Assimilation Experiments with Ground-based GPS Observations in the Canadian Regional Deterministic Prediction System

S. Macpherson¹, L. Fillion¹, G. Deblonde¹, M. Tanguay¹, E. Lapalme¹, M. Lajoie², A. Patoine², P. Vaillancourt¹, M. Reszka², J. St.-James²

¹ Meteorological Research Division, Science and Technology Branch, Environment Canada, Dorval, QC, Canada
² Prediction Development, Meteorological Service of Canada, Environment Canada, Dorval, QC, Canada

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Outline

• Ground-based GPS technology
• The NOAA GB-GPS Network
• GB-GPS data monitoring
• Assimilation of GB-GPS data in the EC RDPS
• Assimilation experiment results
• Summary
• Future Work
Sensing Atmospheric Water Vapour with Ground-based GPS Receivers

GPS Receiver
- high accuracy, dual frequency

Zenith Tropospheric Delay
- \( ZTD = F(P_{s}, PW) \)

Surface Weather Station
- Pressure (\( P_{s} \))
- Temperature (\( T \))
- Relative Humidity (\( RH \))
- Precipitable Water (\( PW \))

\[
ZTD = 10^{-6} \int_{z=sfc}^{toa} Nd\z
\]

Atmosphere
- Refractivity \( N \) induces delay in signal reception
- \( N = k_1 \frac{P}{T} + (k_2 - k_1) \frac{e}{T} + k_3 \frac{e}{T^2} \)

- density (\( P/T \))
- water vapor (\( e \)) dipole moment

\( ZTD \) is estimated from raw GPS receiver data with geodetic processing software (e.g. GAMIT) designed for precise positioning applications.
Mean NWP 6h forecast fields 15 May – 13 July 2011

Components of ZTD

ZTD = ZHD(Ps) + ZWD(PW)

ZHD (mm) ≈ 2.4 · Ps (hPa)
ZWD (mm) ≈ 6 · PW (mm)
Forward Model for ZTD at GPS antenna height
Computing ZTD from NWP (model) fields

\[
\text{ZTDgps} = \text{ZHD}(\text{Pgps}) + \text{ZWDgps}
\]

\[
\text{Pgps} = F(\text{P0}, \text{Tv}_{\text{mean}}, \Delta z) \quad \text{[hydrostatic adjustment]}
\]

\[
\text{ZWDgps} = Z\text{WDm}(\text{P0}, \int [Q/T]) + \Delta Z\text{WD}
\]

\[
\Delta Z\text{WD} = -N_w \cdot \Delta z \quad \text{where } N_w = \text{Function of mean (P, T, Q) in } \Delta z \text{ layer.}
\]

When \( \Delta z > 0 \), “interpolation” option exists to use values on model levels above and below GPS antenna height to get ZTDgps (instead of always using model surface).

For assimilation, max abs(\(\Delta z\)) is set to 1000 metres.

\( \Delta z \) = GPS receiver

<table>
<thead>
<tr>
<th>T, Q on model levels</th>
<th>T, Q on model levels</th>
</tr>
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</table>

\( \text{Pgps} \) \( \text{ZWDgps} \)

\( \text{GPS antenna height} \)

\( \text{model surface} \)

\( \Delta z \)

\( \text{real topography} \)

\( \text{model surface} \)

\( \text{model surface} \)
The NOAA Ground-based GPS Network

- Network started in 1994 by NOAA/FSL (now ESRL) as a research demonstration network
- All-weather GPS ZTD, PW and surface met data (Ps, Ts, RHs) available every 30 minutes
- High data reliability and accuracy that improves with time
- GPS PW data are assimilated operationally in NCEP regional models
- More existing GPS sites in Canada could be added (e.g. provincial GPS receiver networks)
Near-Real-Time GB-GPS Data Monitoring at EC

Comparison of Obs (O) with NWP 6h forecasts (P)

Mean, STD ZTD O-P for ALL FSL sites at ANAL times

ZTD Scatter Plot for ALL_FSL Mar 2012

Number of Observations = 16928
Bias, RMS and Std Dev = -0.17 11.53 11.53
Correlation Coefficient = 0.9975

Histogram of Mean ZTD O-P for ALL_FSL Mar 2012
Assimilation of GB-GPS data

- Assimilation of GPS ZTD from the NOAA GB-GPS network is tested in the EC Regional Deterministic Prediction System (RDPS)
- Collocated GB-GPS surface met data (Ps, Ts, RHs) are also assimilated unless GPS site is within 50 km of reporting surface or upper air site (avoids potential data duplication)
- Quality control of GB-GPS data, performed before assimilation using NWP forecast (first guess = fg), includes:
  - rejection of data based on magnitude of obs-fg (outlier removal)
  - rejection of data based on site obs-fg statistics (e.g., high mean or StdDev, high percentage of bad data, insufficient number of reports to determine statistics, etc.)
  - rejection of ZTD data with high “formal error” > 15 mm
- Mean obs-fg ZTD statistics reveal site-specific biases that are removed before assimilation with a dynamic (10-day running-mean) bias correction system
- Spatial (50 km) and temporal thinning are applied to the GB-GPS data (1 observation per site per 6h analysis window, closest to central time)
Regional Deterministic Prediction System (RDPS)

- Regional GEM Limited Area Model (REG-LAM) – 15 km, 80 hybrid levels (L), top at 0.1hPa
- Initialized every 6h with 4D-Var analysis from 33km 80L Global Deterministic Prediction System (GDPS)
- Driving of REG-LAM forecasts from 55 km 80L global model (provides boundary conditions)
- 3D-Var OPS (4D-Var tests) REG-LAM analysis, with same observations as GDPS assimilated (but clipped), provides initial conditions for 48h forecast
- In development: 10 km REG-LAM, 33 km global driver, 4D-Var, (25 km GDPS)
Regional Deterministic Prediction System (RDPS)

G2 = Global Deterministic Prediction System

**G2** Strato-2bR ANAL

- **Global PILOT P2 ANAL**
- **REG-LAM R2 ANAL**

**G2 obs** (conventional)

- **Global PILOT P2 TRIAL**
- **REG-LAM R2 TRIAL**

**QC**

- **Global PILOT P1 ANAL**
- **REG-LAM R1 ANAL**

**PILOT 48h**

- **REG-LAM 48h**

upper air, surface, aircraft, satellite radiances and winds, NOAA wind profilers and **GPS radio occultation (GPS-RO)**

**G2 obs plus GB-GPS obs** (clipped)

- **3D-Var**
  - **T**
- **4D-Var**

**GB-GPS** data only added to REG-LAM analysis → **No memory of GB-GPS** in system

**TRIAL** = 9h forecast

**PILOT** = driver

No **“GB-GPS”** in TRIALs

No **GB-GPS** in G2

**T-6h**
Assimilation of GB-GPS data

- Assimilation in RDPS assimilation tests with GB-GPS data were done with soon-to-be-operational 4-dimensional variational analysis system (4D-Var)

- GPS ZTD is a **single observation** dependent on vertically integrated quantities, in contrast with true “profile” data from radiosondes, GPS-RO, wind profilers and aircraft. As a result, 3D analysis increments in control variables from ZTD assimilation may not always be optimal.

- Impact of ZTD assimilation on the analysis depends on
  - Magnitude of observed minus trial (first-guess) ZTD difference
  - Jacobian (sensitivity) of ZTD with respect to analysis control variables (surface pressure $P_0$, temperature $T(z)$ and log of specific humidity $LQ(z)$)
  - First-guess (6h forecast) errors for control variables and their covariances (as specified in background error covariance matrix). Note that absolute humidity ($Q$) error increases with increasing $Q$ due to $LQ$ error specification, which means forecast ZTD error increases with PW.
  - Observation error specified for ZTD (increases with observed ZWD (PW)).
GPS ZTD Observation Error Specification

\[ \text{error} = a(m) + b(m) \cdot \text{ZWD} \]

\[ m = \text{month} \]

- Based on linear regression of site monthly ZTD StdDev(obs-F6h) with site mean monthly ZWD(PW); assume ZTD error = StdDev(obs-F6h)
- In analysis, tends to give similar weights for background (F6h) and observation (obs) over wide range of PW, as errors for both F6h and obs ZTD increase as PW increases
Assimilation of GB-GPS Data

- Assimilation of GPS ZTD produces LQ increments in the lower troposphere (below 400 hPa), with little impact on T or P0. LQ increments are max around 700-800 hPa level on average.

- LQ increments are generally small compared to those from conventional observations (e.g. radiosonde humidity).

- P0 analysis increments on the order of 1-2 hPa can occur when trial is very dry (PW < 2 mm)
Assimilation Experiment Results

4D-Var RDPS, summer 2011, 40 dates (00Z and 12Z only)

Verification of 48h RDPS Forecast PW using GB-GPS PW observations

- 25-30% reduction in analysis PW (StdDev) error with smaller reductions at 12h and 24h; generally little impact on StdDev error beyond 24h or model moist bias error
- Small impact of GB-GPS data seen at 48h for SE USA region
- Slight drying in SE USA region at 00h in GPS reduces analysis (00h) moist bias with associated reduction in 00-24h precipitation for Gulf States (not shown)
Assimilation Experiment Results

- Other forecast verifications done include
  - verification of wind, temperature, geopotential height (GZ) and dewpoint depression against **radiosonde observations**
  - verification of 24h **precipitation** accumulations against North American rain gauge networks (SYNO and SHEF)
  - verification with North American surface weather reports (temperature, dewpoint depression, cloud cover, winds)

- Results from these verifications reveal small mixed impact of the GB-GPS data (not shown). Small positive impact on GZ for SE USA region.

- Benefit of GB-GPS data may be masked by cloud and precipitation “spin-up” effects in the REG-LAM forecasts which adversely affect the quality of the short range forecast (0-6h); also, choice of analysis humidity control variable (LQ) may not be best one (could be changed in the future).

- Experiments done for **winter** periods show smaller and more short-lived (< 6h) impact of GB-GPS data assimilation. This is due to fact that average PW is much lower in winter. Thus forecast errors in specific humidity are lower, limiting the impact of observations.
Summary

• Ground-based GPS data (ZTD and surface met) from the NOAA GB-GPS network have been assimilated in experiments with the Environment Canada Regional Deterministic Prediction System (EC RDPS).
• The GB-GPS data have a positive impact on RDPS precipitable water (PW) analyses and 00-24h forecasts (when GB-GPS PW observations are used for verification); conventional forecast verifications reveal little overall impact of GB-GPS.
• In earlier GB-GPS data impact tests, positive impacts were more evident when examining individual forecasts (case studies).
• GB-GPS PW observations are useful for forecast PW verification (even if GB-GPS data not assimilated).
• Conservative assimilation strategy in the experiments combined with limited sample size (40 dates 00Z and 12Z only, summer 2011) may help to explain observed minimal impact of GB-GPS data.
  – only 1 observation per site per 4D-Var analysis (when up to 12 available)
  – no “memory” of GB-GPS data in RDPS (data not in driving GDPS)
Future work

• Test assimilation of GB-GPS data in new 25 km version of the EC global system (GDPS) with continuous ($\Delta t=6h$) analysis cycle where “memory” of assimilated GB-GPS data is retained (15 km GDPS in research)

• Test assimilation of time-series GB-GPS data, accounting for serial observation error correlations (e.g. ECMWF method).

• Test impact of GB-GPS data by removing conventional moisture data over North America (e.g. radiosondes).

• Re-evaluate ZTD observation error specification. Errors as high as 30 mm may be too high considering that actual formal “instrument” errors are as low as 4 mm.

• Examine ZTD bias correction strategy:
  – static vs dynamic, optimal averaging period, etc…
  – better understand source of biases and remove where possible (collaboration with NOAA/ESRL)
  – discrimination of model vs observation bias
Thank You
Assimilation Experiment Results

4D-Var, 3D data thinning for GB-GPS, summer 2011 (latest)

Verification of 00-48h RDPS Forecast PW using GB-GPS PW observations

- PW forecast error is reduced in experiment with GB-GPS (at 00h, 12h and 24h)
- Little impact of GB-GPS on moist forecast (model) bias
- Results by region (next slide) show some differences.
Assimilation Experiment Results

4D-Var, 3D data thinning for GB-GPS, summer 2011 (latest)

Verification of 00-48h RDPS Forecasts using North America surface observations

- Heidke Skill Score for cloud cover categories (clr, sct, bkn, ovc)
- GPS experiment shows some improvement in skill up to 24h
- Verification of other elements (temperature, dewpoint-depression) show small mixed impact overall, with some positive impact (reduced biases) noted for GPS at very short range (0-9h), probably from assimilation of GPS surface met data.
### Assimilation Experiments with RDPS

<table>
<thead>
<tr>
<th>REG-LAM Analysis</th>
<th>GB-GPS Thinning</th>
<th>Periods</th>
<th>Number Dates</th>
<th>Experiment Names</th>
</tr>
</thead>
<tbody>
<tr>
<td>3D-Var FGAT (\Delta t = 36h, 00, 12Z)</td>
<td>4D</td>
<td>Summer 2008</td>
<td>40</td>
<td>ml009e08, ml009h09</td>
</tr>
<tr>
<td></td>
<td>3D</td>
<td>Winter 2008-09</td>
<td>40</td>
<td>ml014e08</td>
</tr>
<tr>
<td>4D-Var, (\Delta t = 12h, 00, 12Z)</td>
<td>3D</td>
<td>Summer 2008</td>
<td>118</td>
<td>sm040e08²</td>
</tr>
<tr>
<td>3D-Var, (\Delta t = 36h, 00, 12Z)</td>
<td>3D</td>
<td>Winter 2008-09</td>
<td>40</td>
<td>sm040h09</td>
</tr>
<tr>
<td>4D-Var, (\Delta t = 36h, 00, 12Z)</td>
<td>3D</td>
<td>Summer 2011</td>
<td>40</td>
<td>sm001e11³</td>
</tr>
</tbody>
</table>

1. **3D thinning** = only keep 1 observation per site (closest to central [analysis] time Ta)
2. **4D thinning** = 30-minute observations are distributed over 9 temporal bins (1 per bin) spanning Ta-3h to Ta+3h
3. Introduced **blacklisting** of GP surface met data at GPS sites within 50 km of a SF/UA station

**\(\Delta t\) = time interval between analyses**

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3D-Var LQ = Log(Q) Analysis Increments

From GB-GPS ZTD only

From Conventional Observations

LQ increments are small compared to those from conventional observations (e.g. radiosondes)
Assimilation Experiment Results

4D-Var, 3D data thinning for GB-GPS, summer 2011 (latest)

\[\text{Std(Obs-ANAL)} < \text{Std(Obs-FG)}\] shows better fit of ANAL to observations compared to FG as result of assimilation.

- Reduction in StdDev is 25-45% on average; some reduction (~5%) occurs even without GB-GPS assimilation due to more accurate Q, Ps fields in analysis, but most of the reduction comes from assimilation of the NOAA network GB-GPS data.

- **FG** = 6 hour REG-LAM forecast ZTD
ZTD Jacobian (w.r.t. humidity Q)
Quality Control for Assimilation: Operations

**Time T**

- **derivate BURP**
  - bgck.gbgpsbcor
    - **bcor**
      - **3DVar**
        - blmetsites
          - bgck.gbgpsqc*
            - Flags blacklisted data and ZTD with *formal error* > 15 mm

- **update_gps_omp**
  - bcorfile
  - blistfile
    - BIAS CORRECTION FILE: mean O-P for each site over last N days (all elements)

- **OMP dbase**
  - up to one month O-P data for each site
  - BLACKLIST (by element): high %rej (bad data), bias, std O-P, insufficient data to evaluate

- Separate job done before QC for analysis

- **T-6h**
  - Retrieve “raw” O-P using corrected ZTD and reversing bcor
  - add O-P
  - get stats

- Ready for assimilation

**POSC**

Applies spatial and temporal thinning
Model (6h forecast) ZTD Errors

\[ ZTD = ZHD(Ps) + ZWD(PW) \]

- Model \( Ps \) error = 0.75 hPa
- Model \( PW \) error = Function (\( \int Q(z) \) error = Function LQ error & Q) = 3 mm (avg) in summer
  - ZHD error = 2.4 \times 0.75 \approx 2 \text{ mm}
  - avg ZWD error = 6 \times 3 = 18 \text{ mm}
  - avg ZTD model error = 18 + 2 = 20 \text{ mm}
  - avg ZTD observation error = 15 \text{ mm}

Mean NWP 6h forecast ZTD 15 May – 13 July 2011

\( ZHD \) (mm) \approx 2.4 \times Ps \) (hPa)
\( ZWD \) (mm) \approx 6 \times PW \) (mm)
GPS ZTD Observation Error Model

- We assume monthly StdDev ZTD (obs-F6h) is a good measure of ZTD observation error for NWP purposes.
- We observe that StdDev ZTD (obs-F6h) is generally higher at sites with higher mean PW.
- We use this to create a ZTD error model that makes use of a linear regression of site StdDev ZTD (obs-F6h) with site mean ZWD(PW).
- Result is ZTD observation error that increases linearly with observed ZWD (where ZWD = ZTD – ZHD(Ps)).
GPS ZTD Observation Biases

- **Bias = Mean (obs-F6h)**
- F6h = 6h NWP (REG-LAM) forecast
- Overall network ZTD bias is near zero
- but there are biases at individual GPS sites
- Abs(Bias) > 10 mm suggests serious problem with the data for the site
- Biases must be removed with a bias correction system prior to data assimilation
- Sources of ZTD bias include
  - biases in 6h forecast Ps, Q fields
  - biases introduced by model ZTD operator
  - biases in ZTD estimates (issues with GPS receiver, location/siting and raw receiver data processing)
- Incorrect receiver antenna height (erroneous site info) produces model ZTD operator bias error (incorrect Δz)