Using GPS for Climate Monitoring

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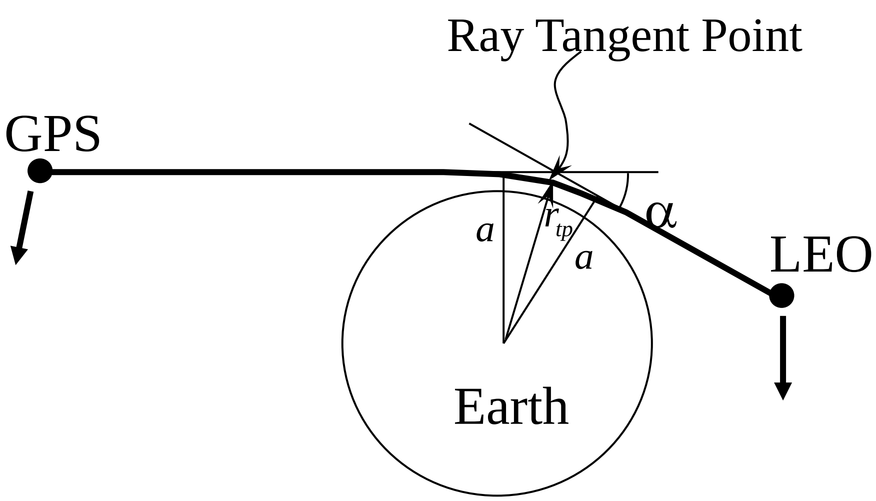
Overview

- Motivation / Measurement Principle
- Ground based and Space based methods
- Ground based results + applications to climate modeling
- Space based applications to climate modeling
- Application to GCOS - Summary

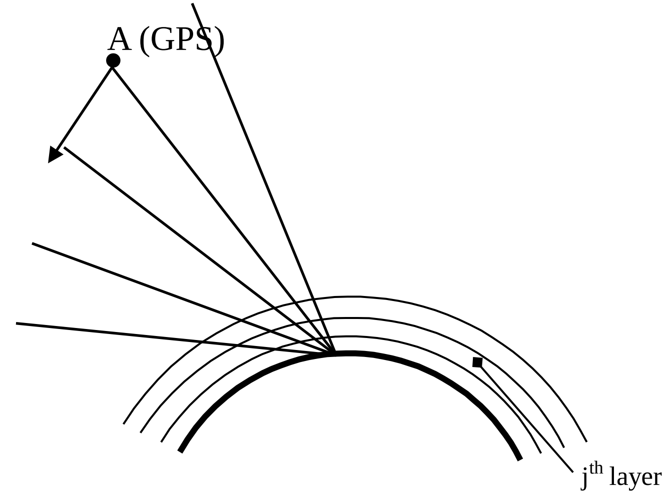
Motivation

With the wide range of atmospheric sensing techniques what can GPS offer in addition?

- All weather
- Continuous operation
- High temporal resolution
- High accuracy
- Independent of radiosondes
- Long-term stability suitable to establish a climate record (data set can be traced to atomic clocks)



Space-based: Profiling

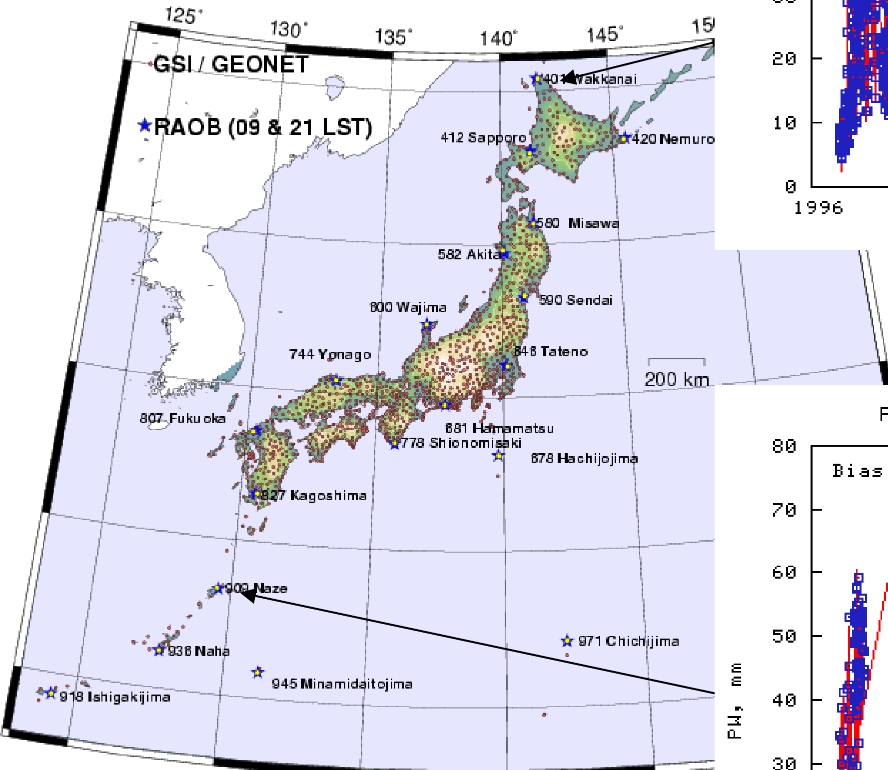


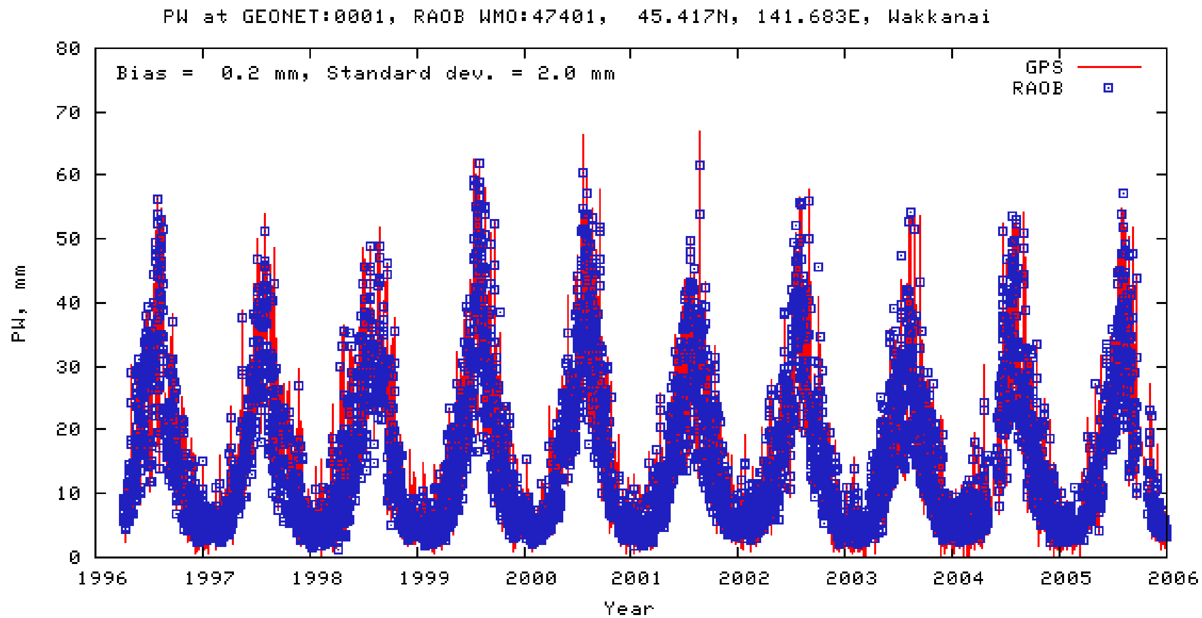
Ground-based: Integrated Delay

- A GPS receiver observes the "travel time" of the signal from the transmitters to the receiving antenna
- It is possible to determine that part of the travel time due to the atmosphere: "atmospheric delay"
- From the "atmospheric delay" of the GPS signal the profile of refractivity or "zenith tropospheric delay" and "zenith precipitable water vapor" can be determined

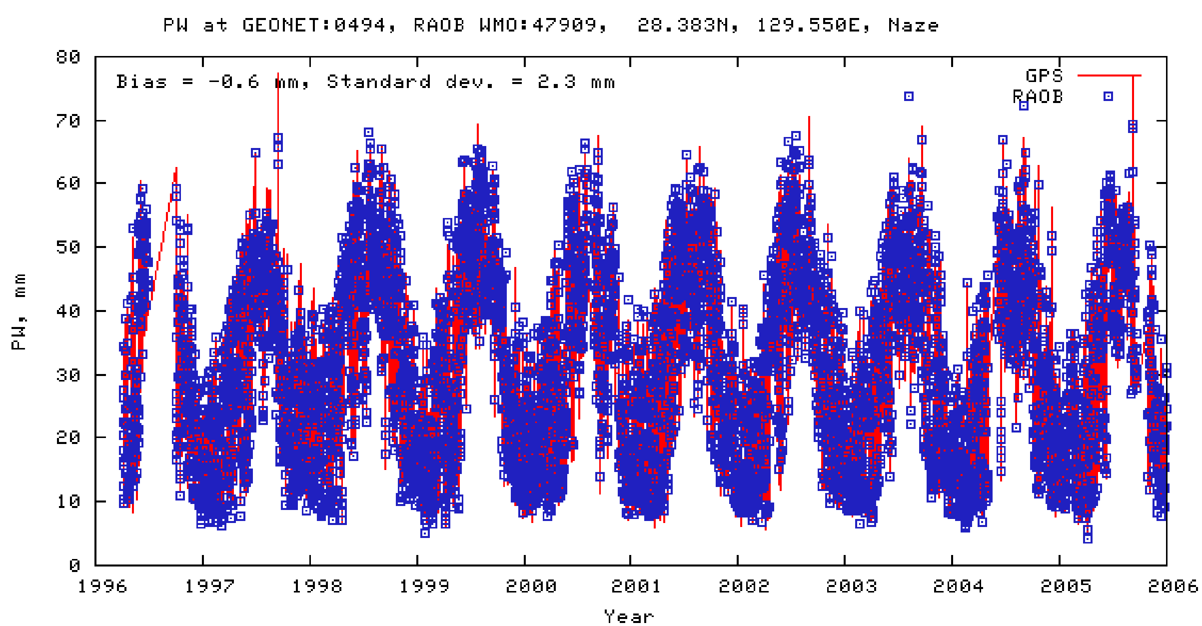
GEONET Japan
1200+ GPS sites

20 radiosonde sites





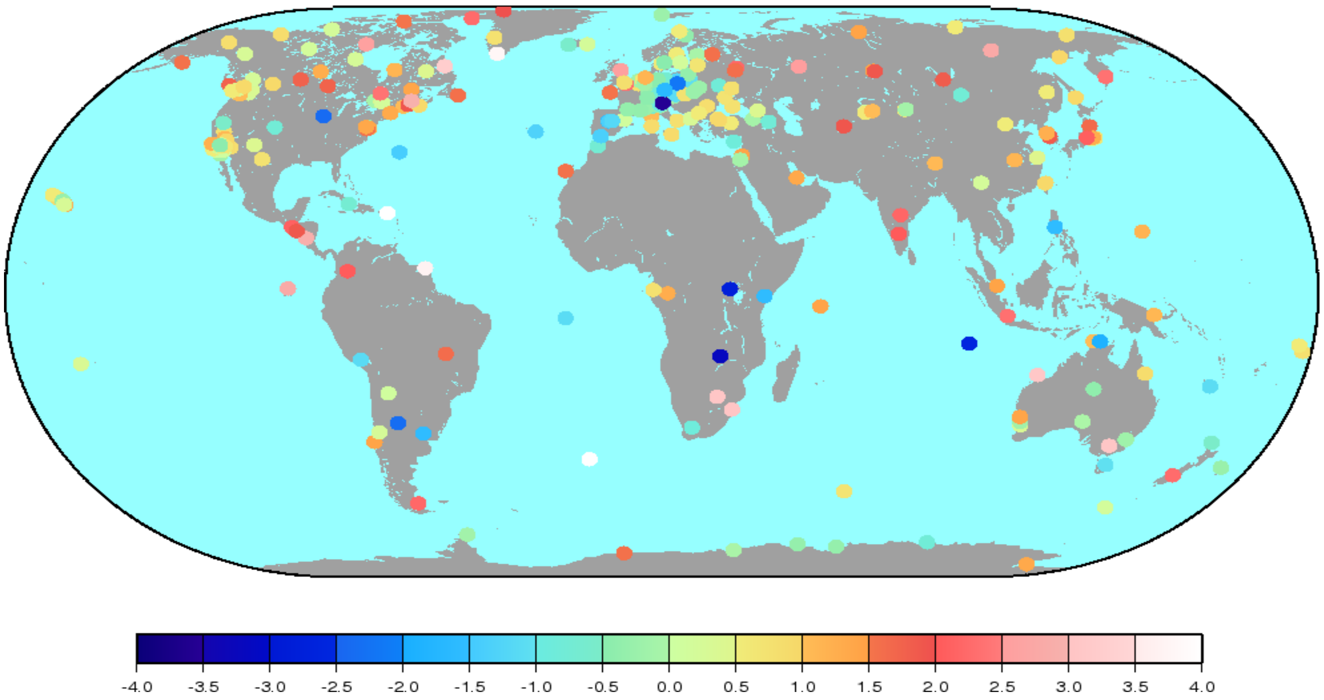
GPS vs. Radiosonde



T. Iwabuchi, UCAR

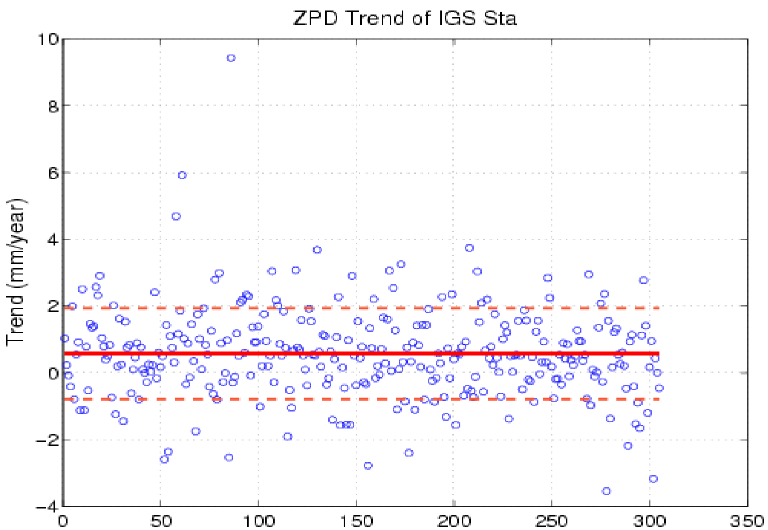
GCOS Meeting Seattle, 22-24 May 06

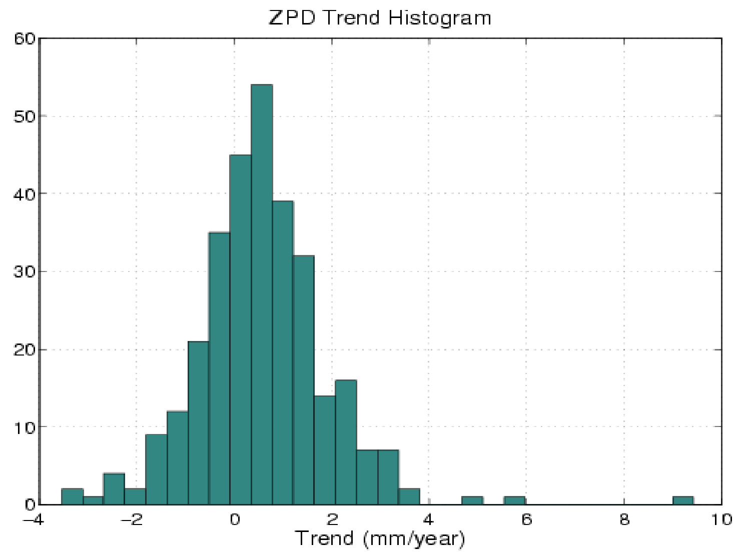
ZPD Trend in mm/year



S. Byun, JPL

Global ZPD Trend Statistics

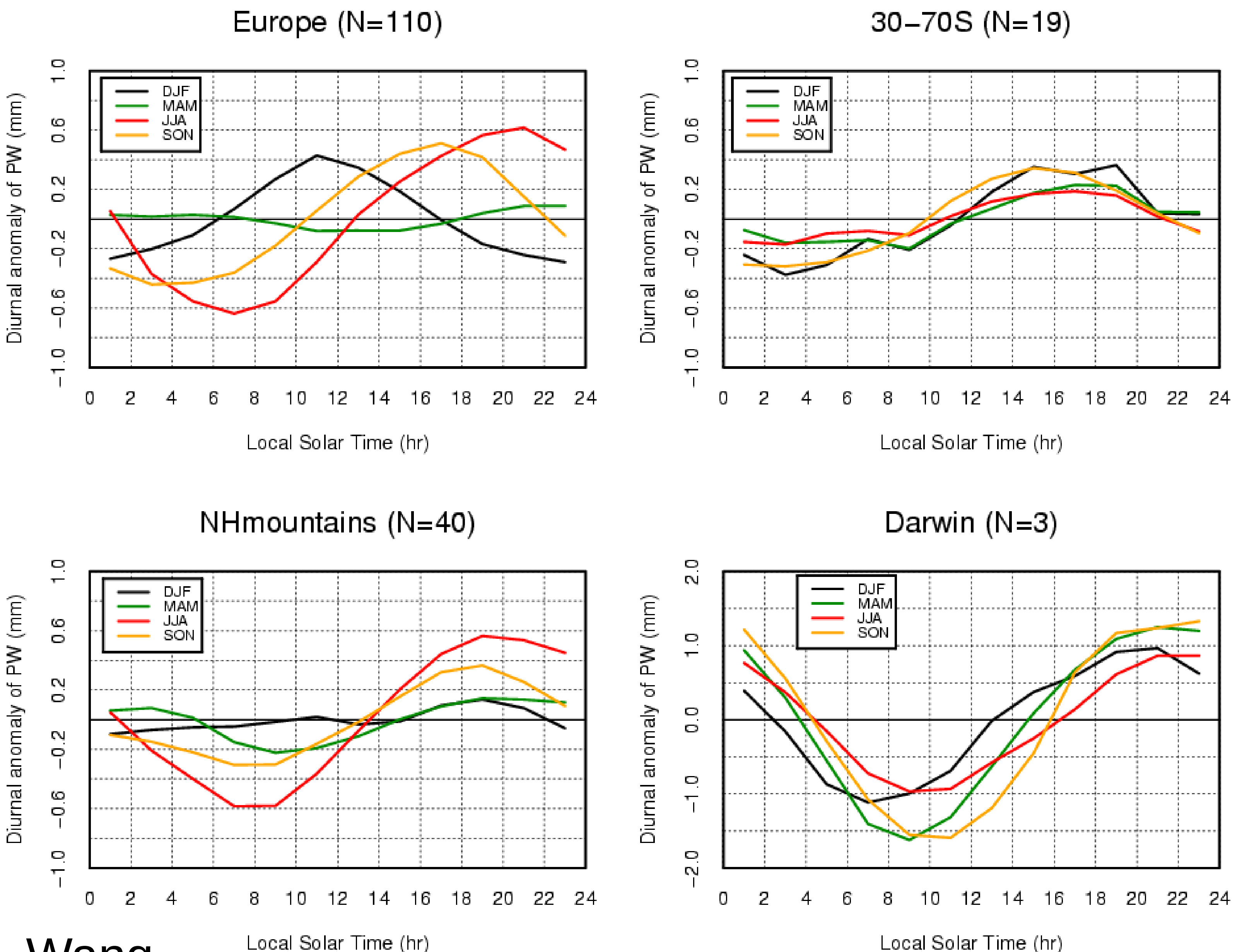




- **Total N = 305 sites (> 1000 days) used**
- **Trend Mean = 0.5724 mm/year**
- **Standard Error in the Mean = 0.0779 mm/year** (0.013 mm / year in PW)
- **The trend result is statistically meaningful**

S. Byun, JPL

Diurnal variations of PW

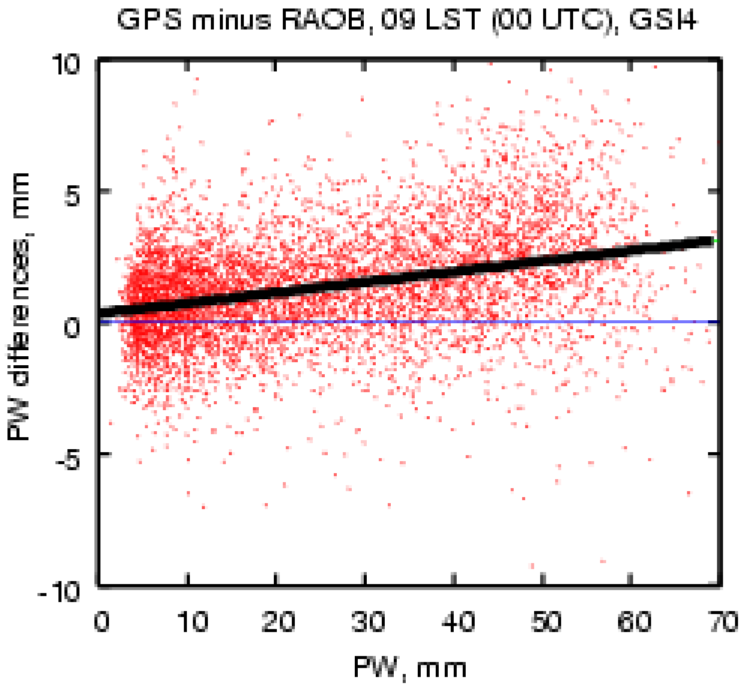


J. Wang

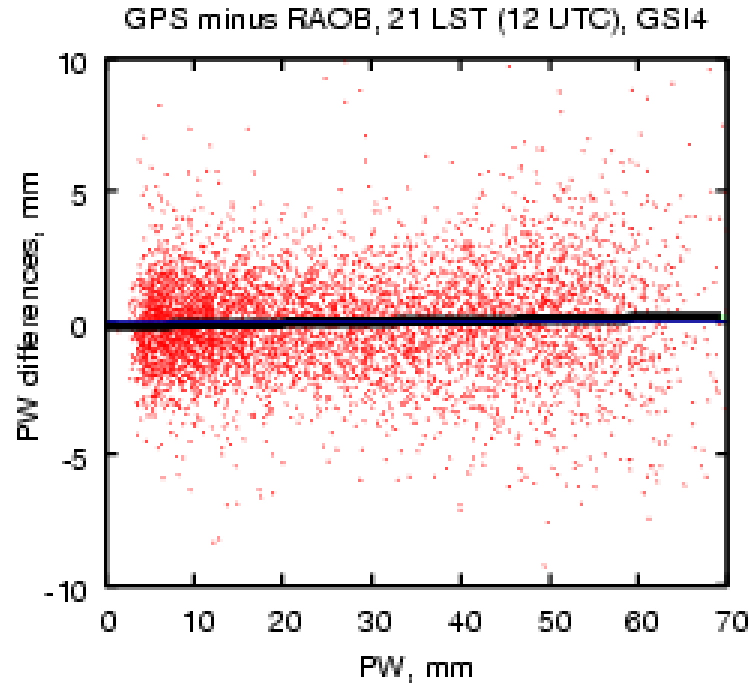
2004 - 2005 GPS minus Radiosonde comparison
all Japanese Radiosonde launches

Radome type 4

Daytime - 09:00 AM



Nighttime - 09:00 PM



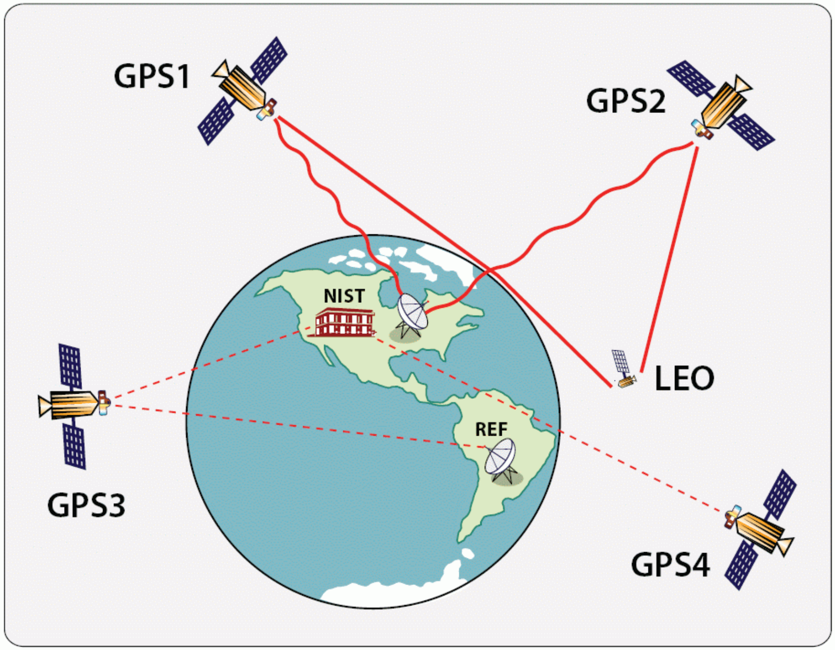
Comparison with GPS shows a ~5% radiosonde dry bias for daytime radiosonde launches

T. Iwabuchi

Ground Based GPS Integrated Water Vapor (IWV) Observations for GCOS

- Accuracy is ~ 1 mm in PWV, long term drift is essentially “not detectable” (avoid changing monuments or antennas!)
- Observations with long-term stability have value for climate monitoring / model testing on their own
- High temporal resolution can help resolve diurnal cycle of water vapor - to test if models get it right
- Instruments can provide a stable baseline against which to validate radiosondes
- Data also needed for sea-level change (to separate tectonic deformation and sea level change)

GPS Radio Occultation



Profiles refractive index vs. height

~100 meter vertical resolution

~500 km horizontal resolution

~500 soundings per day per LEO (24 GPS satellites)

Traceable to NIST definition of second.

COSMIC:

Constellation Observing System for Meteorology, Ionosphere and Climate

National Space Program Office (Taiwan); UCAR COSMIC Project

Launched April 2006

6 satellites up to 3000 soundings per day

S. Leroy, Harvard

GCOS Meeting Seattle, 22-24 May 06

COSMIC launch picture provided by Orbital Sciences Corporation

Launch on April 14, 2006
Vandenberg AFB, CA

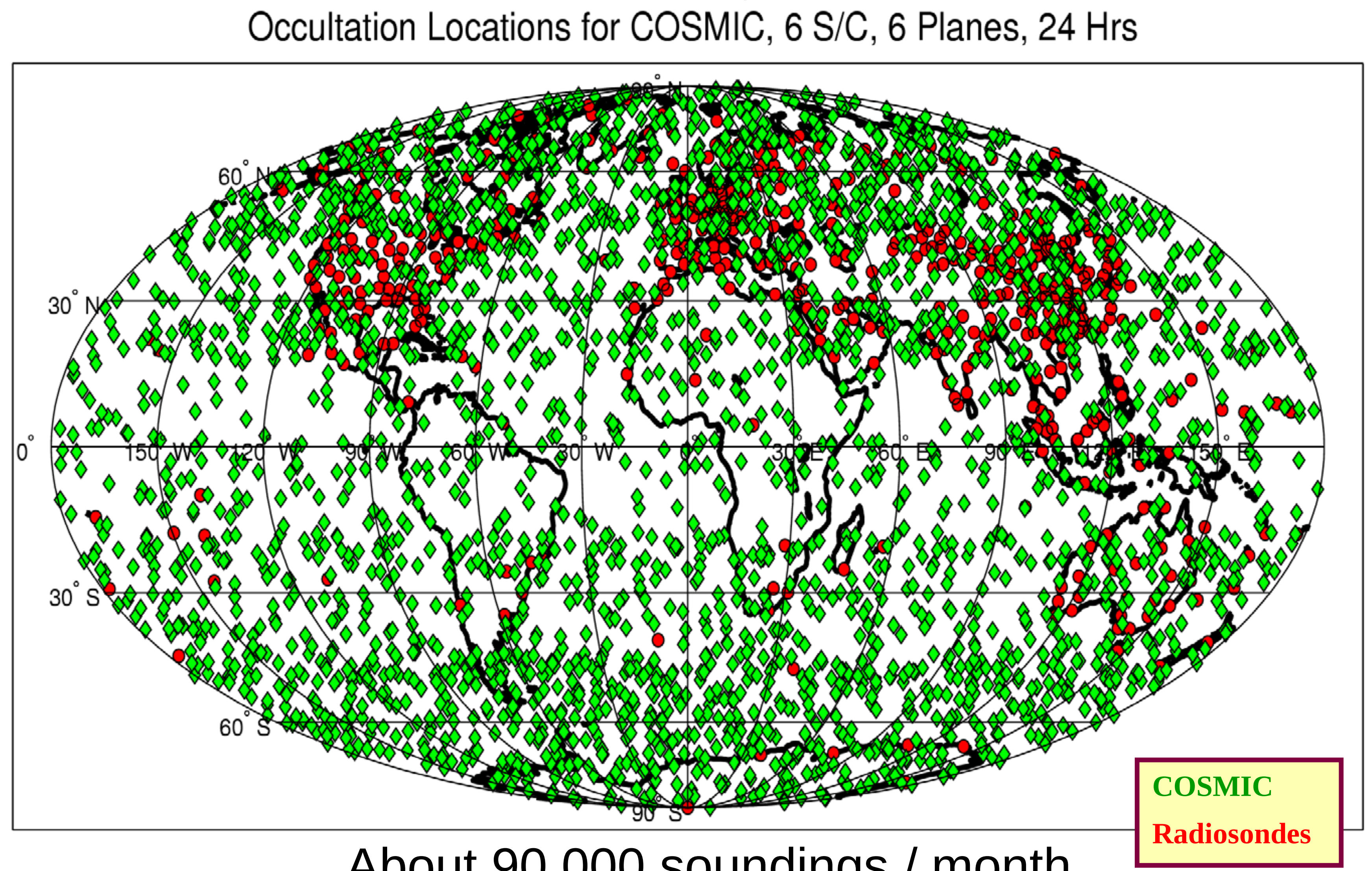
- All six satellites stacked and launched on a Minotaur rocket

- Initial orbit altitude ~500 km; inclination ~72°

- Will be maneuvered into six different orbital planes for optimal global coverage (at ~800 km altitude)

- All satellites are in good health and providing initial data

COSMIC Soundings in 1 Day



About 90,000 soundings / month

Or ~10 soundings / 2.5 x 2.5 pixel / month

All local times sampled every day!

Atmospheric refractive index $n = c / v$ where c is the light velocity in a vacuum and v is the light velocity in the atmosphere

Refractivity $N = 10^6 (n - 1)$

$$N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{P_w}{T^2} - 40.3 \times 10^6 \frac{n_e}{f^2}$$

(1) (2) (3)

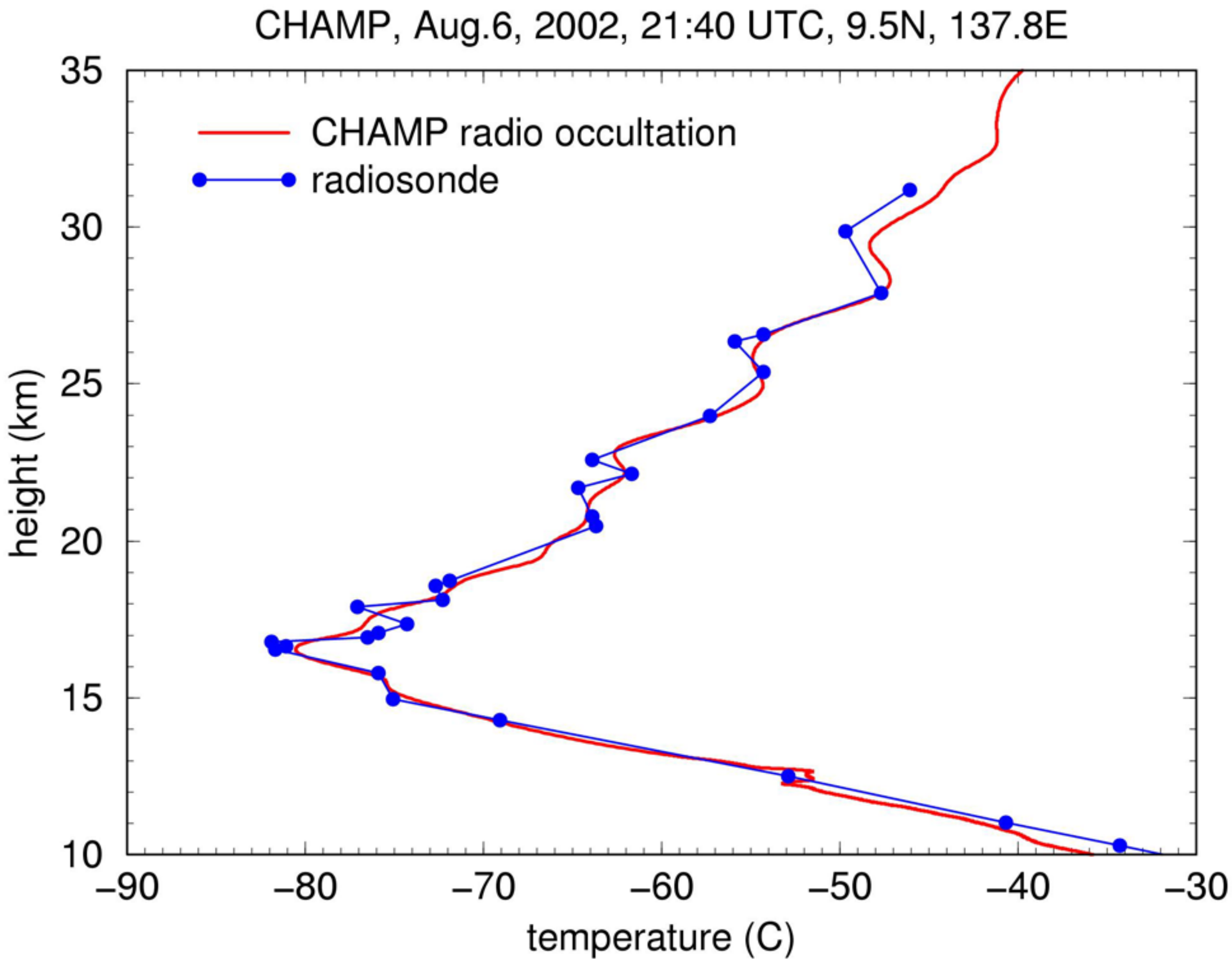
- Hydrostatic dry (1) and wet (2) terms dominate below 70 km

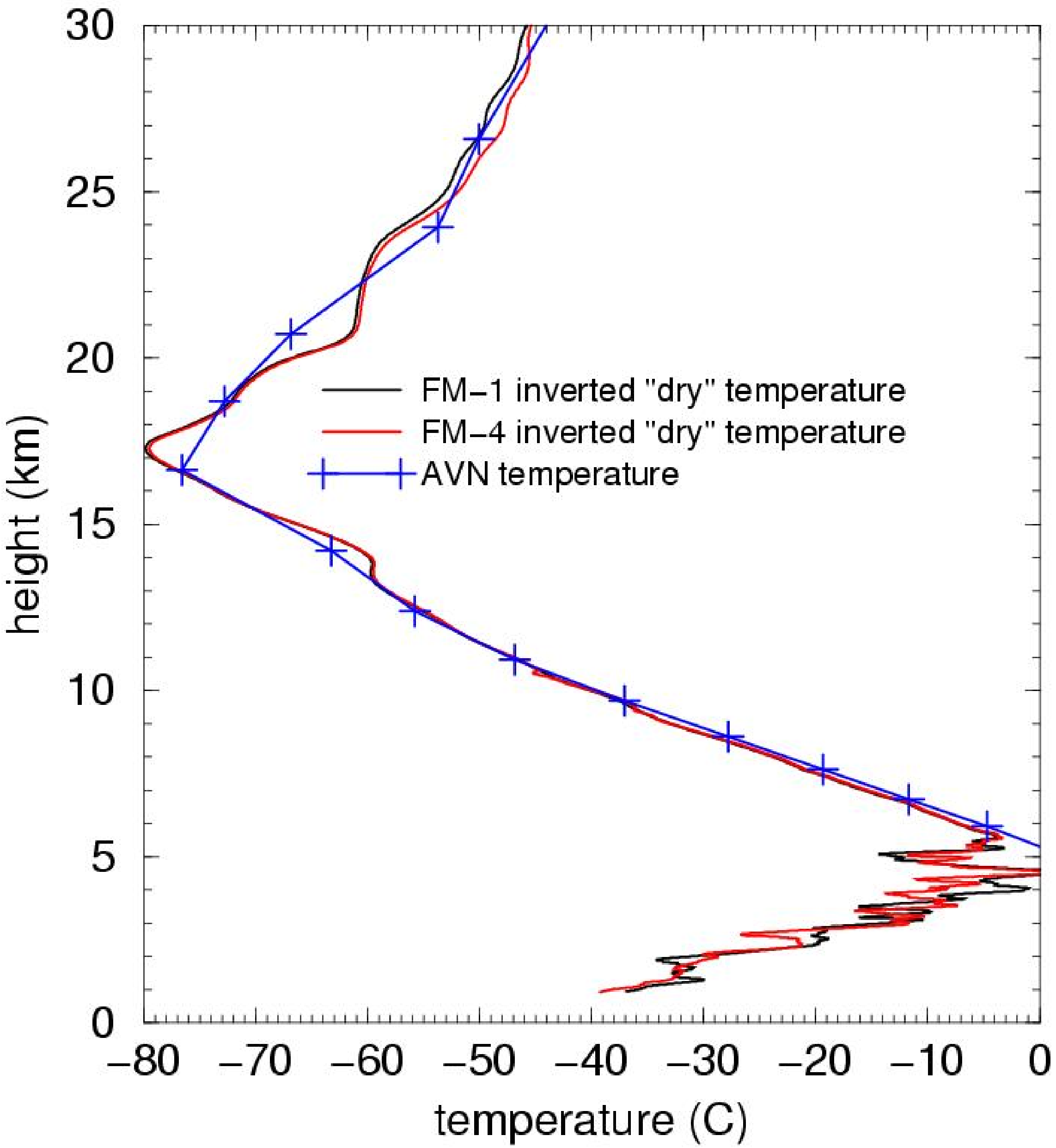
- Wet term (2) becomes important in the troposphere and can constitute up to 30% of refractivity at the surface in the tropics

- In the presence of water vapor, external information information is needed to obtain temperature *and* water vapor

- Liquid water and aerosols are generally ignored

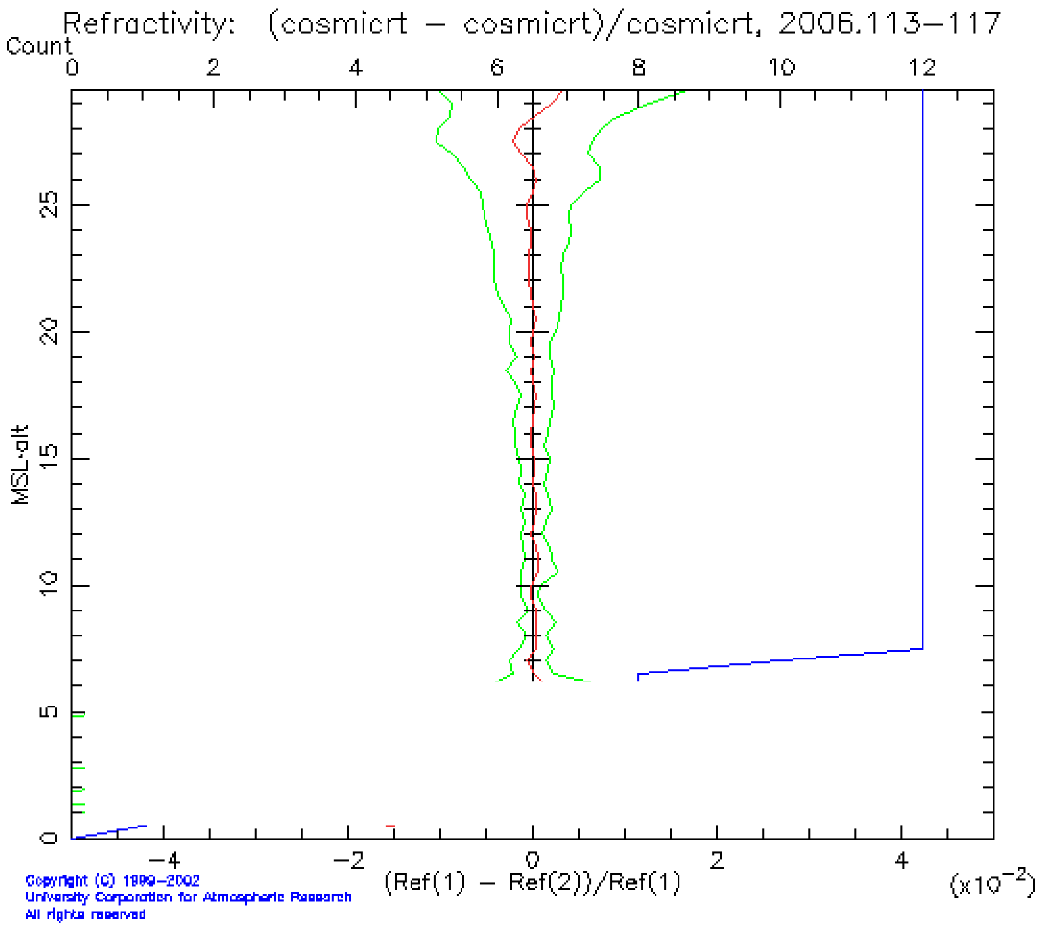
- Ionospheric term (3) dominates above 70 km


CHAMP, Aug.6, 2002, 21:40 UTC, 9.5N, 137.8E
CHAMP radio occultation
radiosonde
height (km)
35
30
25
20
15
10
temperature (C)
−90
−80
−70
−60
−50
−40
−30


30
25
20
15
10
5
0
height (km)
−80
−70
−60
−50
−40
−30
−20
−10
0
temperature (C)
FM−1 inverted "dry" temperature
FM−4 inverted "dry" temperature
AVN temperature

Refractivity Comparison Between Different COSMIC Satellites

(commissioning phase results)

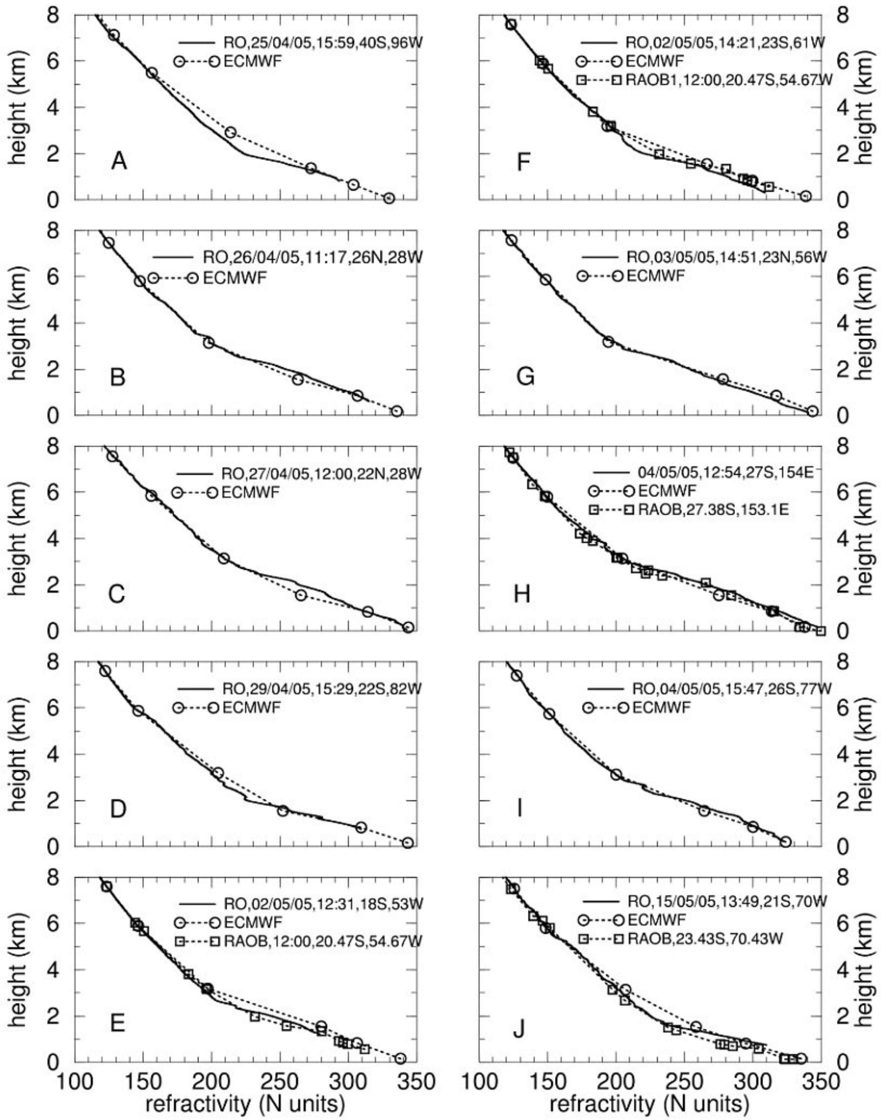


Comparison shows:

No bias 6-25 km

Precision 0.15%

Accuracy 0.15%



Radio Occultation profiles the Planetary Boundary Layer (PBL)

Open Loop Tracking data from “SAC-C” satellite

… requirements from Boulder GCOS meeting

(Workshop I)

Variable	Temperature	Water Vapor	Pressure
Priority (1-4)	1	1	1
Measurement Range	100-350 K	0.1 ppm to 55 g/kg	1 to 1100 hPa
Vertical Range	0 km to stratopause	0 to ~30 km	0 km to stratopause
Vertical Resolution	0.1 km (surface to ~30 km) 0.5 km (above ~30 km)	0.05 km (surface to 5 km) 0.1 km (5 to ~30 km)	0.1 hPa
Precision	0.2 K	0.1 g/kg in lower troposphere 0.001 g/kg in upper troposphere 0.1 ppm stratosphere	0.1 hPa
Accuracy	0.1 K in troposphere 0.2 K in stratosphere	0.5 g/kg in lower troposphere 0.005 g/kg in upper troposphere 0.1 ppm stratosphere	0.1 hPa
Long-Term Stability	0.05 K[1]	[1]1%	0.1 hPa
Comments	[1]The signal over the satellite era is order 0.1-0.2K/decade (Section 2.1.1) so long-term stability needs to be order of magnitude smaller to avoid ambiguity.	[1]Stability is given in percent, but note that accuracy and precision vary by orders of magnitude with height.	

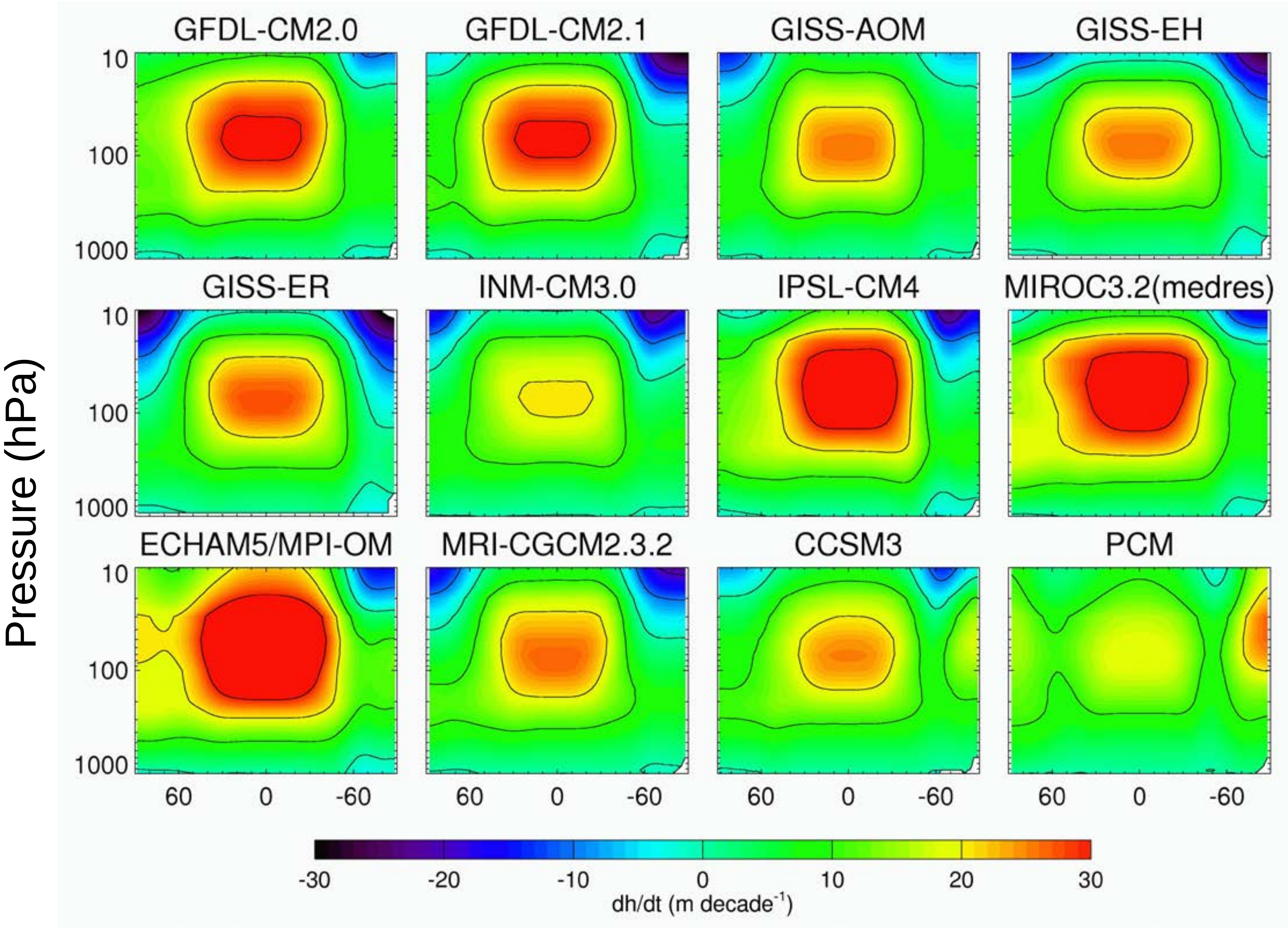
Variable	Temperature	Water Vapor	Pressure
Priority (1-4)	1	1	1
Measurement Range	100-350 K 100-350 K	0.1 ppm to 55 g/kg 0-30 hpa	1 to 1100 hPa 1 -1100 hPa
Vertical Range	0 km to stratopause 0-40 km	0 to ~30 km 0 - 10 km	0 km to stratopause 0-40 km
Vertical Resolution	0.1 km (surface to ~30 km) 0.5 km (above ~30 km) 0.1 km (0-40 km)	0.05 km (surface to 5 km) 0.1 km (5 to ~30 km) 0.1 km (0-10 km)	0.1 hPa
Precision	0.2 K 0.1 K (5-15+ km)	0.1 g/kg in lower troposphere 0.001 g/kg in upper troposphere 0.1 ppm stratosphere 1% 5-10 km	0.1 hPa
Accuracy	0.1 K in troposphere 0.2 K in stratosphere 0.1 K (5-15+ km)	0.5 g/kg in lower troposphere 0.005 g/kg in upper troposphere 0.1 ppm stratosphere	0.1 hPa
Long-Term Stability	0.05 K[1] No Detectable Drift	[1]1%	0.1 hPa No Detectable Drift
Comments	[1]The signal over the satellite era is order 0.1-0.2K/decade (Section 2.1.1) so long-term stability needs to be order of magnitude smaller to avoid ambiguity.	[1]Stability is given in percent, but note that accuracy and precision vary by orders of magnitude with height. RO does not directly measure water vapor - assumed refractivity errors and perfect temperature	Note that RO measures pressure as function height

Variable	Temperature	Water Vapor	Pressure	Refractivity
Priority (1-4)	1	1	1	1
Measurement Range	100-350 K 100-350 K	0.1 ppm to 55 g/kg 0-30 hpa	1 to 1100 hPa 1 -1100 hPa	0.3 - 400 1 - 400
Vertical Range	0 km to stratopause 0-40 km	0 to ~30 km 0 - 10 km	0 km to stratopause 0-40 km	0 km to stratopause 0-40 km
Vertical Resolution	0.1 km (surface to ~30 km) 0.5 km (above ~30 km) 0.1 km (0-40 km)	0.05 km (surface to 5 km) 0.1 km (5 to ~30 km) 0.1 km (0-10 km)	0.1 hPa	0.1 km 0.1 km
Precision	0.2 K 0.1 K (5-15+ km)	0.1 g/kg in lower troposphere 0.001 g/kg in upper troposphere 0.1 ppm stratosphere 1% 5-10 km	0.1 hPa	0.1 % 0.05 % (5-15 + km)
Accuracy	0.1 K in troposphere 0.2 K in stratosphere 0.1 K (5-15+ km)	0.5 g/kg in lower troposphere 0.005 g/kg in upper troposphere 0.1 ppm stratosphere	0.1 hPa	0.1 % 0.05 %
Long-Term Stability	0.05 K[1] No Detectable Drift	[1]1% No Detectable Drift	0.1 hPa No Detectable Drift	0.025% No Detectable Drift
Comments	[1]The signal over the satellite era is order 0.1-0.2K/decade (Section 2.1.1) so long-term stability needs to be order of magnitude smaller to avoid ambiguity.	[1]Stability is given in percent, but note that accuracy and precision vary by orders of magnitude with height. RO does not directly measure water vapor - assumed refractivity errors and perfect temperature	Note that RO measures pressure as function height	Should be included in requirement matrix for future systems.

While RO can provide data to satisfy several requirements from the first GCOS workshop it can best measure quantities that were not included there: i.e. Refractivity or Geopotential heights

Geopotential Height Trends

12 different models



IPCC 4th assesement report created CMEP SRES A1B (+1% CO_2/year until doubling).

S. Leroy

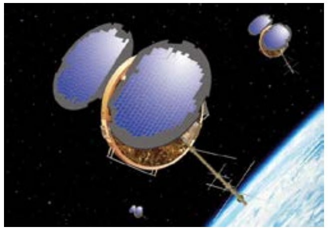
GCOS Meeting Seattle, 22-24 May 06

Because RO determines height and pressure independently it can provide information not available from nadir viewing radiometers

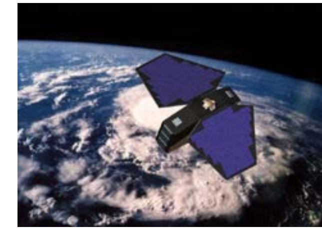
RO can measure geopotenital height (height of a given pressure above geoid) with an accuracy of ~10 m (better with averaging)

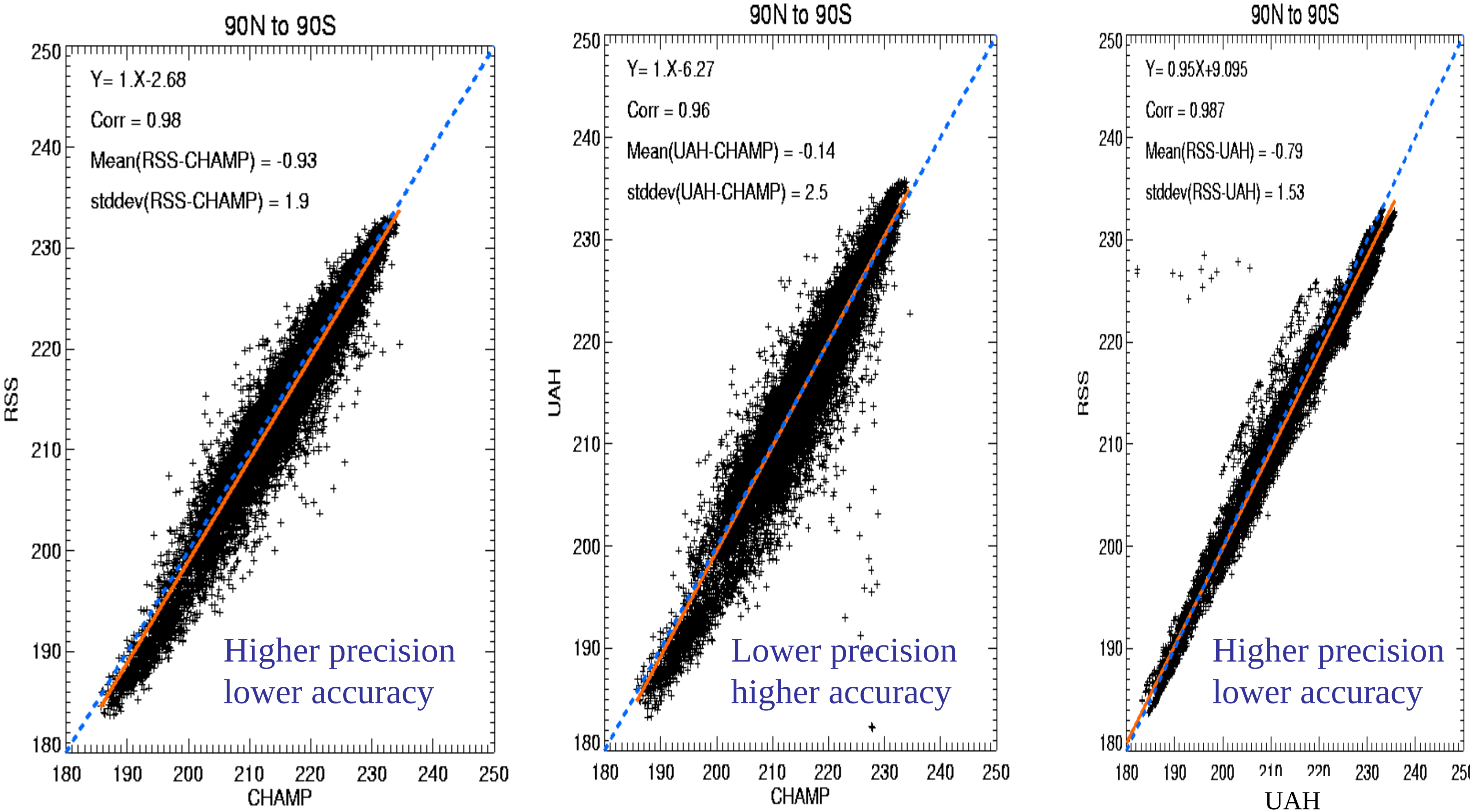
Differences between geopotential heights can be measured by RO to ~0.5 meters in 5-15 km range

Trends (of 10-20 m / decade according to last slide) are detectable by RO and should be used for model testing.



Matched pairs of CHAMP, RSS and UAH for each 10x10 grid for all 51 months





Ben Ho, UCAR

26036 pair of pixels are included

GPS Radio occultation will soon provide ~90,000 high quality global profiles per month (some soundings will be collocated with GCOS Upper Air Networks)

These profiles can meet many requirements for climate sensing

Measurements free of drift and traceable NIST clock