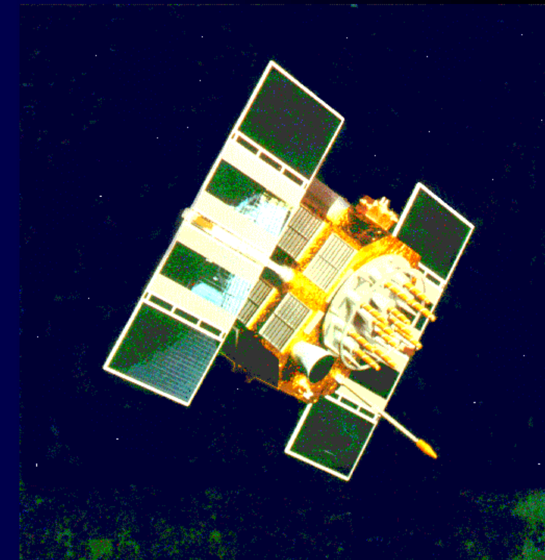

Comparisons of Precipitable Water over Canada Obtained from Ground-based GPS, Radiosondes and GEM Global Analyses and 6-h (Trial) Forecasts

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Centre météorologique canadien

Environment Canada
Canadian Meteorological Centre

ARMA

Outline

1. EC/NRCan Ground-Based GPS project
2. NRCan GPS sites
3. Orbits and ZTD (Zenith Tropospheric Delay) products
4. Sensing PW using Ground-based GPS/ Applications of Ground-based GPS PW
5. Deriving precipitable water from GPS data/ GPS_PW Error Analysis
6. Intercomparison results (GPS, RS, ANAL/TRIAL PW)
7. Estimation of GPS_PW observation error
8. Comparison of GPS ZTD from 2 sources: NRCan and IGS
9. Ground-based GPS in US
10. Conclusions & future work

EC/NRCan Ground-Based GPS Project

• Joint project with Geodetic Survey Division (GSD) of Natural Resources Canada (NRCan) to explore the benefits of GPS measurements for meteorology in Canada and exchange data, products, information and expertise to benefit each other's R+D program.

Activities:

• GSD to provide EC : GPS zenith tropospheric delay estimation + GPS met data

• EC: Evaluation of GPS derived PW (GPS_PW) for possible assimilation in NWP

  • Intercomparison of GPS_PW, PW from radiosondes (RS_PW) and GEM operational analyses and trials (ANAL_PW, TRIAL_PW)

• EC to report results of study to GSD

Precipitable Water (PW)
Integrated Water Vapour (IWV)

$$PW = \frac{1}{\rho_W g} \int_{top}^{sfc} q \, dp$$

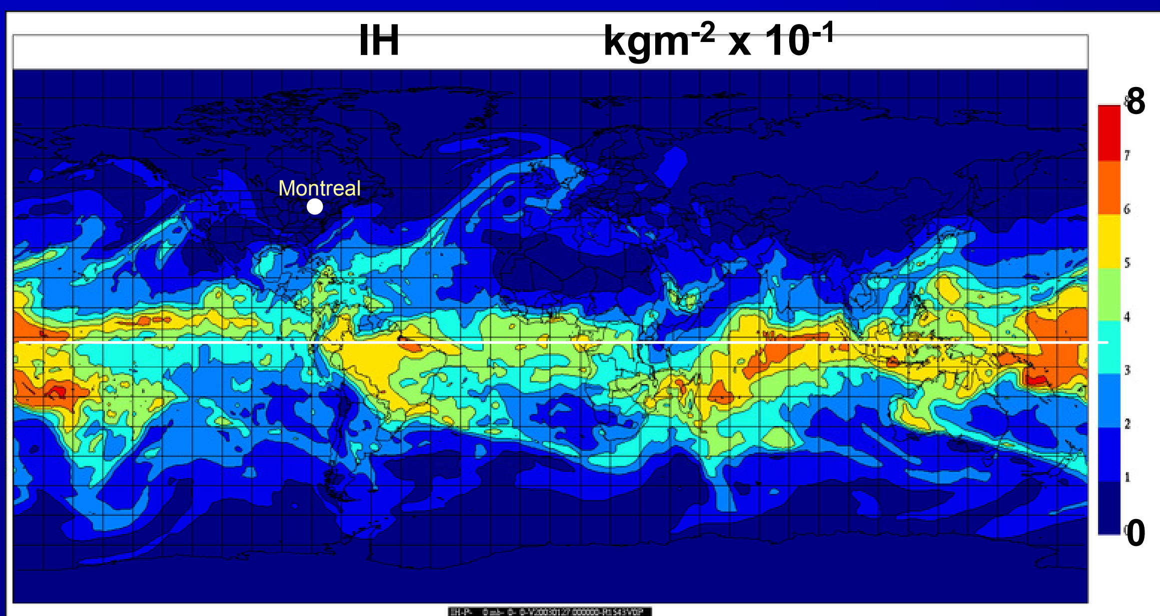
; ***q*** = spec. humidity (HU)

$$IWV = \frac{1}{g} \int_{top}^{sfc} q \, dp$$

$0 < \boldsymbol{IWV} < 80\ \mathrm{kgm}^{-2}$

$0 < \boldsymbol{PW} < 80\ \mathrm{mm}$

January IWV snapshot from GEM (IH field)

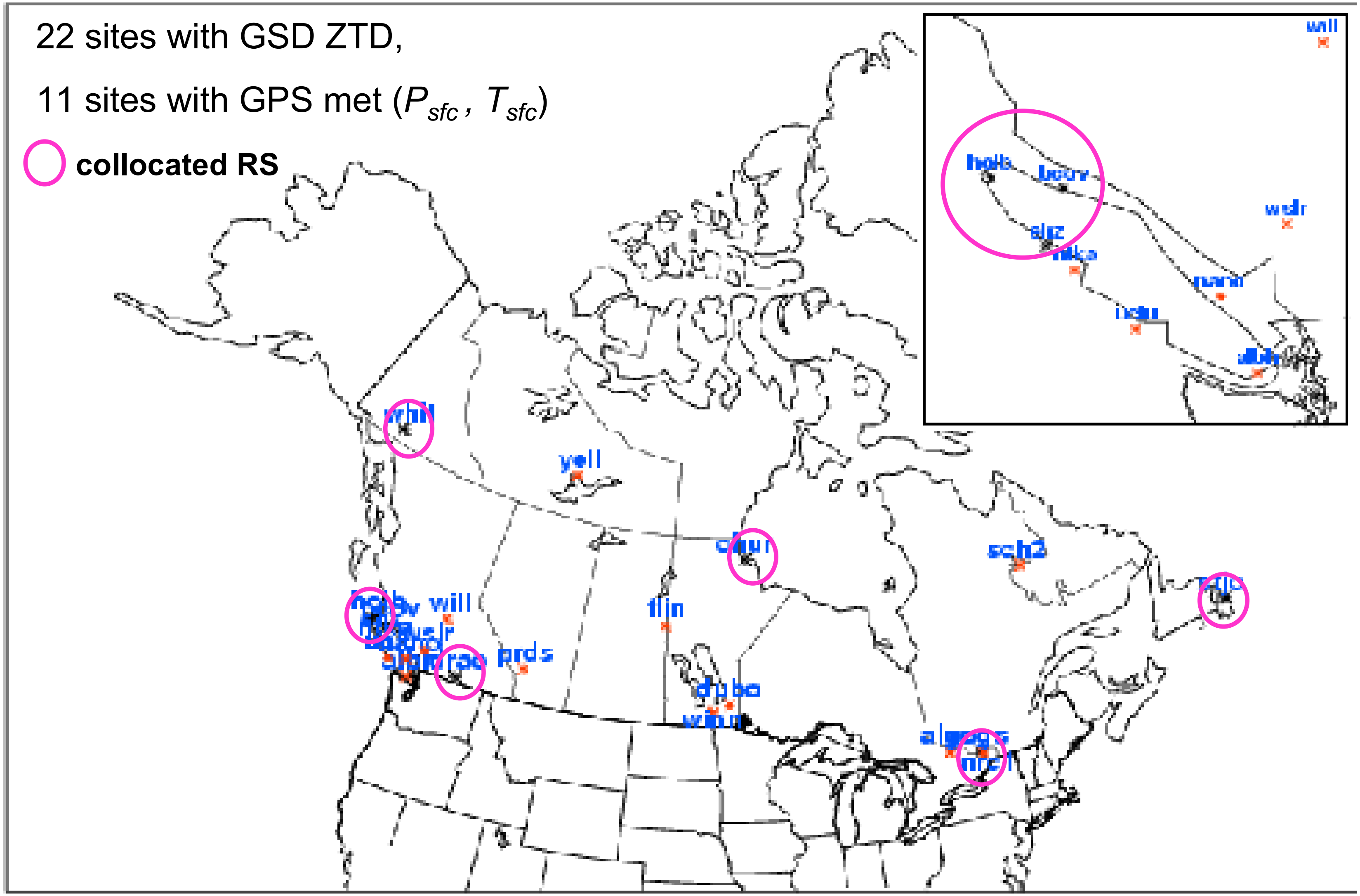


NRCan GPS Sites

22 sites with GSD ZTD,

11 sites with GPS met (P_{sfc} , T_{sfc})

collocated RS



Orbits and ZTD Products for GPS Meteorology

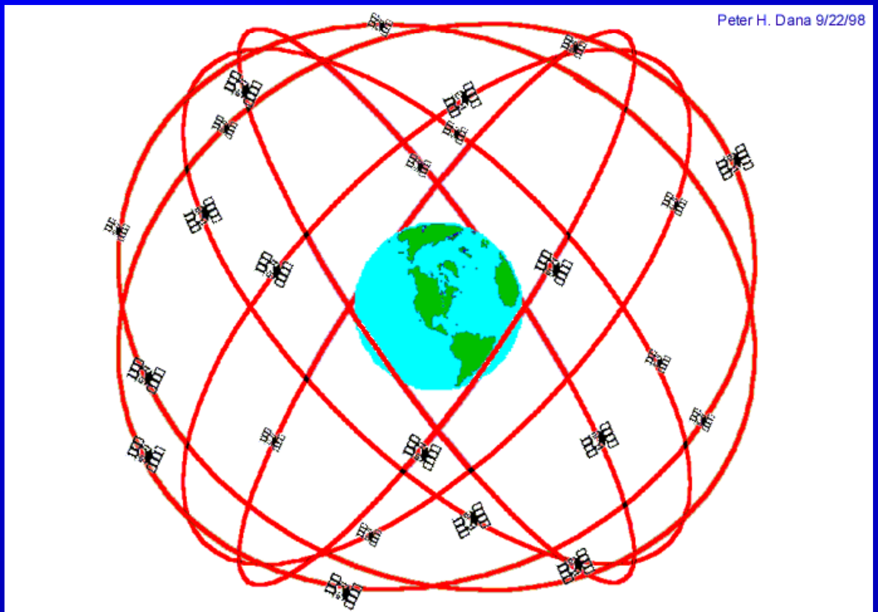
	Latency	ZTD Latency	ZTD Accuracy
Broadcast forecast	real-time	*NA*	*not accurate enough*
Ultra-rapid forecast	real-time	~1 hour	6 mm
Rapid observed	17 hours	*NA*	4+ mm
Final observed	~13 days	~2 weeks	4 mm

• final orbits provide most accurate ZTD and PW but latency prohibits real-time use. (final orbits were used by NRCan to determine ZTD for this study)

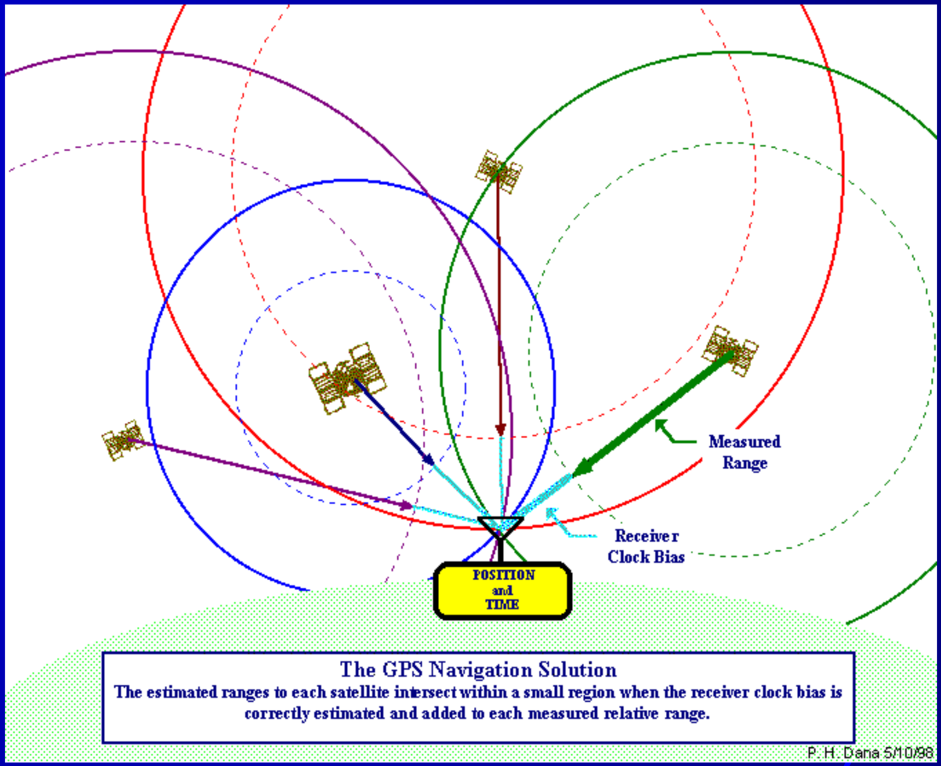
• ultra-rapid orbits consist of observed and <u>predicted</u> orbits updated twice a day. Predicted part can be used to provide satellite positions in real-time for ZTD estimation.

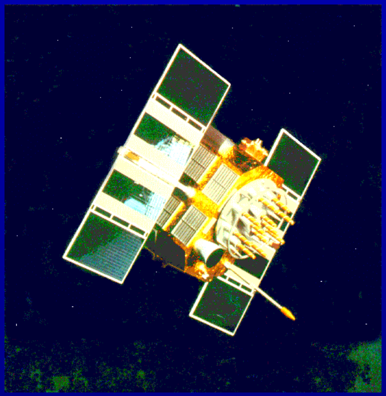
• accuracy of ultra-rapid ZTD not quite good enough yet for accurate GPS_PW. In the near-future, sufficiently accurate orbits will be available for use in real-time applications.

How GPS Works



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination





L1 1.575 GHz

L2 1.228 GHz

Dual Channel

Sensing PW using Ground-based GPS

- use attenuation (delay) of radio signals transmitted from GPS satellites due to water vapour in atmosphere to estimate PW at GPS receiver locations
- need accurate collocated surface pressure measurements (GPS met) to get PW from delay (for reasons explained later)
- global network of GPS receivers already exist (and growing)
- all-weather observations
- high temporal resolution
- no calibration requirements
- potential global coverage (over land). Some countries/geographical areas have dense networks for seismological applications (e.g. Japan, California).

Applications of Ground-based GPS PW

• data assimilation of PW for NWP ==> improved clouds, precipitation, moisture gradients

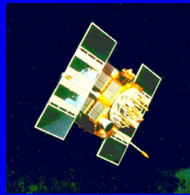
• comparison with other observations (e.g. satellite, WVR, RS)

• monitoring of global climate

• forecasting local storms and lightning (both very dependent on IWV)

• mesoscale & short-range forecasting (esp. precipitation)

• verification of NWP forecasts



History of ground-based GPS

- 1992: Bevis et al. (NCSU, MIT & UCAR) publish paper on proposed use of ground-based GPS network for measurement of IWV.
- 1993,1994: GPS/STORM and GPS-WISP94 field experiment in US ==> Accuracy of GPS_PW was shown to be comparable to WVR and RS.
- 1993: Kuo et al. demonstrate how assimilation of remotely sensed IWV into a mesoscale NWP model can improve short-range precipitation forecasts.
- Future: Galileo -- a European (ESA funded) rival to the current US DoD GPS satellite system. Galileo is designed to provide highly accurate navigation signals from a constellation of 30 satellites operating in the same frequency bands as GPS receivers. This system is projected to be operational by 2008.

GPS signal delay due to atmosphere

Z. DELAY

ionospheric (TEC)
(dispersive)

tropospheric (ZTD)

hydrostatic delay (ZHD)
atmospheric mass

wet delay (ZWD)
water vapour electric dipole moment

2200 - 2700 mm 90% 10%

ZTD = ZHD + ZWD

related to integrated water vapour (IWV)

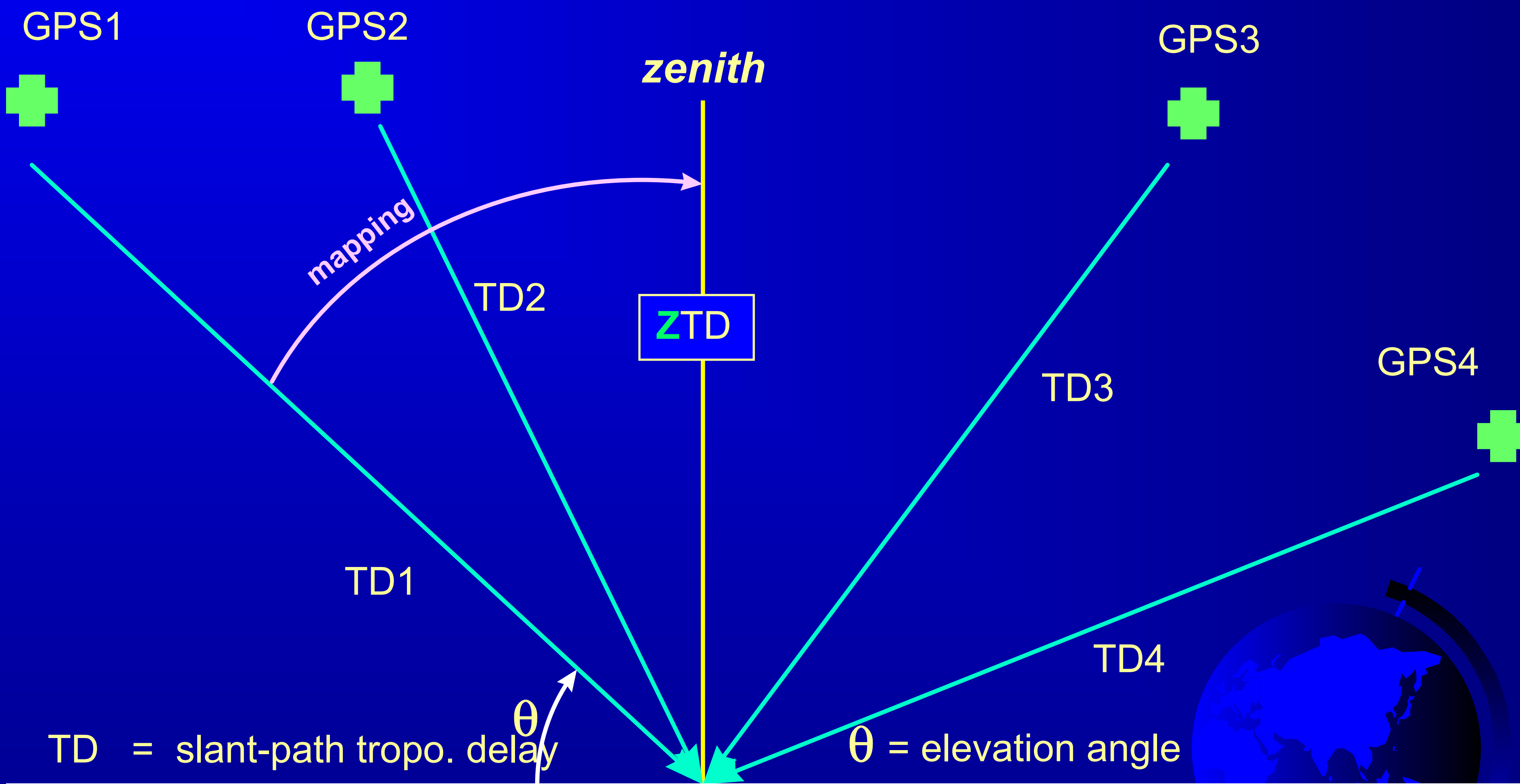
estimated in processing GPS data for network of GPS receivers

ideal setup:
collocated pressure sensor (GPS met)

integrated air density

= F(Psfc)

Slant Delay and Zenith Delay



TD = slant-path tropo. delay

ZTD = zenith tropo. delay

= AVG (ZTD1,…, ZTD4)

θ = elevation angle

TD1 = 1 / sin θ $*$ ZTD1

mapping function

Deriving Precipitable Water (PW) from GPS Data

$$PW(mm) = \frac{1}{\rho_w}\left(\frac{10^6}{(k_3 R_v / T_m) + k_2' R_v}\right)\underbrace{\left(ZTD - C_1 P_S f^{-1}(\lambda, H)\right)}^{ZWD}$$

Vapour-weighted mean temperature

$$T_m = \frac{\int (e/T)dz}{\int (e/T^2)dz}$$

• does not need to be known accurately

How do we get this?

==> calculated from ANAL, TRIAL

Delay estimates from NRCan

Surface pressure:

- **collocated barometer**
- **SYNO** within 50 km
- **ANAL, TRIAL**

This equation can be used to estimate sensitivity of GPS_PW to errors in ZTD, P_S and T_m. ==> next slide

Deriving Precipitable Water (PW) from GPS Data: Error sources

	Error	Error in PW
ZTD	4 mm (IGS)	0.6 mm 2% Moist --> 15% Dry
P_s	1 hPa (SYNO)	0.4 mm 1% Moist --> 10% Dry
T_m	5 K (2%)	0.07 mm Dry (2%) 0.72 mm Moist (2%)

Total PW error
~ 1– 2 mm

1 mm or 25% relative error for dry (PW = 4 mm)

Pressure (P_S) accuracy: PW

- on-site GPS met ==> 0.1 - 0.3 hPa [0.12 mm]
- synoptic, ANAL ==> 0.5 - 1.0 hPa [0.40 mm]
- TRIAL ==> 1.0 - 2.0 hPa [0.80 mm]

- For very dry conditions (PW = 0 to 10 mm) ZTD and P_s errors must be minimized or significant relative (%) errors in PW may result. Errors in T_m are not as important for dry conditions.

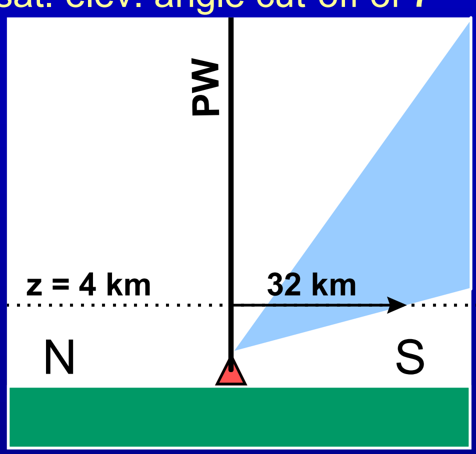
Differences in Sampling Volumes for GPS, RS & ANAL / TRIAL

Differences in effective sampling volumes for GPS_PW, RS_PW and ANAL/TRIAL_PW are important in understanding observed differences from intercomparisons such as done for this study.

GPS

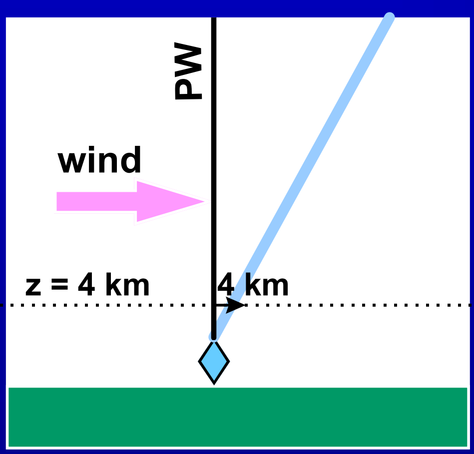
Sampling radius 32 km at 4 km height

sat. elev. angle cut-off of **7** °



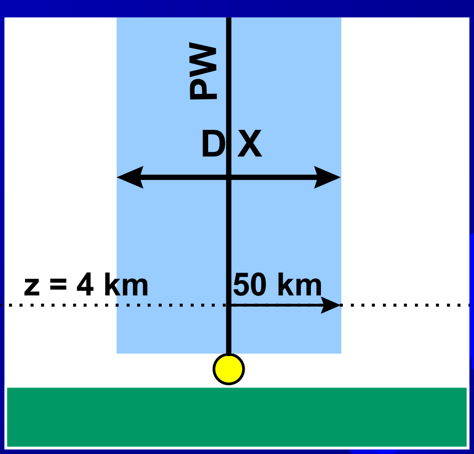
RS

4 km downwind at 4 km height



ANAL / TRIAL

50 km radius for DX = 100 km



DATA used in NRCan/EC Project

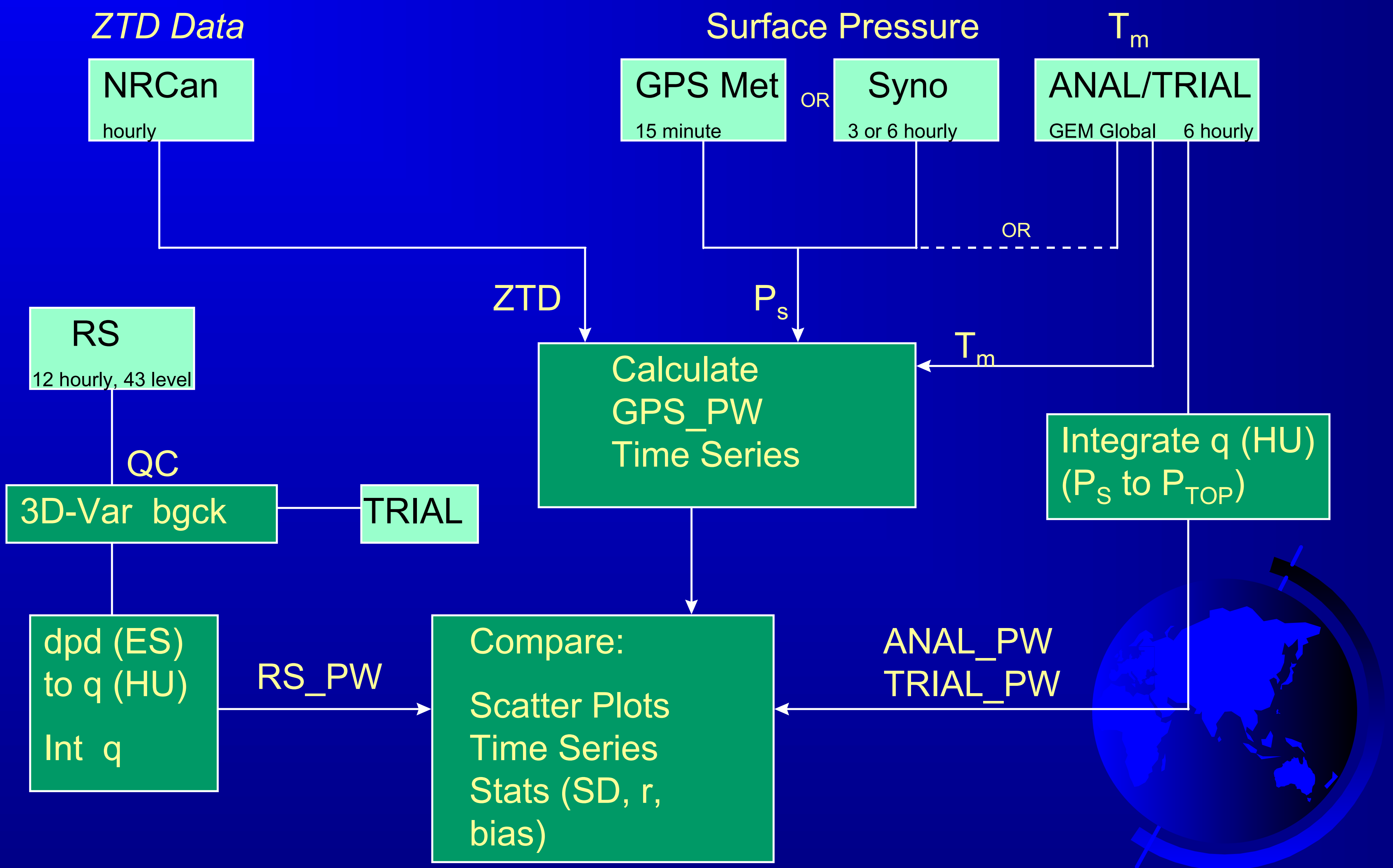
NRCan

- 4 months: April, July, October 2001 & January 2002
- hourly GPS ZTD data (22 sites), final orbit product.
- 15 minute GPS met data (11 sites)

EC

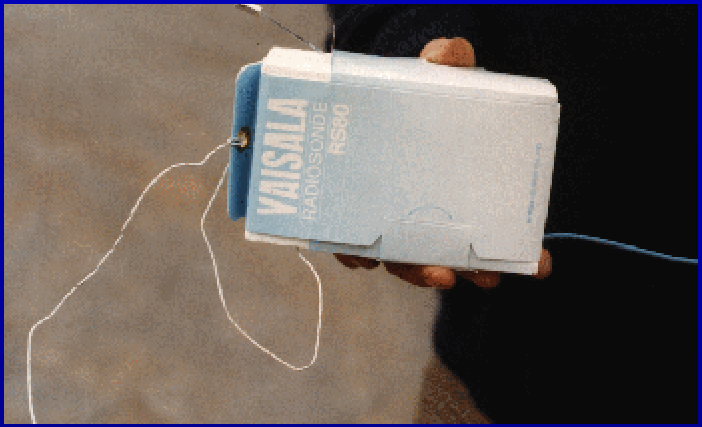
- RS data at 00Z, 12Z (8 GPS sites)
- ANAL/TRIAL at 00Z, 06Z, 12Z, 18Z   (22 sites)

Data Processing Overview



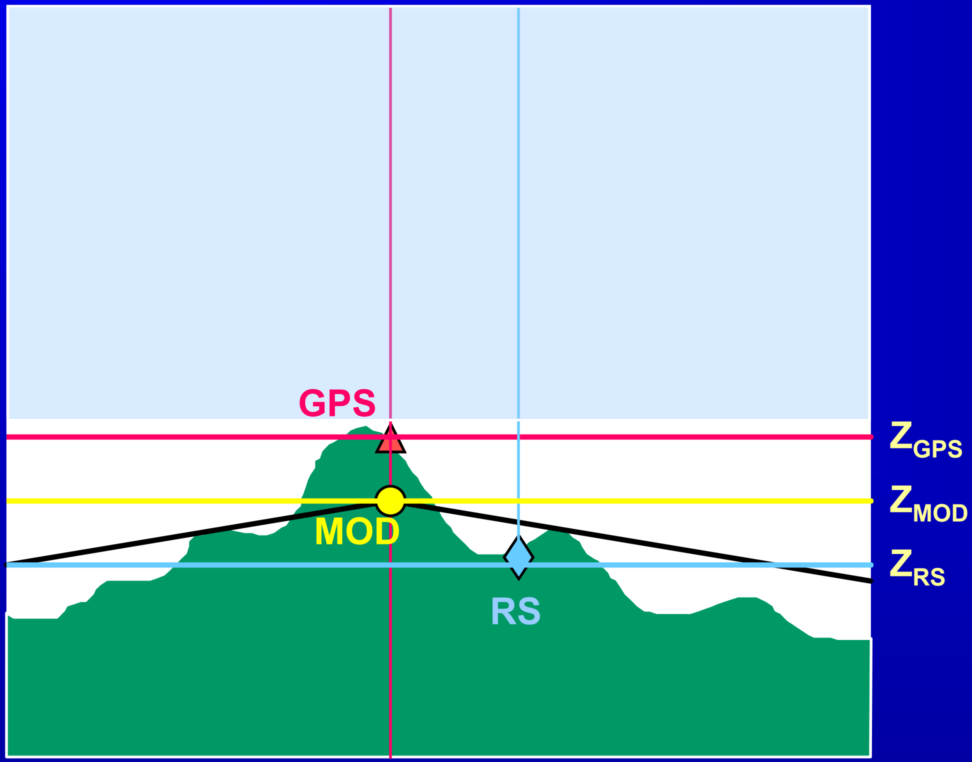
Radiosonde Data

- full vertical resolution data not available due to TEMP transmission format (MAND & SIG levels only)
- boundary layer humidity often is not assimilated due to differences between model and real surface topography (will affect ANAL_PW and TRIAL_PW)
- there is a known dry bias of RH sensor on Vaisala sondes ==> underestimate of RS_PW ==> ANAL too dry
- may be coding errors in TEMP messages



Vaisala RS80 radiosonde

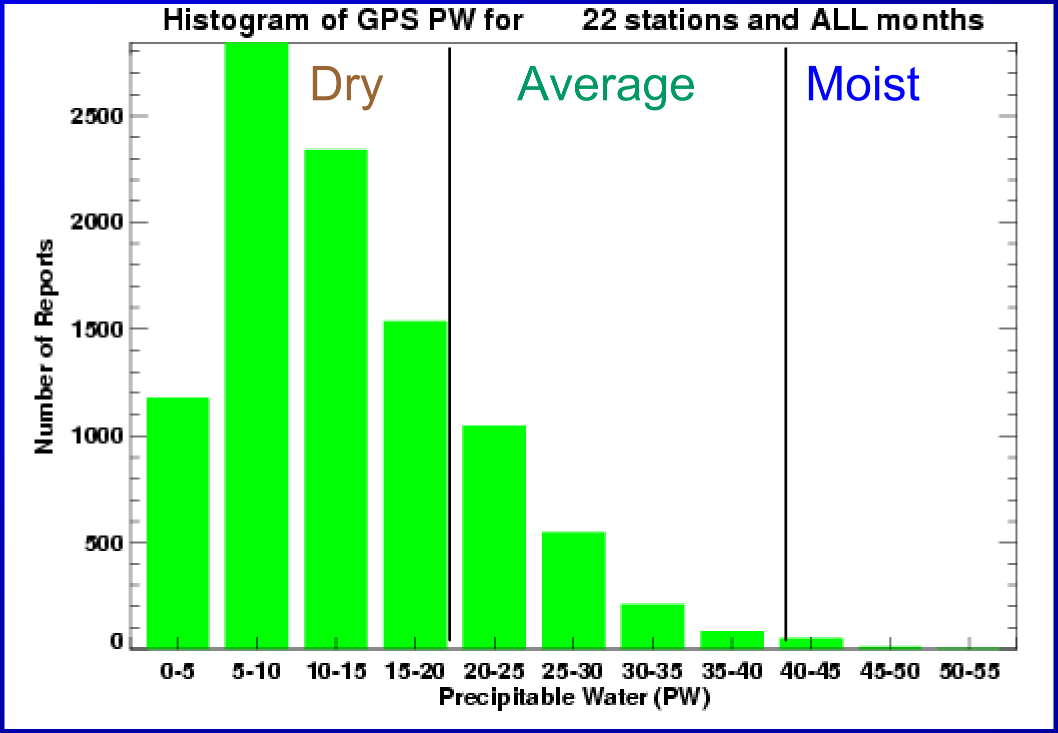
Surface Elevation Differences for RS, GPS and MOD (ANAL or TRIAL)



- must begin vertical integration of q at height of GPS receiver (Z_{GPS})
- integration with respect to pressure: use hydrostatic approx. to determine starting pressure (pressure at Z_{GPS})

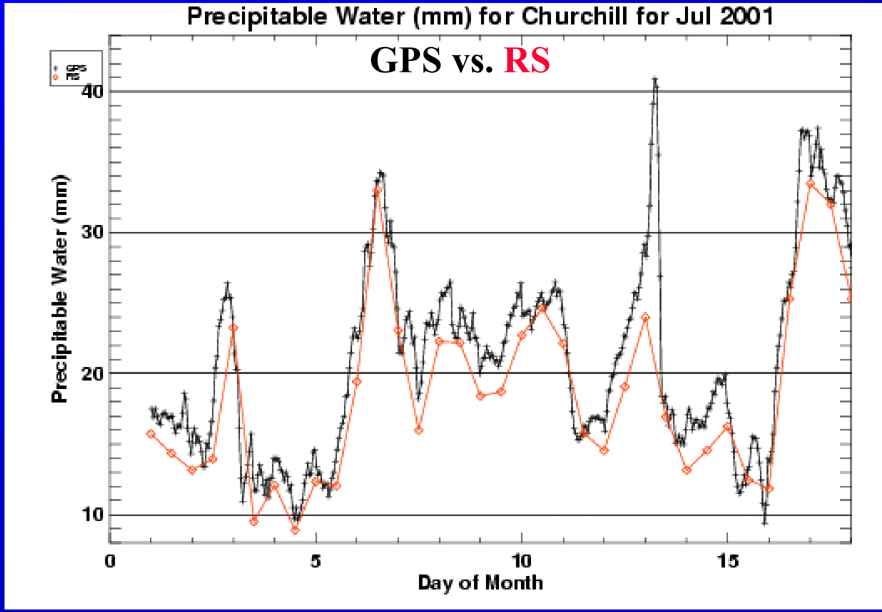
- MOD surface elevation is smoothed so in general Z_{MOD} is different from Z_{GPS} (and Z_{RS})

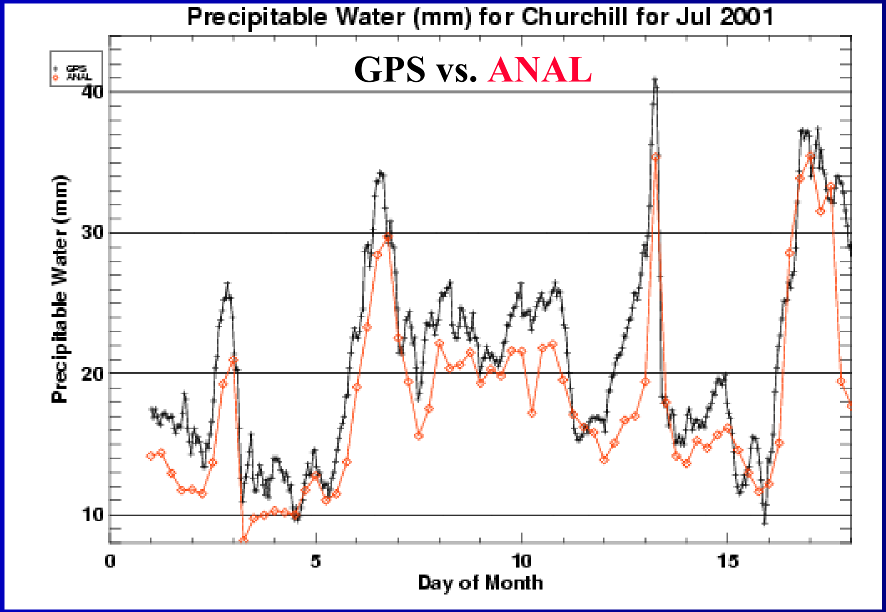
Range of PW observed by GPS (April, July, October 2001, January 2002)

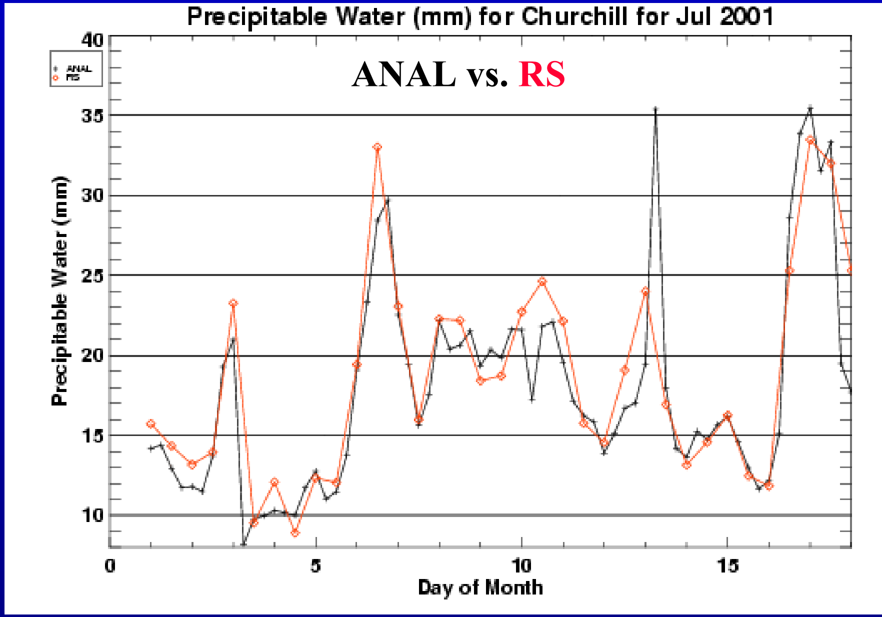


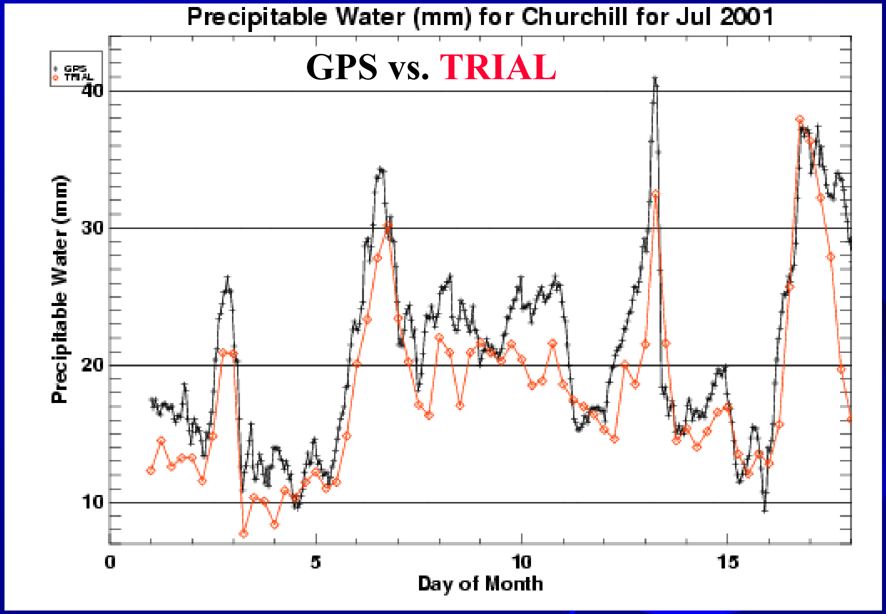
- Most obs are in “dry” zone reflecting Canadian climate
- 4-month comparison statistics that follow therefore based mostly on PW data for dry conditions (PW 0 to 20 mm)

PW Time Series: Examples

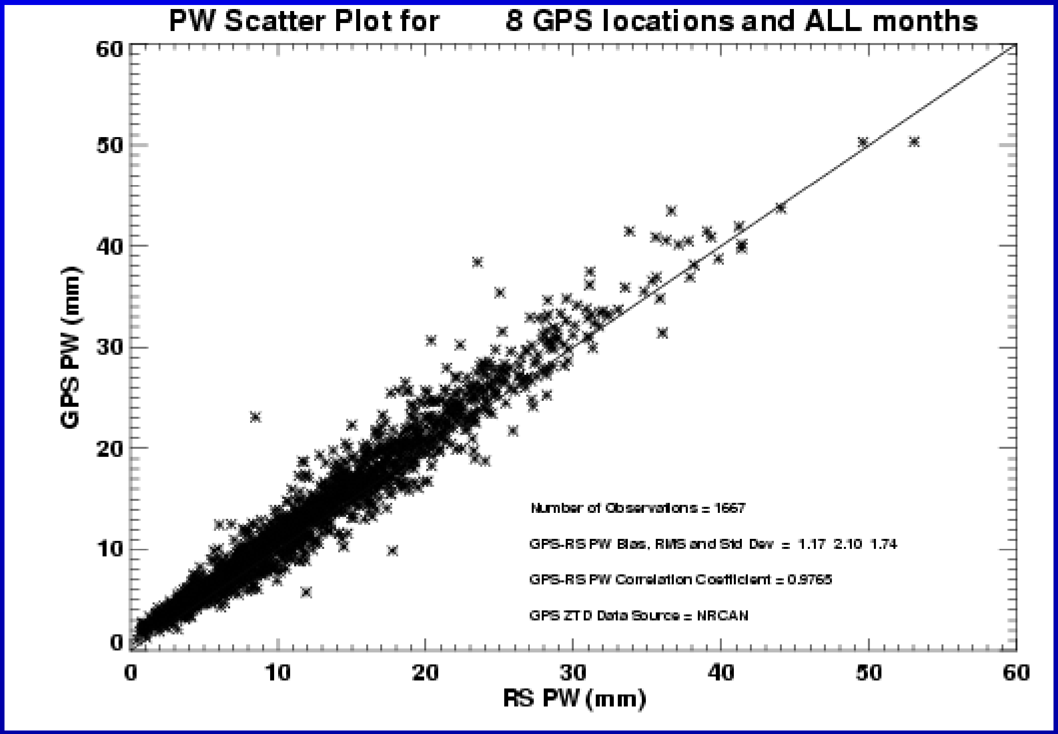








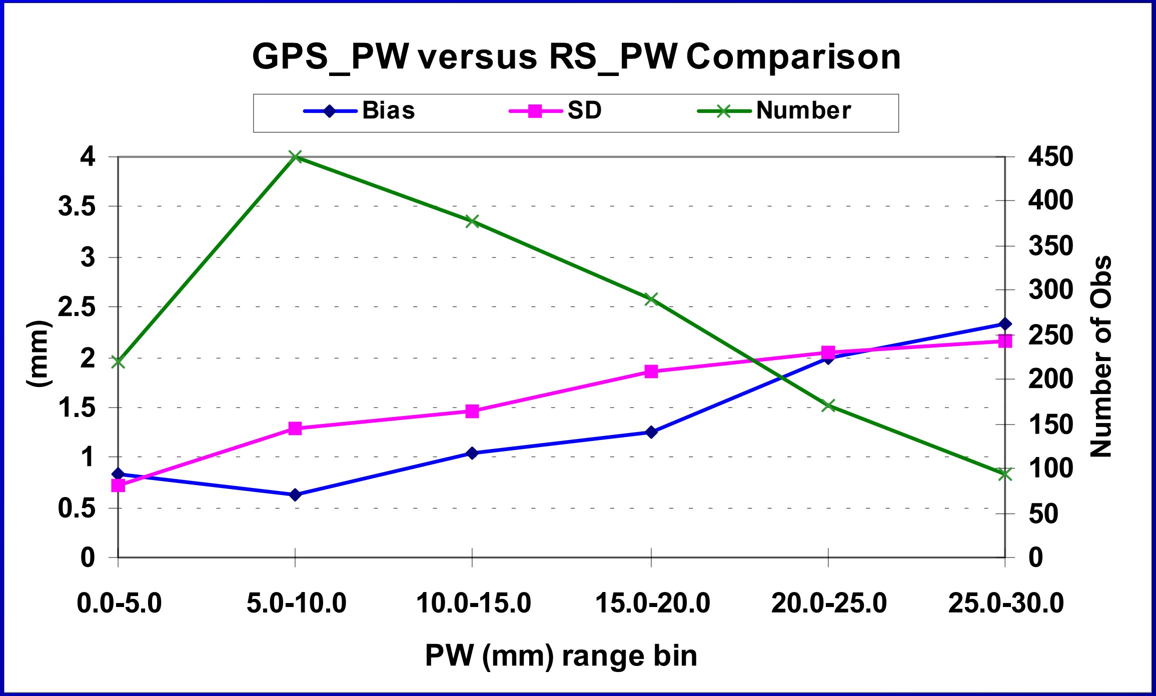
GPS_PW compared with RS_PW



- 00Z, 12Z observations
- April, July, October 2001 January 2002
- Bias = +1.17 mm
- SD = 1.74 mm

- high correlation (r = 0.98)
- moist (+ve) bias of GPS_PW consistent with dry bias of RS
- not a lot of points for PW > 25 mm
- there are a few notable outliers (max diff. = 15 mm)

Variation of GPS-RS PW Bias and SD with PW



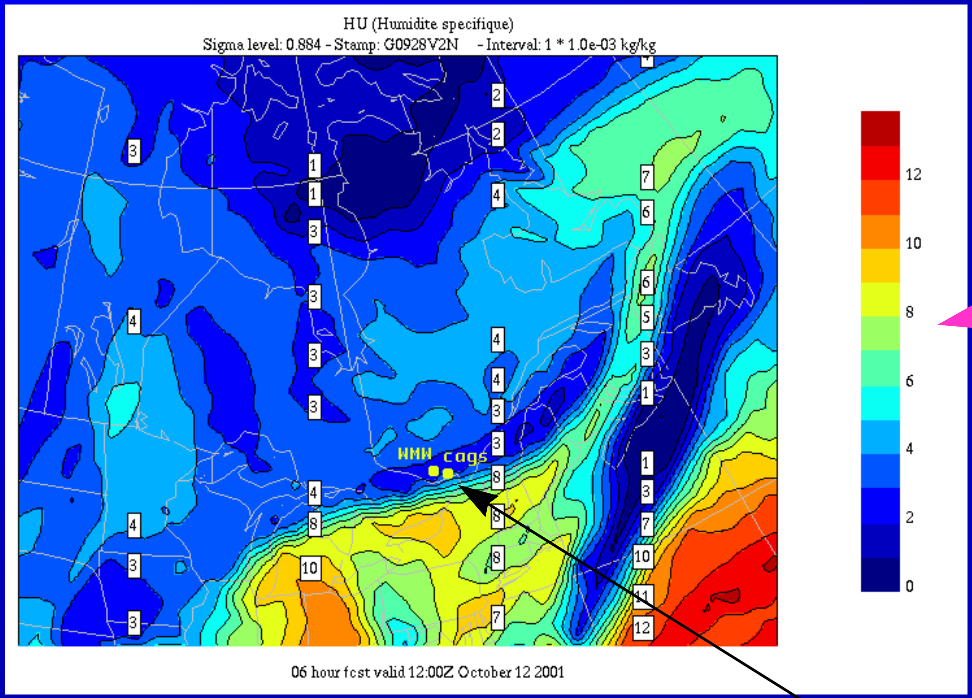
- cut-off at PW of 30 mm due lack of observations
- both bias and SD increase from ~ 1 mm to ~ 2 mm with increasing PW (0 to 30 mm)
- <u>relative</u> (%) bias and SD <u>decrease</u> with increasing PW, from 40% (dry) to 7% (moist)
- increasing absolute bias with PW may be related to dry RH bias of RS (about 10% in lower half of troposphere when RH > 60%).
- increasing SD with PW probably due to sampling differences which can be more significant in the presence of the stronger humidity gradients possible in higher PW conditions

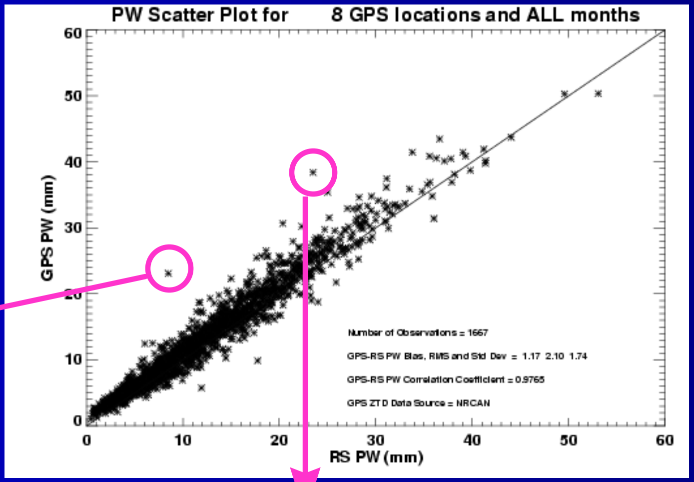
GPS_PW vs RS_PW: Comparison with other studies

Reference	GPS-RS Bias (mm)	GPS-RS Std Dev SD (mm)	GPS-RS Correlation r
This study (Canada 8 sites)*	***1.17***	***1.74***	***0.98***
Köpken 2001 (Sweden, Finland)	-0.66	2.21	0.94
Smith et al. 2001 (Canada 1 site)*	-0.55	NA	0.96
Bokoye et al. 2002 (Canada 1 site 1 month)	-0.10	(rms) 1.80	NA
Ohtani and Naito 2000 (Japan)	-2.70	2.60	NA
Feng et al. 2001 (Australia)	0.66	1.80	NA
Haase et al. (Mediterranean.)	0.85	1.65	NA
Baltink et al. 2002 (Netherlands 1 site)	0.01	1.35	0.98
Coster et al. 1996 (USA 1 site 1 month)*	1.80	2.10	NA
Basili et al. 2001 (Mediterranean. 1 site)*	0.40	1.90	0.97
Wolfe and Gutman 2000 (USA)	-0.60	2.00	0.97

* RS data known to be from Vaisala RS80 sondes

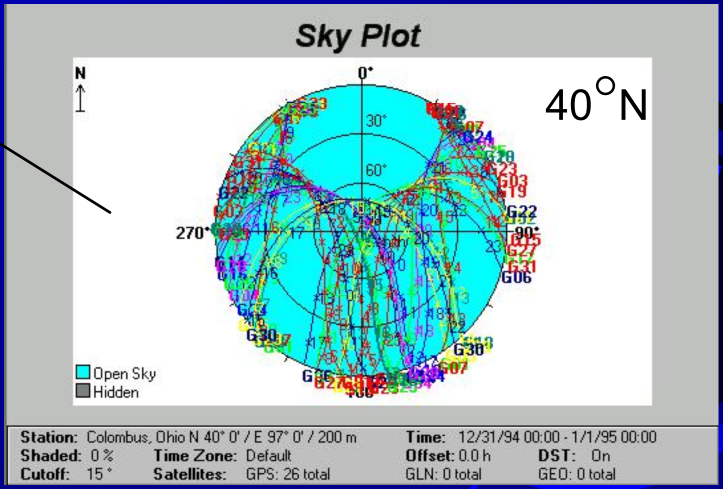
GPS_PW versus RS_PW Outliers (Gatineau)



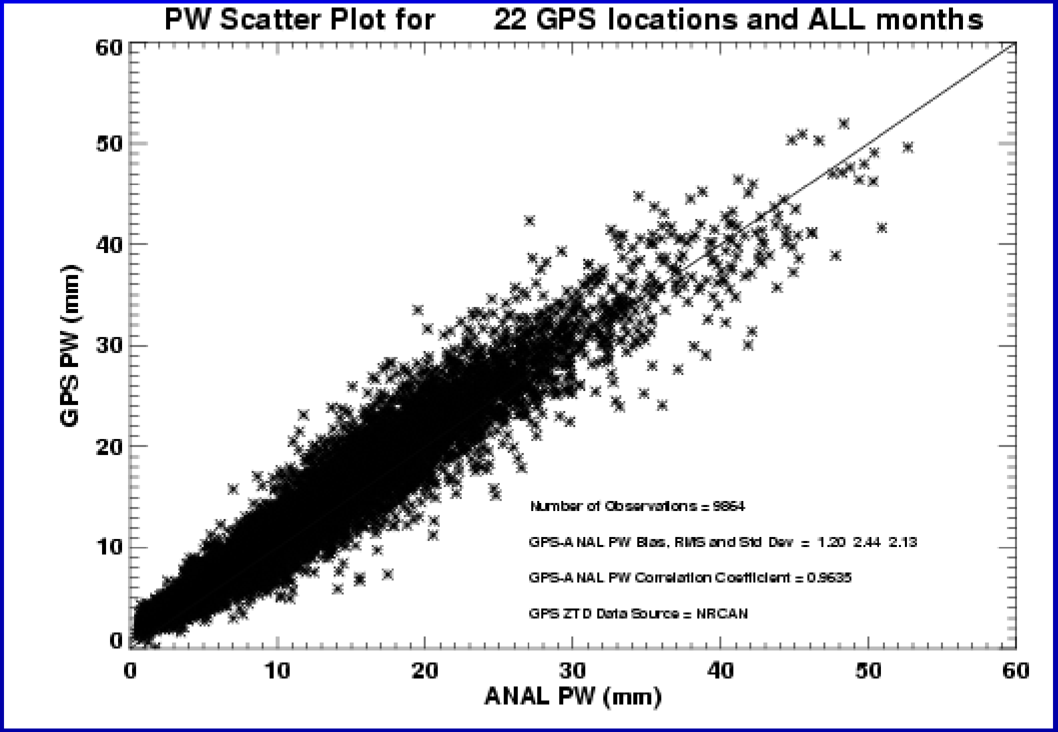


WMW: bad RS dewpoint spread

- Note system to south of cags and associated N-S moisture gradient
- WMW RS site in drier air (Dx = 77 km)
- Sampling of GPS at cags a factor: blind spot to N for mid-latitude sites ==>



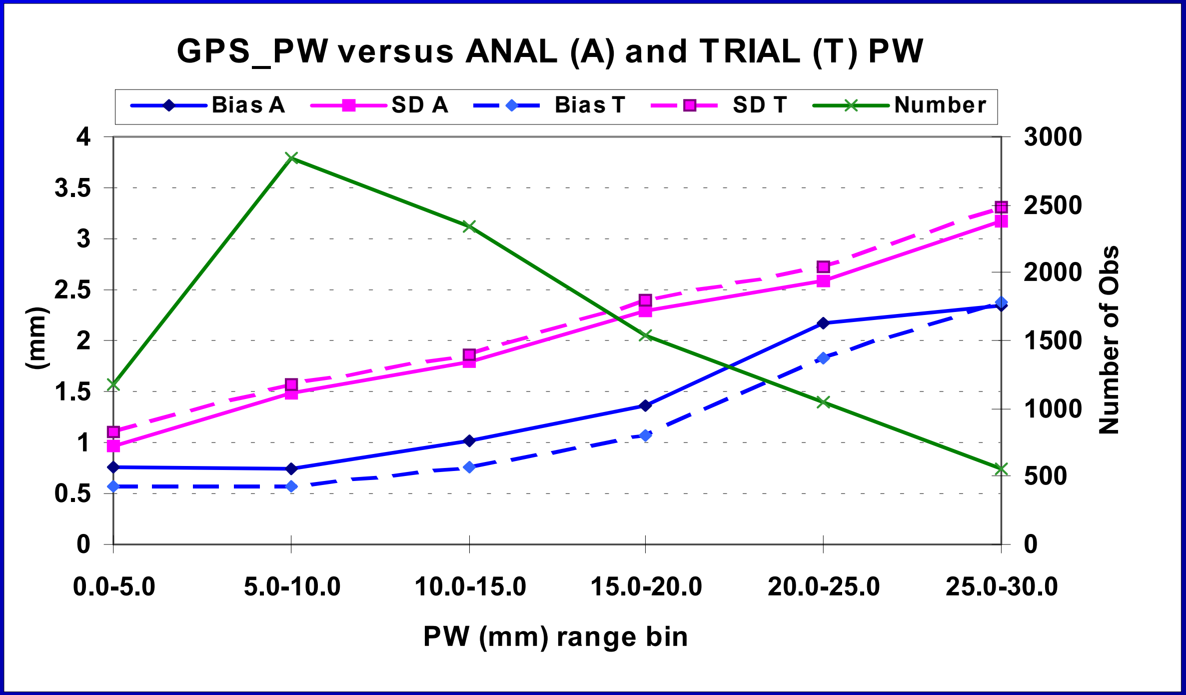
GPS_PW compared with ANAL_PW



- all 22 GPS sites, all 4 months
- Bias = +1.20 mm
- SD = 2.13 mm
- r = 0.96 (high)
- Max Diff. = ~ 17 mm
- GPS vs. TRIAL results very similar

- bias is very similar to GPS_PW vs RS_PW bias (1.17 mm). RS_PW vs ANAL_PW bias =~ 0.
- SD is higher, correlation lower ==> TRIAL errors, no assimilation of low-level humidity observations at many RS sites

Variation of GPS vs ANAL/TRIAL PW Bias and SD with PW



- same increase of bias and SD with PW observed for GPS-RS comparison
- bias a little lower for GPS vs. TRIAL (no assimilation yet of dry-bias RS)
- SD = ~ 3 mm at highest PW (c.f. 2 mm for GPS vs. RS)
- SD = ~ 1 mm at low PW (same as GPS vs. RS)
- larger SD: errors in moisture gradients as represented in ANAL and TRIAL (gradient location errors assoc. with static and moving moisture features)

Estimating Errors Associated with GPS_PW, RS_PW,TRIAL_PW

3-Way Comparison

$$PW_{GPS} = PW + E_{GPS} \qquad PW_{RS} = PW + E_{RS} \qquad PW_{TRIAL} = PW + E_{TRIAL}$$

$$PW_{GPS} - PW_{TRIAL} = E_{GPS} - E_{TRIAL}$$

assume errors are not correlated

$$\overline{(PW_{GPS} - PW_{TRIAL})^2} = \overline{(E_{GPS}^2 - \cancel{2E_{GPS}E_{TRIAL}} + E_{TRIAL}^2)}$$

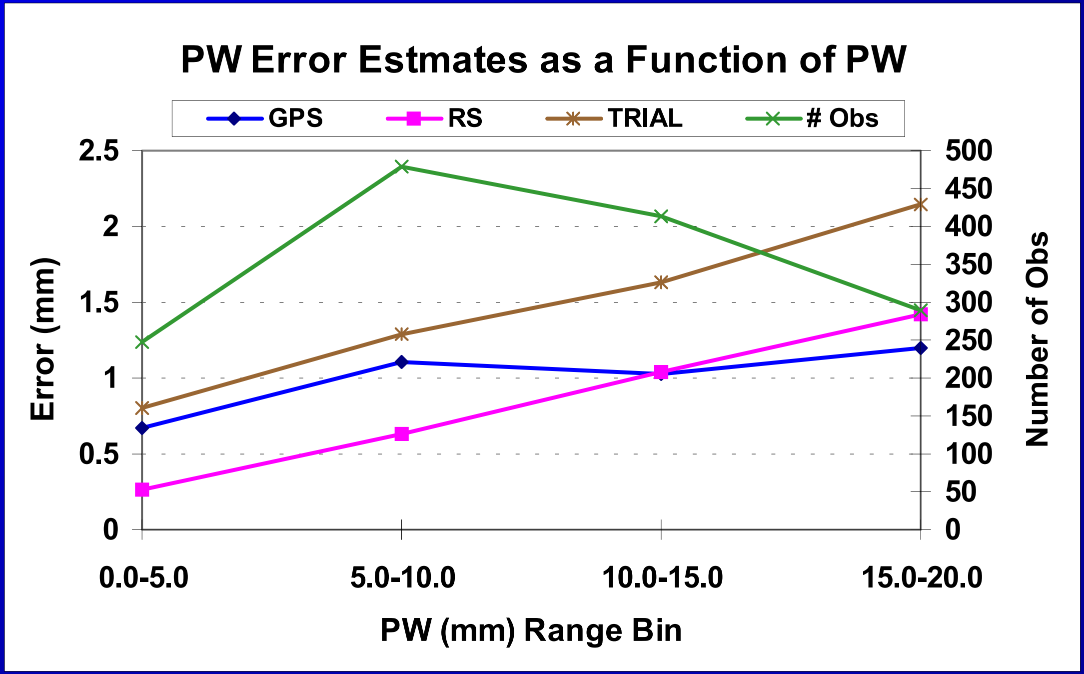
$$\boxed{\begin{aligned} \overline{(PW_{GPS} - PW_{TRIAL})^2} &= SD_{GT}^2 = \overline{E_{GPS}^2} + \overline{E_{TRIAL}^2} \\ \overline{(PW_{GPS} - PW_{RS})^2} &= SD_{GR}^2 = \overline{E_{GPS}^2} + \overline{E_{RS}^2} \\ \overline{(PW_{TRIAL} - PW_{RS})^2} &= SD_{TR}^2 = \overline{E_{TRIAL}^2} + \overline{E_{RS}^2} \end{aligned}}$$

3 equations, 3 unknowns

$$\overline{E_{GPS}} = \sqrt{\frac{SD_{GT}^2 + SD_{GR}^2 - SD_{TR}^2}{2}}$$

SD from intercomparisons

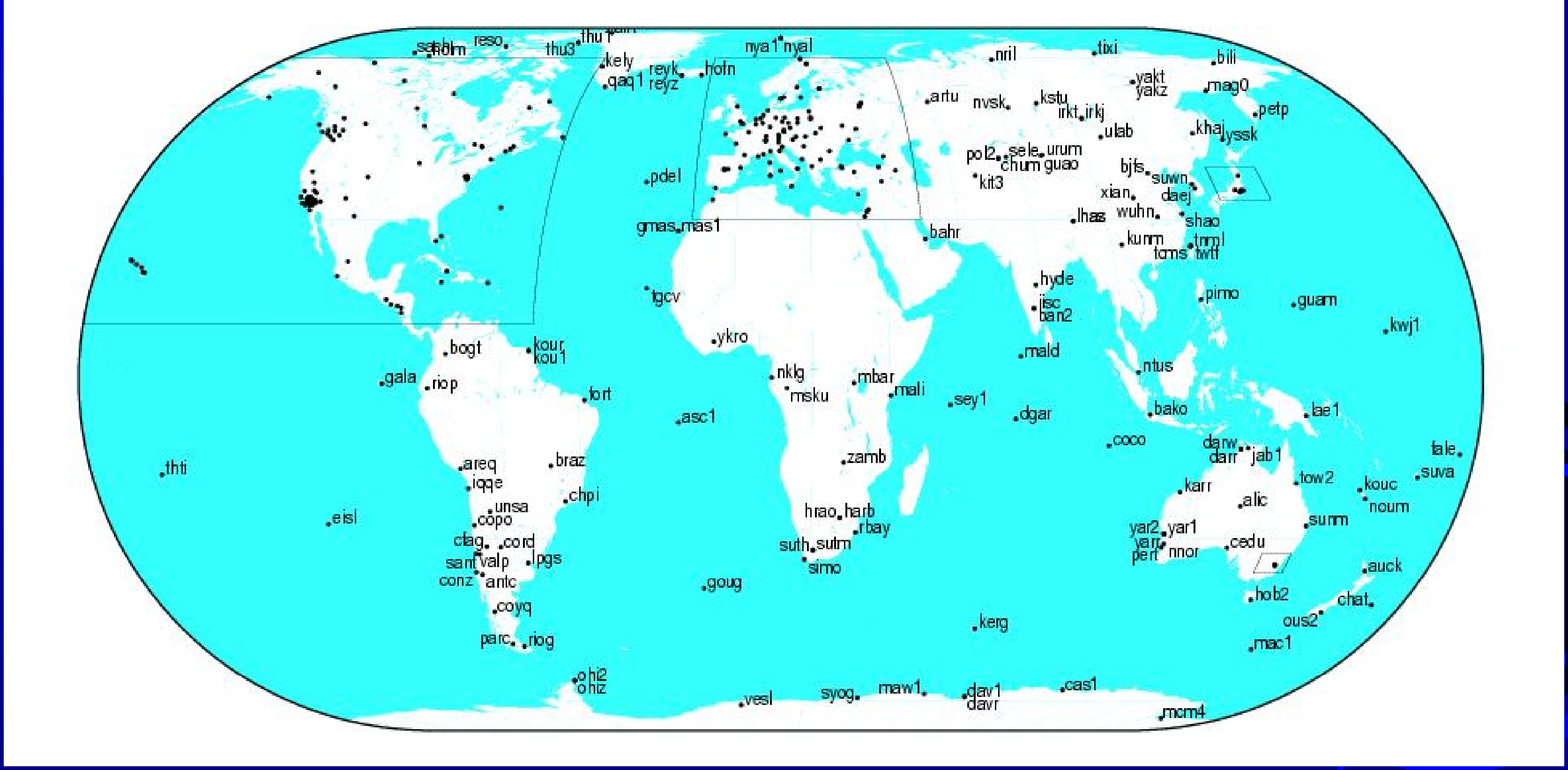
Estimated Errors Associated with GPS_PW, RS_PW and TRIAL_PW (8 sites, RS times)



- RS error increases with PW: from 0.25 to 1.5 mm. RS more accurate for lower PW (0 to 10 mm).
- GPS error constant ~ 1.1 mm. GPS more accurate for higher PW (15 to 20 mm)
- Good agreement between this estimate and PW error derived from source terms (shown on a previous slide)
- > 20 mm? More data needed.
- TRIAL_PW error greater than RS, GPS (no surprise). Near linear increase from 0.75 to 2.2 mm over PW range 0 to 20 mm.

International GPS Service (IGS) Global Network of GPS Sites

- approx. 368 sites world-wide ==> GPS data made available to GPS community
- IGS produces accurate orbits and clocks from GPS data (final, ultra-rapid)
- IGS is also another source of ZTD data that can be used to derive PW
- ZTD products free (internet) and good quality; final ZTD has latency of 3 - 4 weeks



IGS Zenith Total Delay Product

7 AC

- COD
- NRCan
- ESA
- GFZ
- JPL
- NOA
- SIO

→ **IGS** **Averaged** → IGS ZTD product

• each analysis centre (AC) produces its own estimate of ZTD using <u>same</u> GPS data and sites but <u>different</u> processing (software, mapping, satellite cut-off elev., etc.)

• 2-hour time resolution

• latency of 3 - 4 weeks (final product)

• should be more accurate on average than individual AC solution

• available for 175 global GPS sites (44 have GPS Met)

Comparison of NRCan ZTD with IGS ZTD for 3 GPS Sites

ZTD (2200 to 2700 mm) not PW

1 mm ZTD = ~0.15 mm PW   7 mm ZTD = ~1 mm PW

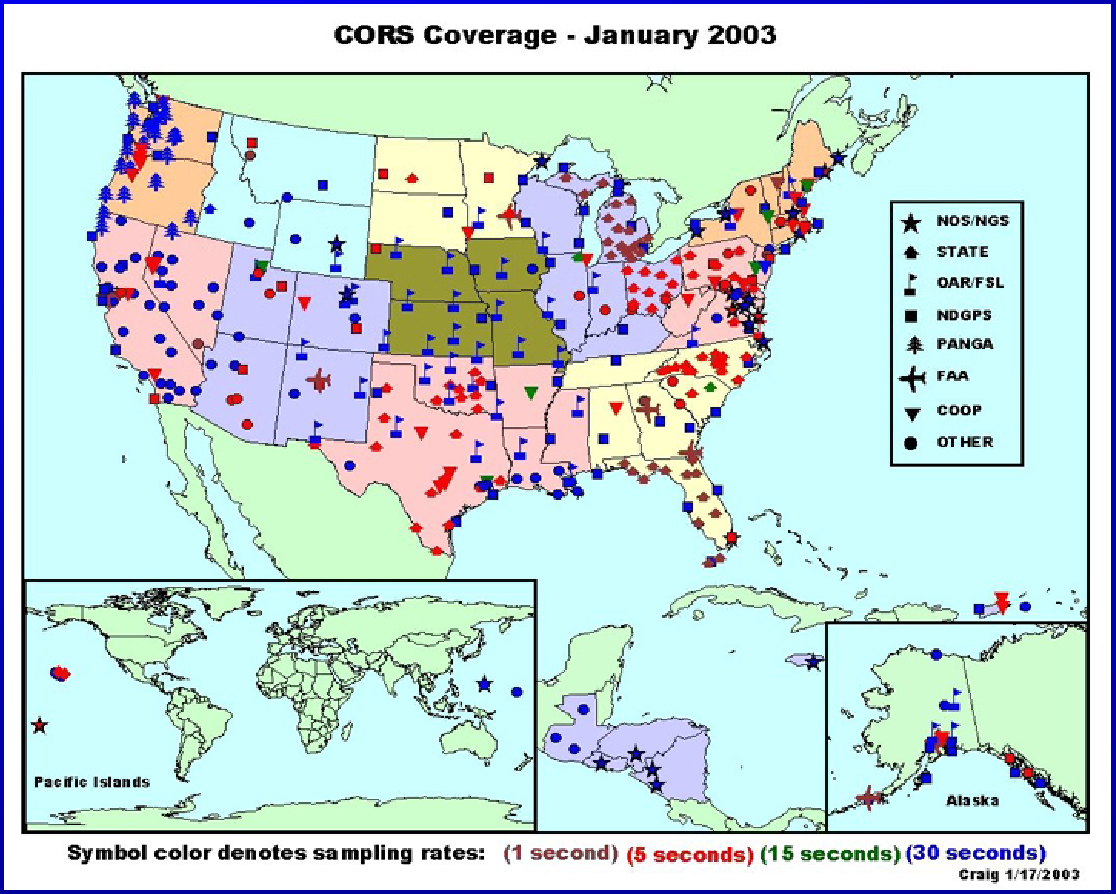
assuming no surface pressure error

Month	NRCan vs. IGS ZTD	Churchill	St. John's	Whitehorse
Jan 2002	*Bias (mm)*	2.35	0.05	0.05
	SD (mm)	2.07	4.44	3.36
	Correlation r	0.991	0.988	0.991
Jul 2001	*Bias (mm)*	4.13	0.79	2.12
	SD (mm)	4.43	6.74	3.23
	Correlation r	0.995	0.994	0.985

- correlation ~ 0.99, positive bias of NRCan ZTD largest at chur
- note differences in bias between sites
- bias higher in July (summer) for all 3 sites
- SD also higher in July except Whitehorse

Ground-based GPS Meteorology in USA

NOAA/NGS CORS Network

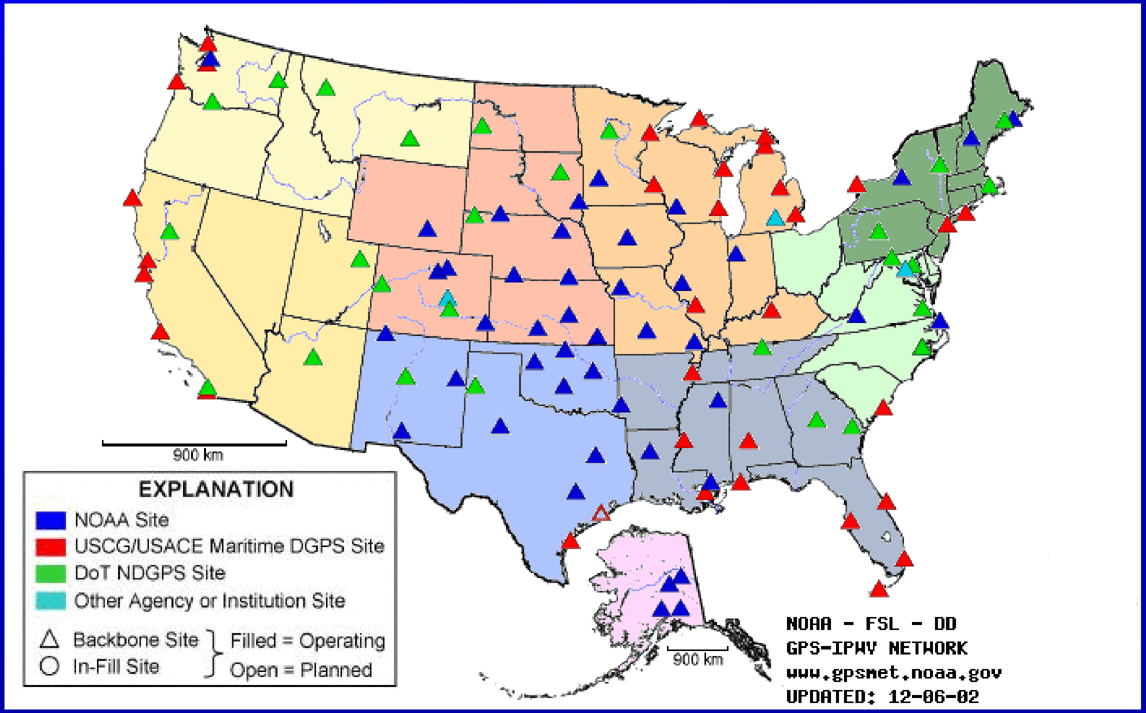


- NOAA/National Geodetic Survey (NGS) coordinates a network of continuously operating reference stations (CORS) in support of 3-dimensional positioning activities throughout the United States and its territories.
- Canada working with US to establish new CORS sites around Great Lakes

- raw GPS data and GPS met data available in near real-time for selected sites at
  http://www.ngs.noaa.gov/CORS/cors-data.html

Ground-based GPS Meteorology in USA

NOAA Forecast Systems Lab GPS-PW Network



- NOAA/FSL operates the GPS-PW network for monitoring integrated water vapour over the US.
- 220 sites
- PW data used for weather forecasting and NWP
- data could be used for assimilation into GEM regional analysis

- GPS PW available in real-time via world wide web:

  http://gpsmet.fsl.noaa.gov/realtimeview/jsp/rti.jsp

Other regions where GPS Meteorology has been applied: Japan (GEONET), Europe (EUREF, COST inititiative), Sweden (SWEPOS), Australia

Conclusions

• GPS positioning error “nuisance factor” for geodesists has become valuable source of atmospheric humidity information to complement existing observations from RS and satellite.

• Statistical analysis based on limited observational data gives a GPS_PW accuracy of about 1 mm. Results are in good agreement with expected accuracy [using PW error sources (Psfc, ZTD, Tm)] and studies by other researchers.

• PW accuracy is comparable to radiosonde, and depending on the range of PW it may be better.

• GPS_PW bias, if any, could not be determined as “reference” was RS observations with a known dry-bias.

• Differences in sampling between the sources of PW help to explain the inter-comparison results, especially those cases where differences in PW were large (i.e. outlier cases)

Conclusions (cont.)

• Good relative (%) accuracy of PW for dry climates such as Canada's depends on accurate measurements of surface pressure. TRIAL pressure accuracy may not be accurate enough (unless ZTD accuracy can be significantly improved).

• In the near-future, derivation of real-time GPS_PW with sufficient accuracy for data assimilation should be possible.

Future Work

• Use GEM <u>regional</u> model ANAL and TRIAL fields for inter-comparisons (Canadian sites)

• Inter-comparisons using data from other GPS sites: IGS (world) and NOAA/FSL (NA)

• 4D-Var Assimilation of North American GPS_PW into regional GEM model

• Slant-delay estimation and 3D vapour tomography. [Univ. of Calgary: Dr. Susan Skone]