3D Multi-Sensor Water Vapor Tomographic Modeling in Hong Kong and its Performance Evaluation

Zhizhao Liu*, Biyan Chen*, W.C. Woo, P.W. Chan & W.K. Wong

The 9th Annual Seminar on Spatial Information Science and Technology (ASSIST 2014), Hong Kong, 19 Dec 2014

* Department of Land Surveying and Geo-Informatics, the Hong Kong Polytechnic University, Hong Kong
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Zhizhao Liu$^1$, Biyan Chen$^1$, Wang Chun Woo$^2$, Pak-wai Chan$^2$, Wai Kin Wong$^2$

$^1$Department of Land Surveying and Geo-Informatics
The Hong Kong Polytechnic University
181 Chatham Road South, Hung Hom, Kowloon, Hong Kong
Tel: (852)2766 5961 Fax: (852)2330 2994
E-mail: lszzliu@polyu.edu.hk

$^2$Hong Kong Observatory, 134A, Nathan Road
Tsim Sha Tsui, Kowloon, Hong Kong
1. Research background

2. Description of multiple water vapor observations

3. Principle of water vapor tomography

4. Tomography model evaluation

5. Conclusion
Significance of water vapor

- Key atmospheric greenhouse gas

- Atmospheric processes:
  - cloud formation
  - hydrological cycle
  - radiative balance
  - evolution of atmospheric storm systems

- To monitor the variation of 3D water vapor
Research background

- Highly populated and extremely humid coastal city
- Average humidity: 78%
- Annual rainfall: 2400 mm
- Typhoon: 3~4 per year
- Extreme weather: thousands of casualties from 1883
- June 18, 1972, 156 people died in landslips caused by heavy rain
Water vapor observation techniques

- Microwave Water Vapor Radiometer (WVR)
- Aerosol Robotic NETwork (AERONET) sunphotometer
- Global Navigation Satellite System (GNSS)
- MODerate resolution Imaging Spectroradiometer (MODIS)
- Radiosonde
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Water vapor observation techniques in HK

Geographical distribution of the GPS, radiosonde, WVR and AERONET stations in Hong Kong

- GPS
- Radiosonde
- WVR
- AERONET
Satellite Positioning Reference Station Network (SatRef):
- 12 GPS stations
- LEICA GRX1200+GNSS (receiver)
- LEIAR25.R4 LEIT (antenna)

Water vapor measurements
- GPS data processed by Bernese 5.0 software
- Zenith tropospheric delay (ZTD), gradients and the residuals
- Parameters are estimated once an hour
The slant wet delay (SWD) can be derived from:

$$SWD = (ZTD - ZHD) \cdot f(z) + \frac{\partial f}{\partial z} \cdot (G_{N.W} \cdot \cos(\phi) + G_{E.W} \cdot \sin(\phi)) + R$$

Meteorological observations:
- Pressure, temperature, relative humidity
- Wet refractivity $N_W$

$$N_W = 71.2952 \frac{e}{T} + 375463 \frac{e}{T^2}$$

water vapor pressure
Water Vapor Radiometer (WVR)

Data interval: 15 minutes
7 oxygen channels
7 water vapor channels

Temperature, humidity and liquid water vapor profiles up to a height of 10 km in zenith mode
Providing accurate precipitable water vapor measurements

Working in the periods with direct sunlight. No data are available at the nighttime or in conditions of precipitation.
theory, temperature, and relative humidity are measured and transmitted to the ground station. The data is then processed and used for various applications, including weather forecasting and climate monitoring.

Hong Kong's only Radiosonde station (Vaisala RS92) is situated at the King's Park.
Numerical Weather Prediction (NWP) model

Based on Japan Meteorological Agency (JMA) non-hydrostatic model

Operating since the rain season in 2010

Horizontal resolution of 2 km and the predictions are updated hourly

Temperature
Dew point
Depression
Geopotential height

NWP model

16 isobaric levels

100 hPa

1000 hPa

608 km

608 km
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Principle of water vapor tomography

- Tomography technique enables us to precisely probe the atmosphere:
  - 3D water vapor distribution
  - Under all weather conditions
  - With high temporal and spatial resolution
Principle of water vapor tomography

GPS Satellites

Atmospheric Water Vapor Voxels

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GPS Receivers

Length of ray in voxel 2

Water vapor refractivity in voxel 2

\[ SWD = a_1 \cdot x_1 + a_2 \cdot x_2 + a_3 \cdot x_3 + a_7 \cdot x_7 + a_8 \cdot x_8 \]

\[ y_G = A_G \cdot x \]
Addition of observations

Vertical constraint:
Average of 3-day radiosonde water vapor profiles prior to tomographic period

Horizontal constraint:
\[ x_5 = \left( x_1 + x_2 + x_3 + x_4 + x_6 + x_7 + x_8 + x_9 \right) / 8 \]
Solution to tomography equation

Using Least-Squares method, the 3D water vapor field can be solved as:

\[
\mathbf{x} = \left( \mathbf{A}_G^T \cdot \mathbf{P}_G \cdot \mathbf{A}_G + \mathbf{A}_W^T \cdot \mathbf{P}_W \cdot \mathbf{A}_W + \mathbf{A}_A^T \cdot \mathbf{P}_A \cdot \mathbf{A}_A + \mathbf{A}_m^T \cdot \mathbf{P}_m \cdot \mathbf{A}_m + \right. \\
\left. \mathbf{A}_R^T \cdot \mathbf{P}_R \cdot \mathbf{A}_R + \mathbf{A}_N^T \cdot \mathbf{P}_N \cdot \mathbf{A}_N + \mathbf{H}_G^T \cdot \mathbf{P}_G \cdot \mathbf{A}_G \right)^{-1} \cdot \left( \mathbf{A}_G^T \cdot \mathbf{P}_G \cdot \mathbf{y}_G + \mathbf{A}_W^T \cdot \mathbf{P}_W \cdot \mathbf{y}_W + \mathbf{A}_A^T \cdot \mathbf{P}_A \cdot \mathbf{y}_A + \mathbf{A}_m^T \cdot \mathbf{P}_m \cdot \mathbf{y}_m + \mathbf{A}_R^T \cdot \mathbf{P}_R \cdot \mathbf{y}_R + \mathbf{A}_N^T \cdot \mathbf{P}_N \cdot \mathbf{y}_N \right)
\]

where \( \mathbf{P} \) matrices with different subscripts represent the weighting matrix for different observations and constraints.

Only approximate solution can be obtained
Solution to tomography equation

- Multiplicative algebraic reconstruction technique (MART) is implemented to improve the final results.

\[
X_j^k |_{i-ray} = X_j^{k-1} |_{i-ray} \left( \frac{Y_i}{\langle A_i, X^{k-1} \rangle} \right) \sum_{j=1}^{n} A_{ij}
\]

A more accurate water vapor density field can be obtained.

relaxation parameter
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Tomography model evaluation

Model evaluation period:
May 1 ~ Sep 30 2013
Evaluation by GPS Station HKLT

9th ASSIST 2014

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<table>
<thead>
<tr>
<th>SWD (mm)</th>
<th>ZWD (mm)</th>
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<td>Bias</td>
<td>RMS</td>
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<td>10.85</td>
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ZWD derived from GPS and tomography during May 1 to September 30, 2013
Evaluation by Radiosonde profiles

Comparison between radiosonde and tomography

Tomography (mm/km) vs. Radiosonde (mm/km)

- **y = 0.989 x + 1.269**
- Bias: 0.85 mm/km
- RMS: 7.13 mm/km
- Correlation Coefficient: 0.9806

RMS errors at different altitude layers:
- 3.30 mm/km at 8 km
- 11.44 mm/km at 12 km
Wet refractivity evaluation by WVR

Comparison between airport WVR and tomography. May 1 to September 30, 2013

\[ y = 0.8683 \times + 6.192 \]

Bias: -0.6353 mm/km
RMS: 9.9351 mm/km
Correlation Coefficient: 0.9705
Conclusion

- A water vapor tomography method using multi-sensor data is developed

- Evaluation using GPS-inferred SWD/ZWD:
  - SWD: 10.85 mm, ZWD: 6.46 mm, PWV: 1.05 mm

- Evaluation using radiosonde water vapor profiles:
  - Overall: 7.13 mm/km, Layers: 3.30~11.44 mm/km

- Wet refractivity evaluation using WVR: 9.94 mm/km
Thanks for your attention

謝謝
Any questions?