Exploiting GNSS for Atmospheric Remote Sensing

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Outline

• GPS observables and atmospheric effects
• NWP for atmosphere error mitigation
• Ground-based estimation techniques – 2D and 3D
• Applications in NWP
• Space-based estimation techniques
• The future
Introduction

• Continuous all-weather real-time GPS observations are available from permanent GPS reference stations worldwide
• Estimates of tropospheric PWV and TEC can be derived from GPS observations in near real-time for meteorology, space weather and atmospheric science applications
• Potential for improved techniques with future GNSS enhancements (GPS modernization and Galileo)
Global Positioning System

- 21 satellites plus 3 spares
- 6 orbital planes
- 55 degrees inclination
- 20,200 km altitude
- 12-hour orbits
- Dual frequency
  (L1 = 1.5 GHz and L2=1.2 GHz)
- At least 4 satellites always in view
Exploiting GNSS for Atmospheric Remote Sensing

GPS Observables (1/2)

Pseudorange

\[ P = c \Delta t \]

Carrier phase range

\[ \Phi = \lambda \phi + N\lambda \]

(Dodson, 1998)
GPS Observables (2/2)

Pseudorange
\[ P = \rho + d_\rho + c(d_{ts} - d_{tr}) + \text{ion} + \text{trop} + \epsilon_p \]

Carrier phase range
\[ \Phi = \rho + d_\rho + c(d_{ts} - d_{tr}) - \text{ion} + \text{trop} + \lambda N + \epsilon_\Phi \]

- \( \rho \) = geometric range
- \( d_\rho \) = orbital errors
- \( d_{ts} \) = satellite clock error
- \( d_{tr} \) = receiver clock error
- \( \text{ion} \) = ionosphere range delay
- \( \text{trop} \) = troposphere range delay
- \( \epsilon \) = noise and multipath
Troposphere Range Error

\[ \Delta r = \int_{h_1}^{h_2} [n(h) - 1] \left( \frac{d\ell}{dh} \right) dh \]

\[ \Delta r = 10^{-6} \int_{h_1}^{h_2} N(h) \left( \frac{d\ell}{dh} \right) dh \]

where

- \( \Delta r \) is the total troposphere range delay
- \( N(h) \) is the vertical refractivity: \( N = (n-1) \times 10^6 \)
- \( d\ell/dh \) is the slant path mapping function
Neutral Atmosphere Refractivity

\[ N = 77.6 \frac{P_d}{T} + 72 \frac{e}{T} + 3.75 \times 10^5 \frac{e}{T^2}, \]

If: \( P_i = P = P_d + e, \)

\[ N = 77.6 \frac{P}{T} + 3.73 \times 10^5 \frac{e}{T^2}, \]

or: \[ N = \frac{77.6}{T} \left( P + \frac{4810e}{T} \right) \]
Troposphere Error Mitigation

Compute hydrostatic and wet zenith troposphere delay from model:

\[ d_{\text{trop}}^Z = 10^{-6} \int_{h_1}^{h_2} N_h \, dh + 10^{-6} \int_{h_1}^{h_2} N_w \, dh = d_h^Z + d_w^Z \]

Map hydrostatic and wet zenith delays to slant with mapping functions:

\[ \Delta r = M_h(E) d_h^Z + M_w(E) d_w^Z \]

where

- \( d_h^Z \) and \( d_w^Z \) are the zenith hydrostatic and wet delays
- \( M_h(E) \) and \( M_w(E) \) are the hydrostatic and wet mapping functions
- \( \Delta r \) is the total troposphere range delay

Troposphere models may consist of separate hydrostatic and wet zenith models and mapping functions, or a combined approach.
1) Use empirical/physical models dependent on surface met measurements
   - hydrostatic model (e.g. Hopfield, Saastamoinen) computed with
     mm-level accuracies (typical absolute zenith delay of 2.20 m)
     - wet delay accuracies no better than 2-3 cm

2) Use NWP to derive range delays
   - P,T and humidity provided in 3D grid
   - derive refractivity values and integrate to determine zenith delays

3) Derive zenith total delay from GNSS observations directly
   - standard approach commonly employed using double-difference
     or PPP methods (Bernese, GAMIT, GIPSY)
   - 3D tomography model (U of C)
Exploiting GNSS for Atmospheric Remote Sensing

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

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

\[
\begin{align*}
\lambda &= \text{rough latitude} \\
\phi &= \text{rough longitude} \\
h &= \text{rough ellipsoidal height} \\
t &= \text{time of observation} \\
N &= \text{approximate geoidal height} \\
H &= \text{approximate orthometric height} \\
\text{ZHD} &= \text{zenith hydrostatic signal delay (m)} \\
\text{ZWD} &= \text{zenith wet signal delay (m)}
\end{align*}
\]

(S. Gutman, 2004)
NWP for Tropospheric Corrections

(S. Gutman, 2004)
NWP Accuracy

- Improvement of 5-10 cm at zenith and 1 m at 15 deg elevation
Troposphere Estimation using GNSS

- In precise positioning applications, the zenith wet delay can be estimated as a “nuisance” parameter with sub-cm accuracy
- Such estimates of wet delay are extremely useful for meteorological applications: GPS Meteorology
- Estimation is based on a carrier phase-based DGPS approach

<table>
<thead>
<tr>
<th></th>
<th>Column Specific Humidity</th>
<th>Total Zenith Delay</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Horizontal Domain</strong></td>
<td>Global / Regional</td>
<td>Global / Regional</td>
</tr>
<tr>
<td><strong>Horizontal Resolution</strong></td>
<td>100-300 km / 50-100 km</td>
<td>100-300 km / 50-100 km</td>
</tr>
<tr>
<td><strong>Time Resolution</strong></td>
<td>1-6 hrs / 15 mns - 1 hr</td>
<td>1-6 hrs / 15 mns - 1 hr</td>
</tr>
<tr>
<td><strong>Absolute Accuracy</strong></td>
<td>1-5 kg/m² / 0.5-1 kg/m²</td>
<td>6-30 mm / 3-6 mm</td>
</tr>
<tr>
<td><strong>Timeliness</strong></td>
<td>1-2 hrs / 30 mns - 2 hrs</td>
<td>1-2 hrs / 30 mns - 2 hrs</td>
</tr>
</tbody>
</table>

(COST 716 Working Group)
Zenith Tropospheric Delay

Assume each slant delay observation is equal to ZTD multiplied by mapping function:

\[ SWD = M(E) \times ZTD \]
Zenith Tropospheric/Wet Delay

Standard Approach

• Assume azimuthal symmetry
• Tropospheric delay assumed to vary only with elevation angle
• Based on IF carrier phase observations
• Least squares or Kalman filter to derive zenith tropospheric delay (ZTD)
• Apply hydrostatic model, based on surface meteorological data
• Recover zenith wet delay
• Precipitable Water Vapour (PWV) = Π × ZWD (mm accuracy)
Zenith Wet Delay

\[
\Phi_{AB}^{ij} = \left( MF_A^i ZTD_A - MF_B^i ZTD_B \right) - \left( MF_A^j ZTD_A - MF_B^j ZTD_B \right) \\
= \left( MF_A^i - MF_A^j \right) ZTD_A - \left( MF_B^i - MF_B^j \right) ZTD_B \\
\approx \left( MF_A^i - MF_A^j \right) (ZTD_A - ZTD_B) \text{ if } MF_A^i \approx MF_B^i \text{ and } MF_A^j \approx MF_B^j
\]
PWV Comparison

GPS vs. EA3 Radiosonde

- EA3: Olds-Didsbury Airport (North of Calgary)
- July 14-27, 2003
Hail Storm - Alberta

- Severe thunderstorms develop NW of Calgary in Rocky Mountain foothills
- Largest storms observed during July
Soil Moisture – Southern Alberta

- Sundrie Soil Moisture Content (%) in Upper 10 cm of Soil

- Dates: 7/15 to 7/26

- Legend:
  - Sundrie A MC (%) 0 - 10 cm
  - Sundrie B MC (%) 0 - 10 cm Layer
  - Sundrie 24 hr Avg PWV (cm)
Large-Scale Networks

SuomiNet
• accuracies of PWV derived using GPS are 1-3 mm
Severe Weather

PWV 20 hr 09/15/99

GOES-8 WV

(C. Rocken)
Real-Time Processing

- University of Calgary P³ software
- Single site solution
- Initial tests Sept. 2004 (U of Calgary)
NOAA Forecast Applications

(S. Gutman, 2004)
## NWP Data Assimilation

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

(S. Gutman, 2004)
Multi-year study with the 60km RUC indicates that GPS makes a consistently positive impact on short-term weather forecast accuracy:

- primarily at the lower levels where most of the moisture resides (i.e. PW more correlated with low-level than upper-level moisture);
- magnitude of impact increases with the number of stations;
- RH forecast improvement is greatest in the cool months when the moisture distribution is more synoptic;
- precipitation forecast accuracy is generally better for heavy precip than light precip events.

<table>
<thead>
<tr>
<th>Level (hPa)</th>
<th>1998-99</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>850</td>
<td>1.5</td>
<td>3.8</td>
<td>3.9</td>
<td>5.0</td>
<td>5.4</td>
</tr>
<tr>
<td>700</td>
<td>1.1</td>
<td>4.1</td>
<td>6.3</td>
<td>6.5</td>
<td>7.0</td>
</tr>
<tr>
<td>500</td>
<td>0.7</td>
<td>2.1</td>
<td>2.0</td>
<td>2.4</td>
<td>3.1</td>
</tr>
<tr>
<td>400</td>
<td>0.3</td>
<td>0.1</td>
<td>-0.4</td>
<td>-0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Mean (850-400)</td>
<td>0.9</td>
<td>2.5</td>
<td>2.9</td>
<td>3.3</td>
<td>4.1</td>
</tr>
<tr>
<td>Mean (850-500)</td>
<td>1.1</td>
<td>3.3</td>
<td>4.1</td>
<td>4.6</td>
<td>5.2</td>
</tr>
</tbody>
</table>
3D Models

- Consider observations from a (real-time) regional GPS network
- Use information in raw double difference to derive 3D (4D) refractivity over the network
- Observe spatial variations (azimuthal asymmetry)
Tomographic Model (1/4)

- Slant wet delays can be used as input to derive a 3D model of wet refractivity

\[ \text{SWD} = 10^{-6} \sum_{i} N_{wi} \Delta s_i \]
Horizonal constraint applied:

- $N_{wi}$ equal to average of refractivity in neighbouring voxels
- Vertical voxels related via Covariance Matrix, $C_x$

\[
SWD = 10^{-6} \sum_i N_{wi} \Delta s_i
\]

\[
C_{x_{i,j}} = a_1 e^{-a_2 h_{i,j}} \quad \text{where } h_{i,j} \text{ is the distance between voxel } i \text{ and } j
\]

Least squares, Kalman filter approach:

- First-order Gauss-Markov describes temporal variation
\[
\n\nabla \Delta SWD_{ab}^{mn} = 10^{-6} \left[ \left( \sum_{i=1} N_{w_i} ds^n_{a_i} - \sum_{j=1} N_{w_j} ds^n_{b_j} \right) \\
- \left( \sum_{k=1} N_{w_k} ds^m_{a_k} - \sum_{l=1} N_{w_l} ds^m_{b_l} \right) \right]
\]

where:

\[\nabla \Delta SWD: \]
observables
\[N_{w}: \text{estimated parameters}\]
Tomographic Model (4/4)

- Tomography adjustment built as module compatible with U of Calgary MultiRef™ software
- MultiRef™ is a real-time network RTK package with double-difference ambiguities resolved between reference stations
- Absolute IF double-difference carrier phase ranges are input for tomography adjustment
- Tomography method modified to accept double difference observations instead of absolute slant path delays
- Voxel dimensions are 50 km x 50 km x 1 km (height)
- GPS troposphere corrections are produced
Simulation Results: $H = 400$ m, Regular Profile

RMS ZWD (model – simulation) $\sim 1.0$ mm
Simulation Results: $H = 400$ m, Inversion Profile

RMS ZWD (model – simulation) $\sim 0.8$ mm
Southern Alberta Network

1. Novatel 600 Antenna
2. Novatel MPC
3. Paroscientific Met3A

AGAME 2004
- Data collection campaign in collaboration with Environment Canada: July 12 - 17, 2004
Test Results: Good Geometry

Number of Observations at \( t = 8.8167 \) UTC

Wet Refractivity at \( t = 9.3333 \) UTC

- Observables
- Number of Observations
- Wet Refractivity (mm/km)
- Height (m)
Test Results: Poor Geometry

Number of Observations at t = 10.25 UTC

Wet Refractivity at t = 10.25 UTC

The graphs show the distribution of number of observations and wet refractivity across different heights and locations. The color scale represents the values, with blue indicating lower values and red indicating higher values.
Sample Results

1800 LT

2200 LT

0400 LT
Radio Occultations

A vertical profile of refractivity can be obtained over the course of one occultation (2-3 minutes) with km resolution

Source: http://www.orbit.nesdis.noaa.gov/smcd/spb/gpsro/
Retrieval Method

\[ \delta \alpha = \begin{bmatrix} \delta \alpha_1 \\ \delta \alpha_2 \\ \delta \alpha_3 \\ \vdots \\ \delta \alpha_m \end{bmatrix} = \begin{bmatrix} x_{11} & 0 & 0 & \cdots & 0 \\ x_{21} & x_{22} & 0 & \cdots & 0 \\ x_{31} & x_{32} & x_{33} & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & x_{m3} & \cdots & x_{mm} \end{bmatrix} \delta(n) \]

\[ \alpha_0 = \nabla n_0 = 0 \]
Sample Results - CHAMP

- CHAMP experiment allows profiling of water vapour over land and water (e.g. Arctic)

(GFZ Potsdam, http://www.gfz-potsdam.de/pb1/GASP)
Sample Results - CHAMP

Temperature profiles near England

At about 95-4-25:00:00 UTC

(U.K. Met Office, 2004)
CanX-2

- Canadian Advanced Nanosatellite eXperiment 2
- Being developed by the Space Flight Laboratory of the University of Toronto Institute for Aerospace Studies (UTIAS/SFL)
- Primary science payload is a GPS occultation experiment designed at the University of Calgary (small, light and inexpensive)
- Data to be post-processed for proof-of-concept low-cost mission
Limitations

• High-altitude stratosphere measurements limited by higher-order ionosphere residuals

• Low-altitude troposphere profiles unavailable due to signal diffraction, multipath and weak L2 signals

• Time delays of 45 minutes or more to obtain profiles (limited by telemetry)

• Missions are expensive and short-term (several years)

Potential:

Useful for forecast (background) model and climate studies
Occultation locations for COSMIC (6 s/c, 3 planes) and EQUARS, 24 hrs

(Yunck, 2004)
The Future – GNSS Remote Sensing

- 3D and 4D modeling of neutral atmosphere improved using occultations from LEOs (thousands per day)
- Improved IF observations with new L2C and eventually triple-frequency GPS
- Additional observations from Galileo!
- Additional observations from improved GLONASS operation
- More and more GNSS reference stations worldwide (But will they be compatible with Galileo and GNSS modernization? And real-time?)
- GPS estimation <=> NWP