Validating Precipitable Water Vapor from Shipborne GNSS Observation using Ground-based and Spaceborne Data

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Overview

• Background
• The Fram Strait Experiment
• GNSS Data Processing
• Results
  – ZTD validation using ground GNSS stations
  – PWV validation using NWP model and radiosonde profiles
  – PWV comparison with WVR onboard altimetry satellites
• Summary
Background: **GNSS Meteorology**

- **Ground-based GNSS atmosphere sounding**
  - GNSS ZTD/PWV: with 6 mm /1 mm accuracy
  - GNSS stations limited to mainland, islands

- **Shipborne GNSS atmosphere sounding**
  - Chadwell, 2001; Rocken, 2005; M. Fujita, 2008
  - To Extend GNSS Meteorology to Ocean

~170,000 ships via AIS
Background: *Shipborne GNSS Applications*

- **To Retrieve Tropospheric Delays Over Ocean**
  - To Improve Weather Forecast

- **To Calibrate ZWD of Onboard WVR for Altimetry Satellites**
  - **SARAL** a joint French-Indian altimetry satellite
  - **HY-2A** an ocean obs./monitoring satellite of China, launched in 2011

- **To Estimate Sea Surface Height**

- **What accuracy could be achieved?**

[Image source: https://www.flickr.com/photos/eumetsat/17391300405]
The Fram Strait Experiment in 2016

- GNSS-Reflectometry Experiment
  - GNSS-R antenna on ship nest
  - Detect ice freeboard height
  - Retrieve ice concentration

- Location: Fram Strait
  - Between Greenland and Svalbard

- Carrier: RV Lance (~60 m)

- Cruise from DOY 238-257
Cruise Trajectory

- **Cruise from DOY 238-257**
  - Svalbard to Greenland: 238 to 249
  - Greenland to Svalbard: 250 to 257

- **Repetivity & Crossover for Comparison**
Experimental Sensors

- GNSS-R antenna on ship nest
- GNSS geodetic antenna for precise positioning
  - 1-Hz GPS/GLONASS/Galileo observations
- Meteorological sensors
  - Pressure, temperature
  - Wind speed
- Ship motion sensors
  - Heave, pitch, roll, heading
Data Collected

- GNSS obs. for Positioning
- Ship Attitude / Wind Speed
- WVR onboard SARAL, a joint French-Indian altimetry satellite
- GNSS stations along coast
- Radiosonde Data
- Numerical Weather Model

Ground GNSS

Radiosonde
GNSS Data Processing

- GNSS Observations at Ground Stations
- Shipborne GNSS Observations
  - GPS-only and Multi-GNSS G/R/E PPP in kinematic mode
  - ZWD estimated as random walk process
  - 30s sampling rate, daily post-processing
- Positioning And Navigation Data Analyst (PANDA)
GNSS ZTD at Ground Stations

- **Daily static PPP ZTD**
  - RMS 0.40 cm Compared to IGS final

- **Aligned to Shipborne Antenna Elevation**
  - Elevation (height above sea level) from 37 m to 1012 m

- **ZTD Correlation Along With Inter-station Distances**

![Graph showing ZTD Differences of Ref. Sites w.r.t. Distance]

<table>
<thead>
<tr>
<th>Reference Site Pairs</th>
<th>ZTD RMS (cm)</th>
<th>Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GROK-GMMA</td>
<td>0.65</td>
<td>320</td>
</tr>
<tr>
<td>BLAS-NRSK</td>
<td>0.50</td>
<td>240</td>
</tr>
<tr>
<td>LEFN-BLAS</td>
<td>0.60</td>
<td>160</td>
</tr>
<tr>
<td>BLAS-GROK</td>
<td>0.45</td>
<td>80</td>
</tr>
<tr>
<td>NRSK-GROK</td>
<td>0.70</td>
<td>400</td>
</tr>
<tr>
<td>NRSK-GMMA</td>
<td>0.80</td>
<td>320</td>
</tr>
<tr>
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<td>0.55</td>
<td>240</td>
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<tr>
<td>LEFN-NRSK</td>
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</tr>
<tr>
<td>LEFN-GROK</td>
<td>0.75</td>
<td>80</td>
</tr>
<tr>
<td>LEFN-GMMA</td>
<td>0.85</td>
<td>400</td>
</tr>
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</table>
Results – Shipborne vs Ground Stations

• ZTD comparison with ground GNSS stations within 300 km
• Good agreement with ground reference GNSS stations
Results – Shipborne vs Ground Stations

- Multi-GNSS ~0.6 cm RMS within 100 km
- Multi-GNSS ~1.1 cm RMS within 300 km
- Multi-GNSS Improvement
  - ~12% (300 km), ~20% (100 km)
Results – Shipborne vs ECMWF

- Multi-GNSS ZTD: 0.65 cm, correlation 98.4%
- Multi-GNSS PWV: 1.09 mm, correlation 96.5%
- Multi-GNSS vs GPS: ~10% improvement
Results – Shipborne vs Radiosonde

- Six Radiosonde Profiles within 2 hour & 200 km
- Multi-GNSS PWV RMS 1.1 mm
Results – Shipborne vs Spaceborne

- Number of Crossover Points ~566 (within 2 h & 200 km)
- Fit RMS ~1.7 mm, Correlation coefficient: ~85%
- SARAL PWV outliers detected: ~5% (green dots)
- Very Small PWV

![Graphs showing comparison of PWV of SARAL and GPS PPP, and SARAL and GRE PPP](image-url)
Results – Shipborne vs Spaceborne

- PWV comparison with SARAL PWV observations
- Within 2h, 50/100/150/200 Km

<table>
<thead>
<tr>
<th>D/km</th>
<th>MEAN</th>
<th>STD</th>
<th>RMS</th>
<th>#PNT</th>
<th>BAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>50/36</td>
<td>1.3</td>
<td>1.3</td>
<td>1.8</td>
<td>70</td>
<td>1.4%</td>
</tr>
<tr>
<td>100/67</td>
<td>0.9</td>
<td>1.5</td>
<td>1.7</td>
<td>216</td>
<td>5.3%</td>
</tr>
<tr>
<td>150/92</td>
<td>0.7</td>
<td>1.7</td>
<td>1.9</td>
<td>347</td>
<td>6.0%</td>
</tr>
<tr>
<td>200/126</td>
<td>0.8</td>
<td>1.8</td>
<td>1.9</td>
<td>570</td>
<td>5.2%</td>
</tr>
</tbody>
</table>
Ongoing Work

- HY-2A (Altimetry) Satellite PWV
  - Detect sea surface wind field, sea surface height, sea surface temperature
  - Altitude: 971 km
  - Inclination: 99.3°
  - Repetitivity: 14/168 days
  - Instruments:
    - Dual-frequency (Ku/C) altimeter
    - Doris
    - Scatterometer
    - Microwave Radiometer Imager

https://directory.eoportal.org/web/eoportal/satellite-missions/h/hy-2a
Ongoing Work

- **Shipborne GNSS**
  - Scientific survey 2014 dedicated for HY-2A WVR calibration
  - About Two Months 1-Hz GPS/GLONASS observation
  - Similar GNSS data processing procedure
Ongoing Work

- Validating HY-2A PWV with shipborne GNSS

  - Bias: <0.5mm, STD: 1.8-2.8mm RMS: <3mm,
  - Distance Related RMS
  - Larger PWV
Summary

• **Shipborne GNSS PWV with 1~2 mm accuracy**

• **Shipborne GNSS PWV potential applications**
  – Contribution to NWP models
  – Validation/calibration of onboard WVR of altimetry satellites

• **Further Work**
  – HY-2A Onboard PWV calibration
  – Sea Surface Height Estimation
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Thanks a lot

Questions?