Orbit and Clock Determination - Galileo

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  • AC processing strategies
• MGEX Galileo product validation
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Galileo Status

• Four Galileo In-Orbit Validation (IOV) satellites in orbit
  - E11 and E12 launched in October 2011
  - E19 and E20 launched in October 2012
• First FOC satellite dual launch planned for August 2014
The IGS MGEX Network

ftp://cddis.gsfc.nasa.gov/pub/gps/data/campaign/mgex/
http://mgex.igs-ip.net/

- Nearly all MGEX stations are tracking Galileo
MGEX products availability

Status: 15-June-2014
Satellite system IDs according to the content of the precise orbit files at ftp://cddis.gsfc.nasa.gov/pub/gps/products/mgex/

MGEX Galileo products availability

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## MGEX Galileo analysis centers

<table>
<thead>
<tr>
<th>Institution</th>
<th>Software</th>
<th>Diff. LVL</th>
<th>Phase center</th>
<th>Arc-length</th>
<th>CLK sampling</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNES/CLS (GRM)</td>
<td>CNES POD GINS</td>
<td>zero</td>
<td>MGEX</td>
<td>30 h</td>
<td>15 min</td>
</tr>
<tr>
<td>CODE (COM)</td>
<td>Bernese 5.3</td>
<td>double (orbit) zero (clock)</td>
<td>ESA</td>
<td>3 d</td>
<td>5 min</td>
</tr>
<tr>
<td>ESOC (ESM)</td>
<td>NAPEOS</td>
<td>zero</td>
<td>ESA</td>
<td>1 d</td>
<td>5 min</td>
</tr>
<tr>
<td>GFZ (GFM)</td>
<td>EPOS.P8</td>
<td>zero</td>
<td>ESA</td>
<td>3 d</td>
<td>5 min</td>
</tr>
<tr>
<td>TUM (TUM)</td>
<td>Bernese 5.0</td>
<td>zero</td>
<td>MGEX</td>
<td>3 d</td>
<td>15 min</td>
</tr>
</tbody>
</table>
MGEX Galileo product validation

“MGEX data analysis at CODE – current status“, Prange et al., presented at the EGU 2013, Vienna:

• Validation of COM, TUM, GRM orbits for different time intervals in 2012 (long arc fit and SLR residuals)

“Quality assessment of Galileo Orbit and Clock Products of the IGS Multi-GNSS Experiment (MGEX)“, Steigenberger et al., presented at the AGU 2013, San Francisco and

“Galileo Orbit and Clock Quality of the IGS Multi-GNSS Experiment“, Steigenberger et al. (2014), accepted for publication in Advances in Space Research:

• Overview, description, validation of MGEX Galileo orbit and clock products
• Validation time interval: 20 weeks from 28 April till 14 September 2013 (day of year 118 – 257/2013, GPS week 1738 – 1757)

=> validation results presented here again (see following slides)
Orbit validation

Day boundary discontinuities

- 3D position difference between consecutive days at midnight

2-day orbit fit RMS

- 2-day orbit fitted through positions of 2 consecutive days
- 3D RMS of 2-day arc w.r.t. original orbits

Satellite Laser Ranging residuals

- Independent optic technique

Orbit comparisons

- Differences between two ACs in radial, along-track, cross-track direction
### Orbit validation

**Common time period** considered, median values given in cm

<table>
<thead>
<tr>
<th>Satellite</th>
<th>COM</th>
<th>GFM</th>
<th>GRM</th>
<th>TUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>E11</td>
<td>4.4</td>
<td>8.1</td>
<td>20.9</td>
<td>5.8</td>
</tr>
<tr>
<td>E12</td>
<td>4.7</td>
<td>8.0</td>
<td>20.7</td>
<td>6.7</td>
</tr>
<tr>
<td>E19</td>
<td>4.8</td>
<td>8.9</td>
<td>28.0</td>
<td>6.3</td>
</tr>
<tr>
<td>E20</td>
<td>4.7</td>
<td>8.5</td>
<td>22.1</td>
<td>6.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Satellite</th>
<th>COM</th>
<th>GFM</th>
<th>GRM</th>
<th>TUM</th>
</tr>
</thead>
<tbody>
<tr>
<td>E11</td>
<td>1.4</td>
<td>2.7</td>
<td>6.6</td>
<td>1.3</td>
</tr>
<tr>
<td>E12</td>
<td>1.4</td>
<td>2.7</td>
<td>6.4</td>
<td>1.5</td>
</tr>
<tr>
<td>E19</td>
<td>1.5</td>
<td>2.9</td>
<td>6.4</td>
<td>1.5</td>
</tr>
<tr>
<td>E20</td>
<td>1.5</td>
<td>3.0</td>
<td>6.7</td>
<td>1.6</td>
</tr>
</tbody>
</table>

http://igs.org
Orbit validation with SLR

Elevation of the Sun above the orbital plane

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Bias [cm]</th>
<th>STD [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>E11</td>
<td>-5.2</td>
<td>8.4</td>
</tr>
<tr>
<td>E12</td>
<td>-5.9</td>
<td>8.1</td>
</tr>
</tbody>
</table>
Orbit validation with SLR

Elevation of the Sun above the orbital plane

http://igs.org
Orbit validation with SLR

SLR Residuals vs. Earth-Satellite-Sun Angle: E11

http://igs.org

Mean bias and standard deviation (STD) of SLR residuals
Orbit differences between ACs for E11

COM vs. GFM
Mean: -0.00 m  STD: 0.03 m
Mean: 0.01 m  STD: 0.08 m
Mean: 0.00 m  STD: 0.05 m

COM vs. GRM
Mean: -0.02 m  STD: 0.10 m
Mean: 0.01 m  STD: 0.31 m
Mean: -0.02 m  STD: 0.16 m

http://igs.org
Broadcast orbit validation

Orbit Comparison E11: Broadcast vs. TUM

Mean: 0.38 m  STD: 0.96 m

Mean: 1.00 m  STD: 2.69 m

Mean: -0.13 m  STD: 2.52 m

Day of Year 2013
Broadcast orbit validation

SLR Validation of Galileo Broadcast Orbits

<table>
<thead>
<tr>
<th>Time period: DOY 1 - 300/2013</th>
</tr>
</thead>
<tbody>
<tr>
<td>Outlier limit: 5 m</td>
</tr>
<tr>
<td>Nominal satellite antenna offsets</td>
</tr>
</tbody>
</table>

Residuals [cm]

<table>
<thead>
<tr>
<th>E11</th>
<th>E12</th>
<th>E19</th>
<th>E20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offset [cm]</td>
<td>36.8</td>
<td>39.4</td>
<td>32.1</td>
</tr>
<tr>
<td>STD [cm]</td>
<td>94.0</td>
<td>88.2</td>
<td>101.6</td>
</tr>
<tr>
<td>RMS [cm]</td>
<td>100.9</td>
<td>96.5</td>
<td>106.5</td>
</tr>
</tbody>
</table>
Clock validation

Linear fit of COM clock estimates for E12

![Graph showing linear fit of COM clock estimates for E12]
Clock validation

Linear fit of COM clock estimates for E12

Active clock: RAFS
Clock validation

Linear fit of COM clock estimates, elevation of the Sun above the orbital plane for E12

Beta angle dependency of satellite clocks
Clock validation

Linear fit of COM clock estimates, elevation of the Sun above the orbital plane, and eclipse seasons for E12

Eclipse seasons visible in the clock fit RMS time series
Clock validation

Median Allan deviations of Galileo PHM clocks from 7 days of data (GPS week 1738; DOY 13/118 - 124)
Clock validation

Median Allan deviations of Galileo PHM clocks from 7 days of data (GPS week 1750; DOY 13/202 - 208)

E11

E12

E19

E20

COM
GFM
GRM
TUM
Clock validation

Median Allan deviations of Galileo RAFS clocks from 3 weeks of data (GPS weeks 1754 – 1757; DOYs 13/234 - 254)

- E11/G25
- E12/G27
- E19
- E20

Galileo RAFS clocks from 3 weeks of data (GPS weeks 1754 – 1757; DOYs 13/234 - 254)
Biases

Galileo–GPS ISB for COM solution (frequencies: L1+L2 GPS, L1+L5 GAL)
Summary and outlook

- MGEX Galileo products with different features available (short latency: TUM; all GNSS included: ESM; long time series: COM, GFM, TUM, GRM)

- Precision of Galileo MGEX products is generally below the one decimeter level

- Radial accuracy as evaluated by SLR is at the one decimeter level with a systematic bias of about 5 cm

- Galileo Broadcast orbits have a meter level accuracy

- Systematic effects visible in orbits and clocks of all ACs due to orbit modeling problems (radiation pressure)

- Modeling deficiencies due to lack of knowledge about the satellites:
  - Satellite antenna phase center offsets and variations
  - Attitude behavior, satellite dimensions, and surface properties