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Evaluation of ocean emissivity models for polarimetric microwave radiometers

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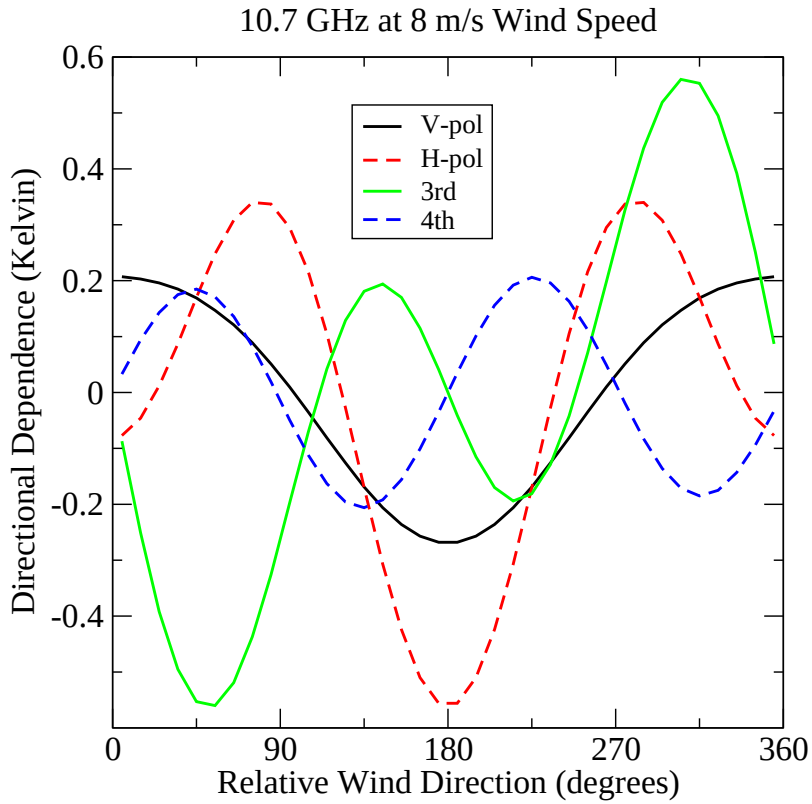
21 November 2019

Space-based Polarimetric Microwave Radiometers

- Chosen by US Dept. of Defense to satisfy multiple needs with one instrument
  - ocean surface vector winds (OSVW)
  - tropical cyclone imagery (primarily at about 37 and 89 GHz)
  - radiances for data assimilation (water vapor and cloud liquid water information)
  - sea ice age and concentration
  - snow water equivalent
  - soil moisture
- WindSat (2003 - present): research mission to demonstrate OSVW capability
- Compact Ocean Wind Vector Radiometer (COWVR): technology demonstration mission scheduled for 2021 launch
- Weather System Follow-on - Microwave (WSF-M): operational mission with contract awarded to Ball Aerospace

Basis for Passive OSVW Retrievals

- Ocean surface emission and scattering vary with wind vector
  - Wind stress drives ocean surface wave spectrum
  - Emission is also enhanced by sea foam
- Wind direction retrieval requires polarimetric radiometer
  - Need 3rd/4th Stokes components to reduce direction ambiguity



$$I_s = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \langle E_h E_h^* \rangle + \langle E_v E_v^* \rangle \\ \langle E_h E_h^* \rangle - \langle E_v E_v^* \rangle \\ 2\Re \langle E_v E_h^* \rangle \\ 2\Im \langle E_v E_h^* \rangle \end{bmatrix} = \begin{bmatrix} T_v + T_h \\ T_v - T_h \\ T_{45} - T_{-45} \\ T_{lc} - T_{rc} \end{bmatrix}$$

WindSat Description

- Designed and built by the Naval Research Laboratory (NRL)
- WindSat measures dual polarization at 6.8 and 23.8 GHz
- WindSat has full polarimetric capability at 10.7, 18.7 and 37 GHz
- 11 feed horns and 22 channels

Freq. (GHz)	Channels	BW (MHz)	EIA (deg)	IFOV (km)
6.8	v, h	125	54.0	39 x 71
10.7	v, h, +/- 45, lc, rc	300	50.3	25 x 38
18.7	v, h, +/- 45, lc, rc	750	55.9	16 x 27
23.8	v, h	500	53.5	20 x 30
37.0	v, h, +/- 45, lc, rc	2000	53.5	8 x 13

COWVR Description

- Designed and built by the Jet Proplusion Laboratory[1]
- COWVR has full polarimetric capability at 18.7, 23.8 and 33.9 GHz
- Single fixed multi-frequency feed horn
- Full 360° scan
- To be deployed on the International Space Station

[1] Brown, et al, DOI: 10.1109/AERO.2017.7943884

Sea Emissivity Models with Direction

Focus here is on 3rd and 4th Stokes signals

- NRL Model
  - Specific to WindSat so limited to WindSat frequencies and polarizations
  - Supports limited range of earth incidence angles
  - Last updated 2009
- Remote Sensing Systems (RSS) model
- FASTEM5 (FASTEM6 changes do not include the 3rd and 4th Stokes)

Form of the NRL Parameterization

Part 1

Geophysical model is parameterized in the following form:

$$
\begin{aligned}
T_{bp} &= T_{bp0} + \tilde{T}_{bp} \\
T_{bp0} &= T_{\mathrm{up}} + \tau(T_S - R_p T_{Rp}) \\
T_{R0} &= (T_S - T_C) - [T_{\mathrm{down}} - T_C(1-\tau)] \\
T_{Rp} &= T_{R0} - [T_{\mathrm{down}} - T_C(1-\tau)]\Omega_p
\end{aligned}
$$

T_{bp0}	direction independent brightness temperature (T_b) for p polarization (vertical or horizontal)
$\tilde{T}_{bp}$	wind direction dependent component of T_b for q component of modified Stokes vector
T_{up}, T_{down}, τ	atmospheric upwelling and downwelling temperatures and transmissivity
R_p	isotropic sea surface reflectivity
T_S, T_C	sea surface and cosmic background temperatures
Ω	correction for scattering of downwelling radiation at the sea surface

Form of the Parameterization

Part 2

The wind direction dependent portion of the T_b is modeled as

$$\tilde{T}_{bp} = -\tau r_{hp} T_{R0}$$

where

for vertical or horizontal polarization $r_{hp} = c_{1p}\cos(\phi_w) + c_{2p}\cos(2\phi_w)$

for third or fourth Stokes $r_{hp} = c_{1p}\sin(\phi_w) + c_{2p}\sin(2\phi_w)$

and ϕ_w is the wind direction relative to look direction of the antenna.

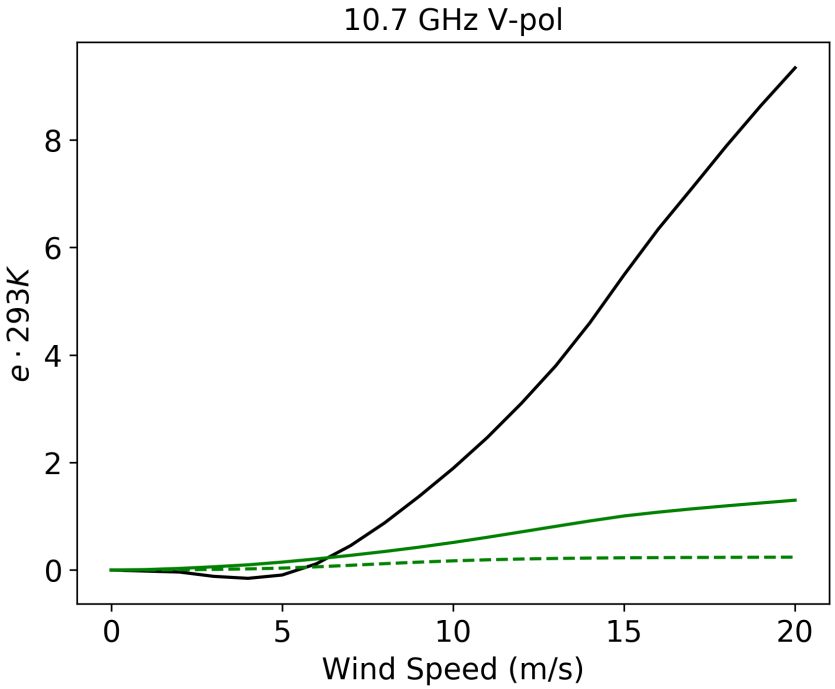
NRL Sea Reflectivity Model

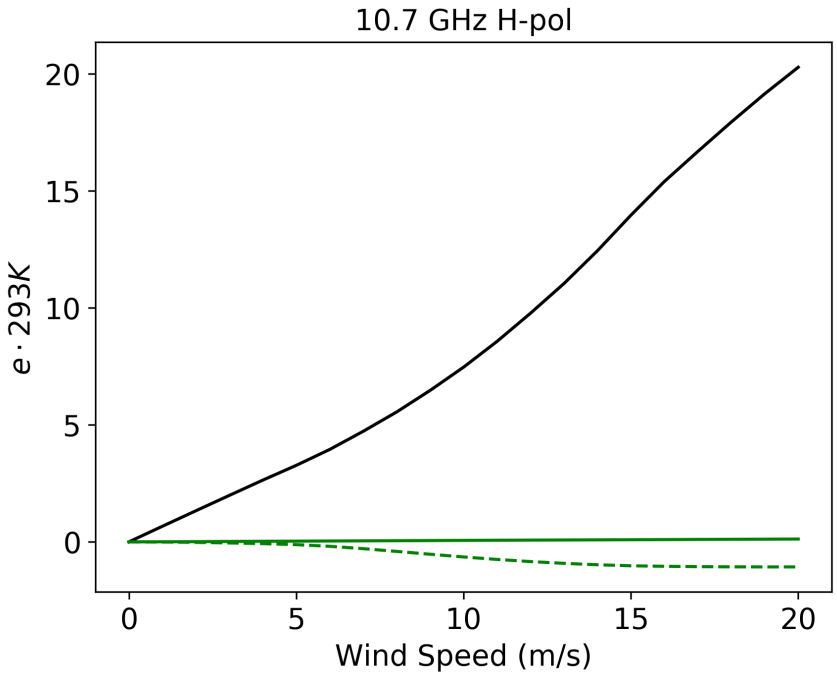
- $R_p = 1 - e_p$ where e_p is the emissivity
- A two-scale rough surface model[2] was used to provide an initial estimate of e_p and Ω over a range of T_S, earth incidence angle (EIA), salinity, and wind speed values
- Reflectivity is divided into specular and wind speed dependent components $R_p = R_{0p} - r_{wp}$
- r_{wp} is a regression fit in T_S and EIA and spline fits for the wind speed dependence
- Empirical methods similar to those reported by Meissner and Wentz[3] were used to
  - correct the wind speed dependence of r_{wp}
  - model the first and second harmonic terms of the reflectivity c_{1p} and c_{2p}
- Our fits for r_{wp}, c_{1p} and c_{2p} have not been changed significantly since IGARSS 2007.

[2] Johnson, DOI: 10.1109/TGRS.2005.855999

[3] Meissner and Wentz, DOI: 10.1109/TGRS.2011.2179662

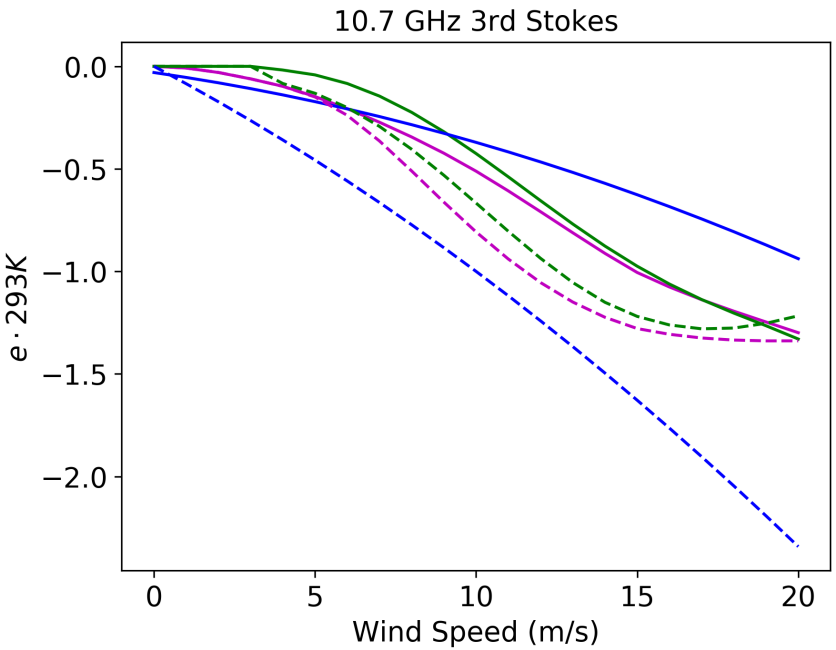
Wind Direction Effect is Small

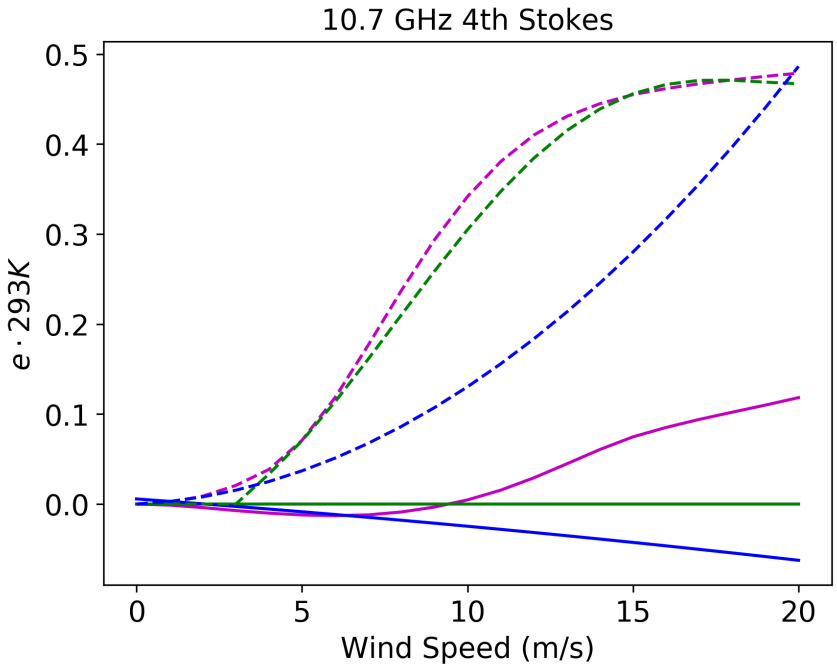




Results from NRL model for WindSat forward scan for SST = 293 K.
Harmonics shown are 0:black, 1:green solid, 2:green dashed.

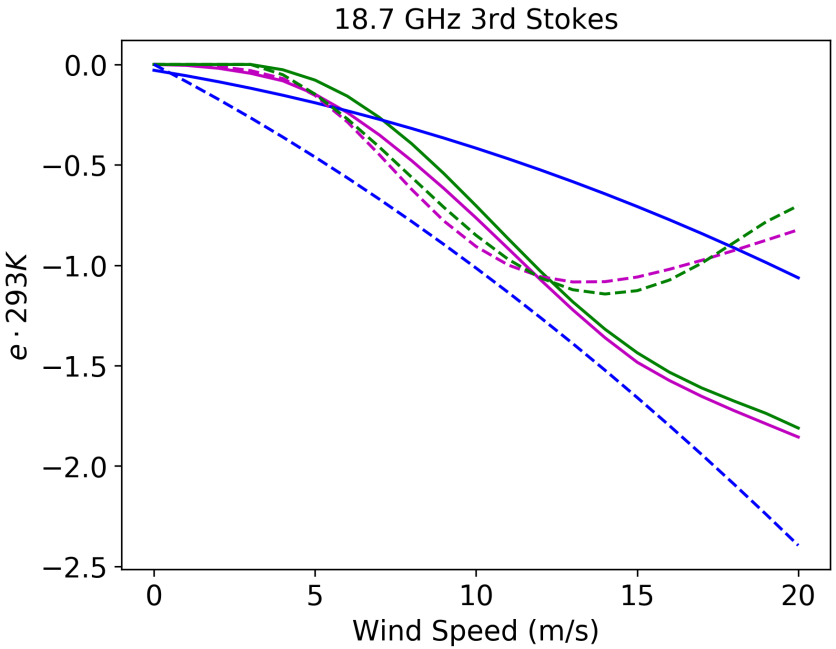
Wind Direction Model Comparison 10.7 GHz 3rd/4th

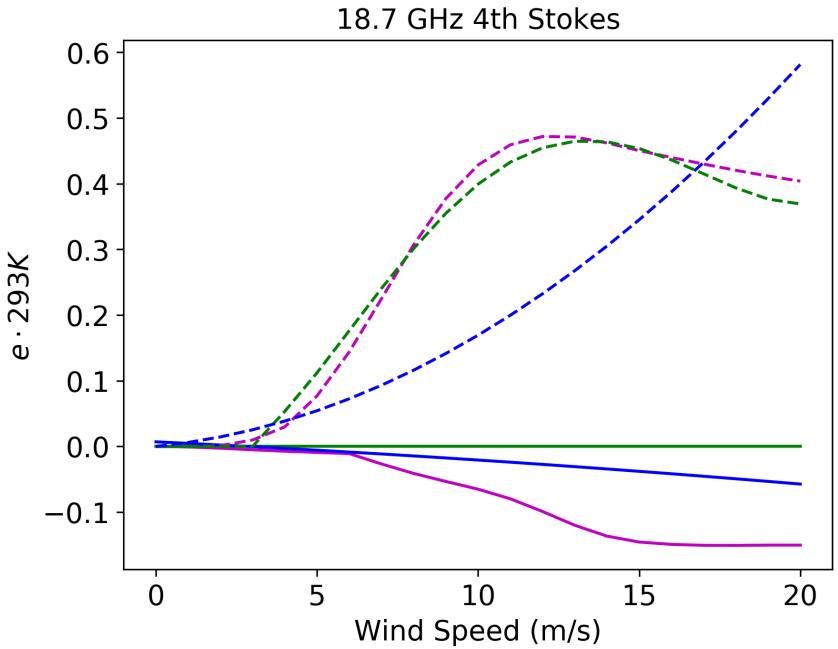




Results for WindSat forward scan from NRL model (magenta), RSS model (green) and FASTEM (blue). Harmonics shown are 1:solid, 2:dashed.

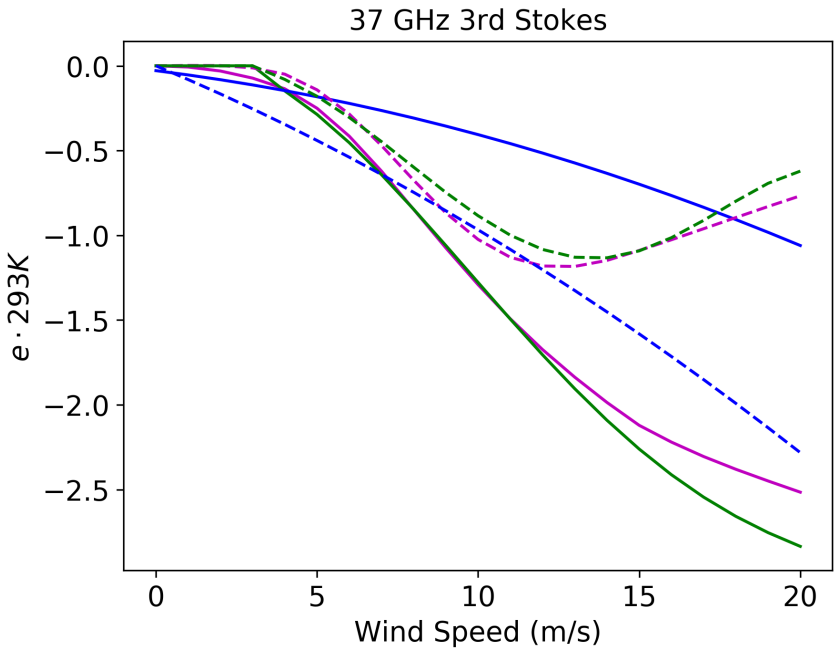
Wind Direction Model Comparison 18.7 GHz 3rd/4th

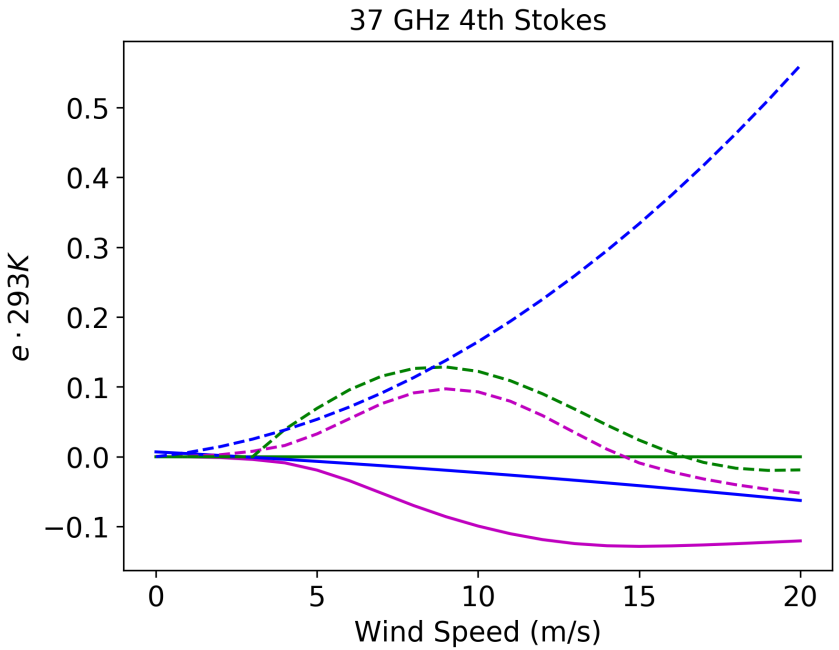




Results for WindSat forward scan from NRL model (magenta), RSS model (green) and FASTEM (blue). Harmonics shown are 1:solid, 2:dashed.

Wind Direction Model Comparison 37 GHz 3rd/4th

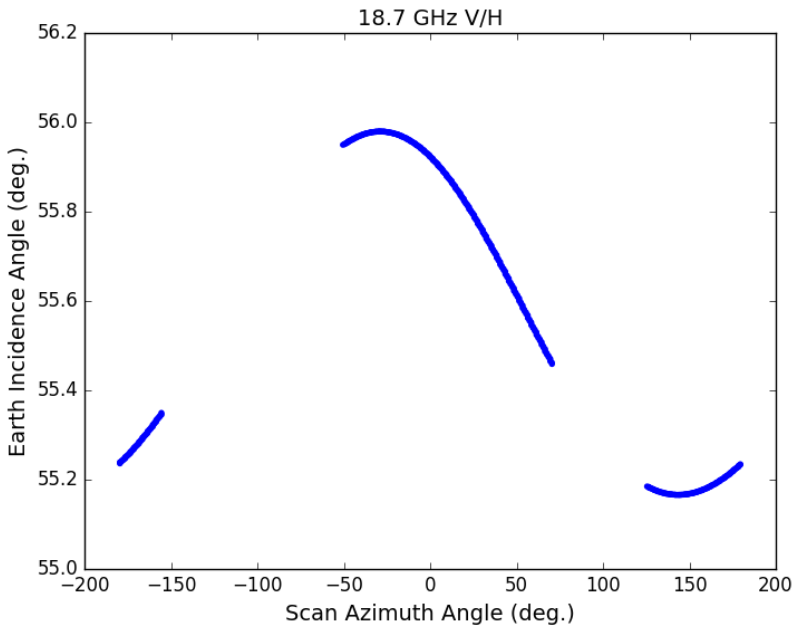


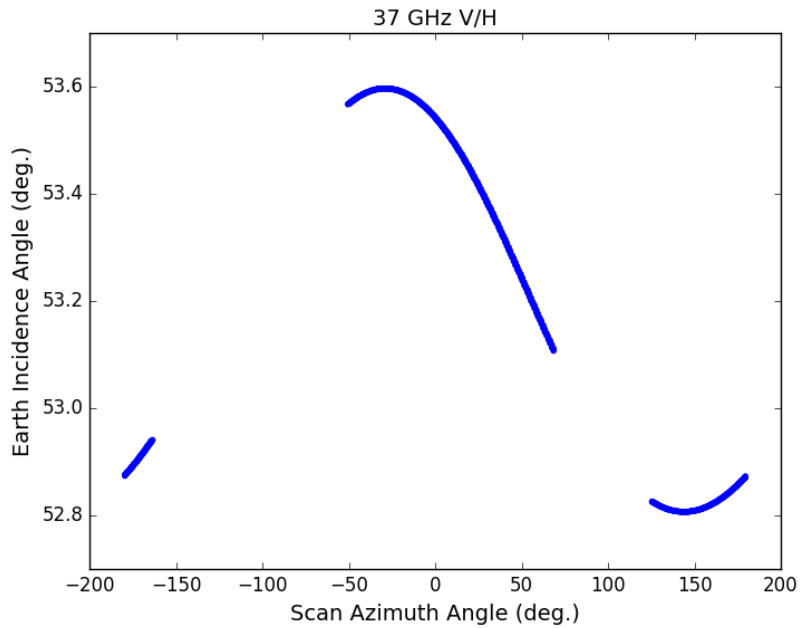


Results for WindSat forward scan from NRL model (magenta), RSS model (green) and FASTEM (blue). Harmonics shown are 1:solid, 2:dashed.

WindSat EIA Variation

The WindSat EIA varies each channel including a systematic along-scan variation which is due to spacecraft pitch and roll[4].



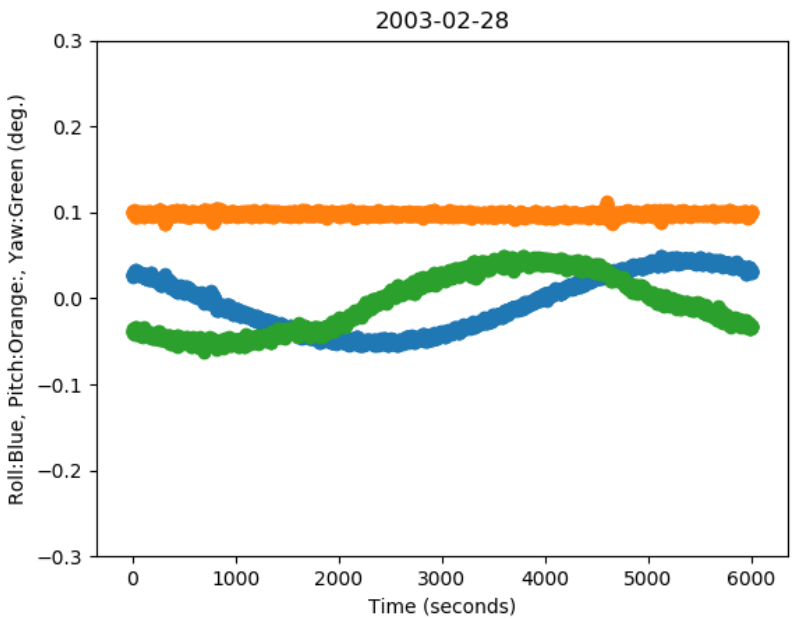


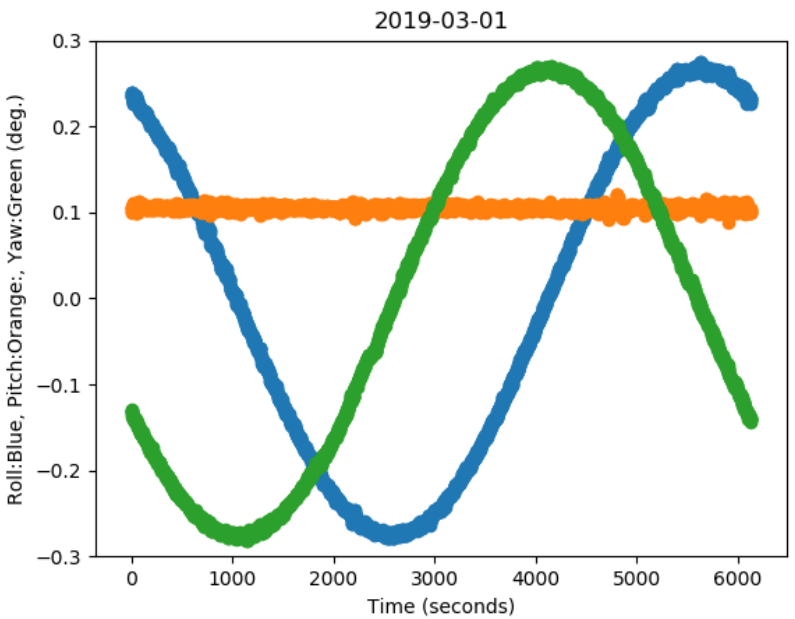
Plots show the mean EIA at each scan position.

[4] Purdy, et al, DOI: 10.1109/TGRS.2005.858415

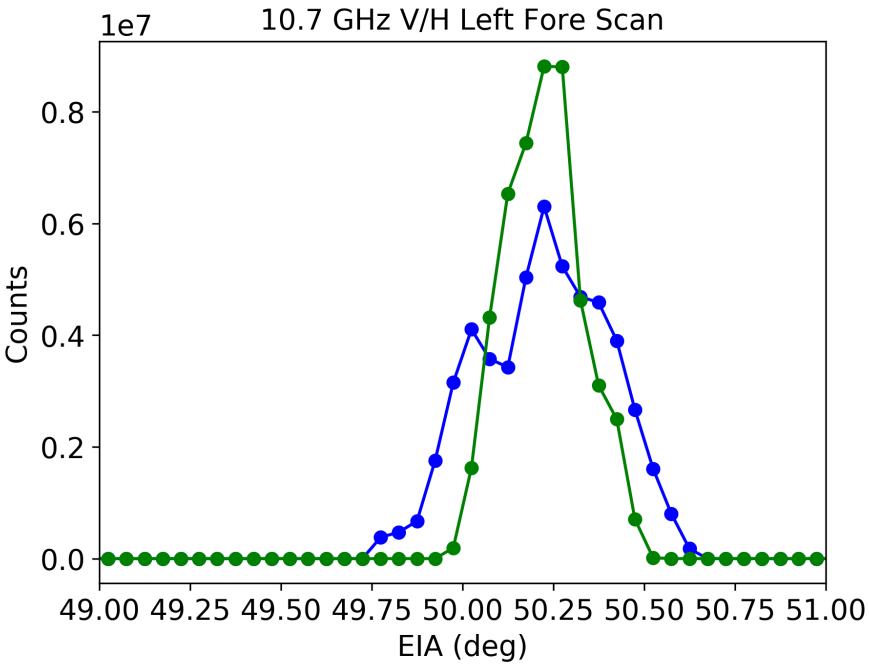
WindSat EIA Variation (part 2)

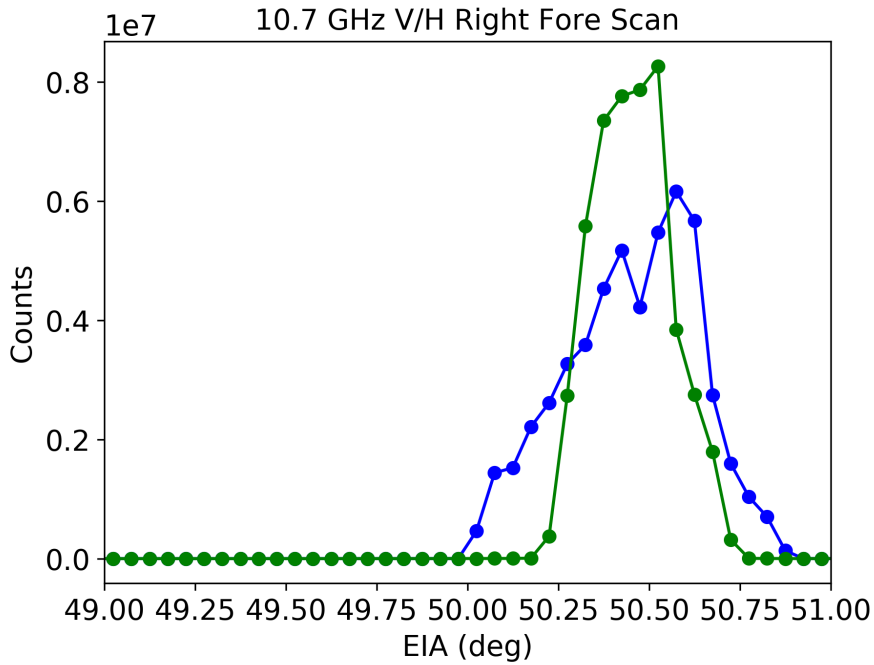
- Attitude control system for Coriolis spacecraft does not account of nutation and precession of earth relative to J2000 epoch.
- Spacecraft roll and yaw vary seasonally and the magnitude of the variation is increasing over time. Pitch is also increasing.
- Plots are for elapsed time during one orbit.





WindSat EIA Variation (part 3)





Histograms of EIA for 2004 (green) and 2018 (blue).

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Conclusions and Future Work

- RSS and NRL models for wind direction harmonics of the sea emissivity show good agreement.
- WindSat has now collected over 16 years of data
- WindSat range of EIAs is increasing
- Plan to test and update NRL model as needed for variation of sea emissivity with EIA