WindSat Data Products and Assimilation

Mike Bettenhausen, Peter Gaiser and the WindSat Team
Remote Sensing Division
Naval Research Laboratory
Washington, DC

Workshop on
Applications of Remotely Sensed Observations in Data Assimilation
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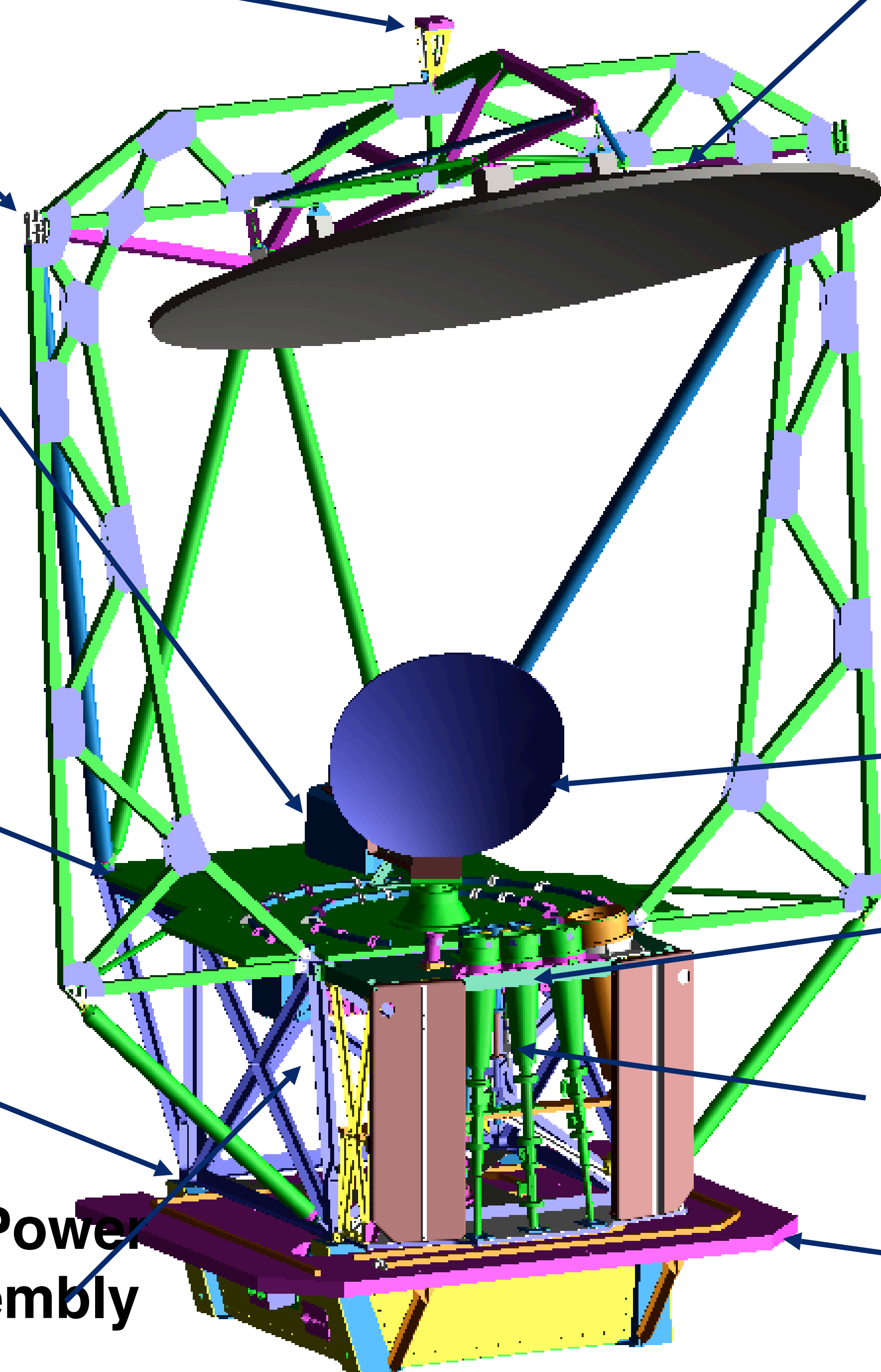
WindSat - Mission Description

- Demonstrate Ocean Surface Wind Speed and Direction Measurement Capability with Polarimetric Microwave Radiometry
- Launched 06 January 2003 on STP's Coriolis Satellite Bus Into a Sun-Synchronous Orbit (830 km; 98.7 deg; 1759 LTAN)
- 3 Year Design Life; Current plan calls for continued operation throughout useful life of Coriolis/WindSat
- Ocean EDRs are produced operationally by the Navy's Fleet Numerical and Meteorological Oceanographic Center (FNMOC)
- Gaiser, et al, IEEE TGRS, Nov. 2004.
- IEEE TGRS WindSat Special Issue, Mar. 2006.
- http://www.nrl.navy.mil/windsat

WindSat Payload Configuration



Height	10.5 ft.
Width	8.25 ft.
Weight	675 lbs.
Power	295 Watts
Spin Rate (Nom)	31.6 rpm
RF	22 Channels 5 Frequencies

WindSat Mission and Data

- WindSat/Coriolis Flies in Sun Synchronous Orbit at an 840-km Altitude
  - 1800 LTAN
  - 1000-km Swath Width (imagery)
- Multiple Data Products Produced
  - IDRs:
    - 37 GHz Imagery at 8 x 13 km Resolution
  - SDRs:
    - Calibrated, Geolocated Brightness Temperatures
  - EDRs:
    - Ocean Surface Wind Vector, SST, Total Precipitable Water, Cloud Liquid Water, Ocean Rain Rate
    - Sea Ice
    - Snow and Land Products under Development
      - Soil moisture retrievals available late 2007

SST Retrieval

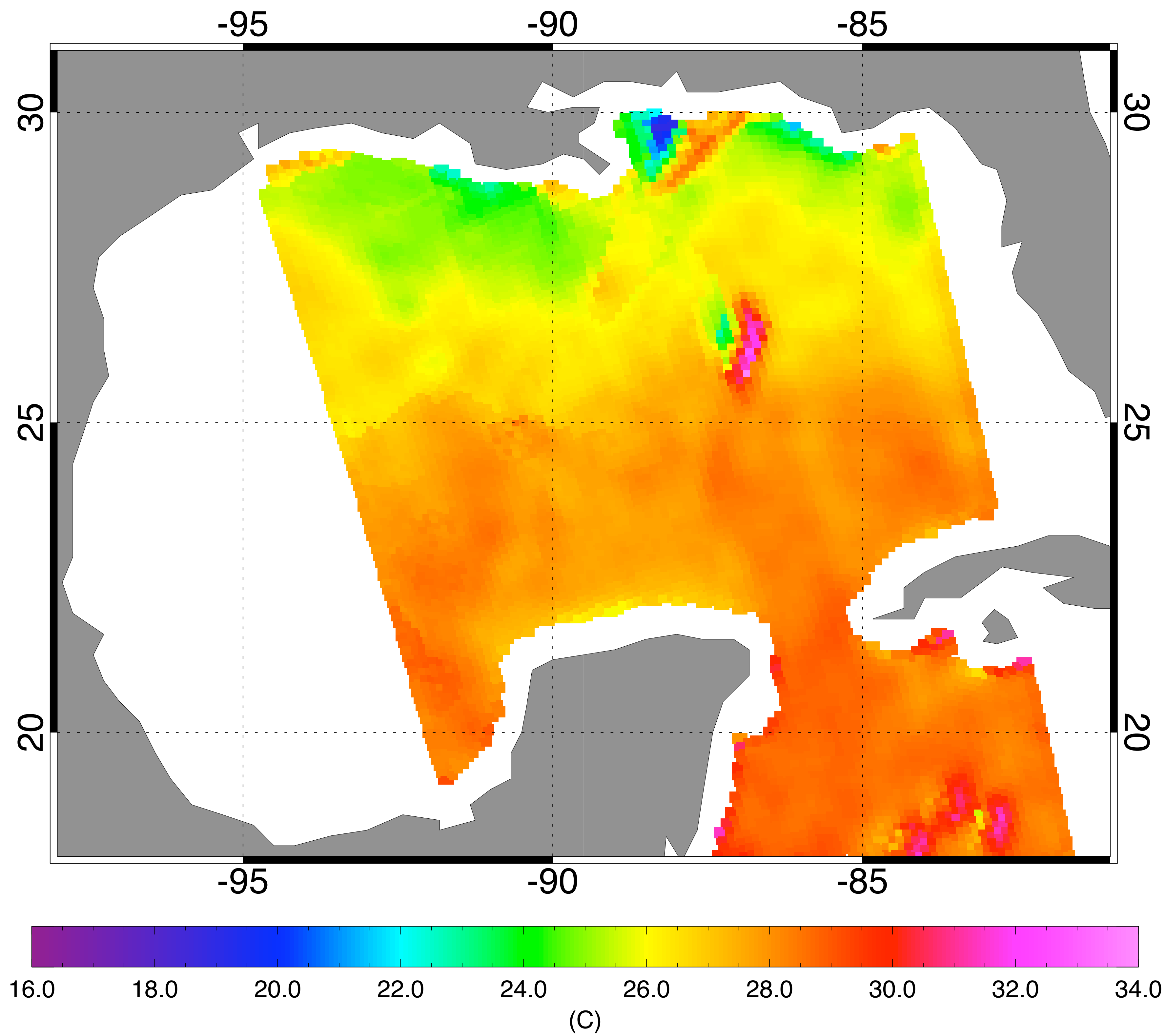
2004-11-03

WindSat Low Res

50 km X 71 km resolution

Rain flagged data is included

Land contamination can be seen near coast lines (75 km)



Wind Retrieval

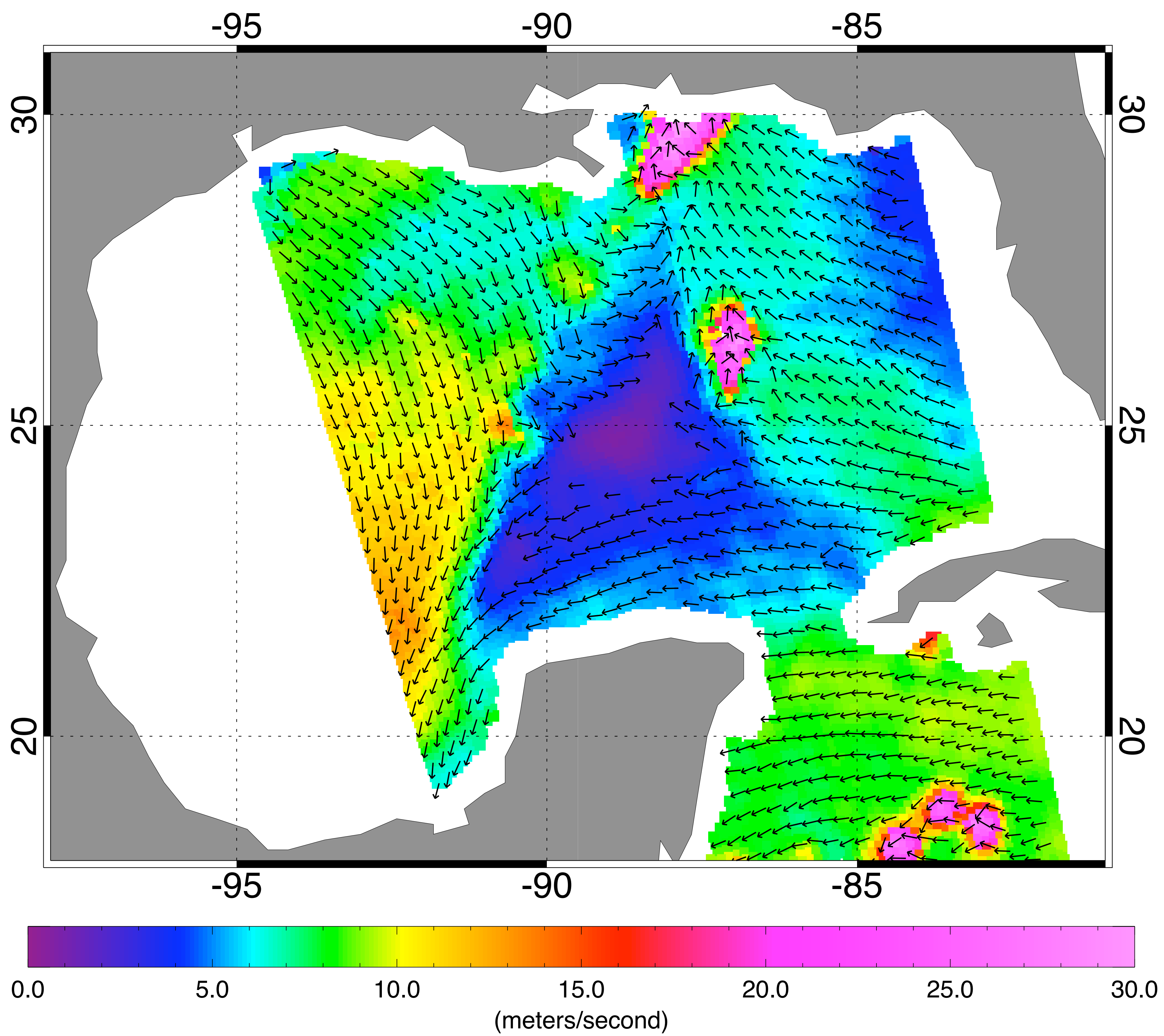
2004-11-03

WindSat Med Res

35 km X 53 km resolution

Rain flagged data is included

Retrievals are shown to within 75 km of the coast

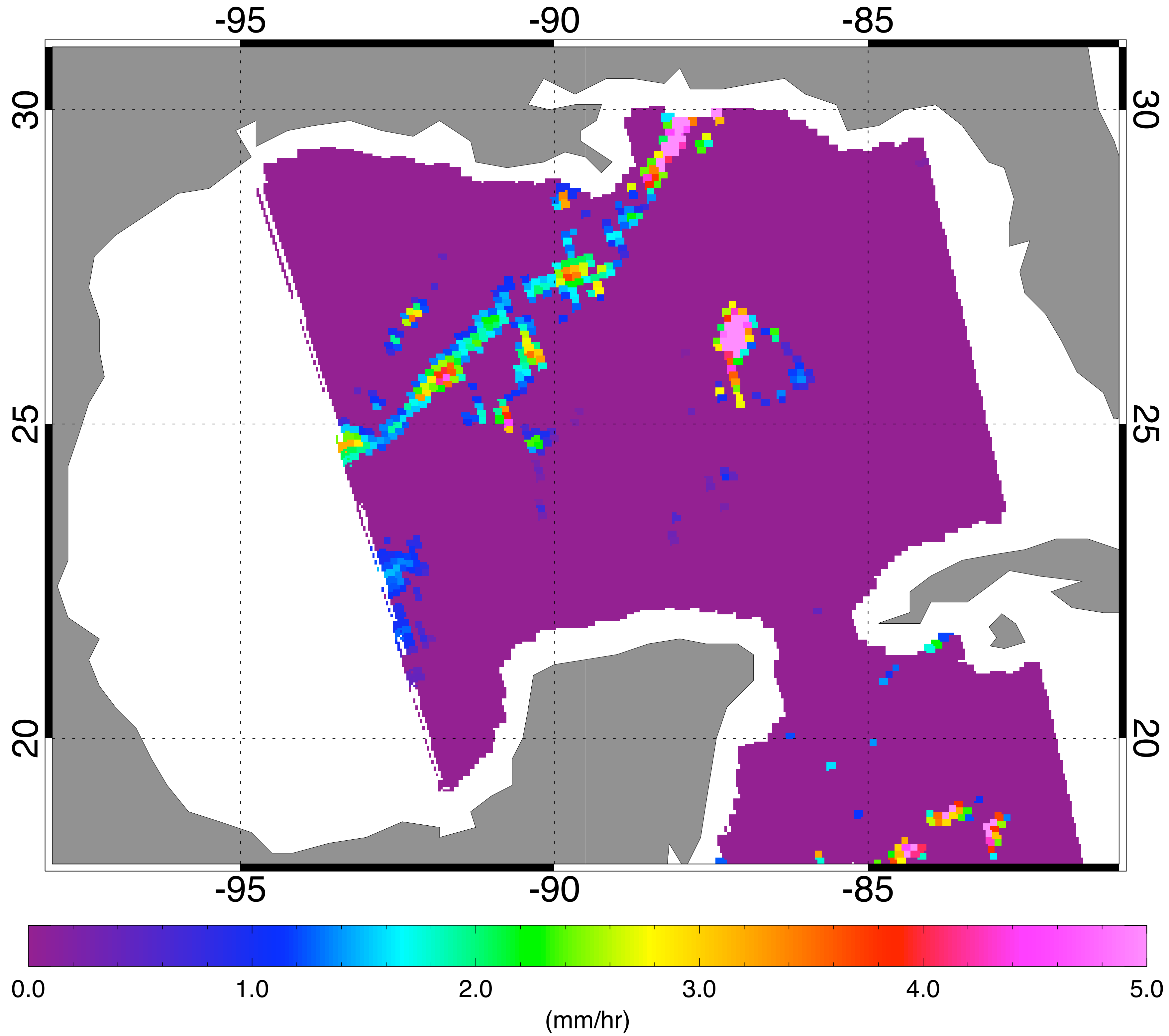


Rain Rate Retrieval

2004-11-03

WindSat

Approx. 14 km resolution



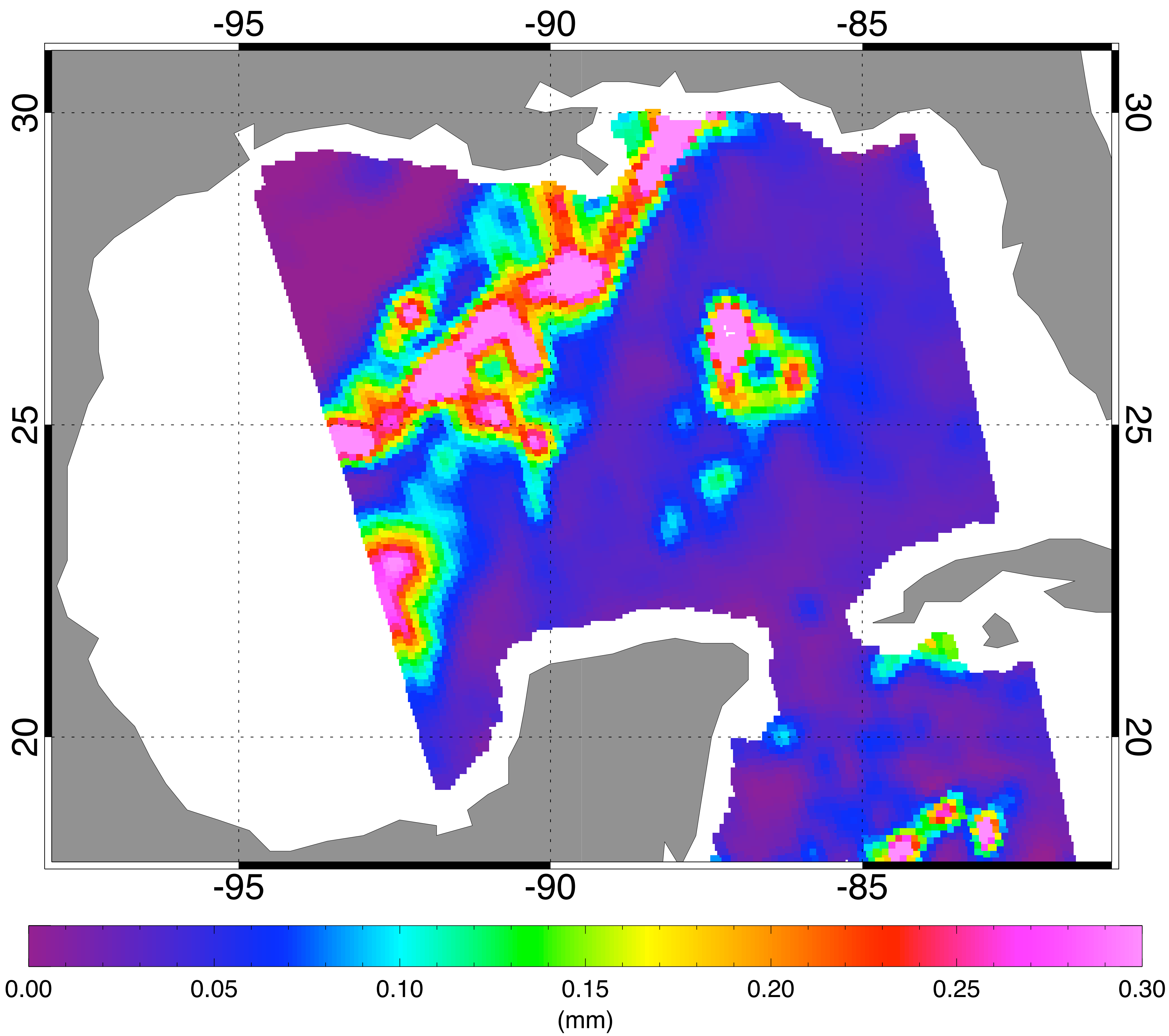
Cloud Liquid Water Retrieval

2004-11-03

WindSat Med Res

35 km X 53 km resolution

Rain is smoothed over larger area at this resolution

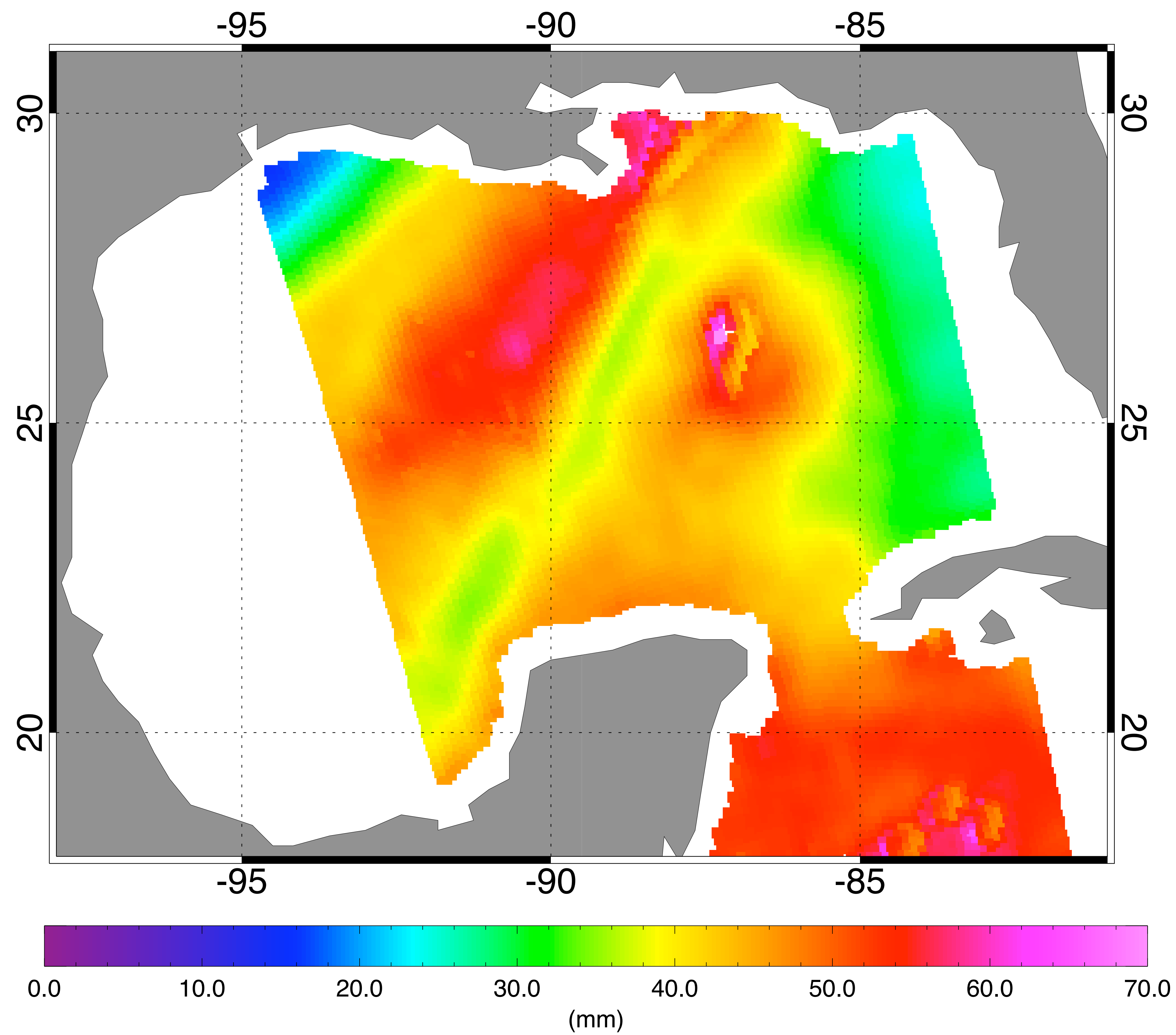


Water Vapor Retrieval

2004-11-03

WindSat Med Res

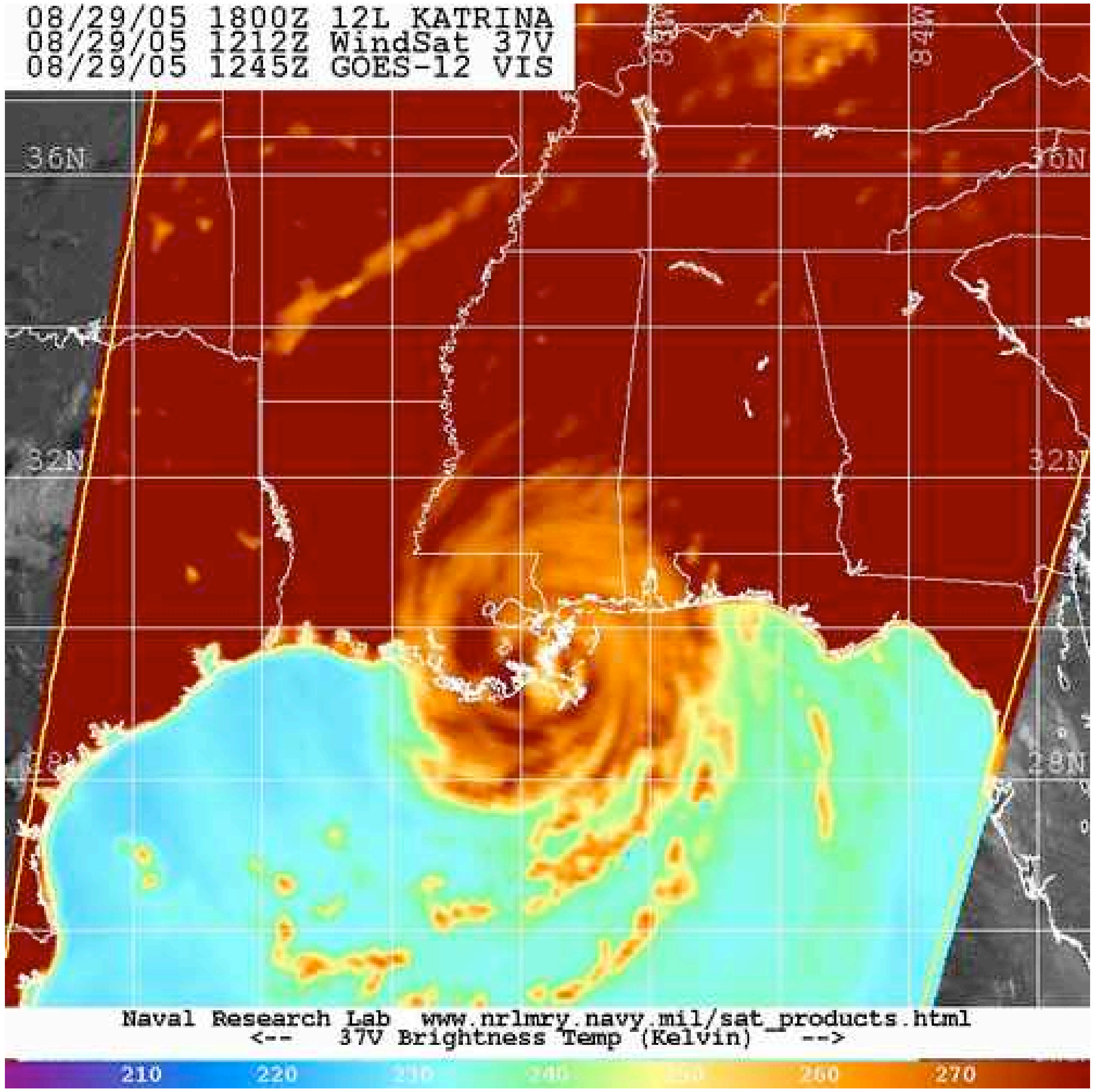
35 km X 53 km resolution



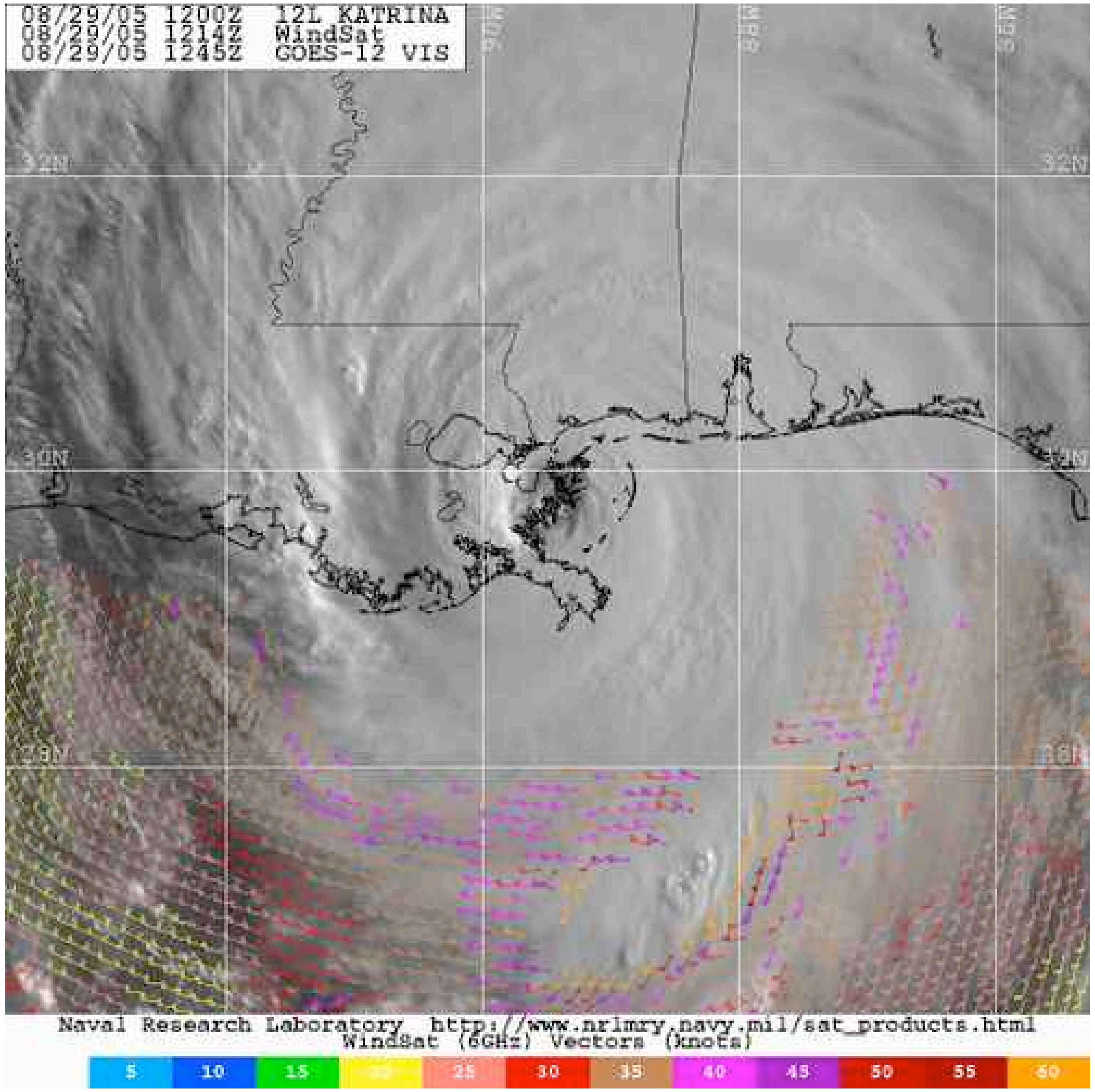
WindSat Operational Data Products

Katrina at Landfall

Imagery

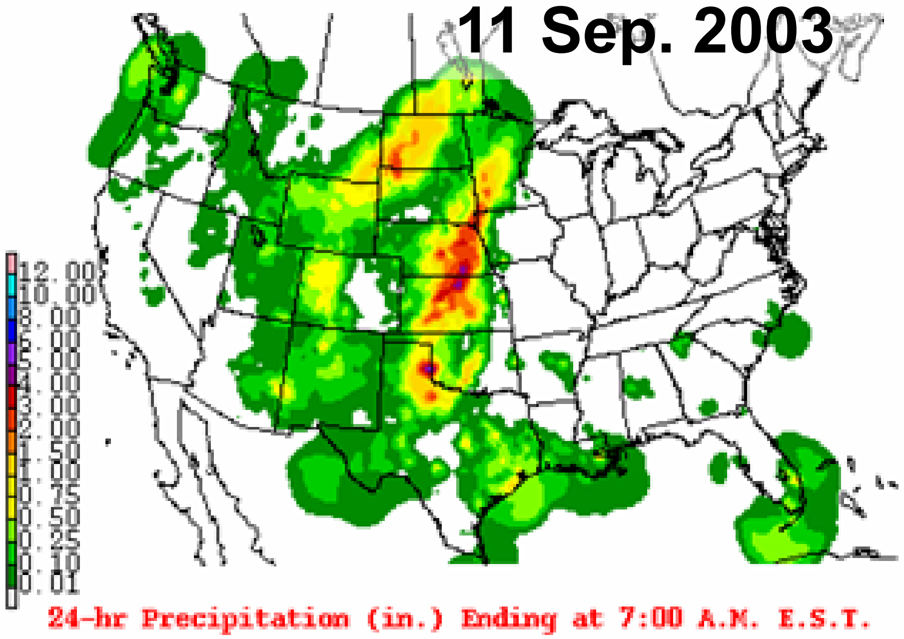


Wind Field

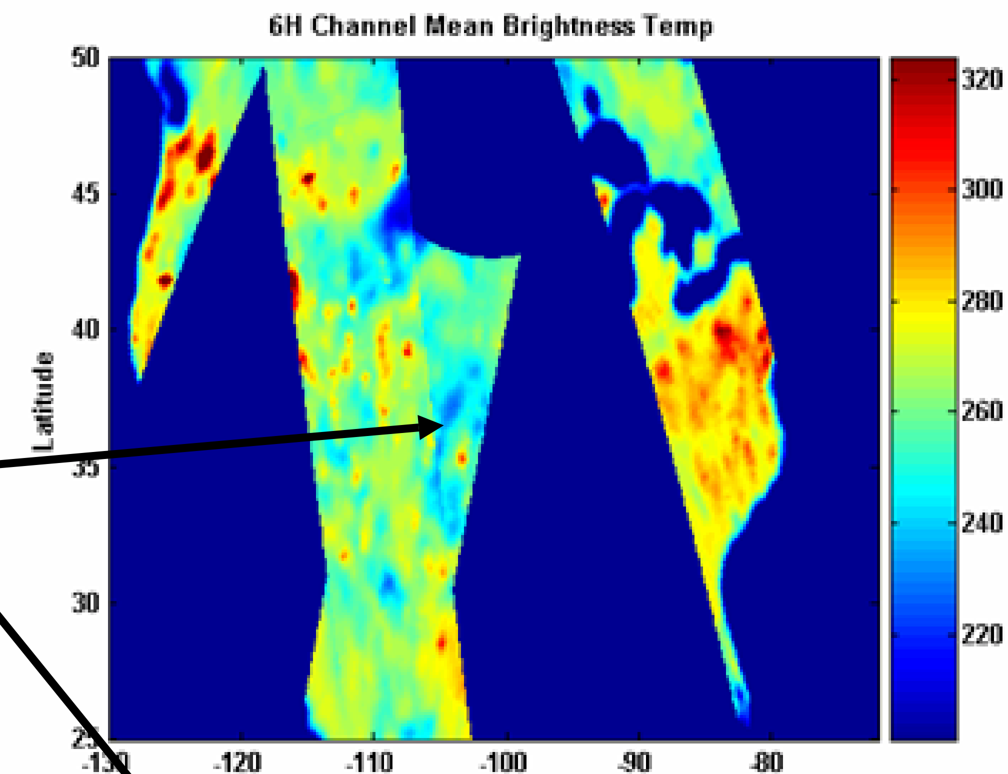


Operational Data Products Generated at FNMOC/NRL-MRY in Near Real Time

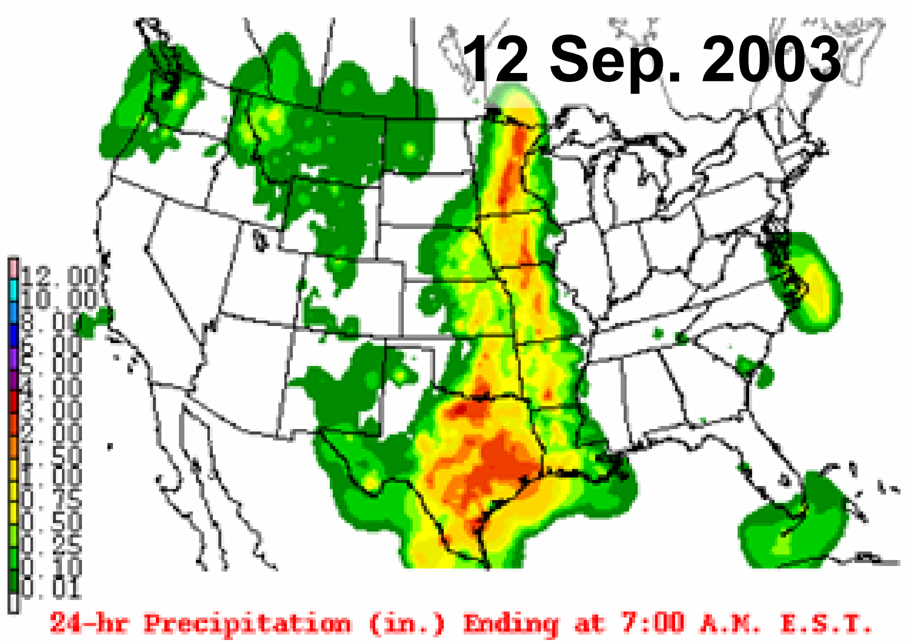
Main Rain Event on Sep. 11-12 2003

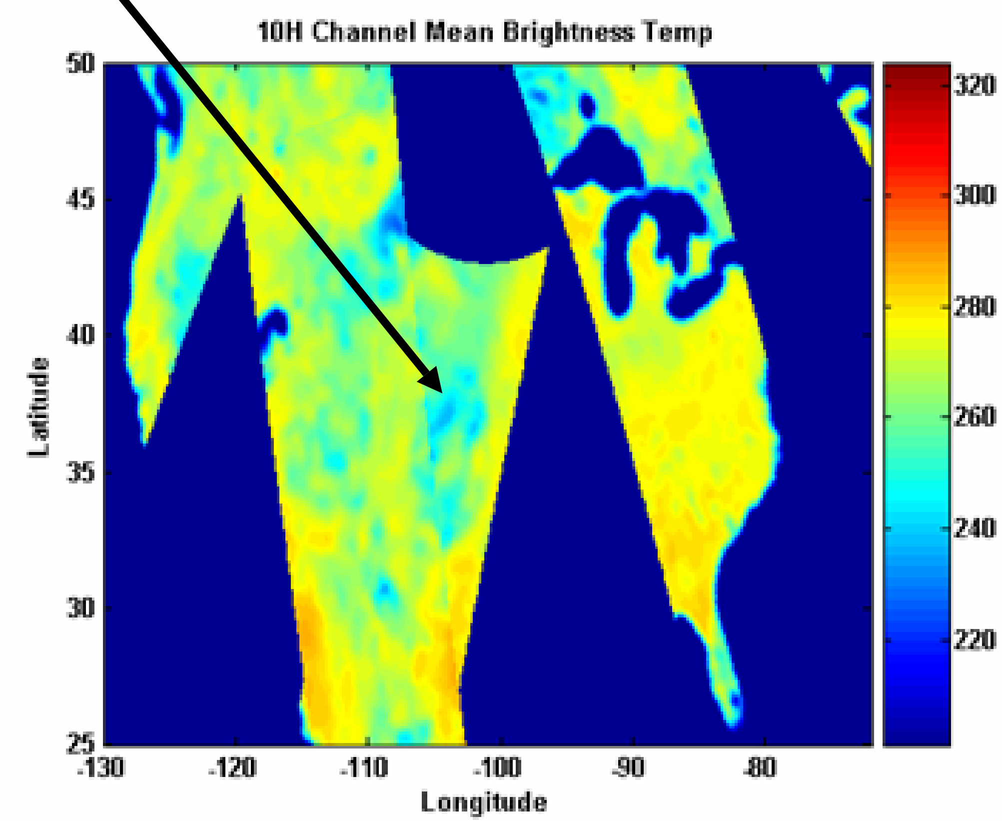


WindSat Rain Event Signals
(11 Sep. 2003)



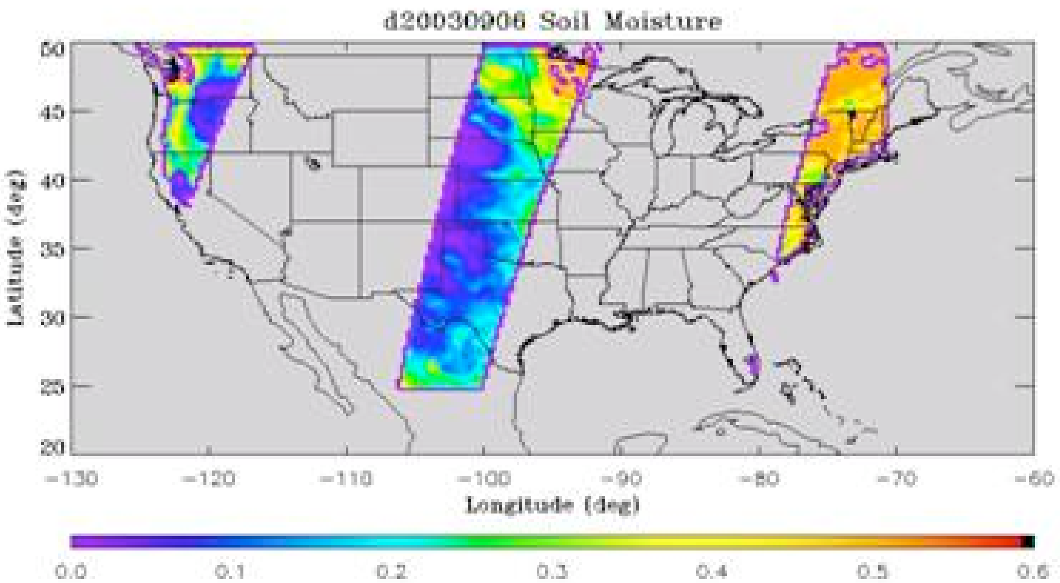
Widespread and Significant Rain Events

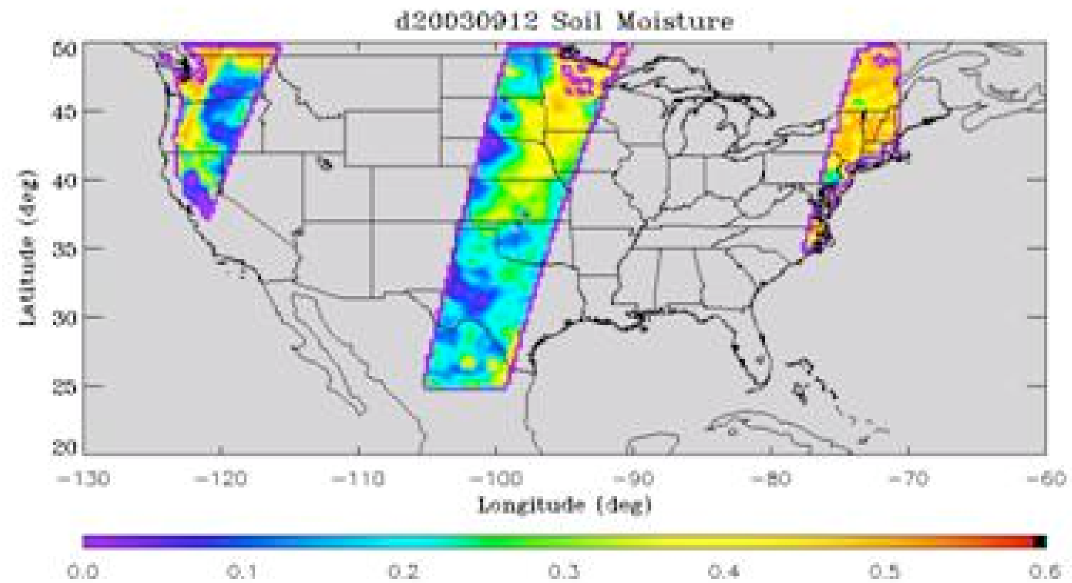


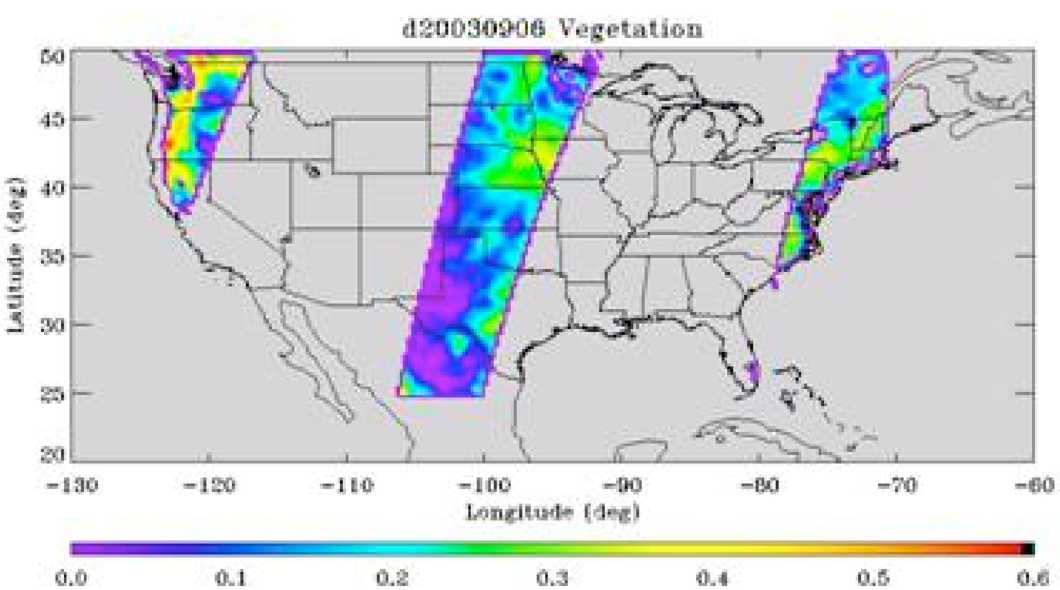


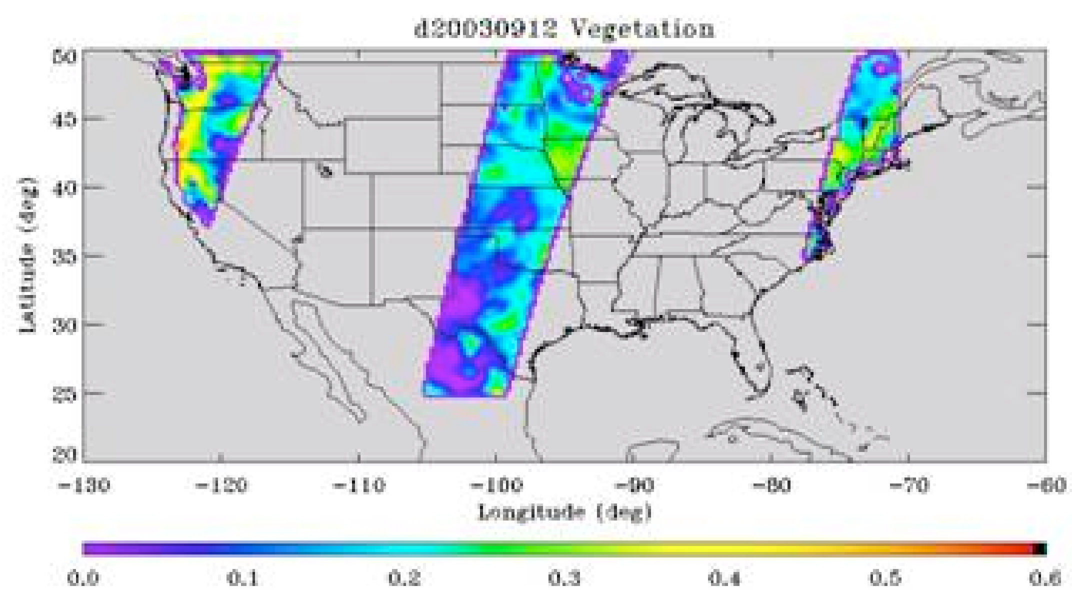
CG/AR

WindSat Land Retrievals
September 12, 2003







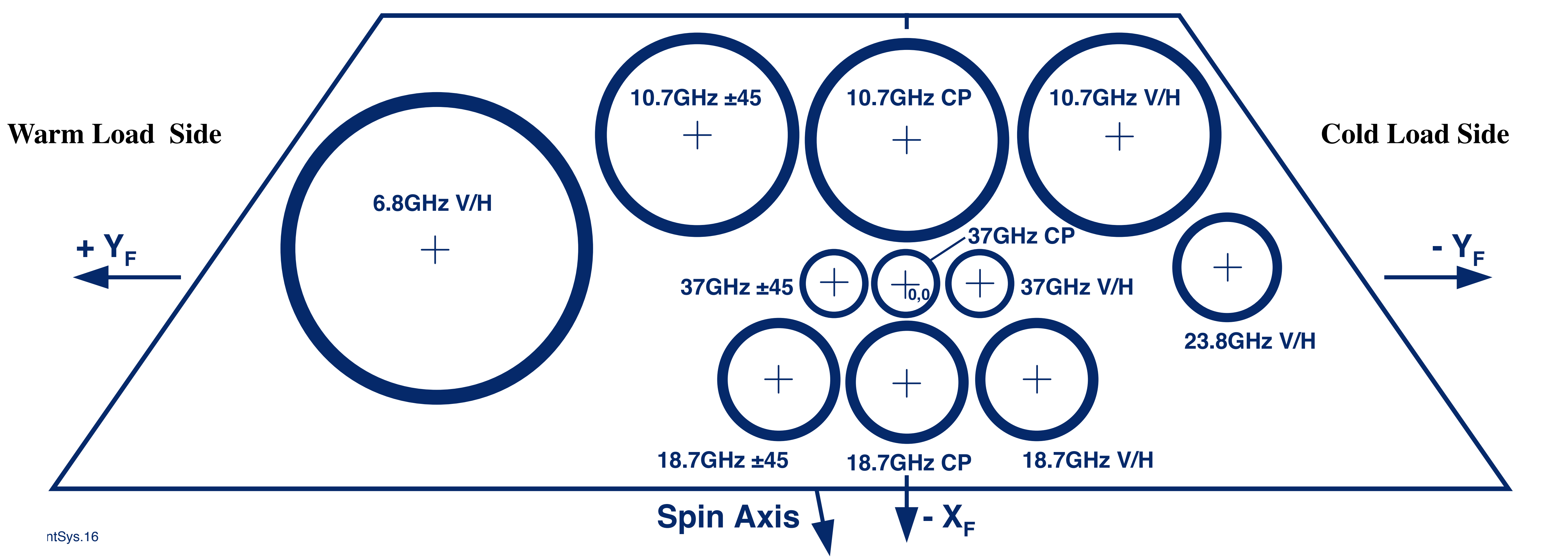


WindSat Channels

WindSat	Freq. (GHz)	6.8	10.7	18.7	23.8	36.5	
	Bandwidth (MHz)	125	300	750	500	2000	
	Polarizations	V,H	V,H,3,4	V,H,3,4	V,H	V,H,3,4	
	IFOV (km x km)	71x39	38x25	27x16	30x20	13x8	
AMSR-E	Freq. (GHz)	6.9	10.65	18.7	23.8	36.5	89.0
	Bandwidth (MHz)	350	100	200	400	1000	3000
	Polarizations	V,H	V,H	V,H	V,H	V,H	V,H
	IFOV (km x km)	75x43	51x29	27x16	32x18	14x8	6x4
SSM/I	Freq. (GHz)			19.35	22.235	37.0	85.5
	Bandwidth (MHz)			200	400	1000	3000
	Polarizations			V,H	V	V,H	V,H
	IFOV (km x km)			69x43	60x40	37x29	15x13

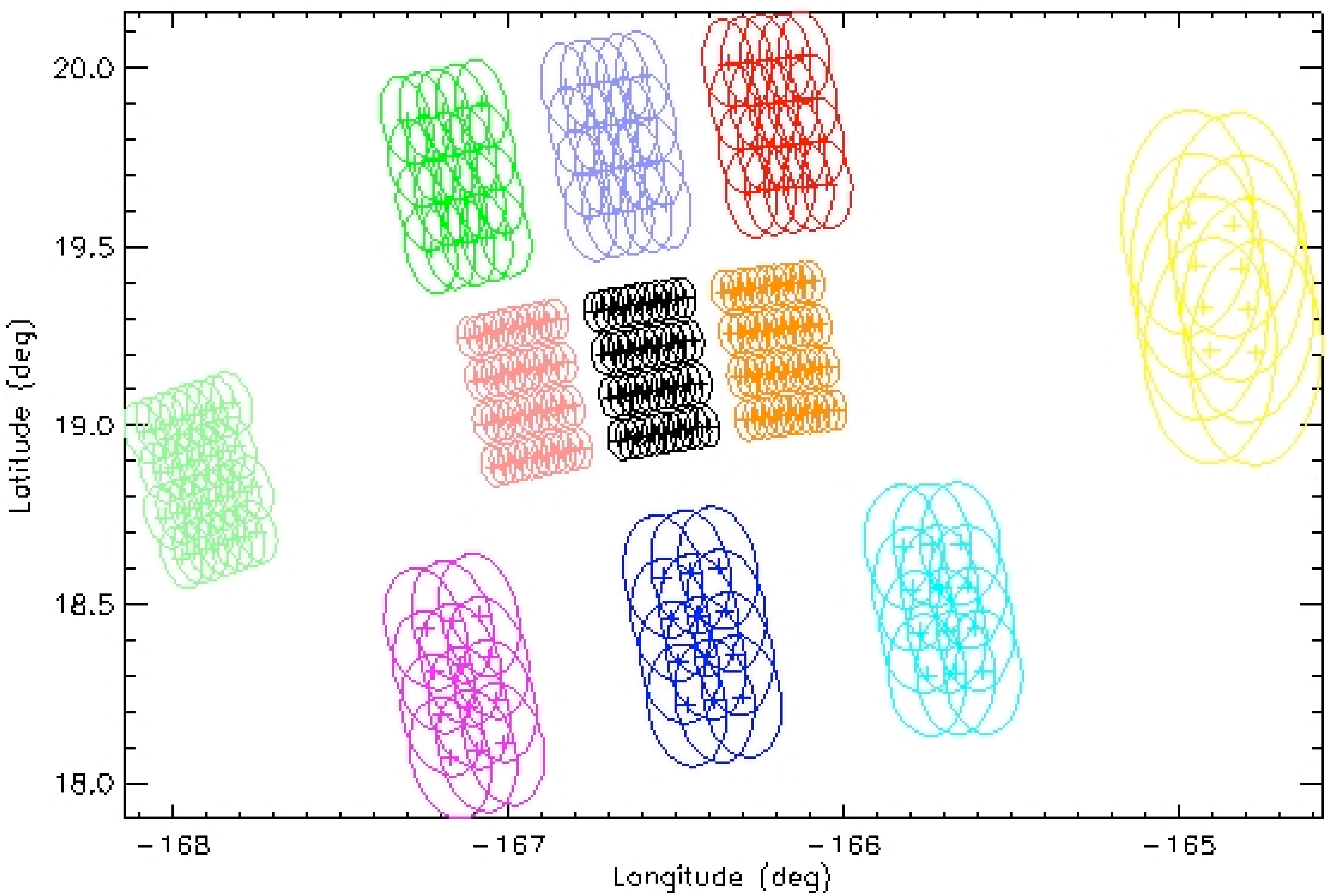
Feedbench View from Main Reflector

11 feed horns
22 measured antenna temperatures



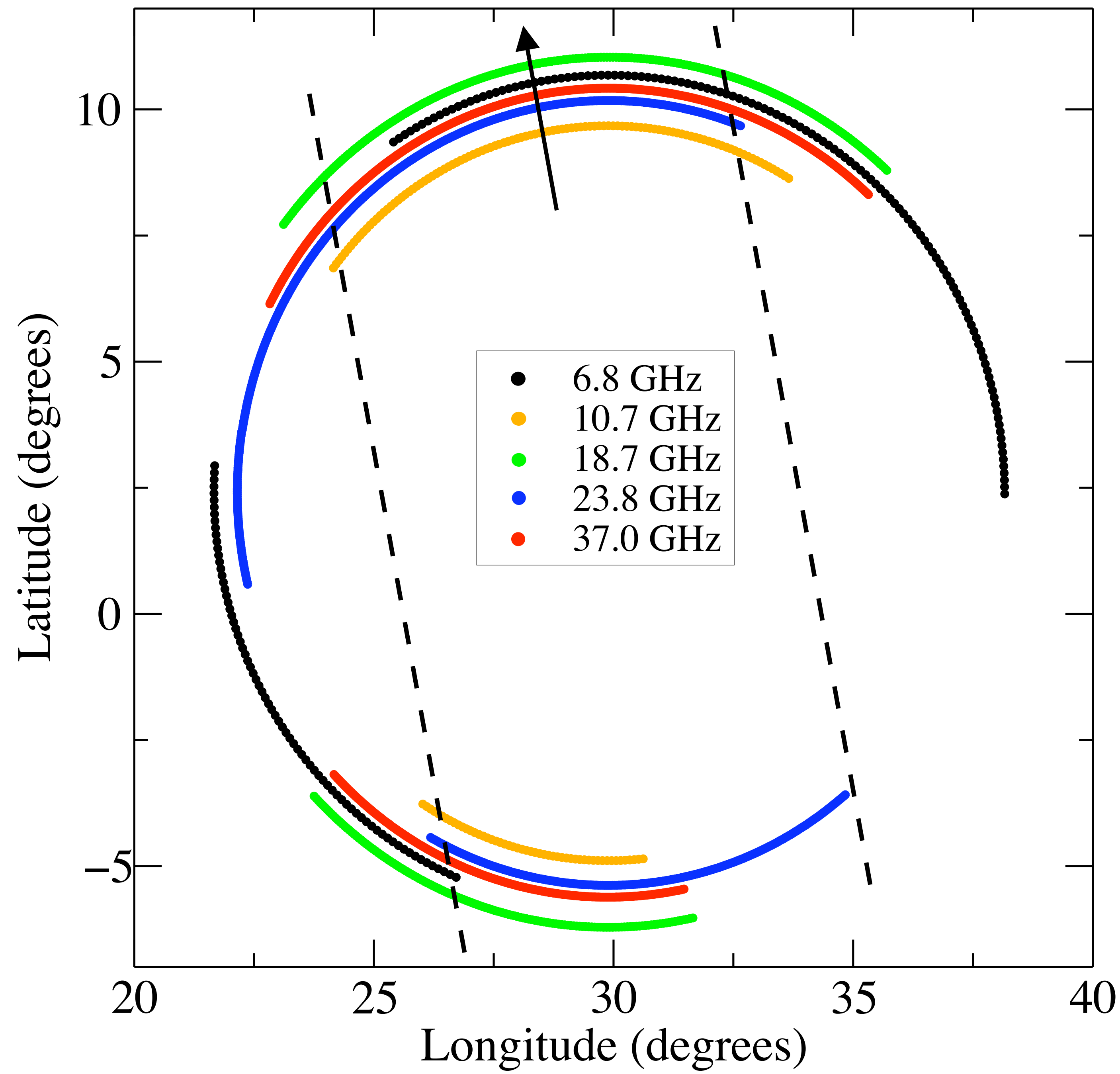
Earth Projected Beams

- Multiple Feeds Results in 11 Sets of Dual-Polarized Antenna Beams
- Beams within Frequency Bands Have Same EIA
- All frequencies and polarizations are resampled and averaged to a common footprint using a modified Backus-Gilbert technique.



Scan Geometry

- Photo on the left shows the feed horns.
- Figure on the right shows angular distribution of measurements for one scan. The radial positions of the 6.8 GHz and 23.8 GHz measurements are nearly the same as the 37 GHz but they have been shifted here for display purposes.

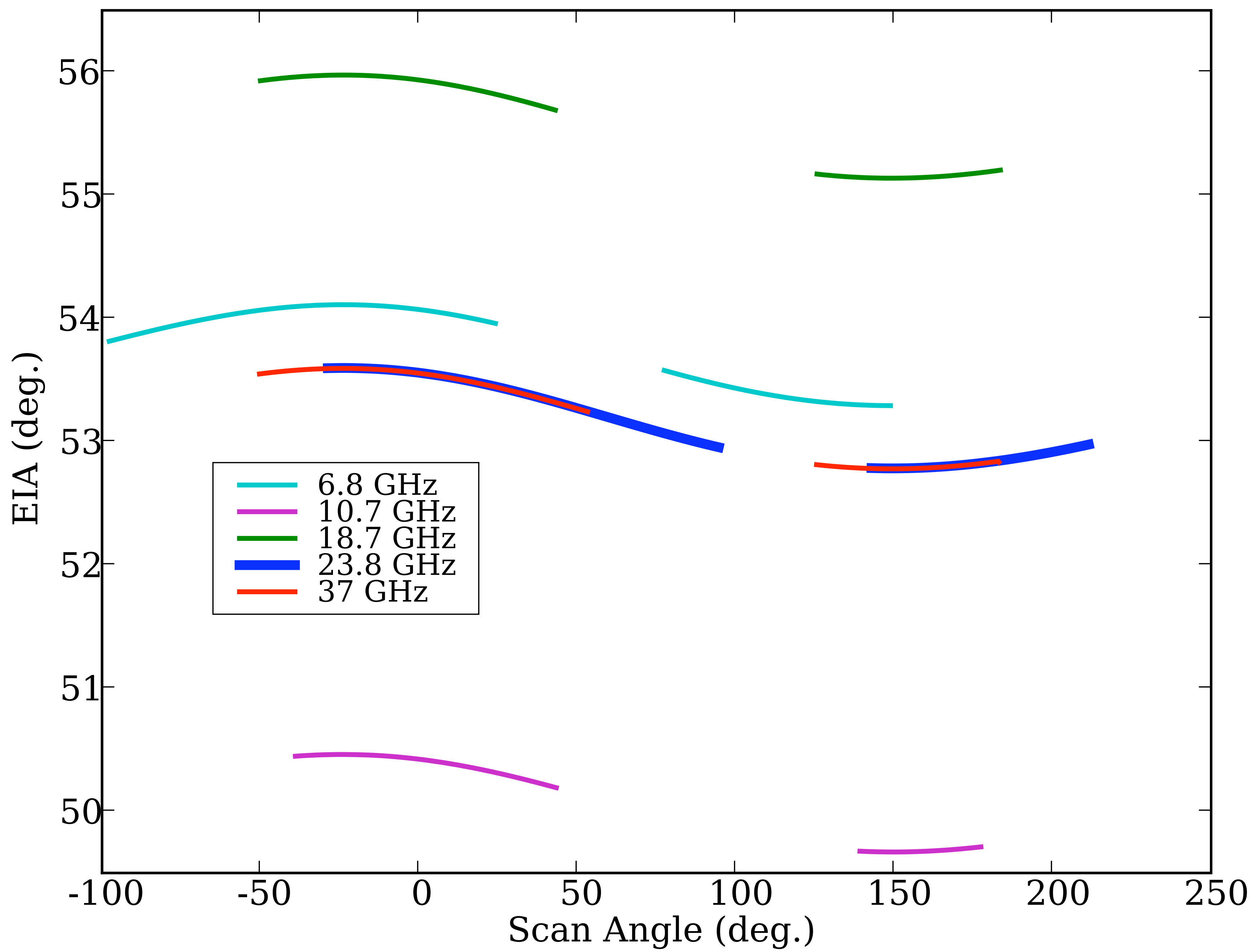


Sensor Data Records (SDRs)

- Antenna pattern correction applied at each frequency.
- All frequencies and polarizations are resampled and averaged to a common footprint.
- Swath width is set to maximum width where all antenna temperatures are available (except the 6.8 GHz).
- Forward swath width is about 900 km.
- Aft swath width is about 300 km.
- Three resolutions:
  - Low: 50 km by 71 km (operational)
  - Medium: 35 km by 53 km (in testing)
  - High: 25 km by 35 km (in testing)

EIA Along Scan Variations

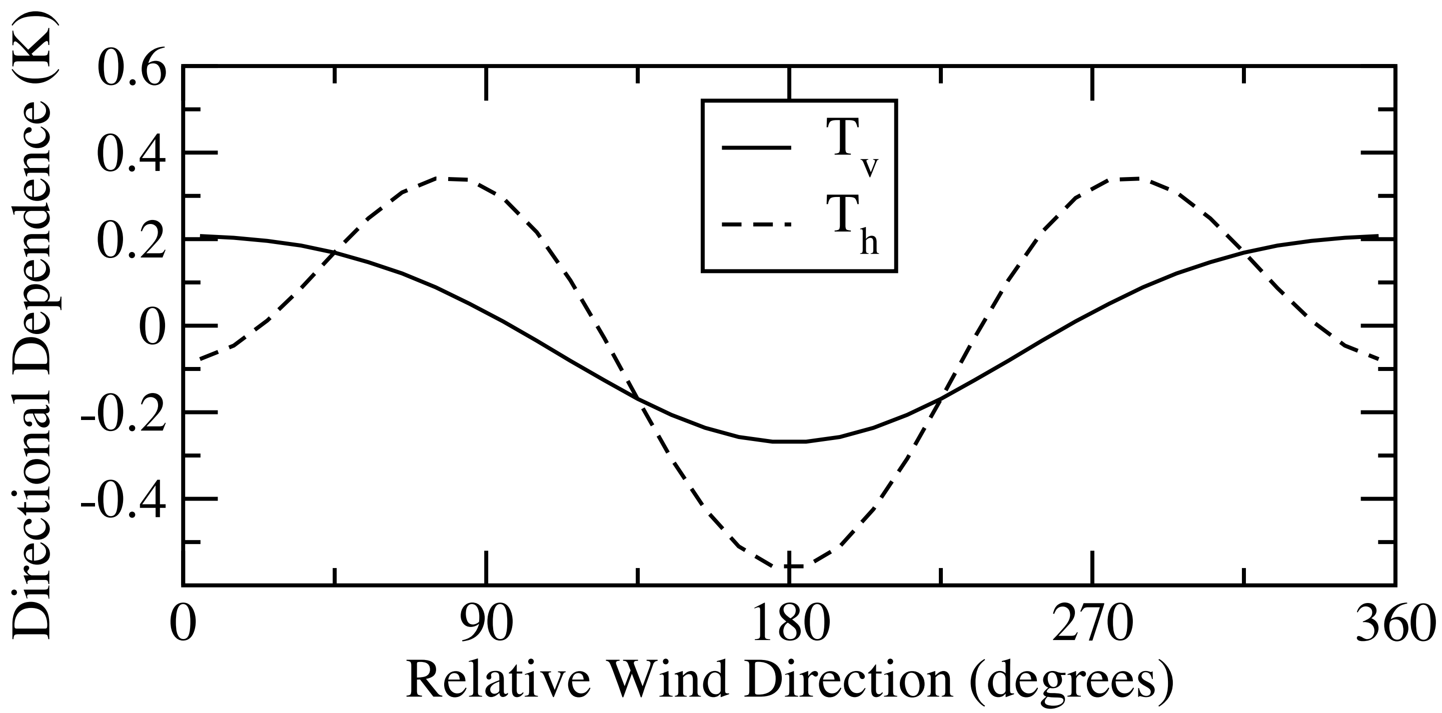
- Earth incidence angle (EIA) varies along scan due to small pitch and roll offsets of WindSat
- This complicates along scan analysis because the analysis much account for the EIA dependence of Tbs
- Similarly the PRA changes along scan which affects the 3rd Stokes Tbs

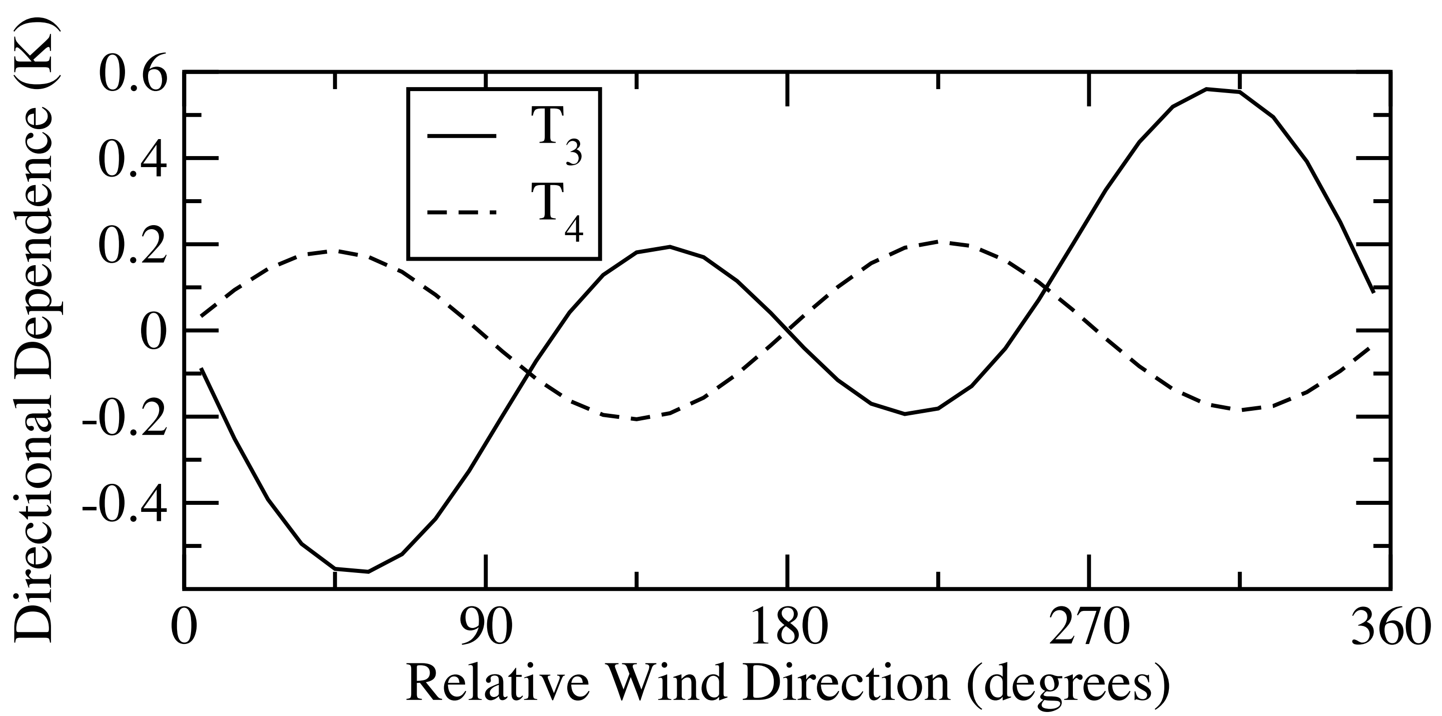


Polarimetric Radiometry

- Ocean surface emission and reflection vary with wind vector
  - Wind direction dependence from anisotropic distribution of wind driven waves
  - Wind direction signal in V, H polarizations is two orders of magnitude smaller than background signal
  - WindSat is fully polarimetric at 10.7, 18.7 and 37 GHz
- Noise and knowledge error requirements are tighter
- T_3 and T_4 are zero-mean signals and residual biases contribute to wind direction errors

10.7 GHz at 8 m/s Wind Speed





Polarimetric Radiometry

- Polarimetric radiometry measures Stokes vector
- Two means of measuring
  - Correlation of primary polarizations
  - Direct measure of ±45, LHC, RHC polarizations (WindSat)

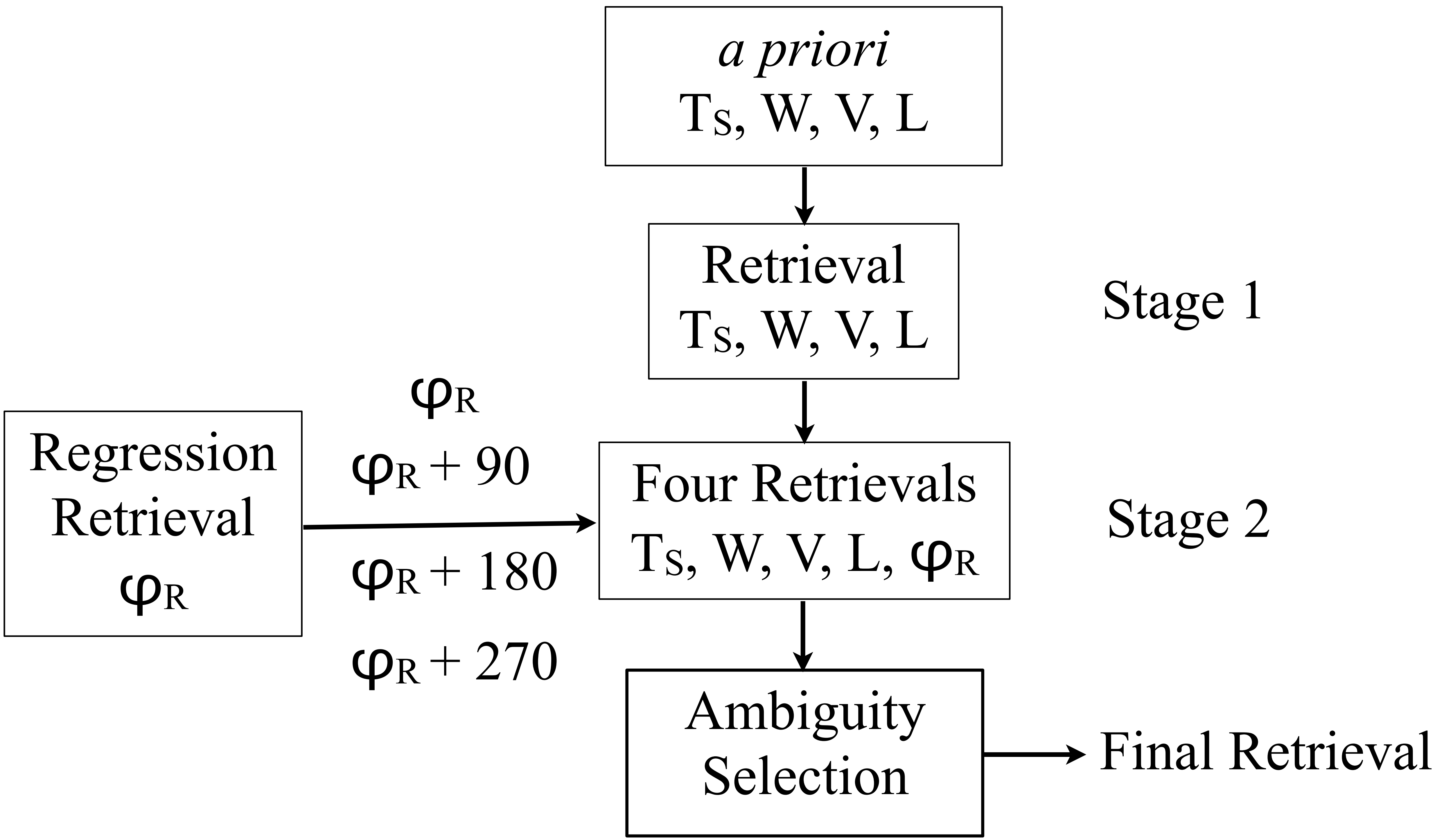
$$I_s = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \langle E_h E_h^* \rangle + \langle E_v E_v^* \rangle \\ \langle E_h E_h^* \rangle - \langle E_v E_v^* \rangle \\ 2\,\mathrm{Re}\langle E_v E_h^* \rangle \\ 2\,\mathrm{Im}\langle E_v E_h^* \rangle \end{bmatrix} = \begin{bmatrix}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

- First two rows (I, Q): Available from "Dual Polarization" Systems (SSM/I, SSMIS)
- Last two rows (U, V): New Capability Available from "Polarimetric" Systems (WindSat)

Retrievals

- Physically-based algorithm using nonlinear optimization (NRL)
  - Uses physical forward model
  - Solves for all EDRs simultaneously
- Empirical regression technique (NRL)
  - Two-stage regression for wind vector components
  - Maximum likelihood estimator (MLE) for final wind direction
- Maximum Likelihood Estimator (NOAA)
  - Uses empirical forward model for wind vector retrievals
  - Regression retrievals for other EDRs
  - Solves for each EDR separately
- Other retrieved EDRs are columnar water vapor, cloud liquid water, SST
- Ocean rain rate, land and sea ice products are retrieved separately

Ocean Retrievals



Overview of Optimal Estimation

- Iterative method to minimize the cost function

$$\Phi = \underbrace{(\hat{x} - x_a)^T S_a^{-1} (\hat{x} - x_a)}_{\text{Cost of moving away from a-priori values for x}} + \underbrace{(y - F(\hat{x}))^T S_y^{-1} (y - F(\hat{x}))}_{\chi^2}$$

where

x = true values of the "state vector" $[T_S, W, \phi_R, V, L]$
$\hat{x}$ = retrieved state vector
x_a = a – priori values for state vector
S_a = a – priori error covariance matrix

y = measurement vector (measured brightness temperatures),
F = parameterized forward model function
S_y = Error covaraince matrix for y

Optimal Estimation Procedure

Initialize state vector to the *a priori* and iterate:

$$x_{i+1} = x_a + \left(S_a^{-1} + K_i^T S_y^{-1} K_i\right)^{-1} K_i^T S_y^{-1} \left[y - y_i + K_i \left(x_i - x_a\right)\right]$$

Kernel is computed from the forward model function:

$$K_i = \left.\frac{\partial F}{\partial x}\right|_{x=x_i}$$

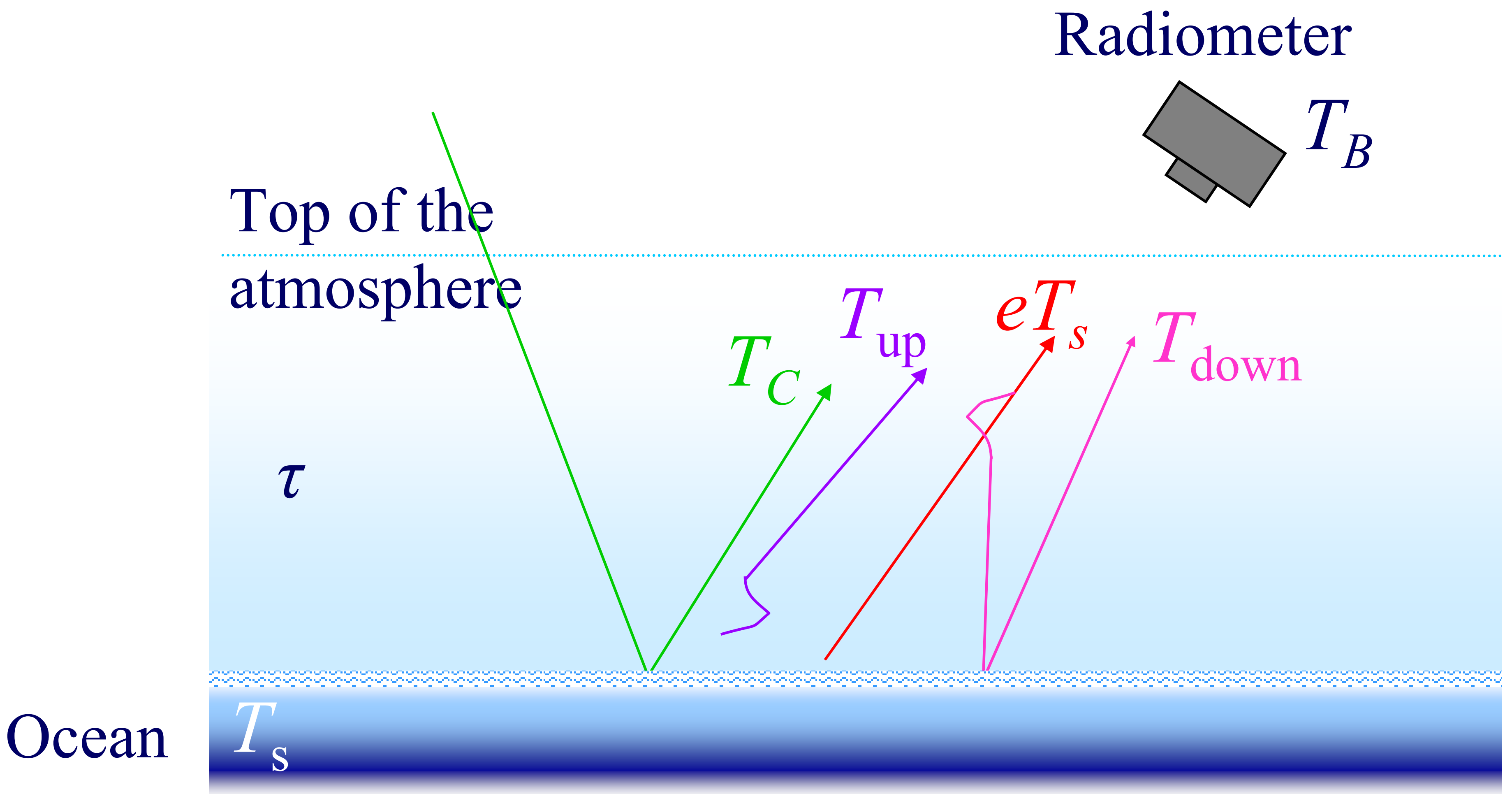
Estimate for the retrieval error covariance:

$$\hat{S}_n = \left(S_a^{-1} + K_n^T S_y^{-1} K_n\right)^{-1}$$

Convergence test:

$$\left(x_i - x_{i+1}\right)^T \hat{S}_{i+1}^{-1} \left(x_i - x_{i+1}\right) < N/4$$

Radiative Transfer Components



$$T_{v,h} = T_{up} + \tau \left[e_p T_S + r_p \left(\tilde{\Omega} T_{down} + \tau T_C \right) \right]$$

$$T_{3,4} = \tau e_p \left[T_S - \left(T_{down} + \tau T_C \right) \right]$$

Forward Model Components

- Sea emissivity and reflectivity
  - Two-scale model
    - small scale roughess
    - large scale gravity waves
  - Empirical corrections are made to account for foam and modeling errors
  - Harmonics correction
    - $(e_{measured} - e_{model}) = c_0 + (c_1 + c_2\ W) \sin(\varphi) + (c_3 + c_4\ W) \sin(2\varphi)$
    - sin applies for for 3rd and 4th Stokes
    - sin is replaced with cos for V and H polarizations
- Atmospheric model
  - One-layer approximation
  - Parameterized model to match full radiative transfer calculations
    - parameterization in terms of water vapor and cloud liquid water

Atmospheric Radiative Transfer

- Water Vapor Absorption
  - Rosenkranz, 1998, "Water Vapor Microwave Continuum…"
- Cloud Liquid Water Absorption
  - Rayleigh approx to Mie Scattering (Goldstein, 1951)
    - Dielectric Constant of pure water
      - Double Debye Model from MPM-93
- Oxygen Absorption
  - Liebe, Millimeter Wave Propagation Model, 1993 (MPM-93)
- Parameterized for retrievals
  - $\tau = \exp\left[-\sec\theta\left(A_O + A_V + A_L\right)\right]$
  - T_{up}, T_{down} and cross-sections in terms of V, L

Observation Error Estimate

- For our physically based retrievals we estimate an observation error covariance matrix using our forward model and matchup data
- Parameterized RTM is used to compare to Tbs (SDRs)
- NCEP NWP analysis or satellite data is collocated with WindSat Tbs
  - NCEP SST interpolated to WindSat location
  - QuikSCAT winds within 27 km and 60 min. or NCEP winds withing 60 min. and interpolated to WindSat location
  - SSM/I or TMI wave vapor and cloud liquid water within 25 km and 35 min.

Observation Errors

- Estimates include modeling error, spatial and temporal sampling error (WindSat vs. matchup), errors in matchup data, residual Tb calibration errors

Table shows the standard deviation of the observation error (K) for each channel 10.7 through 37 GHz.

V, H, 3, 4 refer to vertical, horizontal, third and fourth Stokes.

LR is the low resolution 50 km x 71 km footprint and MR is the medium resolution 35 km x 53 km footprint.

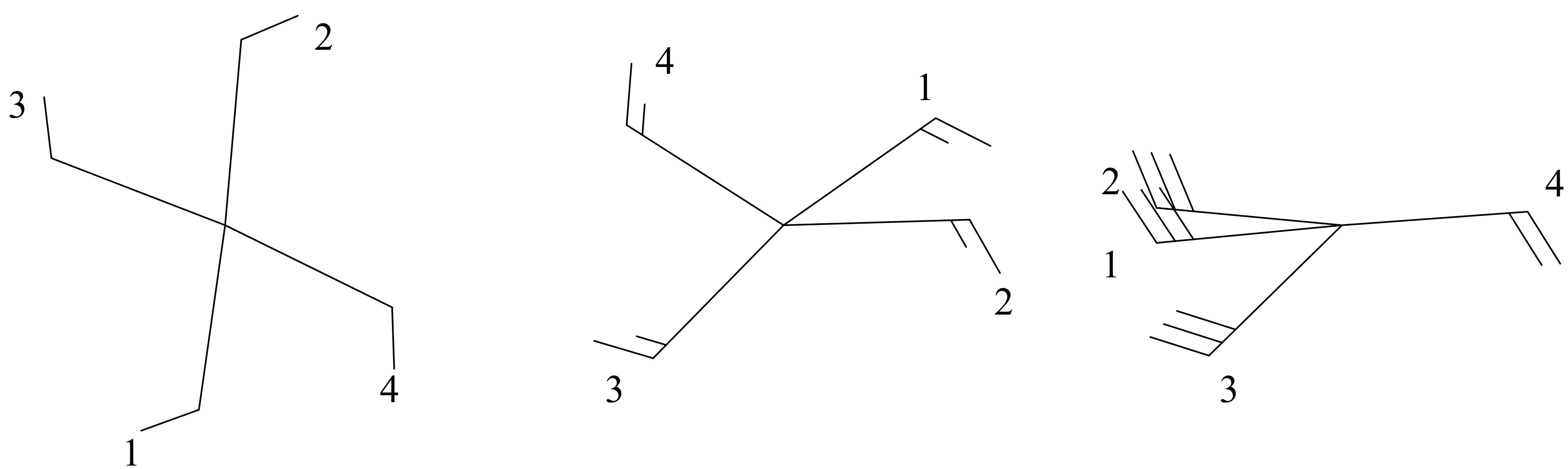
Freq.(GHz)	Pol.	LR	MR
10.7	V	0.47	0.49
10.7	H	0.70	0.70
10.7	3	0.14	0.15
10.7	4	0.08	0.10
18.7	V	0.49	0.50
18.7	H	0.99	1.00
18.7	3	0.18	0.19
18.7	4	0.11	0.12
23.8	V	1.14	1.15
23.8	H	2.14	2.15
37.0	V	1.13	1.14
37.0	H	2.41	2.42
37.0	3	0.19	0.20
37.0	4	0.06	0.08

Wind Direction Ambiguity Removal

- Circular Vector Median Filter
  - Based on S.J. Shaffer, et al., TGRS, 29, 1991
  - Minimize cost function:
- 7x7 box size (h = 3)
  - Central pixel is included in cost function
- Cost Function weighting (w_{mn})
  - by wind speed because skill improves with wind speed
  - by first rank χ^2 probability
  - weight = Prob(χ^2)**0.2 * min(1.0, 0.1 * wind speed)
- Nudging (optional)
  - Uses spatially interpolated winds from NWP model
  - Nudge using ambigutiesy where Prob(χ^2) > 0.5 Prob(χ^2) for 1st rank (except in the presence of rain, RFI, etc.
  - Use 1st rank if closest ambiguity is not at least 30 deg. closer than the 1st rank ambiguity
- Assimilation techniques generally have not used our selected ambiguity

Ambiguity Characteristics

- Depends on the Retrieval Algorithm
- Depends on wind speed and relative wind direction
  - Ambiguity decreases at high wind speeds



W (m/s)
4.7
4.6
4.5
4.3

W (m/s)
9.1
9.1
8.9
8.5

W (m/s)
15.1
15.4
15.1
9.8

Quality Control Flagging

- No retrieval is performed when the EIAs or Tbs are out-of-bounds
- Retrievals are flagged as “low confidence” for any of the following conditions:
  - Rain using a flag based on the cloud liquid water retrieval
  - Ice
  - RFI at 10.7 GHz
  - Land contamination
  - Inland lakes and sheltered bodies of water
  - Beam averaging threshold
  - Satellite attitude transient
- Corrections have been applied for:
  - Warm load calibration errors due to thermal gradients on the warm load from solar intrusion
  - Cold load anomalies due to space based RFI and lunar intrusion

Quality Control Flagging (cont'd)

- Monthly sea ice extent climatology
  - Ice flagging is done using ratios of the 18.7 and 10.7 GHz v-pol and the 23.8 and 18.7 GHz v-pol
- RFI at 10.7 GHz around Europe (descending) and off the east coast of South America (ascending)
  - Refection of TV broadcast satellites off sea surface
  - Other smaller sources may present
- Land contamination
  - Footprints at each resolution are convolved with high resolution land mask
  - Orientation of elliptical footprint is accounted for

Retrieval Performance

- Still evolving with calibration and algorithm improvements
- Wind speed at high wind speeds and wind direction in light precipitation is an active area of research
- Wind direction at low wind continues to improve with refinements in calibration and our forward model
- Most studies of performance have used data archived at NASA JPL PO.DAAC which was released in early 2006 (version 1.9.0)
- Current operational retrievals include improvements from the archived data

Retrieval Performance

- Twelve month data set
- Wind speed and direction relative to NCEP GFS
- SST relative to NCEP GFS
- Water vapor and cloud relative to SSM/I

EDR	Bias	Std.Dev.	RMS
SST (K)	-0.1	0.7	0.7
W First Rank (m/s)	0.10	0.81	0.82
W Selected (m/s)	0.07	0.79	0.79
Water Vapor (mm)	0.01	0.91	0.91
Cloud Water (mm)	-0.004	0.030	0.030

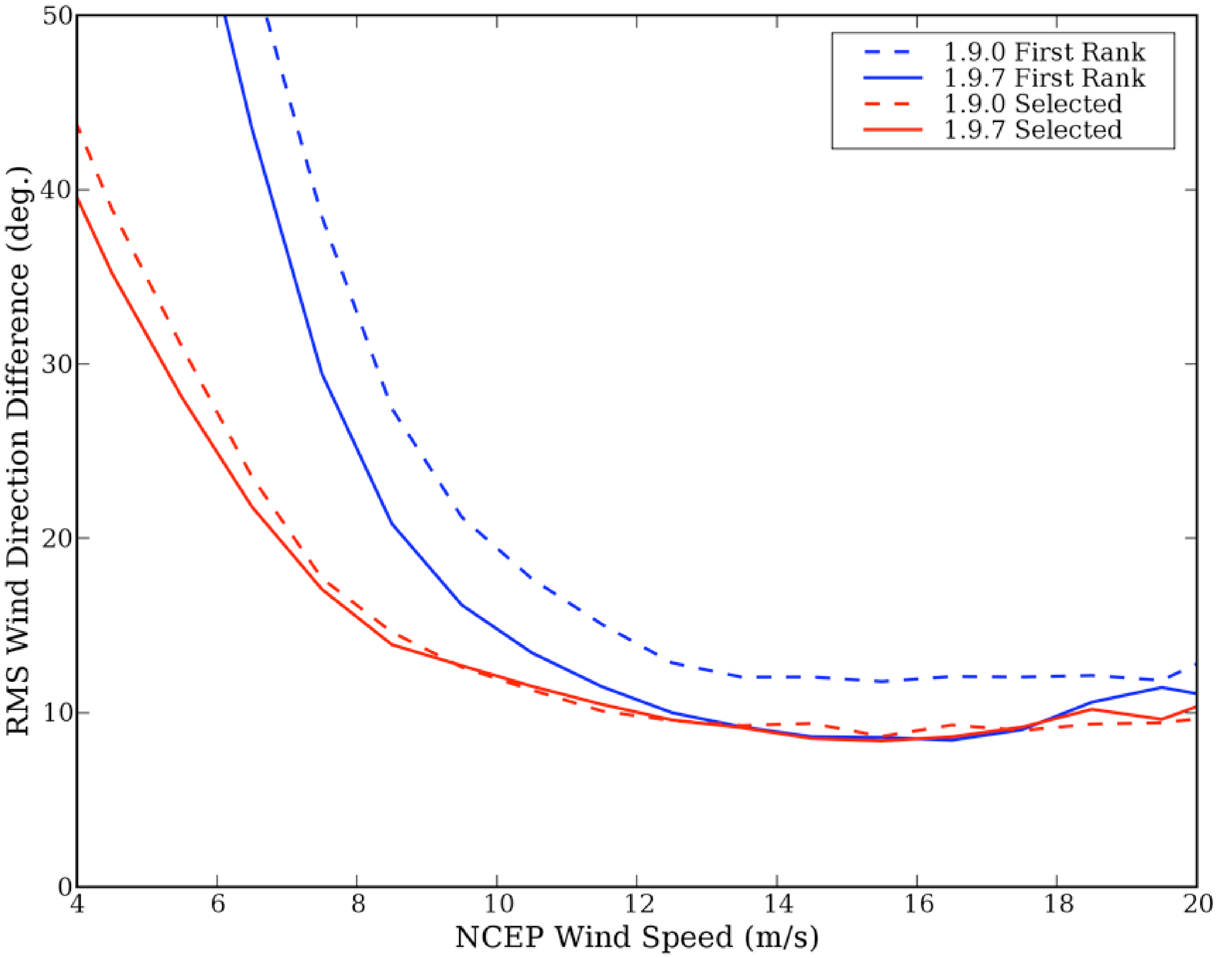
Retrieval Performance vs. Buoys

- Twelve month data set
- TAO and PIRATA buoys for SST
- NDBC buoys for wind speed and direction

EDR	Bias	Std.Dev.	RMS
SST (K)	-0.15	0.35	0.38
W Selected (m/s)	0.3	1.2	1.2
Wind Dir. (deg). > 5 m/s wind speed			17.8
Wind Dir. (deg). > 3 m/s wind speed			23.2

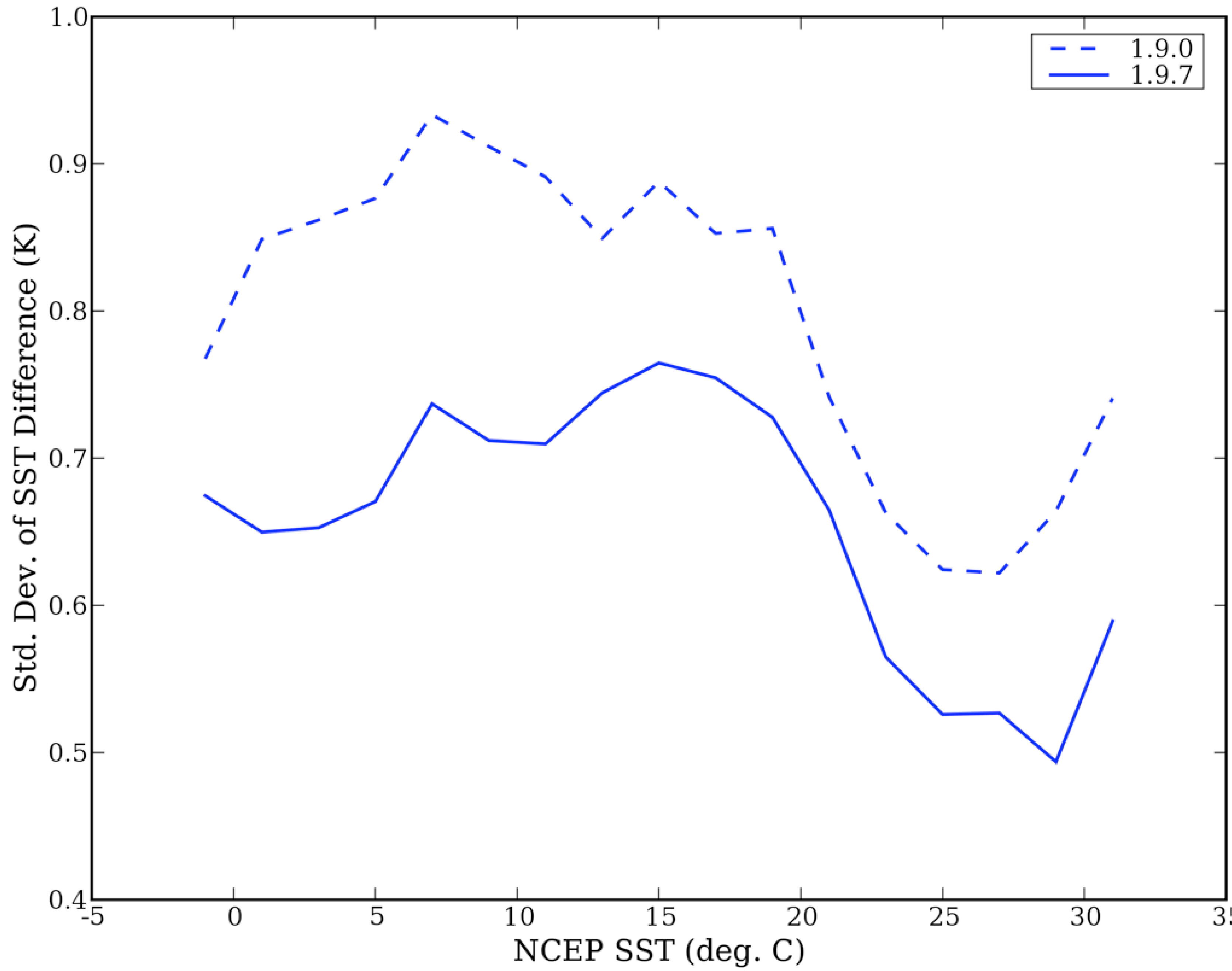
Wind Direction Performance

- One month (200402) of data compared to NCEP final analysis
- Version 1.9.0 data used closest NCEP analysis to initialize median filter
- Results shown for 1.9.7 use only NCEP analysis that precedes WindSat observation time and only nudges below ~ 9 m/s (and in rain)
- Results exclude rain, land contamination, etc.



SST Performance

- One month (200402) of data compared to NCEP final analysis
- Results exclude rain, land contamination, etc.
- Retrieval bias has not changed significantly
- Results versus TAO/ Pirata Buoys (~ 14000 points for 10 months)
  - bias: -0.15
  - std. dev.: 0.35



Wind Assimilation Studies

- NRL-MRY/FNMOC NAVDAS/NOGAPS
  - superob and closest to model background
  - small positive impact on 500 mb and 1000 mb anomaly correlations
  - operational since Dec. 2006
  - reported in JCSDA newsletter Dec. 2006, Pauley, Goerss, Pauley
- JCSDA/U. Wisconsin
  - superob and closest to model background
  - small positive impact on 500 mb and 1000 mb anomaly correlations
  - reported at JCSDA Workshop May 2007, Bi, et al
- AOML
  - variational analysis method
  - positive impact on cyclone forecasts
  - reported at AMS 2007 Annual Meeting, Atlas, et al
- UK Met Office (Candy and English)
  - variational assimilation
  - positive impact on mean sea level pressure and cyclone forecasts

Comments on Wind Assimilation

- All the studies to date have used procedures developed for scatterometers
- New methods may be needed to better utilize radiometer winds
- Direct assimilation of the radiances or use of background as *a priori* in our retrieval may improve impact
  - research planned at UK Met Office, NRL and U. Wisconsin
- Synergy between winds and other radiometer information (SST, precipitable water vapor and cloud liquid water)?

Assimilation of Other Products

- Information on precipitable water vapor and cloud liquid water can be assimilated using techniques developed for SSM/I
  - water vapor and cloud retrievals
  - direct radiance assimilation
- Potential for SST assimilation
  - similar to AMSR-E
  - microwave SST assimilation is current research topic
- Potential soil moisture retrieval assimilation
  - Relatively new research area
  - WindSat soil moisture product available late 2007