Accurate Weather Forecasting for Radio Astronomy

Ronald J Maddalena
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Outline

- Very brief overview of the forecasting method
- Accuracy of forecasts
  - Can one determine causes for inaccuracies?
  - Accuracy of 22 and 41-45 GHz forecasts
    - $\Delta\tau < 0.01$
    - Good enough for high-accuracy calibration
- Reliability of forecasts
  - Approximately 5 days when observing < 18 GHz, and between 25-35 GHz
  - Otherwise, 2-3 days

The influence of the weather at cm- and mm-wavelengths

- Opacity
  - Calibration
  - System performance – Tsys
  - Observing techniques
  - Hardware design
- Refraction
  - Pointing
  - Air Mass
    - Calibration
    - Pulsar Timing
    - Interferometer & VLB phase errors
  - Aperture phase errors
- Cloud Cover
  - Continuum performance
  - Pointing & Calibration
- Winds
  - Pointing
  - Safety
- Telescope Scheduling
  - Proportion of proposals that should be accepted
  - Telescope productivity

Broad-brush goals of this research

Improve our estimations of:

- Current conditions
  - Calibration, pointing, safety, telescope productivity
- Near-future conditions
  - Safety, telescope productivity
- Past conditions
  - Calibration
  - Weather statistics
    - Telescope productivity, hardware decisions, observing techniques, proposal acceptance

Project inspiration

- Unfortunately, the standard products of the weather services (other than winds, cloud cover, precipitation, and PW somewhat) do not serve radio astronomy directly.
- But, can we use the products of the weather services for radio astronomy?

Project inspiration

- Lehto : Measured vertical weather profiles are an excellent way of determining past observing conditions
  - No practical way to obtain vertical profiles and use Harry’s technique until…
- Maciolek : Vertical profiles are now easily available on the WWW for the current time and are forecasted!!

Vertical profiles

- Atmospheric pressure, temperature, and humidity as a function of height above a site (and much more).
- Derived from *Geostationary Operational Environmental Satellite* **(**GOES) soundings and, now less often, balloon soundings
- Generated by the *National Weather Service*, an agency of the *NOAA*.

Bufkit, a great vertical profile viewer

http://www.wbuf.noaa.gov/bufkit/bufkit.html

Bufkit and Bufkit files

- 65 layers from ground level to 30 km
  - Stratospheric (Tropopause ~10 km)
- Layers finely spaced (~40 m) at the lower heights, wider spaced in the stratosphere
- Available for Elkins, Hot Springs, Lewisburg

Bufkit and Bufkit files

- North American Mesoscale (NAM)
  - The 3.5 day (84 hours) forecasts
  - Updated 4-times a day
  - 12 km horizontal resolution
  - 1 hour temporal resolution
  - Finer detail than other operational forecast models
  - 1350 stations, all North America

Bufkit and Bufkit files

- Global Forecast System (GFS)
  - 7.5-day (180 hrs) forecasts
  - Based on the first half of the 16-day GFS models
  - 35 km horizontal resolution
  - 3 hour temporal resolution
  - Updated twice a day
  - Do not include percentage cloud cover
  - 1450 stations, some overseas

Bufkit and Bufkit files

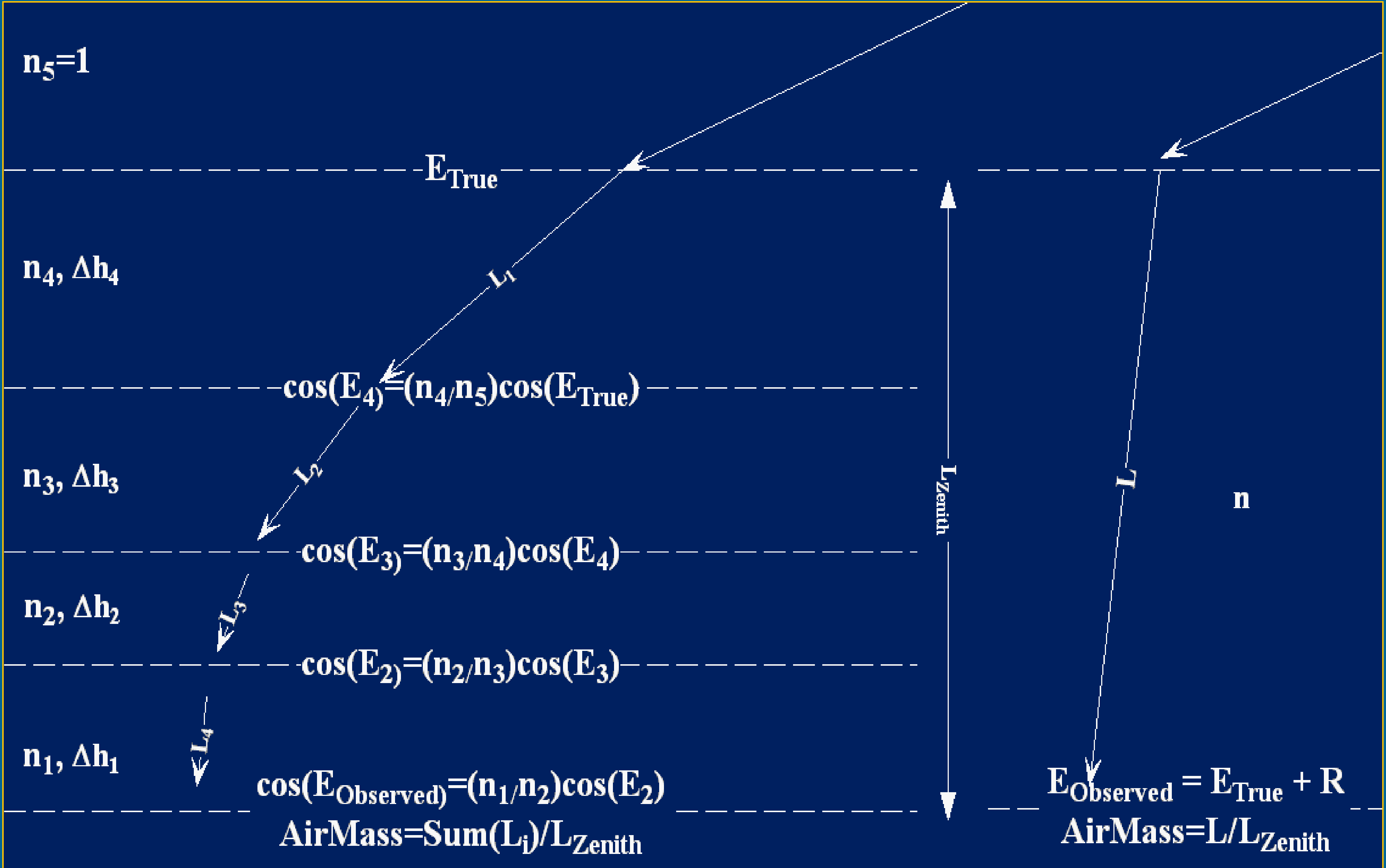
- Rapid Update Cycle
  - Accurate short range 0-12 hrs only
  - Updated hourly with an hour delay in distribution (processing time)
  - 12 km horizontal resolution
  - 1 hour temporal resolution
  - Recently started to archive

Bufkit files available for “Standard Stations”

How it works….

h	T	P	DP	CFRL	Δh	ρ_{Water}	ρ_{Dry}	n	ΔElev	κ_{Dry}	κ_{H2O} Cont	κ_{H2O} Line	κ_{O2}	$\kappa_{Hydrosols}$	κ_{Total}	ΔT_{Sys}
30 km																
…																
920 m																
880 m																
									R						τ	T_{Sys}
															T_{Atm}	

Generate a table for every desired frequency, site, time



$\cos(E_4)=(n_{4/}n_5)\cos(E_{True})$

$\cos(E_3)=(n_{3/}n_4)\cos(E_4)$

$\cos(E_2)=(n_{2/}n_3)\cos(E_3)$

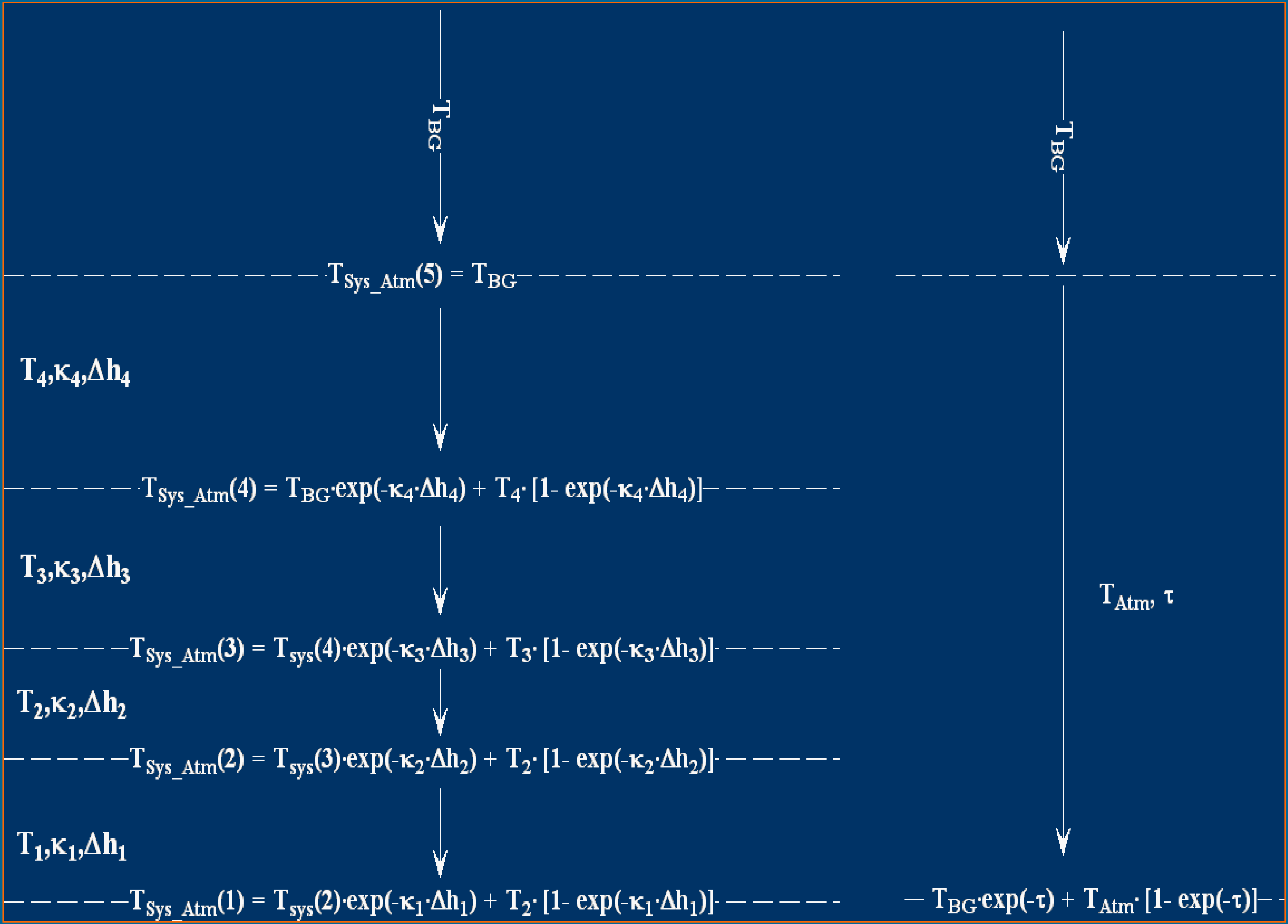
$\cos(E_{Observed})=(n_{1/}n_2)\cos(E_2)$

$AirMass=Sum(L_i)/L_{Zenith}$

$E_{Observed} = E_{True} + R$

$AirMass=L/L_{Zenith}$

Grossly exaggerated and assuming plane parallel approximation



$T_{Sys\_Atm}(5) = T_{BG}$

$T_4, \kappa_4, \Delta h_4$

$T_{Sys\_Atm}(4) = T_{BG} \cdot \exp(-\kappa_4 \cdot \Delta h_4) + T_4 \cdot [1 - \exp(-\kappa_4 \cdot \Delta h_4)]$

$T_3, \kappa_3, \Delta h_3$

$T_{Sys\_Atm}(3) = T_{sys}(4) \cdot \exp(-\kappa_3 \cdot \Delta h_3) + T_3 \cdot [1 - \exp(-\kappa_3 \cdot \Delta h_3)]$

$T_2, \kappa_2, \Delta h_2$

$T_{Sys\_Atm}(2) = T_{sys}(3) \cdot \exp(-\kappa_2 \cdot \Delta h_2) + T_2 \cdot [1 - \exp(-\kappa_2 \cdot \Delta h_2)]$

$T_1, \kappa_1, \Delta h_1$

$T_{Sys\_Atm}(1) = T_{sys}(2) \cdot \exp(-\kappa_1 \cdot \Delta h_1) + T_2 \cdot [1 - \exp(-\kappa_1 \cdot \Delta h_1)]$

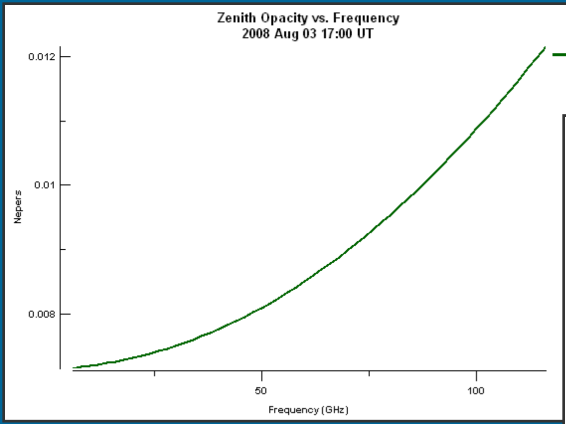
T_{Atm}, τ

$T_{BG} \cdot \exp(-\tau) + T_{Atm} \cdot [1 - \exp(-\tau)]$

Current modeling and limitations

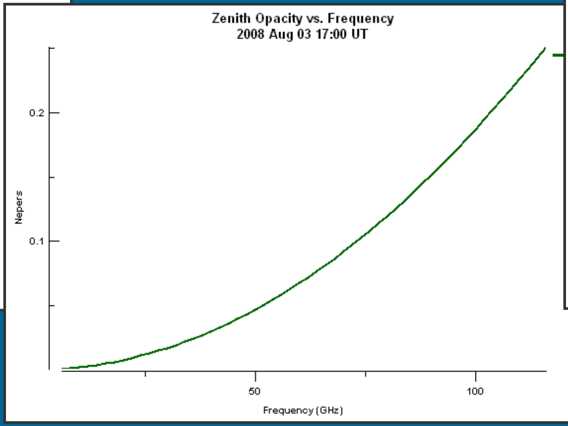
- Uses Liebe’s *Microwave Propagation Model*, with Danese & Partridge’s (1989) modifications plus some practical simplifications
  - Current implementation < 230 GHz
  - Uses ‘fuzzy’ caches
  - Uses the Froome & Essen frequency-independent approximation of refraction (to save processing time)
  - Model for determining opacities from clouds (hydrosols) may not match observations
    - Schwab, Hogg, Owen model for water drop density and size may not be accurate enough
  - No available models handle precipitation

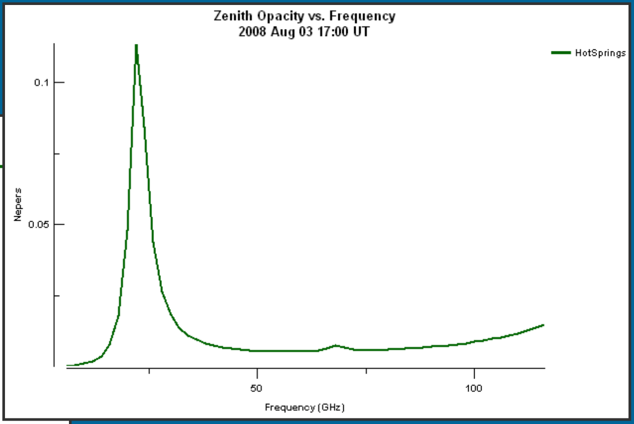
Opacities from the various components



Dry Air Continuum

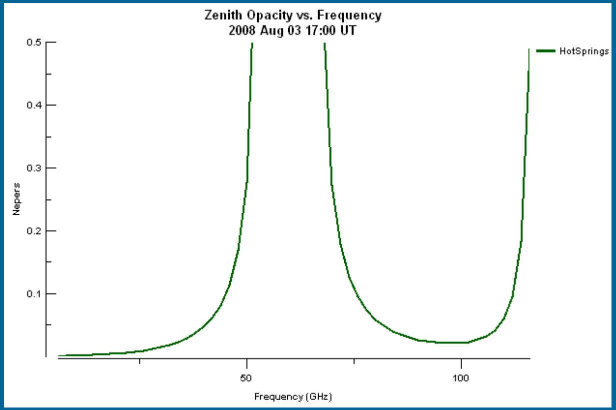
Water Continuum



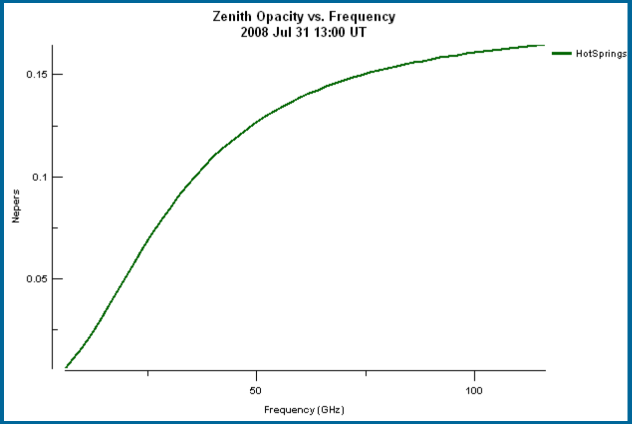


Water Line

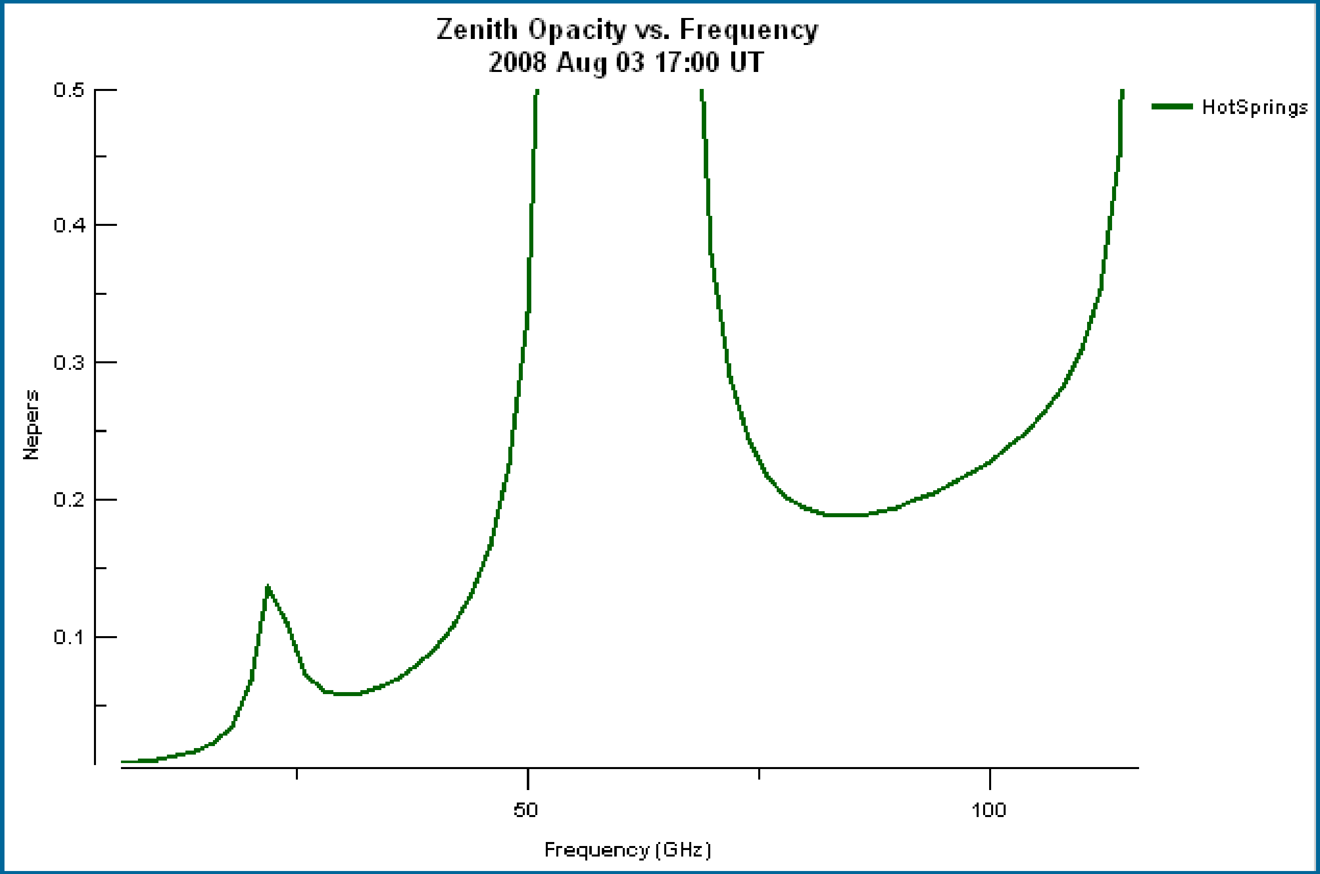
Oxygen Line



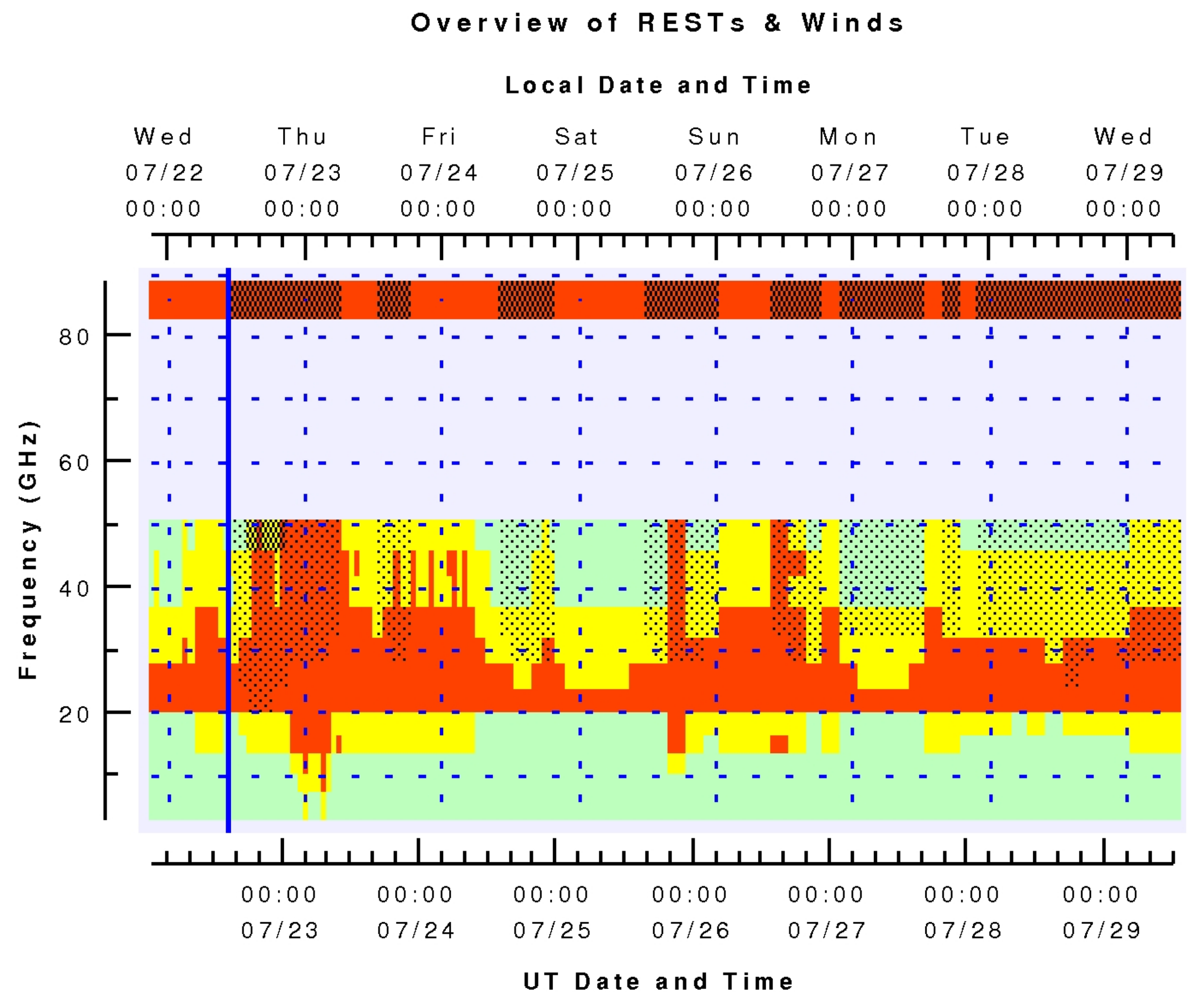
Hydrosols



Opacities from the various components

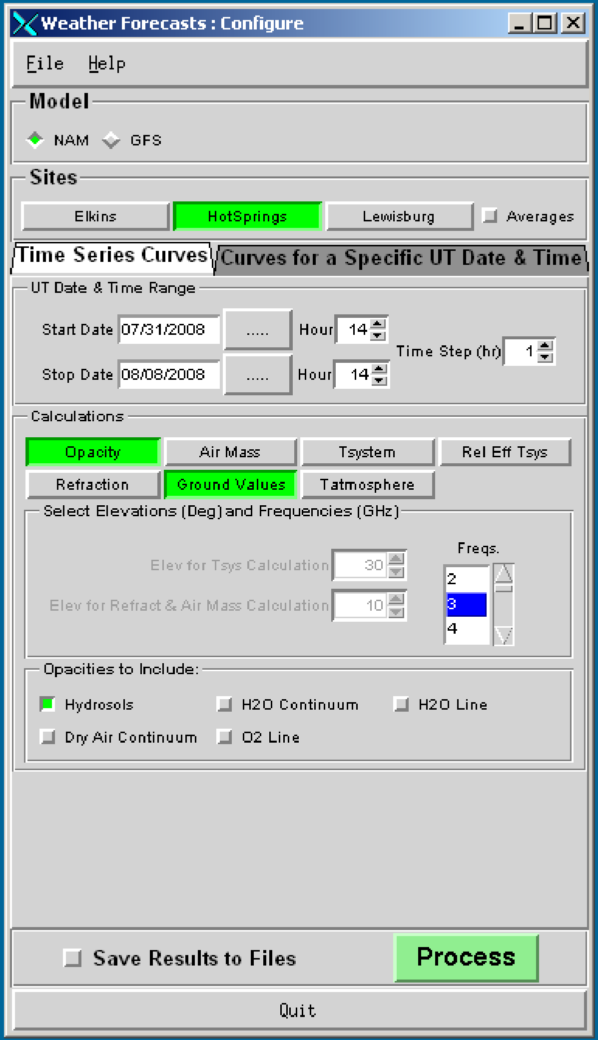


Total Opacity



- http://www.gb.nrao.edu/~rmaddale/Weather/

User Software: cleo forecasts


Weather Forecasts : Configure

Model: ● NAM ○ GFS

Sites: Elkins | HotSprings (selected) | Lewisburg | ☐ Averages

Time Series Curves | Curves for a Specific UT Date & Time

UT Date & Time Range

Start Date 07/31/2008 Hour 14

Stop Date 08/08/2008 Hour 14

Time Step (hr) 1

Calculations: Opacity (selected) | Air Mass | Tsystem | Rel Eff Tsys | Refraction | Ground Values (selected) | Tatmosphere

Select Elevations (Deg) and Frequencies (GHz)

Elev for Tsys Calculation 30

Elev for Refract & Air Mass Calculation 10

Freqs. 2, 3 (selected), 4

Opacities to Include:

☑ Hydrosols ☐ H2O Continuum ☐ H2O Line

☐ Dry Air Continuum ☐ O2 Line

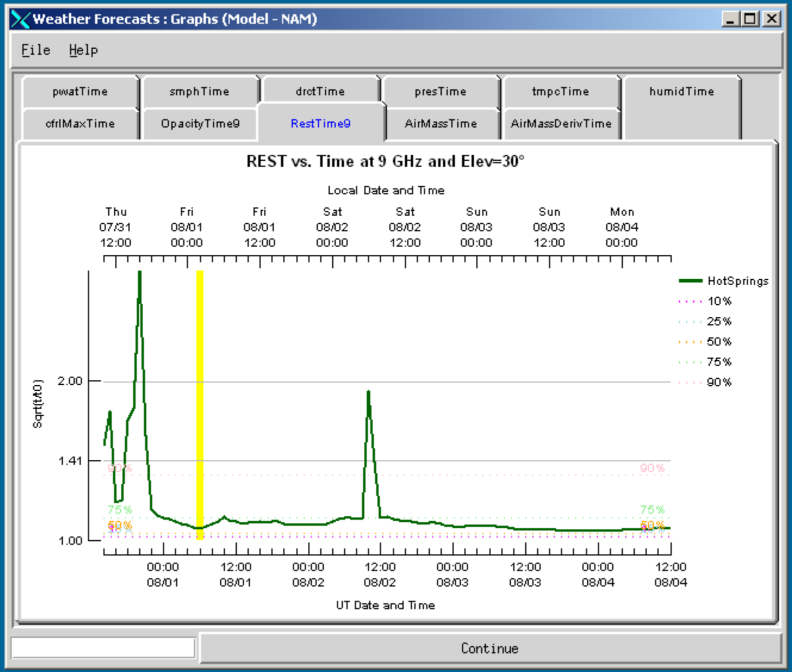
☐ Save Results to Files

Type:

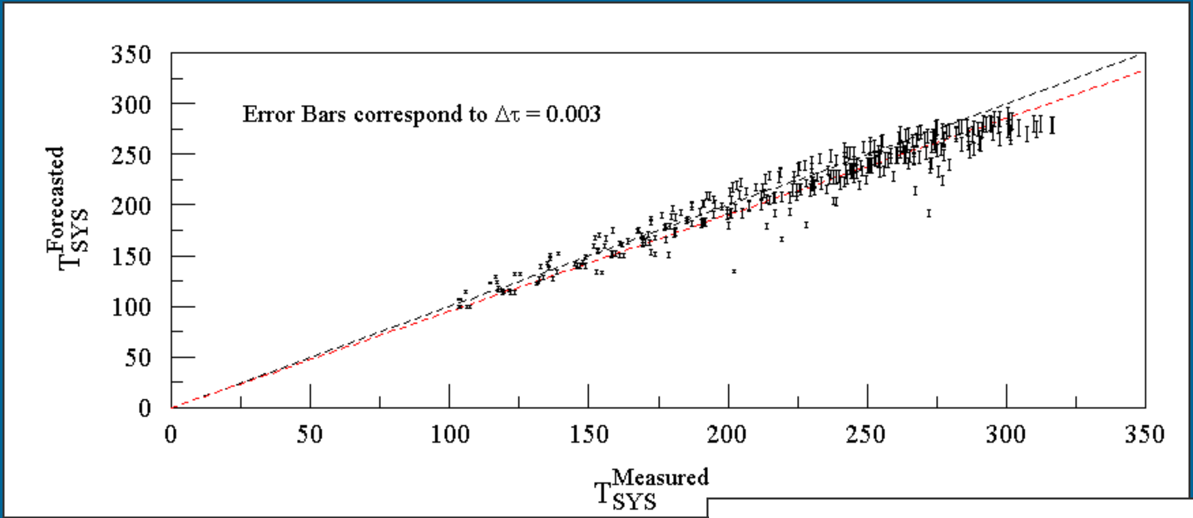
cleo forecasts

Or

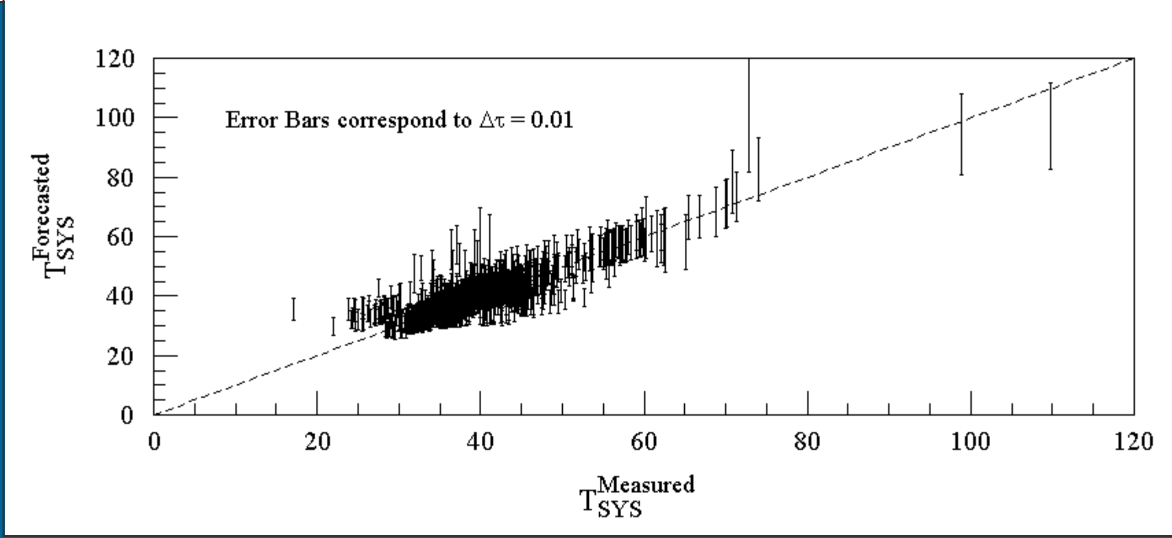
cleo forecasts -help


Weather Forecasts : Graphs (Model - NAM)

Without further adieu



45 GHz



22 GHz

Determining causes for differences between forecasted and measured T_{sys}

$$T_{SYS} = T_{Rcvr} + T_{Spill} + T_{CMB} e^{-\tau \cdot A} + T_{ATM} \cdot (1 - e^{-\tau \cdot A})$$

$$T_{SYS}^{Measured} = (1+g) \cdot T_{SYS}$$

$$T_{SYS}^{Forecasted} = \left(T_{Rcvr} + \Delta T_{Rcvr}\right) + T_{Spill} + T_{CMB} e^{-\tau \cdot A} + T_{ATM} \cdot (1 - e^{-(\tau + \Delta\tau) \cdot A})$$

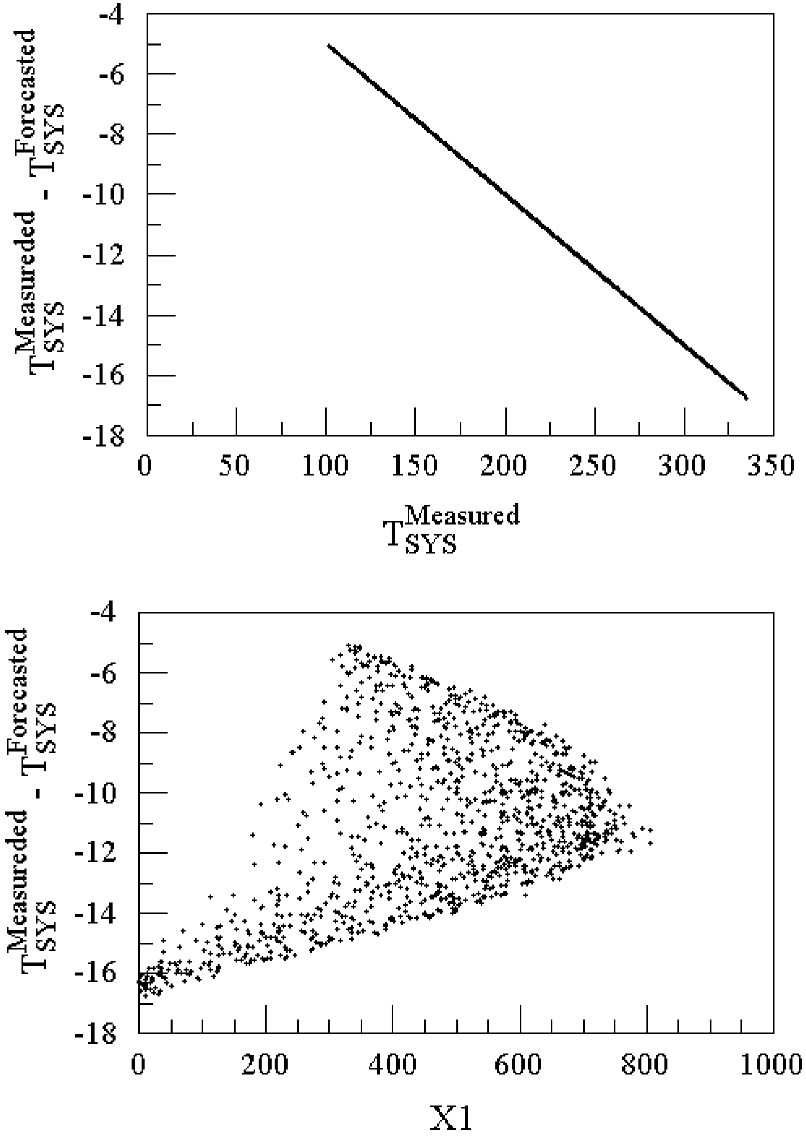
$$T_{SYS}^{Measured} - T_{SYS}^{Forecasted} = \Delta T_{Rcvr} + \left(\frac{g}{g+1} \right) \cdot T_{SYS}^{Measured} + T_{ATM} \cdot (e^{-(\tau + \Delta\tau) \cdot A} - e^{-\tau \cdot A})$$

$$\begin{aligned} T_{SYS}^{Measured} - T_{SYS}^{Forecasted} &= \Delta T_{Rcvr} + f \cdot T_{SYS}^{Measured} + \Delta\tau \cdot (T_{ATM} \cdot A \cdot e^{-\tau \cdot A}) \\ &\approx a + b \cdot x_0 + c \cdot x_1 \end{aligned}$$

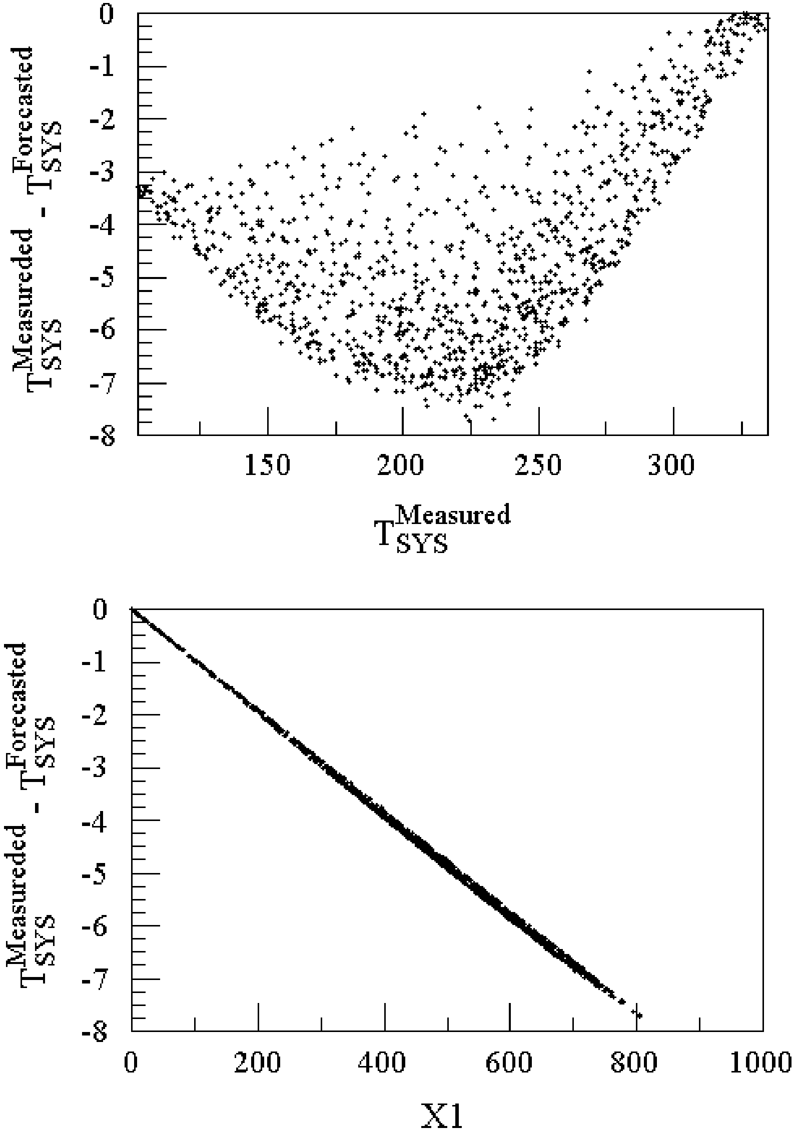
Differences between forecasted and measured T_{sys}

- Least squares fit for of a slightly-curved 2-dim surface with axes T_{Sys}^{Meas} and x_1
- Surface is flat when is $\Delta\tau$ is small
- Care to ensure fitted coefficients aren't highly correlated -- covariant matrix
- Use simulations (synthetic measured and forecasted T_{sys} with and without typical randomness) to explore:
  - The best data to obtain a low-correlation fit
  - Influence of correlation on fitted results

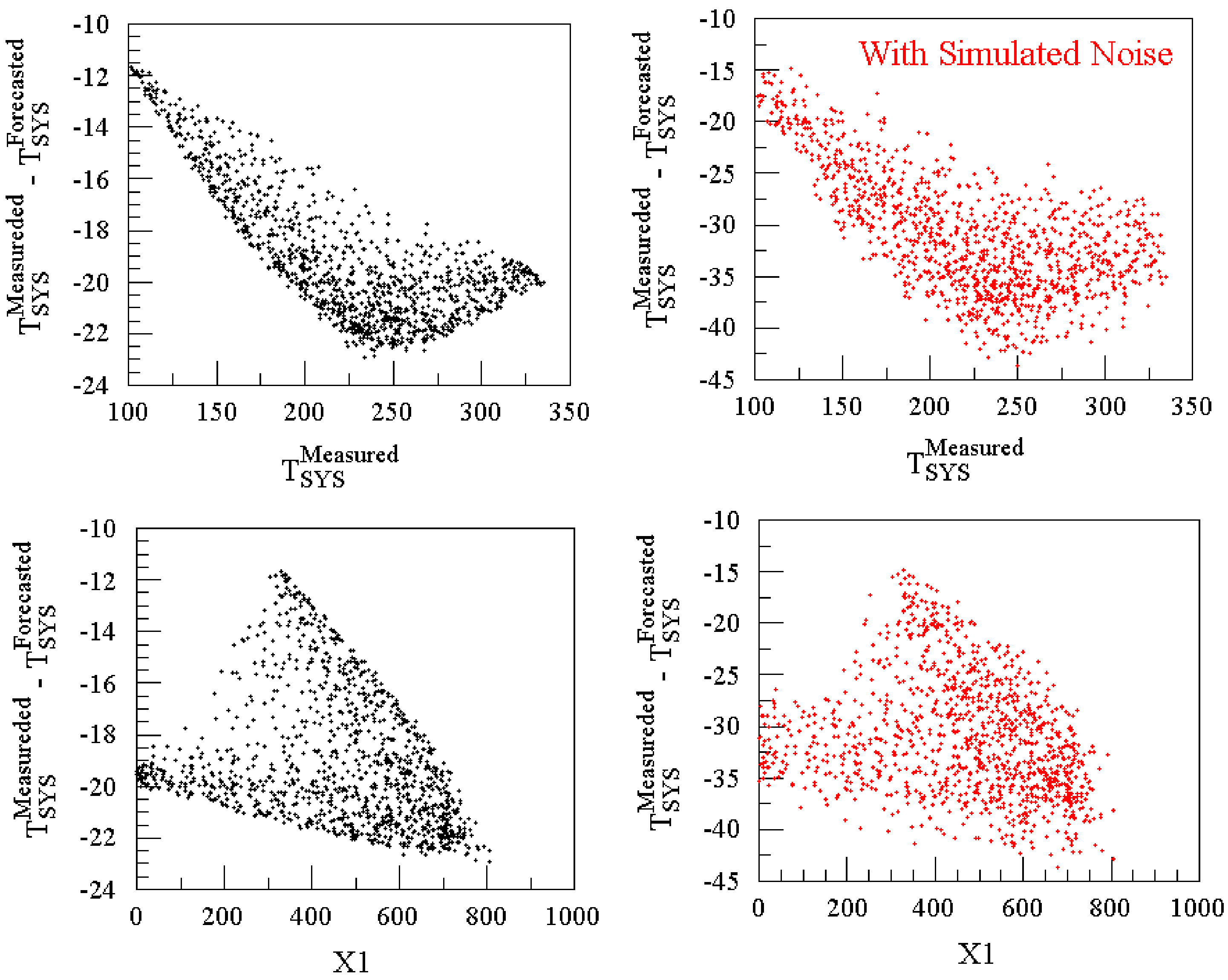
Signature of a 5% error in T_{cal}

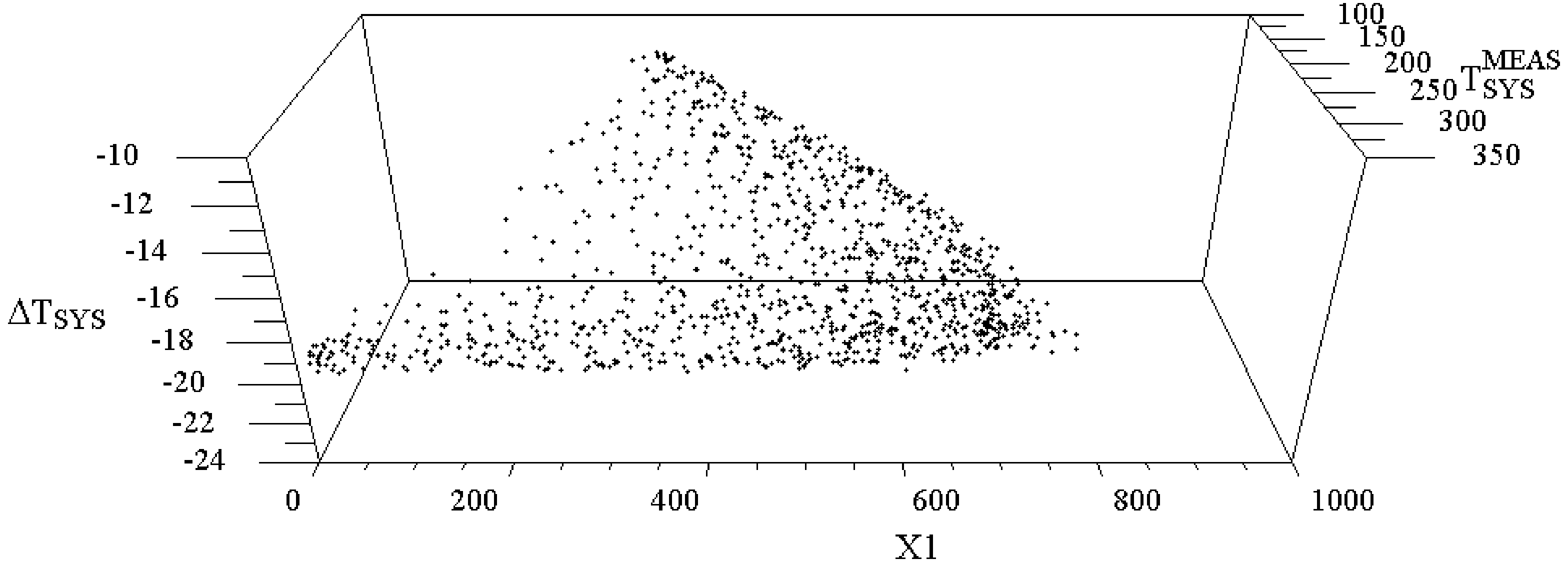


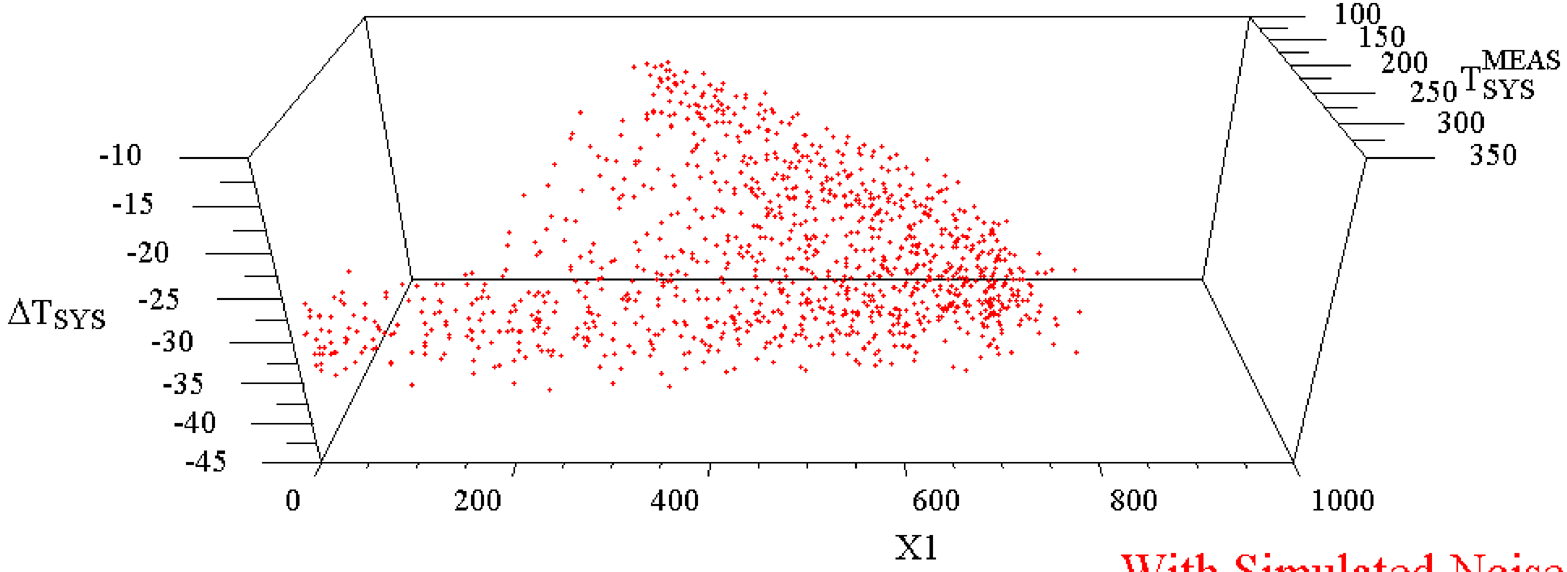
Signature of a 0.01 error in τ



Signature of a 0.01 error in τ, 3K error in T_{Rcvr}, and 5% error in T_{Cal}



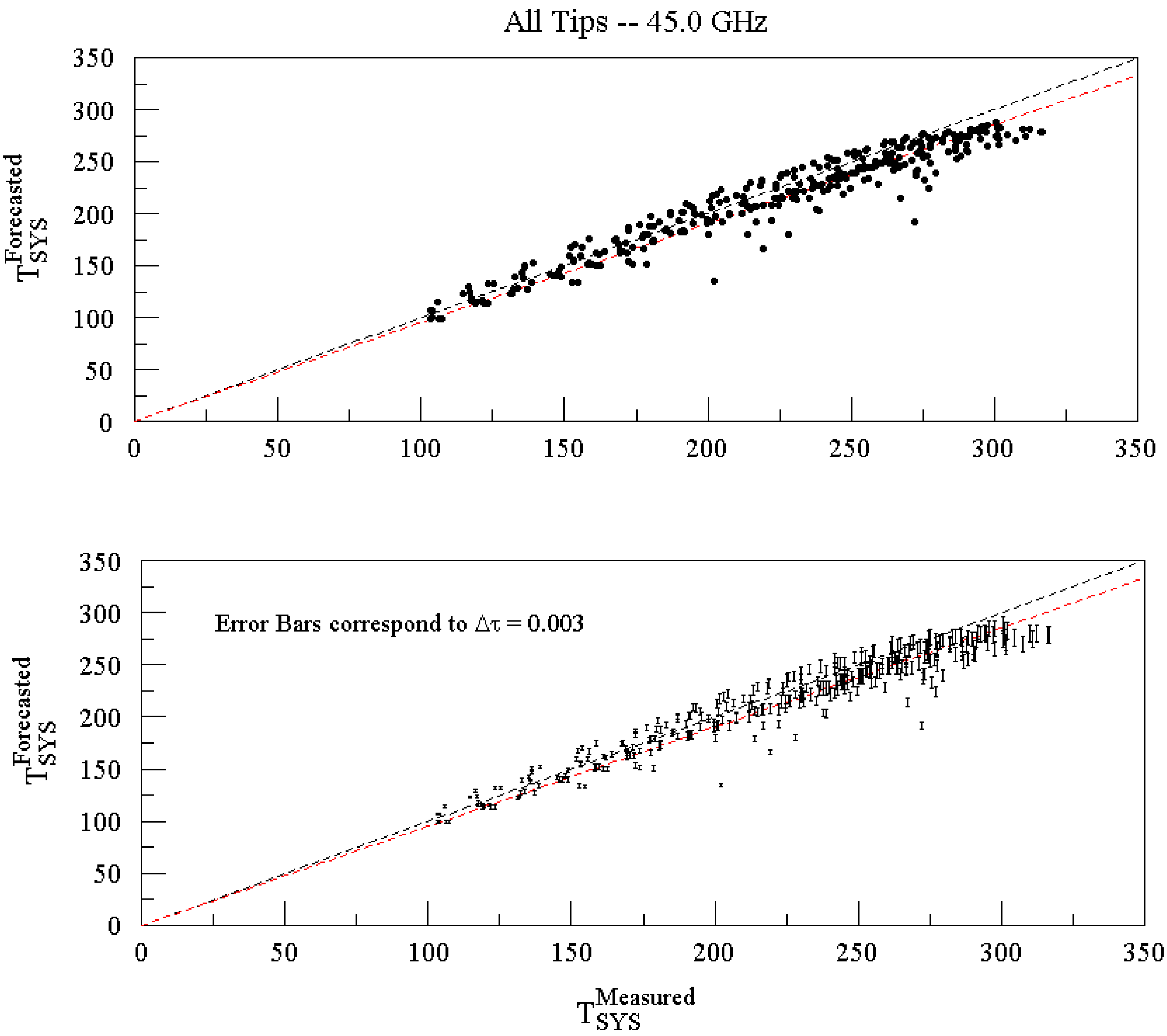




With Simulated Noise

Accuracy of forecasts

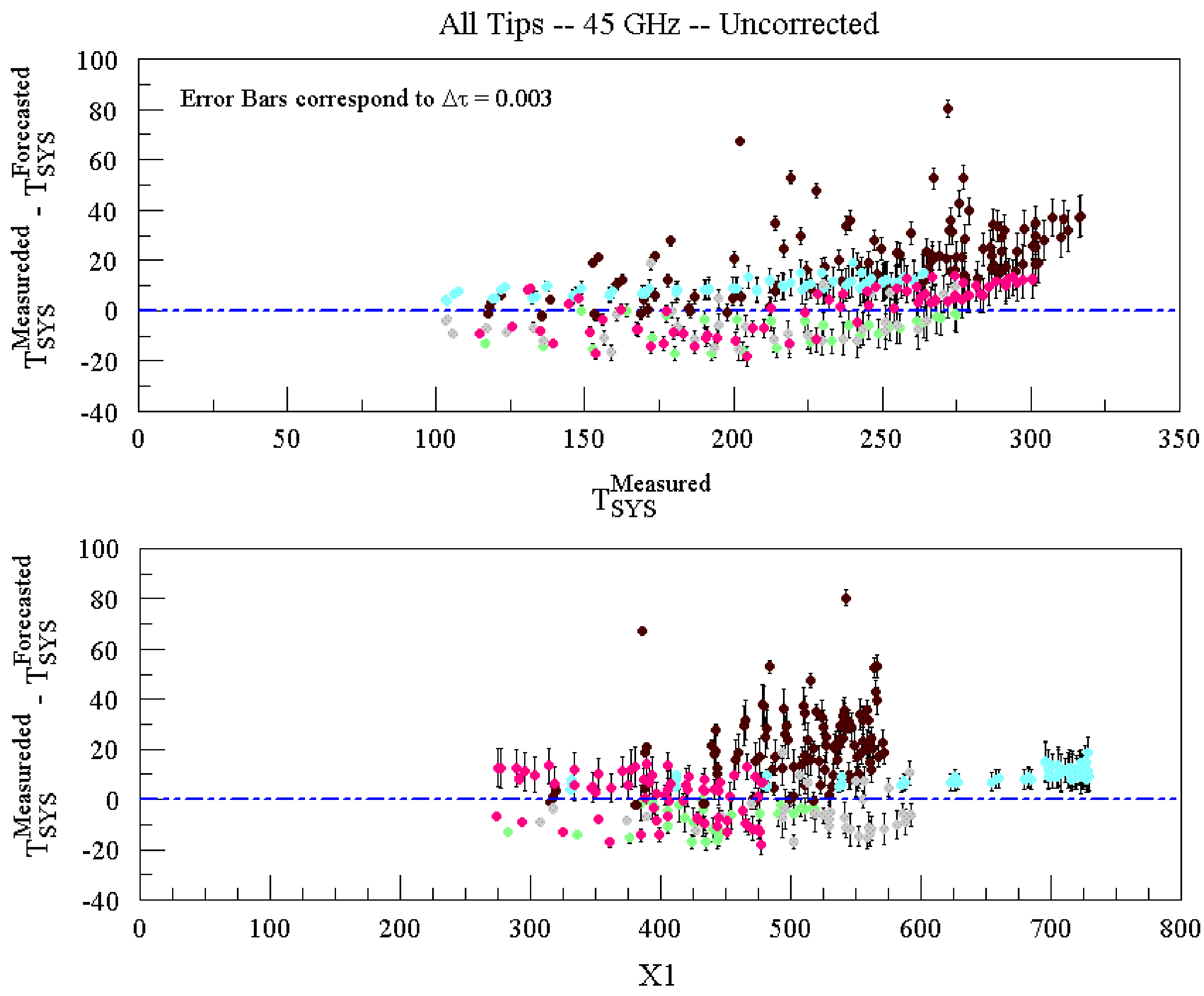
- Must measure T_{sys} at all but mainly low elevation data under reasonable but varied weather conditions
- The higher T_{rcvr}, the better
- Be careful of instrumental affects like non-linearities and bandpass smearing of T_{cal} values
- Experiment:
  - 45 GHz tips
    - Large T_{rcvr}
    - Interesting frequency for testing problematic hydrosols model
  - Use the GBT Spectrometer
    - Gives 4 frequencies simultaneously over 4 GHz
    - Balance power levels at each elevation
    - 12.5 MHz bandwidth
  - Elevations from 42 to 5.2 (A=1.5 to 9.7)
  - All reasonable opacity conditions



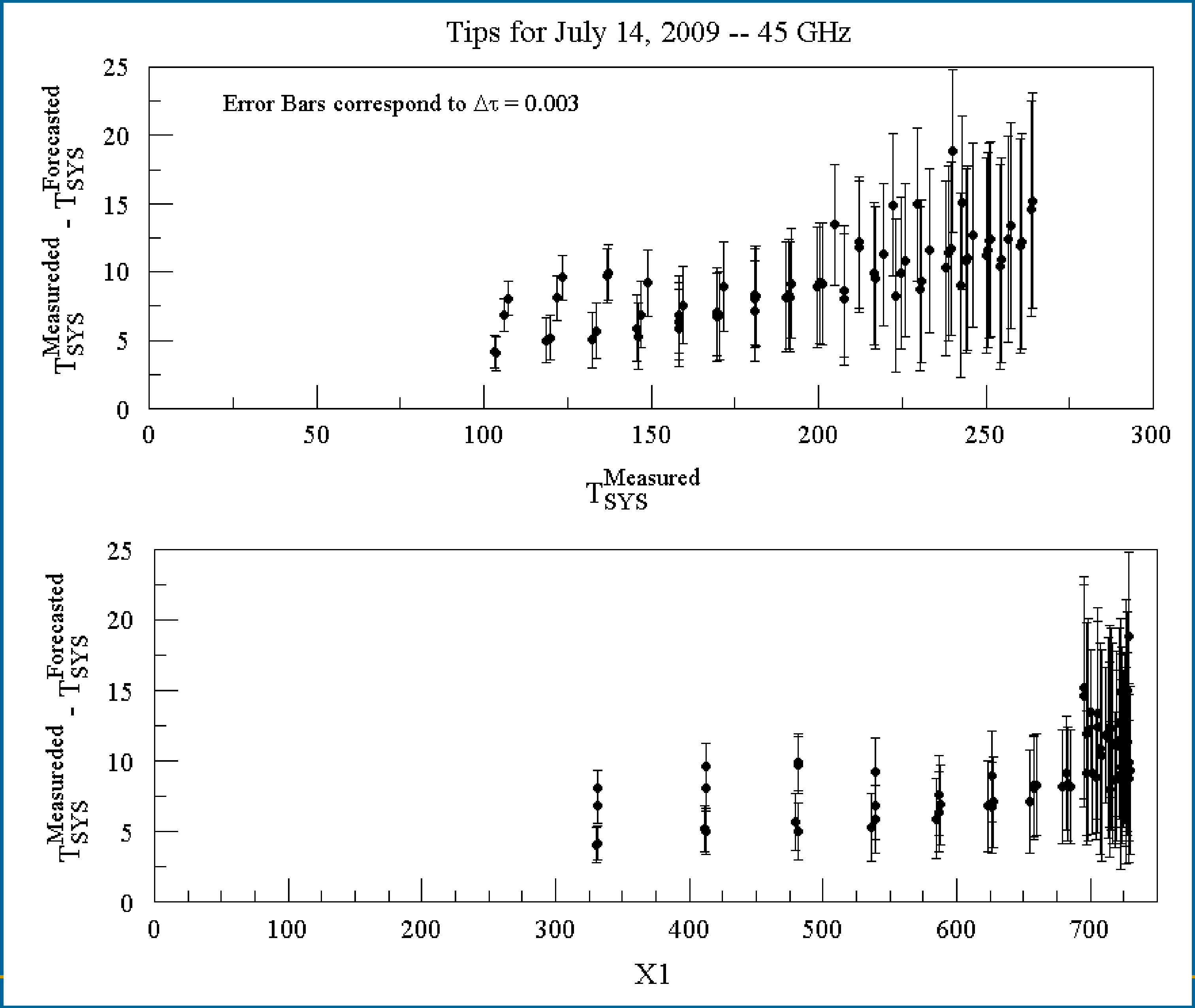
All Tips -- 45.0 GHz

Accuracy of 45 GHz forecasts

- Five summer days
  - τ = 0.136 to 0.250
  - Air Mass = 1.5 to 9.7
  - RESTs = 1.09 – 1.60
    - 50 to 85% weather conditions
- rms = 14.6 K



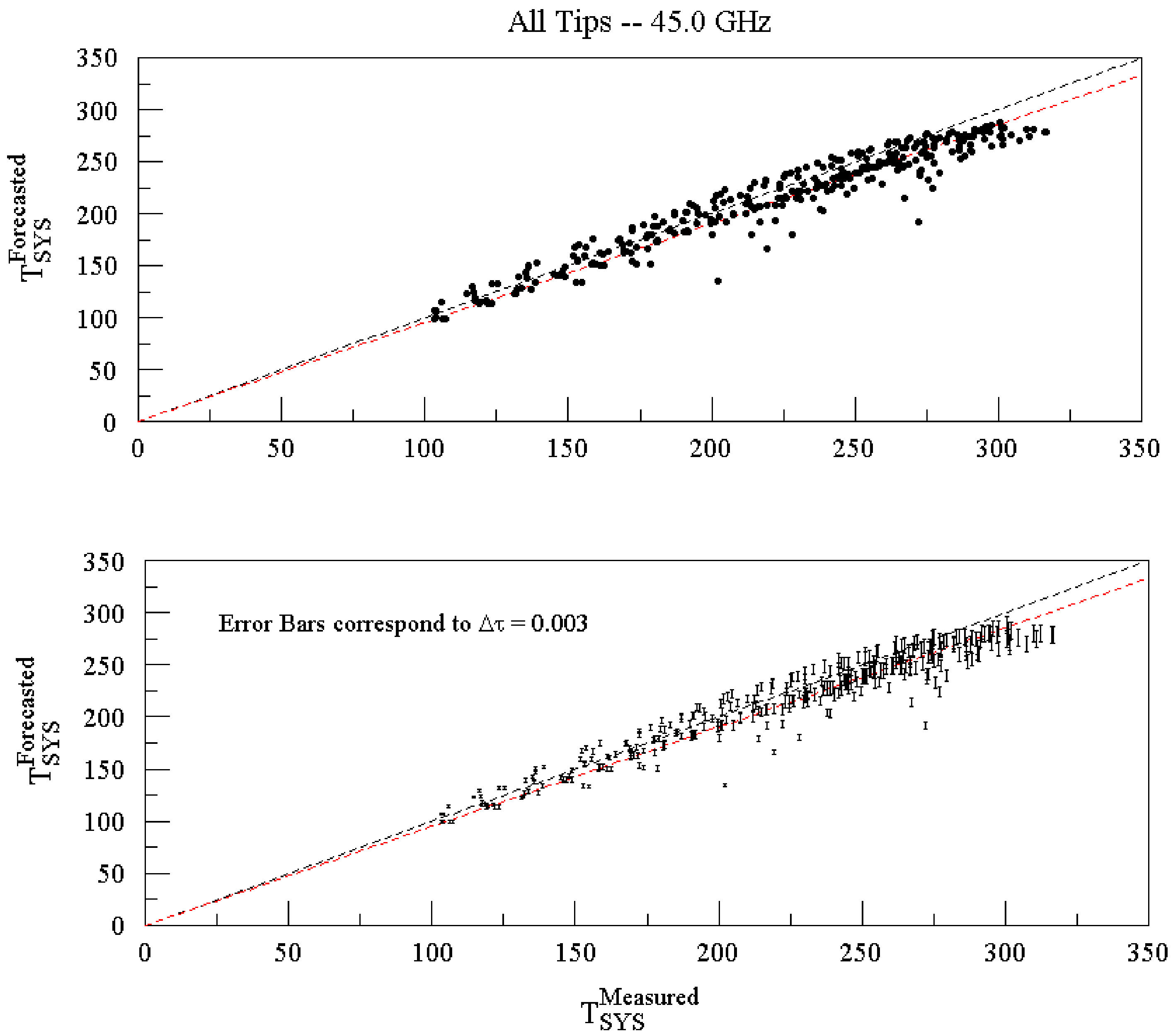
All Tips -- 45 GHz -- Uncorrected



Tips for July 14, 2009 -- 45 GHz

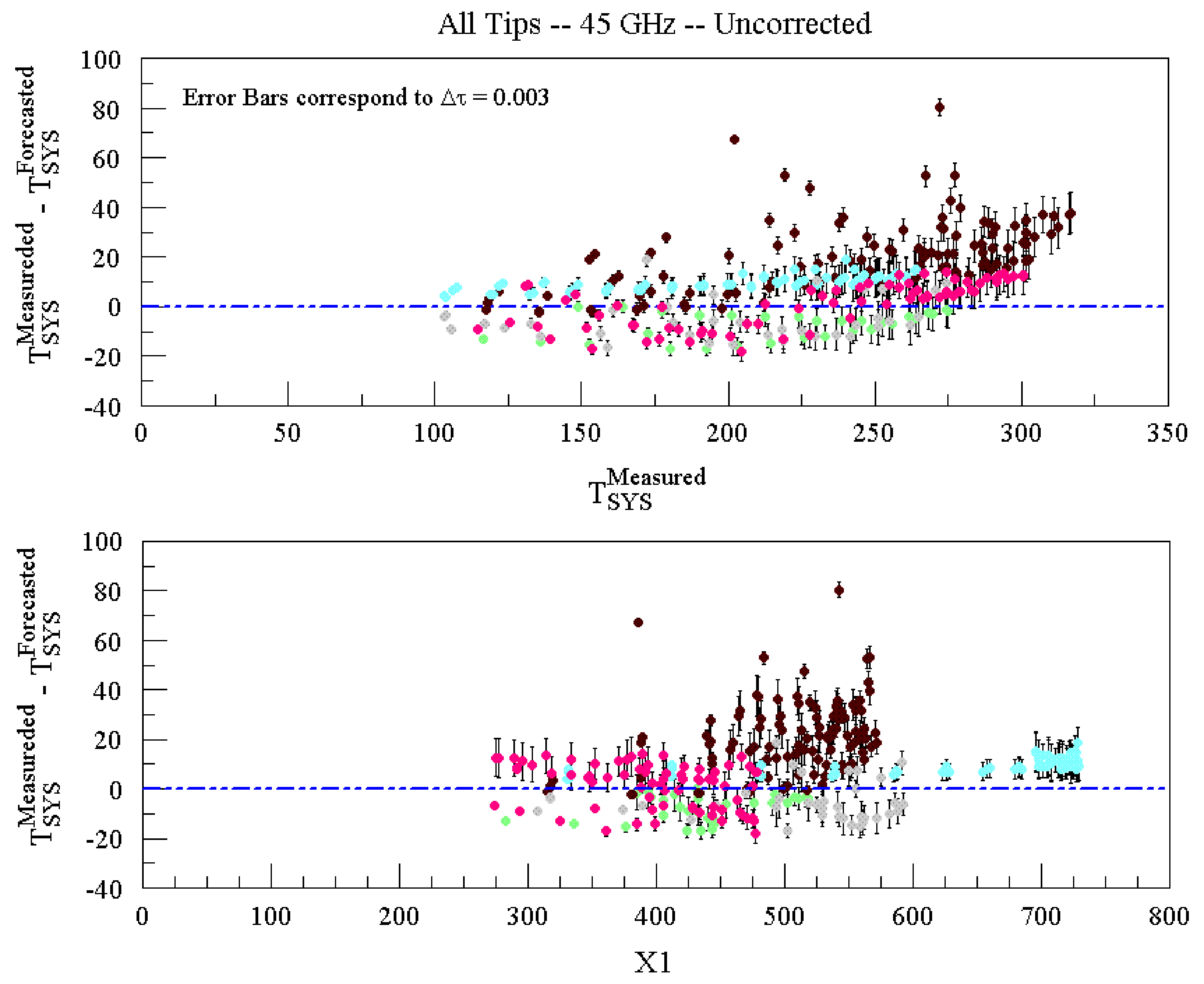
Accuracy of 45 GHz forecasts

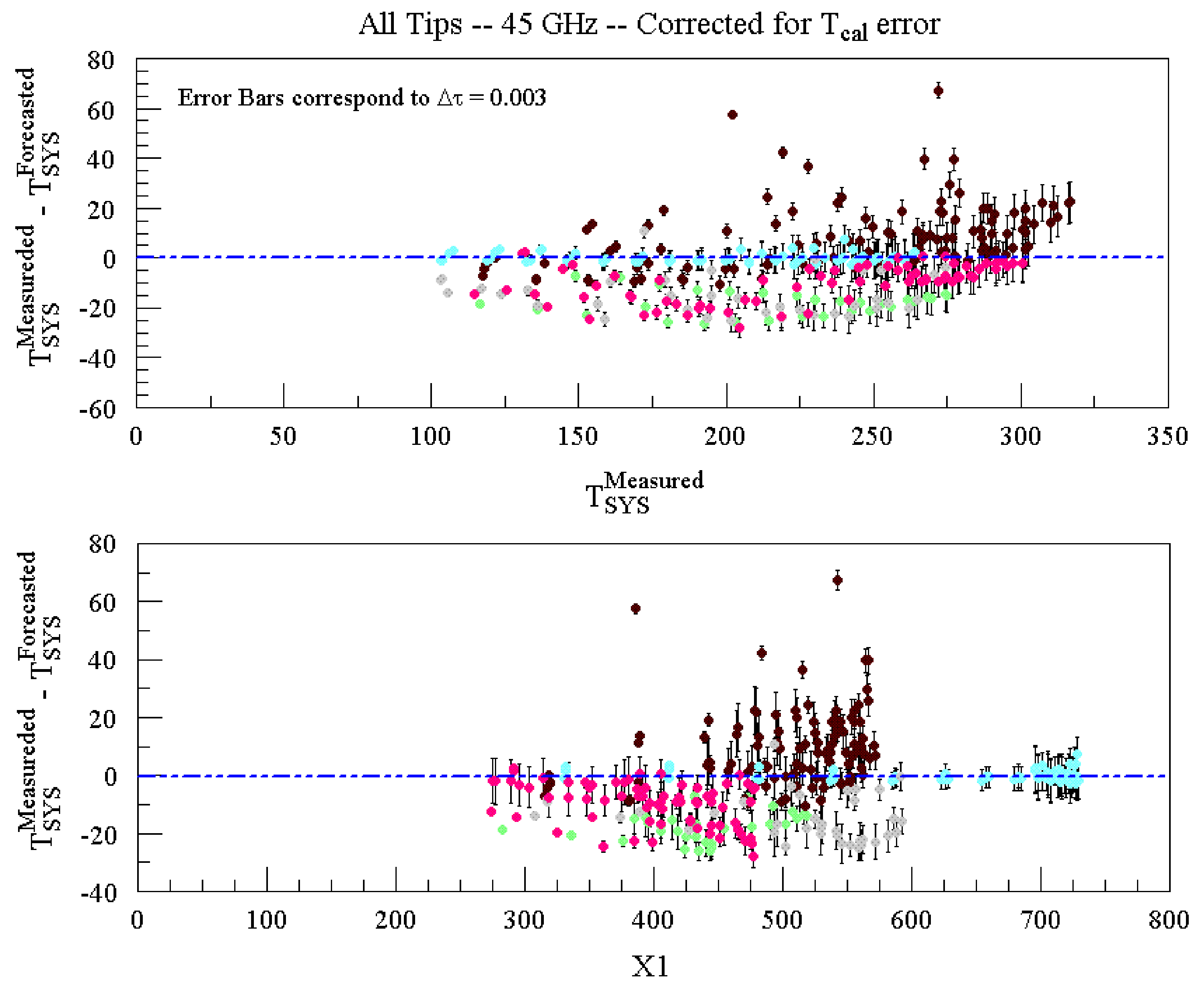
- July 14, 2009 data
  - rms = 2.96 K
  - Fitting for just f (T_{cal} error) reduced rms to 1.97 and would require a 5% error in T_{cal}
  - Fitting for and f and ΔT_{rcvr} reduced rms to 1.98 K
  - Fitting for f, ΔT_{rcvr}, and $\Delta\tau$ reduced rms to 1.97 K
  - Fitting for $\Delta\tau$ or $\Delta\tau$ and ΔT_{rcvr} reduced rms to only 2.36 K and would require $\Delta\tau = 0.016$
- The most likely source of any difference is a 5% error in T_{cal}
- The most likely upper value of $\Delta\tau = 0.006$
  - The most skeptical upper limit is 0.016



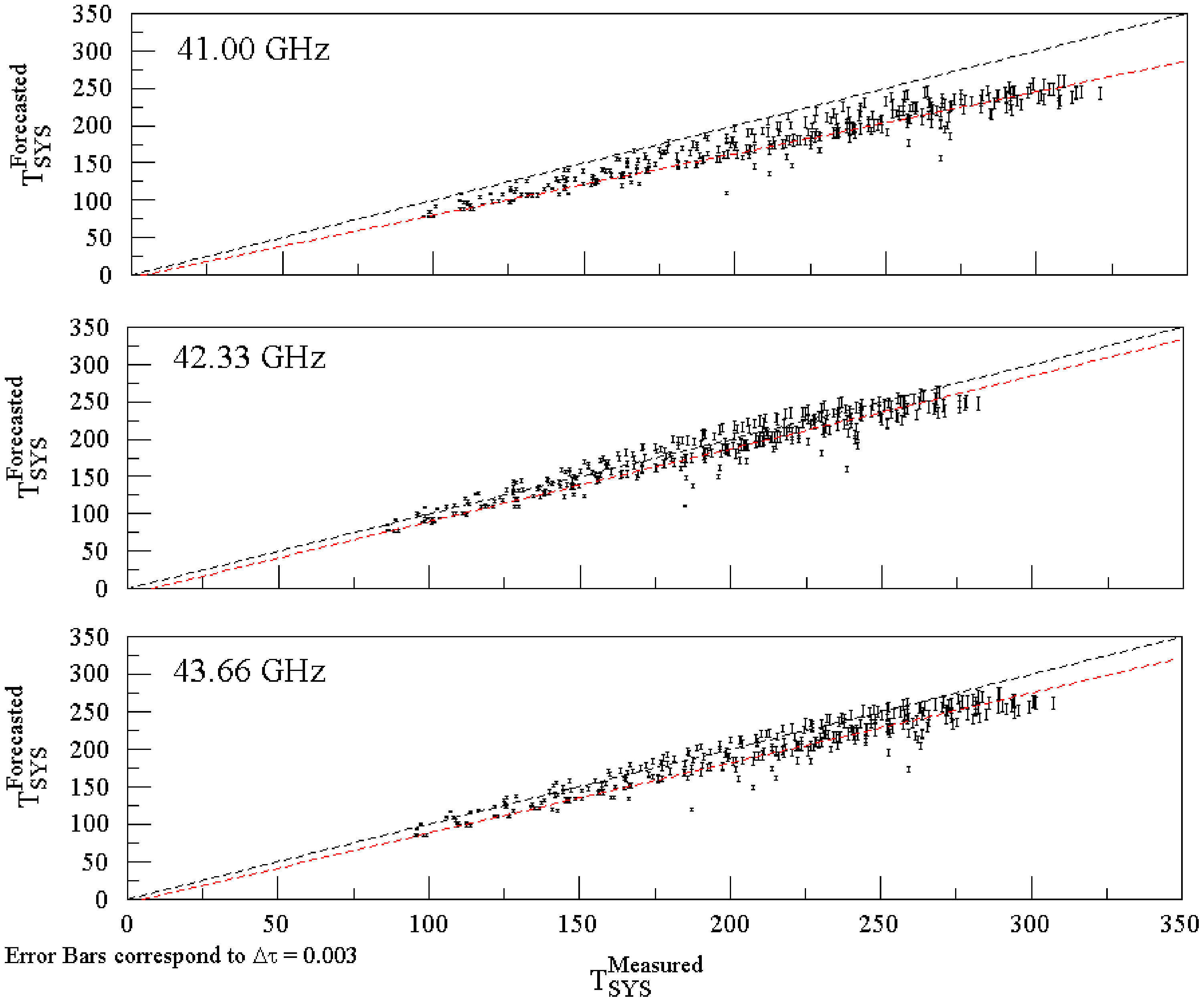
All Tips -- 45.0 GHz

Error Bars correspond to $\Delta\tau = 0.003$


All Tips -- 45 GHz -- Uncorrected
Error Bars correspond to Δτ = 0.003
$T_{SYS}^{Measureded} - T_{SYS}^{Forecasted}$
100
80
60
40
20
0
-20
-40
0
50
100
150
200
250
300
350
$T_{SYS}^{Measured}$
$T_{SYS}^{Measureded} - T_{SYS}^{Forecasted}$
100
80
60
40
20
0
-20
-40
0
100
200
300
400
500
600
700
800
X1



All Tips -- 45 GHz -- Corrected for T_{cal} error



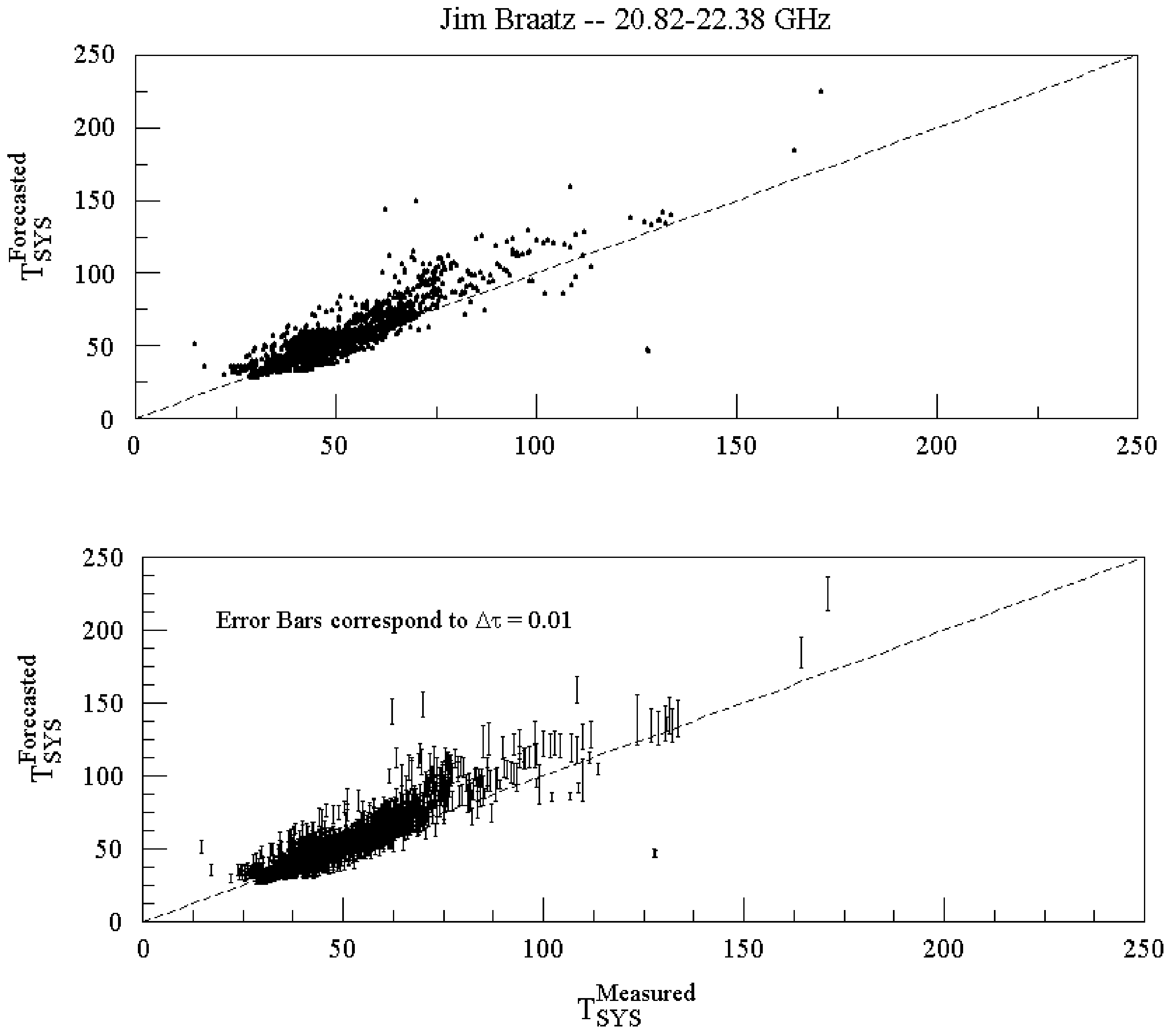
Error Bars correspond to Δτ = 0.003

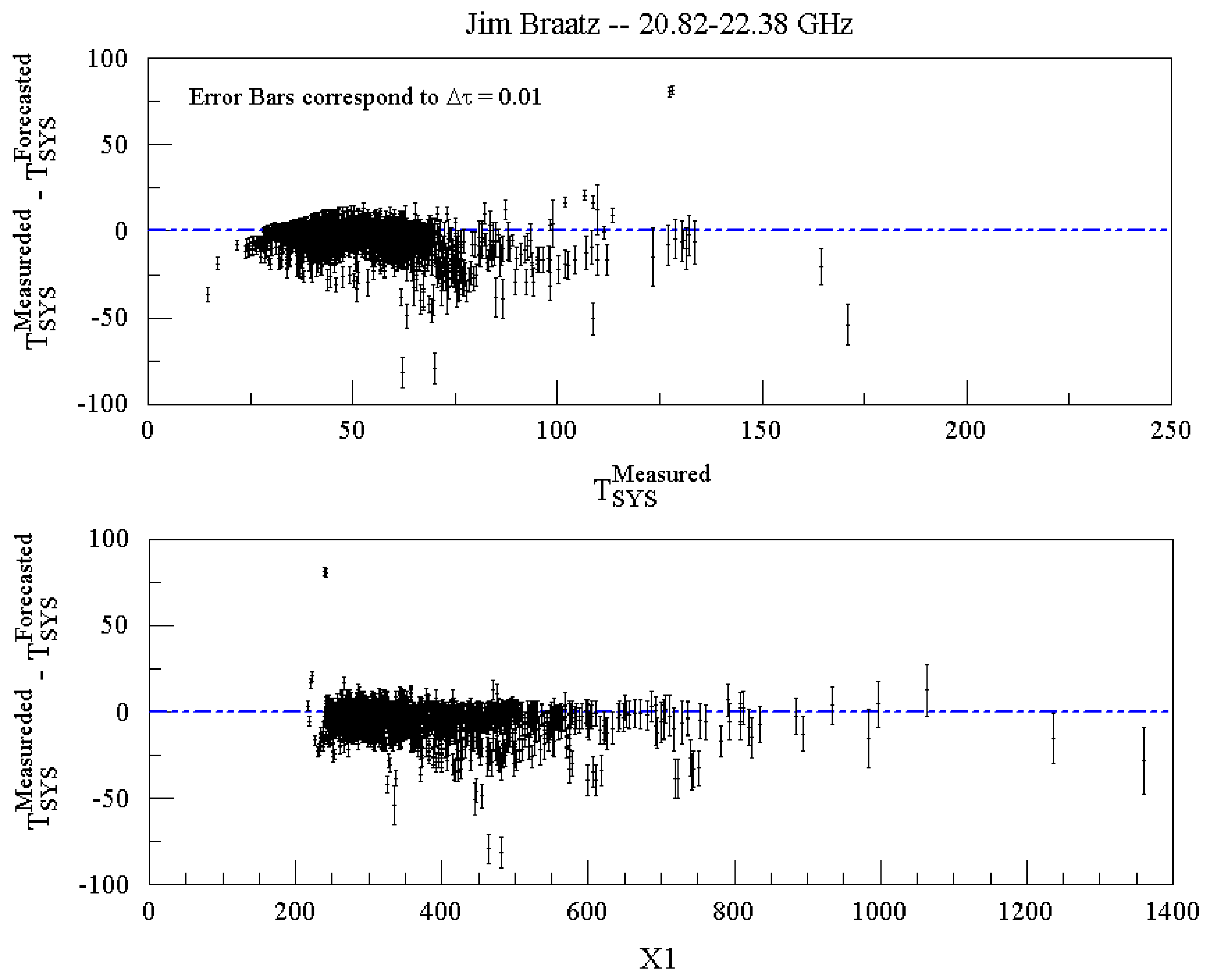
Conclusions on the accuracy of 41-45 GHz forecasts

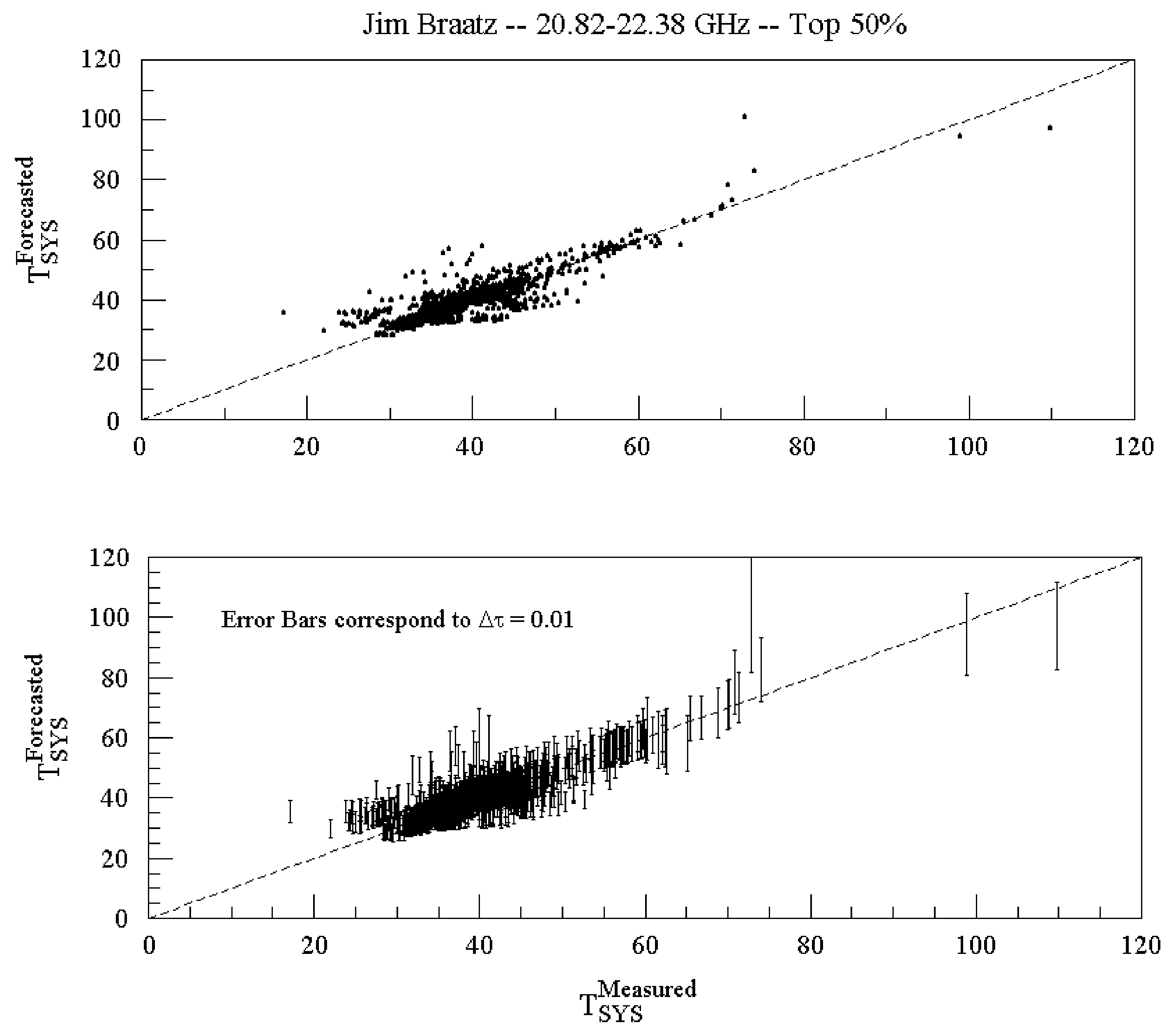
- In all cases, fitting for $\Delta\tau$ did not improve Chi Square in a statistically significant way (F-tests)
- Most likely upper estimates for $\Delta\tau$ were 0.006 or lower.
- Errors in T_{cal} dominate (5-20%)
- Errors in T_{rcvr} were 5-7K

Accuracy of 22 GHz Forecasts

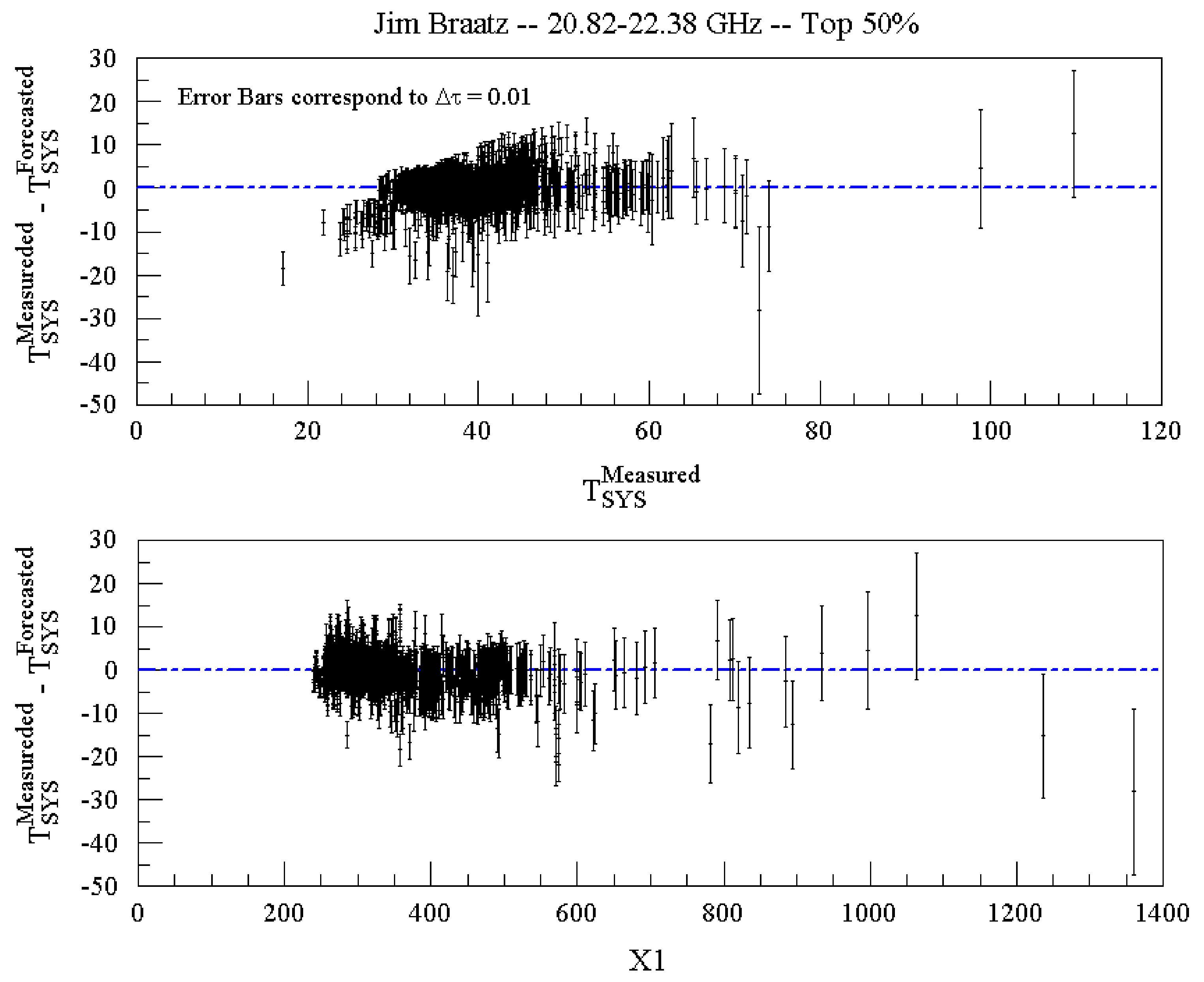
- Used Jim Braatz's measured T_{sys} taken over 3 years and a wide range of weather conditions, elevations, etc.
  - $\tau = 0.021 - 0.305$
  - Elevation = 86.2 – 7.5
  - Air Mass = 1 – 7.29
  - Frequency = 20.82 – 22.38 GHz


Jim Braatz -- 20.82-22.38 GHz
$T_{SYS}^{Forecasted}$
0
50
100
150
200
250
0
50
100
150
200
250
Error Bars correspond to $\Delta\tau = 0.01$
$T_{SYS}^{Forecasted}$
0
50
100
150
200
250
0
50
100
150
200
250
$T_{SYS}^{Measured}$


Jim Braatz -- 20.82-22.38 GHz
Error Bars correspond to Δτ = 0.01
$T_{SYS}^{Measureded} - T_{SYS}^{Forecasted}$
100
50
0
-50
-100
0
50
100
150
200
250
$T_{SYS}^{Measured}$
$T_{SYS}^{Measureded} - T_{SYS}^{Forecasted}$
100
50
0
-50
-100
0
200
400
600
800
1000
1200
1400
X1



Jim Braatz -- 20.82-22.38 GHz -- Top 50%

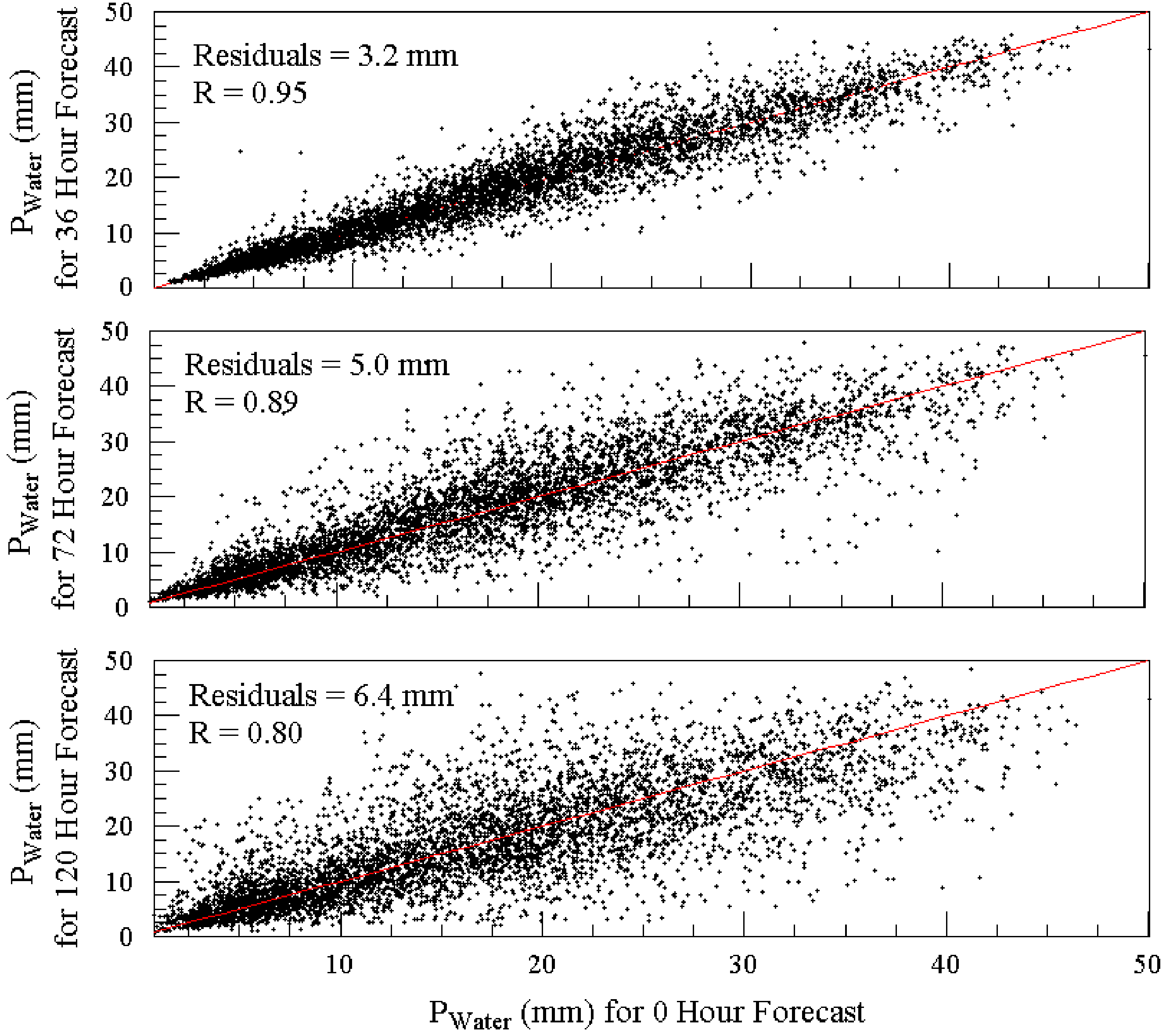

Jim Braatz -- 20.82-22.38 GHz -- Top 50%
Error Bars correspond to Δτ = 0.01
$T_{SYS}^{Measureded} - T_{SYS}^{Forecasted}$
30
20
10
0
-10
-20
-30
-40
-50
0
20
40
60
80
100
120
$T_{SYS}^{Measured}$
$T_{SYS}^{Measureded} - T_{SYS}^{Forecasted}$
30
20
10
0
-10
-20
-30
-40
-50
0
200
400
600
800
1000
1200
1400
X1

Conclusions on accuracy of 22 GHz forecasts

- As with 41-45 GHz, fitting for $\Delta\tau$ did not improve Chi Square in a statistically significant way
- Most likely upper estimates for $\Delta\tau$ is ~0.011.
- Errors in T_{cal} dominate (~25%)
- For top 50% of Jim's data, no fits improved the rms (3.5 K)
  - Most likely upper estimate of $\Delta\tau$ for the best days is ~0.005.

Reliability of forecasts

- Since the latest T_{sys} forecasts and the real world agree, we should then ask: How far ahead can one predict radio astronomy weather?
  - Forecasts update every 6 hrs
  - Forecasts extend 180 hrs
  - Every hr is forecasted 30 times
  - How does the 180 hrs, 172, … 48, 24, … 6 hr forecasts agree with the 0 hr forecast?
    - At what point does the correlation coefficient between an extended forecast and 0hr forecasts drop significantly?



P_{Water} (mm) for 36 Hour Forecast
Residuals = 3.2 mm
R = 0.95
P_{Water} (mm) for 72 Hour Forecast
Residuals = 5.0 mm
R = 0.89
P_{Water} (mm) for 120 Hour Forecast
Residuals = 6.4 mm
R = 0.80
0
10
20
30
40
50
P_{Water} (mm) for 0 Hour Forecast

Correlation coefficients for P_{Water}

NAM		
Hr	R	rms (mm)
6	0.985	1.76
12	0.978	2.11
18	0.972	2.41
24	0.968	2.58
30	0.960	2.91
36	0.952	3.15
42	0.942	3.46
48	0.932	3.73
54	0.922	4.03
60	0.910	4.35
66	0.898	4.64
72	0.885	4.95
78	0.875	5.19

GFS3		
Hr	R	rms (mm)
84	0.869	5.15
96	0.852	5.49
108	0.825	5.98
120	0.796	6.43
132	0.754	7.10
144	0.726	7.52
156	0.708	7.85
168	0.682	8.18

Correlation coefficients for Winds

NAM		
Hr	R	rms (MPH)
6	0.902	2.00
12	0.820	2.65
18	0.797	2.83
24	0.777	2.83
30	0.762	3.00
36	0.753	3.00
42	0.749	3.00
48	0.744	3.00
54	0.734	3.00
60	0.685	3.32
66	0.628	3.61
72	0.577	3.74
78	0.579	3.61

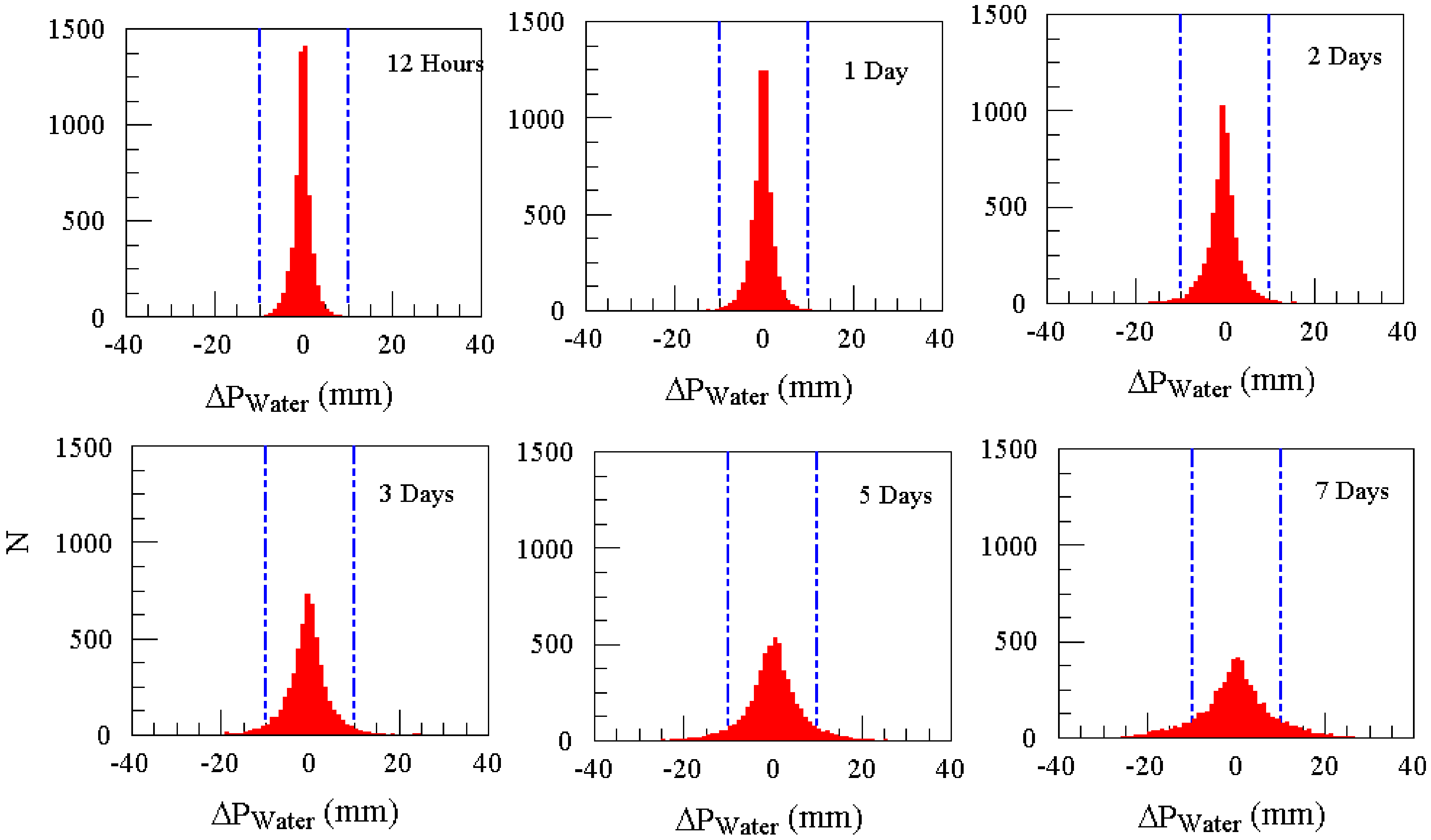
GFS3		
Hr	R	rms (MPH)
84	0.771	2.83
96	0.769	3.00
108	0.746	3.00
120	0.749	3.00
132	0.751	3.00
144	0.739	3.00
156	0.755	3.00
168	0.734	3.16

Correlation coefficients for Cloud Coverage

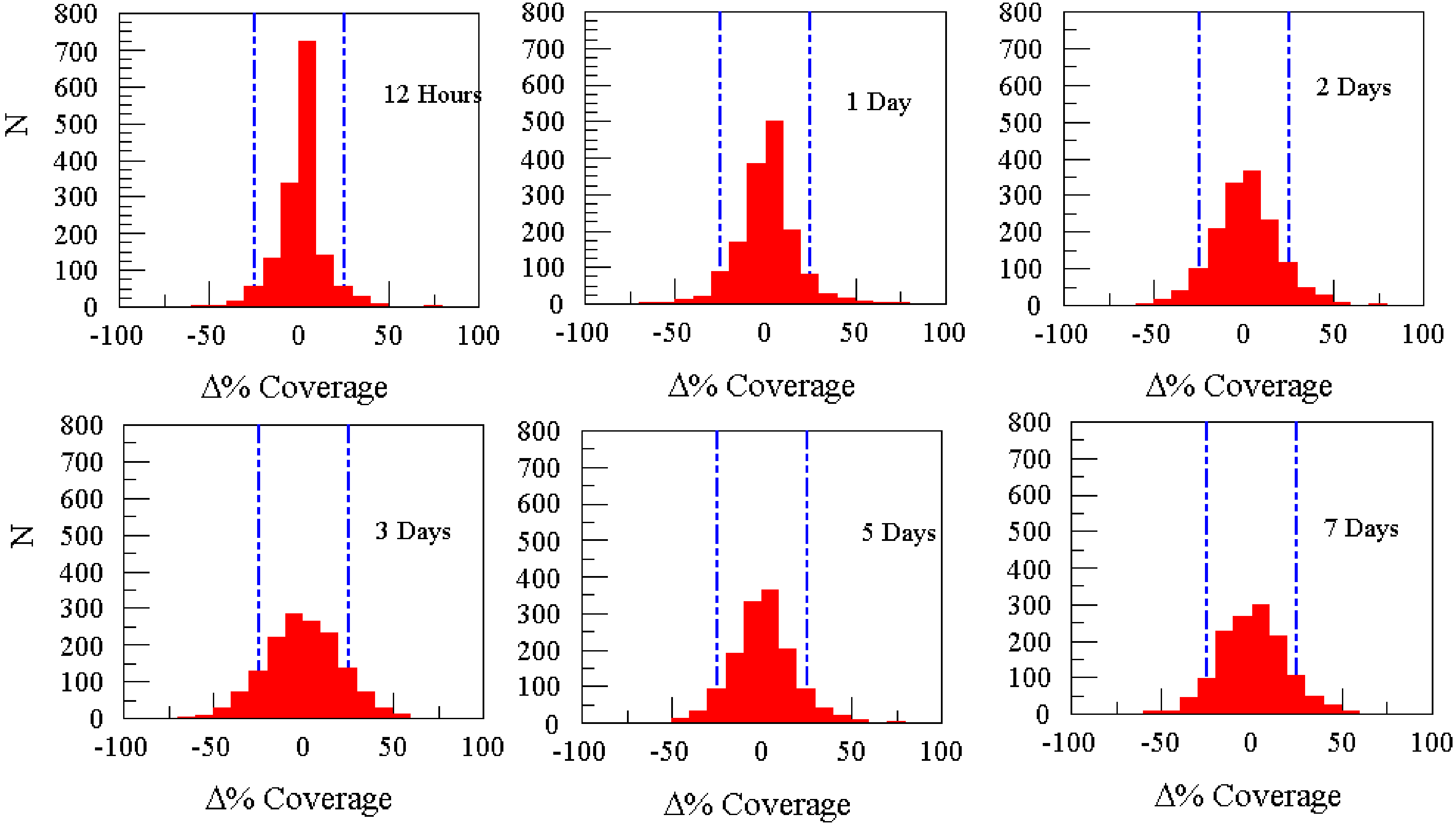
NAM		
Hr	R	rms (%)
6	0.933	11.09
12	0.900	13.49
18	0.876	14.83
24	0.847	16.22
30	0.828	17.18
36	0.823	17.44
42	0.811	17.86
48	0.789	18.68
54	0.786	18.79
60	0.758	19.77
66	0.734	20.57
72	0.719	21.07
78	0.689	22.02

GFS3		
Hr	R	rms (%)
84	0.833	16.94
96	0.830	17.18
108	0.826	17.35
120	0.816	17.66
132	0.812	17.92
144	0.787	18.68
156	0.779	19.08
168	0.792	18.57

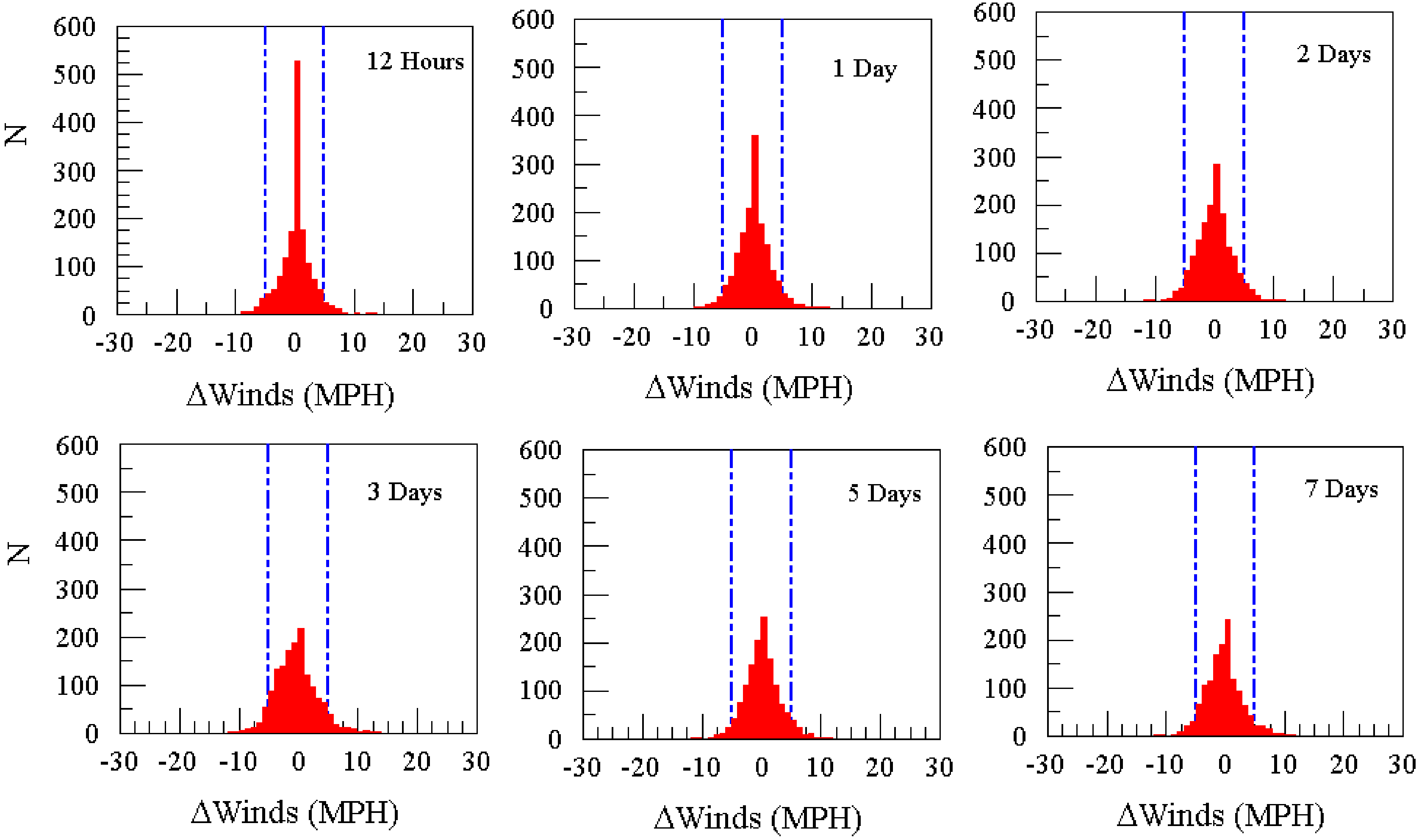
Change in Forecasted P_{Water}

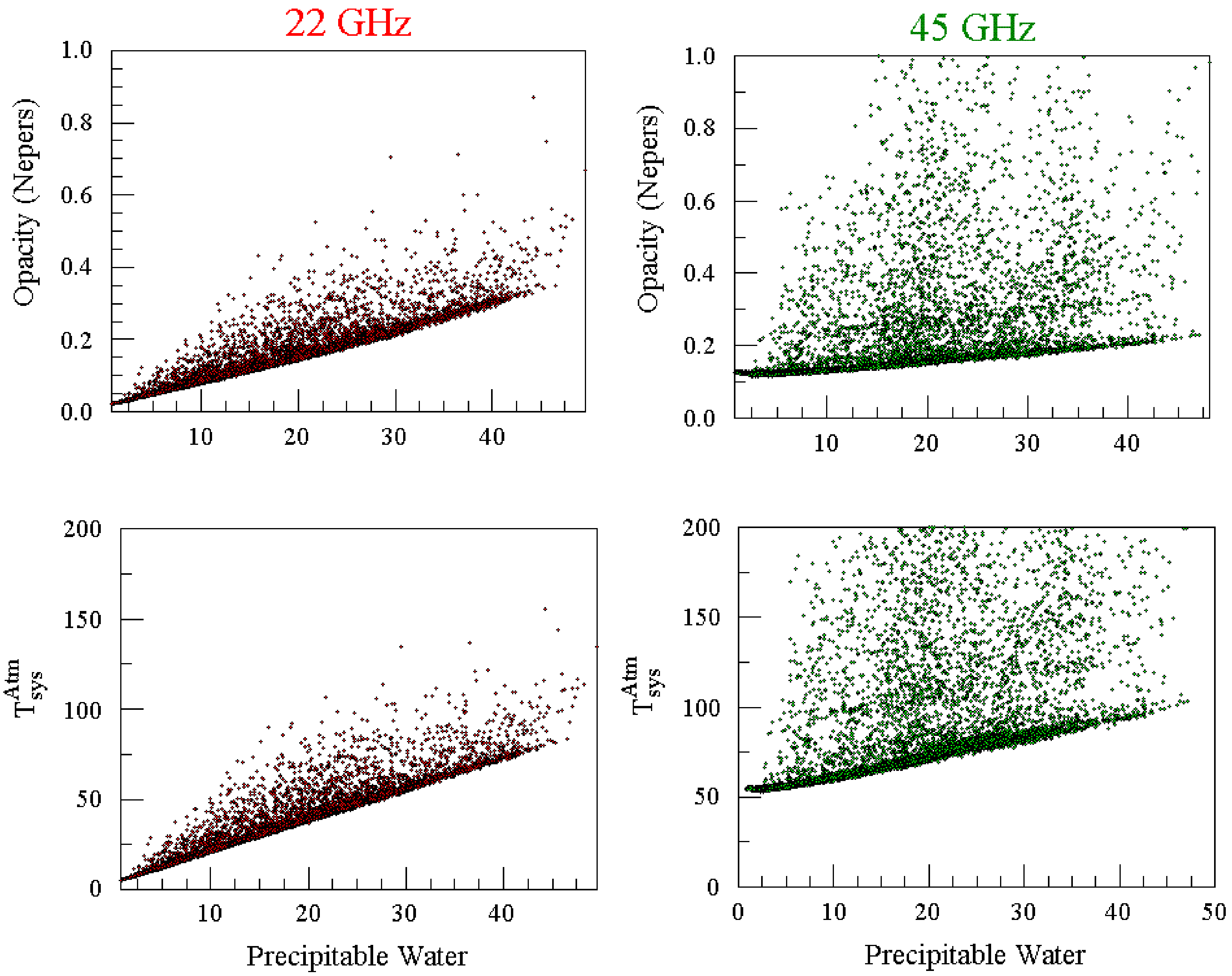


Change in Forecasted Cloud Coverage

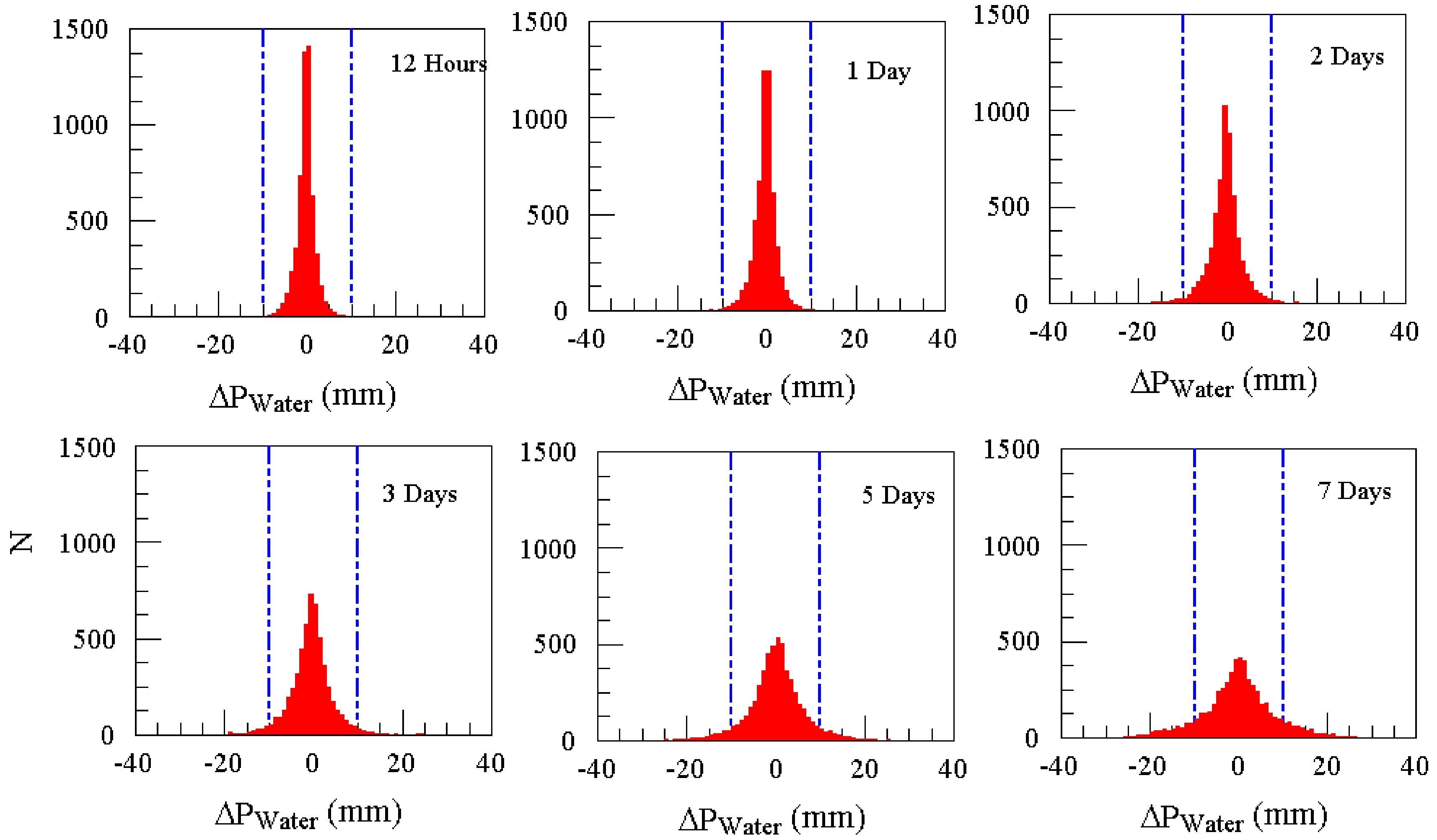


Change in Forecasted Winds




22 GHz
45 GHz
Opacity (Nepers)
1.0
0.8
0.6
0.4
0.2
0.0
10
20
30
40
Opacity (Nepers)
1.0
0.8
0.6
0.4
0.2
0.0
10
20
30
40
T_{sys}^{Atm}
200
150
100
50
0
10
20
30
40
Precipitable Water
T_{sys}^{Atm}
200
150
100
50
0
0
10
20
30
40
50
Precipitable Water

Change in Forecasted P_{Water}



Conclusions on reliability

- Cloud coverage
  - 5 days for spectral line observing
  - Unknown for continuum observing
  - But, how do forecasted cloud coverage match with observed?
- Opacity forecasts for spectral line observing are good for:
  - ~2 days for 22 GHz
  - ~3 days for 45 GHz,
  - ~5 days for anything else
- Wind forecasts are good for 5 days
  - But, how do forecasted winds match with measured winds?

Conclusions

- Very brief overview of the forecasting method
- Accuracy of forecasts
  - Can one determine causes for inaccuracies?
  - Accuracy of 22 and 41-45 GHz forecasts
    - $\Delta\tau < 0.01$
    - Good enough for high-accuracy calibration
- Reliability of forecasts
  - Approximately 5 days when observing < 18 GHz, and between 25-35 GHz
  - Otherwise, 2-3 days