Aquarius Radar Cal / Val and Results
4th SMAP Cal/Val Workshop
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Outline of Talk

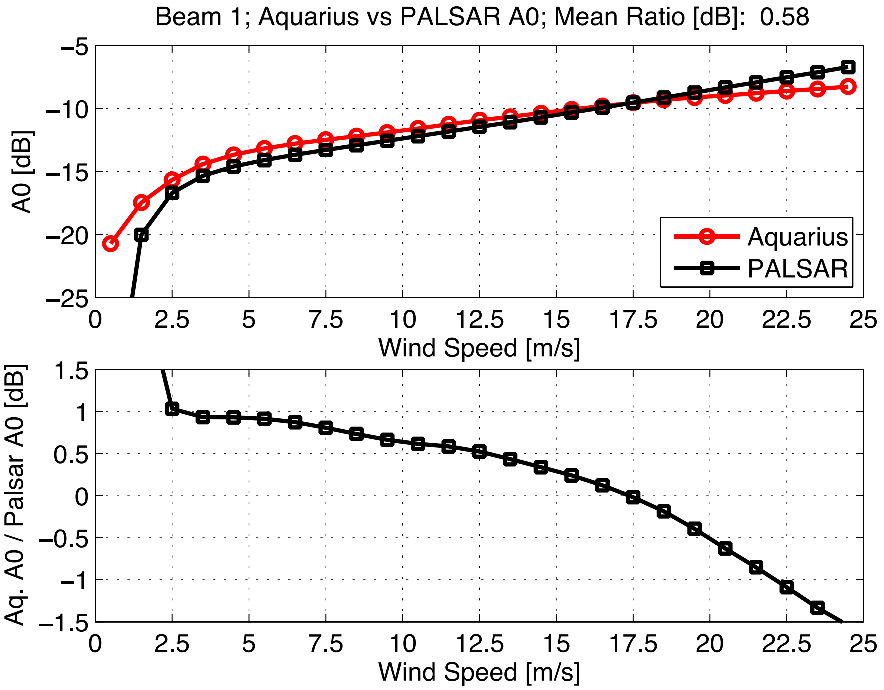
- Radiometric calibration used for Aquarius
  - Relative calibration to PALSAR over ocean and land
  - Tracking of long term calibration stability over ocean
- Faraday rotation estimation and correction:
  - Scatterometer Faraday rotation correction
  - Estimation of the antenna pattern correction (APC) from the data itself
  - Improved radiometer Faraday rotation estimates
- Wind retrieval algorithms and performance:
  - Scatterometer-only winds
  - Combined Active Passive (CAP) winds

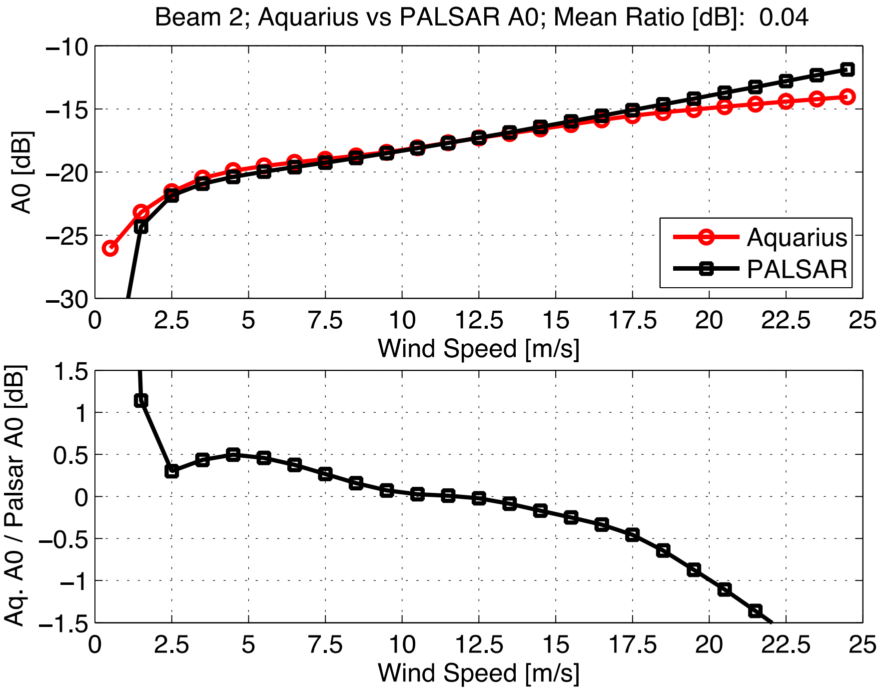
Ocean Comparison
Aquarius HH / PALSAR HH

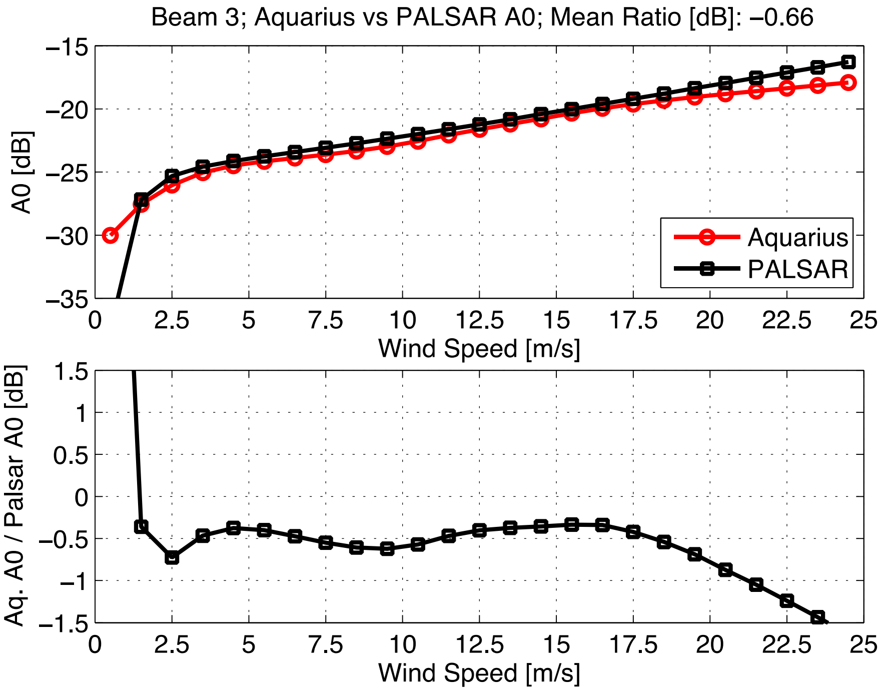
Plots of PALSAR HH GMF (black square)
and our Aquarius HH GMF (red o)

Beam	1	2	3
Mean Ratio [dB]	0.58	0.04	-0.66

Table computing wind speed PDF weighted mean ratio of Aquarius GMF divided by PALSAR GMF


Beam 1; Aquarius vs PALSAR A0; Mean Ratio [dB]: 0.58

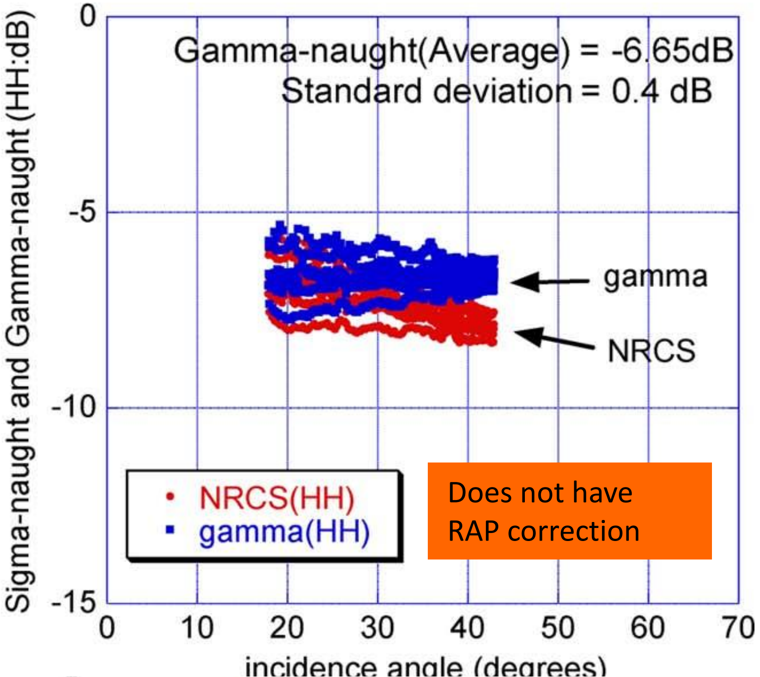

Beam 2; Aquarius vs PALSAR A0; Mean Ratio [dB]: 0.04


Beam 3; Aquarius vs PALSAR A0; Mean Ratio [dB]: −0.66

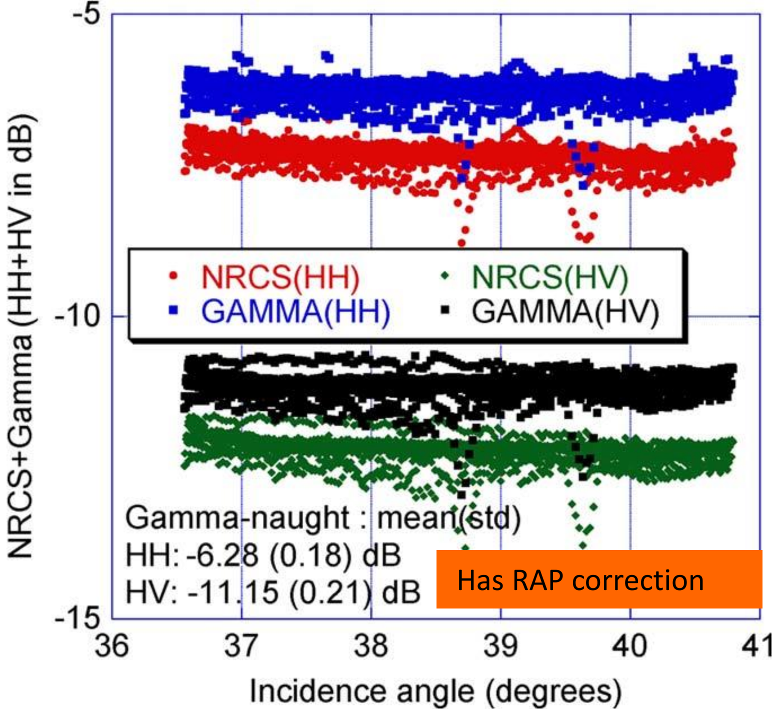
Amazon γ_0

$$\gamma_0 = \sigma_0 / \cos(\theta_{inc})$$

- PALSAR found γ_0 values in the Amazon stable across 20-45 degrees in incidence angle*
  - Wet-dry seasonal difference of ~ 0.27 dB**
  - Wet season is approx. Nov-April
- Best estimates are:
  - HH ~ -6.28 dB (std 0.18)
  - HV ~ -11.15 dB (std 0.21)



Does not have RAP correction



Has RAP correction

*M. Shimada, O. Isoguchi, T. Tadono, and K. Isono. Palsar radiometric and geometric calibration. Geoscience and Remote Sensing, IEEE Transactions on, 47(12):3915 – 3932, dec. 2009 (Images from this source)

**M. Shimada. Long-term stability of l-band normalized radar cross section of amazon rainforest using the jers-1 sar. Canadian Journal of Remote Sensing, 31(1):132–137, 2005.

RAP correction is range antenna pattern correction

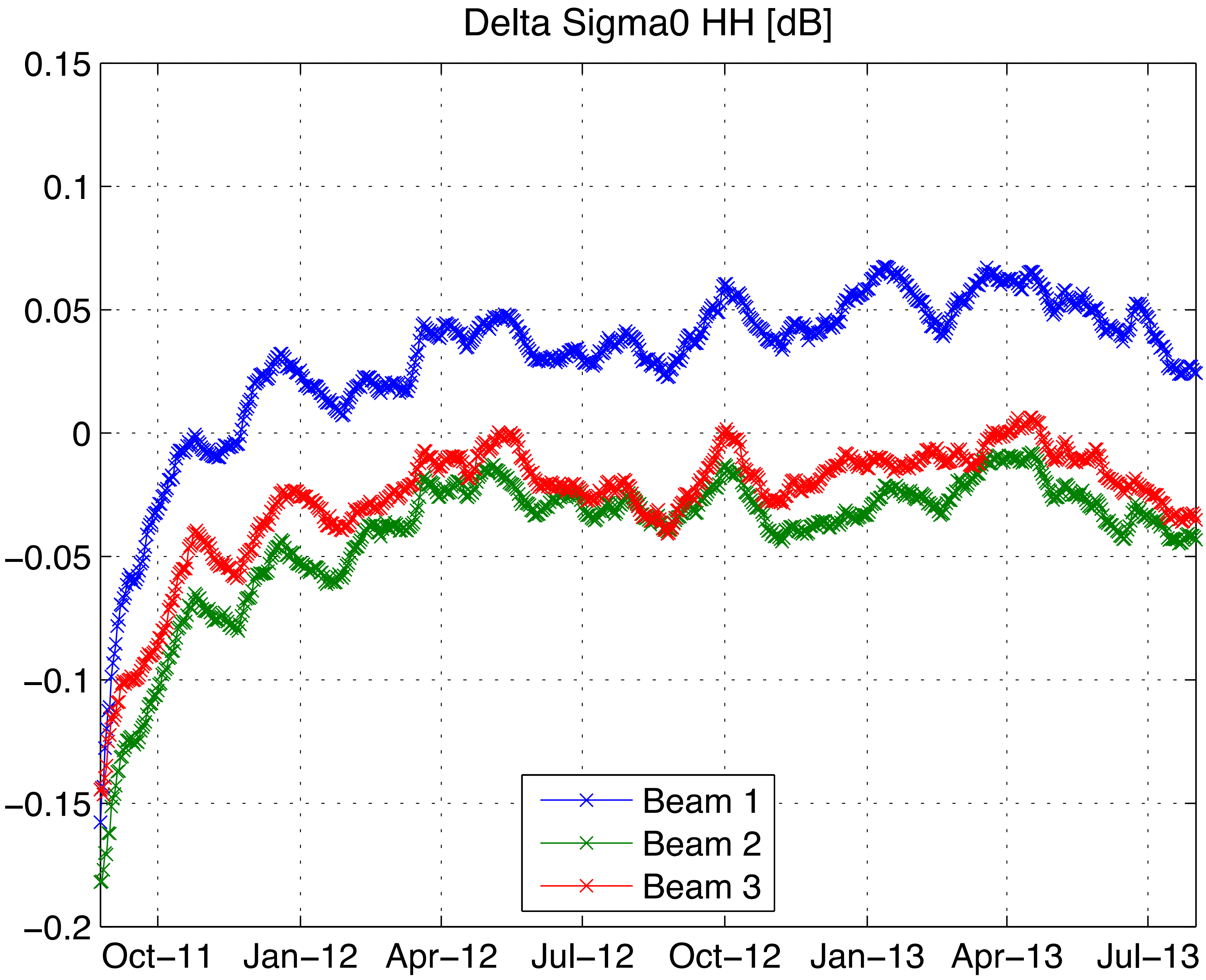
Amazon bias estimation compared to PALSAR
PALSAR values: HH: -6.28 dB; HV: -11.15 dB

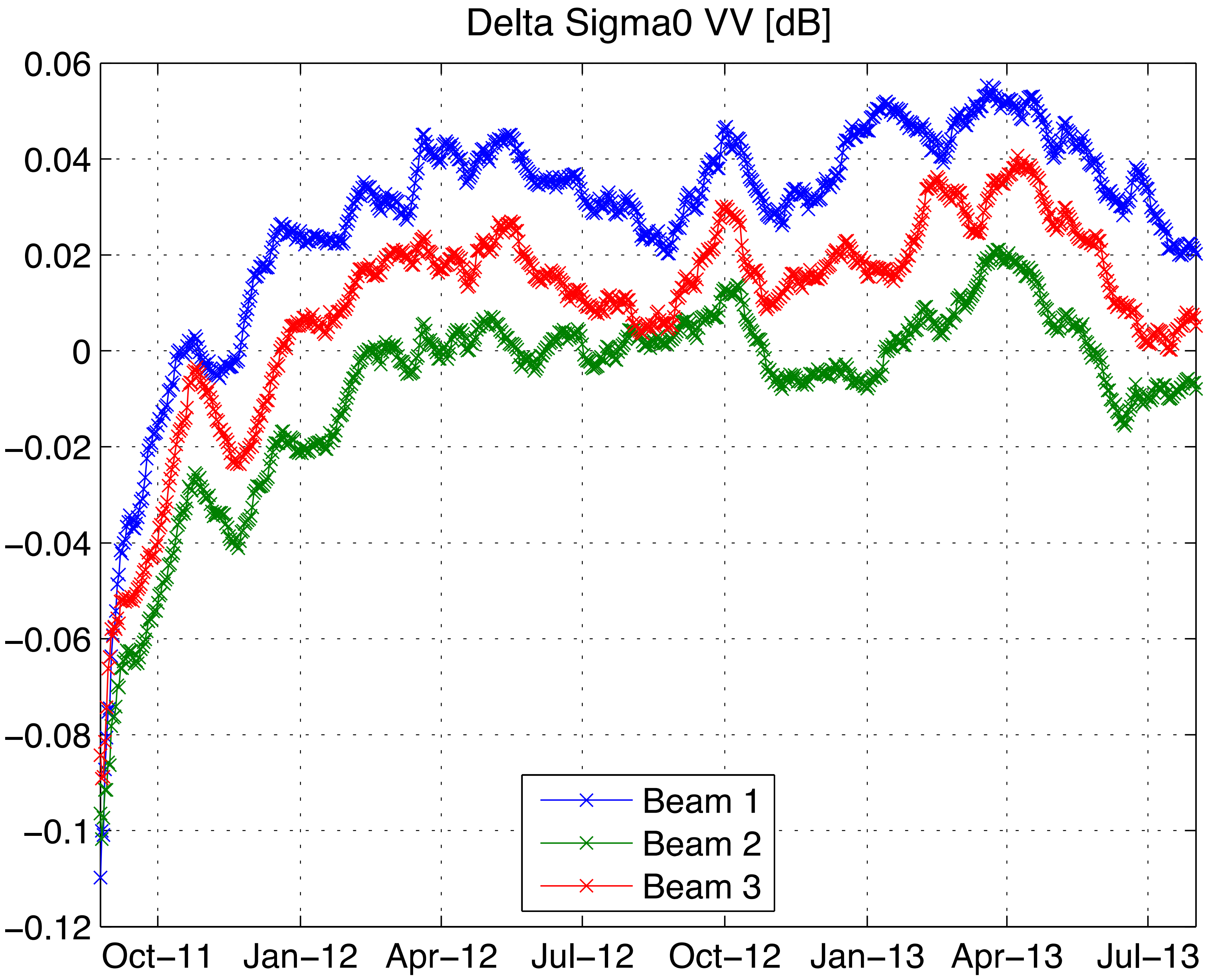
Asc / Dec	Beam 1	Beam 2	Beam 3
All HH	-0.04	-0.04	0.02
Ascending HH	-0.02	-0.05	-0.03
Descending HH	-0.07	-0.03	0.10
All VV	-0.09	-0.02	0.01
Ascending VV	-0.07	-0.04	0.00
Descending VV	-0.11	0.00	0.03
All HV	0.01	0.11	0.05
Ascending HV	0.03	0.09	0.01
Descending HV	-0.02	0.13	0.10

No significant ascending / descending difference

Computation of Scatterometer Stability

- We compare the observed TOA HH and VV NRCS to the expected HH / VV NRCS
  - Require no RFI detected
  - Require latitude within +/- 50
  - Require NCEP to be within [3,15] m/s
  - Filter out known anomalous revs
- Compute the moving 28 day window average of:
  - $\Delta\sigma_0 = (\sigma_0^{obs} - \sigma_0^{gmf})/\sigma_0^{gmf}$, in natural units
  - Plot $\Delta\sigma_0$ in dB


Delta Sigma0 HH [dB]
0.15
0.1
0.05
0
−0.05
−0.1
−0.15
−0.2
Oct−11
Jan−12
Apr−12
Jul−12
Oct−12
Jan−13
Apr−13
Jul−13
Beam 1
Beam 2
Beam 3


Delta Sigma0 VV [dB]
0.06
0.04
0.02
0
−0.02
−0.04
−0.06
−0.08
−0.1
−0.12
Oct−11
Jan−12
Apr−12
Jul−12
Oct−12
Jan−13
Apr−13
Jul−13
Beam 1
Beam 2
Beam 3

Faraday Rotation Correction

- For correction of scatterometer data:
  - Use ancillary total electron content and magnetic field model of the Earth
  - Use non-linear cost function to find optimal Faraday rotation corrected σ_0, given the observed σ_0 and model Faraday rotation angle
- Aquarius also measures 3rd Stokes, enabling estimation of Faraday rotation for polarized regions
  - Radiometer based estimates much better over oceans than land
  - Faraday rotation estimate is sensitive to cross-pol isolation

Model Faraday Angle:

$$\theta_F = 2.6 \times 10^{-13}\,\mathrm{TEC}_{\mathrm{slant}} B \lambda^2 \cos\chi$$

Non-Linear Measurement Model:

$$\sigma^M_{HH} = \sigma^{true}_{HH}\cos^4\theta_F + \sigma^{true}_{VV}\sin^4\theta_F - 2\rho_{HHVV}\cos^2\theta_F\sin^2\theta_F\sqrt{\sigma^{true}_{VV}\sigma^{true}_{HH}}$$

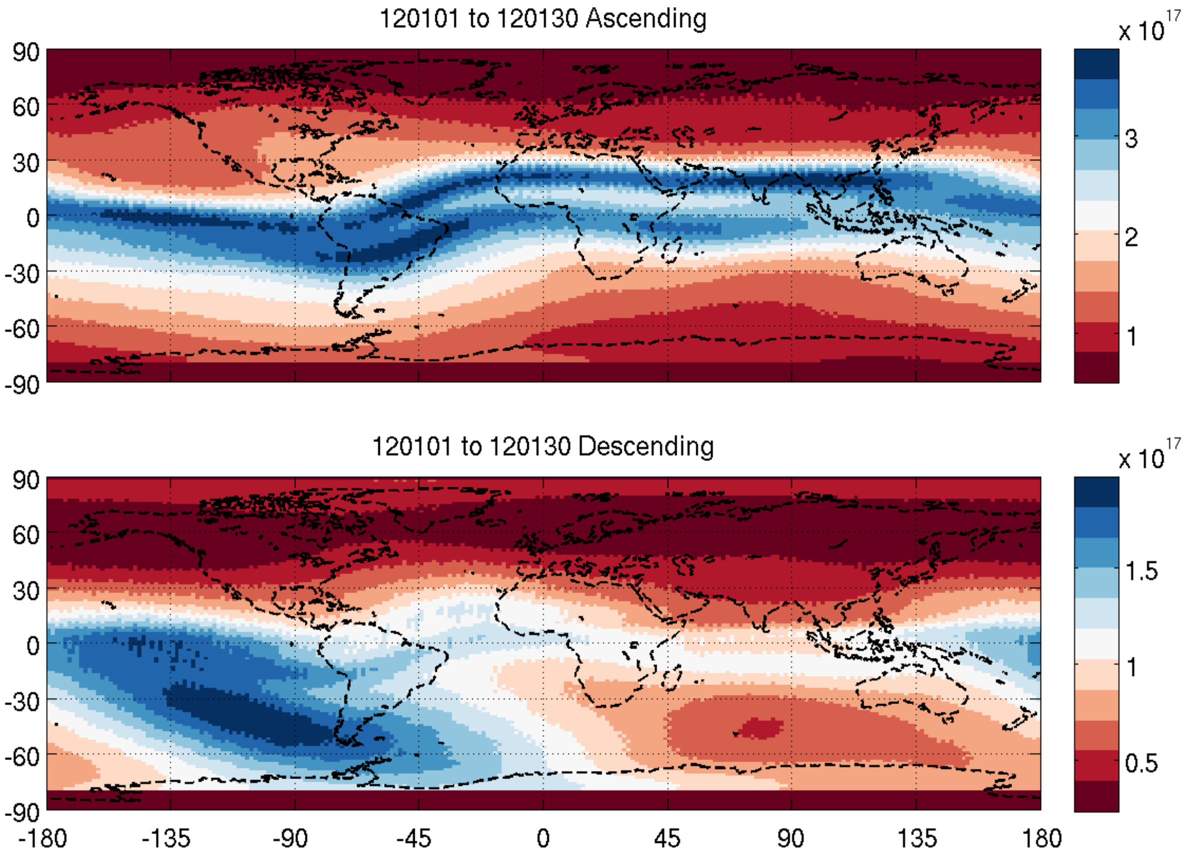
$$\sigma^M_{VV} = \sigma^{true}_{HH}\sin^4\theta_F + \sigma^{true}_{VV}\cos^4\theta_F - 2\rho_{HHVV}\cos^2\theta_F\sin^2\theta_F\sqrt{\sigma^{true}_{VV}\sigma^{true}_{HH}}$$

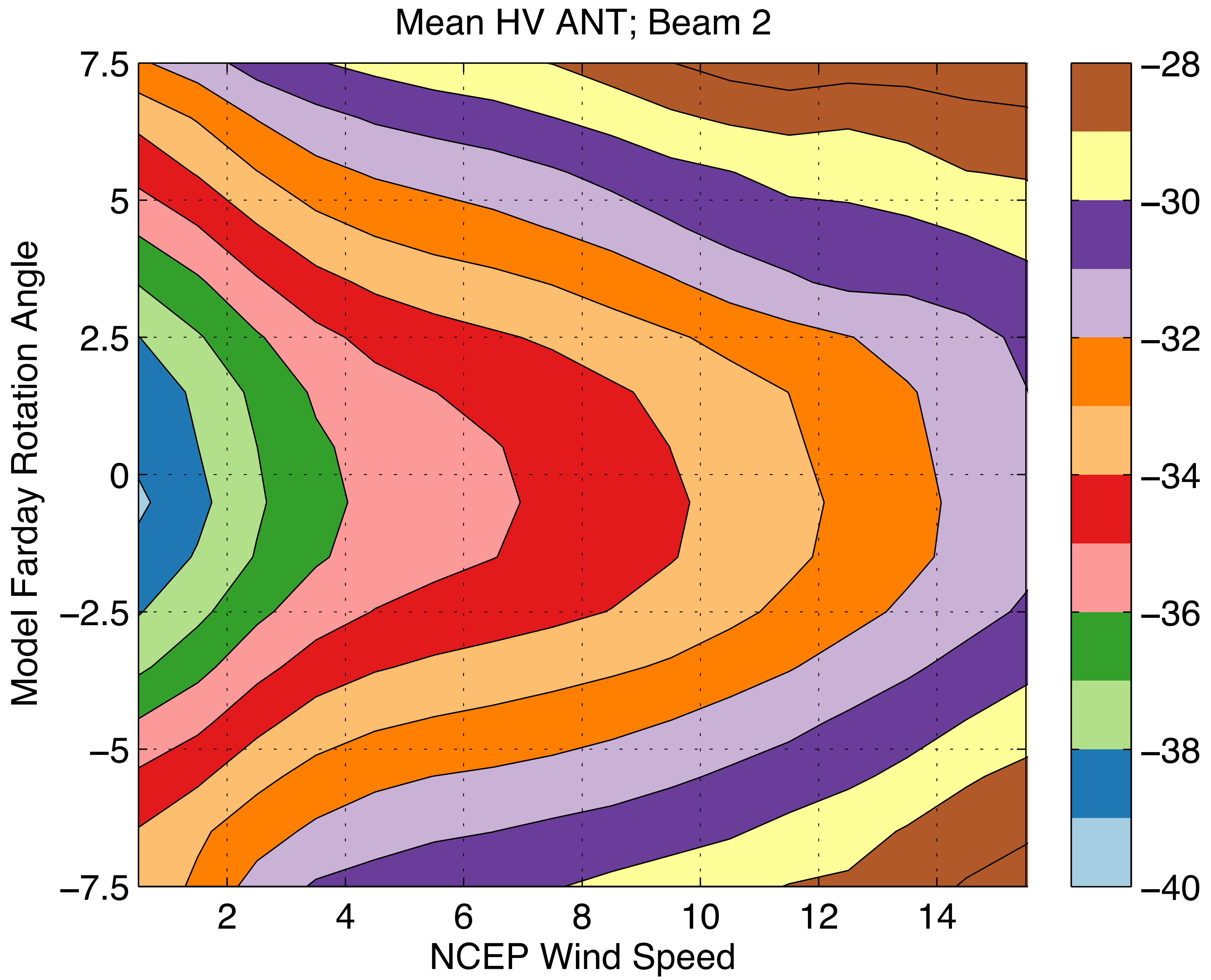
$$\sigma^M_{HV} = \frac{1}{2}\left(f_{HHHV}\sigma^{true}_{HH} + f_{VVHV}\sigma^{true}_{VV}\right) + \left(\sigma^{true}_{HH} + \sigma^{true}_{VV} + 2\rho_{HHVV}\sqrt{\sigma^{true}_{VV}\sigma^{true}_{HH}}\right)\cos^2\theta_F\sin^2\theta_F$$

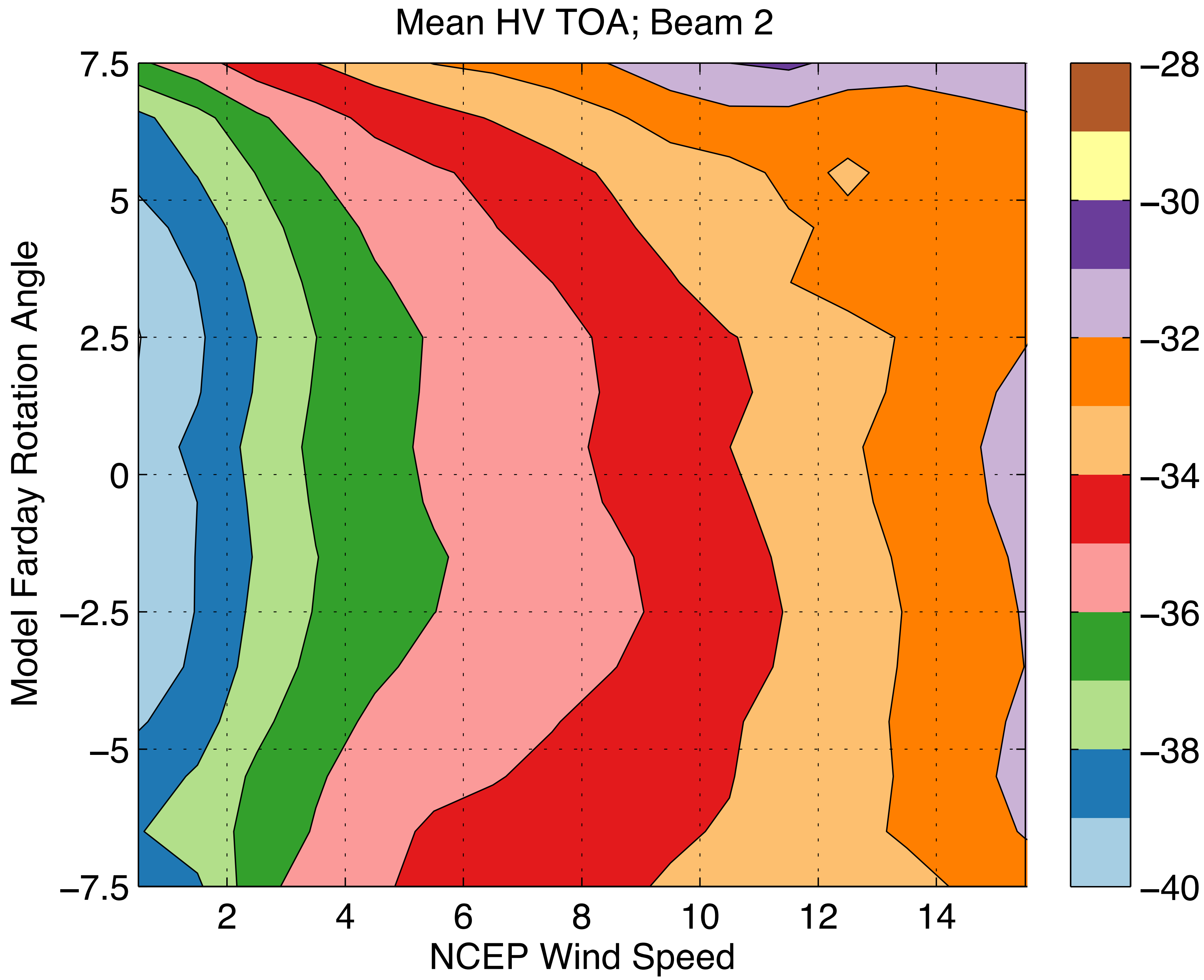
Cost Function

$$J\left(\sigma^{true}_{HH}, \sigma^{true}_{VV}\right) = \sum_{ipol=HH,VV}\left(\sigma^{obs}_{ipol}\ln\left(\frac{\sigma^{obs}_{ipol}}{\sigma^{M}_{ipol}}\right)\right)^2$$

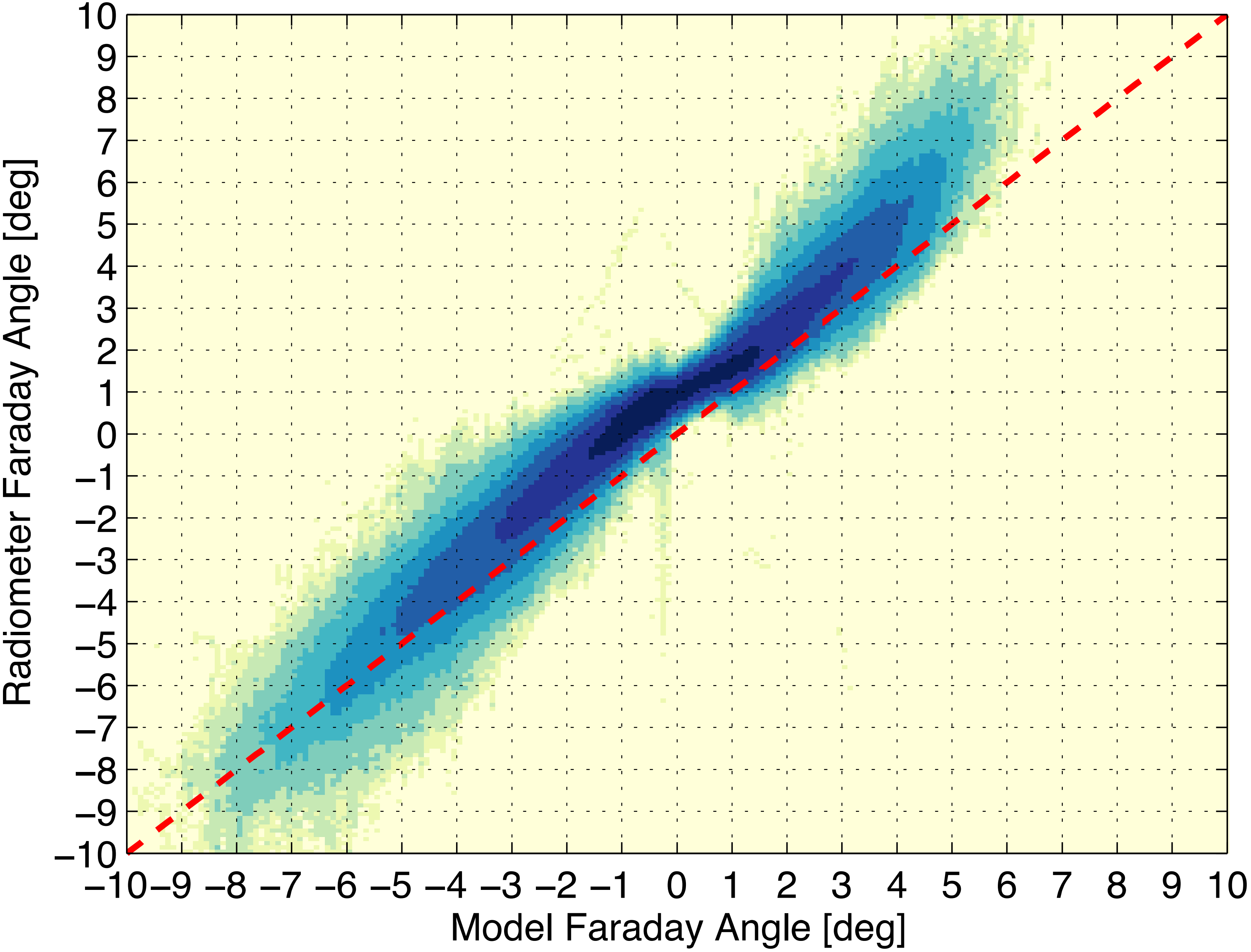
Total Electron Content Scaled to Aquarius Altitude

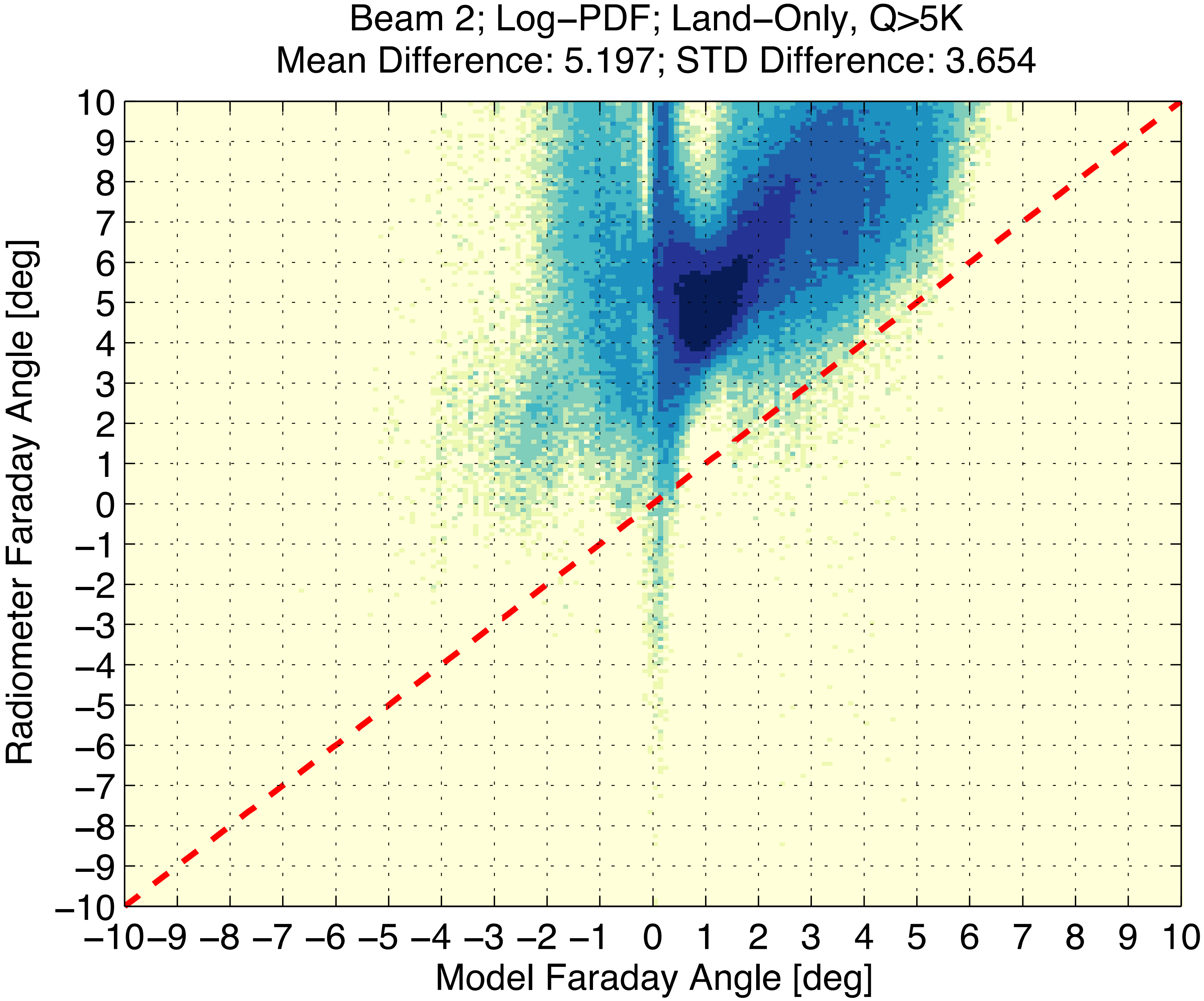



Mean HV ANT; Beam 2
Model Farday Rotation Angle
7.5
5
2.5
0
−2.5
−5
−7.5
2
4
6
8
10
12
14
NCEP Wind Speed
−28
−30
−32
−34
−36
−38
−40


Mean HV TOA; Beam 2
Model Farday Rotation Angle
7.5
5
2.5
0
−2.5
−5
−7.5
2
4
6
8
10
12
14
NCEP Wind Speed
−28
−30
−32
−34
−36
−38
−40

Beam 2; Log−PDF; Ocean−Only
Mean Difference: 0.785; STD Difference: 0.599



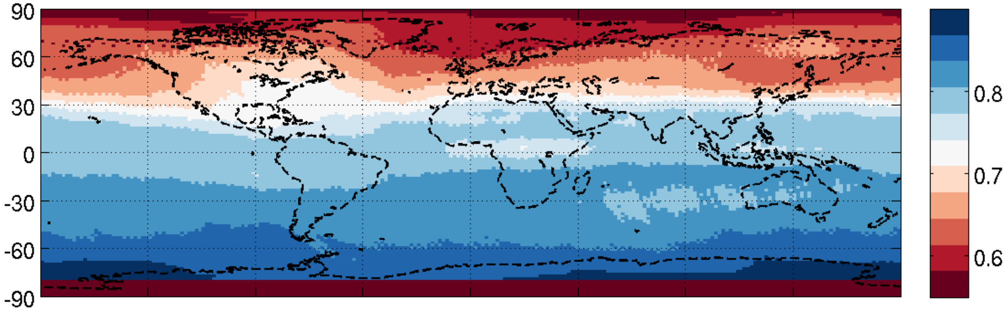

Beam 2; Log−PDF; Land−Only, Q>5K
Mean Difference: 5.197; STD Difference: 3.654
Radiometer Faraday Angle [deg]
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
−10
−9
−8
−7
−6
−5
−4
−3
−2
−1
0
1
2
3
4
5
6
7
8
9
10
Model Faraday Angle [deg]

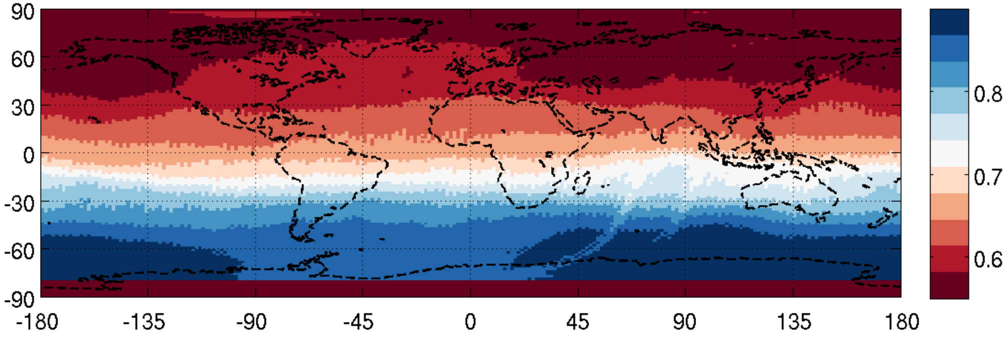
Derivation of Radiometer Antenna Pattern Correction (APC)

- Use ancillary data and forward model of the Aquarius observations
  - Ancillary TEC scale factor from E. Dinnat improves model Faraday rotation angle
  - Use ancillary up-welling, down-welling, galactic, solar, lunar, etc. contribution to Ta contained in Aquarius L2 files
  - We obtain an estimate of the Ta only due to Earth contribution, which is related to the T at top-of-ionosphere by the APC matrix
- Perform a least-squares fit to determine the APC matrix from the data itself
  - We then use this APC matrix to correct the data
  - We derive a new Faraday rotation estimate from the radiometer assuming all residual 3rd Stokes after APC correction is due to Faraday rotation (Yueh 2001)

TEC Scale Factors and Value

- TEC Scale factors provided by E. Dinnat, and were from NeQuick model
- We do not use this model in the operational processing because it is a monthly climatology, and has discontinuities at monthly boundaries


120101 to 120130 Ascending


120101 to 120130 Descending

APC Matrix Fitting

- All of following are vectors in I,Q,U basis
  - $T_{A,meas}$ = rad_Tf{H,V,3}
  - $T_{A,space}$ = rad_galact_Ta_dir_{H,V,3}+rad_solar_Ta_dir_{H,V,3}
  - $T_{A,ref}$ = rad_galact_Ta_ref_{H,V,3}+rad_solar_Ta_ref_{H,V,3}+rad_moon_Ta_ref_{H,V,3}+rad_solar_Ta_bak_{H,V,3}
- $F(\theta_m)$ is Faraday rotation operator for model Faraday rotation angle. **Model is based on VTEC product and E. Dinnat's TEC scale factor maps.**
- $F^{-1}(\theta_{l2})$ is inverse of Faraday rotation operator for L2 Faraday rotation angle
- $T_{BE,toa}$ is model TOA brightness temperature (vector in I,Q,U basis)

$$APC\left[\hat{T}_{A,meas} - \hat{T}_{A,space}\right] = \hat{F}(\theta_m)\left[\hat{T}_{BE,toa} + \hat{F}^{-1}(\theta_{L2})\left[APC_{L2}\right]^{-1}\hat{T}_{A,ref}\right]$$

$$APC\left[\hat{T}_{A,meas} - \hat{T}_{A,space}\right] = \begin{bmatrix} I_{sim} \\ Q_{sim} \\ U_{sim} \end{bmatrix} = \hat{F}(q_m)\left[\hat{T}_{BE,toa} + \hat{F}^{-1}(q_{L2})\left[APC_{L2}\right]^{-1}\hat{T}_{A,ref}\right]$$

Set of N Equations for each row of APC:

$$M_F \begin{bmatrix} A_{11} \\ A_{12} \\ A_{13} \end{bmatrix} = \begin{bmatrix} I_{sim}^{1} \\ \vdots \\ I_{sim}^{N} \end{bmatrix}$$

$$M_F \begin{bmatrix} A_{21} \\ A_{22} \\ A_{23} \end{bmatrix} = \begin{bmatrix} Q_{sim}^{1} \\ \vdots \\ Q_{sim}^{N} \end{bmatrix}$$

$$M_F \begin{bmatrix} A_{31} \\ A_{32} \\ A_{33} \end{bmatrix} = \begin{bmatrix} U_{sim}^{1} \\ \vdots \\ U_{sim}^{N} \end{bmatrix}$$

Least-Squares Problem: (Ax=b)

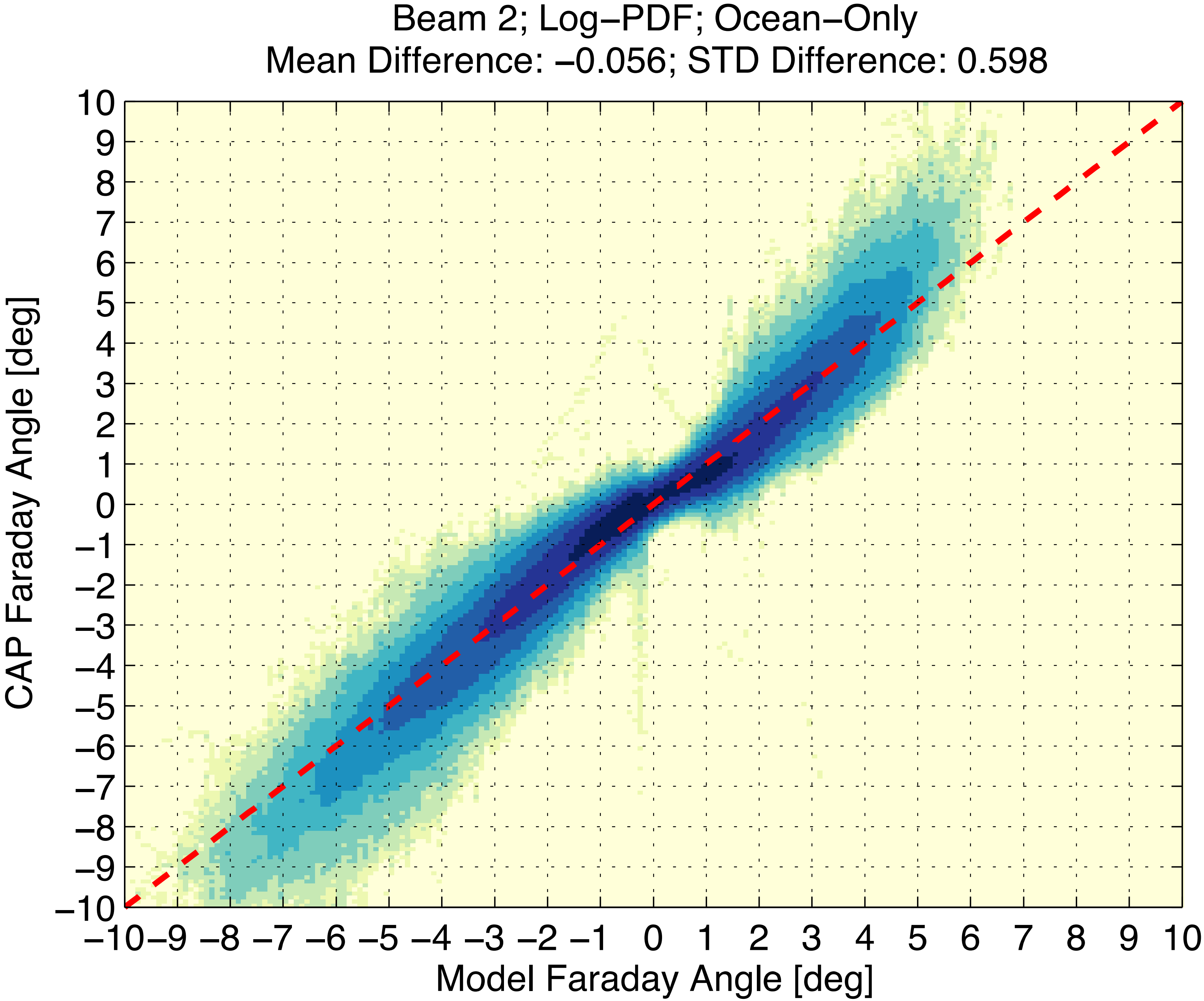
$$M_F^T M_F \begin{bmatrix} A_{11} \\ A_{12} \\ A_{13} \end{bmatrix} = M_F^T \begin{bmatrix} I_{sim}^{1} \\ \vdots \\ I_{sim}^{N} \end{bmatrix}$$

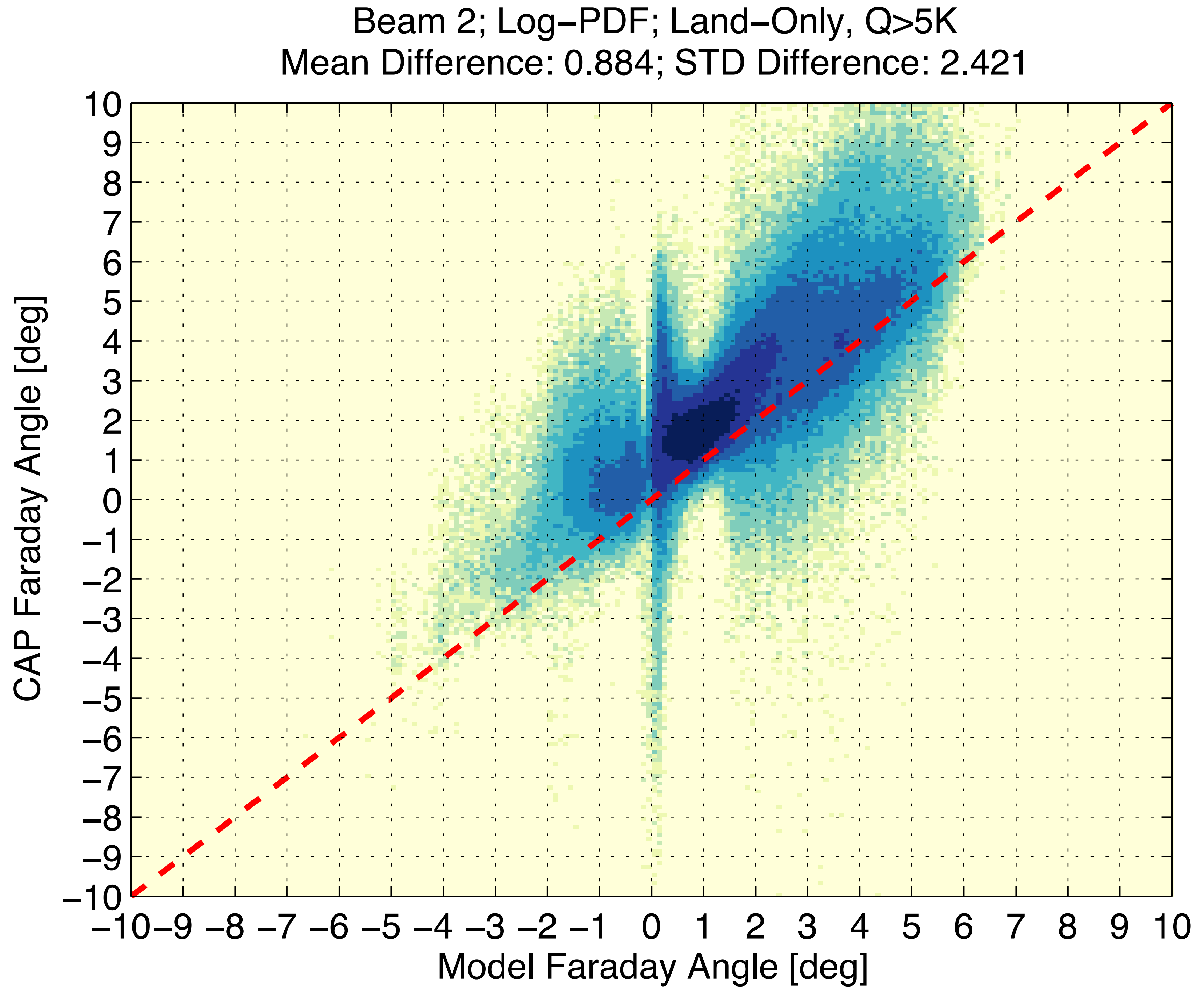
$$M_F^T M_F \begin{bmatrix} A_{21} \\ A_{22} \\ A_{23} \end{bmatrix} = M_F^T \begin{bmatrix} Q_{sim}^{1} \\ \vdots \\ Q_{sim}^{N} \end{bmatrix}$$

$$M_F^T M_F \begin{bmatrix} A_{31} \\ A_{32} \\ A_{33} \end{bmatrix} = M_F^T \begin{bmatrix} U_{sim}^{1} \\ \vdots \\ U_{sim}^{N} \end{bmatrix}$$

Where:

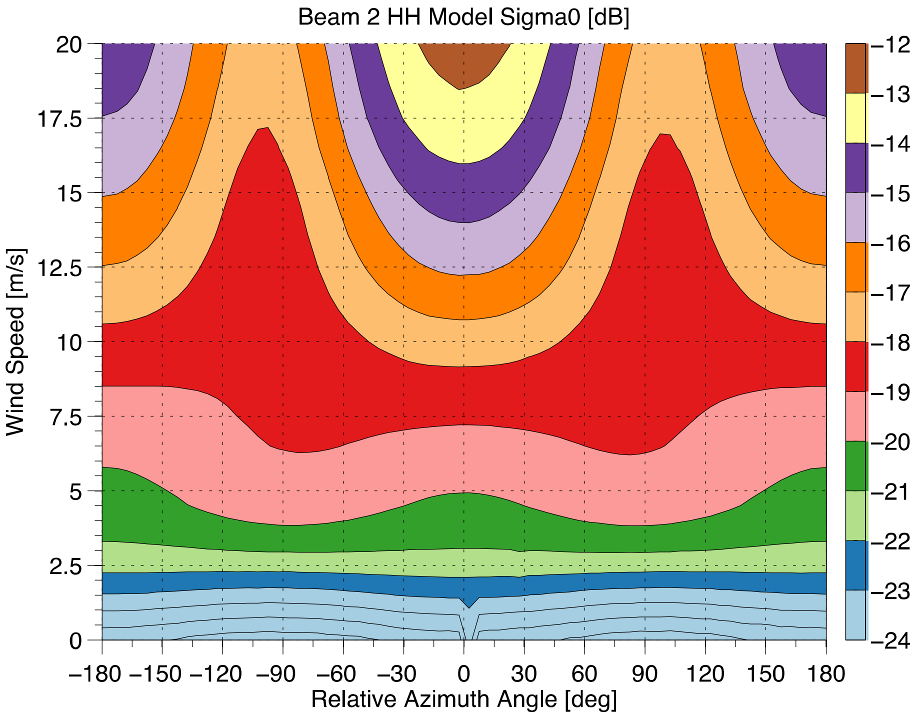
$$M_F \equiv \begin{bmatrix} I_{A,meas}^{1} - I_{A,space}^{1} & Q_{A,meas}^{1} - Q_{A,space}^{1} & U_{A,meas}^{1} - U_{A,space}^{1} \\ \vdots & \vdots & \vdots \\ I_{A,meas}^{N} - I_{A,space}^{N} & Q_{A,meas}^{N} - Q_{A,space}^{N} & U_{A,meas}^{N} - U_{A,space}^{N} \end{bmatrix}$$

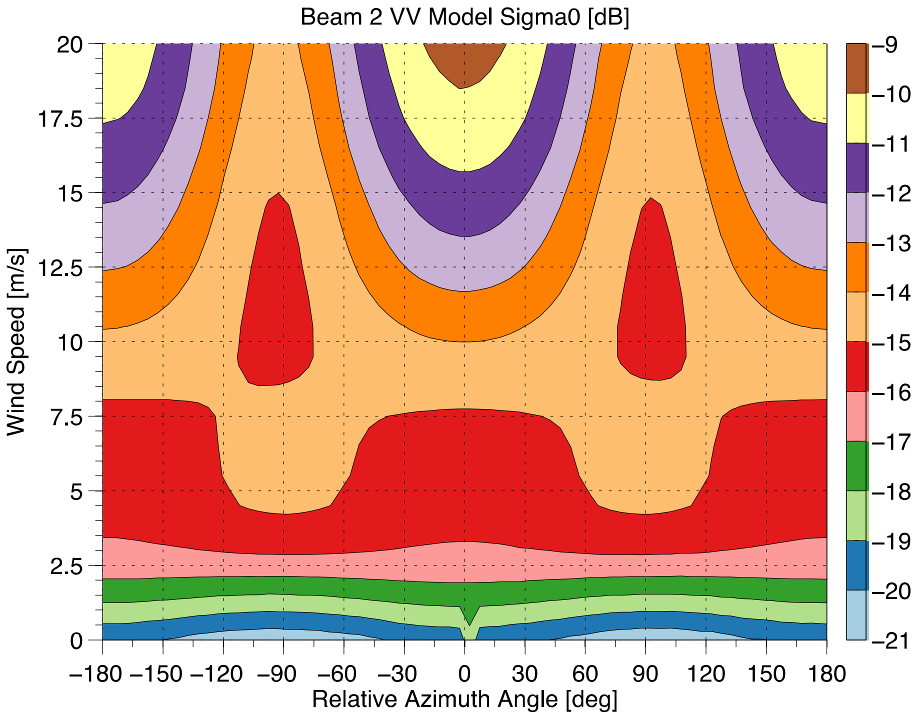

Beam 2; Log−PDF; Ocean−Only
Mean Difference: −0.056; STD Difference: 0.598
CAP Faraday Angle [deg]
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
−10 −9 −8 −7 −6 −5 −4 −3 −2 −1 0 1 2 3 4 5 6 7 8 9 10
Model Faraday Angle [deg]


Beam 2; Log−PDF; Land−Only, Q>5K
Mean Difference: 0.884; STD Difference: 2.421
CAP Faraday Angle [deg]
Model Faraday Angle [deg]
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
−4
−5
−6
−7
−8
−9
−10
−10
−9
−8
−7
−6
−5
−4
−3
−2
−1
0
1
2
3
4
5
6
7
8
9
10

L-Band Ocean Model Function

- Aquarius beam 2 has incidence angle of 38.5°, most similar to SMAP
- Change in sign of A2 near 8 m/s: Causes σ_0 to be non-monotonic in speed for cross-wind
- Very large directional modulation for higher wind speeds: cross-wind σ_0 have low sensitivity to wind speed


Beam 2 HH Model Sigma0 [dB]


Beam 2 VV Model Sigma0 [dB]

Wind Retrieval Algorithms

- Scatterometer Only Speed Retrieval
  - Dual polarization retrieval implemented in V2.0 L2 data.
  - Have considered HH only and VV only retrieval as well as a tri-polarization retrieval.
- Combined Active Passive (CAP) Speed, Direction and SSS Retrieval

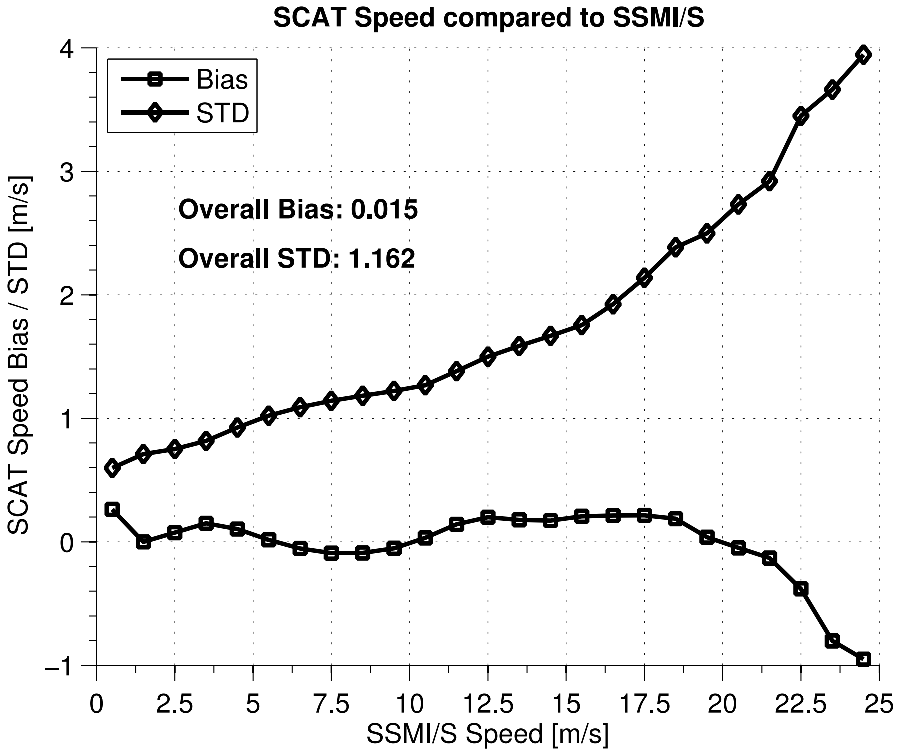
Scat. Wind Ret Cost Function:

$$J = -\left[\frac{\left(\sigma_{0,HH}^{gmf} - \sigma_{0,HH}^{obs}\right)}{kp_{HH}\sigma_{0,HH}^{obs}}\right]^2 - \left[\frac{\left(\sigma_{0,VV}^{gmf} - \sigma_{0,VV}^{obs}\right)}{kp_{VV}\sigma_{0,VV}^{obs}}\right]^2$$

Tri-Pol Cost Function:

$$J = -\left[\frac{\left(\sigma_{0,HH}^{gmf} - \sigma_{0,HH}^{obs}\right)}{kp_{HH}\sigma_{0,HH}^{obs}}\right]^2 - \left[\frac{\left(\sigma_{0,VV}^{gmf} - \sigma_{0,VV}^{obs}\right)}{kp_{VV}\sigma_{0,VV}^{obs}}\right]^2 - \alpha(w_{NCEP})\left[\frac{\left(\sigma_{0,HV}^{gmf} - \sigma_{0,HV}^{obs}\right)}{kp_{HV}\sigma_{0,HV}^{obs}}\right]^2$$

Scatterometer Only Wind Speed Performance



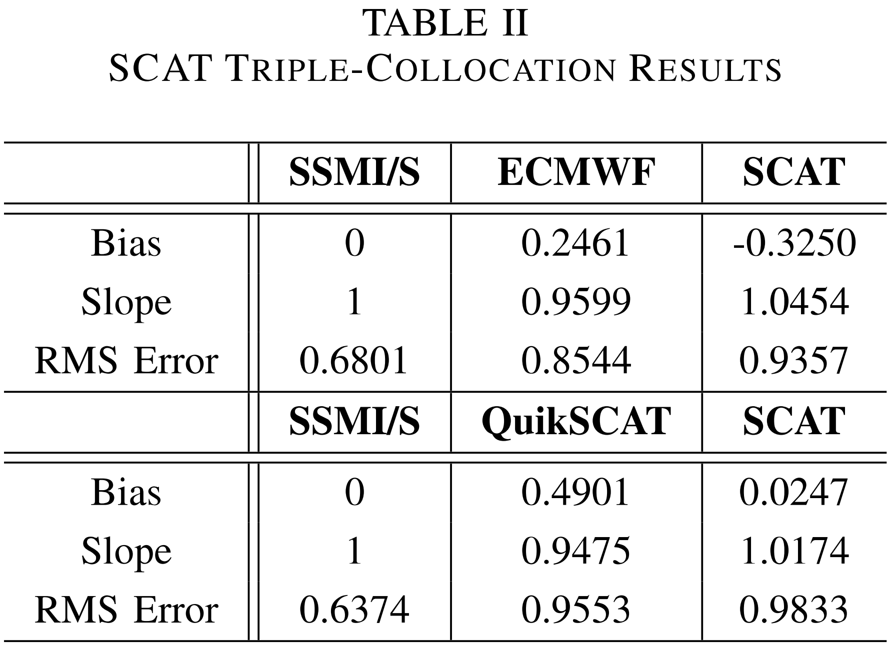
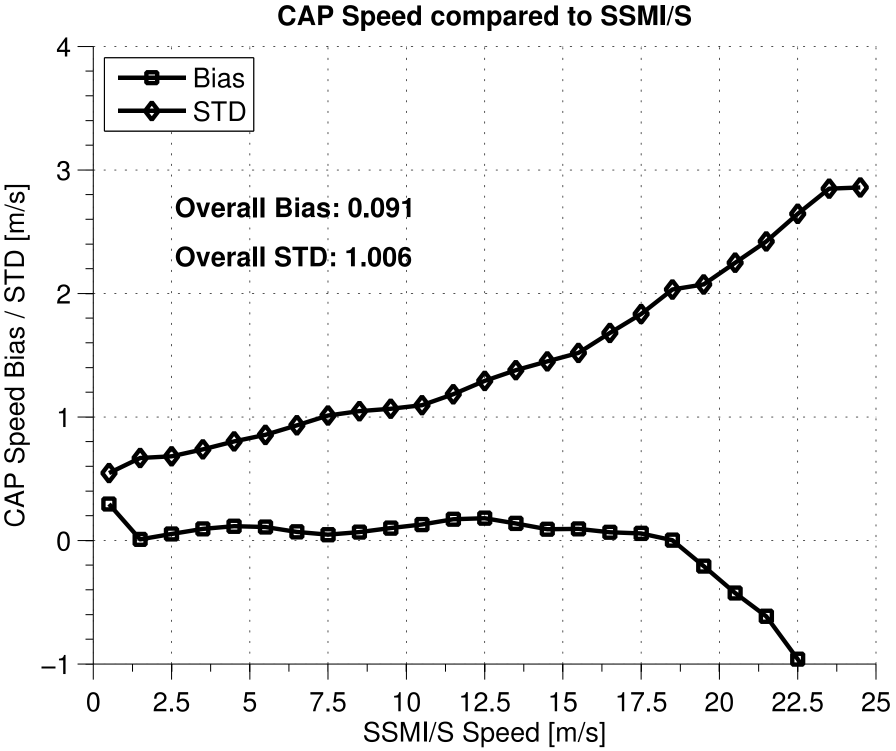


TABLE II
SCAT TRIPLE-COLLOCATION RESULTS

	SSMI/S	**ECMWF**	**SCAT**
Bias	0	0.2461	-0.3250
Slope	1	0.9599	1.0454
RMS Error	0.6801	0.8544	0.9357
	SSMI/S	**QuikSCAT**	**SCAT**
Bias	0	0.4901	0.0247
Slope	1	0.9475	1.0174
RMS Error	0.6374	0.9553	0.9833

Fore, A.G.; Yueh, S.H.; Tang, W.; Hayashi, A.K.; Lagerloef, G.S.E., "Aquarius Wind Speed Products: Algorithms and Validation," Geoscience and Remote Sensing, IEEE Transactions on , vol.PP, no.99, pp.1,8, 0. doi: 10.1109/TGRS.2013.2267616

CAP Wind Speed Performance



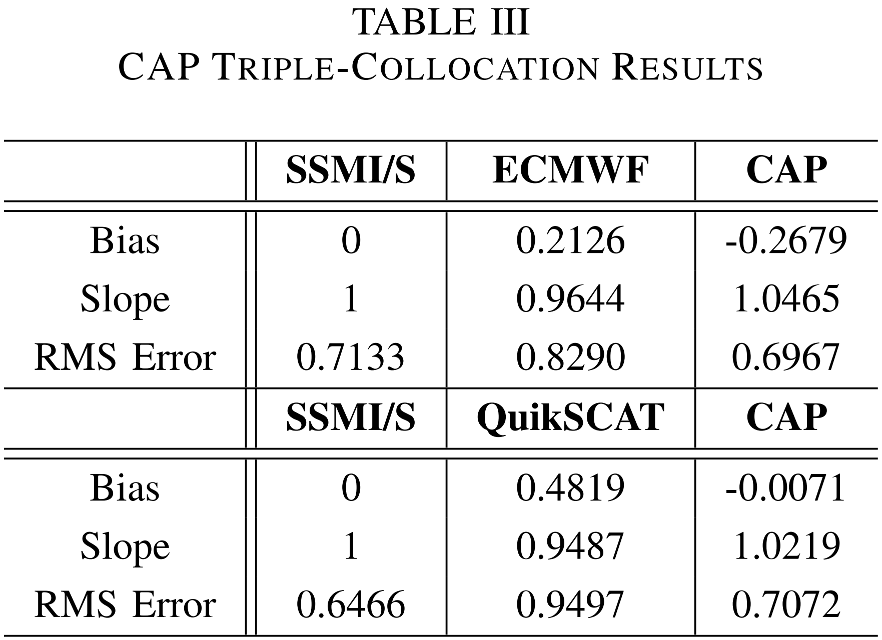
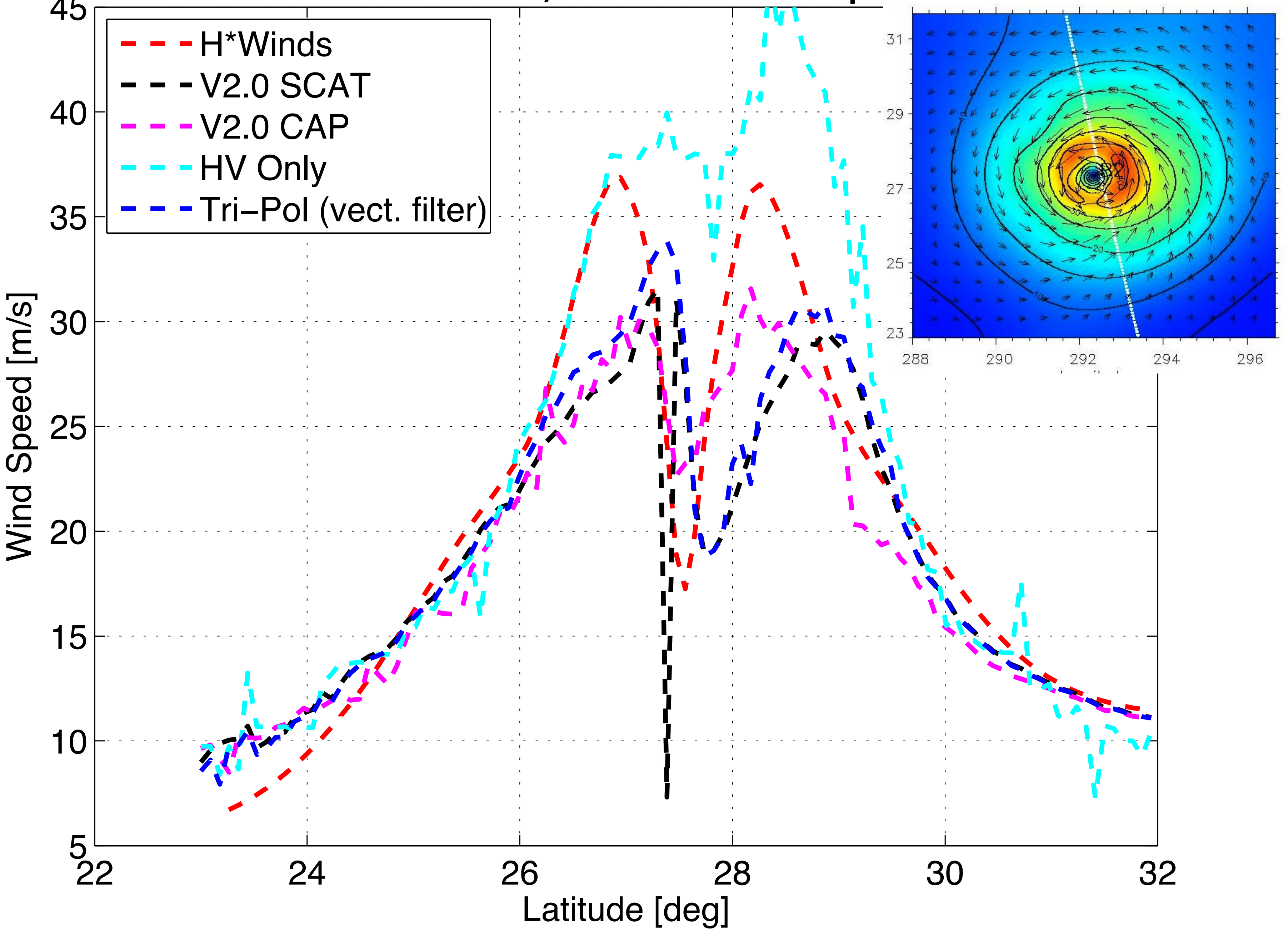


TABLE III
CAP TRIPLE-COLLOCATION RESULTS

	SSMI/S	**ECMWF**	**CAP**
Bias	0	0.2126	-0.2679
Slope	1	0.9644	1.0465
RMS Error	0.7133	0.8290	0.6967
	SSMI/S	**QuikSCAT**	**CAP**
Bias	0	0.4819	-0.0071
Slope	1	0.9487	1.0219
RMS Error	0.6466	0.9497	0.7072

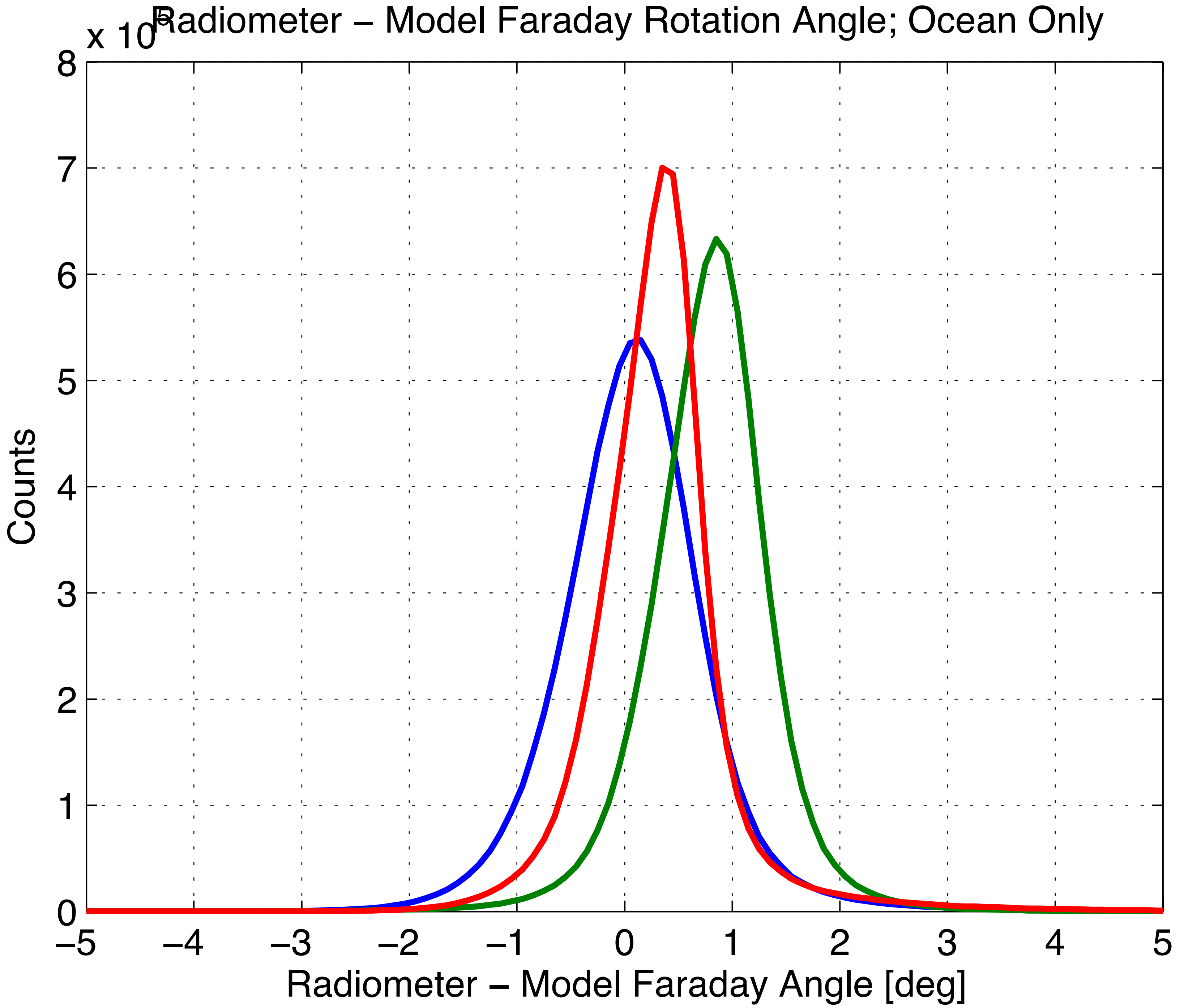
Fore, A.G.; Yueh, S.H.; Tang, W.; Hayashi, A.K.; Lagerloef, G.S.E., "Aquarius Wind Speed Products: Algorithms and Validation," Geoscience and Remote Sensing, IEEE Transactions on , vol.PP, no.99, pp.1,8, 0. doi: 10.1109/TGRS.2013.2267616

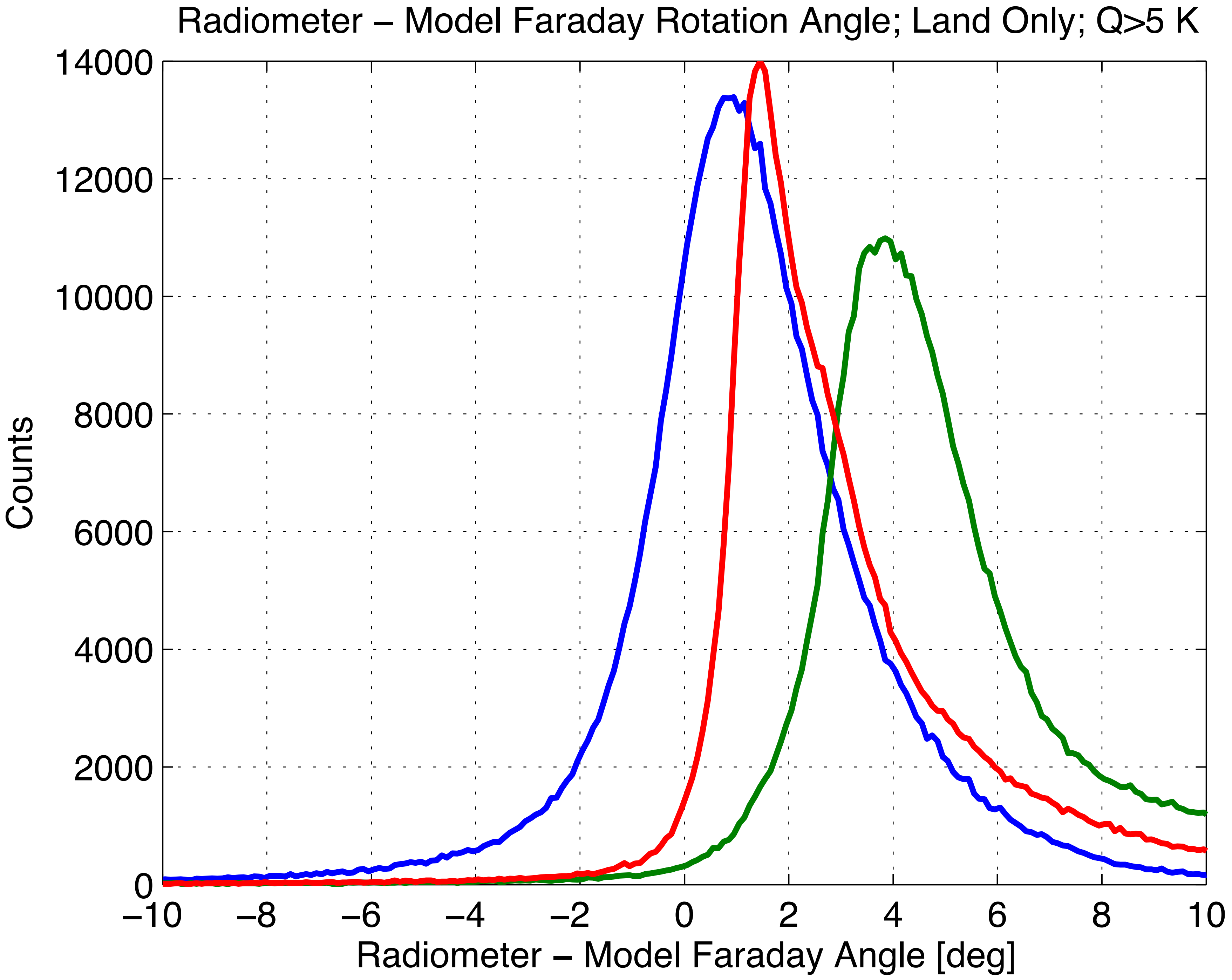
Hurricane Katia; Beam 2 of Aquarius

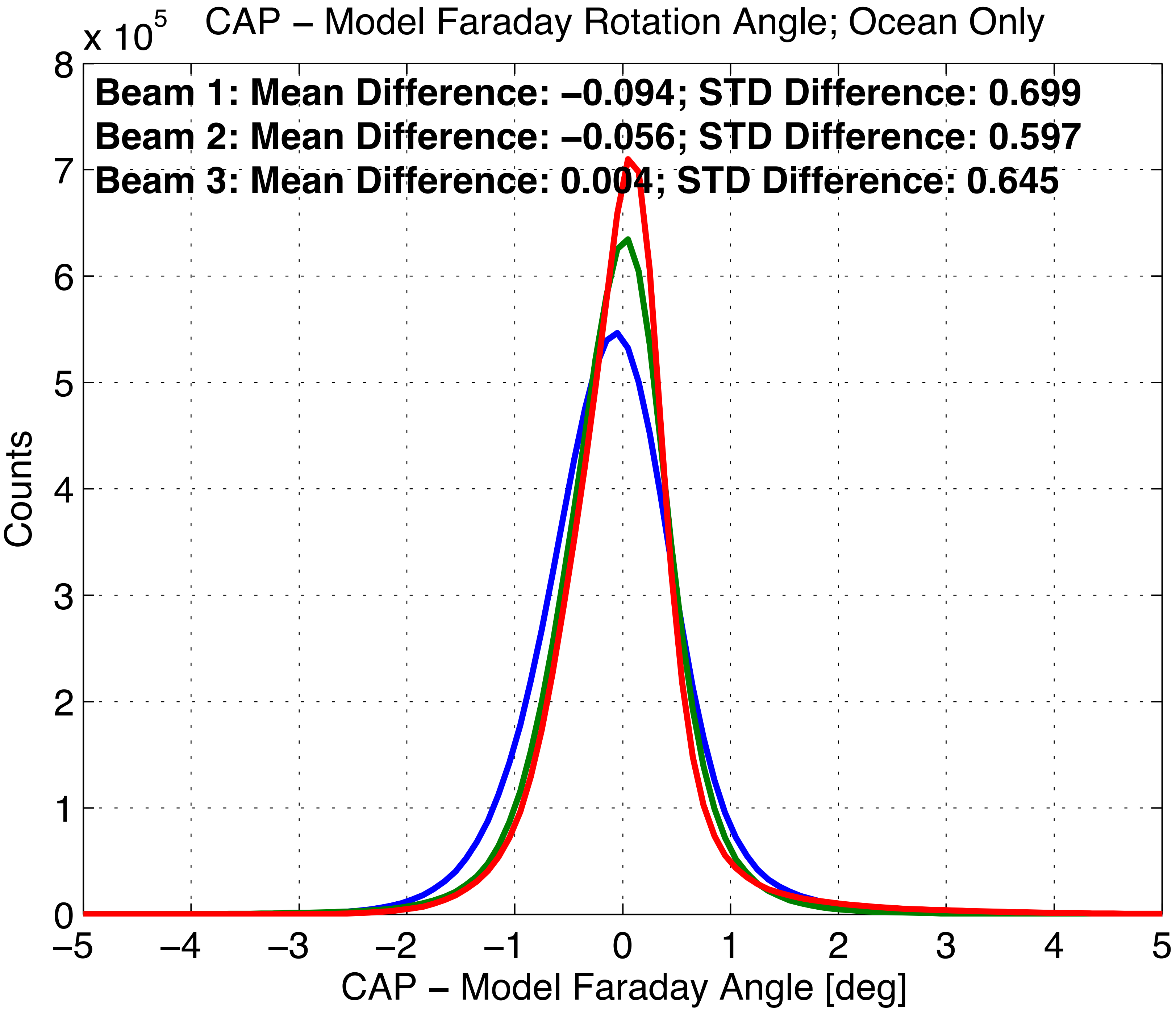


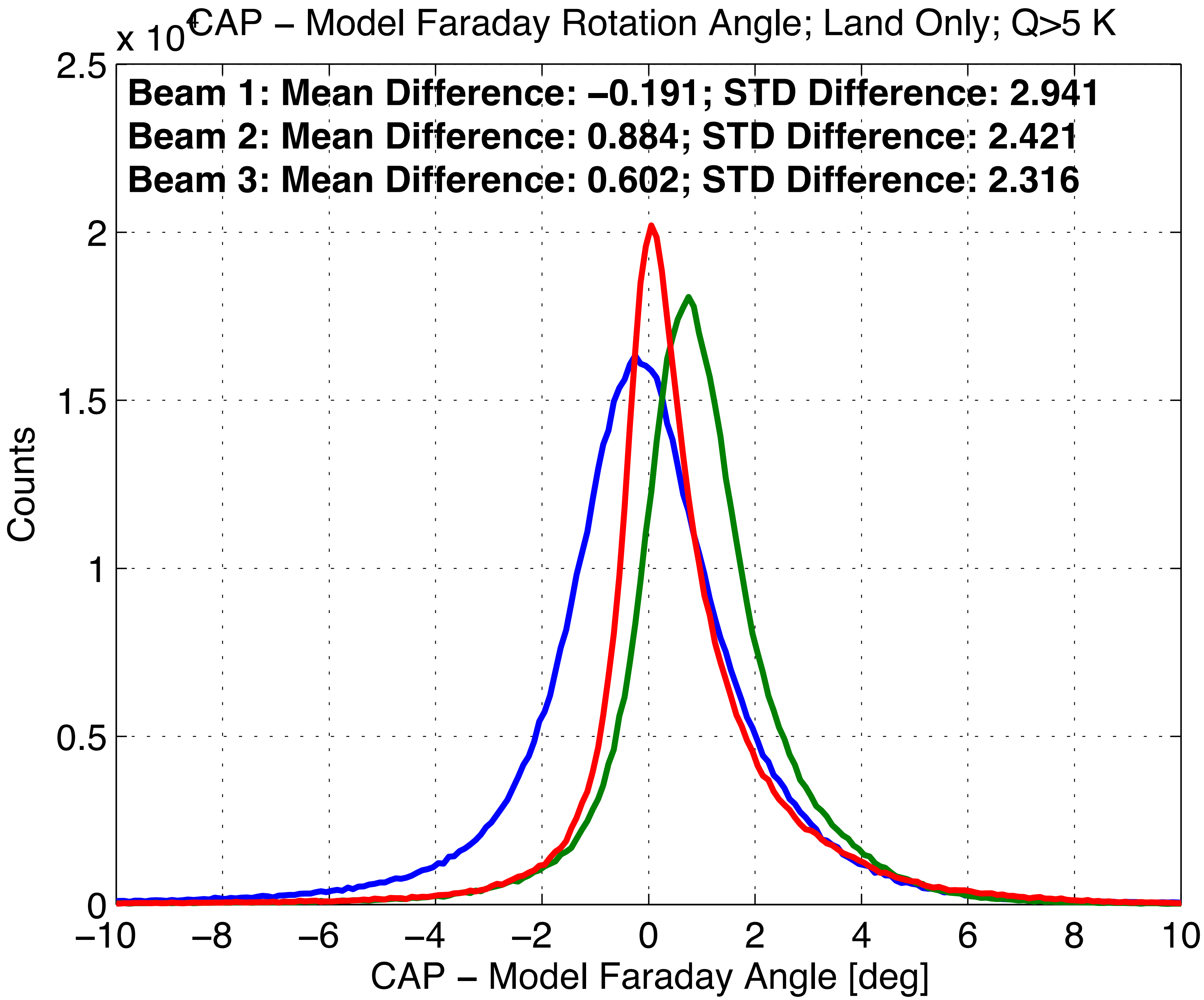
Summary

- Absolute and long-term calibration:
  - Using the Amazon we can estimate Aquarius / PALSAR bias over land at 1/10th of dB level
  - Using ocean, we can track scatterometer stability at a few hundredths of dB level
- Scatterometer Faraday rotation correction:
  - Using ancillary total electron content data and magnetic field model of Earth we compute a model Faraday rotation angle
  - Using the observations available to us, we formulate a measurement model and solve a non-linear optimization problem for the Faraday rotation corrected σ_0
- Faraday rotation estimation from radiometer:
  - We find that STD of radiometer – model Faraday rotation angle to be about 0.7 deg for Aquarius over ocean
  - Larger noise in 3rd Stokes over land causes about 2-3 deg in STD over land
- Wind speed retrieval:
  - Using the scatterometer data only, we obtain RMS wind speed performance of about 1 m/s
  - Using the CAP method we obtain about 0.7 m/s RMS wind speed performance, showing L-band to be capable for ocean vector wind retrieval


Radiometer – Model Faraday Rotation Angle; Ocean Only
x 10^5
8
7
6
5
4
3
2
1
0
Counts
–5
–4
–3
–2
–1
0
1
2
3
4
5
Radiometer – Model Faraday Angle [deg]


Radiometer – Model Faraday Rotation Angle; Land Only; Q>5 K
Counts
14000
12000
10000
8000
6000
4000
2000
0
−10
−8
−6
−4
−2
0
2
4
6
8
10
Radiometer – Model Faraday Angle [deg]


CAP – Model Faraday Rotation Angle; Ocean Only
x 10^5
Beam 1: Mean Difference: –0.094; STD Difference: 0.699
Beam 2: Mean Difference: –0.056; STD Difference: 0.597
Beam 3: Mean Difference: 0.004; STD Difference: 0.645
Counts
0
1
2
3
4
5
6
7
8
–5
–4
–3
–2
–1
0
1
2
3
4
5
CAP – Model Faraday Angle [deg]


CAP – Model Faraday Rotation Angle; Land Only; Q>5 K
x 10^4
2.5
2
1.5
1
0.5
0
Counts
Beam 1: Mean Difference: –0.191; STD Difference: 2.941
Beam 2: Mean Difference: 0.884; STD Difference: 2.421
Beam 3: Mean Difference: 0.602; STD Difference: 2.316
–10
–8
–6
–4
–2
0
2
4
6
8
10
CAP – Model Faraday Angle [deg]

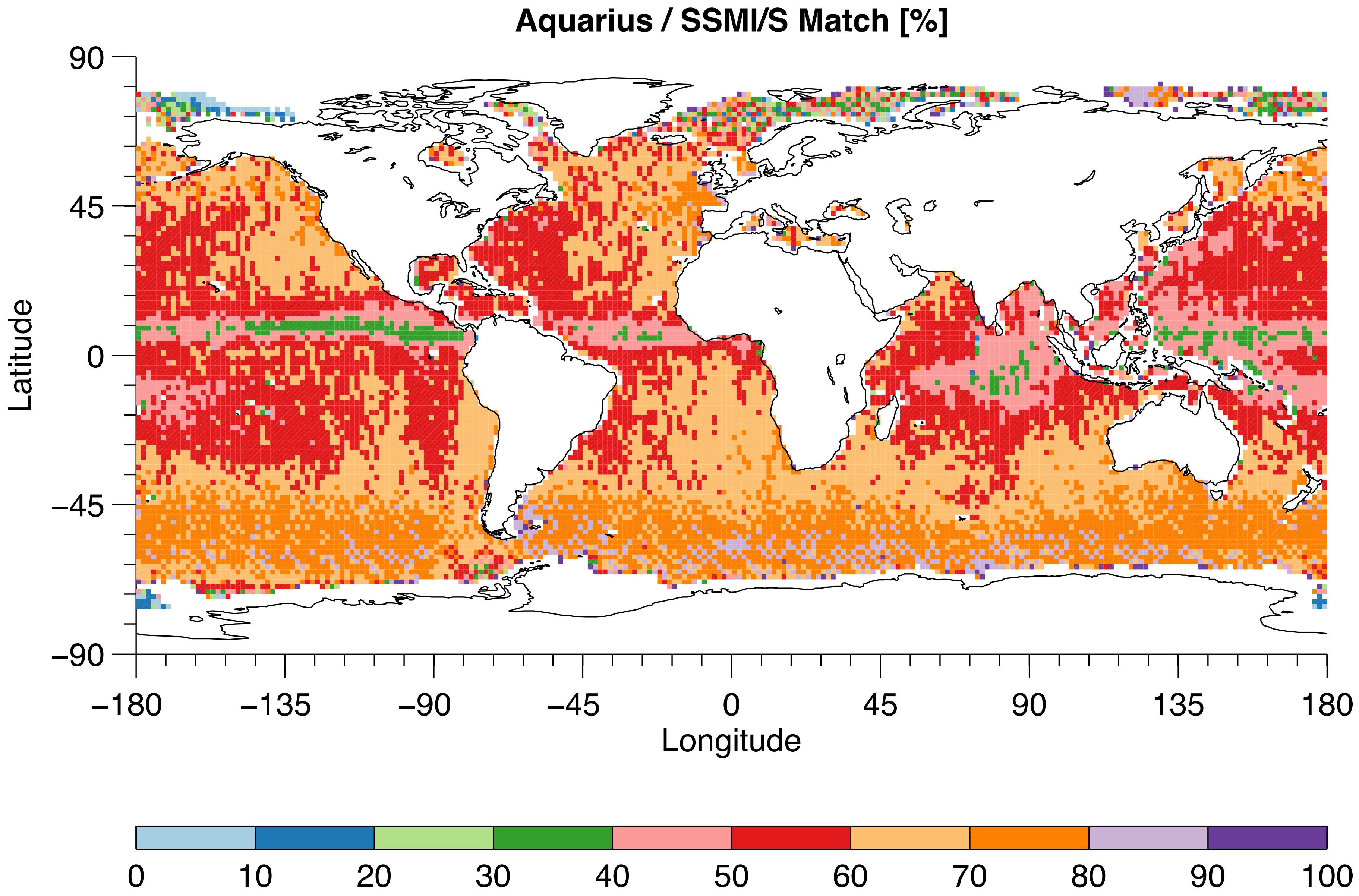


Fig. 1. Percent of Aquarius data for which there is a rain-free SSMI/S matchup.