EMPIRICAL POLARIZATION DISTRIBUTION MODELS: UPDATE

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

POLARIZATION: RECAP

- Polarization state fully specified by degree of polarization *P*, angle of polarization χ and total intensity *I* (alternatively, may be specified by Stokes parameters *I, Q, U*)

Polarized radiance

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

Total reflectance *Total radiance*

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

where

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

- Uncertainty due to polarization contributes to uncertainty in reflectance:

Imager's sensitivity to polarization

$$\delta_{RI} = \sqrt{\delta_{\rho_0}^2 + \left(\frac{mP}{1+mP}\right)^2 (\delta_m^2 + \delta_P^2)}$$

CLARREO's own accuracy *Uncertainties in m and P*

- *m* is a function of χ. Sun and Xiong [2007] have shown *cyclical* dependence for MODIS. The exact dependence would be established by CLARREO instrument. For now, this dependence is folded into δ_m (use mean δ_m)

RECENT RESULTS

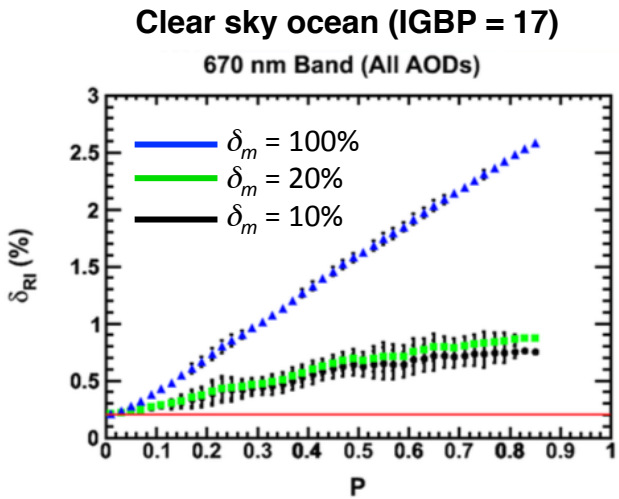
- "Empirical Polarization Distribution Models for CLARREO-Imager Intercalibration" (with Costy Lukashin) focusing on clear-sky ocean PDMs published in March in JTECH (doi:10.1175/JTECH-D-15-0165.1)
- Implemented a working version (C++/C) of the PDM module to retrieve degree of polarization P and angle of polarization χ, with corresponding std. dev., based on PARASOL data
- **Module inputs**: Solar Azimuth, Detector Azimuth, VZA, SZA, IGBP, wind speed (if ocean), cloud phase (if cloudy), cloud fraction, AOD (if clear) from MODIS/VIIRS, season (if applicable)
- **Module outputs**: empirical mean P, mean χ, δP, $\delta\chi$, theoretical P and χ (ADRTM)
- PDM lookup tables stored as **HDF files**
  - Have a working version of the module for the 8 PDMs with the highest polarizations and interpolated P and χ.
  - So far, PDMs are in the form of histogram bin values, but working on function fits (more on this in what follows)

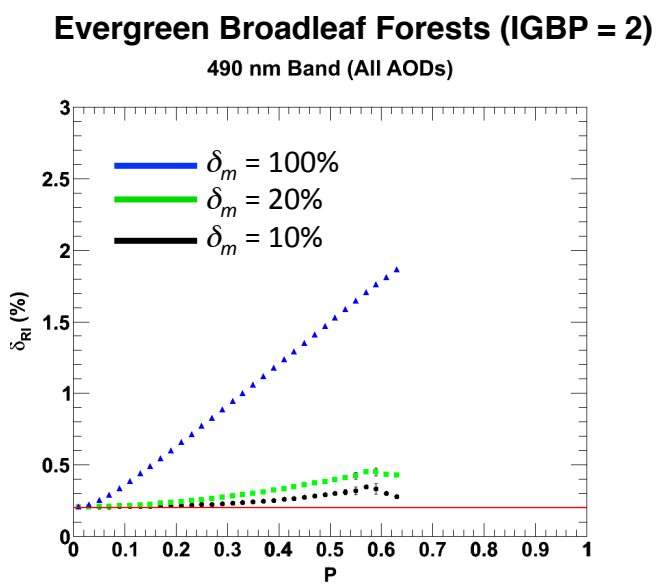
PDM CLASSIFICATION

- Compute total means and std. devs for P PDMs
- Consider highest polarization scenarios:
  - Pick shortest available wavelength (**λ = 490 nm**)
  - **SZA = 40** (close to the typical range of Brewster's angles)
- Start with PDMs at least 2 std. dev. away from 0
- The rest of the PDMs might need to be stratified by seasons. (Possibly more than one year of PARASOL data will be needed. Similar PDMs will also be combined.)
  - Indications that in some cases more data/ stratification will not help due to natural variability and resolution issues

IGBP	Surface Type	P mean	P std. dev.
1	Evergreen needle-leaf forest	0.19	0.11
2	Evergreen broad-leaf forest	0.26	0.07
3	Deciduous needle-leaf forest	0.14	0.11
4	Deciduous broad-leaf forest	0.20	0.11
5	Mixed forest	0.16	0.12
6	Closed shrubland	0.18	0.12
7	Open shrubland	0.17	0.10
8	Woody savannas	0.17	0.12
9	Savannas	0.23	0.06
10	Grasslands	0.18	0.09
11	Permanent wetlands	0.16	0.13
12	Croplands	0.20	0.08
13	Urban and Built-up	0.24	0.09
14	Cropland Mosaics	0.21	0.09
15	Permanent snow and ice	0.05	0.05
16	Bare soil and rocks	0.16	0.06
17	Water Bodies	0.31	0.08
18	Tundra	0.13	0.12

P UNCERTAINTIES

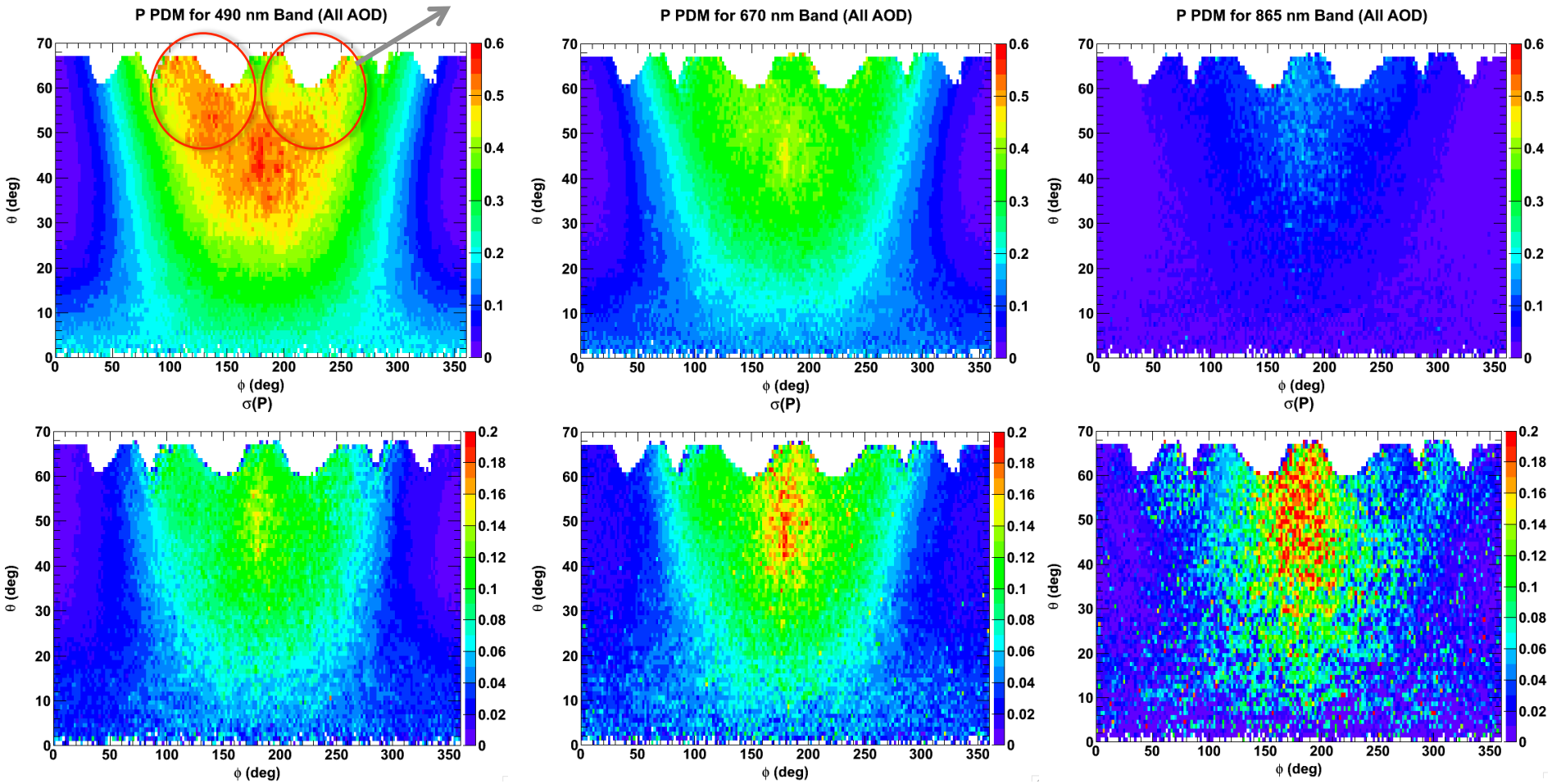




- Plot shows **intercal. uncertainty in reflectance** vs. degree of polarization assuming the intercalibrated imager's sensitivity to polarization m = 0.03 and δ_m set to three different values
- Considering CLARREO's own target uncertainty due to polarization $\delta_{\rho 0}$ = 0.15%, one can conclude that:
  - values of P < 0.1, may be considered below noise threshold. Thus:
    - due to sharp drop-off in P (e.g., next slide), some PDM's for 670 and 865 nm can be neglected
    - snow-covered surfaces can be neglected (IGBP=15, 19 and 20)
  - Low slope indicates intercal. P is insensitive to std. devs <≈ 0.1.
    - PDM uncertainties have roughly the necessary precision

P PDMs FOR EVERGREEN BROADLEAF FOREST (IGBP = 2)

Difference (north/south) in sampled regions (aerosols)



Sharp *P* drop-off

FIT FUNCTION

- Peform a χ^2 fit on *P* PDM:

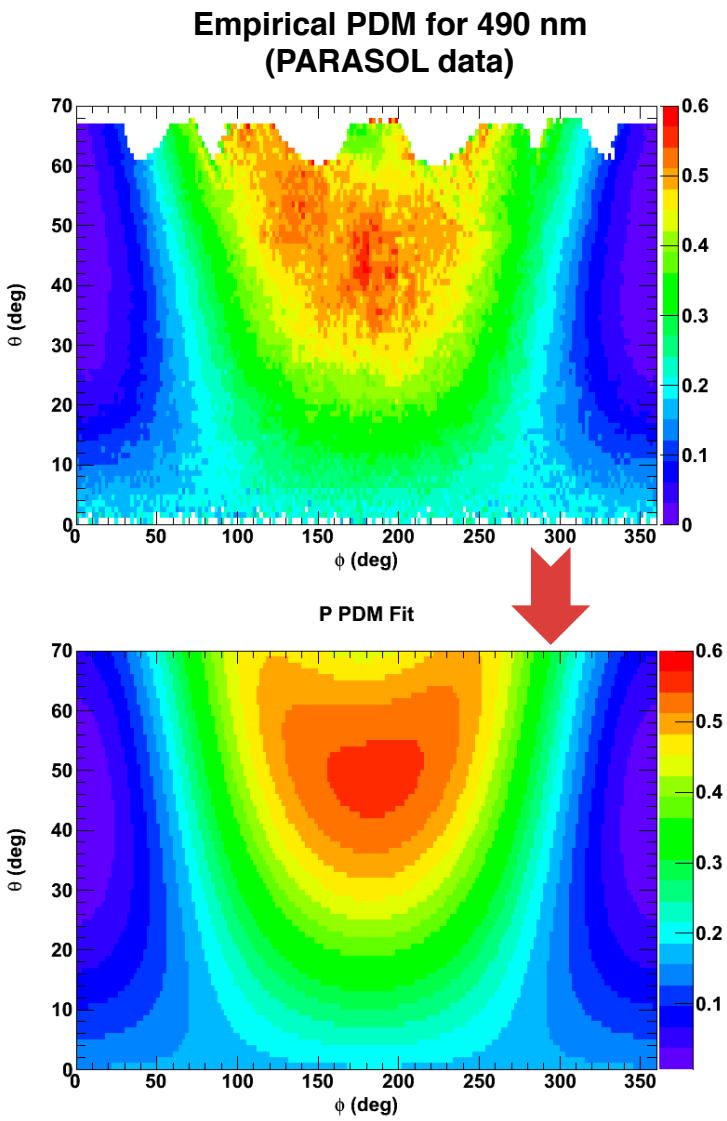
Gaussians describing (mostly) glint region

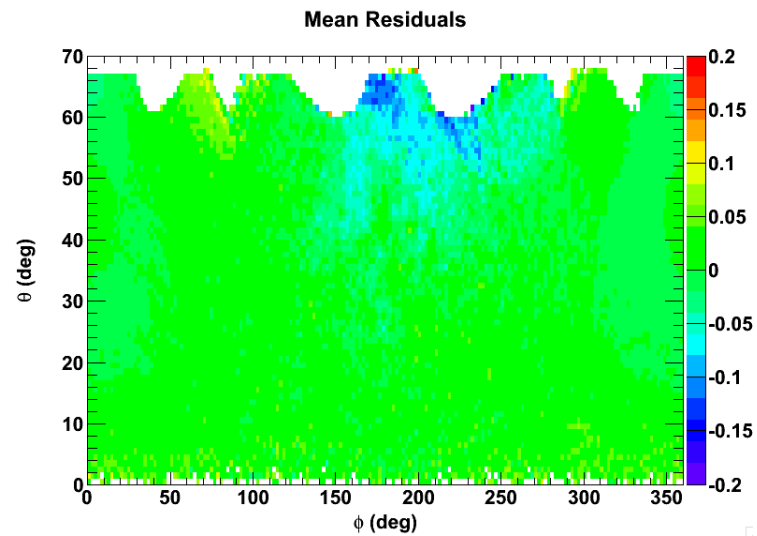
$$f(\phi,\theta) = N\exp\left(-\frac{(\phi-\mu_1)^2}{2\sigma_1^2}\right)\exp\left(-\frac{(\theta-\mu_2)^2}{2\sigma_2^2}\right) + \frac{1-\cos^2\Theta}{1+\cos^2\Theta+\frac{4}{3}AM\left\{\frac{\exp(-M\tau)}{1-\exp(-M\tau)}\right\}}$$

based on 1st order scattering approximation (away from glint)

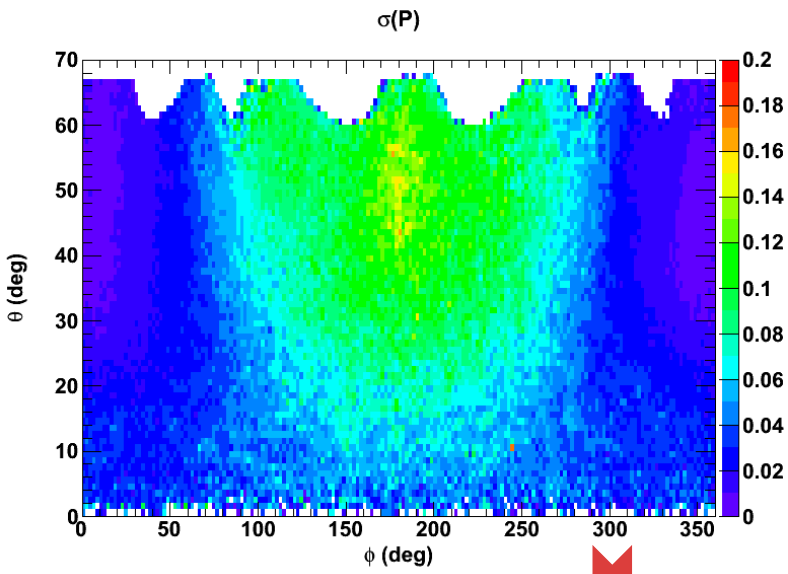
$\phi = RAZ$, $\theta = VZA$
$\cos\Theta = \cos\theta\cos\theta_s + \sin\theta\sin\theta_s\cos\phi$,
$M = 1/\cos\theta + 1/\cos\theta_s$
and N, μ_1, σ_1, μ_2, σ_2, A, τ are fit parameters.

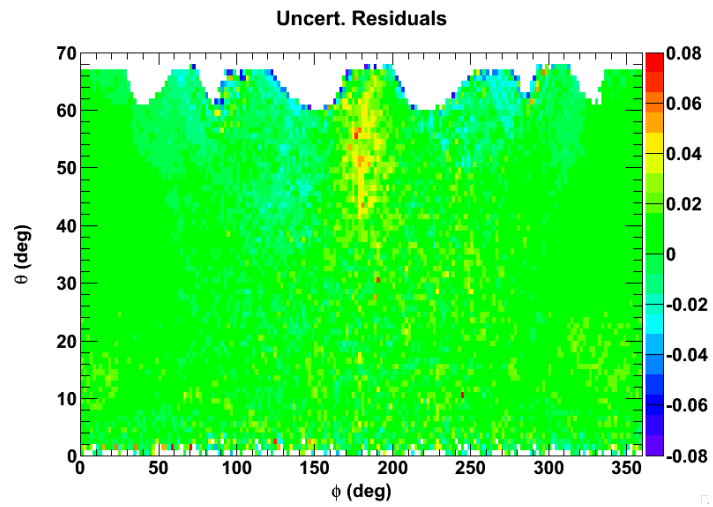
SAMPLE PDM FIT RESULTS (λ = 490 nm, 40°<SZA<50°): MEANS

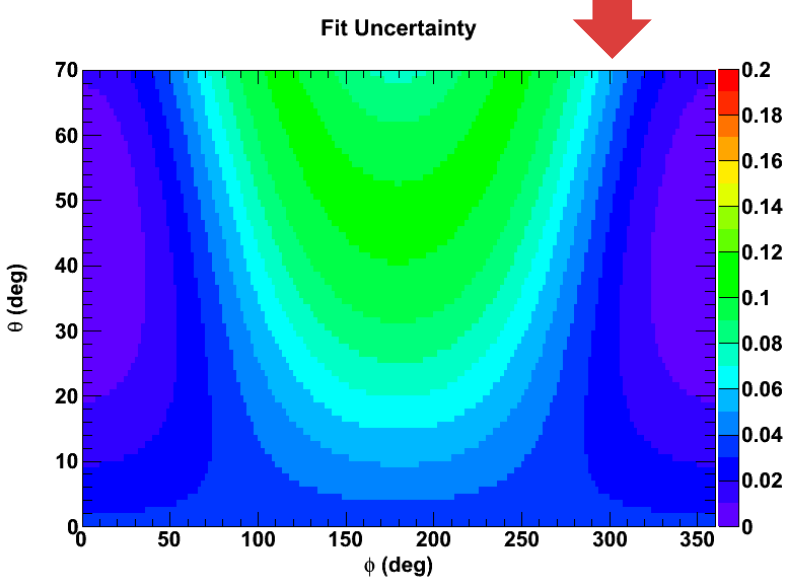




SAMPLE PDM FIT RESULTS (λ = 490 nm, 40°<SZA<50°): UNCERTAINTIES







70% C.L. (≈1σ) uncertainty

FIT QUALITY

χ^2/NDF = 0.818

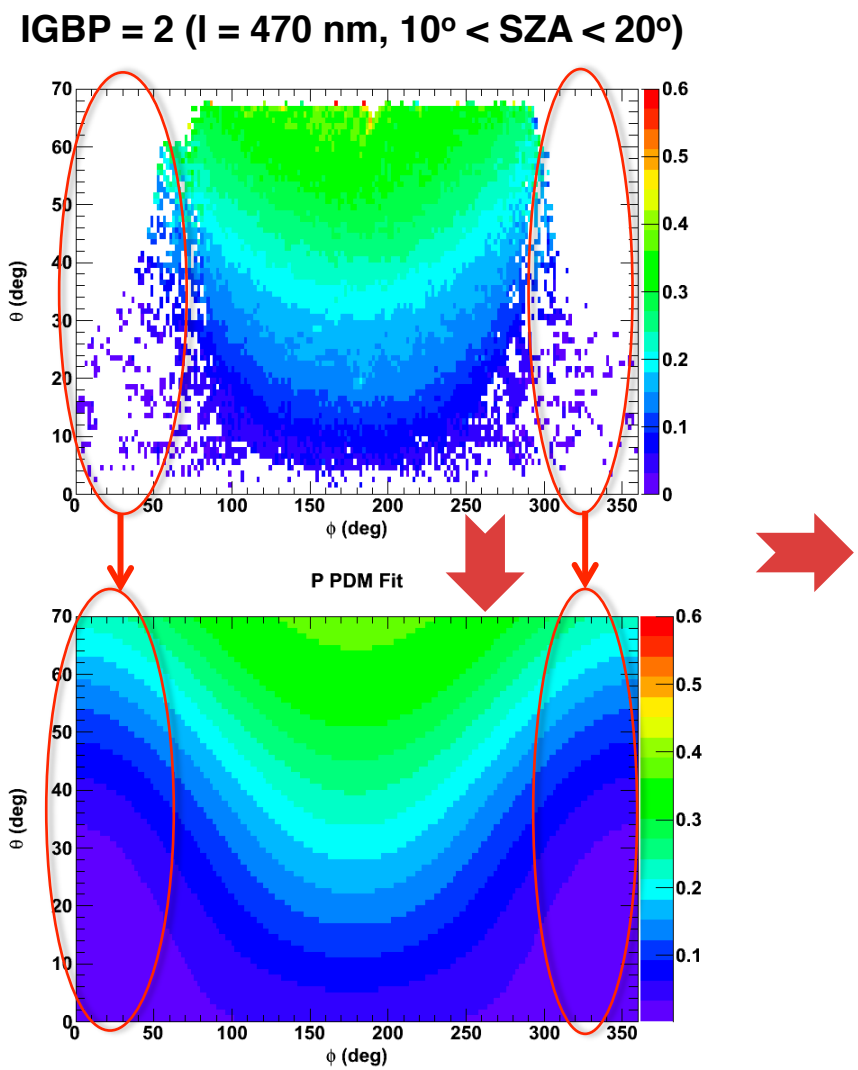
EXT NO.	PARAMETER NAME	VALUE	ERROR
1	N	1.55996e-01	1.24564e-02
2	$\mu 1$	1.85518e+02	1.55317e+00
3	$\sigma 1$	7.49105e+01	1.05573e+00
4	$\mu 2$	5.15448e+01	2.72753e+00
5	$\sigma 2$	2.71257e+01	1.68721e+00
6	θs	4.35347e+01	4.18066e-01
7	A	1.16881e-06	4.94814e-07
8	τ	1.02451e-06	4.34421e-07

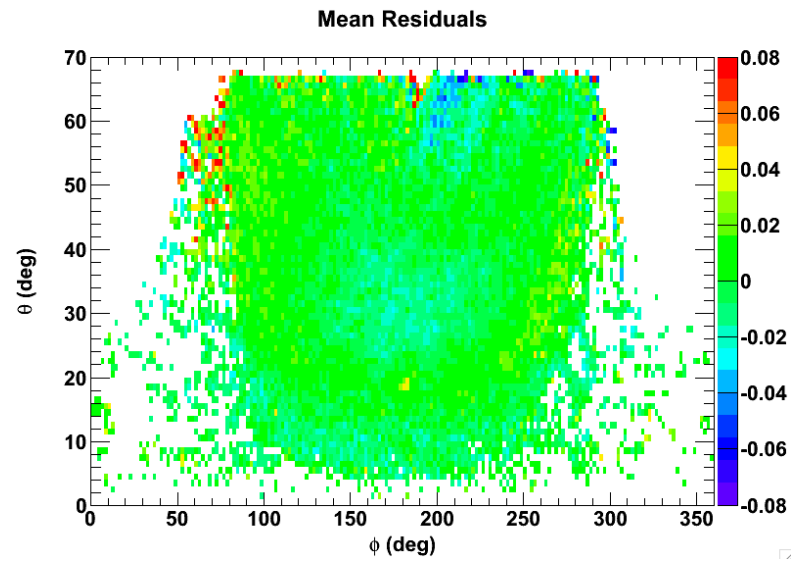
PARAMETER CORRELATION COEFFICIENTS

NO.	1	2	3	4	5	6	7	8
1	1.000	-0.270	-0.432	0.575	0.430	0.741	0.029	-0.060
2	-0.270	1.000	-0.017	-0.107	0.114	-0.241	-0.005	0.017
3	-0.432	-0.017	1.000	-0.007	-0.008	-0.102	-0.006	0.009
4	0.575	-0.107	-0.007	1.000	0.785	0.706	0.017	-0.051
5	0.430	0.114	-0.008	0.785	1.000	0.331	0.029	-0.034
6	0.741	-0.241	-0.102	0.706	0.331	1.000	0.015	-0.068
7	0.029	-0.005	-0.006	0.017	0.029	0.015	1.000	0.995
8	-0.060	0.017	0.009	-0.051	-0.034	-0.068	0.995	1.000

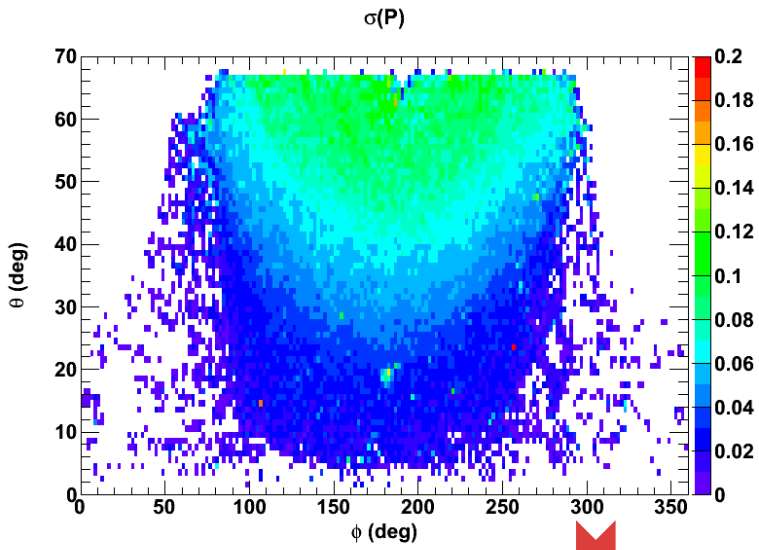
Highly correlated

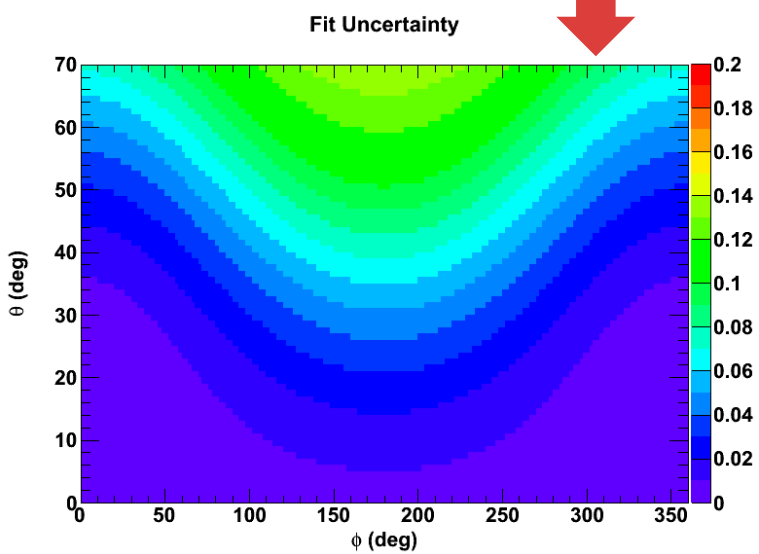
SAMPLE PDM FIT RESULTS (λ = 490 nm, 10°<SZA<20°): MEANS

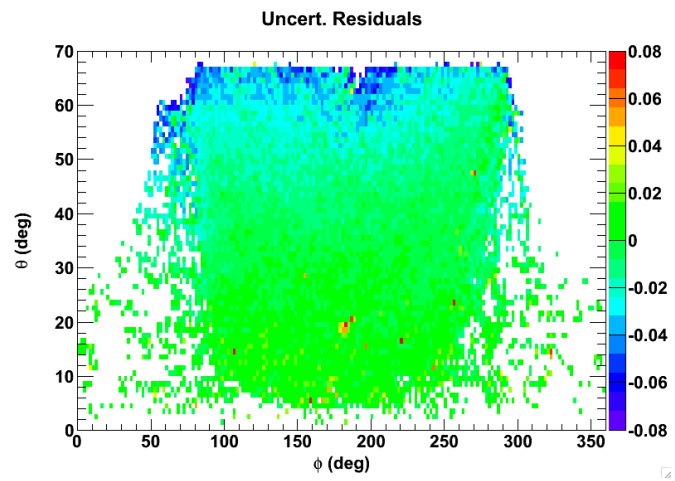




SAMPLE PDM FIT RESULTS (λ = 490 nm, 10°<SZA<20°): UNCERTAINTIES







FIT QUALITY

χ^2/NDF = 0.197

EXT NO.	PARAMETER NAME	VALUE	ERROR
1	N	7.24370e-02	7.24231e-03
2	$\mu 1$	1.77770e+02	1.09914e+00
3	$\sigma 1$	7.67892e+01	3.81888e+00
4	$\mu 2$	2.44281e+01	3.78188e+00
5	$\sigma 2$	2.29358e+01	3.58394e+00
6	θs	7.77357e+00	1.10029e+00
7	A	5.51248e-07	2.93038e-07
8	τ	4.75676e-07	2.47620e-07

PARAMETER CORRELATION COEFFICIENTS

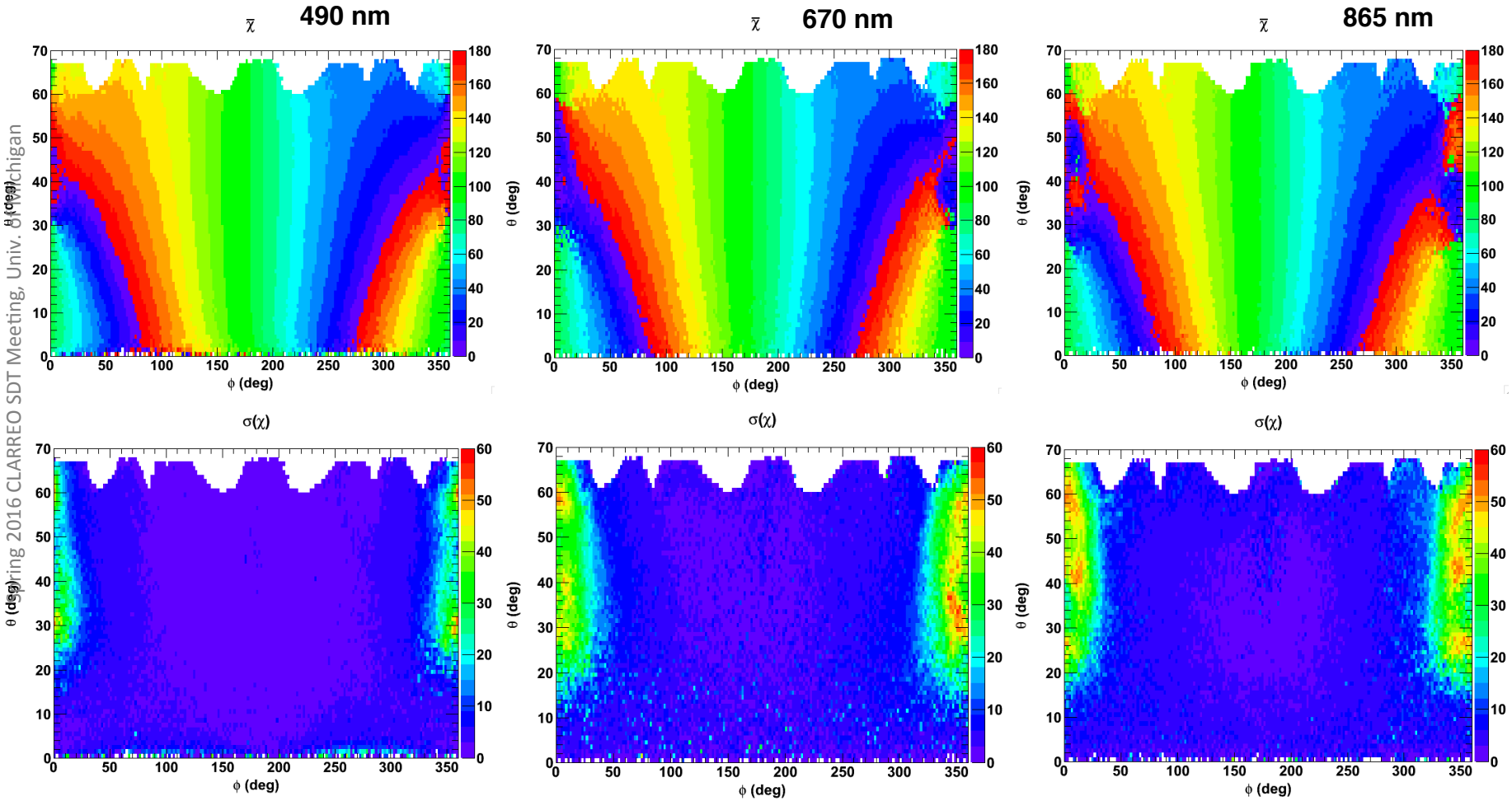
NO.	1	2	3	4	5	6	7	8
1	1.000	0.189	0.283	0.744	0.568	-0.705	0.024	-0.079
2	0.189	1.000	0.314	0.112	0.324	-0.162	0.009	-0.018
3	0.283	0.314	1.000	0.037	0.304	-0.136	0.003	-0.016
4	0.744	0.112	0.037	1.000	0.873	-0.268	0.145	-0.014
5	0.568	0.324	0.304	0.873	1.000	-0.244	0.129	-0.013
6	-0.705	-0.162	-0.136	-0.268	-0.244	1.000	0.135	0.133
7	0.024	0.009	0.003	0.145	0.129	0.135	1.000	0.984
8	-0.079	-0.018	-0.016	-0.014	-0.013	0.133	0.984	1.000

P PDMS: SUMMARY

- PDM fits, advantages:
  - As with any fits, PDM fits useful to smooth out statistical fluctuations and fill gaps in data
  - Compact (only 7-8 parameters) and universal (applied to any scene type)
  - Robust, even for low-statistics PDMs
- Final empirical P PDMs will be recorded in the form of the fit coefficients to $f(\phi,\theta)$ and per-bin fit uncertainties.

χ DISTRIBUTIONS (IGBP = 2)

$40^o < SZA < 50^o$



χ: SINGLE SCATTERING APPROXIMATION

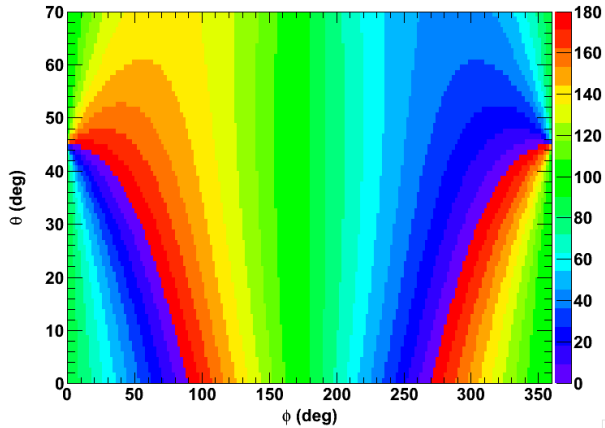
$$\cos \chi_{ss} = \frac{\sin \theta_s \sin \phi}{\sin \Theta},$$

$\phi = RAZ$, $\theta = VZA$

$\cos \Theta = \cos \theta \cos \theta_s + \sin \theta \sin \theta_s \cos \phi,$

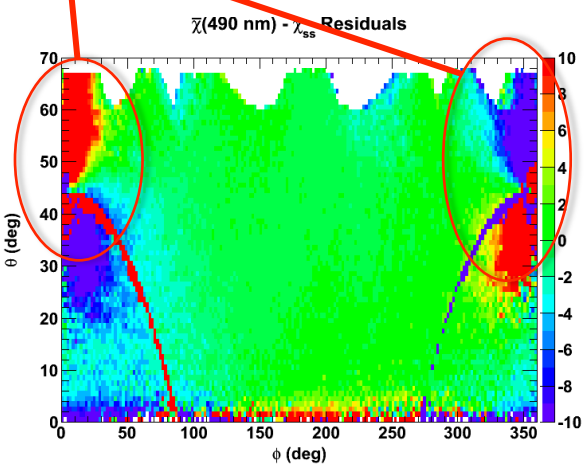
EMPIRICAL PDM – SINGLE SCATTERING COMPARISON

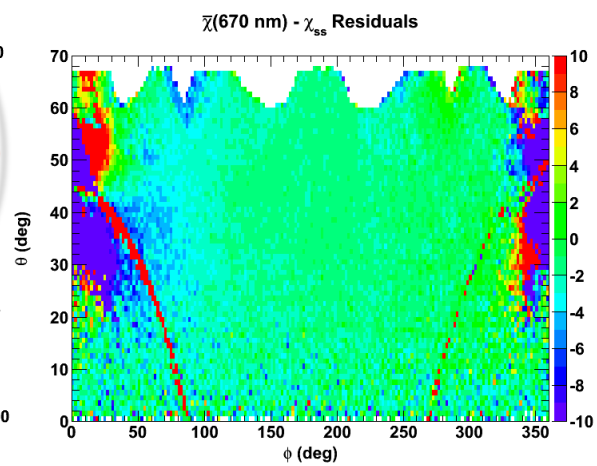
Single Scattering χ_{ss}

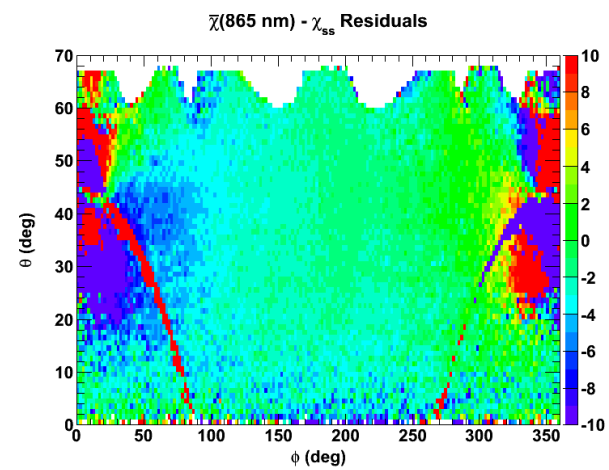


Not a fit, χ_{ss} function from previous slide

χ limited by Q resolution



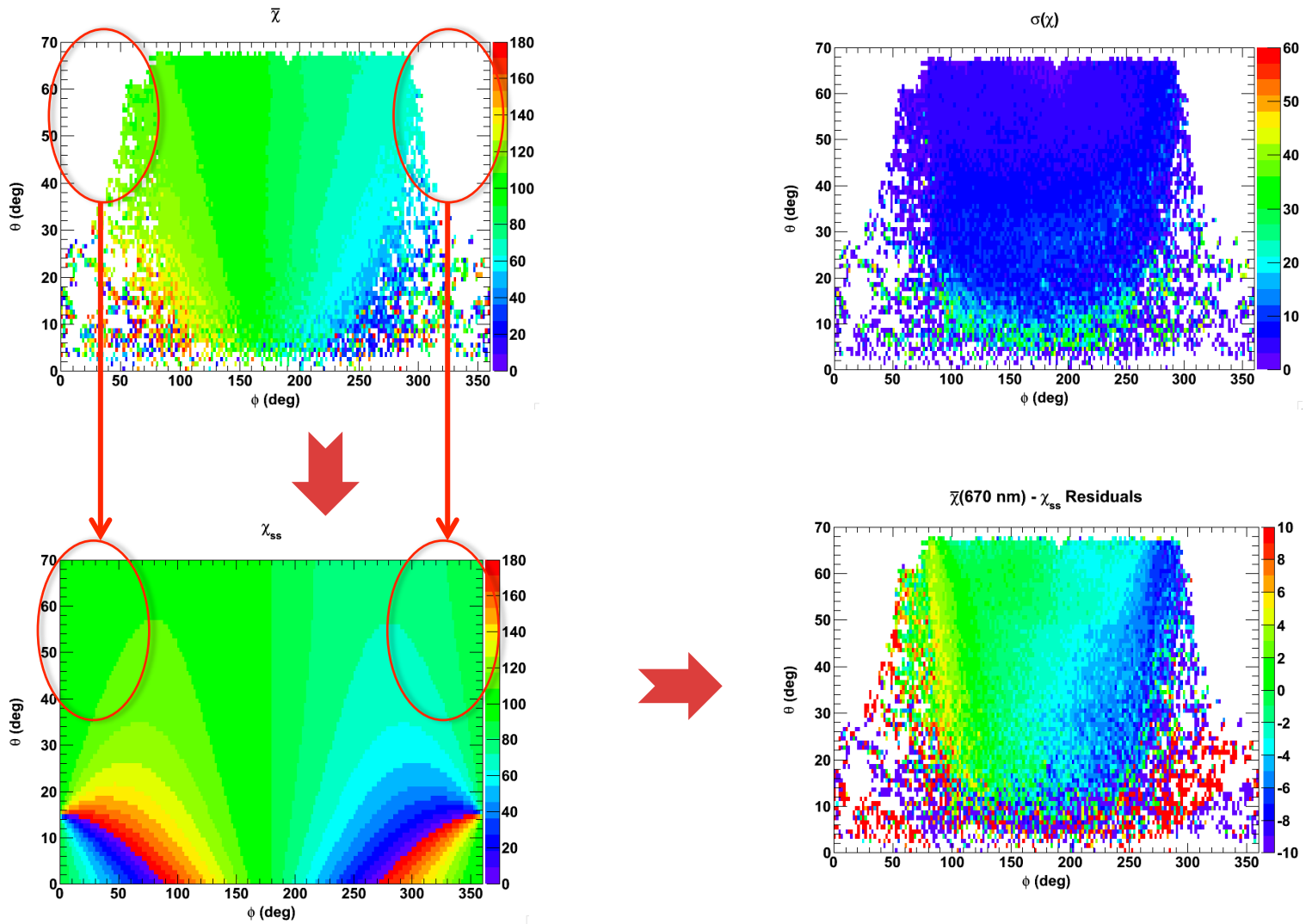




Residuals show more bias at larger λ

LOW STATISICS χ PDM (670 NM)

10° < SZA < 20°



χ PDMS: SUMMARY

- Single scattering χ agrees with empirical χ to within +/-4° in the 50° < RAZ < 310° region
- In the region RAZ = 0°/360°, SZA = VZA:
  - PARASOL has low resolution in χ
  - Single scattering most likely not a good approximation there: higher order scattering model needed
- Plan to use hybrid approach for final recorded χ values:
  - Region around RAZ = 0°/360°, SZA = VZA use empirical means + uncertainties
  - Elsewhere for bins with sufficient statistics (e.g. > 10 entries) use empirical means + uncertainties. For low stats bins or bins with 0 entries use χ_{ss} approximation (=> no uncertainties)

TO BE DONE

- Fits for P PDMs for highest polarizations
- Finish χ PDMs for highest polarizations
- Work on lower polarizations
- Implement ice & water clouds PDMs

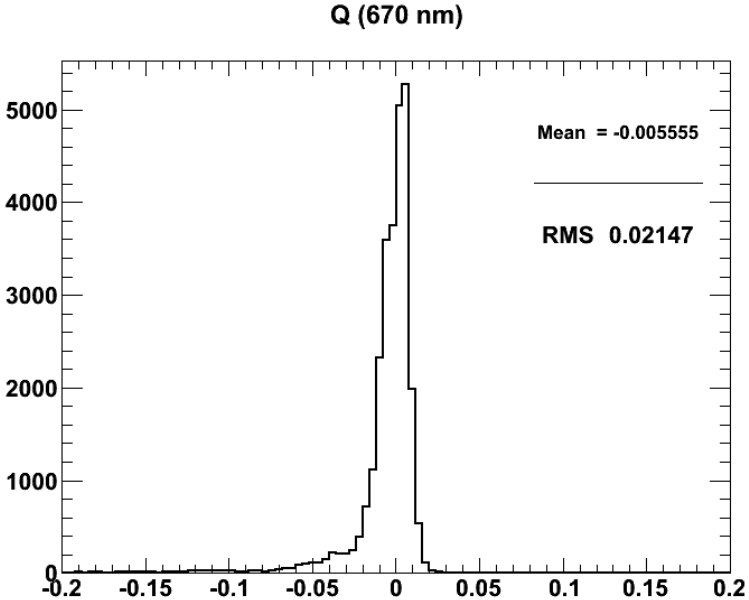
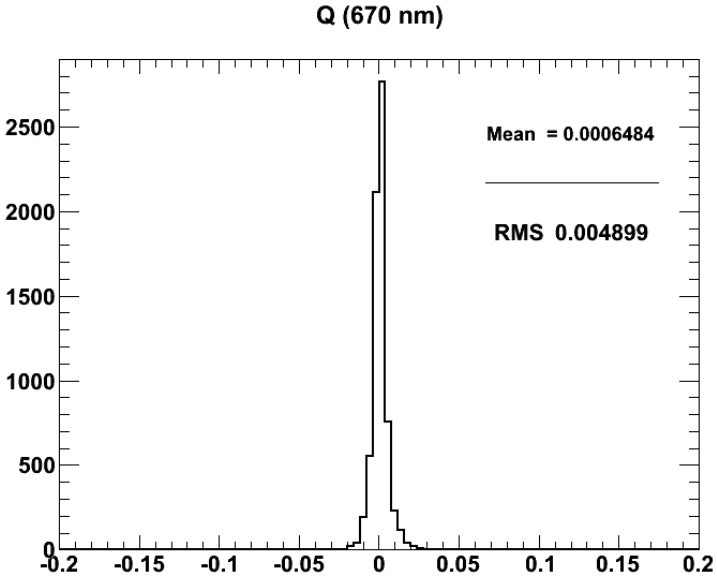
BACKUP

HIGH χ UNCERTAINTY REGIONS

- Regions RAZ = 0°/360°, SZA = VZA have Stokes paramer ≈ 0°, close to PARASOL's resolution
- For single scattering Q = 0 is undefined, need higher order scattering:

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

χ PDM central region: 50 < RAZ < 300



χ PDM high-uncertainty region: RAZ > 310, VZA > 30