NOAA Forecast Systems Laboratory
2004 Technical Review

GPS-Met Observing Systems

Presented by

GPS-Met Observing Systems Branch
NOAA Research Forecast Systems Laboratory
Demonstration Division

January 27, 2004

Tech Review Agenda

Topic	Speaker	Time
Overview/Introduction:	Seth Gutman FSL/DD	1330 - 1345
GPS Satellite Orbits:	Peng Fang SIO/SOPAC	1345 - 1400
NWP Model Studies:	Tracy Smith FSL/FRD CIRA	1400 – 1415
Break		1415 - 1430
Data Products & Services:	Susan Sahm FSL/DD	1430 - 1445
Data Applications:	Daphne Grant FSL/DD	1445 - 1500
Operational Transition:	Kirk Holub FSL/DD	1500 - 1515
Concluding Remarks:	Seth Gutman	1515 – 1520
Questions:		1520 – 1530

Overview/Introduction

- The GPS-Met project started in 1993 as a collaboration between FSL, UCAR and NCSU to determine if & how GPS could be used to measure atmospheric moisture.
- It has evolved into a collaboration between FSL, other NOAA organizations, other federal, state and local government agencies, universities, and the private sector.
- This level of cooperation has permitted us to develop, test and evaluate a new upper-air observing system for less than 10% of the Demonstration Division’s budget.
- Major accomplishments include: specification of the observation accuracy and error covariance; co-development of real-time data processing techniques; verification of positive impact on Wx forecast accuracy; definition and exploration of new applications.

Collaborations

FSL	FRD, TOD, AD, SDD, MD, A&R, ITS
NOAA Research	ETL, AL, AMOL, CMDL, PMEL, GLERL, SEC
Other NOAA:	NWS (NDBC, ER, SR, CR, WR, AR, NCEP), NOS (NGS, CO-OPS), NESDIS (ORA), NGDC, NCDC
Federal Gov't:	DOT (FHWA), DHS (USCG), DOD (USN, USAF, USACE), NASA (LaRC, JPL, GFSC), DOE (ARM)
Universities:	SIO, UH, UCAR, MIT, H-SAO, OSU, Purdue, U. Calgary, USM, CU, CSU, LSU, and SuomiNet
Other Gov't:	AZ (various), AKDOT, CO (various), FDOT, MDOT, MNDOT, OHDOT, OKDOT, NYDOT, NCDOT, TXDOT, VTDOT

Supporting the NOAA Strategic Plan

- GPS-Met observations contribute to 3 of 4 NOAA Mission Goals:
  - Understanding climate variability and change to enhance society's ability to plan and respond;
  - Serving society's needs for weather and water information;
  - Supporting the Nation's commerce with information for safe, efficient, and environmentally sound transportation.

- GPS-Met also contributes to 4 of 6 cross-cutting priorities essential to support NOAA mission goals:
  - integrated global environmental observation and data management systems;
  - sound, reliable state-of-the-art research;
  - international cooperation and collaboration; and
  - homeland security.

Supporting the FSL Strategic Plan

- FSL conducts applied meteorological R&D to create and improve short-term warning and weather forecast systems, models, and observing technologies.
- Ground-based GPS-Met contributes to all of these activities by providing high accuracy moisture observations under all weather conditions to forecasters, modelers, and researchers.
- The unique capabilities of FSL have enabled the GPS-Met observing system to be developed, tested, and validated in a relatively short period.
- Positive impact on Wx forecast accuracy has been demonstrated and verified using the FSL-developed RUC.
- Lessons learned from using FX-Net will be applied to AWIPS, as we build GPS-Met display applications for WFOs in collaboration with SDD and MD.

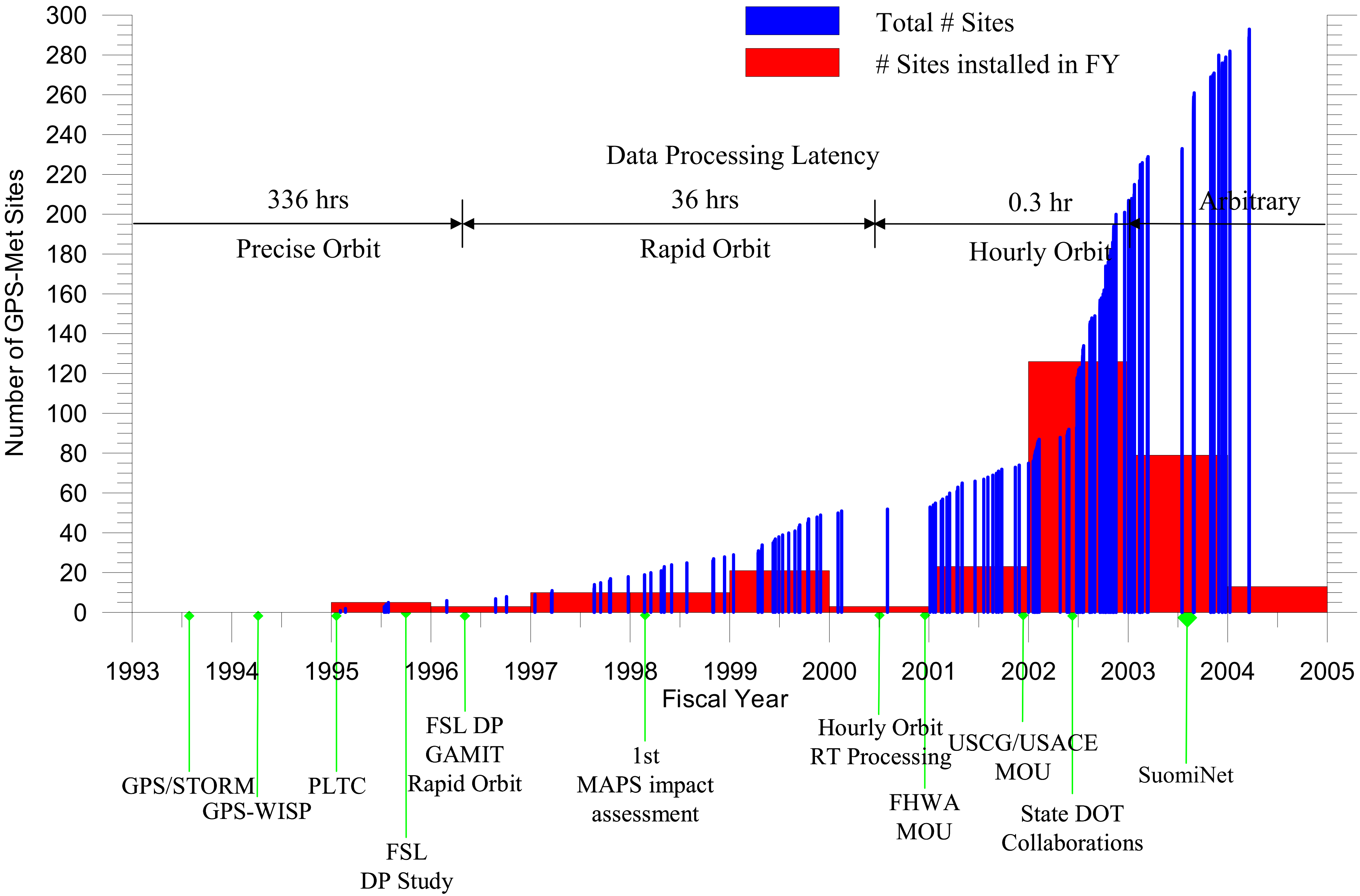
Technology Transfer/Outreach

- FSL transfers new scientific and technological advances to its clients, including the National Weather Service, Department of Defense, foreign weather forecasting agencies, and private interests.
- To facilitate this, DD funded a modest outreach activity led by Sher Schranz of FSL/TOD and CIRA, with assistance from Rhonda Lange, Will von Dauster and John Osborne.
- Joe Golden also provided assistance, especially with forecast offices.
- Efforts concentrated on NWS, FHWA, and DOD users.
- Ongoing cooperation with Patty Miller and the MADIS group has greatly expanded access to GPS-Met data and products.

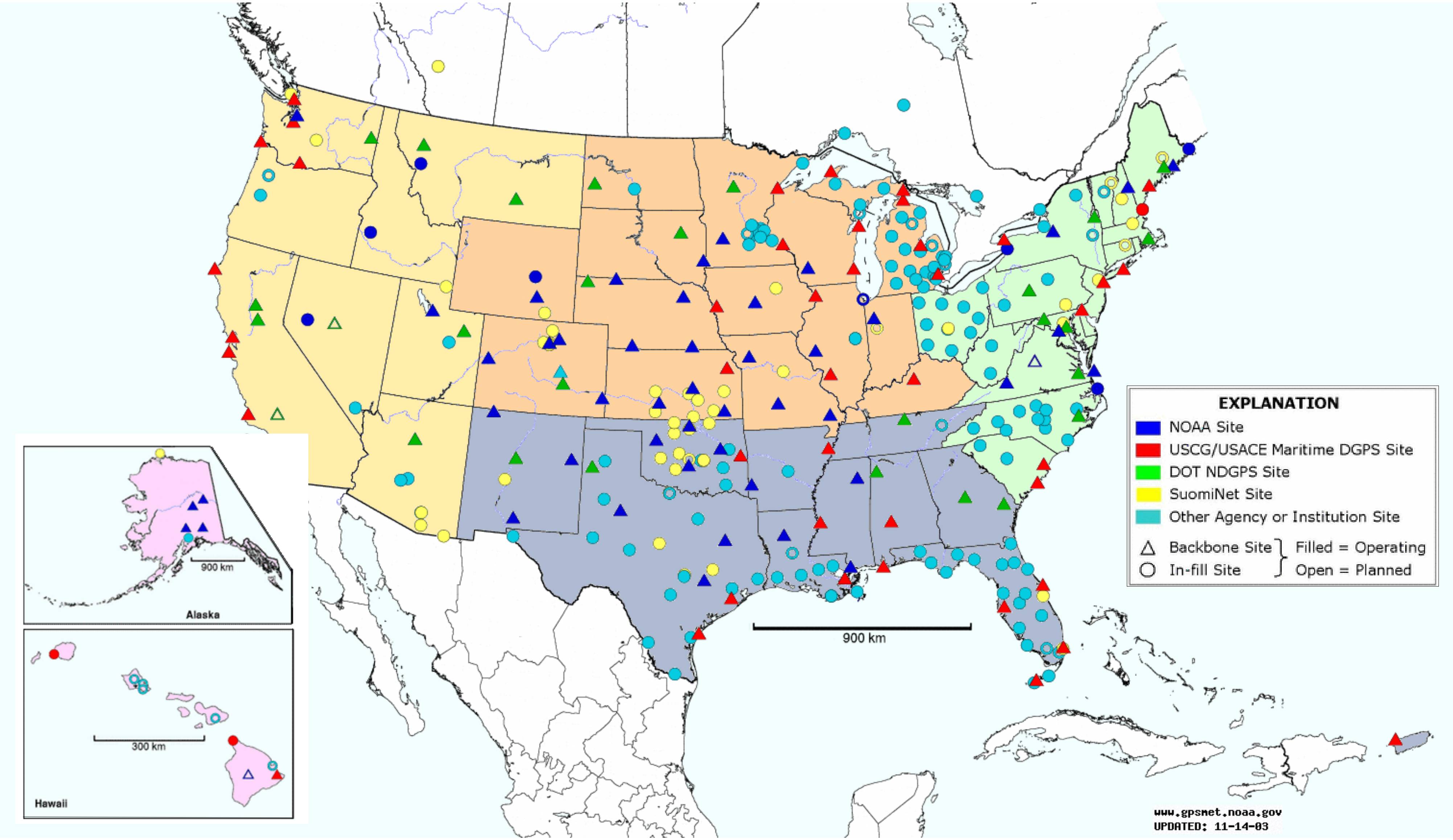
Since 2002 Tech Review

- The original system architecture (GPS + collocated Sfc. Met + dedicated comms) was modified to enable us to use GPS sites without all of these attributes.
- We created the backbone site vs. infill site distinction.
- The number of sites in the network increased from 121 to 291.
- The number of systems in the processing array went from 12 to 18.
- Latency (mean time from the end of a 30-min session until PW is delivered) decreased from 20 minutes to 14 minutes.
- The number of GPS sites within 50 km of an NWS UA site increased from 4 to 48.

History, Evolution & Critical Decisions



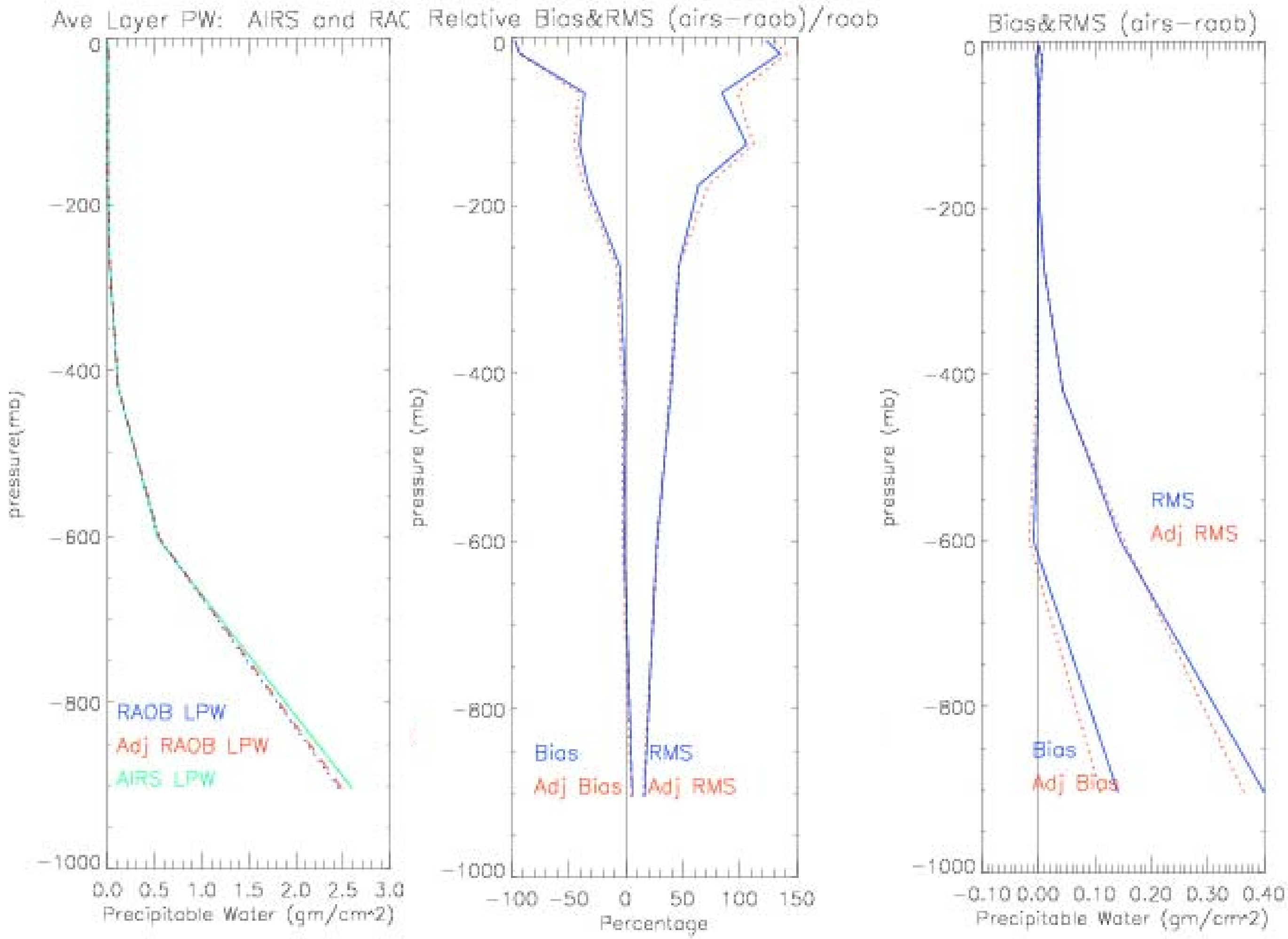
GPS-Met Demonstration Network

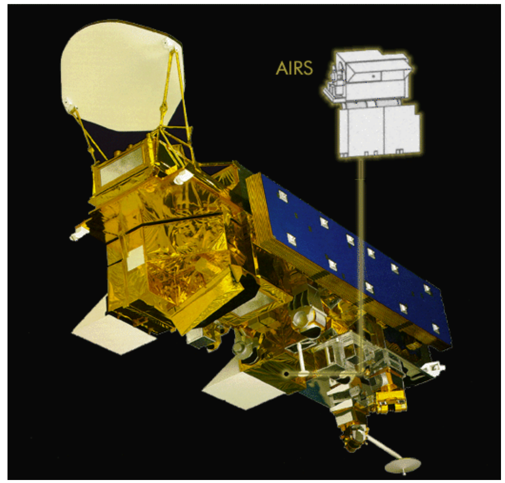


291 GPS-Met Sites + 38 waiting for positions

Since 2002 Tech Review

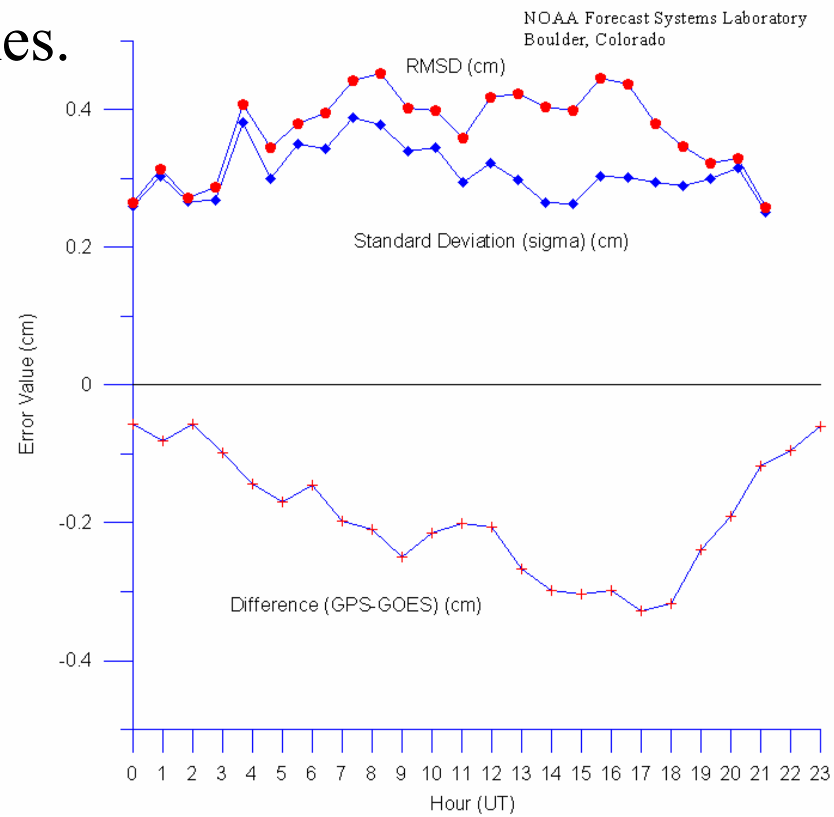
- NASA Co-PI on Aqua/AIRS science team. Provided calibration-validation PW data to all investigators.
  - Participating in AIRS cal/val experiments with NESDIS/ORA.





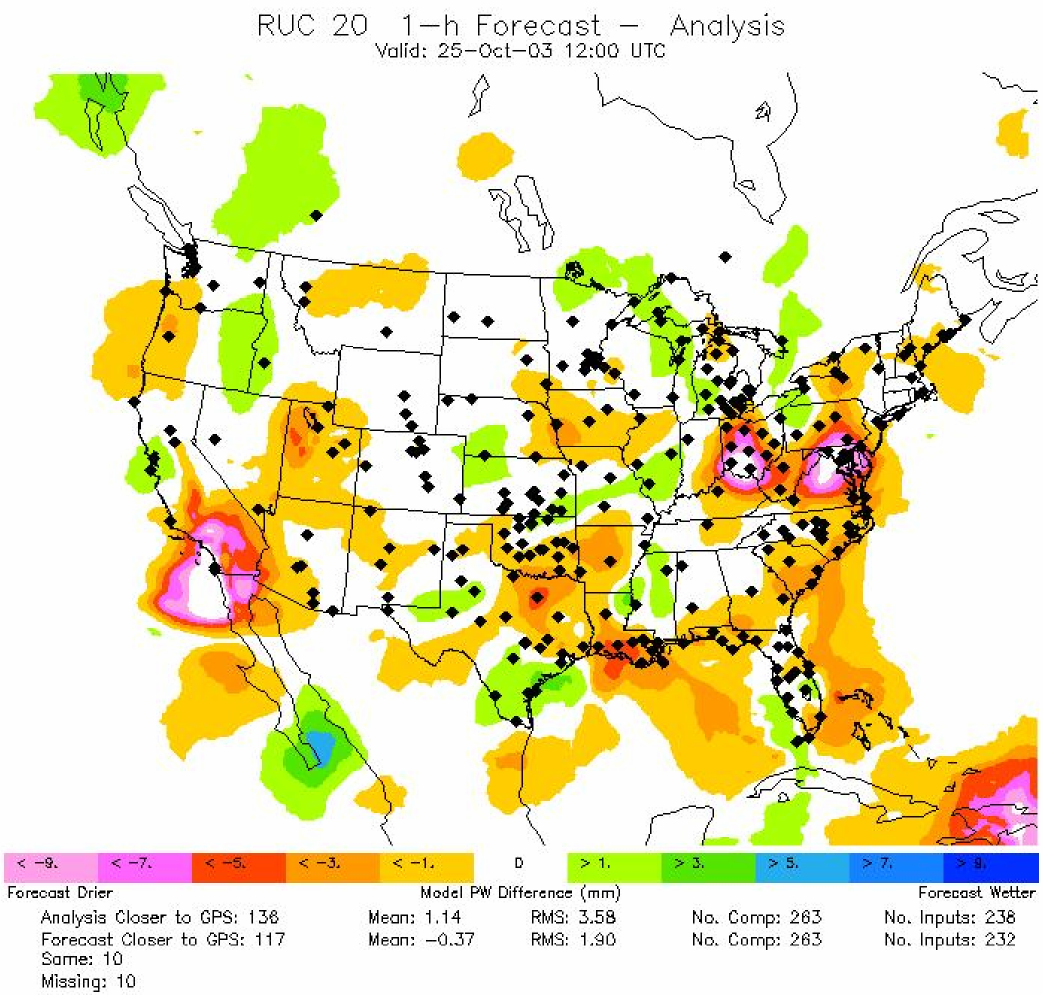
Since 2002 Tech Review

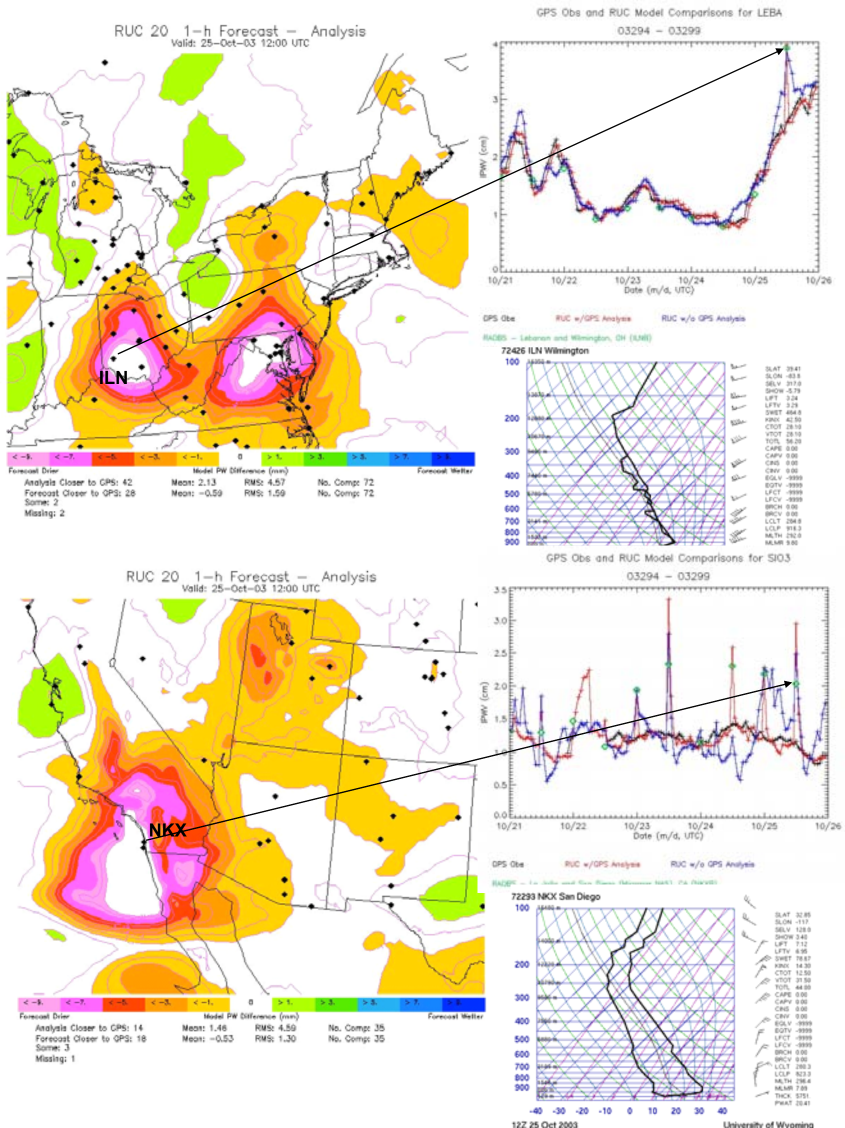
- Participated in IHOP 2002. Provided real-time data and analysis to all investigators.
  - In collaboration with researchers at NESDIS and CIMMS, Dan Birkenheuer and I are studying the temporal observation error structure of GOES-8 PW retrievals during IHOP by comparing them with GPS and sondes at synoptic and asynoptic times.



Since 2002 Tech Review

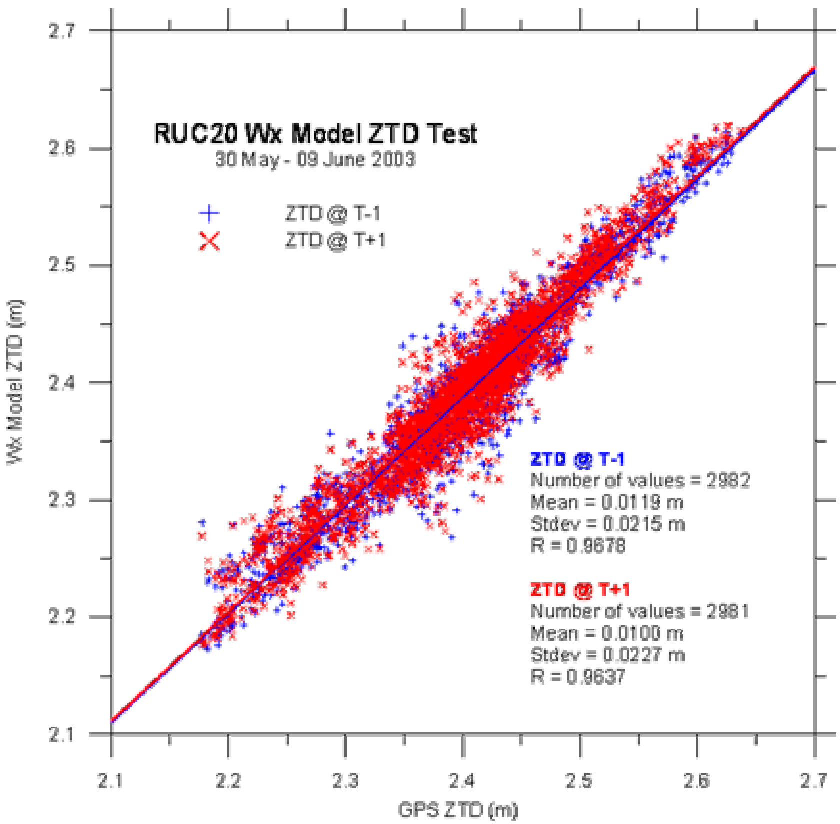
- By comparing GPS-IPW and PW from rawinsondes, we discovered that it is possible for GPS to identify problematic moisture soundings with high POD and low FAR.

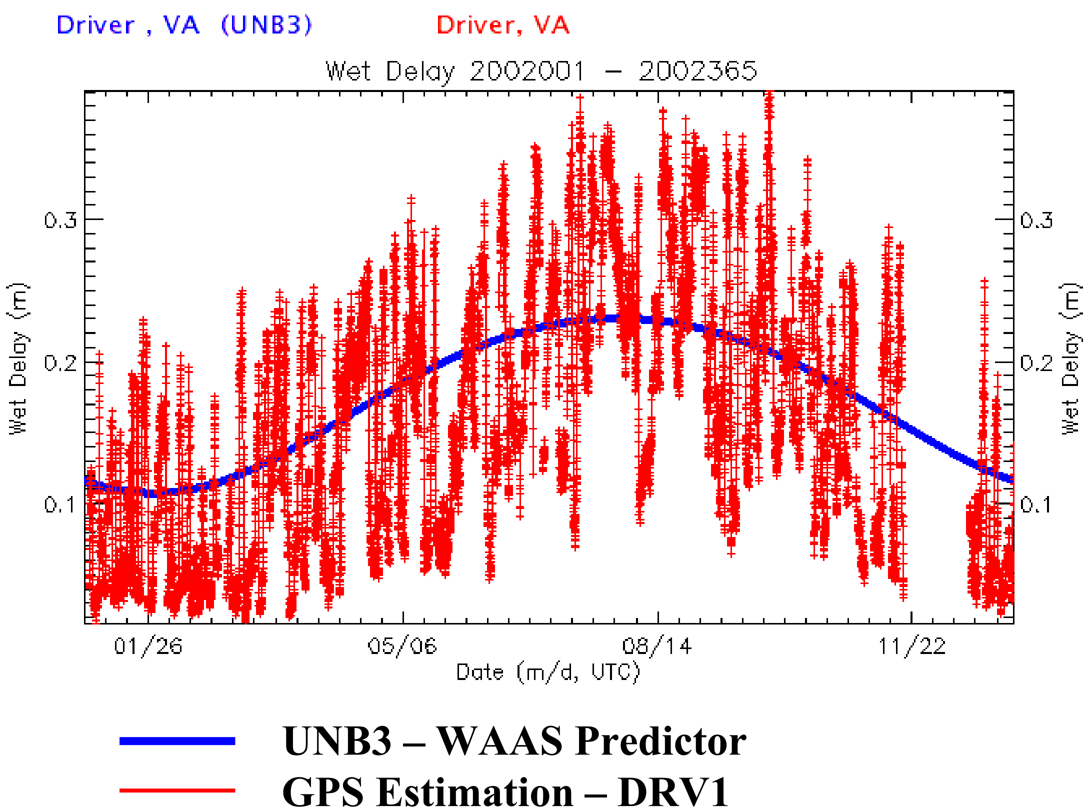




Since 2002 Tech Review

- We received modest funding from the Interagency GPS Executive Board to study the feasibility of using space and conventional Wx models to reduce the impact of atmospheric refractivity on high accuracy GPS positioning and navigation.





NOAA Forecast Systems Laboratory
GPS-Met Observing System
2004 Technical Review

Impact of Imperfect Orbits on Ground-Based GPS Atmospheric Sensing Application

Peng Fang

Scripps Orbit and Permanent Array Center (SOPAC)

University of California San Diego

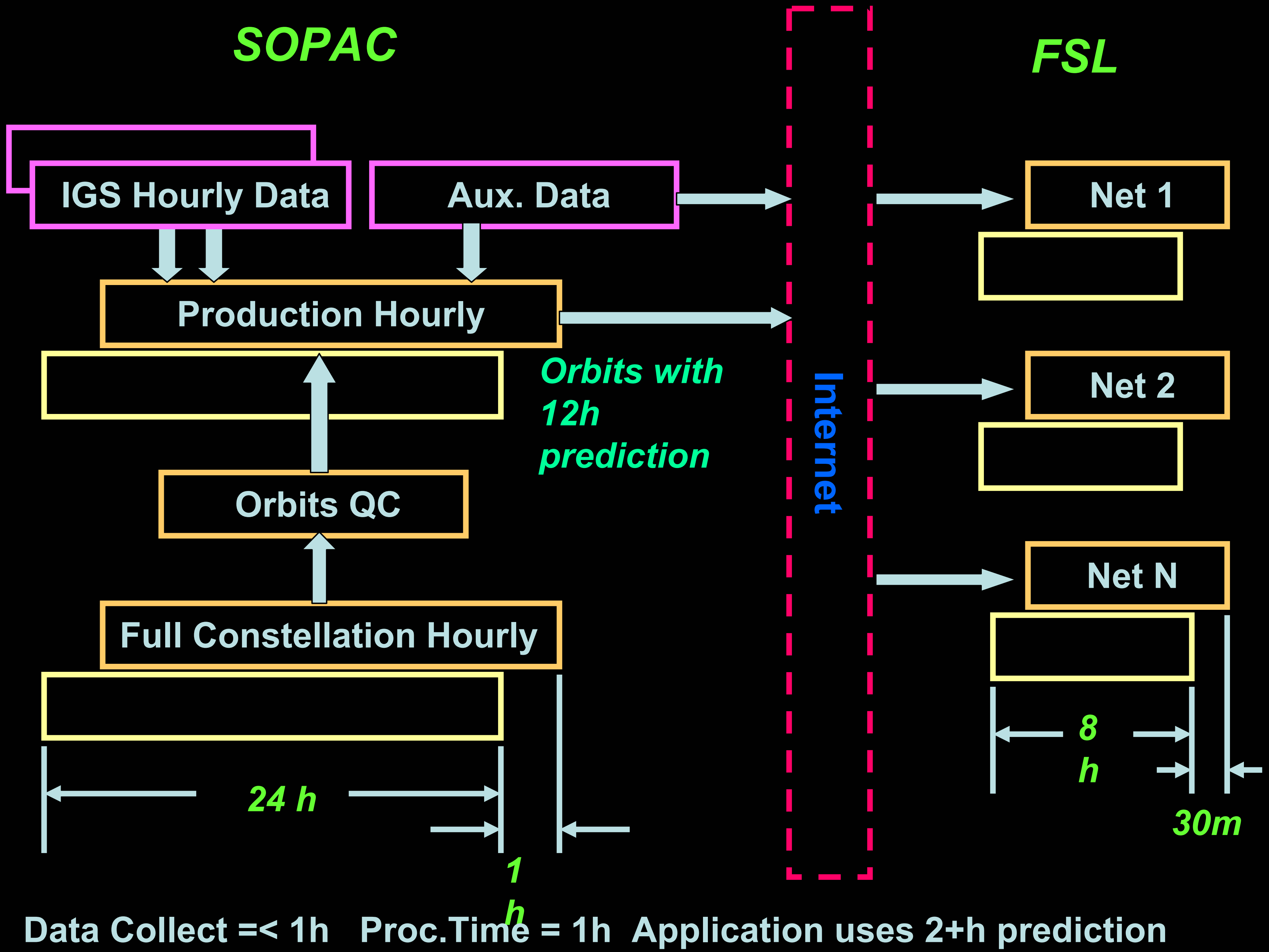
January 27, 2004

Outline

- SOPAC Hourly Orbits
- Factors Affecting Orbit Performance
  1. Global Network Configuration
  2. Observation Span and Data latency
  3. Satellite Performance
  4. Auxiliary Information
  5. Reliability of Operational Facilities
- Impact upon GPS/MET Applications
- Solutions to Various Problems

SOPAC Hourly Orbits

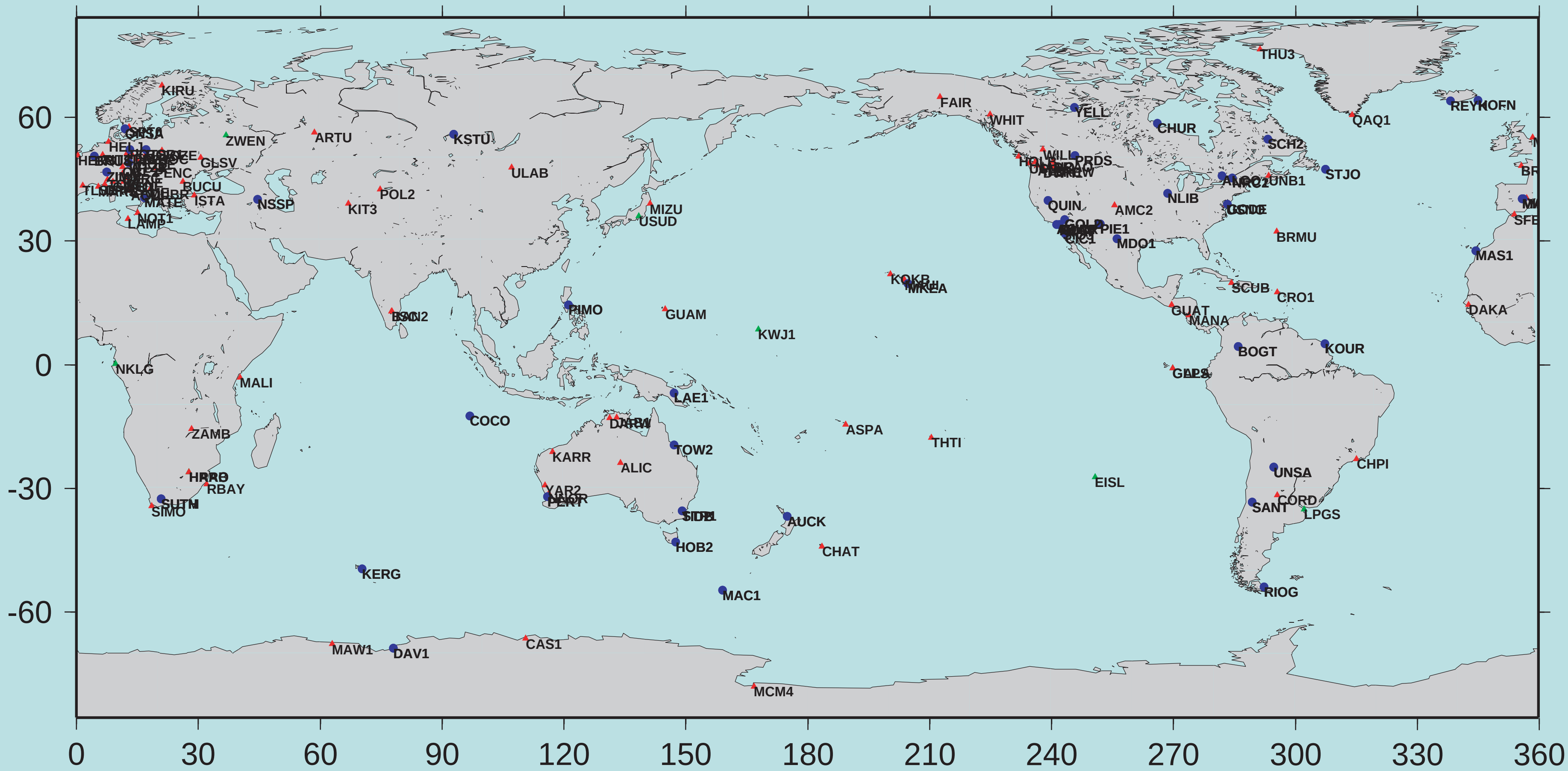
- Sliding window technique
  1. 24 hour data span (reason: maintain orbit continuity by fitting longer arc)
  2. Rejecting under performing satellites using internal and external checking
  3. Separate full constellation processing for resuming previously rejected satellites
  4. Duplicated data acquisition from multiple sources


SOPAC
FSL
IGS Hourly Data
Aux. Data
Production Hourly
Orbits with
12h
prediction
Internet
Net 1
Net 2
Net N
Orbits QC
Full Constellation Hourly
24 h
1
h
8
h
30m
Data Collect =< 1h Proc.Time = 1h Application uses 2+h prediction

Global Network Configuration

- When tracking network has large gaps (network holes), there will be very little or no data to fit the orbits over the paths above them. Thus the orbital characteristics could not be modeled well, resulting in poor prediction.

IGS hourly sites of global tracking network



Blue = to be used   Red = Possible to use   Green = temporarily unavailable

Observation Span and Data latency

- Longer span helps fitting longer orbital arc which in turn helps the orbit prediction. However the processing burden increases. One key parameter, “once per rev.”, could not be estimated well with short observation span.
- Higher latency means effective processing data span decreased.

Satellite Performance

- Satellite reposition
- Misbehaving satellites

1. Eclipsing
2. Reset
3. Higher general noise level

Auxiliary Information

- Earth Orientation Parameters (polar motion, UT) e.g. poor prediction, missing update -> biased orbits -> biased tropo. delay estimates. e.g. over shoot at bending
- Global reference frame e.g. Earthquake or site configuration change (antenna/receiver/monument) on tightly constrained sites -> error goes into orbit

Reliability of Operational Facilities

- Hardware failure (most often: RAM, hard drive, power supply)
- Data server overloading (shared scripts, executables, auxiliary files)
- Processing node overloading (usually after network interruption)
- Intranet interruption (e.g. DNS down)
- Internet interruption (e.g. maintenance, unusual event)

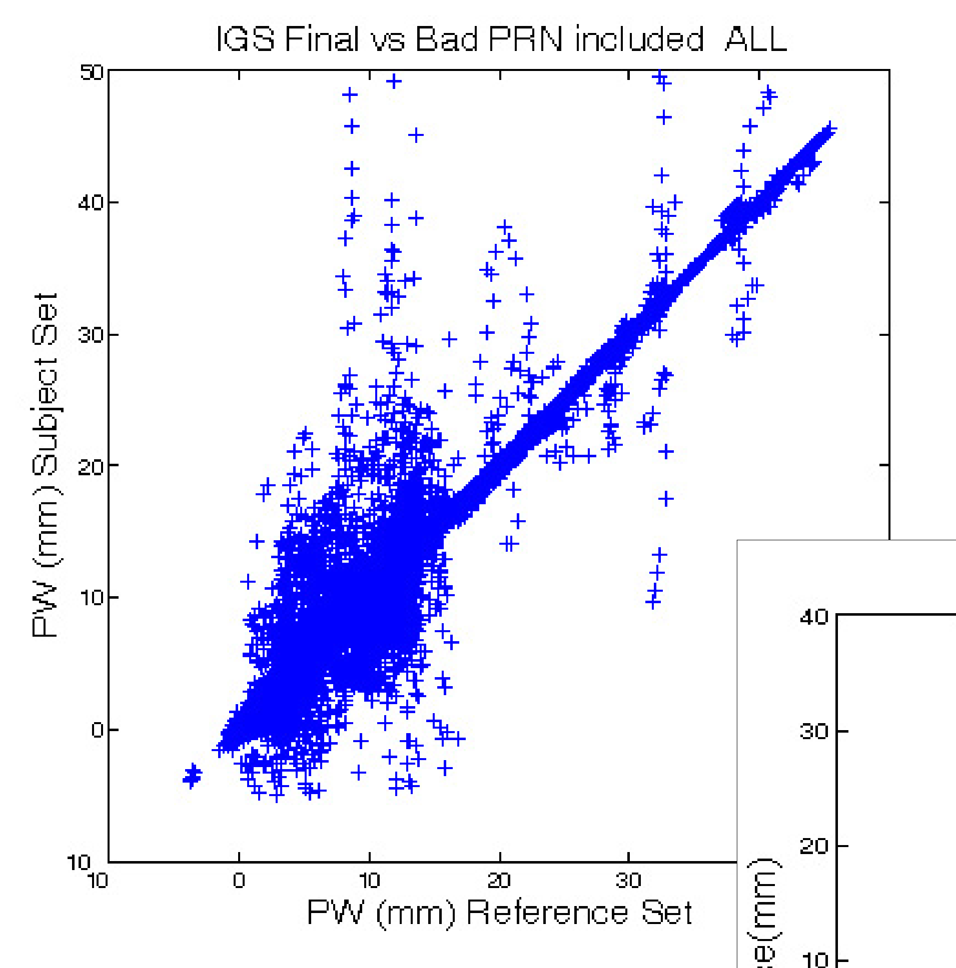
Impact upon GPS/MET Applications

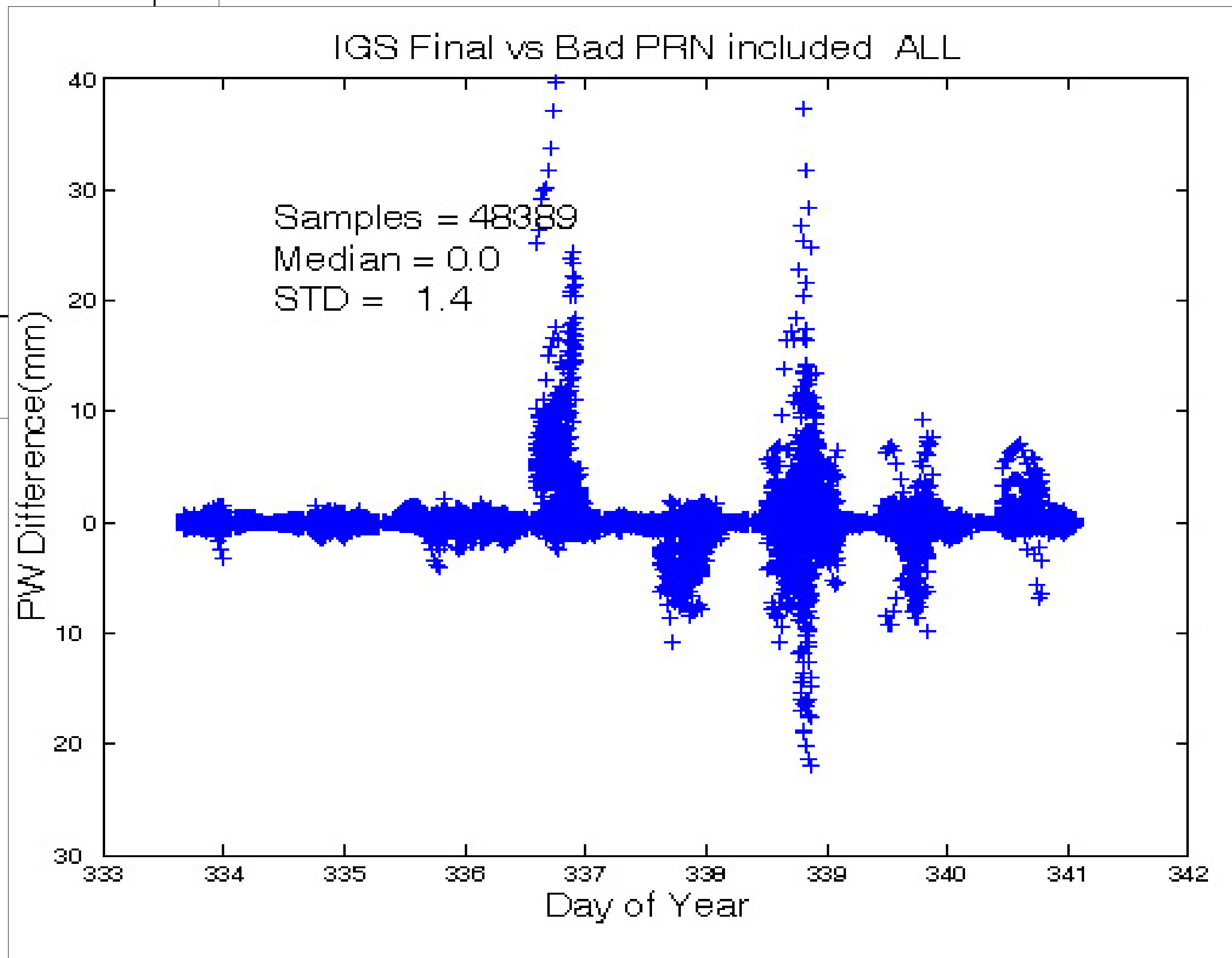
- Poor performing satellite included
- Poor configuration of global tracking network used
- Poor latency of data supply (less data to fit orbit, predicted orbit would not be good)
- Late orbit delivery (not to show) note: this is different from previous point. Using predicted orbits up to 8 hours should be OK

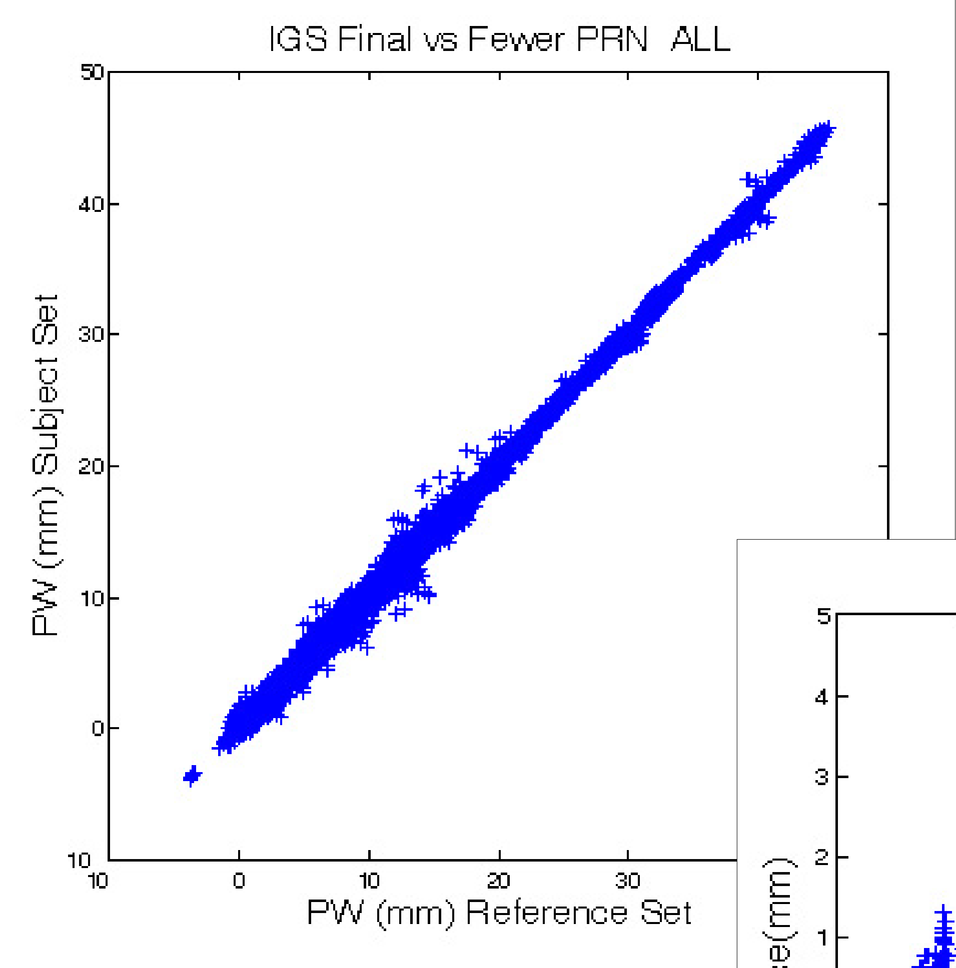
Experiment Setup

- Reference set: IGS final orbits
- GW1247 PRN24 (336) PRN31 (338,339)
- Reduced satellite from 27/28 to 22
- Removed last 6 hour observation
- Excluded 5 sites usually having latency problem

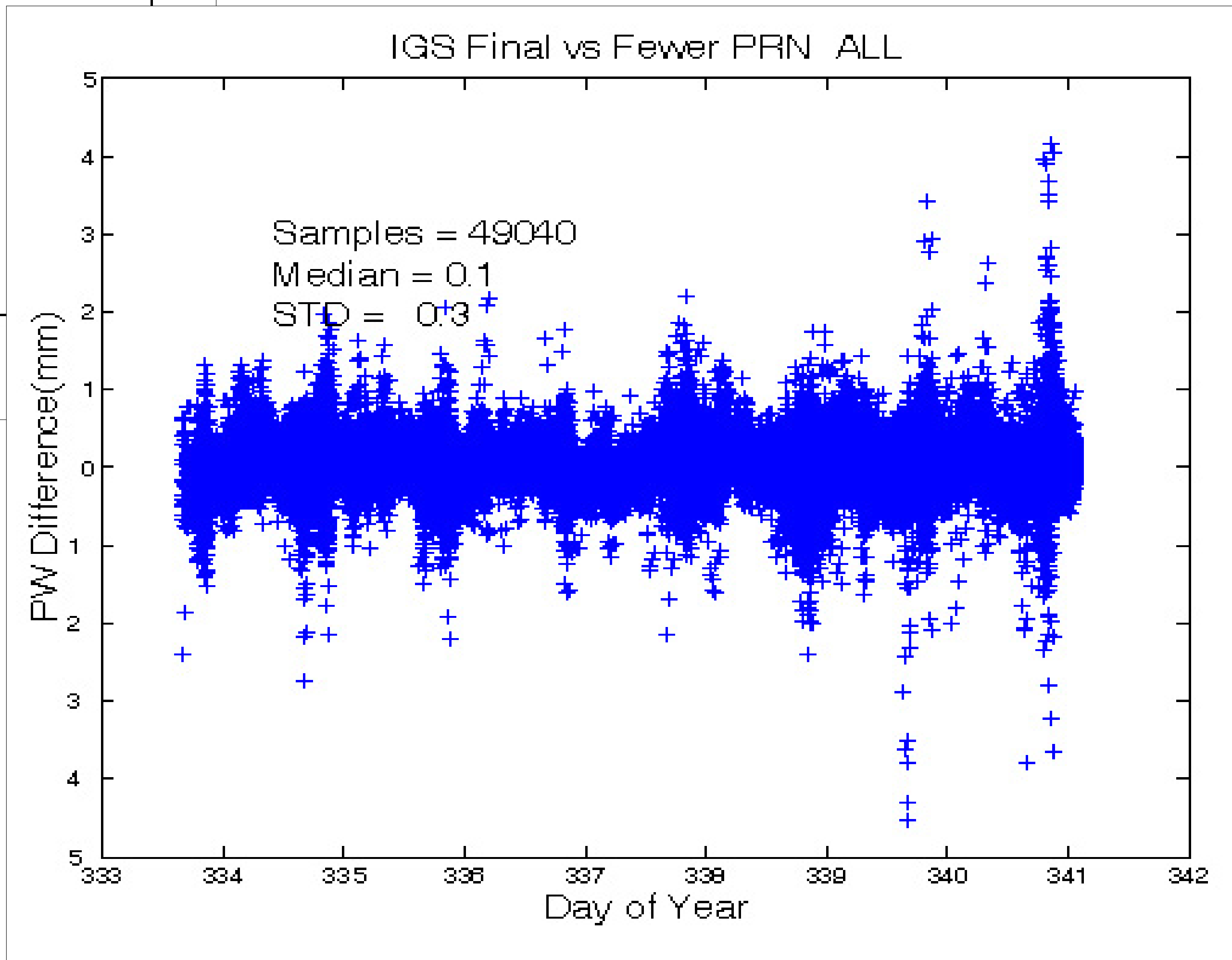
Total number of solutions: 24x8x5x2


IGS Final vs Bad PRN included ALL
PW (mm) Subject Set
PW (mm) Reference Set
50
40
30
20
10
0
10
10
0
10
20
30

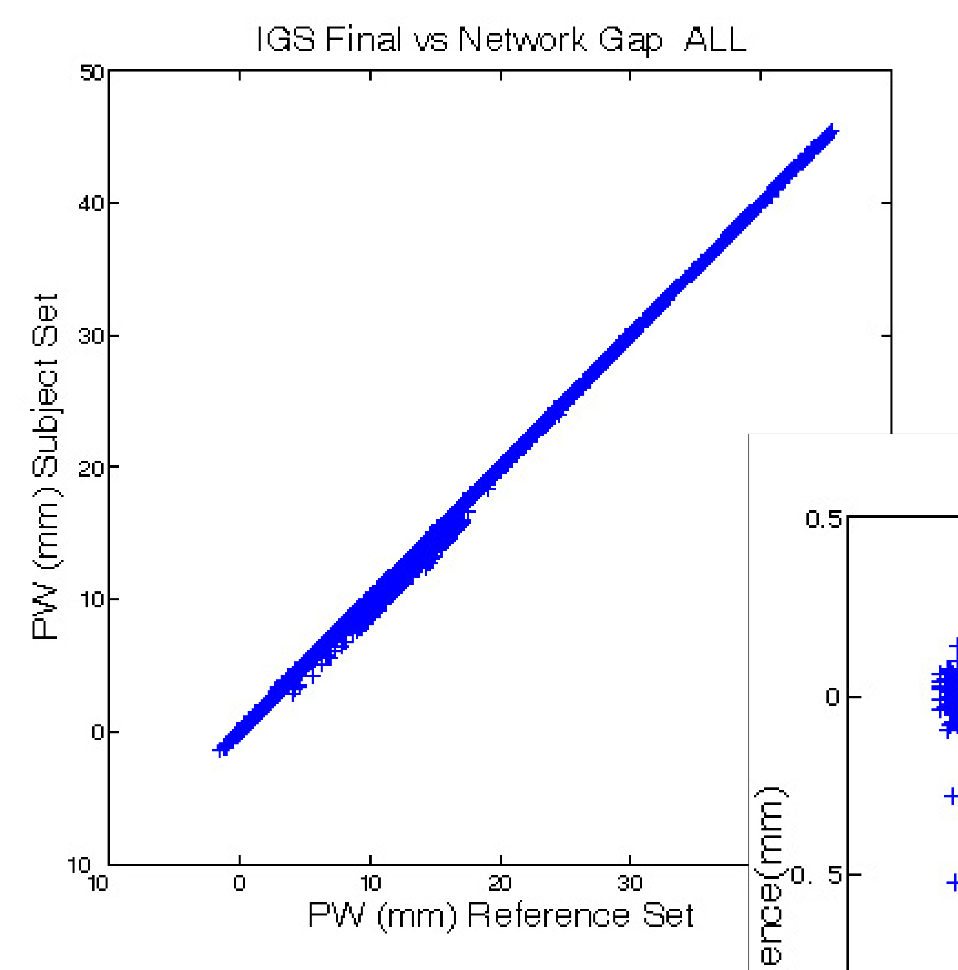

IGS Final vs Bad PRN included ALL
Samples = 48389
Median = 0.0
STD =   1.4
PW Difference(mm)
Day of Year
40
30
20
10
0
10
20
30
333
334
335
336
337
338
339
340
341
342

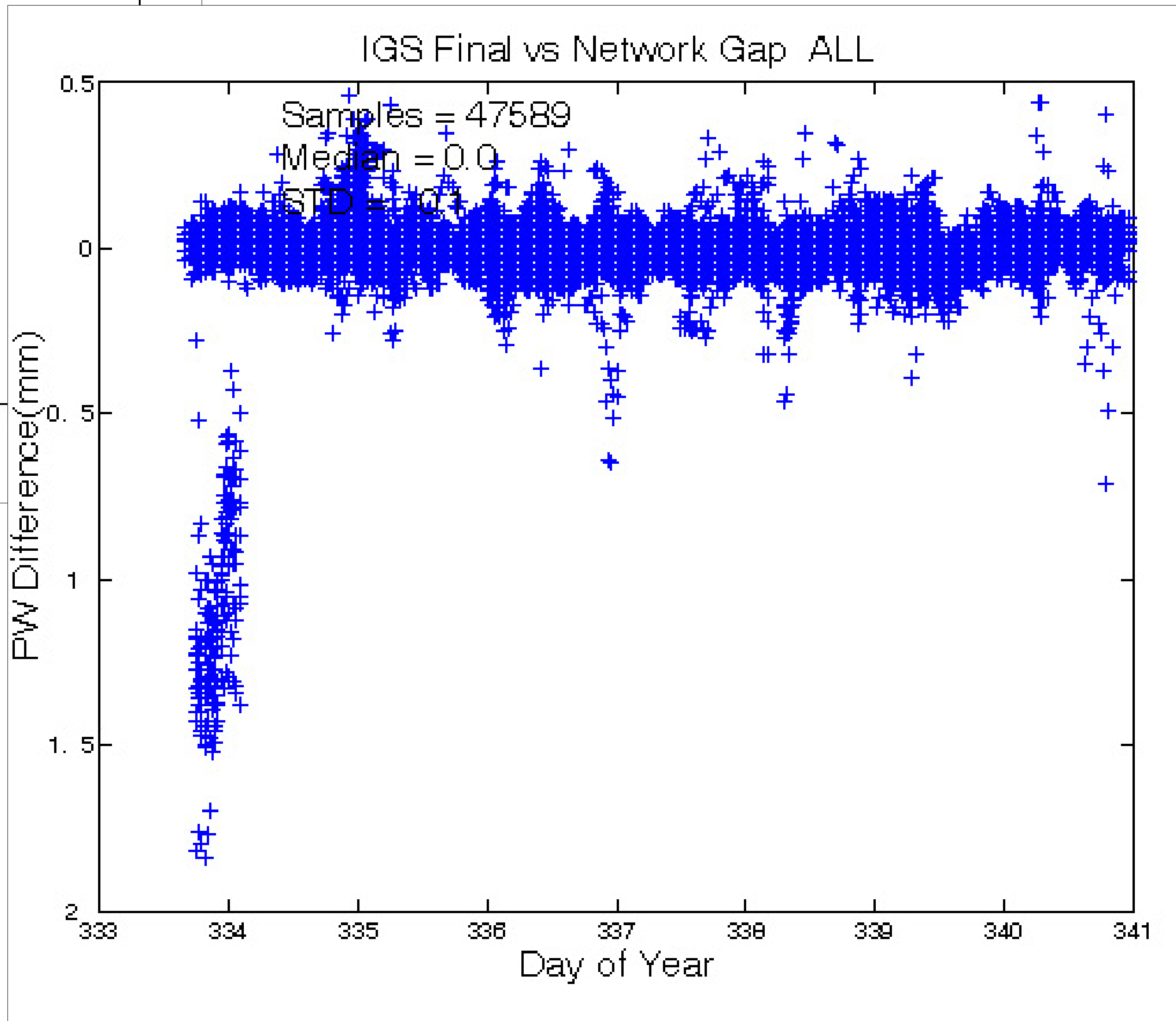


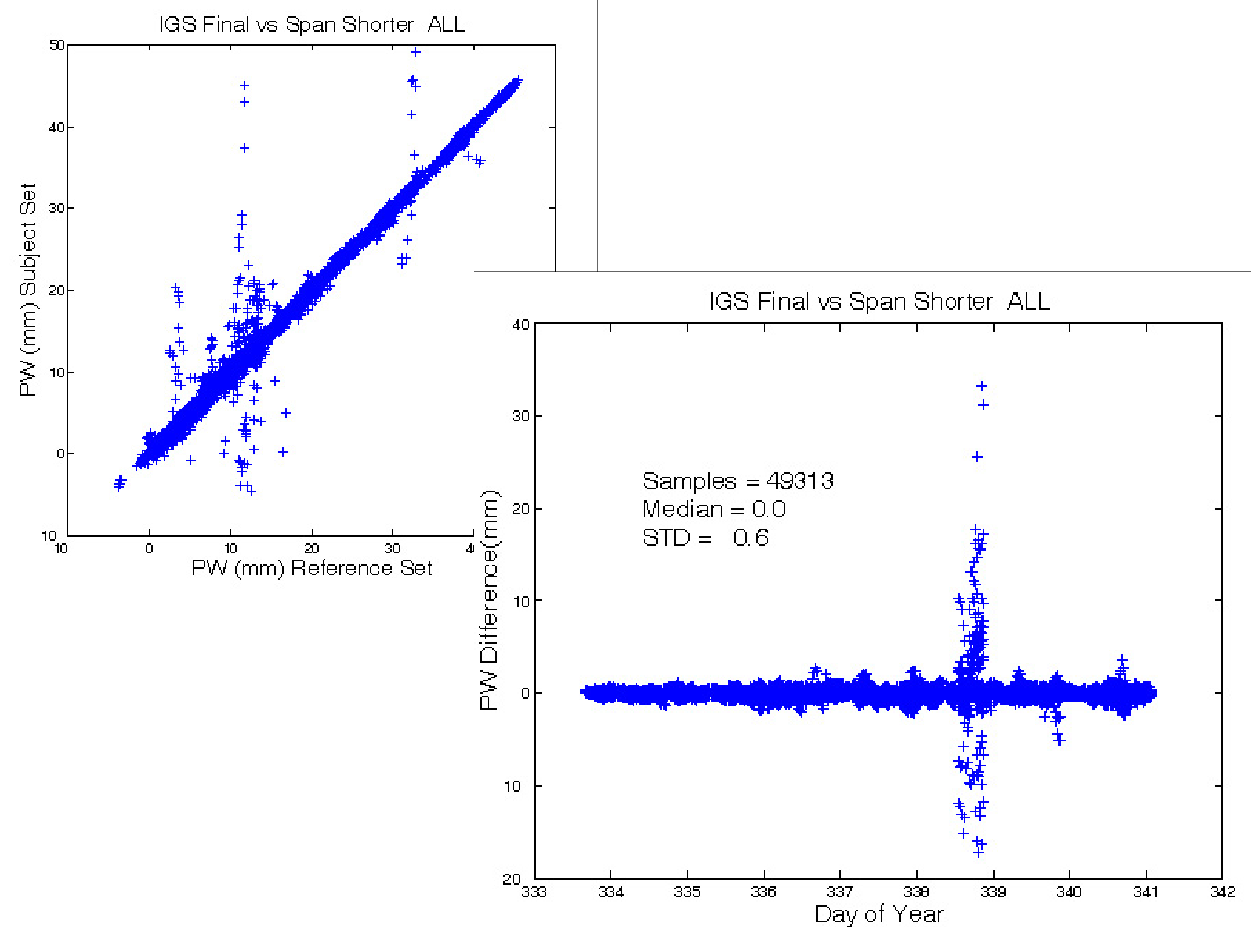
IGS Final vs Fewer PRN ALL
PW (mm) Subject Set
PW (mm) Reference Set



IGS Final vs Fewer PRN ALL
Samples = 49040
Median = 0.1
STD = 0.3
PW Difference(mm)
Day of Year


IGS Final vs Network Gap ALL
PW (mm) Subject Set
PW (mm) Reference Set


IGS Final vs Network Gap ALL
Samples = 47589
Median = 0.0
PW Difference(mm)
Day of Year


IGS Final vs Span Shorter ALL
PW (mm) Subject Set
PW (mm) Reference Set
IGS Final vs Span Shorter ALL
Samples = 49313
Median = 0.0
STD = 0.6
PW Difference(mm)
Day of Year

Solutions to Various Problems

- System redundancy
- Increased session span
- Independent check
- Improvement in QC procedures
- **Reject satellite to be repositioned in advance**
- **Have alternative orbits ready**

NOAA Forecast Systems Laboratory
GPS-Met Observing System
2004 Technical Review

Ongoing Assessment of GPS-IPW Impact on RUC Forecasts

Tracy Lorraine Smith
Forecast Research Division

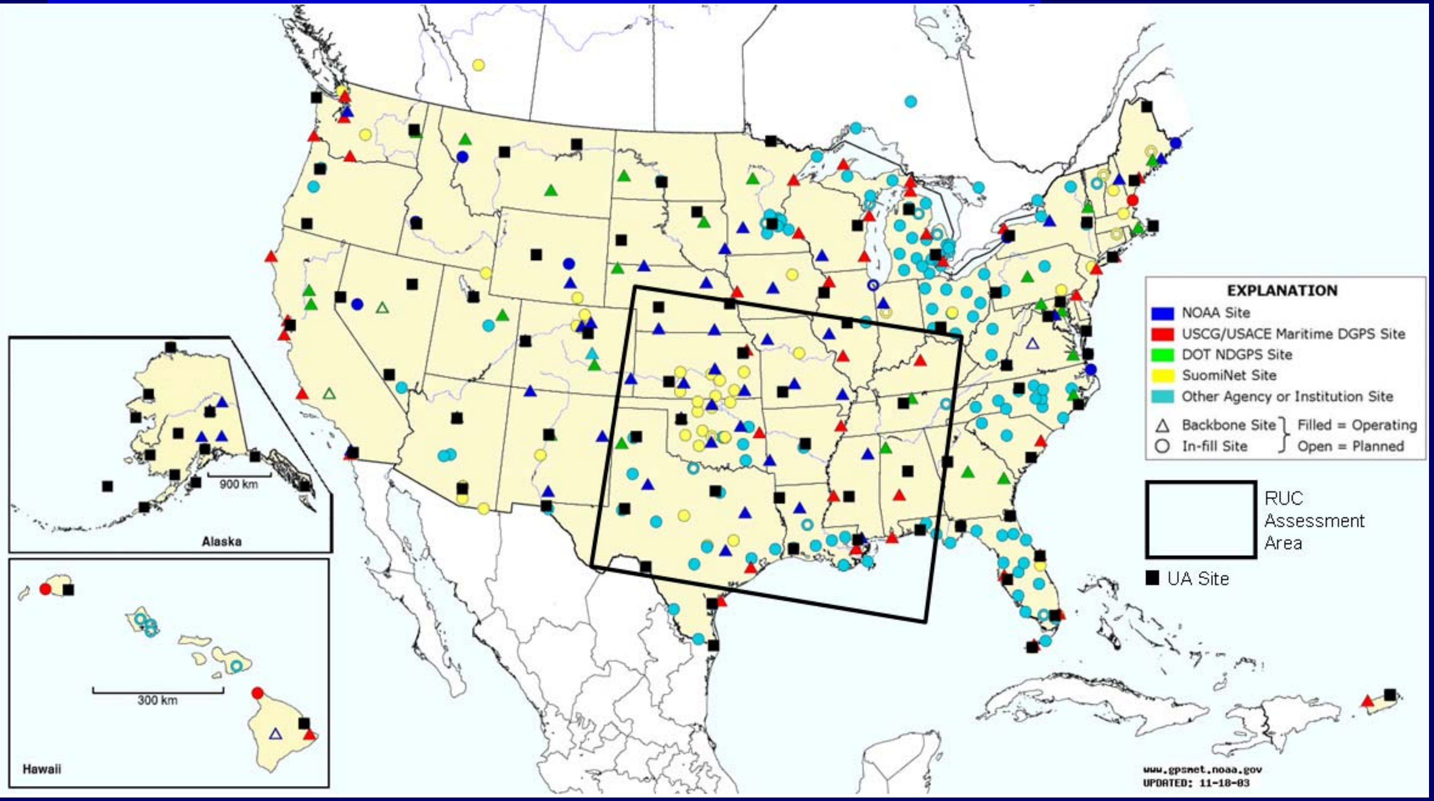
January 27, 2004

RUC experiments for GPS impact

- **60km RUC**
  - 1998 – 2003
  - Ongoing 3h cycles with and without GPS IPW assimilation
- **20km RUC**
  - 5-day experiment – May 2000
  - 15-day experiment- February 2001
  - Ongoing 1h assimilation cycles with and without GPS IPW assimilation, comparisons and statistics available

http://waylon.fsl.noaa.gov/cgi-bin/ruc20/ruc20.cgi

NOAA/FSL GPS network



← 291 stations

http://gpsmet.noaa.gov

Information from
Seth Gutman,
Seth.I.Gutman@noaa.gov

Current accuracy - IPW

- RMS error <1.5 mm
- bias <0.25 mm (positive)

Latency – 18 min, use 'hourly orbit' – from RUC requirement

00-30 min avg, available at +48 min

Hourly Data for RUC60/RUC20

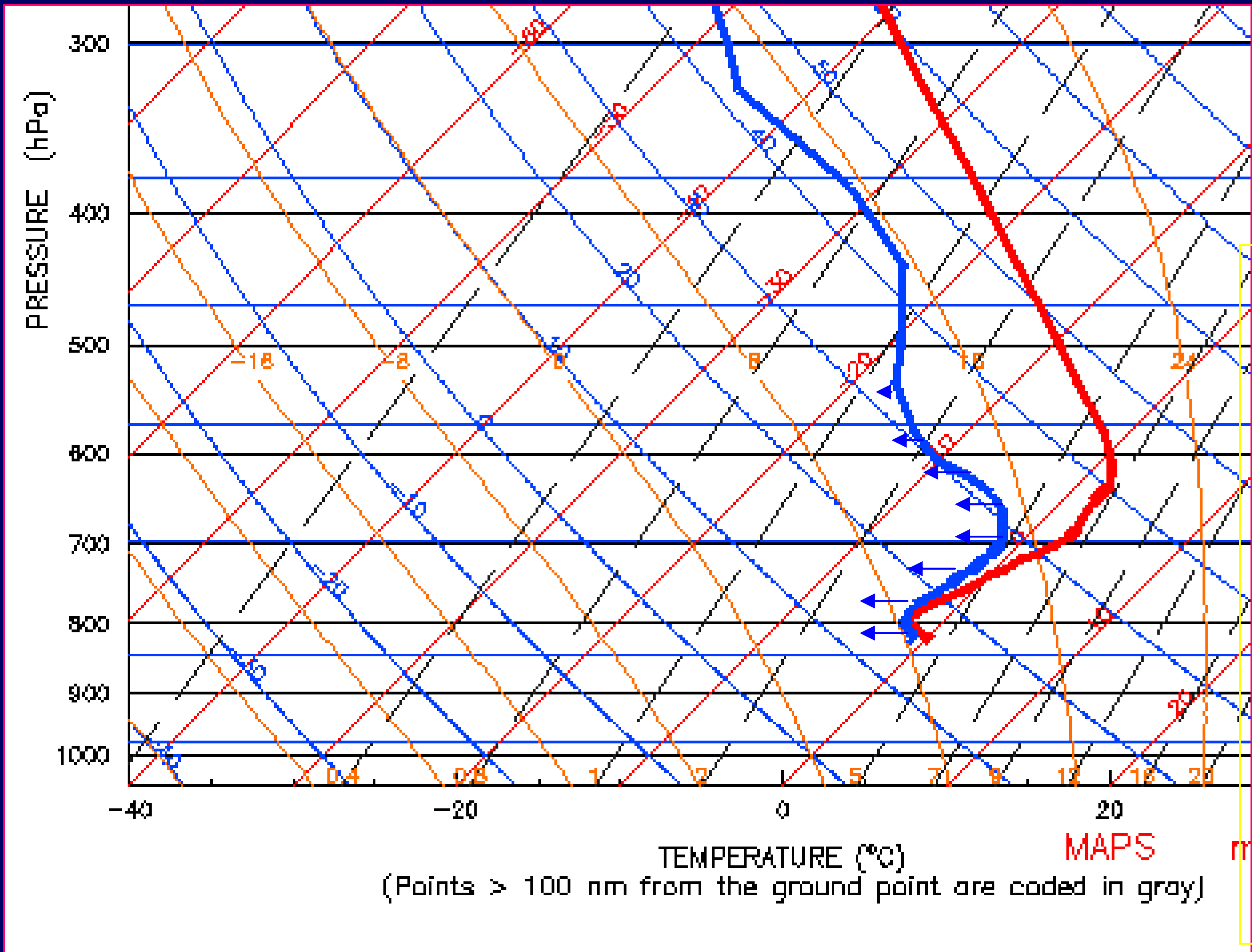
Data Type	~Number	Frequency
Rawinsonde (balloons)	80	/12h
NOAA 404 MHz wind profilers	31	/ 1h
PBL (915 MHz) wind profilers	24	/ 1h
RASS virtual temperatures	10	/ 1h
VAD winds (WSR-88D radars)	110-130	/ 1h
Aircraft (ACARS)	1400-4500	/ 1h
Surface/METAR	1500-1700	/ 1h
Surface/Buoy	100-150	/ 1h
Surface/Mesonet	2500-4000	/ 1h
GOES cloud-drift winds	1000-2500	/ 1h
GOES precipitable water	1500-3000	/ 1h
GPS precipitable water	278	/ 1h
SSM/I precipitable water	1000-4000	/ 6h
GOES cloud-top pressure/temp	10km res	/ 1h
Ship reports/dropsondes	as available	

Much competing data for GPS-IPW over US

Optimal interpolation analysis for precipitable water obs

- 2-d analysis of PW (ob – bkg)
- percentage correction applied to water vapor mixing ratio at all levels

Unavoidable problem – aliasing, esp. vert



PW ob errors

- GPS 1 mm
- GOES 3 mm

1h forecast error

5 mm

RUC20 PW changes

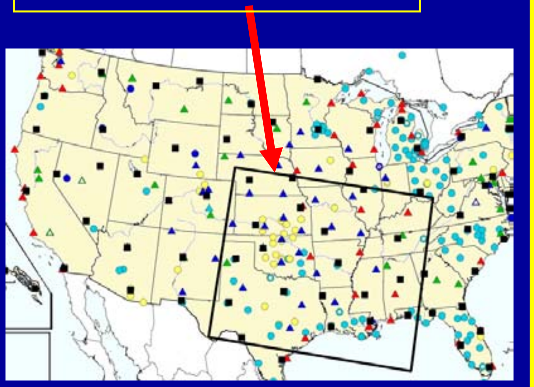
- Account for station vs. model terrain difference
- no change above 500 hPa
- iterated solution w/ PW, cloud, in situ analysis

Conclusions – RUC60 GPS impact tests

Multi-year study with the 60km RUC indicates that GPS-Met makes a small but consistent positive impact on short-term weather forecast accuracy:

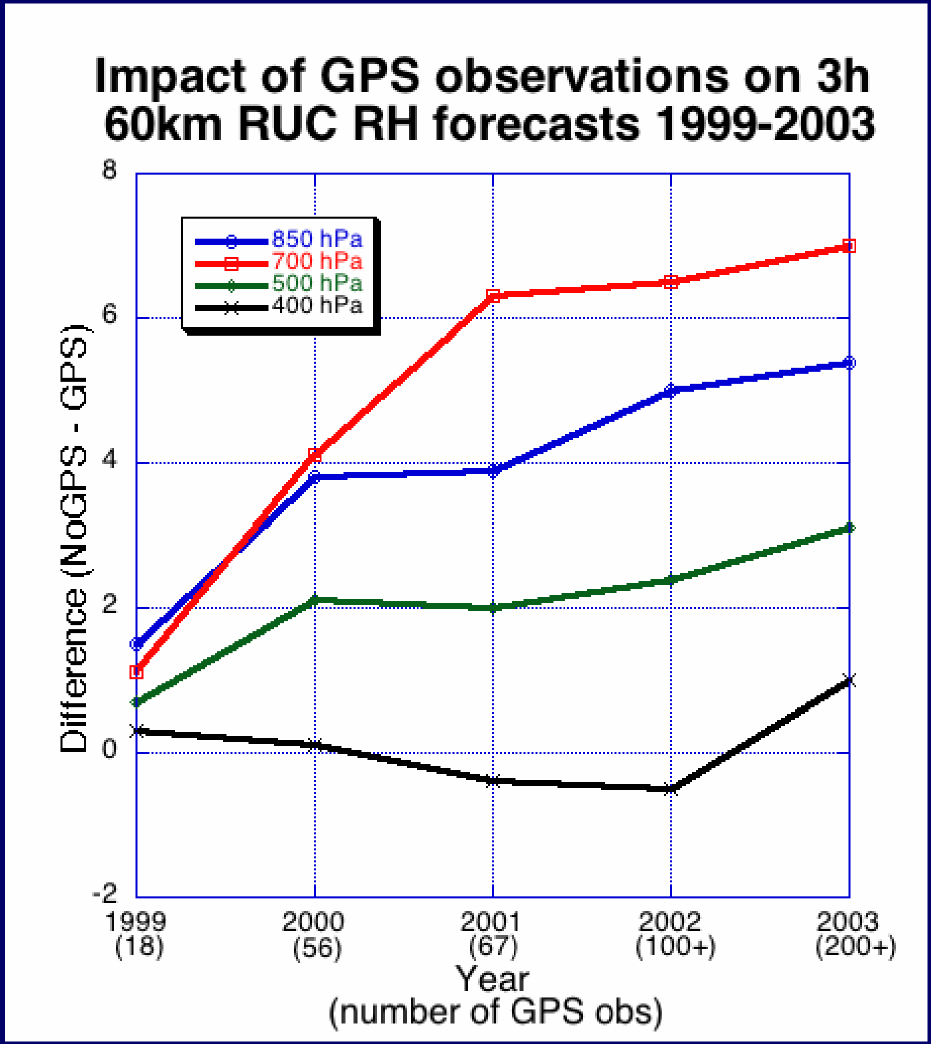
- primarily at the lower levels where most of the moisture resides
  - IPW more correlated w/ *low*-level moisture
- magnitude of impact consistently increases with the number of stations
- RH forecast improvement is greatest in the cool months when convection is less frequent and the moisture distribution is more synoptic scale.
- impact on precipitation forecast accuracy generally increases with precipitation amount threshold

Verification area



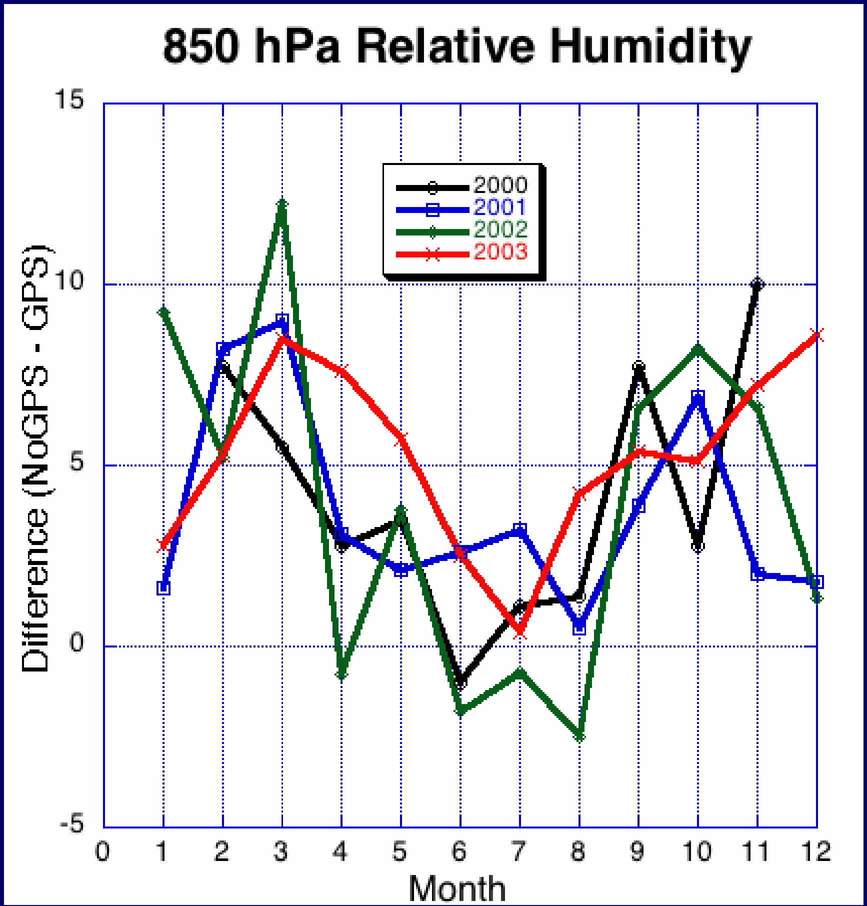
No. Sta	18	56	67	100+	200+
Level	**1998-99**	**2000**	**2001**	**2002**	**2003**
	% improvement (normalized by total error)				
850	1.5	3.8	3.9	5.0	5.4
700	1.1	4.1	6.3	6.5	7.0
500	0.7	2.1	2.0	2.4	3.1
400	0.3	0.1	-0.4	-0.5	1.0
Mean (850-400)	0.9	2.5	2.9	3.3	4.1
Mean (850-500)	1.1	3.3	4.1	4.6	5.2

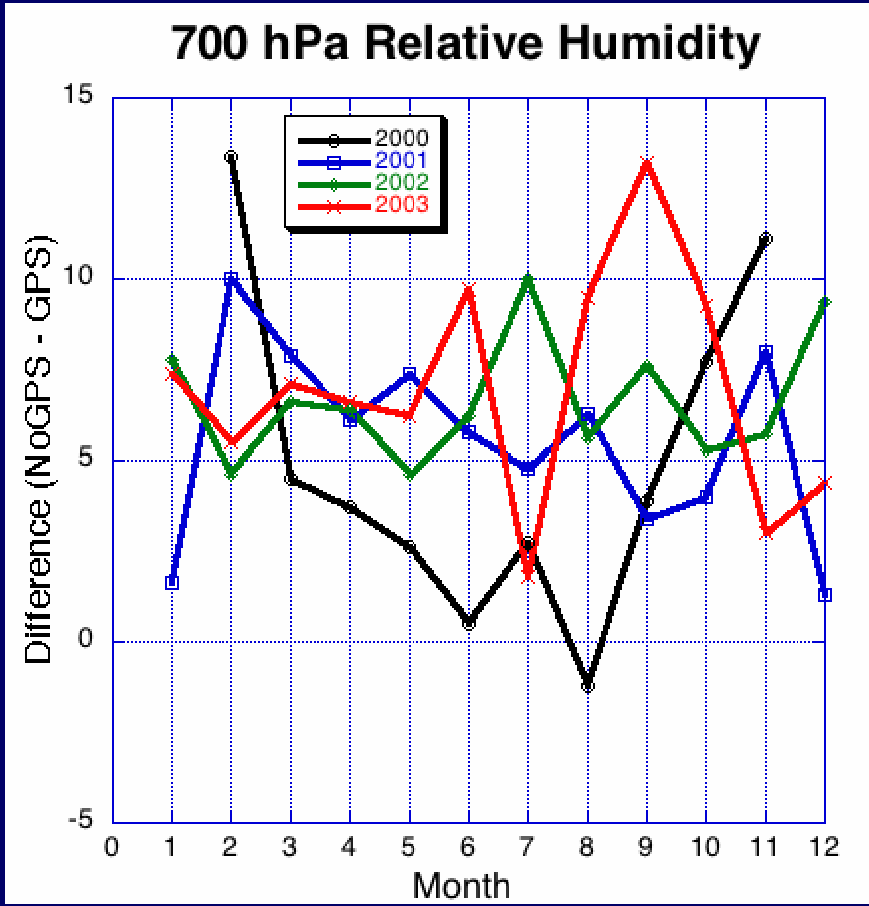
Impact of GPS-IPW increases as the number of GPS observations increase



Largest impact at 700 and 850 hPa, lower troposphere

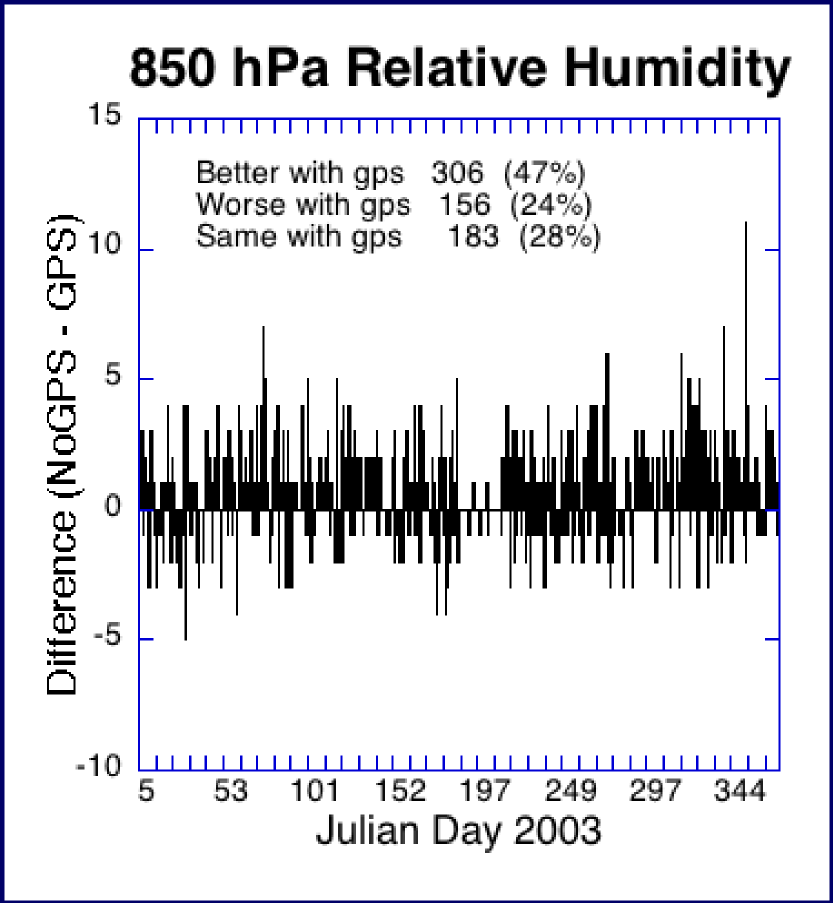
Monthly variation of GPS impact on 3h RH forecasts

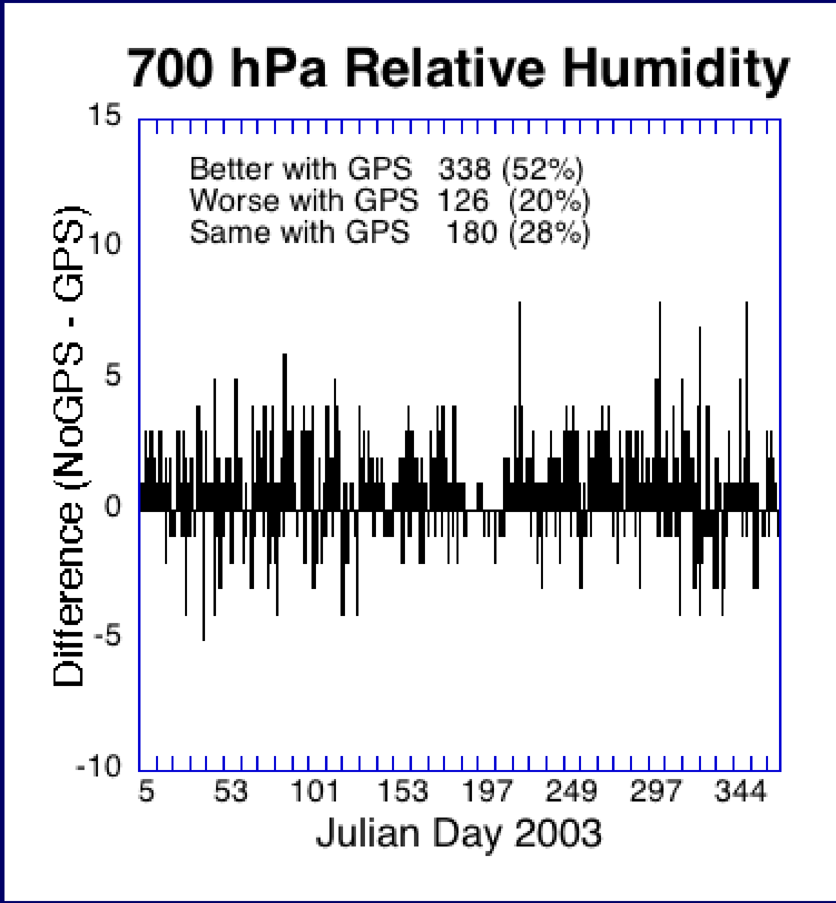




At 850 hPa there is a definite seasonal modality on the magnitude of the impact not seen at 700 hPa

Impact of GPS on 3h RH forecasts verified against RAOBS at 00 and 12 UTC 01 Jan 03 - 31 Dec 03





Run by run verification shows impact can vary widely.
Impact is greatly affected by weather regime.

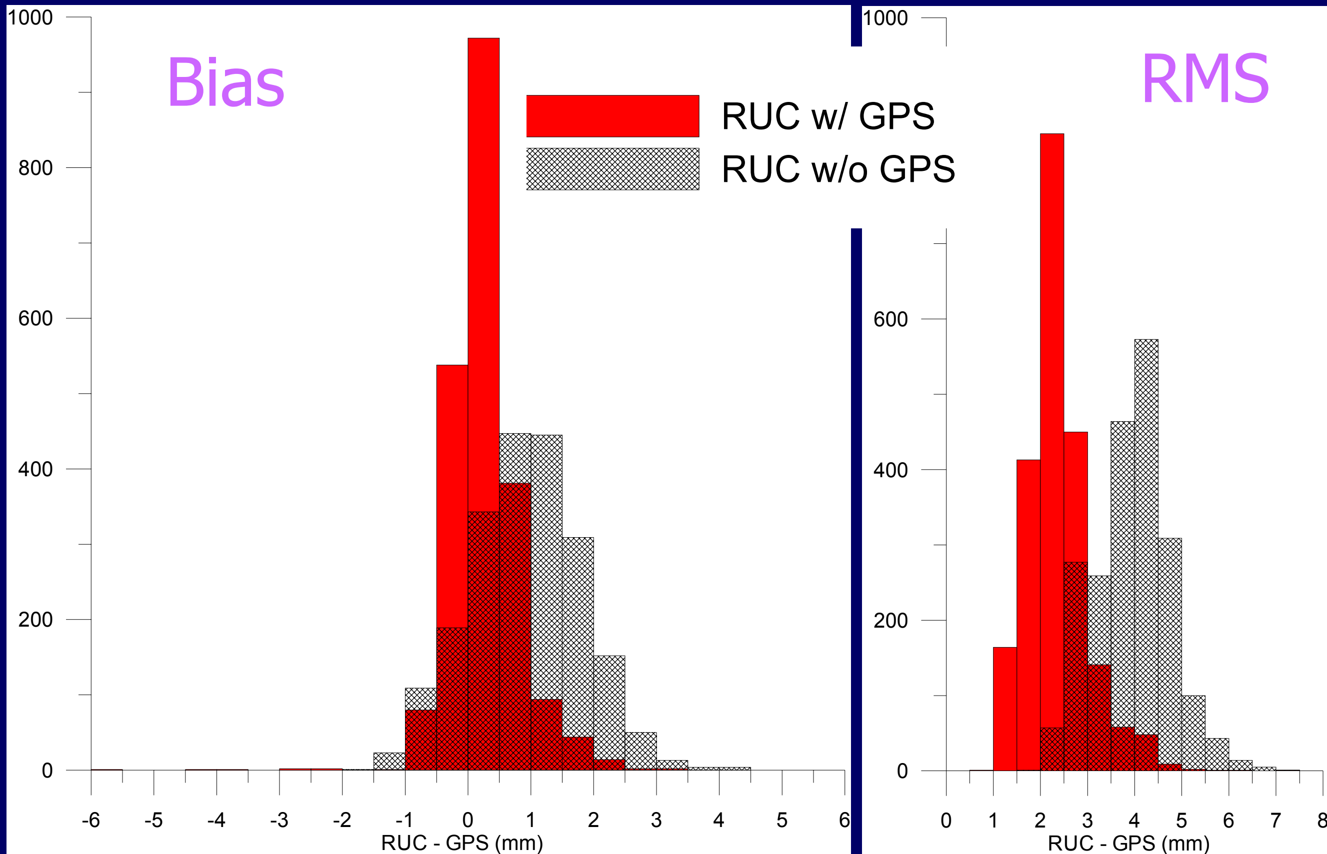
RUC experiments for GPS impact

– **60km RUC**
  - 1998 – 2003
  - Ongoing 3h cycles with and without GPS IPW assimilation

– **20km RUC**
  - 5-day experiment – May 2000
  - 15-day experiment- February 2001
  - Ongoing 1h assimilation cycles with and without GPS IPW assimilation, comparisons and statistics available

http://waylon.fsl.noaa.gov/cgi-bin/ruc20/ruc20.cgi

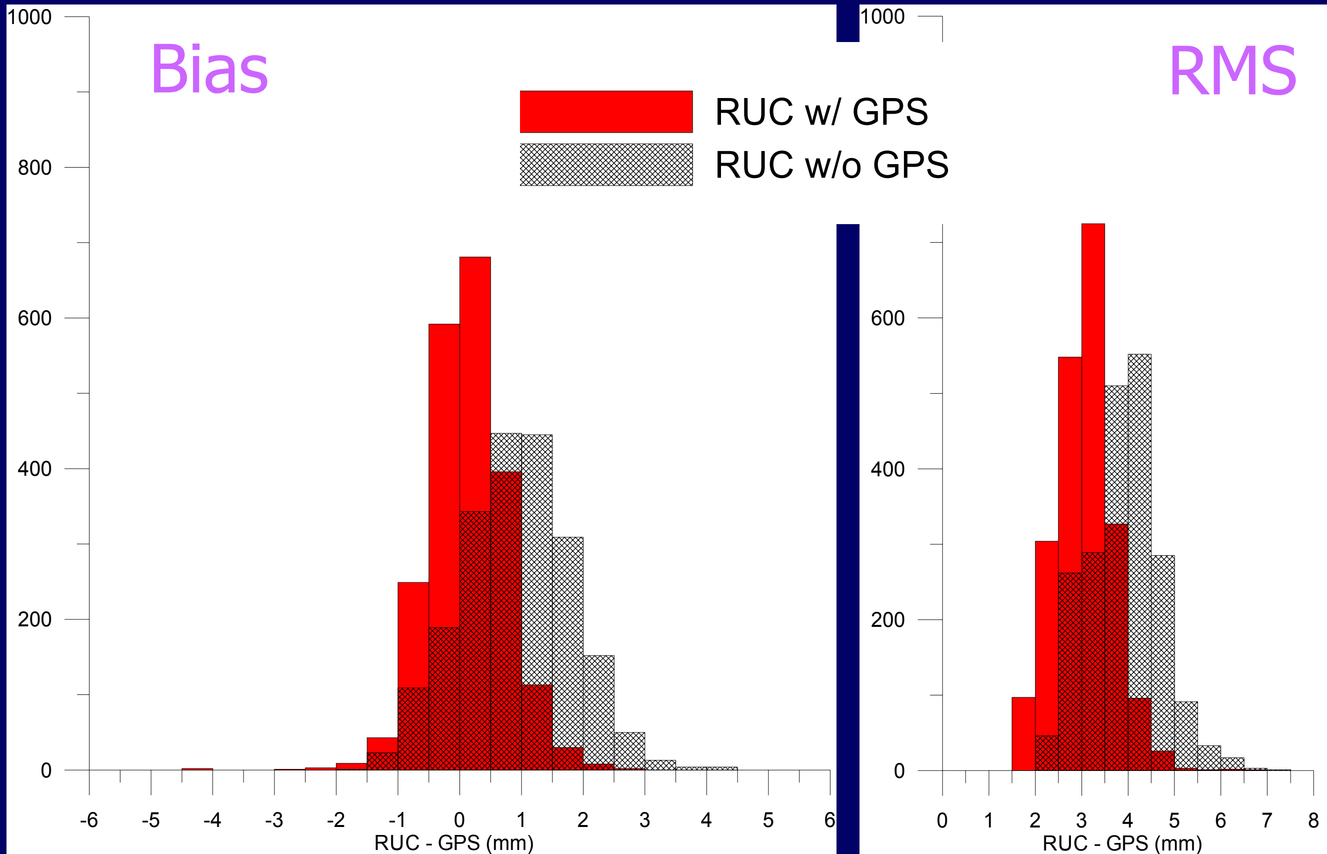
IPW differences between 20km RUC **analyses** and GPS-IPW obs at ~225 sites for 25 Jul - 22 Oct 2003



With GPS	RUC-GPS	RMS
Number	2135	2135
Mean (mm)	0.25	2.36

Without GPS	RUC-GPS	RMS
Number	2103	2103
Mean (mm)	1.16	3.94

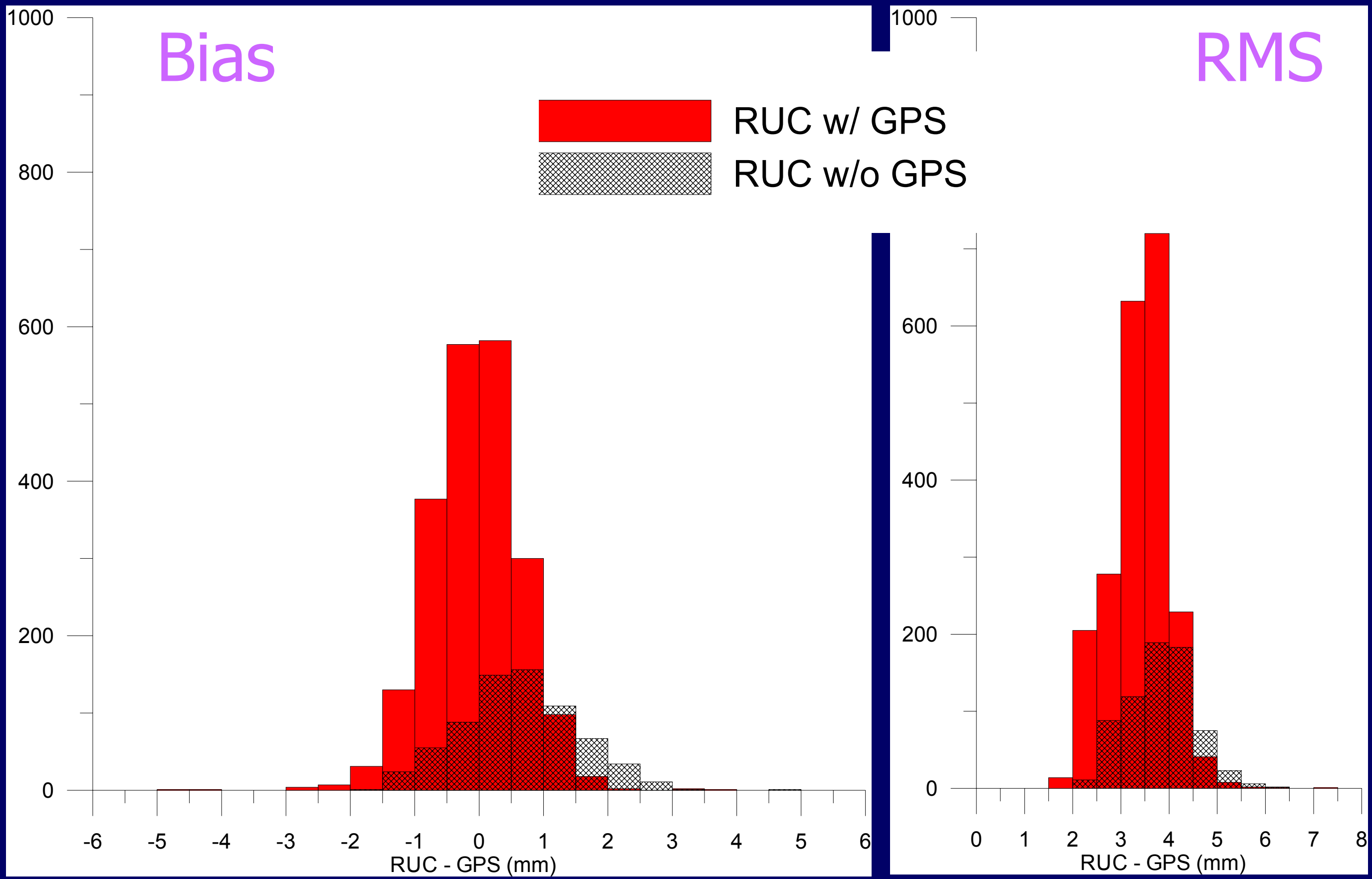
IPW differences between 20km RUC **3h forecasts** and GPS-IPW obs at ~225 sites for 25 Jul - 22 Oct 2003



With GPS	RUC-GPS	RMS
Number	2131	2131
Mean (mm)	0.13	3.07

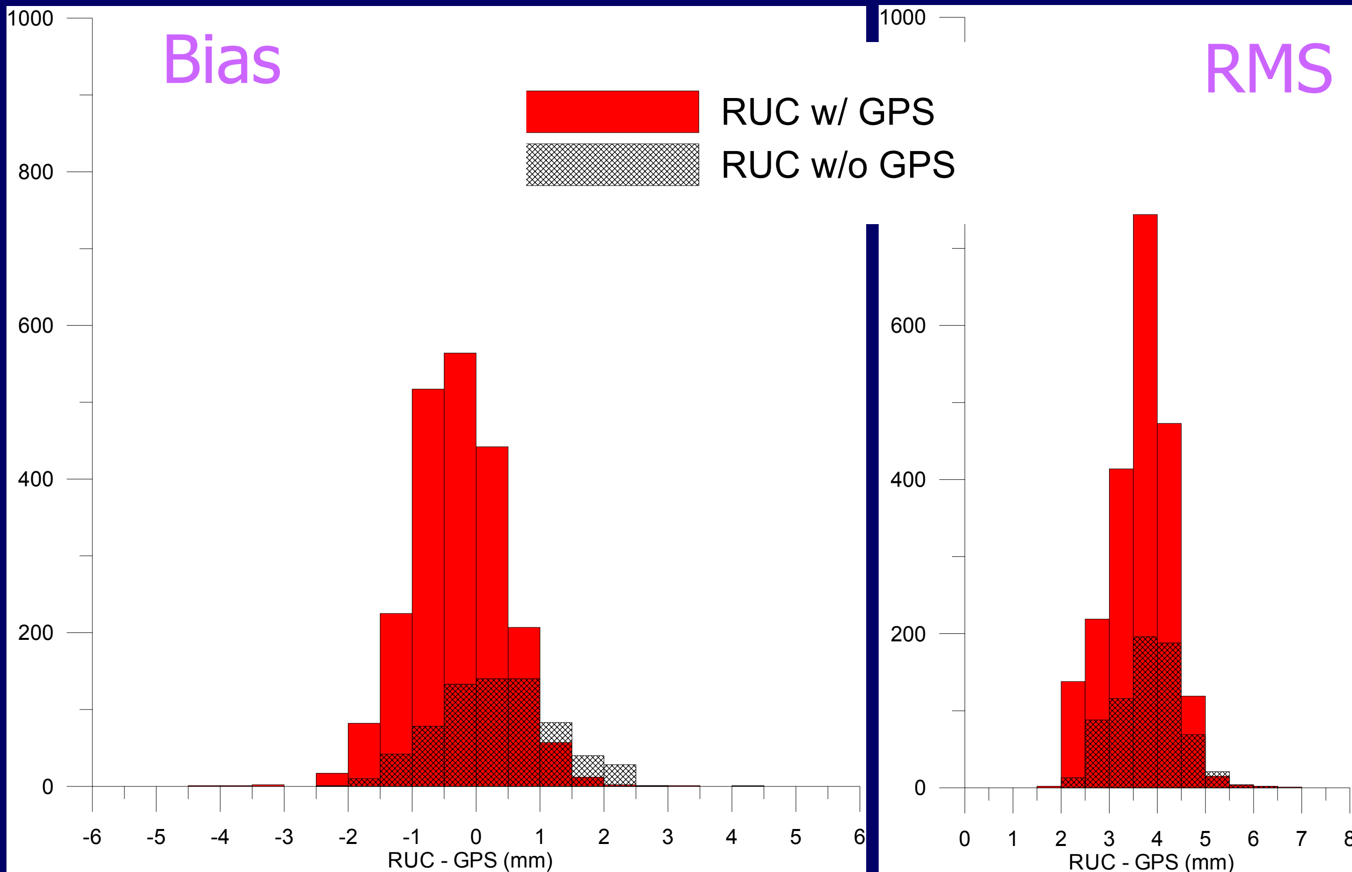
Without GPS	RUC-GPS	RMS
Number	2131	2089
Mean (mm)	3.07	3.92

IPW differences between 20km RUC **6h forecasts** and GPS-IPW obs at ~225 sites for 25 Jul - 22 Oct 2003



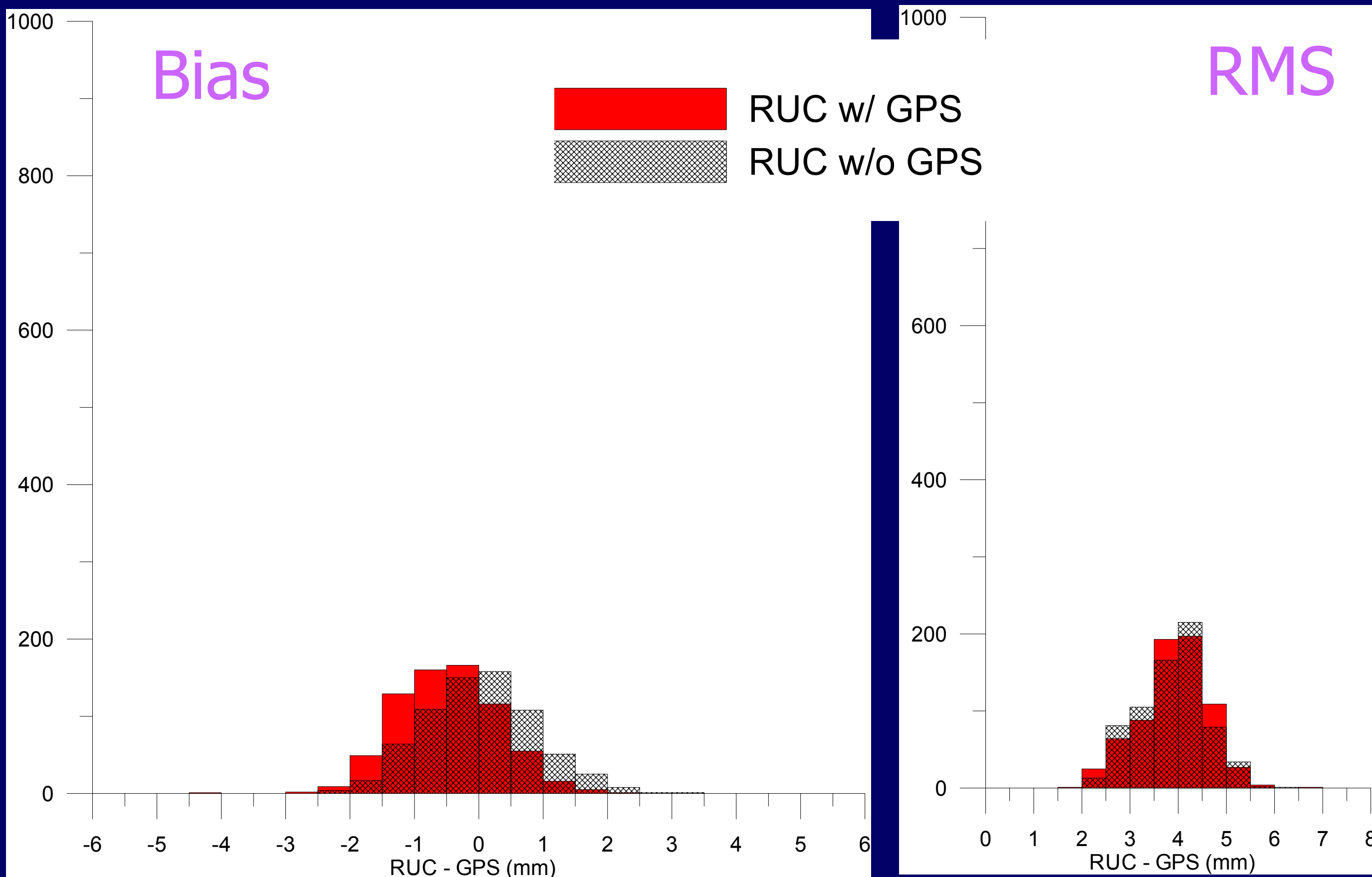
With GPS	RUC-GPS	RMS	**Without GPS**	RUC-GPS	RMS
Number	2131	2131	Number	696	696
Mean (mm)	-0.06	3.40	Mean (mm)	0.62	3.84

IPW differences between 20km RUC **9h forecasts** and GPS-IPW obs at ~225 sites for 25 Jul - 22 Oct 2003



With GPS	RUC-GPS	RMS	**Without GPS**	RUC-GPS	RMS
Number	2131	2131	Number	697	697
Mean (mm)	-0.30	3.65	Mean (mm)	0.33	3.82

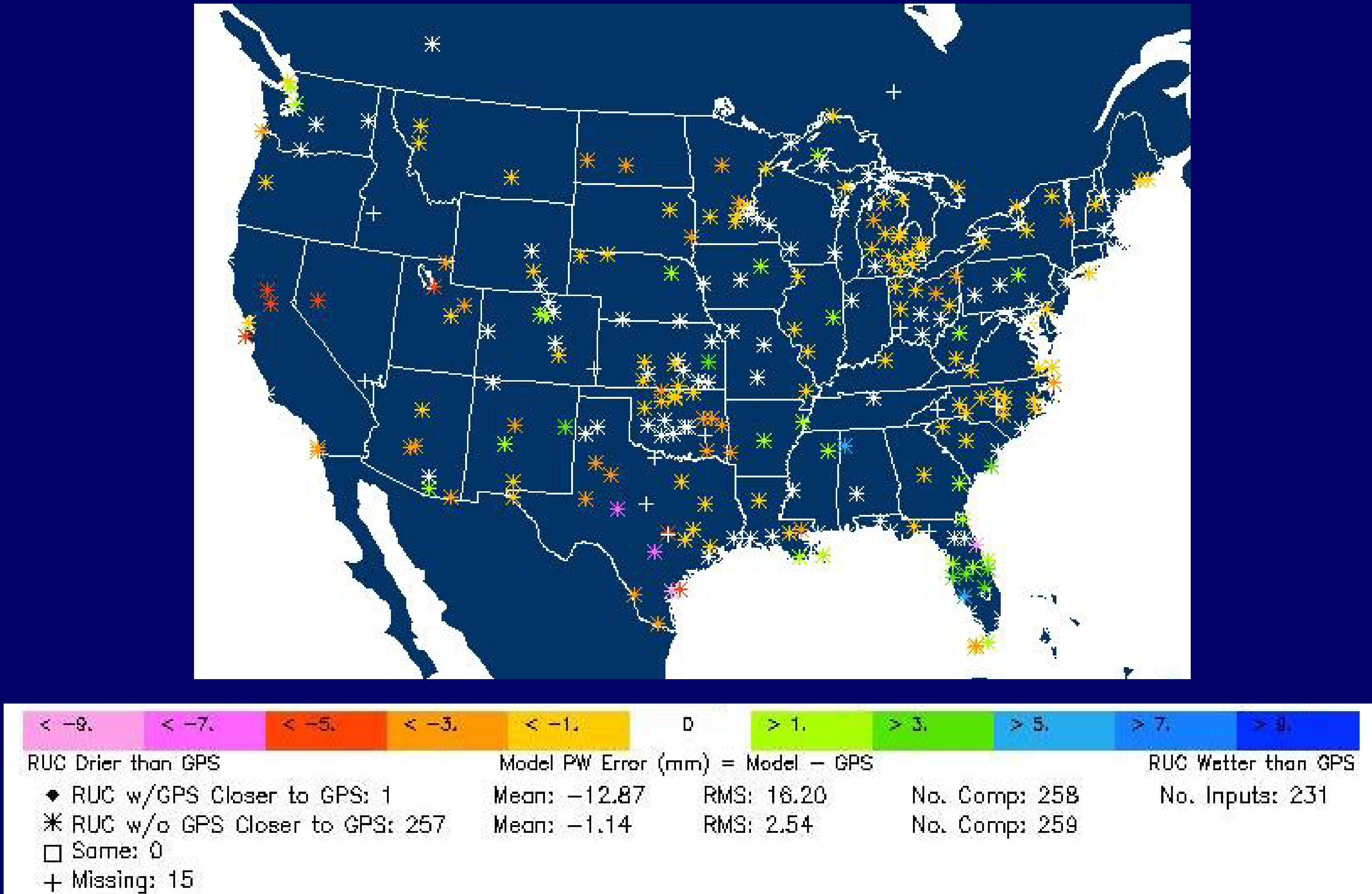
IPW differences between 20km RUC **12h forecasts** and GPS-IPW obs at ~225 sites for 25 Jul - 22 Oct 2003



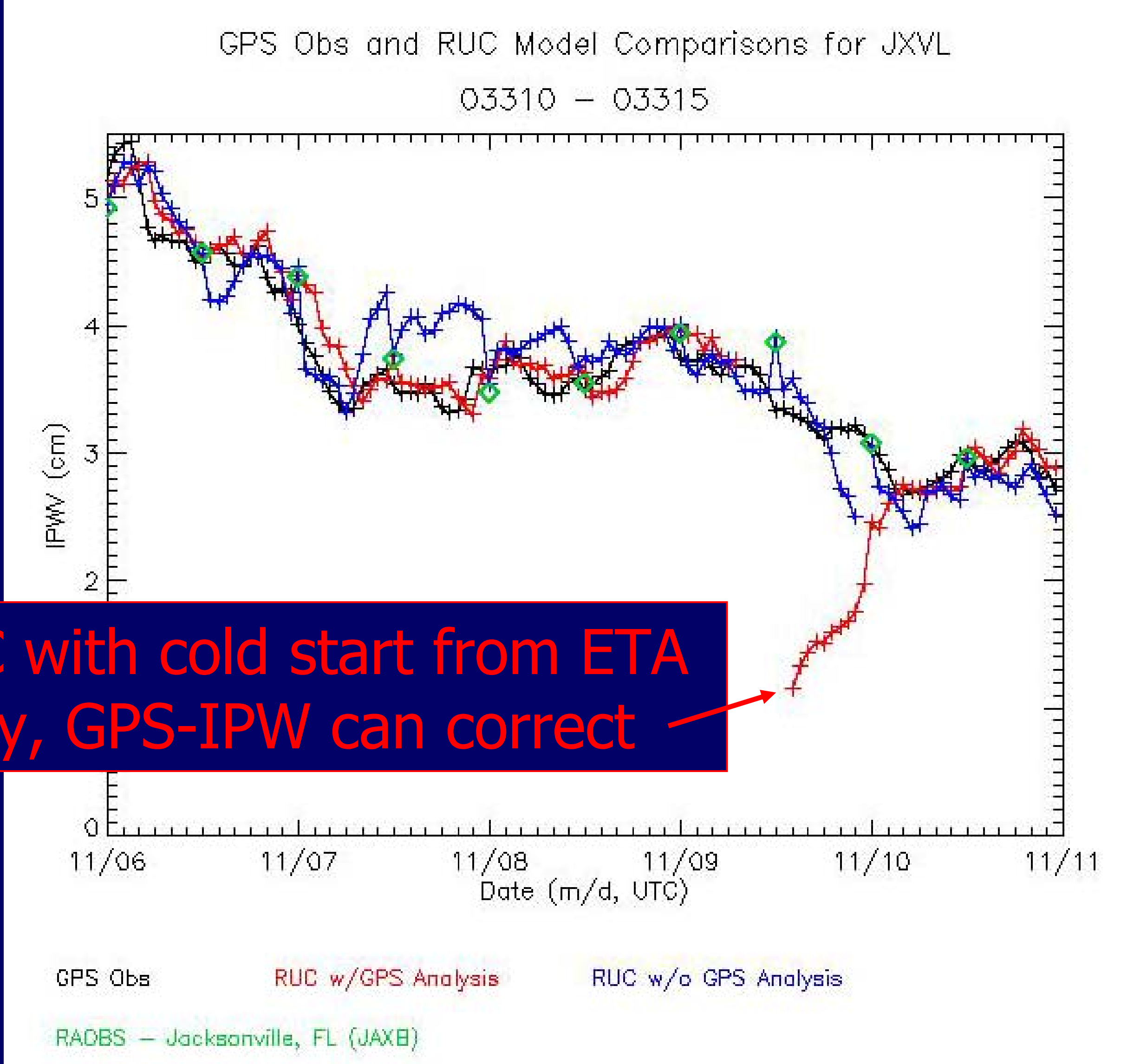
With GPS	RUC-GPS	RMS
Number	709	709
Mean (mm)	-0.48	3.91

Without GPS	RUC-GPS	RMS
Number	696	696
Mean (mm)	0.03	3.89

Difference RUC20 analysis with GPS minus RUC20 without GPS 9 Nov 2003 1500 UTC

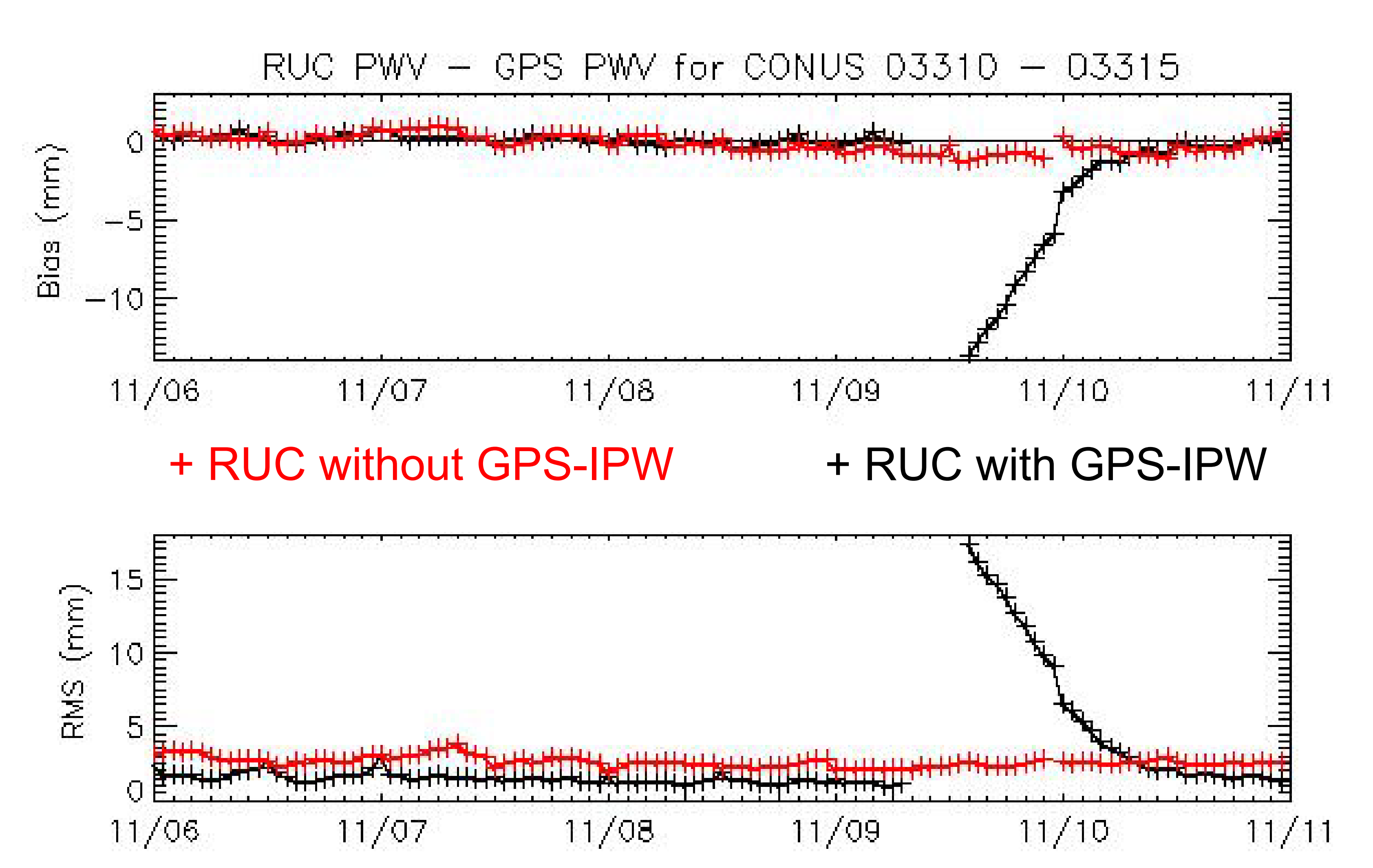


Time series of RUC IPW, GPS IPW, and RAOB IPW at Jacksonville, FL for 6 - 11 November 2003



FSL RUC with cold start from ETA is too dry, GPS-IPW can correct

Bias and RMS for 20km RUC with and without GPS-IPW for 6-11 Nov 2003



Cold start for FSL RUC with GPS, GPS-IPW helps RUC to recover from dry bias, high RMS error 9 hrs before RAOBs

Conclusions from RUC20 GPS impact studies

- Impact on 3h RH forecasts similar to that from RUC60
- IPW forecast improvement evident out to 9 h
- Interactive, ongoing assessment of GPS impact is enhanced by the GPS/model comparison webpage

Future

Multi-week RUC20 retrospective impact tests

Assimilation into operational RUC20 at NCEP

http://ruc.fsl.noaa.gov

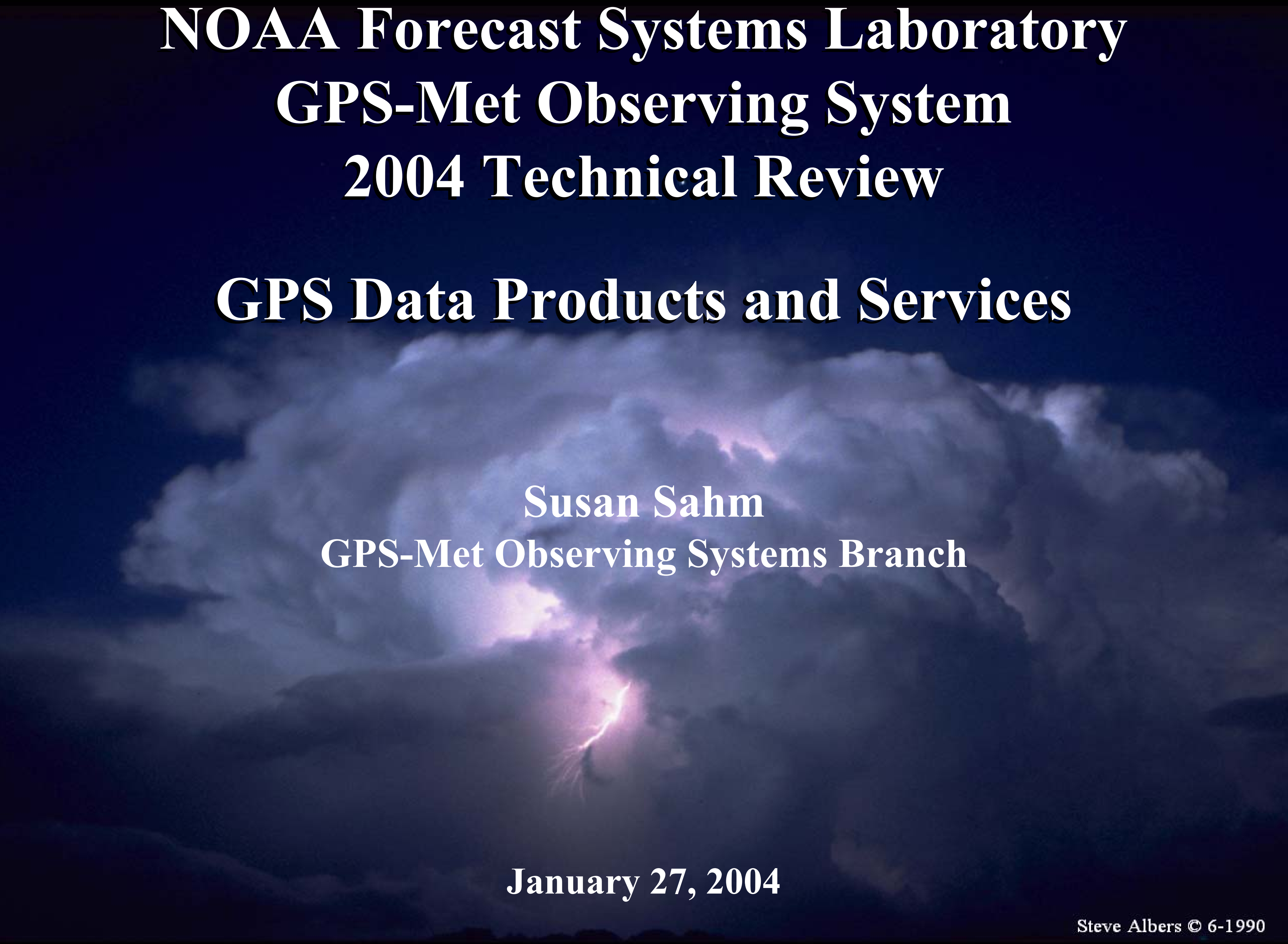
All FSL RUC forecasts (out to 48h) initialized with GPS-IPW

NOAA Forecast Systems Laboratory
GPS-Met Observing System
2004 Technical Review

GPS Data Products and Services

Susan Sahm
GPS-Met Observing Systems Branch

January 27, 2004



Steve Albers © 6-1990

New GPS-Met Products & Services

- In collaboration with FSL/FRD*, we developed a web-based tool to assist modelers and researchers to compare and evaluate IPW derived from GPS, rawinsondes, and NWP models.

- In response to a request from Ryan Jewell, a forecaster at the Storm Prediction Center (SPC) in Norman, OK, we can now produce experimental 1-h, 2-h, and 3-h precipitable water vapor-change products every hour.

- With modest funding from the Interagency GPS Executive Board (IGEB),** we evaluated the feasibility of using NWP models to produce tropospheric signal delay correctors for high accuracy NDGPS positioning and navigation.

* Our thanks to Stan Benjamin, Tracy Smith, Kevin Brundage, and Bill Moninger

** Our thanks to Jim Arnold - FHWA Technical Point of Contact

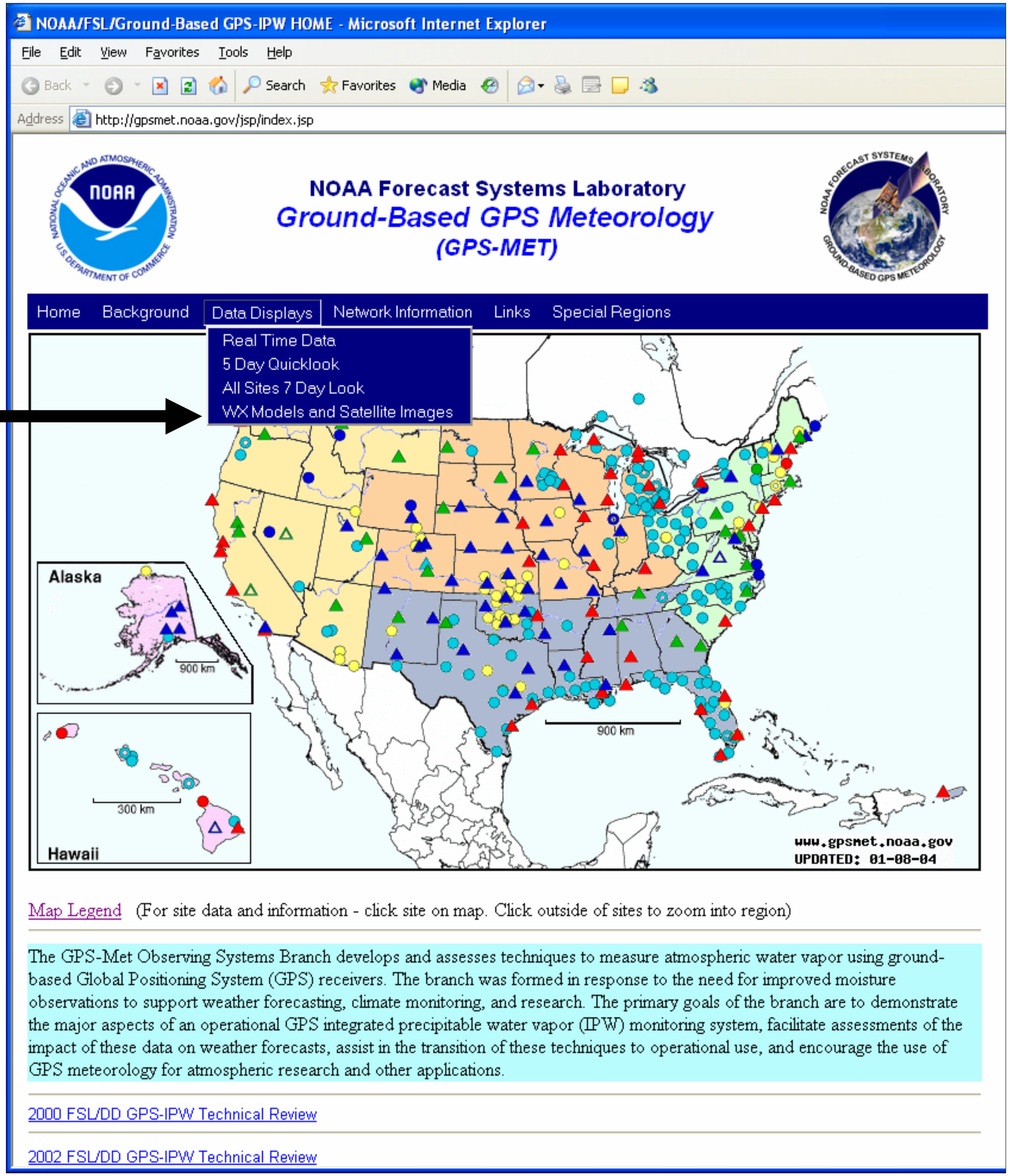
New GPS-Met Products & Services

- We have received many requests from WFOs to make some of the GPS-Met web displays available on AWIPS workstations.
  - We are collaborating with FSL/SDD* and the SOOs at several WFOs to prototype D2D applications using existing depictables.
  - We are working with NWS and SDD to include many of these capabilities in the next AWIPS build along with the new wind profiler and RASS products.
  - On 01/07/04, David Helms (OST Science Plans Branch) recommended GPS-IPW displays be included in AWIPS OB5.

*Thanks to Herb Grote, Susan Williams, and Patty Miller

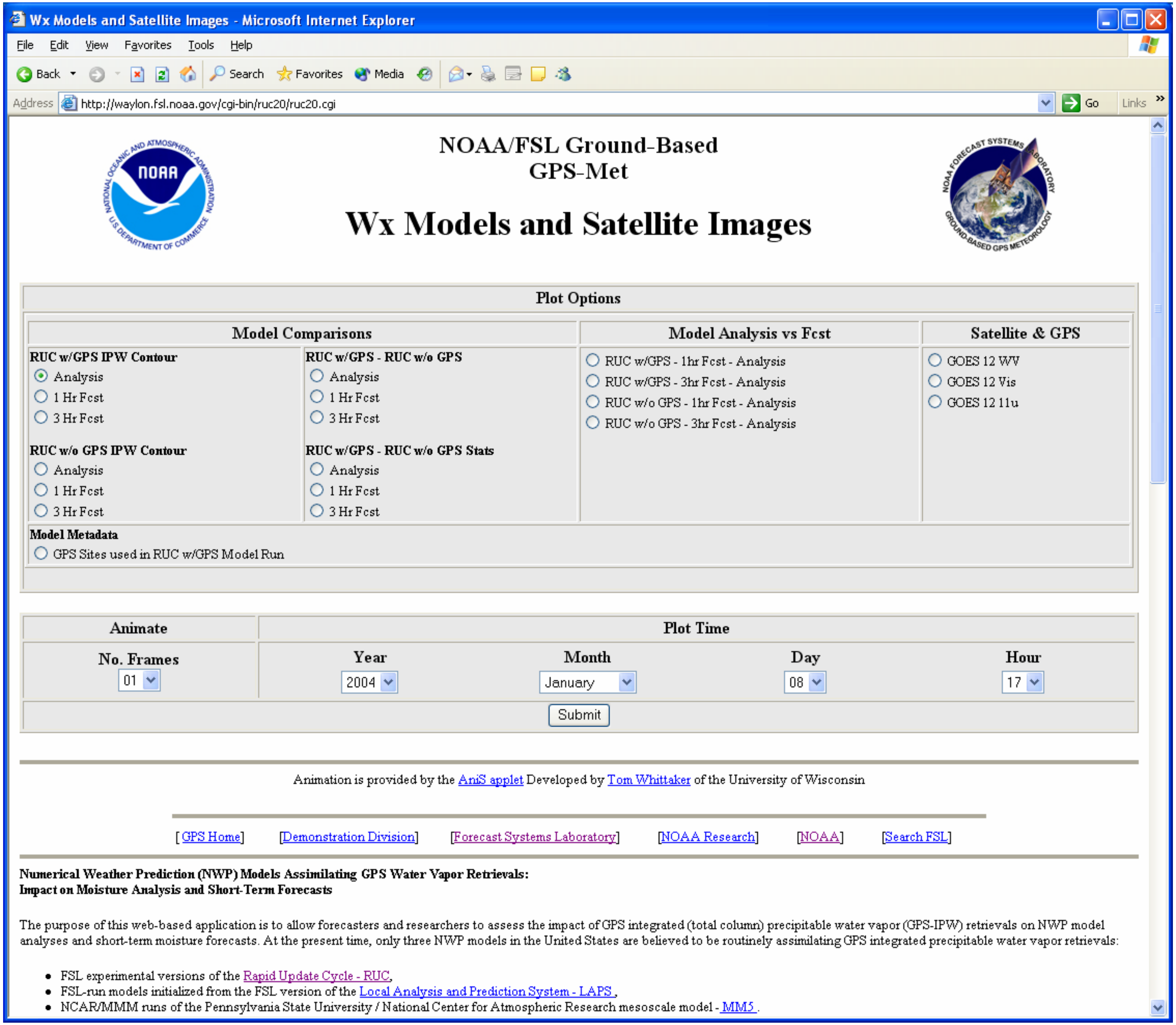
Wx Models & Satellite Images Web Site

http://gpsmet.noaa.gov



Wx Models & Satellite Images Web Site

FORECAST SYSTEMS LABORATORY
BOULDER, COLORADO



Wx Models and Satellite Images - Microsoft Internet Explorer

File Edit View Favorites Tools Help

Back Search Favorites Media

Address http://waylon.fsl.noaa.gov/cgi-bin/ruc20/ruc20.cgi Go Links

NOAA/FSL Ground-Based
GPS-Met

Wx Models and Satellite Images

Plot Options			
Model Comparisons		Model Analysis vs Fcst	Satellite & GPS
RUC w/GPS IPW Contour Analysis 1 Hr Fcst 3 Hr Fcst	**RUC w/GPS - RUC w/o GPS** Analysis 1 Hr Fcst 3 Hr Fcst	RUC w/GPS - 1hr Fcst - Analysis RUC w/GPS - 3hr Fcst - Analysis RUC w/o GPS - 1hr Fcst - Analysis RUC w/o GPS - 3hr Fcst - Analysis	GOES 12 WV GOES 12 Vis GOES 12 11u
RUC w/o GPS IPW Contour Analysis 1 Hr Fcst 3 Hr Fcst	**RUC w/GPS - RUC w/o GPS Stats** Analysis 1 Hr Fcst 3 Hr Fcst		
Model Metadata GPS Sites used in RUC w/GPS Model Run			

Animate	Plot Time			
No. Frames	Year	Month	Day	Hour
01	2004	January	08	17

Submit

Animation is provided by the AniS applet Developed by Tom Whittaker of the University of Wisconsin

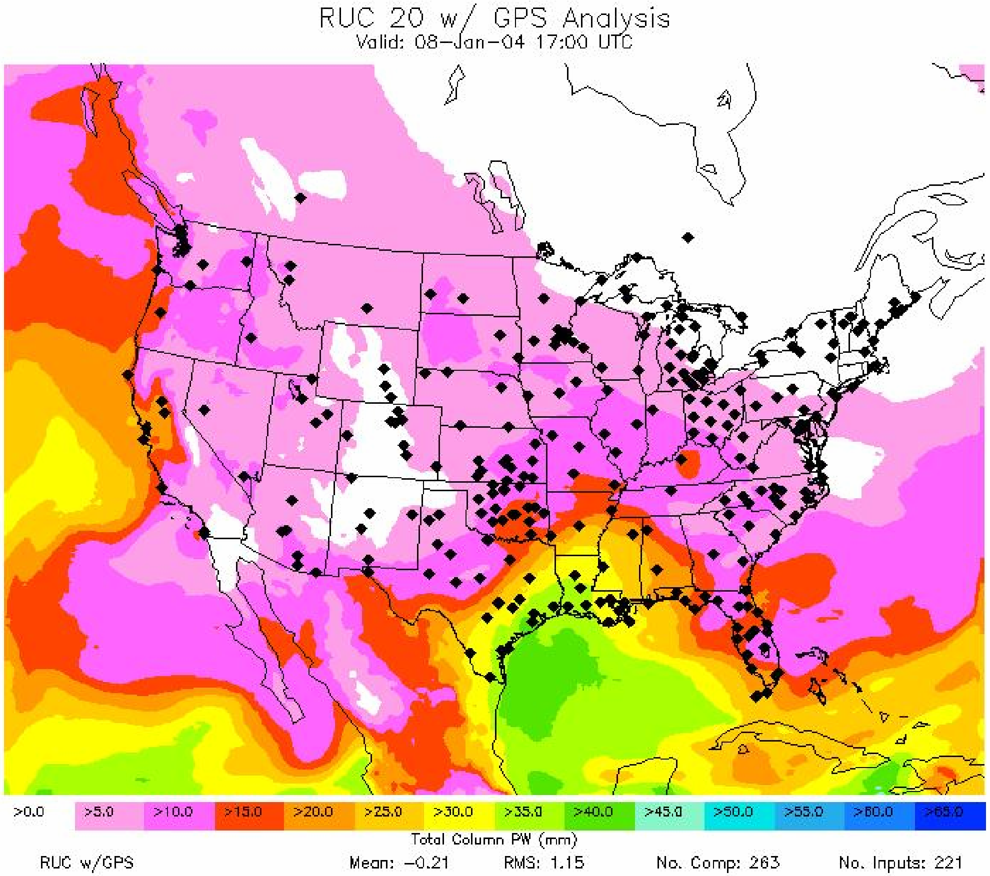
[GPS Home] [Demonstration Division] [Forecast Systems Laboratory] [NOAA Research] [NOAA] [Search FSL]

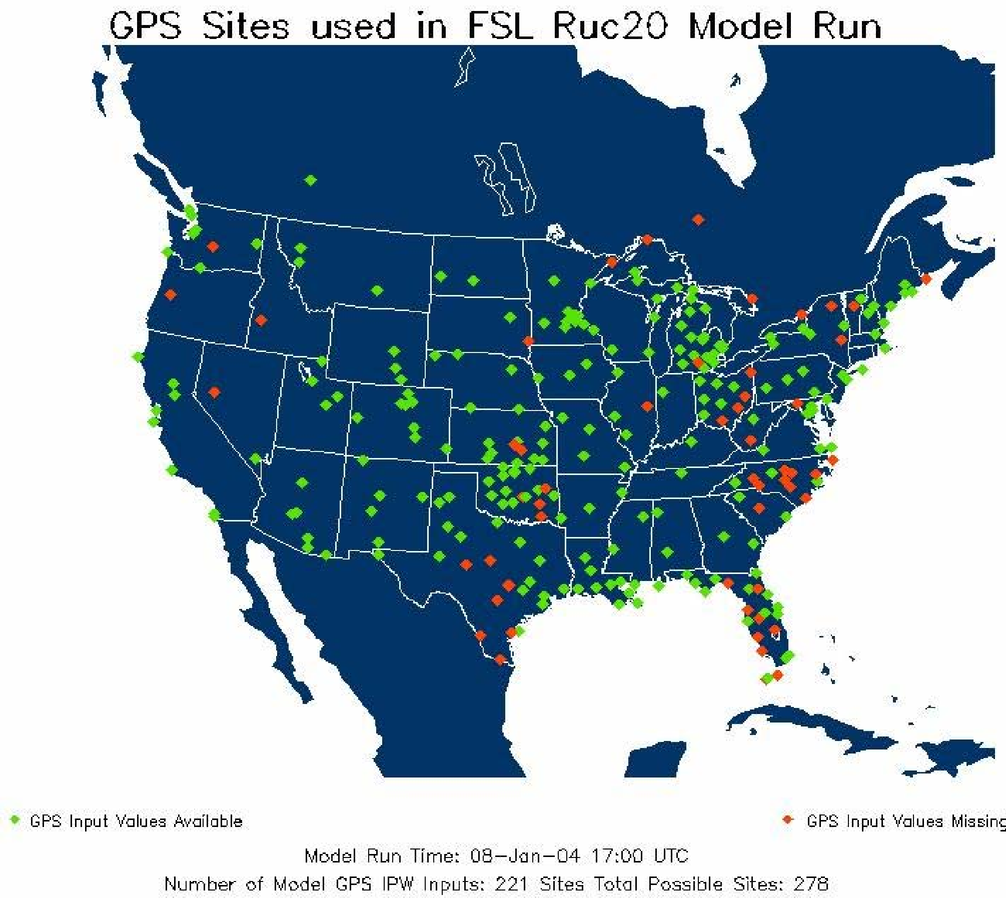
Numerical Weather Prediction (NWP) Models Assimilating GPS Water Vapor Retrievals:
Impact on Moisture Analysis and Short-Term Forecasts

The purpose of this web-based application is to allow forecasters and researchers to assess the impact of GPS integrated (total column) precipitable water vapor (GPS-IPW) retrievals on NWP model analyses and short-term moisture forecasts. At the present time, only three NWP models in the United States are believed to be routinely assimilating GPS integrated precipitable water vapor retrievals:

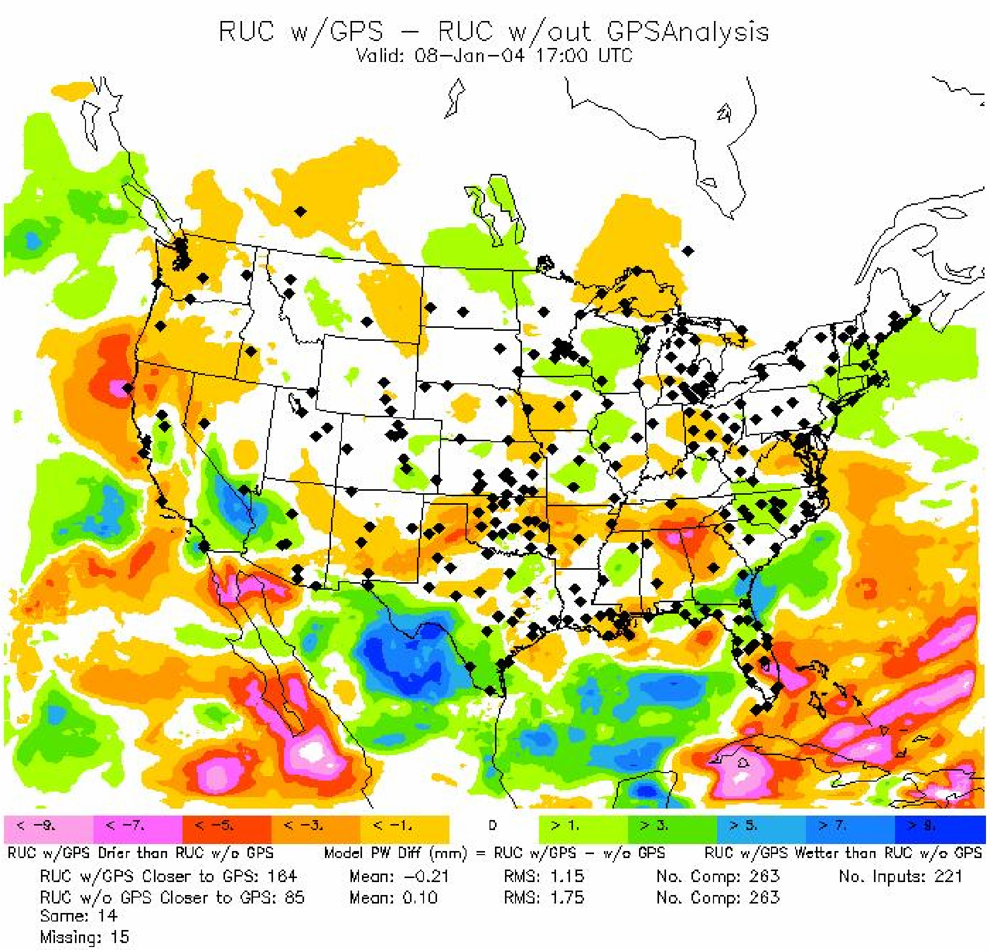
- FSL experimental versions of the Rapid Update Cycle - RUC,
- FSL-run models initialized from the FSL version of the Local Analysis and Prediction System - LAPS ,
- NCAR/MMM runs of the Pennsylvania State University / National Center for Atmospheric Research mesoscale model - MM5 .

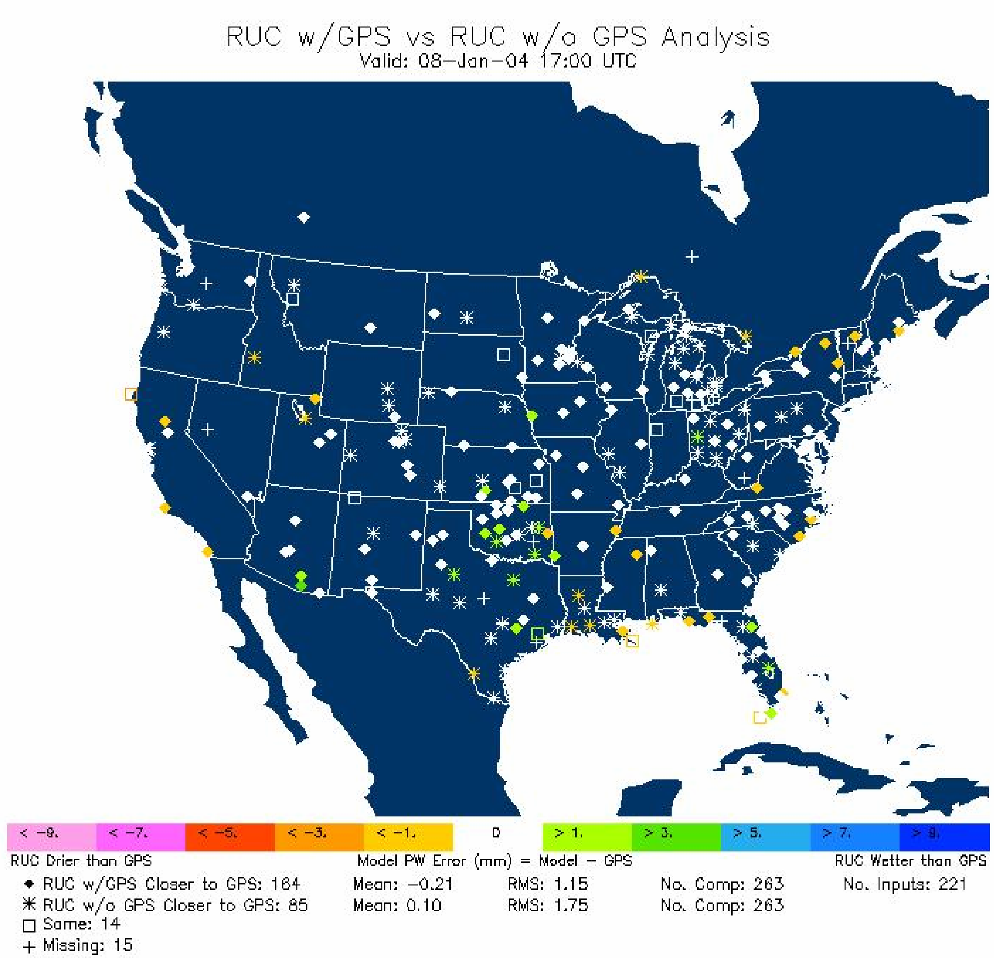
Wx Models & Satellite Images Web Site



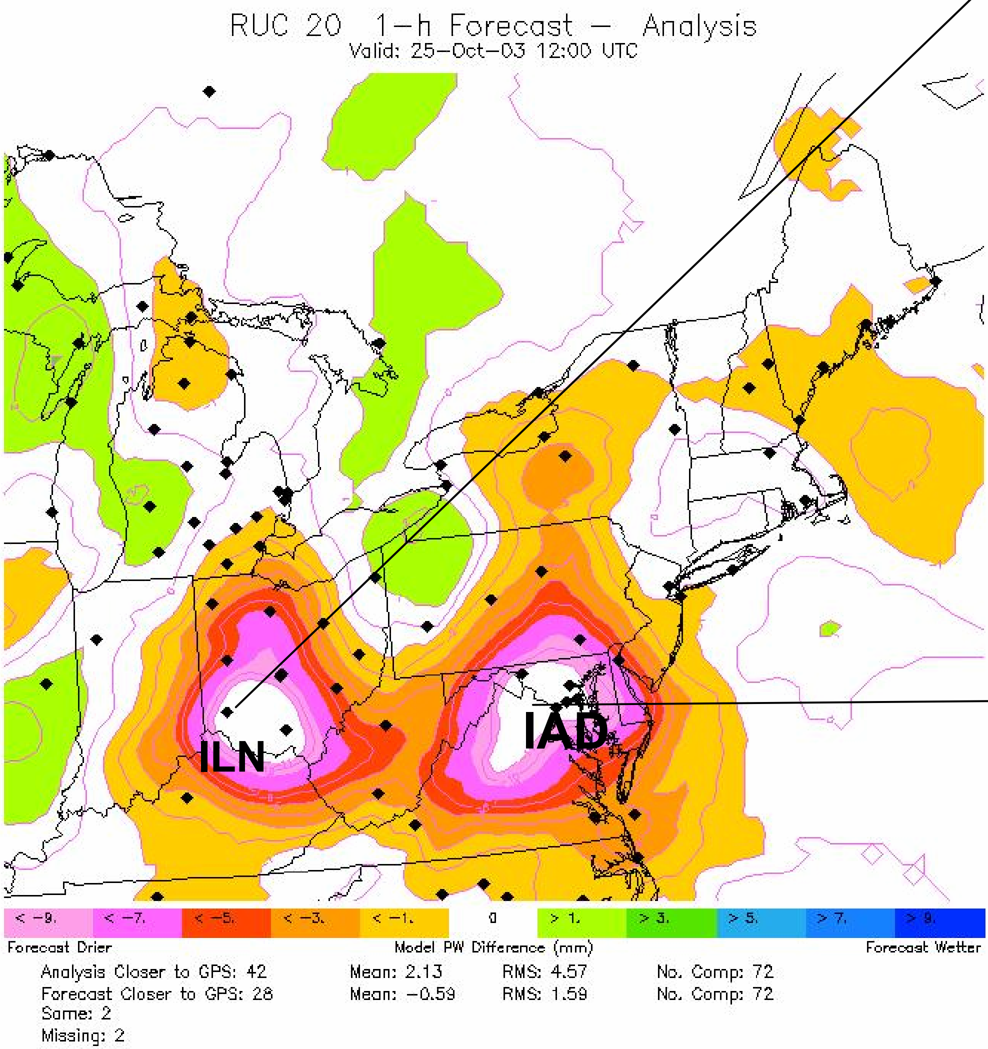


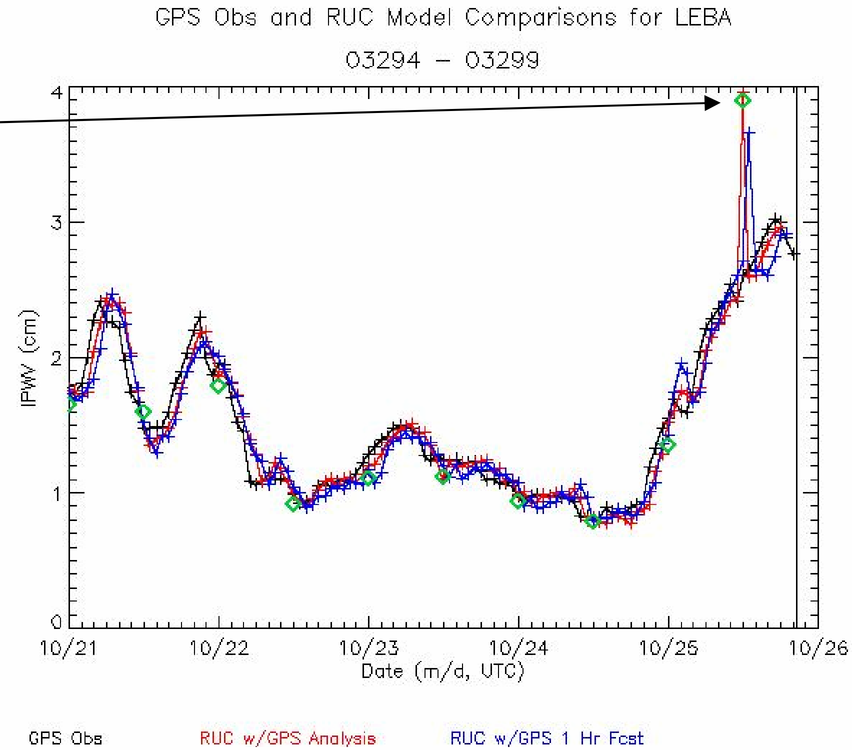
Wx Models & Satellite Images Web Site

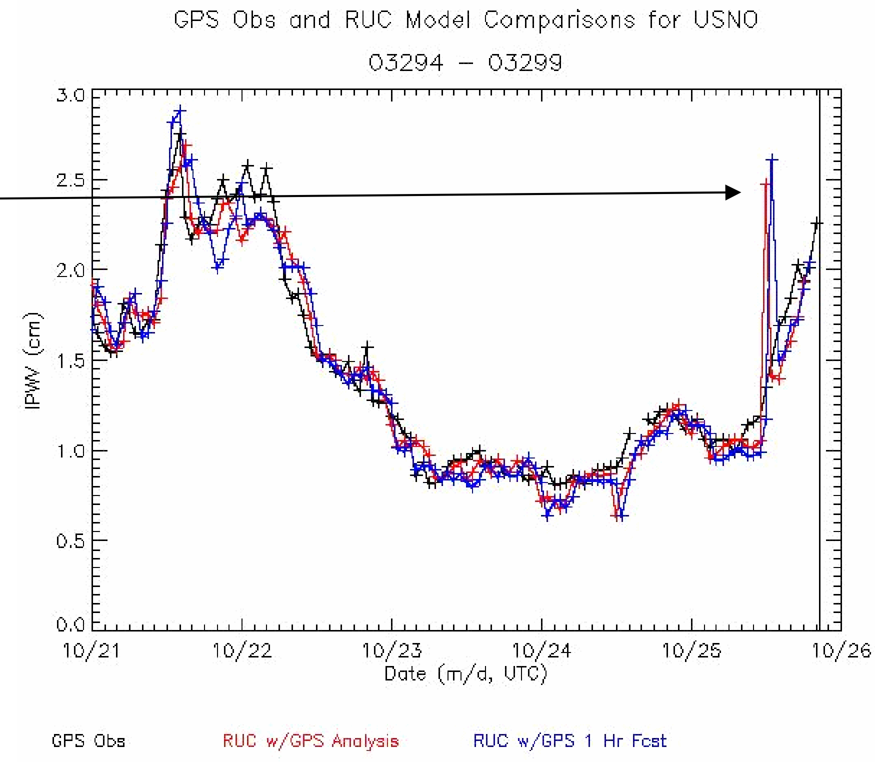




An Unanticipated Application

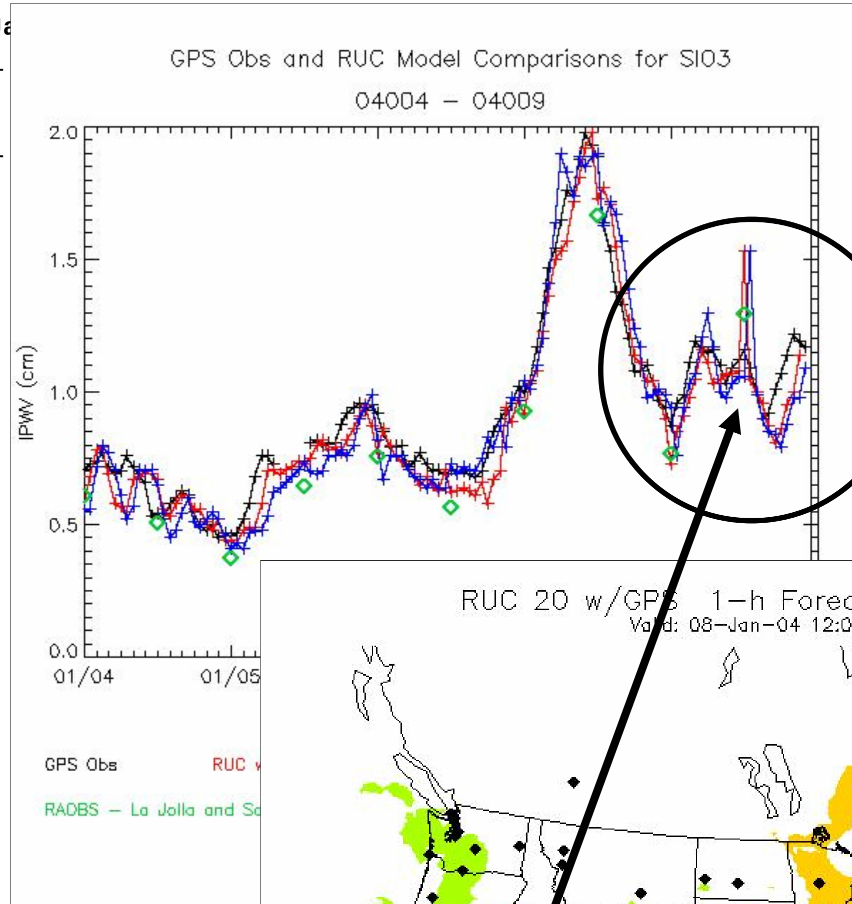


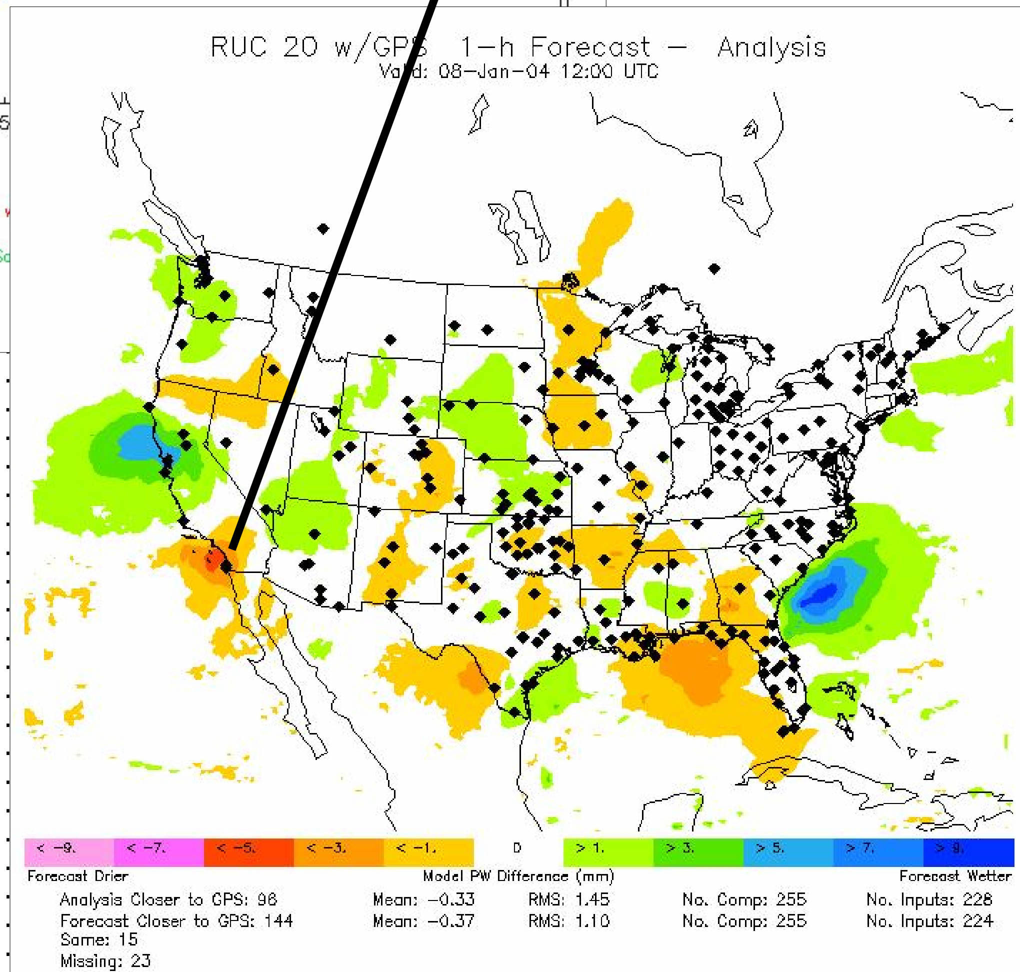




72293 NKX San Diego Observations at 12Z 08 Ja

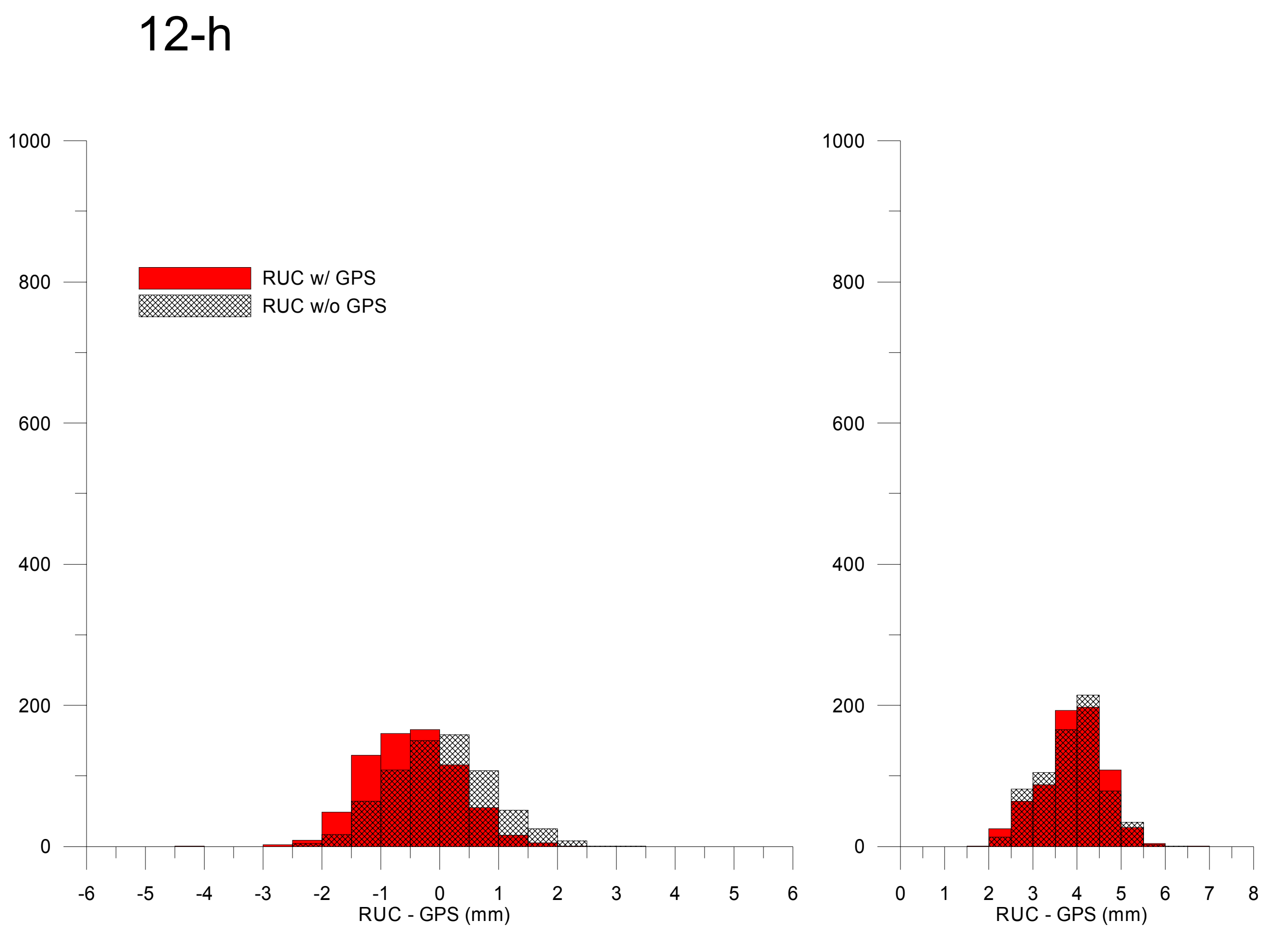
PRES hPa	HGHT m	TEMP C	DWPT C	RELH %	MIXR g/kg	DRCT deg			
400.0	7380	-30.3	-44.3	24	0.19	10			
386.3	7620	-32.4	-45.9	25	0.16	0			
353.5	8230	-37.6	-49.9	27	0.11	345			
309.6	9144	-45.5	-55.9	30	0.06	345			
300.0	9360	-47.3	-57.3	31	0.06	350			
282.1	9754	-50.3	-60.0	31	0.04	345			
269.1	10058	-52.7	-62.1	31	0.03	305			
250.0	10530	-56.3	-65.3	31	0.02	290			
244.8	10668	-55.2	-64.4	31	0.03	285			
223.0	11278	-50.4	-60.4	30	0.05	250			
200.0	11990	-44.7	-55.7	28	0.10	250			
196.0	12126	-43.7	-54.7	29	0.12	253			
194.1	12192	-44.1	-55.1	29	0.11	255			
184.0	12543	-46.2	-57.0	28	0.09	260			
161.3	13411	-51.6	-61.8	28	0.06	275			
150.0	13890	-54.5	-64.5	28	0.04	265			
139.9	14326	-57.9	-67.4	29	0.03	255			
131.0	14741	-61.1	-70.1	29	0.02	258			
127.0	14935	-61.0	-70.0	29	0.02	260			
120.9	15240	-60.8	-69.8	30	0.03	265			
117.0	15442	-60.7	-69.7	30	0.03	262			
104.1	16154	-65.6	-73.9	31	0.02	250			
100.0	16400	-67.3	-75.3	31	0.01	245			
99.0	16459	-67.5	-75.5	31	0.01	245			
94.9	16715	-68.1	-76.1	31	0.01	251			
76.7	17983	-70.6	-77.9	33	0.01	280			
72.9	18288	-71.2	-78.3	34	0.01	280	16	426.7	426.
70.0	18530	-71.7	-78.7	35	0.01	260	11	430.7	430.
65.8	18898	-72.5	-79.5	34	0.01	245	12	436.7	436.
62.9	19158	-73.1	-80.1	34	0.01	251	12	440.9	441.
59.3	19507	-72.4	-79.7	33	0.01	260	12	450.0	450.
50.0	20510	-70.5	-78.5	30	0.02	275	6	476.9	477.
43.5	21336	-70.2	-78.2	30	0.02	280	5	496.9	497.
36.6	22368	-69.9	-77.9	30	0.03	338	5	523.0	523.
30.0	23570	-64.7	-72.7	32	0.07	45	4	567.7	568.
27.7	24057	-63.3	-72.3	29	0.08	26	5	584.7	585.
20.0	26060	-61.7	-70.7	29	0.14	310	7	646.6	647.
17.7	26822	-60.9	-69.9	29	0.18	270	12	672.2	673.
16.9	27127	-60.5	-69.5	30	0.19	265	13	682.8	684.
16.1	27432	-60.2	-69.2	30	0.21	270	14	693.5	695.
14.5	28063	-59.5	-68.5	30	0.26	298	15	716.2	718.
13.9	28346	-58.9	-68.0	30	0.29	310	16	727.6	730.
10.0	30420	-54.1	-64.1	28	0.69	310	24	816.5	824.
9.9	30480	-53.9	-64.0	28	0.71	310	25	819.3	827.
8.2	31699	-50.4	-61.3	26	1.22	295	19	878.6	892.
8.0	31865	-49.9	-60.9	26	1.31			887.0	902.
7.7	32116	-48.7	-59.7	27	1.59			901.5	920.





FORECAST SYSTEMS LABORATORY
BOULDER, COLORADO

Statistical Analysis Using the Web Tool



Bias

RMS

Statistical comparison of RUC 20 model analysis (with and without GPS IPW retrievals) for the 90 day period from 25 July to 22 October, 2003.

SPC Water Vapor Change Maps

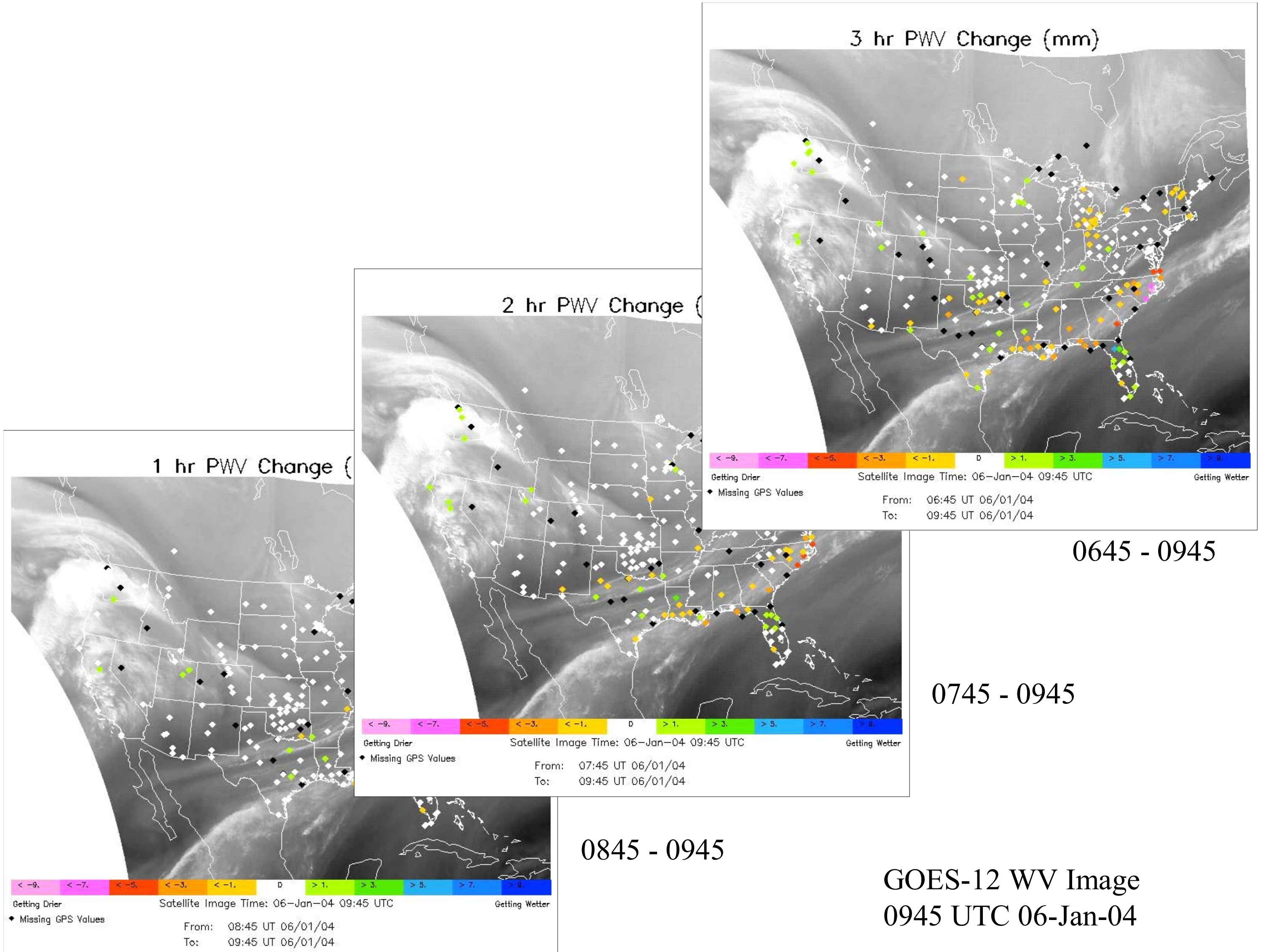
- Forecasters at Blacksburg, Flagstaff and other WFOs have observed that when the environment is rapidly changing, having higher temporal resolution (30 minute) GPS moisture observations can be very helpful.
- High temporal frequency GPS moisture observations improve overall situational awareness, and this almost always makes a positive impact on forecast services during active weather.
- GPS moisture observations have the potential to improve warning lead times during emergency situations like flash flood events, but this has not yet been verified.

SPC Water Vapor Change Maps

- Forecasters at the SPC have found that GPS IPW data can be used to track the return flow of moisture off the Gulf over a stable layer. Obviously, this cannot not be detected from surface observations alone. Knowing this, SPC feels that they can improve their forecasts of where severe elevated convection will form.
- Water vapor time change fields (1, 2, and 3-hr) can give the forecaster an idea of where moisture is converging. This helps infer where the moist boundary layer is deepening with time and where the first storms are likely to form.

SPC Water Vapor Change Maps

- To assist SPC in evaluating a PW change product, we produced maps of 1, 2, and 3-h PW change at GPS-Met sites overlain on GOES WV images.



0645 - 0945

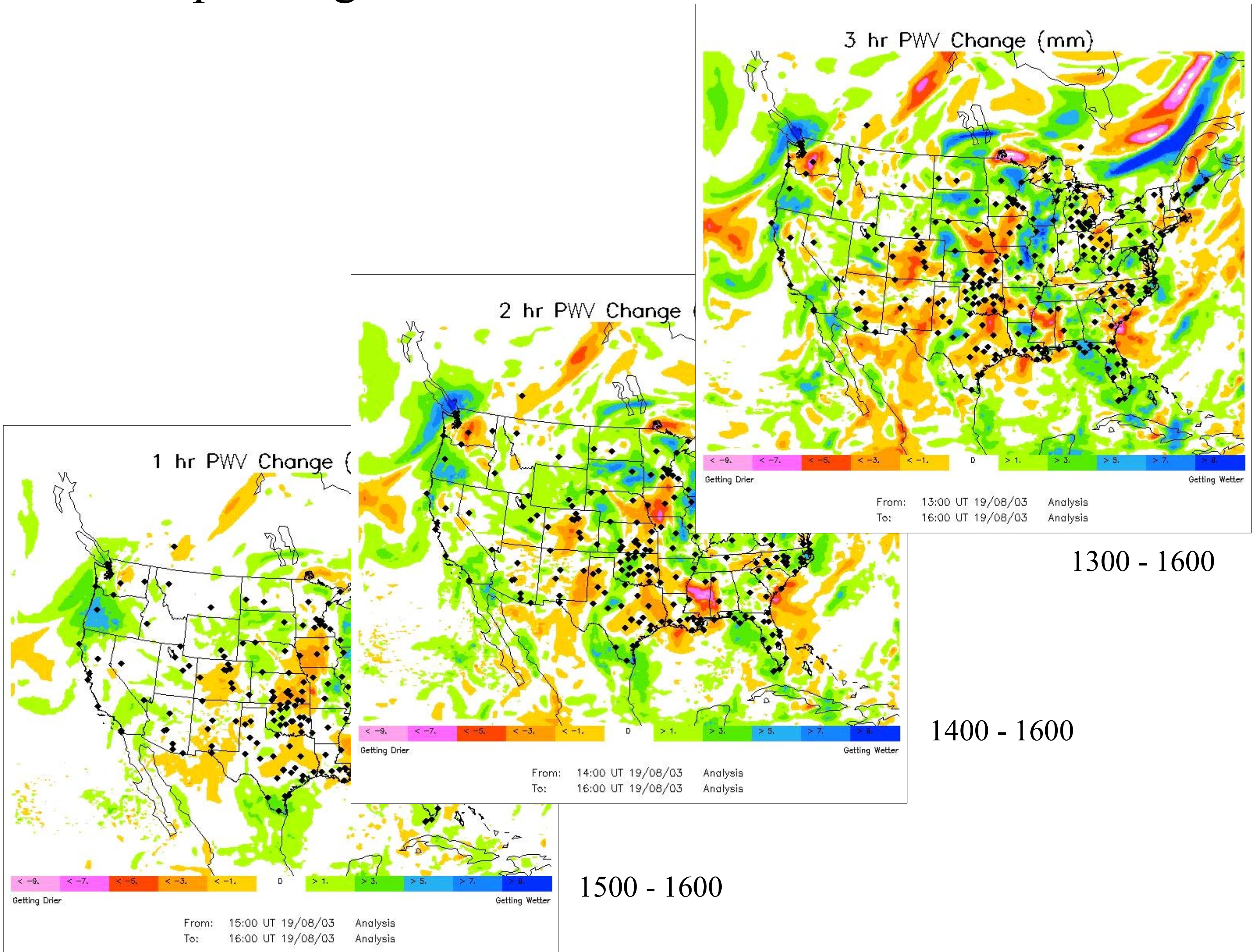
0745 - 0945

0845 - 0945

GOES-12 WV Image
0945 UTC 06-Jan-04

SPC Water Vapor Change Maps

- We also created 1, 2, and 3-h PW change contour maps using the FSL version of the RUC 20.



1300 - 1600

1400 - 1600

1500 - 1600

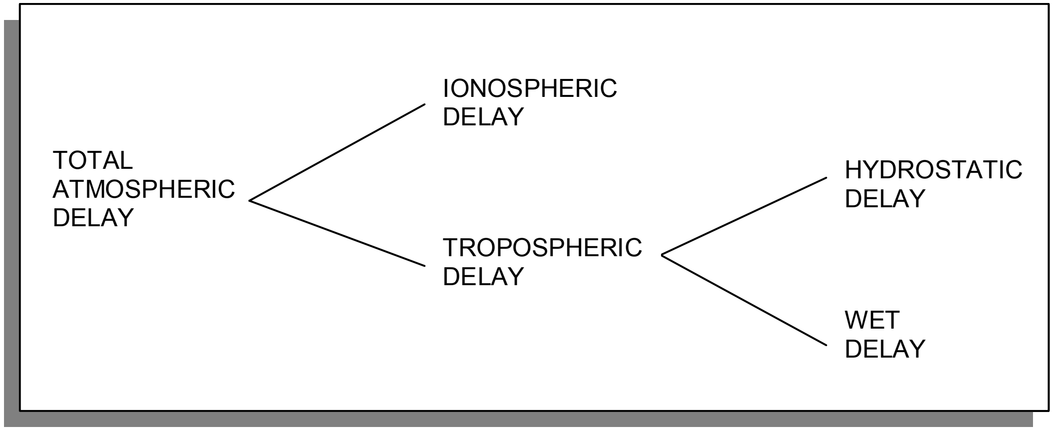
SPC Water Vapor Change Maps

- The approach that SPC is considering for the short-term is to ingest point data directly from FSL to display on their N-AWIPS work stations themselves.
- SPC would prefer to work with ***observations*** rather than ***products***, and they have asked us to move toward a denser observing network with more uniform geographic coverage.

HA-NDGPS Project

- The High Accuracy Nationwide Differential Global Positioning System (NDGPS) Modernization Program is a multi-agency effort to improve Nationwide Differential GPS accuracy.
- To achieve the real-time accuracy target of < 20 cm, ***signal delays caused by the ionosphere and troposphere must be taken into account***. Modeling is one way to do this.
- Agencies involved in the study are:
  - FSL – nowcasting tropospheric delays;
  - Space Environment Center (SEC) – nowcasting ionospheric delays;
  - National Geodetic Survey (NGS) – describing/ articulating ionospheric & tropospheric correctors;

Atmospheric Signal Delay Structure



$$N = -40.3x10^{6}\frac{n_e}{f} + 77.6\frac{P_d}{T} + 70.4\frac{P_v}{T} + 3.739\frac{P_v}{T^2}$$

Ionospheric Term | Dry Term | Wet Term

Tropospheric Terms (Dry Term + Wet Term)

N = refractivity = $(n\text{-}1) \times 10^6$

n_e = electron number density (m^{-3})

f = radio frequency (Hz)

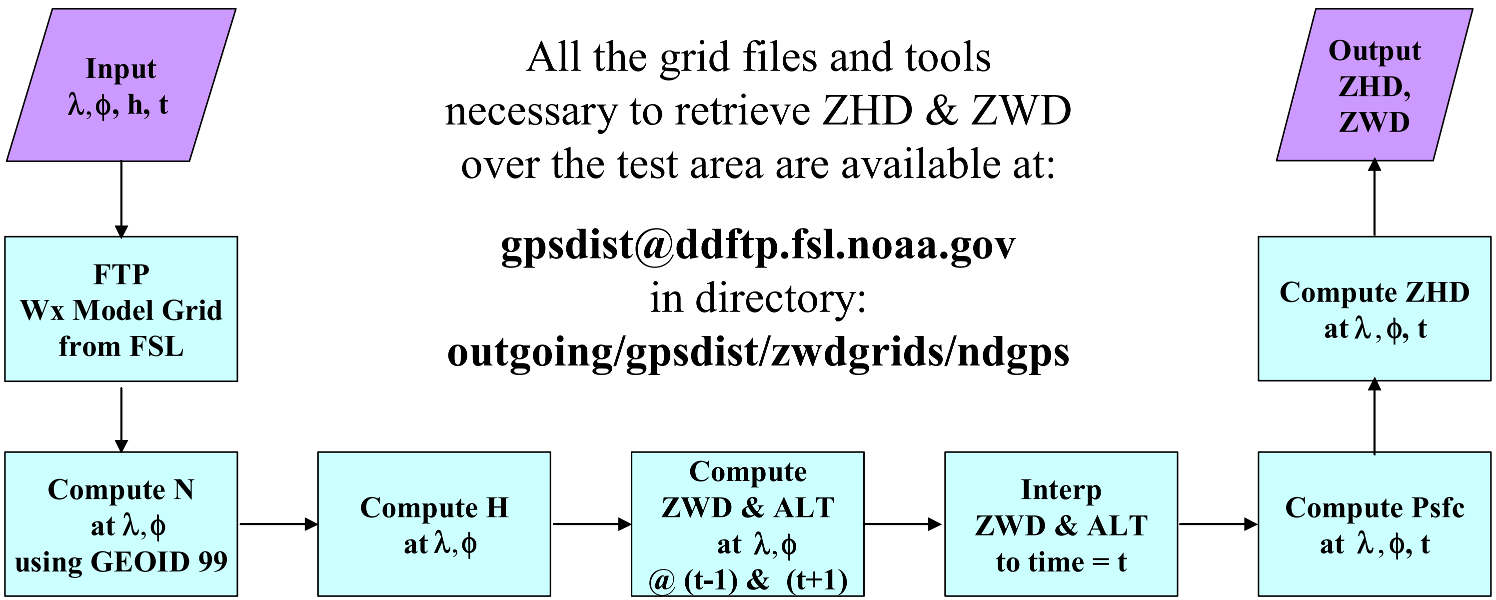
P_d = atmospheric pressure (hPa)

P_v = water vapor pressure (hPa)

Note that: $\frac{P_v}{T}$ = q, water vapor mixing ratio (gm/kg)

HA-NDGPS Project

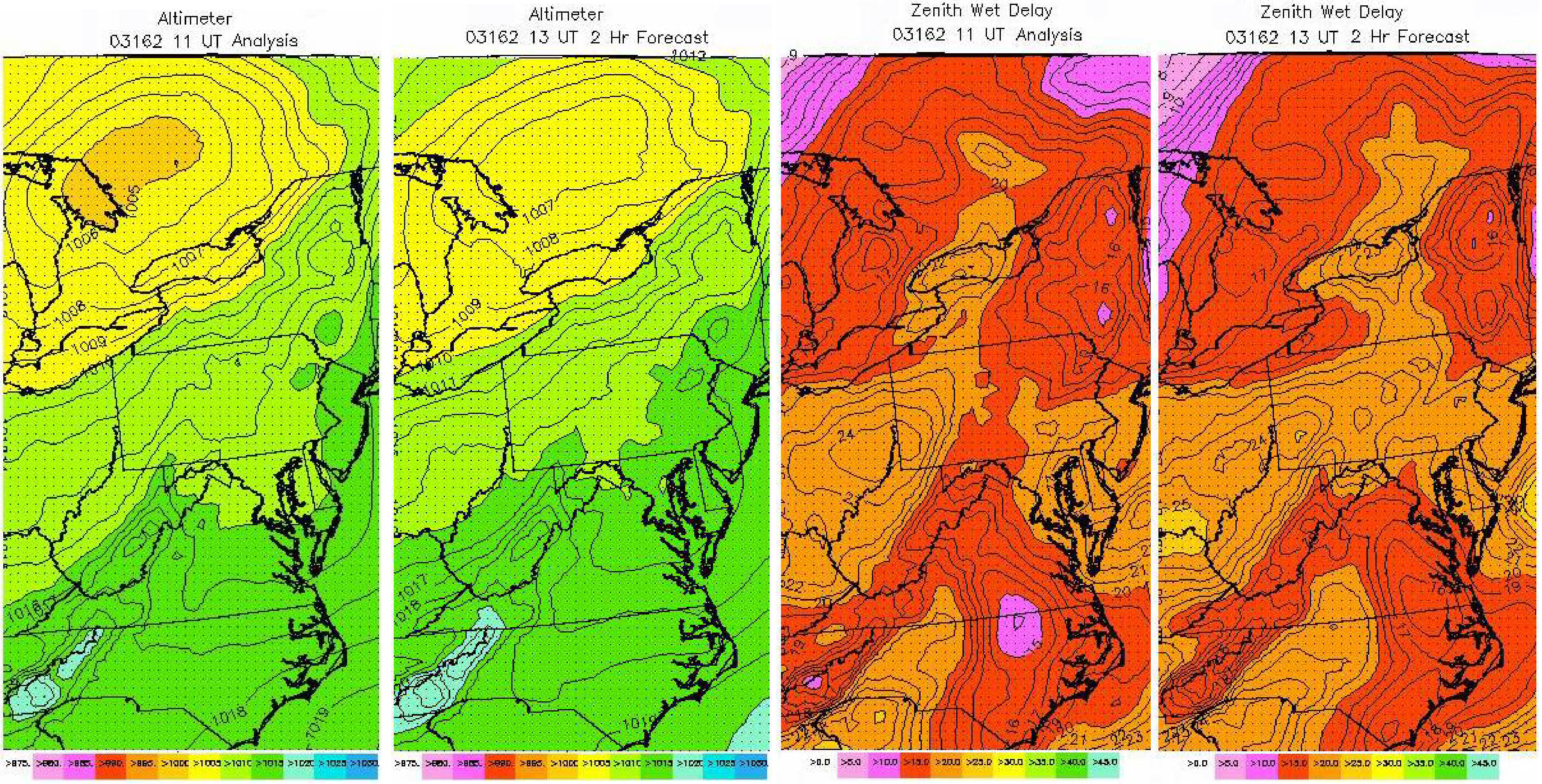
- Every hour, we compute estimates of dry refractivity (derived from model pressure at a constant geopotential height) and wet refractivity (derived from condensation pressure converted to mixing ratio, and integrated from the model surface elevation to the modeled height of the tropopause.)
- We developed a tool kit to compute ZTD from wet and dry refractivity at any location in the model domain site using these grids and user specified site parameters.



All the grid files and tools necessary to retrieve ZHD & ZWD over the test area are available at:

gpsdist@ddftp.fsl.noaa.gov
in directory:
outgoing/gpsdist/zwdgrids/ndgps

HA-NDGPS Project
Sample Contour Files



ZHD ZWD

- This product is being evaluated by U. Calgary, U. Southern Mississippi (USM), and contractors to the USCG and the FHWA; no results are available to date.

D2D Prototypes

- We will continue to work with AWIPS users to determine requirements for the GPS D2D displays.
- We will work with FSL/SDD to develop displays using existing depictables.
- Regular meetings will be held with SDD to relay user feedback.
- When the requirements have been compiled, SDD personnel will determine which displays may be incorporated into the next AWIPS workstation build.

D2D Prototype Displays Under Consideration

- Model derived PW
  - ETA, RUC, GFS
- Data Merges
  - GPS-IPW + satellite images
  - GPS-IPW +WSR-88D amplitude products
  - GPS-IPW +WSR-88D precip products
  - GPS-IPW + lightning
  - GPS-IPW + NPN profiler wind barbs at various levels.
- PW site climatology. Might take the form of monthly average PW and range. Presented as point of comparison for current value.

NOAA Forecast Systems Laboratory
GPS-Met Observing System
2004 Technical Review

GPS Data Applications

Daphne Grant
NPN Operations Branch

January 27, 2004

GPS-Met Applications

- DD runs an application every day that finds all area forecast discussions (AFD's) with references to GPS or IPW.
- Each reference was categorized by:
  - forecast office;
  - date & time;
  - GPS site ID or region;
  - how GPS data were used (e.g. comparisons to models, satellite, ACARS, RAOBS, etc.)
- After analyzing the results, forecasters at the 6 WFOs most often discussing GPS were asked to answer some questions about how they were using these data.

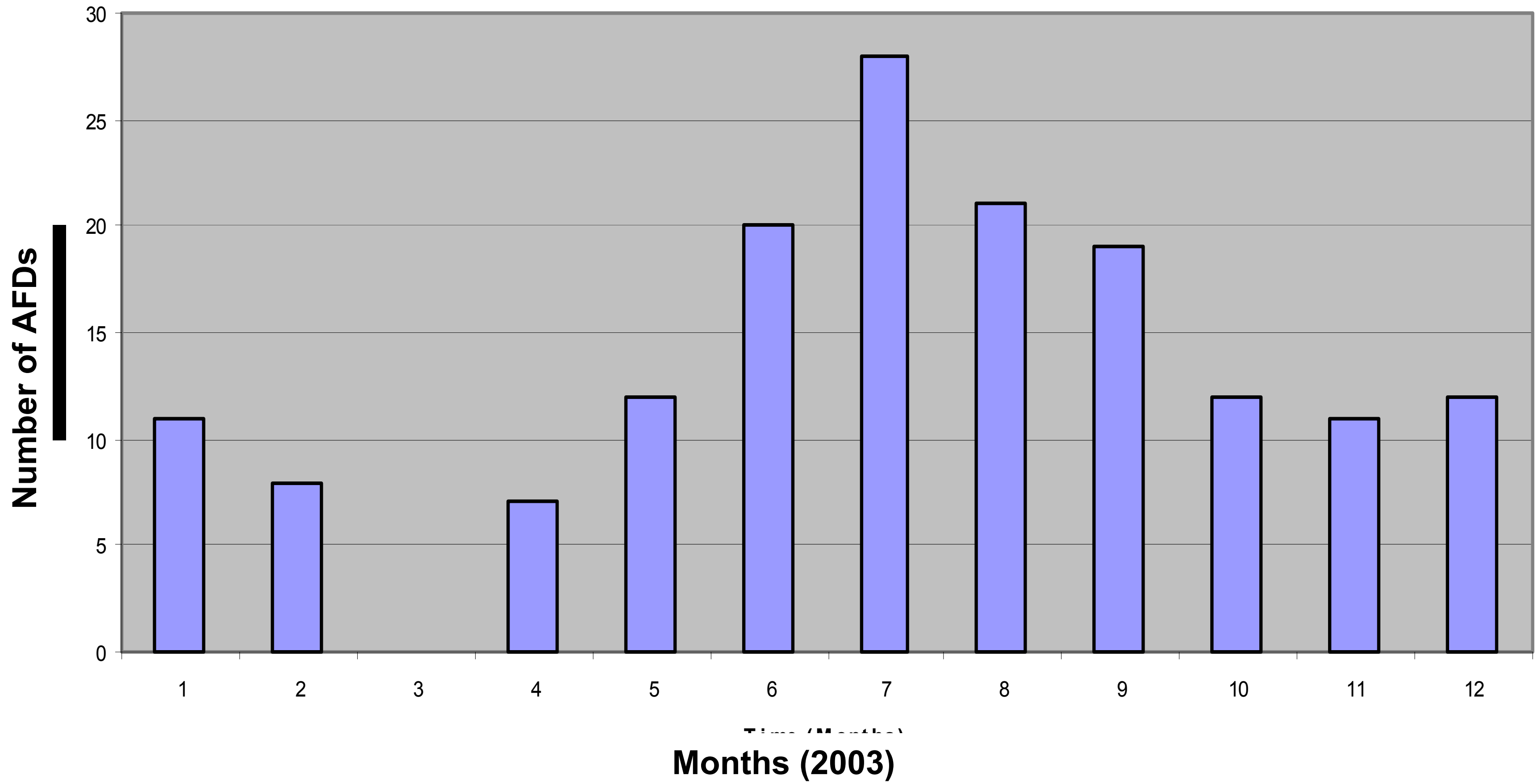
Number GPS Discussions By WFO

NWS Office	Refs	Rank
Flagstaff, AZ	**30**	**1**
Miami, FL	**25**	**2**
Burlington, VT	**24**	**3**
Houston/Galveston, TX	**19**	**4**
Jacksonville, FL	**11**	**5**
Key West, FL	**10**	**6**
Phoenix, AZ	6	7
Salt Lake City, UT	5	8
Chicago, IL	4	9
Melbourne, FL	4	9
Jackson, KY	2	10
La Crosse, WI	2	10
Morristown, TN	2	10
Ruskin, FL	2	10

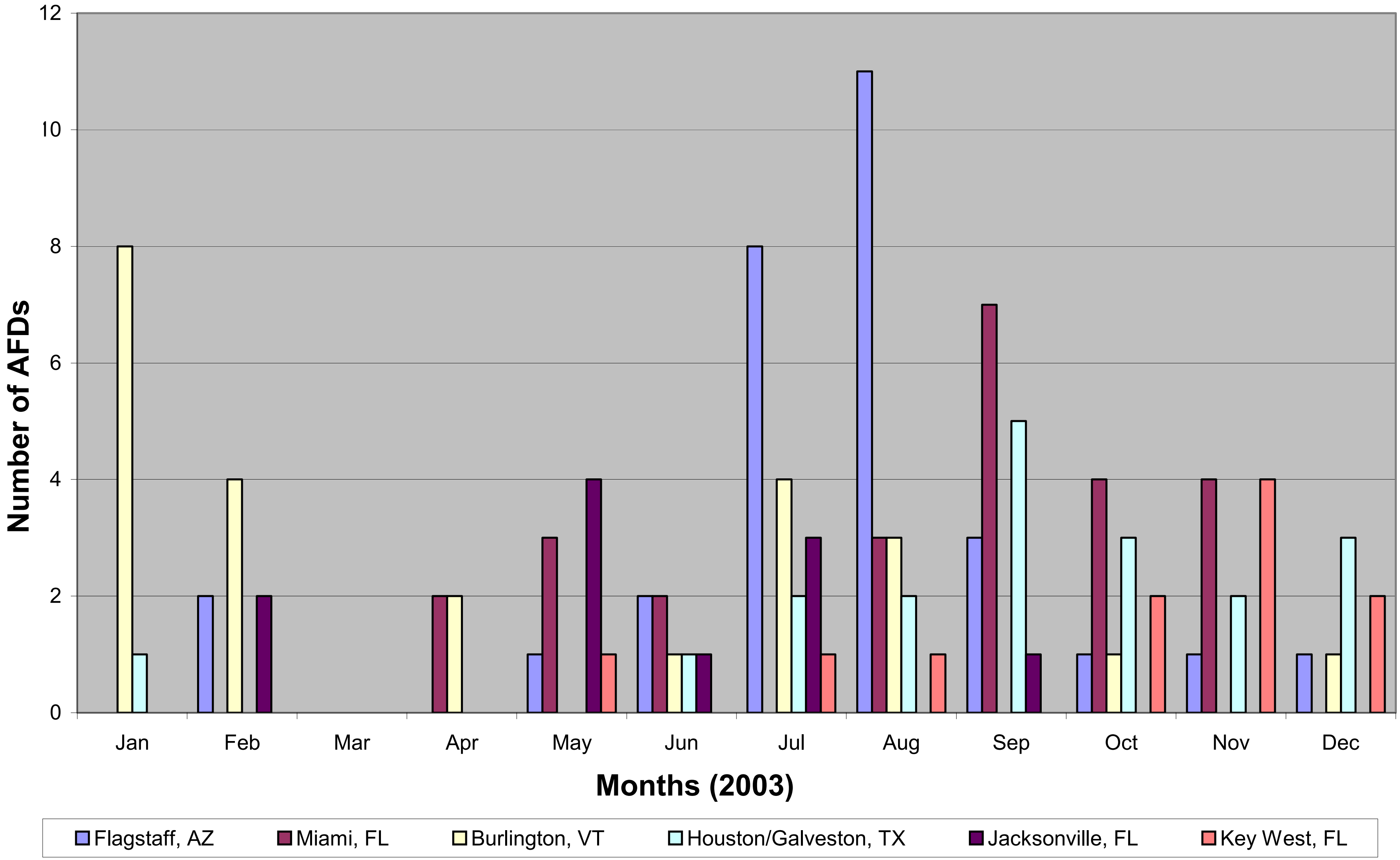
NWS Office	Refs	Rank
Baltimore MD/Washington D.C.	1	11
Binghamton, NY	1	11
Blacksburg, VA	1	11
Cleveland, OH	1	11
Denver, CO	1	11
Duluth, MN	1	11
Lake Charles, LA	1	11
Lincoln, IL	1	11
Nashville, TN	1	11
New Orleans/Baton Rouge, LA	1	11
Pittsburgh, PA	1	11
St. Louis, MO	1	11
Tucson, AZ	1	11
Upton, NY	1	11

28 WFO’s included GPS in their forecast discussions during 2003.

Total No. Discussions/Month



Discussions/Month By WFO



GPS Discussions

- GPS IPW retrievals were compared with NWP models 60 times: GPS verified the model 44 times and contradicted it 16 times.
- The GPS data were compared to raobs soundings 54 times: 46 times they agreed and 8 times they disagreed.
- The GPS data by itself was the subject of discussion 53 times.
- The GPS data were compared with satellites 29 times: 24 times it verified the interpretation and 5 times it contradicted the interpretation.
- The GPS data were compared to surface dewpoints 3 times.
- GPS data were compared to ACARS data 3 times: they agreed 2 times and disagreed once.

Forecast Applications Survey

- We identified the top 6 reporting WFOs: Flagstaff, Miami, Burlington, Houston/Galveston, Jacksonville, and Key West.
- We e-mailed a survey to forecasters at these offices asking 8 questions and 5 responded.
- Questions:
  1) Considering the GPS data products and services provided, how are we (the GPS-Met Branch) doing?
  2) What are the strengths of the data?
  3) What are the weaknesses of the data?
  4) When is the data the most useful?
  5) When is the data the least useful?
  6) What can we do better? / what can we improve upon?
  7) When looking at soundings, do you look at RAOB soundings or satellite soundings?
  8) Do you have any questions or additional comments?

Survey Results

1) **Considering the GPS data products and services provided, how are we (the GPS-Met Branch) doing?**

- Most of the forecasters agreed that the GPS-Met branch is providing good access to real-time data.
    - “doing a great job of providing data in real-time…”
    - “web interface easy to use to get data.”
    - “The data is fairly robust…”

Survey Results

2) What are the strengths of the data?

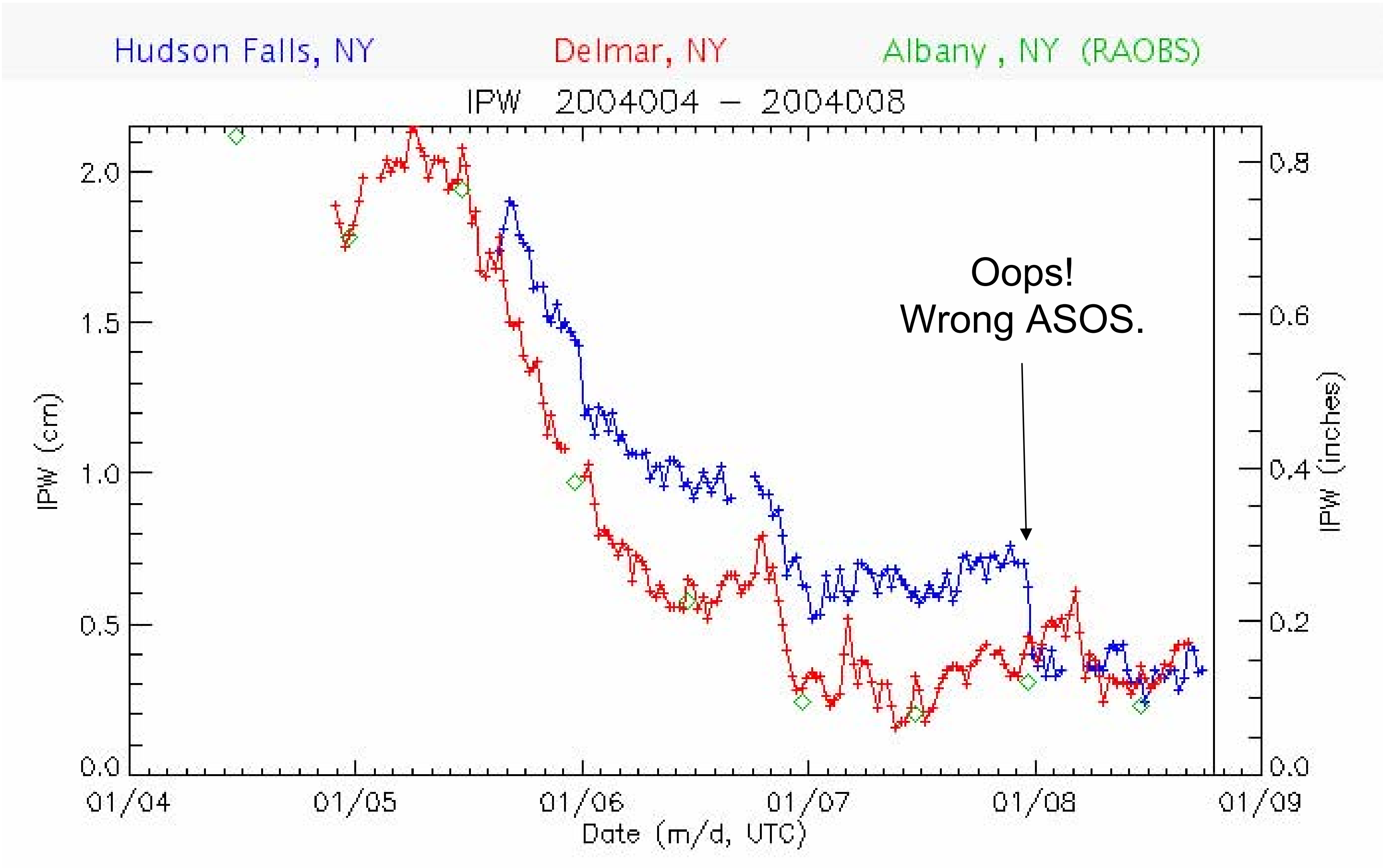
- The primary response was accuracy and temporal data frequency. People also liked the following features:
  - being able to plot multiple sites along with raob data;
  - the GPS sites are spatially laid out;
  - "helps to validate (or invalidate) NWP forecasts."

Survey Results

3) What are the weaknesses of the data?

- The most common answer was that the data has holes in it. Other responses are:
  - "…its latency arriving into AWIPS."
  - … there isn't an IPWV climatology.
  - The Burlington, VT forecaster discovered that one nearby site, Hudson Falls, NY, had a consistent wet bias.

    Bill Murray wrote, "The IPW data frequently looks to be a tad high on it's reading of PW when compared to RUC/ETA/GFS/NGM PW data."



Hudson Falls, NY
Delmar, NY
Albany , NY (RAOBS)
IPW 2004004 - 2004008
Oops!
Wrong ASOS.
IPW (cm)
IPW (inches)
2.0
1.5
1.0
0.5
0.0
0.8
0.6
0.4
0.2
0.0
01/04
01/05
01/06
01/07
01/08
01/09
Date (m/d, UTC)

Survey Results

4) When is the data the most useful?

- In Flagstaff, the data are most useful during the summer monsoon season and during the cold season with the approach of a trough or low pressure system.
- In Florida, the data was most useful for the
  - Convective season
  - Frontal passages
  - Tropical systems/cyclones/surges/waves
- In Burlington, GPS data are most useful when they are expecting precipitation or severe weather.

Survey Results

5) When is the data the least useful?

- All responses were the same… "it's the least useful when there is quiet weather."

6) What can we do better? What can we improve upon?

- The responses were:
  - "…more flexible GUI on the web page."
  - "…it would be nice to resolve the latency issues."
  - "…plan views of IPW data would be great to have overlaid onto model data in AWIPS."
  - The forecaster at Key West asked for a station at Marathon Key. Since FDoT has a site there, and we have been using it to produce IPW for some time, we need to keep the local forecast offices up-to-date on the resources available to them.

Survey Results

7) When looking at soundings, do you look at raob soundings or satellite soundings?

- The responses were mixed.
  - "…we look at all these data sources."
  - "…never look at satellite soundings."
  - "…use time series plots of IPW off your website."

8) Do you have any questions or additional comments?

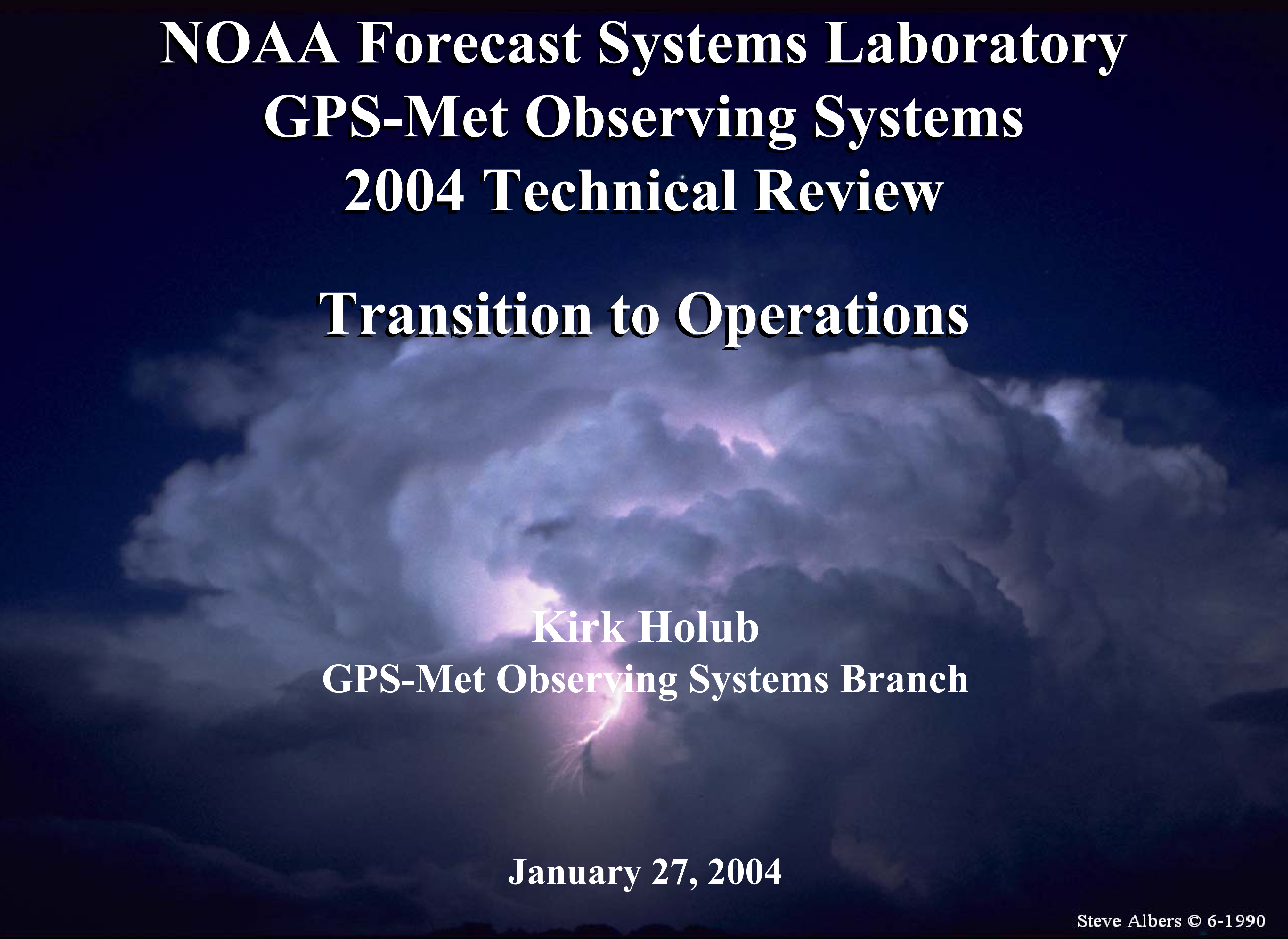
- All responses stated that the GPS data are extremely useful and they tend to look at the data more than the forecast discussions may indicate.

Survey Results

- Some of the other responses included:
  - "this data has been very valuable to the forecast staff here"
  - "put a quick user survey on your website to try and get more feedback about the data."
  - "I hope people realize the positive impact that this data has on forecast operations. To me it's critical."

NOAA Forecast Systems Laboratory
GPS-Met Observing Systems
2004 Technical Review

Transition to Operations

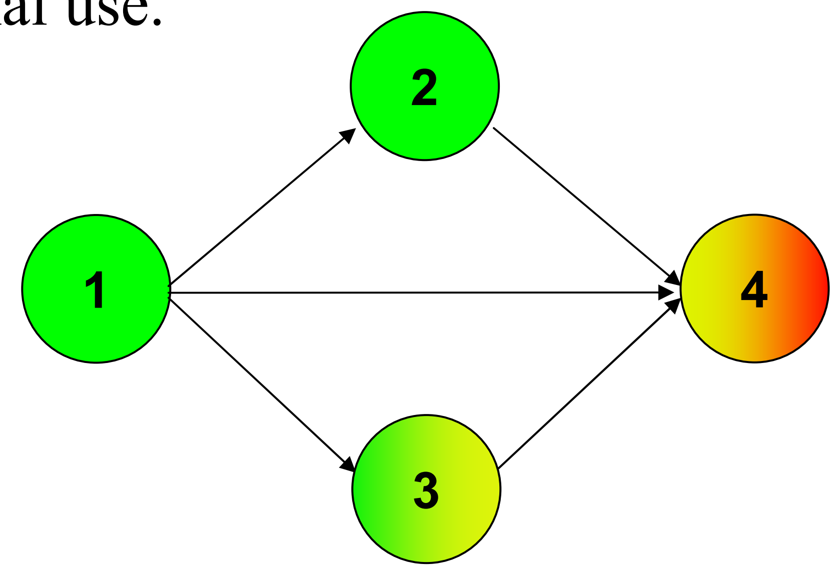


Kirk Holub
GPS-Met Observing Systems Branch

January 27, 2004

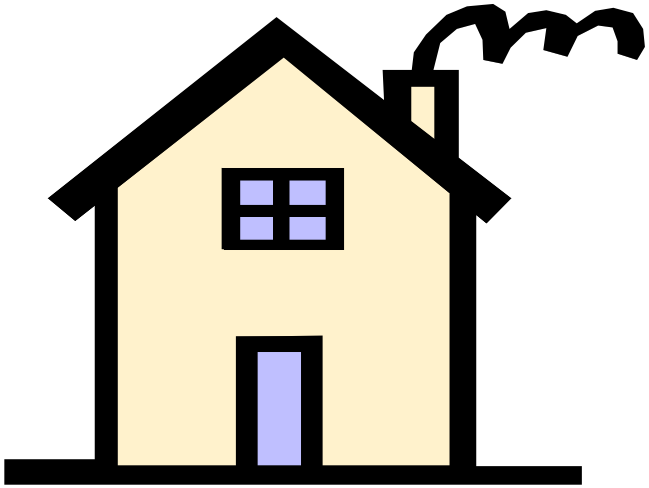
GPS-Met Project Objectives

1. Demonstrate the major aspects of an operational GPS IPW monitoring system. [Satisfied since April 2000.]
2. Facilitate assessments of the impact of these data on weather forecasts. [Continuous since 1998.]
3. Encourage the use of GPS meteorology for atmospheric research and other applications. [Continuous since 1994.]
4. Assist in the transition of these techniques to operational use.



GPS-Met System Attributes

FSL Prototype



- Provides shelter from the elements
- Provides a place to store some 'stuff‘
- Cozy, single family dwelling
- Wooden frame construction
- Cedar shake roof
- Utilities?
- Adds security as required

NWS Operational System

- Provides shelter from the elements
- Provides a place to store a lot of 'stuff'
- Provides room for growth
- Built using reinforced concrete
- Has a tile roof
- Has a crawl space to access utilities
- Has built-in security features

Operational System Upgrades

- GPS-Met prototype was designed to test ideas and flesh-out requirements, not to be an operational system:
  - reliability was not a driver;
  - system has several points of failure and no automated fail-over capabilities.
- Prototype lacks flexibility:
  - implementation is fixed to accommodate a 30-min data acquisition/processing cycle;
  - schedule driven instead of event driven;
  - consists of many highly coupled, but loosely coherent scripts.
- Components are not well integrated:
  - database is used primarily by the web site;
  - adding or deleting sites, and changing the configuration of the sub-networks is a time consuming manual process.

System Attributes

FSL Prototype System	Operational System
Delivers IPW estimates every 30 minutes	Deliver IPW estimates at arbitrary (user selectable) times
Data available in ASCII, netCDF, and BUFR formats	Data available in any required format
Data stored as ASCII flat files	Data stored in a relational database
Schedule driven	Event driven
Many separate programs that interact with each other	Fewer, well integrated programs
Database primarily supports web applications	Database is an integral component of the entire system
Can process hundreds of stations	Can process thousands of stations
Manual configuration change management and semi-automated site addition/deletion capabilities	Automated configuration change management including site addition/deletion capabilities
Partially documented	Fully documented

Critical Operational Needs

- Reliable GPS Satellite Orbits:
  - currently using International GPS Service (IGS) global tracking data; and
  - SOPAC hourly orbits and 2-h predictions for real-time operations ~ 95% reliable;
  - alternate source of orbits or orbit prediction QC; or
  - near real-time notification of changes in GPS constellation status by USAF. Civilian NANUs are not reliable.

- Reliable GPS data collection from CORS:
  - reliability for "backbone sites" > 90%;
  - reliability for "infill sites" ~ 80%;
  - reliable, low latency data delivery was never part of NGS/CORS requirements;
  - staffed 24/7 operation is needed.

Critical Operational Needs

- Reliable higher temporal resolution surface met sensor data are needed for “infill sites”:
  - most operational automated surface observing systems (e.g. ASOS & AWOS) report only once per hour;
  - the current GPS-Met system needs 30-min data or less;
  - operational system will need ~ 5-min resolution.
- Reliable Response to System Problems:
  - operator needed on duty 24/7;
  - sys admin/analyst needed on call 24/7.

Other Transition Issues

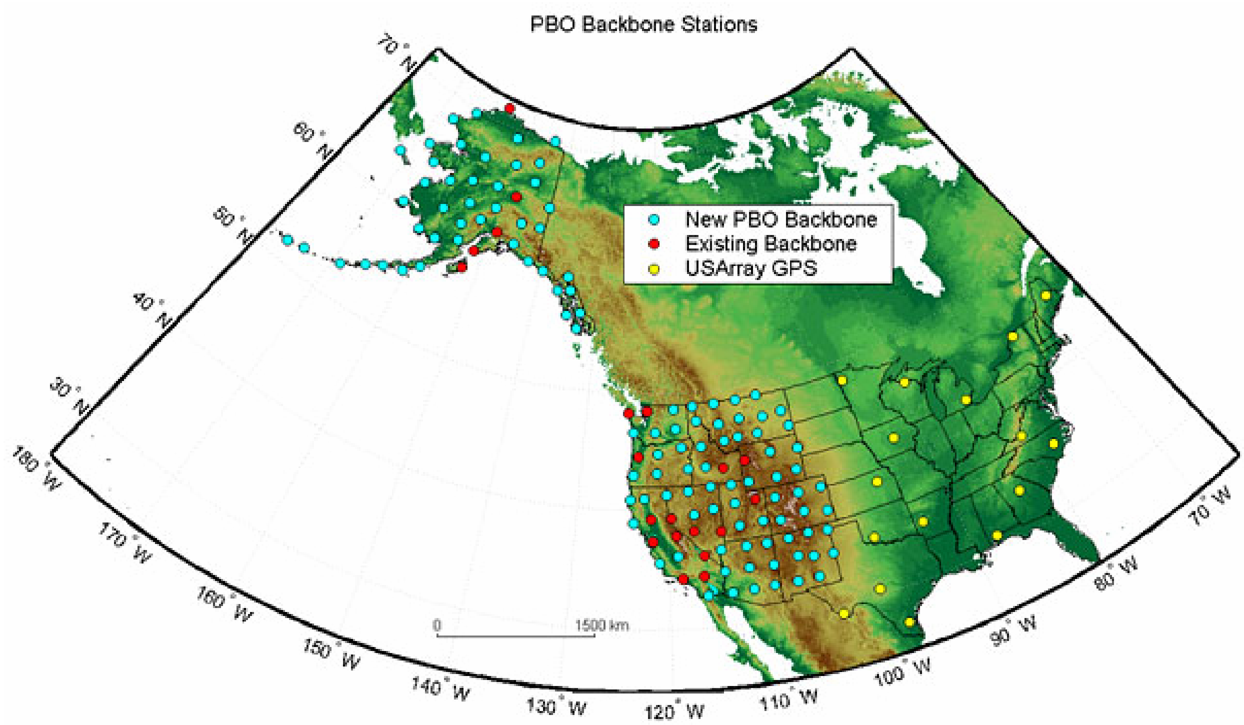
- FSL-owned GPS Receivers:
  - systems at NPN sites, some WFOs, and other locations are near end-of-life and will need to be replaced soon.

- GPS at other NOAA sites:
  - systems at UA sites to validate raob moisture soundings;
  - upgrade RRS?

- Location of the GPS-Met Operations:
  - FSL uses network solutions and long-baseline fiducial sites to estimate ZTD;
  - centralized data collection & processing is preferred but not necessary;
  - centralized monitoring is also preferred but not necessary.

Other Transition Issues

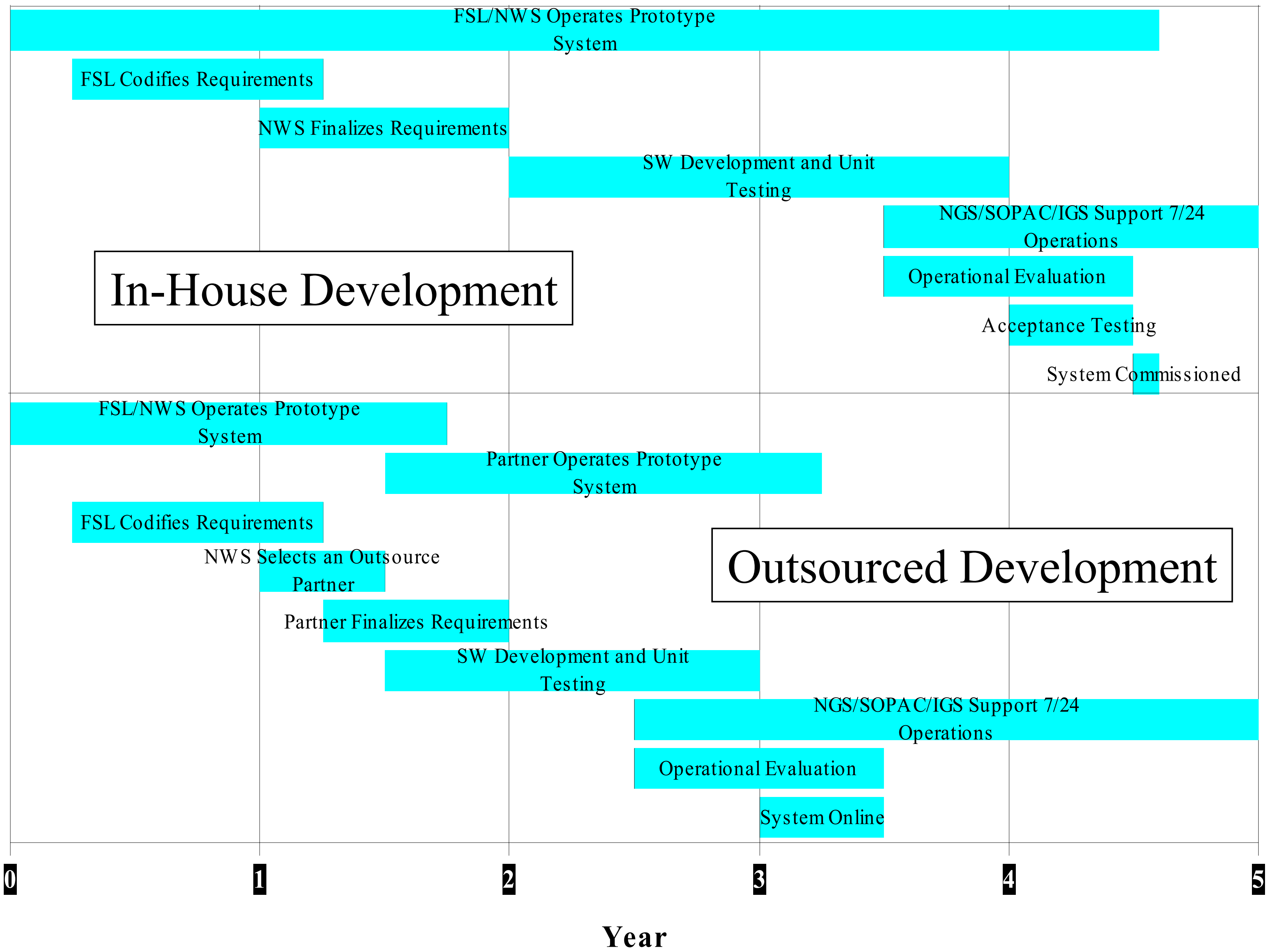
- Reducing Data Latency from "Infill Sites":
  - infill sites are primarily owned by non-federal government agencies and universities;
  - these organizations rarely need data in real-time;
  - as a rule, they are willing and technically capable of providing low latency data to NOAA at no cost, but sometimes lack the resources to do so;
  - a good example is the Plate Boundary Observatory.



Other Transition Issues

- PBO is part of the EarthScope Program funded by NSF.
- It will consist of about 120 continuously operating reference stations with ~200 km spacing in the western U.S. and Alaska.
- Each station will have GPS and Sfc Met sensors, but data will only be retrieved once per day unless other provisions are made.
- Should NOAA provide resources to other agencies to upgrade and maintain PBO (or other agency) sites used for GPS-Met?
- And what about SuomiNet?
  - not supported by NSF after 2005;
  - should NOAA "adopt" these sites, and collaborate with/support university-owners?

Transition Timelines



Conclusion

- The prototype system does what was expected of it.
- Many critical issues must be addressed in order to achieve 7/24 operations; but all are achievable
- If the outsourced development approach is used, an operational system could be online in 3+ years
- If the in-house approach is used, an operational system could be commissioned by 4+ years

NOAA Forecast Systems Laboratory
GPS-Met Observing Systems
2004 Technical Review

Concluding Remarks

Seth Gutman
GPS-Met Observing Systems Branch

January 27, 2004

GPS Satellite Orbits

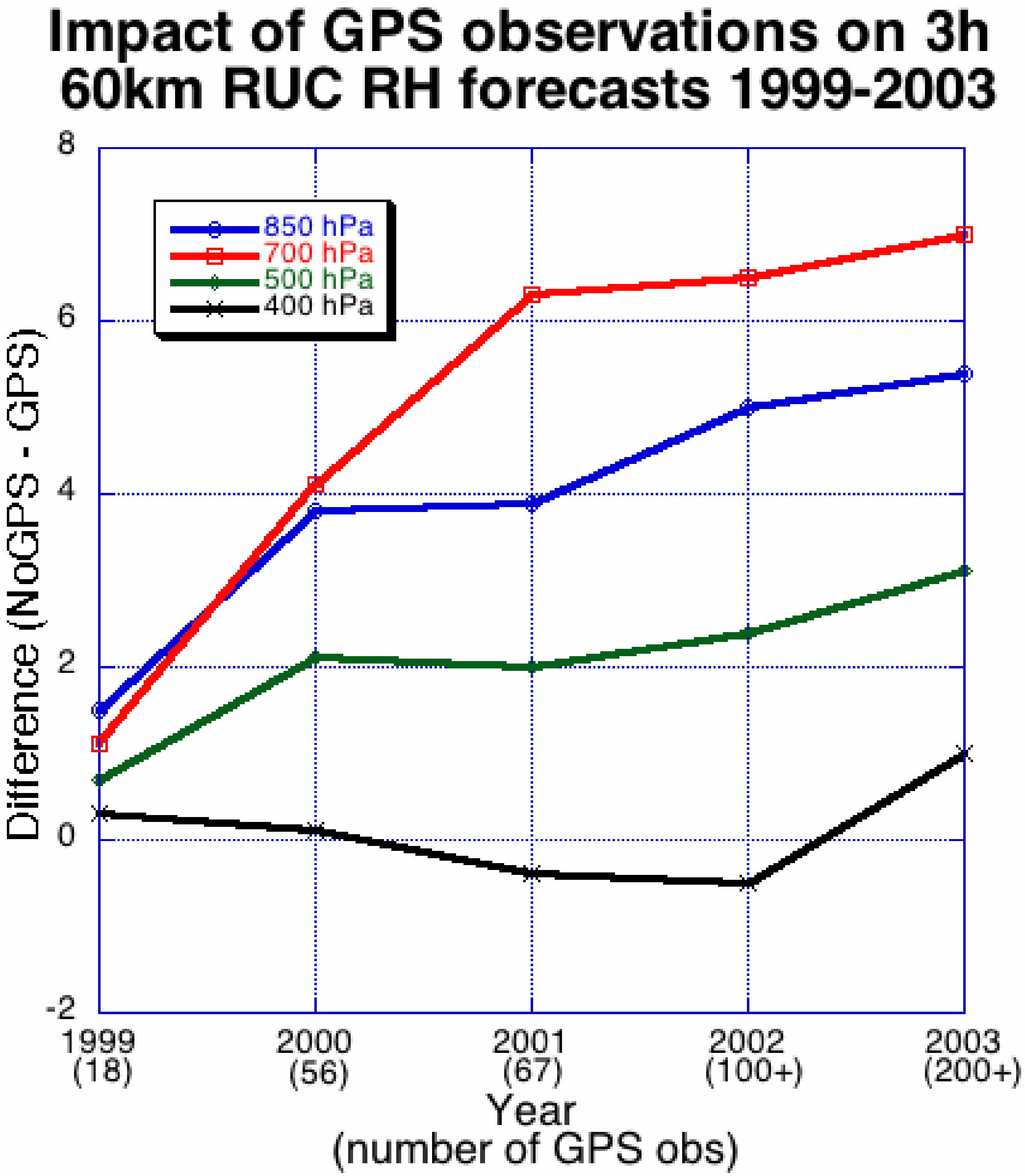
- The ability to compute sufficiently accurate GPS satellite orbits in real-time has been a fundamental technical driver in GPS meteorology.
- In the past, orbit quality control was not an issue because the GPS constellation was performing well, and there was lots of time for the IGS Orbit Centers to edit the data and compute the orbits.
- The introduction of the SOPAC hourly orbit in 2000, and the implementation of the sliding window processing technique, essentially solved the real-time problem... except for one thing.
- In the past year, there have been several satellite maneuvers that have adversely effected the quality of our retrievals, and negatively impacted the models assimilating them.

GPS Satellite Orbits

- Improved techniques to identify orbit prediction errors are ***absolutely essential for operational use of GPS-Met***.

- Possible approaches include:
  - apply autonomous quality control procedures that allow an errant satellite to be…
    - identified,
    - its data removed from the ZTD solution, and
    - its status monitored until the orbit can be accurately predicted again; or
  - get real-time notification from USAF of a change in status of a satellite because of a problem or maneuver…
    - data from the satellite is not used until it is stabilized and returned to FOC.

GPS Impact on NWP Forecasts



Products and Services

- What success we have had in of our ability to:
  - monitor GPS-Met accuracy;
  - evaluate data and test hypotheses;
  - understand how mesoscale models like the RUC handle integrated observations like GPS;
  - provide forecasters with timely moisture information;
  - and facilitate our outreach activities;

  are in large part attributable to the products and services we have developed to serve various user communities.

- Engaging users directly, especially NWS, has resulted in:
  - proposed incorporation of GPS-Met and new profiler data into the next build of AWIPS;
  - incorporation of GPS-Met into the next (and final) bundles of the operational RUC and Eta models;

Products and Services

- proposed addition of GPS-Met observation capability into the next upgrade of the Radiosonde Replacement System (RSS);
- interest in using GPS-Met for validating NWS rawinsonde moisture soundings;
- interest in using data from the IGS global network to build a global comparative data set for the next reanalysis of AMSU temperature and moisture measurements.
- the possibility of NOAA providing operational tropospheric and ionospheric signal delay models for HA-NDGPS to DOT and USCG.

Applications

- Forecasters appear to be reasonably satisfied with our efforts to provide reliable products and services.
- Subjective use of GPS-Met is in its infancy.
- Expanded use at WFOs will depend on their ability to access these observations via AWIPS.
- Developing useful AWIPS applications in collaboration with other FSL Divisions and the WFOs is an exciting challenge that we are eager to take on.

Transition to Operations

- Given adequate orbit QC, there are no obvious technical reasons why GPS-Met cannot transition to NWS operations in the relatively near future.
- The cost and time to do so is modest compared to other system transitions.
- We're ready to go!

Any Questions?