GNSS Orbit and Clock Determination for (Near-)Real-time Occultation Data Processing

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Motivation

- Bending angle retrieved from comparison of observed Doppler with straight-line model
- Model depends on
  - GNSS and LEO position
  - GNSS and LEO velocity
  - GNSS and LEO clock (frequency)
- GNSS and LEO POD
Requirements

➤ Timeliness
  ➤ Near-real time („as fast as possible“)
  ➤ Metop: Bending angle delivery 2¼ h after RO event

➤ Accuracy
  ➤ Kursinski et al. (1997): 0.05 mm/s along-track velocity uncertainty introduces a negligible error (<0.2% at 50–60 km altitude) into atmospheric parameters
  ➤ Adopted as 2σ threshold for Metop
  ➤ Corresponds roughly to 10 cm POD accuracy

Notes on Accuracy Requirement

- Commonly accepted, frequently copied but rarely re-assessed
- 0.05 mm/s reflects the assessed POD accuracy at the time, not necessarily the actual needs
- Relative bending angle error is most pronounced at high altitudes, but current use in NRT data assimilation is typically limited to 40 km altitude
- 0.05 mm/s corresponds to 2e-13 relative frequency stability, but GNSS clock variance at short intervals is typically much higher
GNSS Clock Characterization

- Allen deviation $\sigma_y(\tau)$ measures variance of average frequency over given time interval
- Determines error of interpolated clock solutions
- Depends on frequency standard (Cesium, Rubidium, H-maser) and clock generation (Hauschild et al. 2013)
- Typically $>10^{-12}$ at $\tau<10$s
- Analysis at short $\tau$ affected by receiver noise (see also Griggs et al. 2013)

GNSS Orbit and Clock Products – IGS

- International GNSS Service (IGS) is key provider of GPS data products
- Global network, numerous analysis centers; various offline products
- New Real-Time Service (RTS; http://rts.igs.org)
- Combined R/Trpoduct: orbit RMS ~ 3cm, clock std.dev ~0.10-0.15 ns
GNSS Orbit and Clock Products – Other Providers

- JPL Global Differential GPS (GDGPS) [http://www.gdgps.net/](http://www.gdgps.net/)
  - Very large network
  - GPS+GLO real-time product
  - <10 cm position, sub-ns clocks
  - TDRSS Augmentation Service (TASS)
- ESA/ESOC Ground Support Network (GSN) [http://dgn7.esoc.esa.int/projects/gras-ground-support-network/](http://dgn7.esoc.esa.int/projects/gras-ground-support-network/)
  - Originally built up for GRAS/Metop support
  - High performance near-real-time product
- Industrial PPP service providers
  - FUGRO G2
  - Trimble RTX
  - ...
Towards a Multi-GNSS Service

- Various new and emerging constellations
  - BeiDou, Galileo, IRNSS, QZSS
  - Open signals on multiple (up to 3) frequencies
  - Prospects for real-time orbit and clock corrections (QZSS LEX, Galileo CS?)

- IGS Multi-GNSS Experiment (MGEX)
  - [http://igs.org/mgex/](http://igs.org/mgex/)
  - Global multi-GNSS network (~85 stations, ~65 R/T)
  - Initial Galileo and QZSS orbit & clock products
  - Real-time Galileo orbit & clock product in preparation (DLR, BKG, others)
GNSS Based Precise Orbit Determination of LEO Satellites

Concepts
- Undifferenced, PPP-style processing of dual-frequency code and carrier-phase
- Use of known GNSS orbit and clock products
- Auxiliary spacecraft data (attitude, etc.)
- High-fidelity dynamical and observation models
- Empirical accelerations (reduced dynamics approach)
- Estimation of dynamical params, epoch wise clocks, biases, …

Tools
- Numerous GNSS processing and POD S/W packages (BERNESE, EPOS, GEODYN, GIPSY-OASIS, GHOST, NAPEOS, ZOOM, …)
- High consistency (e.g. 5 cm 3D rms in Metop POD study, Montenbruck et al. 2009)
- Adequate processing speed (~5 min/day) for near-real-time execution

DLR/EUMETSAT NRT POD Study

- 1 month of GRAS observations (POD and RO)
- Two POD s/w packages (NAPEOS, GHOST)
- Three GPS orbit & clock products (CODE rapid, GSN NRT, RETICLE R/T)
- NRT-style processing
- Complementary R/T Navigation Filter with broadcast ephemerides
- Bending angle computation for RO events based on POD and RTNAV solutions

Near-Real-Time POD Results

<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>
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<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>
</tbody>
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<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>
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<td>+0.00 ± 0.02</td>
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<td>NRT_RTC_N</td>
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<td>+0.00 ± 0.02</td>
<td>0.05</td>
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<td>NRT_RTC_G</td>
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<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>
</tbody>
</table>

All results referred to OFF_COR_G solution

Type: OFF=Offline, NRT=Near-Real-Time
GPS product: COR=CODE rapid, RTC=RETICLE, GSN=Ground Support Network
Software: N=NAPEOS, G=GHOST
Near-Real-Time POD Results (cntd.)

- Highly consistent results obtained with different s/w package
  - 5 cm / 0.05 mm/s (3D rms) agreement in accord with earlier studies
  - Small biases due to different modelling differences (radial and cross-track acceleration)

- Highly consistent results obtained with different (near-)real-time GPS orbit and clock products

- NRT POD products have essentially the same quality as final products
  - Benefit of batch least-squares estimation scheme
Real-Time Orbit Determination

- Real-time navigation filter
  - RTNAV software for playback data processing on ground
  - Replicates Phoenix-XNS software (PROBA-2, GRAPHIC version)
  - Flight code compatible with common onboard CPU (32-bit 30 MHz)

- Employed Models
  - 40x40 gravity field, luni-solar perturbations, drag & SRP, empirical accelerations
  - Weekly Earth orientation parameter updates
  - Dual-frequency pseudorange and phase observations (at 30s intervals)
  - GPS broadcast ephemerides

Real-Time Orbit Determination Results

- Ten times lower performance than ground-based POD
- Still ~ 0.2 mm/s along-track velocity accuracy

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<th>Position (3D rms, [mm])</th>
</tr>
</thead>
<tbody>
<tr>
<td>RT_BCE</td>
<td>+7 ± 195</td>
<td>+157 ± 329</td>
<td>+25 ± 228</td>
<td>473</td>
</tr>
<tr>
<td>Solution</td>
<td>Radial [mm/s]</td>
<td>Along-track [mm/s]</td>
<td>Cross-track [mm/s]</td>
<td>Velocity (3D rms, [mm/s])</td>
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<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>
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</table>
Bending Angles Comparison

Montenbruck et al. 2013
Bending Angles Comparison (cntd.)

- Offline vs. near-real-time POD
  - Virtually identical standard deviation of bending angles w.r.t. to forward modeling from ECMWF data up to altitudes of >50 km

- (Simulated) real-time onboard orbit determination vs. „precise“ results
  - Discernible differences above 40 km
  - Accuracy compatible with data weighting in assimilation for NRT weather forecast
Vision RO 2020

- Onboard orbit determination (and geometric optics bending angles computation) as a complement to full-featured ground processing in future RO missions
- Fast real-time download of bending angles via Orbcomm or Inmarsat
- Improved accuracy through high-performance GNSS clocks and/or real-time correction data
Summary and Conclusions

- (Near-)real-time GPS/GLO orbit and clock products for RO work
  - Free public services (IGS RTS) and dedicated providers with guarantee-of-service
  - High-accuracy enables LEO POD with (more than) adequate accuracy

- Multi-GNSS agenda
  - Global real-time multi-GNSS network(s) established (e.g. MGEX)
  - R/T Galileo (+QZSS+BeiDou) products within reach
  - Still waiting for FOC, space receivers and flight data

- Real-time onboard POD and RO processing
  - Acceptable accuracy; compatible with onboard computing power
  - Low data volume (bending angles) enables instantaneous downlink