Water Vapor Tomographic Modeling and Performance Evaluation Using Multi-sensor Data in Hong Kong


*The Hong Kong Polytechnic University
Water Vapor Tomographic Modeling and Performance Evaluation Using Multi-Sensor Data in Hong Kong

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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: 2,400 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

Atmospheric Water Vapor Observation

- 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

Area of Hong Kong: 1,100 km$^2$
Population: ~8.0 million
GPS Network in Hong Kong

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
GPS-estimated water vapor

The slant wet delay (SWD) can be derived from:

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

Synoptic observations:

- Pressure, temperature, relative humidity
- Wet refractivity \( N_W \)

\[
N_W = 71.2952 \frac{e}{T} + 375463 \frac{e}{T^2}
\]
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
- Provide accurate precipitable water vapor measurements
- Work in the periods with direct sunlight. No data at nighttime or in precipitation.

AERONET (AErosol Robotic NETwork)
Radiosonde

Launched daily at UTC 0:00 and 12:00

Pressure, temperature, relative humidity etc.

Hong Kong’s only Radiosonde station (Vaisala RS92) situated at the King’s Park

Wet refractivity profile
Numerical Weather Prediction (NWP) model

- Based on Japan Meteorological Agency (JMA) non-hydrostatic model
- Operating since the rain season of 2010
- Horizontal resolution of 2 km and the predictions are updated hourly

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NWP model

- Temperature
- Dew point depression
- Geopotential height

16 isobaric levels
1000 hPa
100 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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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

Radiosonde gives 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:

\[
x = \left( A_G^T \cdot P_G \cdot A_G + A_W^T \cdot P_W \cdot A_W + A_A^T \cdot P_A \cdot A_A + A_s^T \cdot P_s \cdot A_s + \right.

\[
A_R^T \cdot P_R \cdot A_R + A_N^T \cdot P_N \cdot A_N + H^T \cdot P_G \cdot A_G \right)^{-1} \cdot \left( A_G^T \cdot P_G \cdot y_G + \right.

\[
A_W^T \cdot P_W \cdot y_W + A_A^T \cdot P_A \cdot y_A + A_s^T \cdot P_s \cdot y_s + A_R^T \cdot P_R \cdot y_R + A_N^T \cdot P_N \cdot y_N \right)
\]

where \( P \) 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

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

A more accurate water vapor density field can be obtained

relaxation parameter
Tomographic wet refractivity field

Evolution of wet refractivity field on 12 May 2013 (modeling interval: 30 minutes)
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Tomography model evaluation

**Model evaluation period:**
May 1 ~ Sept 30, 2013 (5 months)
Evaluation at GPS Station HKLT

### ZWD derived from GPS and tomography during May 1 to September 30, 2013

<table>
<thead>
<tr>
<th>SWD (mm)</th>
<th>ZWD (mm)</th>
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<tr>
<td>Bias</td>
<td>RMS</td>
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<td>-0.57</td>
<td>10.85</td>
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In the graph, the data points represent the ZWD derived from GPS and tomography over the specified period. The graph shows a comparison between GPS and tomography across different days of the year in 2013.
Evaluation by Radiosonde profiles

Comparison between radiosonde and tomography

Bias: 0.85 mm/km
RMS: 7.13 mm/km
Correlation Coefficient: 0.9806

RMS errors at different altitude layers

3.30 mm/km
11.44 mm/km
Wet refractivity evaluation by WVR

Comparison between WVR at HK airport & tomography
Wet refractivity evaluation by ECMWF

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Longitude (°E)
Latitude (°N)

RMS error (mm/km)
Height (km)

Overall Bias: 1.67 mm/km
Overall RMS: 7.21 mm/km
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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

- Wet refractivity profiles evaluation:
  - Radiosonde: Overall: 7.13 mm/km, single layer: 3.30~11.44 mm/km
  - WVR: Overall: 7.29 mm/km, single layer: 3.69~13.78 mm/km
  - ECMWF: Overall: 7.21 mm/km, single layer: 3.26~11.41 mm/km
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Thank you very much!
Thanks for your attention

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