GNSS Radio Occultation Research in Japan, Data Assimilation Study and Development of a New Satellite Constellation

Y. Shoji¹, H. Owada², H. Seko¹, J. T. S. Sumantyo³, T. Tsuda⁴, and N. Yen⁵

1. Meteorological Research Institute, Japan
2. Japan Meteorological Agency, Japan
3. CEReS, Chiba University, Japan
4. RISH, Kyoto University, Japan
5. National Space Organization, Taiwan
Contents

1. Advances of operational GNSS RO Data Assimilation System of the JMA
2. Assessment of synergetic effect of ground based GNSS and GNSS RO for a heavy rainfall prediction
3. Development of two microsatellites for observation of continental land deformation
Contents

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History

- **March 22, 2007**  
  The Japan Meteorological Agency (JMA) began assimilating GNSS RO refractivity data into its operational global NWP system

- **November 1, 2010**  
  Operational DA of Formosat-3/COSMIC refractivity was started

- **December 18, 2012**  
  Revisions were implemented in the system. The major updates are:  
  - Additional use of refractivity data from TerraSAR-X and C/NOFS  
  - Resumption of GRACE-A refractivity data assimilation

  The number of assimilated RO data increased threefold relative to the previous operation.

  - Updates of observation operators and elimination of the bias correction procedure
Improvements of observation operators (1)

Vertical interpolation

<table>
<thead>
<tr>
<th>Old (routine)</th>
<th>New</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Conversion: <strong>geopotential height</strong> to <strong>geometric height</strong> for each model grid point</td>
<td>• Conversion: <strong>geometric height</strong> to <strong>geopotential height</strong> for observation</td>
</tr>
<tr>
<td>• Vertical interpolation: in <strong>geometric height</strong> scale</td>
<td>• Vertical interpolation: in <strong>geopotential height</strong> scale</td>
</tr>
<tr>
<td>• Earth’s radius: WGS-84</td>
<td>• Earth’s effective radius and gravity: Somigliana’s equation</td>
</tr>
</tbody>
</table>

\[ h = \frac{R \times z}{R - z} \]

\[ z = \frac{R \times h}{R + h} \]

\[ z = \frac{g_{lat}}{g_{wmo}} \frac{R_e \times h}{R_e + h} \]

- \( h \): geometric height
- \( R \): Earth’s radius
- \( z \): geopotential height
- \( R_e \): Earth’s effective radius
- \( g_{lat} \): gravity at the latitude of observation
- \( g_{wmo} \): gravity at 45N or 45S

Owada 2013
Difference between the Old and New conversion equations

In case of converting 20 km (geometric height) to geopotential height

Difference of geopotential heights (m) (Old – New)

Owada 2013
Improvements of observation operators (2)

Old (routine)

Forward

\[ N = c_1 \times \frac{p}{T} + c_2 \times \frac{e}{T^2} \]

Tangent linear

\[ \delta N = \left( \begin{pmatrix} - \frac{c_1}{T^2} p - 2c_2 \frac{e}{T^3} \end{pmatrix} \right) \begin{pmatrix} c_2 \left( \frac{1}{T^2} \right) \end{pmatrix} \begin{pmatrix} \delta T \delta e \end{pmatrix} \]

\( N \): refractivity
\( c_1, c_2 \): constants
\( p \): pressure (hPa), \( e \): water vapor pressure (hPa), \( T \): temperature (K)

Smith and Weintraub (1953)

Owada 2013
Improvements of observation operators (2)

New
Forward

\[ N = c_1 \times \frac{(p - e)}{T} + c_1' \times \frac{e}{T} + c_2 \times \frac{e}{T^2} \]

Tangent linear

\[ \delta N = \begin{pmatrix} -\frac{c_1}{T^2} (p - e) - c_1' \frac{e}{T^2} - 2c_2 \frac{e}{T^3} \\ -\frac{c_1}{T} + c_1' \frac{1}{T} + \frac{c_2}{T^2} - \frac{c_1}{T} \end{pmatrix} \begin{pmatrix} \delta T \\ \delta e \\ \delta p \end{pmatrix} \]

\( N \): refractivity
\( c_1, c_1', c_2 \): constants
\( p \): pressure (hPa), \( e \): water vapor pressure (hPa), \( T \): temperature (K)

Bevis et al. (1994)

Owada 2013
Other updates

• Eliminate the bias correction
  – Because the new algorithm to convert between height scales reduced the existent systematic biases

• Update the gross error check
  – The normalized O-B ((O-B)/B*100) is used in the check instead of O-B

• Update the observation errors

• Increase the number of assimilated data
  – Eliminate the lower altitude limit for data selection
  – Change the interval of vertical thinning from 1km to 0.5km
  – The number increases threefold relative to the routine
RESULTS OF OBSERVATION SYSTEM EXPERIMENTS FOR THE UPDATES

Periods of the experiments


Experiments

CNTL: Baseline
TEST: Baseline + updates

Owada 2013
Mean and standard deviation of fractional refractivity differences \((\frac{O - B}{B} \times 100)\) between Metop-A observations (O) and model simulations (B) as a function of geometric height in the TEST and CNTL experiments for August 2011. Observations above 30 km (shown in grey) were not used in either experiment due to the presence of biases between observations and model simulations.

- **CNTL**: There was a positive bias in the tropics and negative biases in the Arctic and Antarctic.
- **TEST**: The biases were clearly reduced.

Owada 2013
Monthly average of analyzed sea surface pressure differences between TEST and CNTL for August 2011 (left) and January 2012 (right)

- The effect of RO data assimilation is noticeable around the Antarctic.
  - where surface weather observation stations are sparse.
- The increments in the TEST experiment were brought by the incorporation of pressure perturbation in the new operators.

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Torrential rainfall on 16 July 2004

- At Ohyu, rainfall amount of 133mm/day was observed by this rainfall band.

Seko 2010
Reproduced 3-hour rainfall of forecast time from 0 to 3 hours reproduced from the analyzed fields. Valid time is 15 to 18 JST 16 July 2004.

Heavy rainfall was not reproduced by assimilation of conventional data.
Motivation
How the simultaneous assimilations of GNSS RO and Ground GNSS data modify the water vapor distribution?

Schematic illustrations of the observation operators of (a) PWV and SWV and (b) RO data. Thick solid line and broken line indicates actual topography and model topography, respectively. Thin lines indicate the planes that cross the model grids.

Seko 2010
Positions of RO and ground-based GPS data

- Grids distribution of which spatial interpolation weights are positive in the assimilations of ground-based GPS data (PWV, SWV) and RO data.

Seko 2010
D-values of ground-based GPS data

- D-value of PWV (Obs. - First guess) from 12 JST to 15 JST.

Seko 2010
Rainfalls region predicted from analyzed fields (GPS data)

(a) RO  (b) PWV  (c) SWV  
(d) RO+PWV  (e) RO+SWV

Reproduced 3-hour rainfall of forecast time from 0 to 3 hours reproduced from the analyzed fields. Valid time is 15 to 18 JST 16 July 2004.

Seko 2010
Synergistic improvement using RO and ground-based GPS data

- When both data were assimilated, the increments had both features of RO and ground-based GPS data.

Seko 2010
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Project abstract
• Center for Environmental Remote Sensing (CEReS) of Chiba University is developing GNSS-RO sensor onboard microsatellite (GAIA-I: 50 kg class) to observe the relationship of ionospheric phenomenon and land deformation (Wide area and low resolution).
• CEReS collaborates with Indonesian Aerospace Agency (LAPAN) to develop circularly polarized synthetic aperture radar (CP-SAR) onboard microsatellite (GAIA-II: 100 kg class) to observe land deformation (local and high resolution).

Expected impact
• Scientific impact
  1) GNSS-RO onboard microsatellite (GAIA-I):
     • Observation of global land deformation and change of total electron contents
     • Observation of atmospheric temperature, water vapor, sea surface height, gravity etc
     • Observation of earthquake precursor and the mechanism in global area
  2) CP-SAR onboard microsatellite (GAIA-II):
     • Observation using circular polarization and its study for new applications
     • Local observation of land deformation
Earth Observation using the GAIA-I and GAIA-II

**GNSS-RO onboard microsatellite (GAIA-I):**
- Indirectly observation of land deformation using GNSS-RO sensor
- Investigation of relationship of global land deformation and electrondensity change in ionosphere
- Mapping of Earth surface temperature, water vapor, sea surface wind, sea surface height (tsunami), gravity etc
- Investigation of earthquake precursor and its mechanism in wide area and low resolution

**CP-SAR onboard microsatellite (GAIA-II):**
- Directly observation of land deformation using CP-SAR sensor
- Local observation of land deformation and high resolution
- Investigation of global land deformation precisely

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**Observation of land deformation in high resolution using CP-SAR sensor**

**ULF**

**Continental land deformation**
(Nankai through earthquake etc)

**Wide area and low resolution of land deformation monitoring using GNSS-RO**

**Refraction in ionosphere**
(TEC, electron temperature, humidity etc)

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**Sumantyo 2013**
## Satellite Requirements

<table>
<thead>
<tr>
<th></th>
<th>GAIA-I</th>
<th>GAIA-II</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mission Instruments</strong></td>
<td>GPS Radio Occultation</td>
<td>Synthetic Aperture Radar</td>
</tr>
<tr>
<td></td>
<td>Electron Temperature Probe</td>
<td>Electron Temperature Probe</td>
</tr>
<tr>
<td><strong>Attitude Control</strong></td>
<td>Nadir pointing</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3-axis stabilization, +/-3°</td>
<td>3-axis stabilization, +/-0.2°</td>
</tr>
<tr>
<td><strong>Data Storage</strong></td>
<td>450 MBytes (for 3-day mission data)</td>
<td>10 GbBtes</td>
</tr>
<tr>
<td><strong>Communication</strong></td>
<td>S-band for TLM/CMD</td>
<td>S-band for TLM/CMD</td>
</tr>
<tr>
<td></td>
<td>X-band for Mission Data, 10 Mbps</td>
<td>X-band for Mission Data, 15 Mbps</td>
</tr>
<tr>
<td><strong>Power</strong></td>
<td>&gt; 90 W Avg.</td>
<td>&gt; 150 W Avg.</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>&lt; 50 kg</td>
<td>&lt; 100 kg</td>
</tr>
<tr>
<td><strong>Orbit</strong></td>
<td>550 - 800 km</td>
<td>550 - 800 km</td>
</tr>
<tr>
<td></td>
<td>Circular orbit at any inclination</td>
<td>Circular orbit at any inclination</td>
</tr>
<tr>
<td><strong>Design Life</strong></td>
<td>1 year</td>
<td>1 year</td>
</tr>
</tbody>
</table>

Sumantyo 2013
Collaborators :
Kyoto University – Japan (Prof. Toshitaka Tsuda)
National Cheng Kung University – Taiwan (Prof. Koh-ichiro Oyama)
Chiba University – Japan (Prof. Katsumi Hattori)

GNSS-Radio Occultation (GNSS-RO) IGORS
1. **Advances of operational GNSS RO Data Assimilation System of the JMA**
   a. Advanced system has been implemented since December 18, 2012.
   b. The effect of improvements is noticeable around the Antarctic.

2. **Assessment of synergetic effect of ground based GNSS and GNSS RO for a heavy rainfall prediction**
   a. Simultaneous assimilation of SWV and RO produced the rainfall system closest to the observed one, because SWV made the contrast of water vapor along the northern side of the rainfall region and RO increased the low-level water vapor.

3. **Development of two microsatellites for observation of continental land deformation**
   a. The plan has started year 2013 and is aiming to launch GNSS RO mission satellite by year 2017.
Thank you for your attention.