Impact of Satellite Orbits and Clocks on Radio Occultation (RO) Data Processing

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IROWG-2
Estes Park, CO
28 March – 3 April 2012
Overview

- Introduction
  - ERA-CLIM project
  - Contribution from EUMETSAT

- Impact of satellite orbit and clock quality in MetOp RO data processing
  - Post-processing using final GPS products (ERA-CLIM)
  - NRT using various NRT and RT GPS products (operational)

- COSMIC POD at EUMETSAT
  - Results and discussion on achievable accuracy
Introduction

- European Re-Analysis of global CLIMate observations (ERA-CLIM)
  - Project headed by ECMWF
  - Re-analysis of in-situ and satellite observation data in generating consistent global model of Earth’s climate system
  - Objective is to improve on numerical weather forecasting

- EUMETSAT RO activity in ERA-CLIM
  - Provide reprocessed GPS RO observations (2001-present) from MetOp, COSMIC, CHAMP, GRACE, etc
    - Maintain consistency in using the type of GPS products
    - Investigation into GPS orbit and clock products and their impact on POD and in turn RO bending angle profile
Impact of satellite clocks in MetOp RO data processing

- Simple layout of post-processing architecture
  - GPS raw data processing
  - Precise orbit determination
  - RO data processing
  - Comparison with ECMWF model
Impact of satellite clocks in MetOp RO data processing

GPS Final Orbit and Clock Products

- GPS orbit product – 15 mins interval
- GPS clock product – 5-min, 15-min interval (standard) and others (table)
Studying impact of GPS clock products on RO

- Generated two sets of solution
  - ESOC Repro1 (interpolated 30s GPS clocks)
  - CODE OPS (estimated 30s GPS clocks)

- Results from analysis
  - MetOp orbit (POD)
  - Bending angle (using geometric optics processing)
Impact of satellite clocks in MetOp RO data processing

- Studying impact of GPS final products on RO
  - ESOC Repro1 (5 min clocks) vs CODE OPS (30s clocks)
Impact of satellite clocks in MetOp RO data processing

Assessment of MetOp POD

Arc-wise (RMS) statistics derived from 4-hr orbital overlap

![Graph showing along-track velocity comparison between estimated and interpolated clocks]

- **Estimated Clocks**:
  - Along-track velocity: < 0.02 mm/s
  - Median: 0.007 mm/s
- **Interpolated Clocks**:
  - Along-track velocity: < 0.03 mm/s
  - Median: 0.012 mm/s

3D Position (due to interpolated GPS clock errors): < 2 cm (RMS)
Impact of satellite clocks in MetOp RO data processing

Assessment of bending angle

![Graphs showing GRAS 5min Bias and GRAS 5min Std Dev for different latitudes and statistics for GRAS 5min Bias and GRAS 5min Std Dev](image)

- **Start:** 200709300101
- **End:** 200710302355
- **Occ/day:** 628
- **Fail:** 3.4%
- **Wghs:** 93.4%
- **No match:** 562

- **Low Lat (6958)**
- **Mid Lat (7890)**
- **High Lat (4609)**
Impact of satellite clocks in MetOp RO data processing

Assessment of bending angle

- No visible impact at < 40 km impact height
- Better STDEV from estimated 30s clocks > 40 km impact height
Near Real Time Analysis
Impact of satellite clocks in MetOp NRT RO data processing

- **STUDY** (Collaboration with GSOC/DLR)
  Assess different GPS based NRT POD concepts with GRAS data (Nov 15 to Dec 15 2011)
  - Different NRT GPS products
  - Different POD s/w tools
  ⇒ Focus on:
    - achieved along-track velocity accuracy
    - resulting bending angles

- **MOTIVATION**
  - Better understand the effect of NRT LEO and GPS orbits in RO
  - Provide design recommendations/ requirements for future RO missions
**System Setup**

- **GPS products:**
  - CODE rapid (reference)
  - GSN/ESA
  - RETICLE/DLR
  - Broadcast Ephemeris (BCE)

- **POD tools**
  - ESA/NAPEOS (BAHN) (Batch Filter)
  - DLR/GHOST (Batch Filter)
  - DLR/RTNAV (Extended Kalman Filter)

- **ECMWF forward modelling for comparison of Bending Angles (BA)**
Impact of satellite clocks in MetOp NRT RO data processing

GPS products and POD setups

<table>
<thead>
<tr>
<th>Description</th>
<th>COR</th>
<th>GSN</th>
<th>RTC</th>
<th>BCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Category</td>
<td>post-processed</td>
<td>near-real-time</td>
<td>real-time</td>
<td>real-time</td>
</tr>
<tr>
<td>Originator</td>
<td>CODE</td>
<td>ESA/ESOC</td>
<td>DLR/GSOC</td>
<td>GPS</td>
</tr>
<tr>
<td>Network</td>
<td>IGS</td>
<td>GSN</td>
<td>IGS R/T &amp; DLR</td>
<td>GPS</td>
</tr>
<tr>
<td>Arc length</td>
<td>24 h</td>
<td>orbit: 24 h + 19 h(pred) clock: 30 m</td>
<td>-</td>
<td>2 h</td>
</tr>
<tr>
<td>Update interval</td>
<td>24 h</td>
<td>orbit: 3 h</td>
<td>-</td>
<td>2 h</td>
</tr>
<tr>
<td>Latency</td>
<td>12 h</td>
<td>orbit: 60-90 m clock: &lt;45 m</td>
<td>&lt;10s</td>
<td>-</td>
</tr>
<tr>
<td>Step size</td>
<td>orbit: 15 m, clock: 30 s</td>
<td>orbit: 15 m clock: &lt;45 m</td>
<td>10 s</td>
<td>-</td>
</tr>
</tbody>
</table>

6 different processing chains:

Napeos: COR (24h arc, daily), GSN (6h arc, 1.5h freq.), RTC (6h arc, 1.5h freq)

GHOST: COR (24h arc, daily), RTC (6h arc, 1.5h freq)

RTNAV: BCE (simulated real time)
### Results - POD

<table>
<thead>
<tr>
<th>Solution</th>
<th>Radial [mm]</th>
<th>Along-track [mm]</th>
<th>Cross-track [mm]</th>
<th>Position (3D rms, [mm])</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF_COR_N</td>
<td>-6 ± 16</td>
<td>-2 ± 40</td>
<td>+23 ± 13</td>
<td>51</td>
</tr>
<tr>
<td>NRT_RTC_N</td>
<td>-7 ± 19</td>
<td>+1 ± 39</td>
<td>+23 ± 16</td>
<td>52</td>
</tr>
<tr>
<td>NRT_RTC_G</td>
<td>+1 ± 18</td>
<td>-3 ± 36</td>
<td>-1 ± 14</td>
<td>43</td>
</tr>
<tr>
<td>NRT_GSN</td>
<td>-6 ± 18</td>
<td>-2 ± 39</td>
<td>+23 ± 15</td>
<td>51</td>
</tr>
<tr>
<td>RT_BCE</td>
<td>+7 ± 195</td>
<td>+157 ± 329</td>
<td>+25 ± 228</td>
<td>473</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Solution</th>
<th>Radial [mm/s]</th>
<th>Along-track [mm/s]</th>
<th>Cross-track [mm/s]</th>
<th>Velocity (3D rms, [mm/s])</th>
</tr>
</thead>
<tbody>
<tr>
<td>OFF_COR_N</td>
<td>0.00 ± 0.03</td>
<td>-0.01 ± 0.03</td>
<td>0.00 ± 0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>NRT_RTC_N</td>
<td>0.00 ± 0.03</td>
<td>-0.01 ± 0.03</td>
<td>0.00 ± 0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>NRT_RTC_G</td>
<td>0.00 ± 0.03</td>
<td>0.00 ± 0.02</td>
<td>0.00 ± 0.01</td>
<td>0.04</td>
</tr>
<tr>
<td>NRT_GSN</td>
<td>0.00 ± 0.03</td>
<td>-0.01 ± 0.03</td>
<td>0.00 ± 0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>RT_BCE</td>
<td>-0.15 ± 0.34</td>
<td>+0.06 ± 0.16</td>
<td>0.01 ± 0.24</td>
<td>0.48</td>
</tr>
</tbody>
</table>

- All NRT solution < 0.1mm/s along track
- Offline & NRT solutions (NAPEOS vs Ghost) agreement ~ 5cm
- Small inter-agency biases in radial (6mm) and cross-track (23mm)
- Simulated RT orbit have a factor 10 larger error in MetOp pos. and vel., but only a factor 2 for along track vel.
Results – NRT Bending Angle

- 15100 rising and setting occultation events, only Geometric Optics processing
- Offline (one day lag) processing provides up to 10% more occultations (unhealthy satellites)
- All NRT solutions provide an almost identical bending angle performance
- Slight deviation at high altitude from BCE-derived BA
Assessment of COSMIC POD
COSMIC Precise Orbit Determination

- Two sets of statistics for 6 COSMIC s/c
  - 2-10 August 2006
  - 26 Nov – 3 Dec 2008

- Internal (orbit overlap) assessment (stats based on median)
  - 3D position (RMS) < 25 cm
    [exclude FM6 in 2006]
  - Along-track velocity (RMS) < 0.1 mm/s
External orbit assessment (stats based on median)

- CDAAC (online products)
- JPL (reprocessed orbits)

3D position < 60 cm

Along-track velocity < 0.2 mm/s
Summary and Conclusions

- Impact of satellite orbit & clocks on RO processing
  - POD performance and bending angle statistics from post-processing (ERA-CLIM) and NRT (operational) have been assessed using one month of MetOp data
  - MetOp along-track velocity accuracy (POD)
    - Post-processed < 0.02 mm/s
    - NRT < 0.05 mm/s
    - RT ~ 0.2 mm/s
  - Bending angle performance
    - Clock interpolation error (5min→30s) induced no significant difference
    - NRT and rapid solutions are identical
    - RT compatible with NRT for height up to 40km

- COSMIC POD
  - Overall POD (EUM, UCAR, JPL) results show good agreement