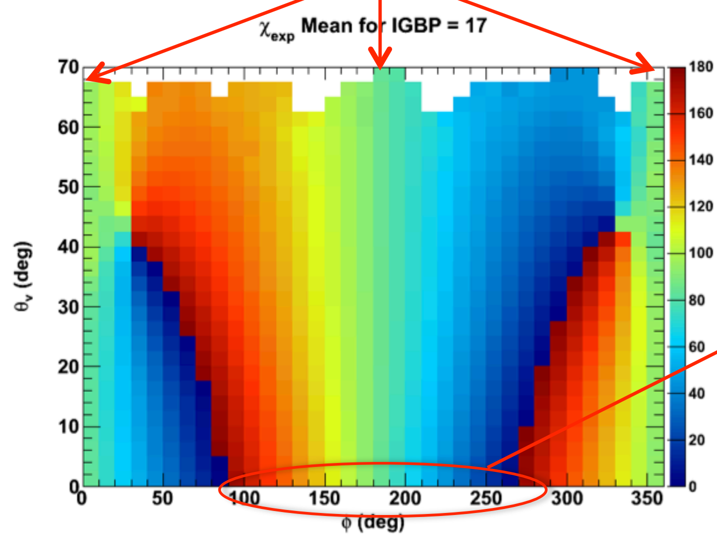
where:

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

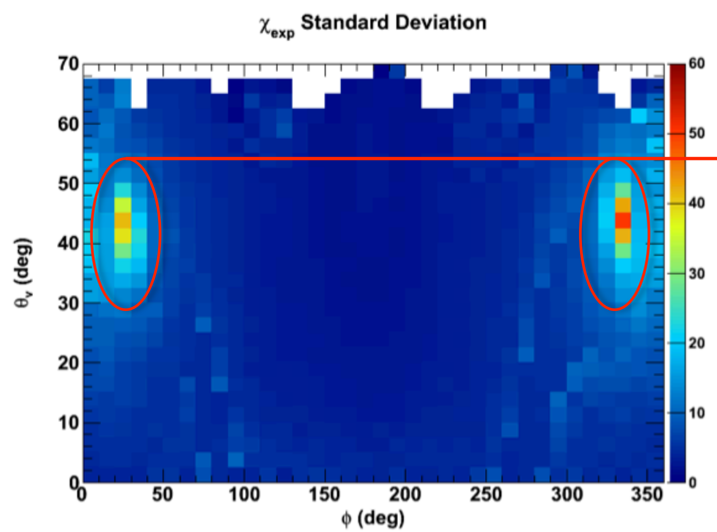
Daniel Goldin

χ PDM'S FOR CLEAR-SKY WATER BODIES (PARASOL 2006)

Principal and scattering planes coincide ➔ $\chi = \psi = 90^o$



At VZA = 0, 1 degree in VZA ⇔ 1 degree in χ



High std deviations: low polarization region

RELATIVE INTERCALIBRATION (RI) UNCERTAINTY

imager (MODIS, VIIRS) reflectance

$$\rho_{imager} = \frac{\rho_0}{(1+mP)}$$

Imager sensitivity to polarization

C. Lukashin et al. (IEEE Trans. Geosci. Remote Sens. V. 51, No.3, 2013)

Error propagation

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

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

Relative uncertainties:

$\delta_0 = \sigma_{\rho 0}/\rho_0$: CLARREO's own uncertainty
+ intercalibration auto-correlation unc.
+ imager unc.

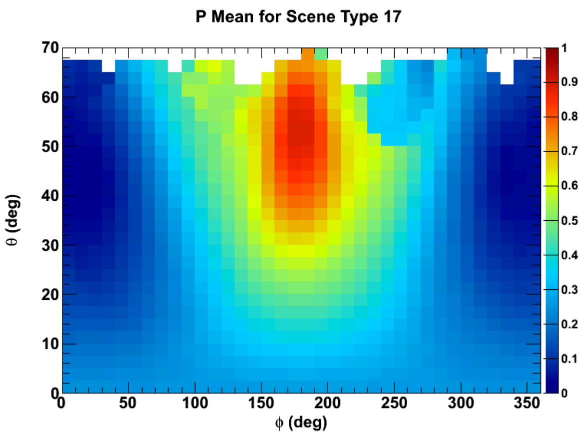
$\delta_m = \sigma_m/m$: unc. in imager sensitivity to polarization

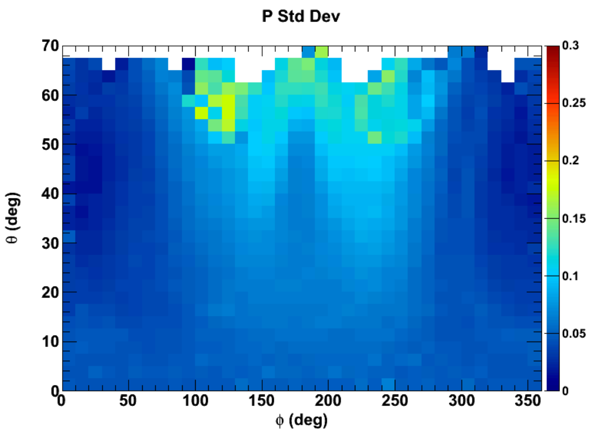
$\delta_P = \sigma_P/P$: polarization unc. from PDMs

Next steps:

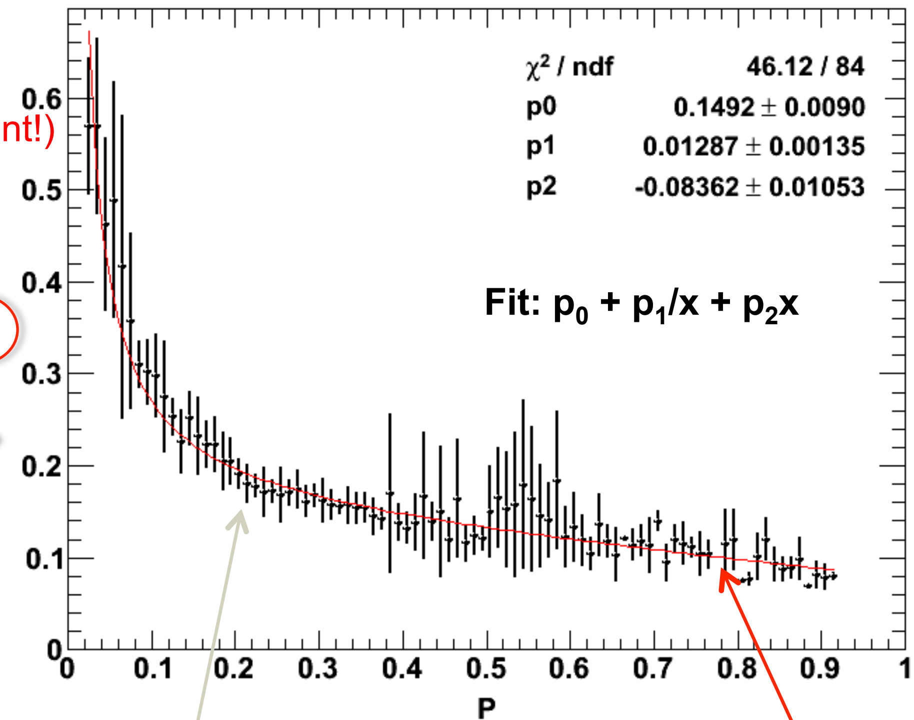
1. Fix some variables at reasonable values, let others vary:
   - $\delta_0 = 0.2\%$ (k = 1)
   - *m* and δ_m will vary
2. Plot δ_P vs *P* and parametrize it
3. Plot δ_{RI} vs *P* using the values in step 1 and 2.

δ_P *VS P* FIT FOR WATER BODIES





fraction
(not percent!)



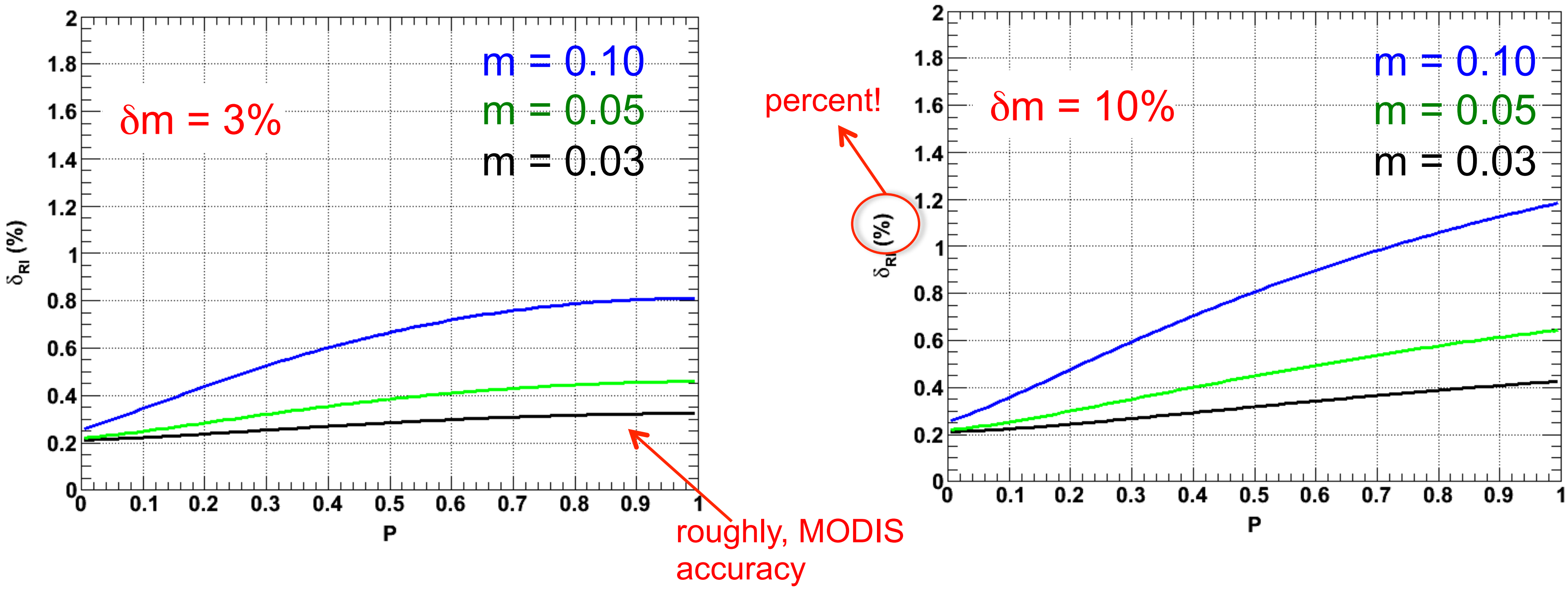
Error bars from
PDM uncertainties

δ_P behaves as we'd like it to behave: gets smaller as P increases

RI IMAGER UNCERTAINTY FOR WATER BODIES FROM δP vs P FITS

$\delta_0 = 0.2\%$

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



- **Degradation in imager's sensitivity (m or δm) leads to greater error in imager's reflectance measurements**

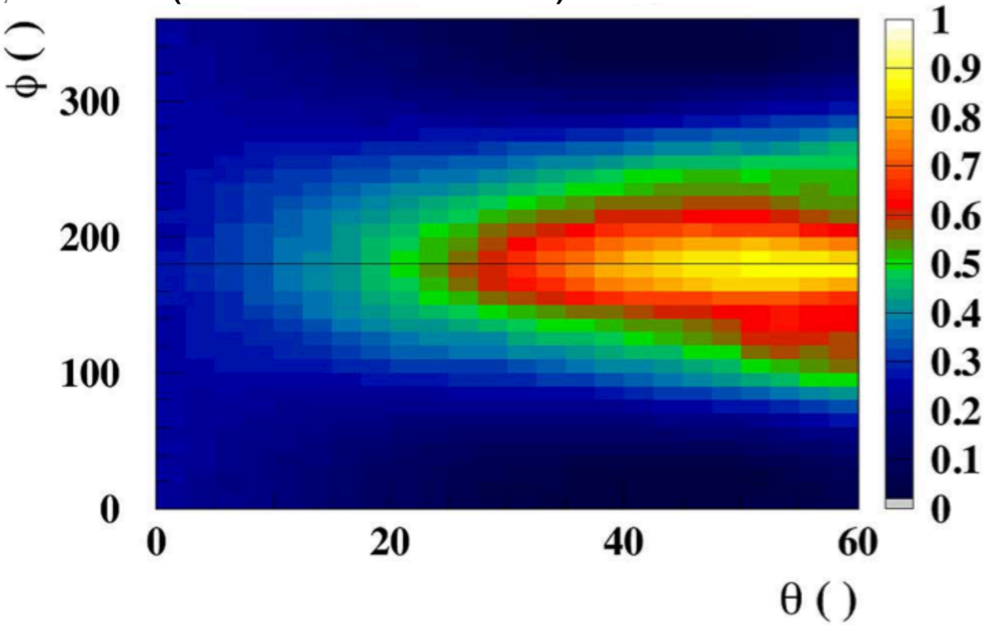
CONCLUSIONS AND PLANS

- 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

BACKUP

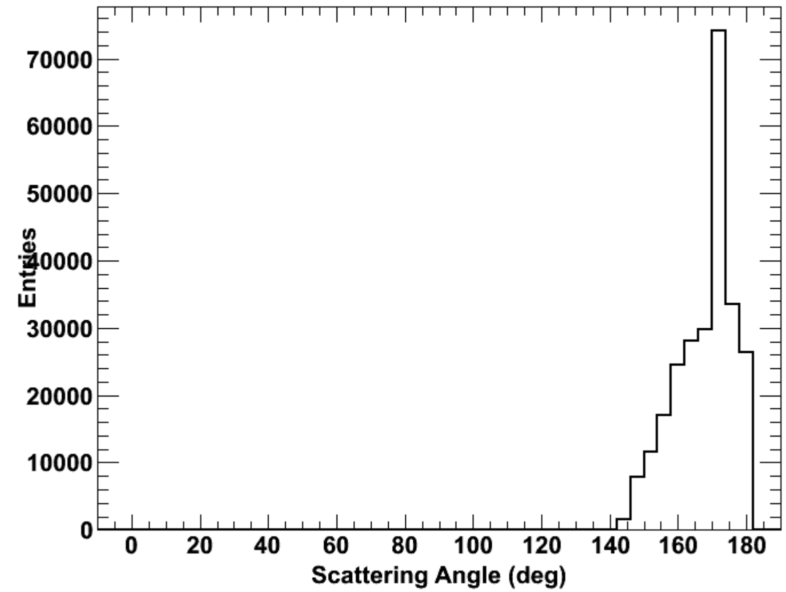
DOES PDM FOR THE DEGREE OF POLARIZATION MAKE SENSE?

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



Note: flipped θ, ϕ axes

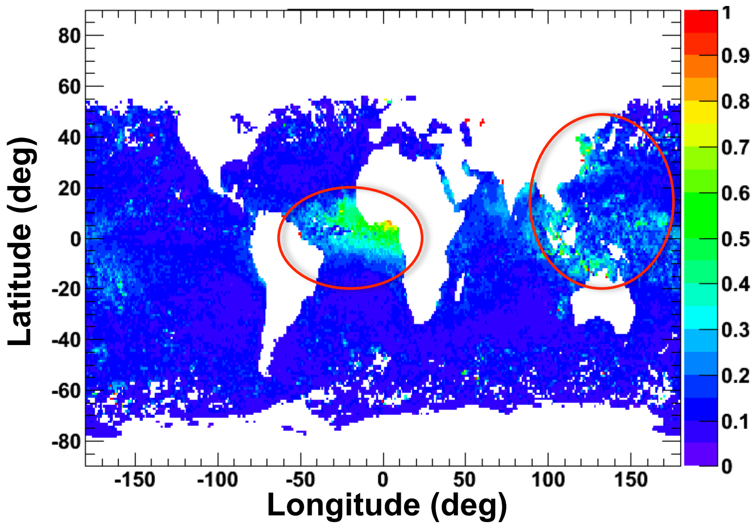
Pick P_{max} region
$\theta > 30$, $170 < \phi < 190$
and plot scattering angle



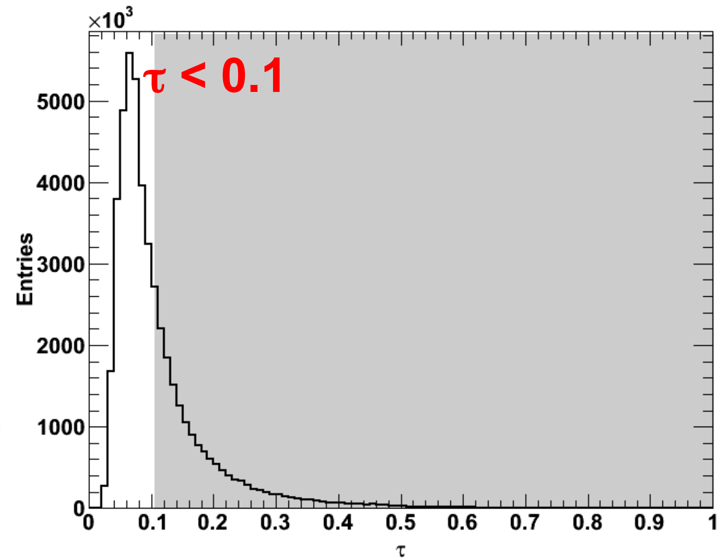
Max polarization occurs for the scatt angle > 140 (rainbow region) as expected

(I) SAMPLE PDM FOR CLEAR SKY OVER WATER BODIES: AEROSOL EFFECTS

Aerosols from PARASOL 2006



Aerosol Optical Depth (τ)



Cuts on Data

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Optical depth (τ)	< 0.1
λ	670 nm

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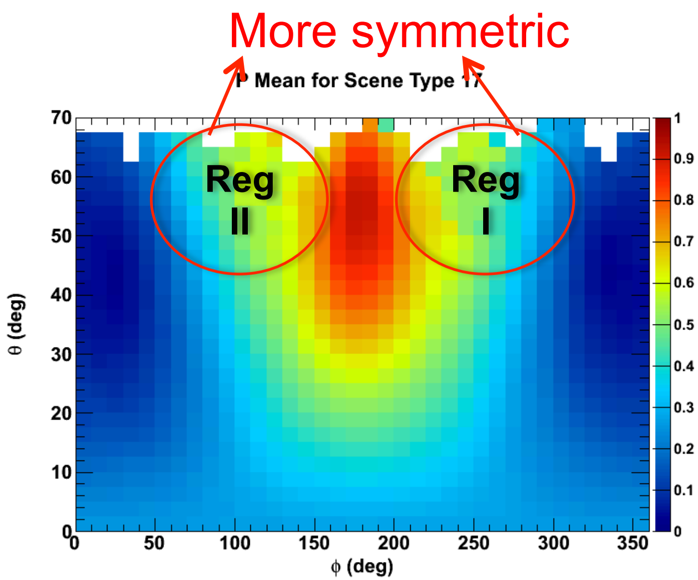
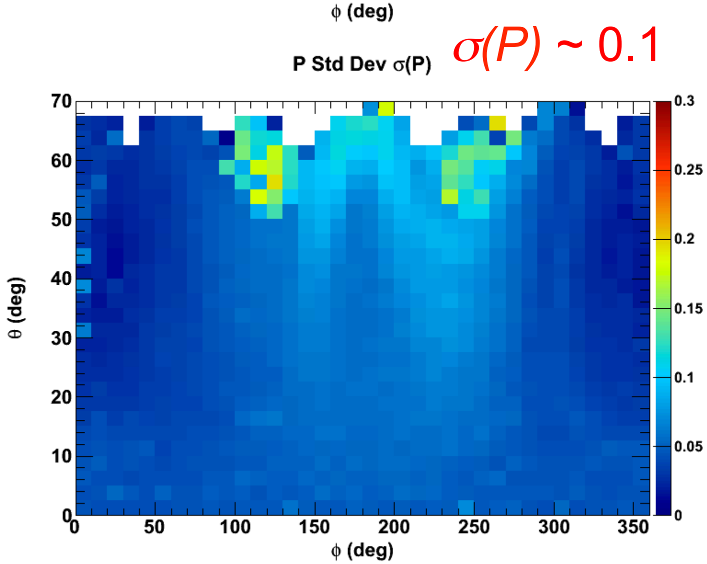
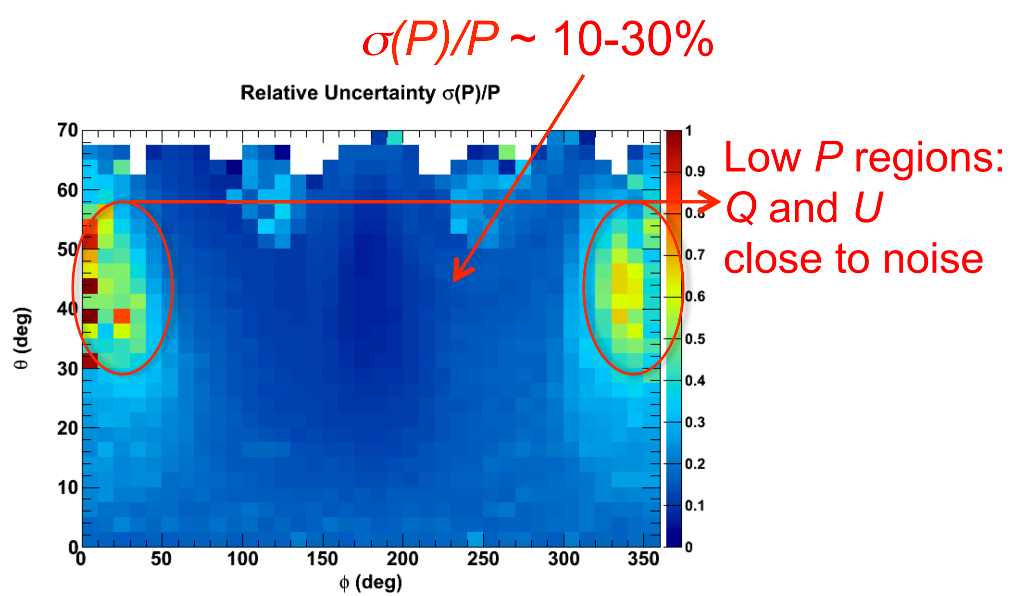


PDM from Slide 7, but with aerosol optical depth cut (previous slide)



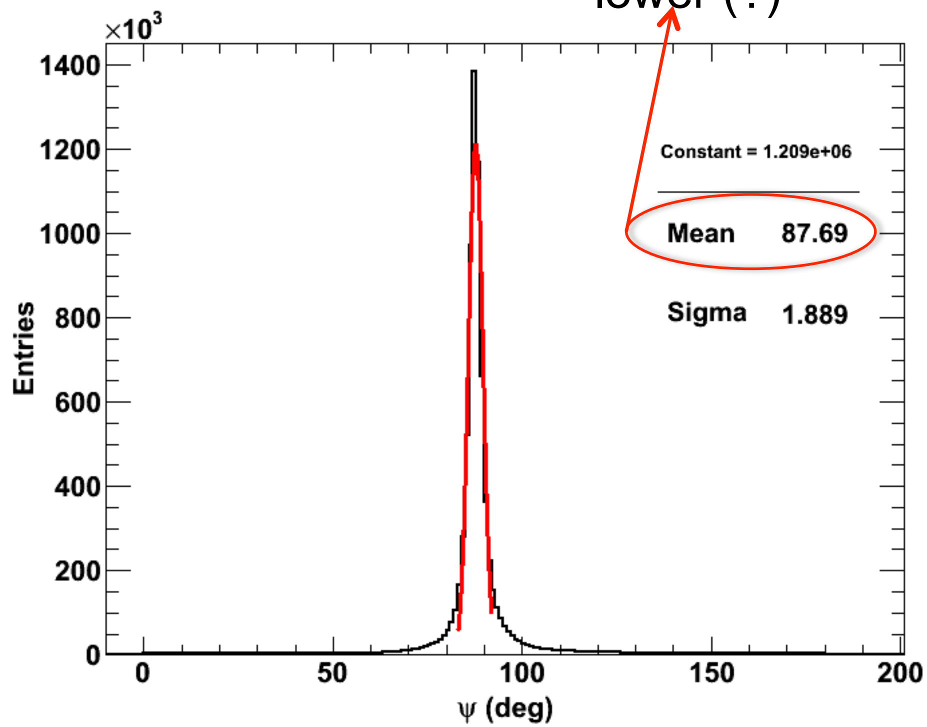


DO χ PDMS MAKE SENSE? LOOK AT ψ

From χ, angle relative to principal plane, calculate ψ, angle relative to scattering plane.

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

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



Angle of Linear Polarization
relative to scattering plane

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

where:

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