Multi-GNSS: Update, Latest Developments and Science Issues in Transition Document

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19th PNT Advisory Board Meeting
June 29, 2017
Baltimore Marriott Inner Harbor at Camden Yards
110 South Eutaw Street
Baltimore, MD 21201
USA
Contents

- Multi-GNSS in 2017
- Latest developments in Multi-GNSS
- Science in the transition document: key points
- IGS White Paper on Satellite Metadata
- Science in the transition document: recommendations
- Additional material:
  - MGEX: status within the IGS
  - MGEX@CODE: update
### Multi-GNSS in 2017

**Status:** May 2017

<table>
<thead>
<tr>
<th>System</th>
<th>Blocks</th>
<th>Signals</th>
<th>Sats*</th>
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<tbody>
<tr>
<td>GPS</td>
<td>IIR</td>
<td>L1 C/A, L1/L2 P(Y) +L2C +L5</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>IIR-M</td>
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<td>7+(1)</td>
</tr>
<tr>
<td></td>
<td>IIF</td>
<td></td>
<td>12</td>
</tr>
<tr>
<td>GLONASS</td>
<td>M</td>
<td>L1/L2 C/A+P</td>
<td>21+(2)</td>
</tr>
<tr>
<td></td>
<td>M+</td>
<td>L1/L2 C/A+P, L3 (CDMA)</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>K1</td>
<td>L1/L2 C/A+P, L3 (CDMA)</td>
<td>1+(1)</td>
</tr>
<tr>
<td>BeiDou</td>
<td>GEO</td>
<td>B1, B2, B3</td>
<td>5+(1)</td>
</tr>
<tr>
<td></td>
<td>IGSO</td>
<td>B1, B2, B3</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>MEO</td>
<td>B1, B2, B3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>3rd generation</td>
<td>B1, B3</td>
<td>(5)</td>
</tr>
<tr>
<td>Galileo</td>
<td>IOV</td>
<td>E1, E6, E5a/b/ab</td>
<td>3+(1)</td>
</tr>
<tr>
<td></td>
<td>FOC</td>
<td>E1, E6, E5a/b/ab</td>
<td>6+(6)</td>
</tr>
<tr>
<td>QZSS</td>
<td>IGSO</td>
<td>L1 C/A, L1C, SAIF L2C, E6 LEX, L5</td>
<td>1</td>
</tr>
<tr>
<td>IRNSS</td>
<td>IGSO</td>
<td>L5, S</td>
<td>6+(1)</td>
</tr>
</tbody>
</table>

*Status May 2017; brackets indicate satellites not declared healthy/operational

**From Steigenberger & Montenbruck (2017)**

**International Association of Geodesy**
Multi-GNSS: the systems 2017

Close to 100 GNSS & RNSS satellites have different characteristics (semi-major axes $a$, eccentricities $e$, inclinations $i$) and different signals, tracking modes.

QZSS and Galileo FOC1 satellites have elliptic orbits ($e\approx0.075$, $e\approx0.16$, respectively)

From Prange et al. (2015).
Transition: key points

GNSS is fundamental for Earth and atmosphere sciences. From the permanent IGS tracking network (top, left) the ITRF positions/velocities (top, right), polar motion (bottom, left) and variations of Length of Day (bottom, right) are derived. Final IERS products include all space techniques!
Transition: key points

IGS products enable, e.g., precise orbit and gravity field determination – the latter in combination with GRACE inter-satellite link. Left: GRACE twin satellites, right: gravity anomalies from GRACE
Transition: Recommended Actions (I)

Recommended Actions

In order to ensure high-accuracy multi-GNSS applications the following action items are proposed from the point of view of science:

- The PNT advisory board recommends to minimize bureaucratic obstacles hindering the use of all GNSS signals and it endorses all measures to mitigate or to avoid interference.
- The PNT advisory board recommends that all future GPS satellites should be equipped with SLR reflectors for independent orbit validation.
- The PNT advisory board recommends free access to GPS satellite information needed for precise orbit determination and expresses its expectations towards other GNSS providers to act in the same sense.
- The PNT board endorses all monitoring and coordinating activities for scientific GNSS applications of the IGS and International Committee on GNSS (ICG), in particular in the area of multi-GNSS.

Recommendations from the science part of the transition document

International Association of Geodesy
Multi-GNSS: Latest developments

**Galileo IOV Satellite Metadata**

**Table of Contents**
- Section 1: Introduction
- Section 2: Galileo IOV Reference Frame
- Section 3: Attitude Law
  - Subsection 3.1: Yaw Steering Law
  - Subsection 3.2: Yaw Steering Law (ANTEX Reference Frame Convention)
- Section 4: Mass and Centre Of Mass
- Section 5: Navigation Antenna Phase Centre Corrections
  - Subsection 5.1: Antenna Reference Point (ARP)
  - Subsection 5.2: Measured Phase Centre Offsets and Variations
  - Subsection 5.3: ANTEX PCVs
- Section 6: Geometry
- Section 7: Laser Retractor Reflector Location
- Section 8: Satellite Group Delay
  - Subsection 8.1: Measured Satellite Group Delay
  - Subsection 8.2: Differential Code Bias
- Section 9: Glossary
- Section 10: GNSS Bibliography

Left: Publication of satellite meta data for Galileo IOV satellites in Dec. 2016

Right: Successful launch of QZS-2 on June 1, 2017 (publication of metadata imminent)

Moreover: first dual-frequency observation on BDS-3
Multi-GNSS: Latest developments

IGS White Paper on Satellite and Operations Information for Generation of Precise GNSS Orbit and Clock Products

O. Montenbruck on behalf of the IGS Multi-GNSS Working Group

Abstract

The International GNSS Service (IGS) provides precise orbit and clock solutions for GNSS satellites that support a wide range of science and engineering applications with numerous benefits for society at large. All IGS data and products are made freely available to the scientific community and the general public. To best fulfill its mission, the IGS depends on information from the GNSS providers concerning the characteristics of individual types of satellites as well as their operations. This white paper describes the parameters needed to ensure the highest possible performance of IGS products for all constellations and motivates the need for provision of satellite and operations information by the GNSS providers. All information requested by the IGS is considered to be sufficiently abstract such as to neither interfere with the GNSS providers' safety and security interests nor with intellectual property rights.

Montenbruck et al (2017c) IGS White Paper on Metadata asking system providers for information concerning mass, center of mass, antenna & reflector data, solar panels, radiated power, satellite attitude, and manoeuvres

→ White paper should be endorsed by PNT!

International Association of Geodesy
In view of the now available IGS White Paper on GNSS metadata, we recommend that

- the board takes note of the IGS White Paper
- the board endorses/encourages its application for GPS
MGEX: Orbit Validation

Knowledge-based vs. Empirical Models

A priori box-wing model for QZS-1, based on metadata combined with empirical model ECOM (blue), without a priori model (red). From Montenbruck et al. (2017b). 

**Bottom-line:** the better the a priori knowledge, the better the results.

International Association of Geodesy
References


L. Prange et al. (2016) CODE’s five-system orbit and clock solution—the challenges of multi-GNSS data analysis, J. Geod. 91(4), pp. 345-360


O. Montenbruck, on behalf of IGS Multi-GNSS Working Group: (2017c) IGS White Paper on Satellite and Operations Information for Generation of precise GNSS orbits and clock products – to be posted under http://www.igs.org/
The following slides document
- The work the MGEX experiment/pilot and
- the work of one of its analysis centers (CODE)
- A semi-empirical model for the QZS-1 satellite
The MGEX ground-tracking network

Currently, about 190 Multi-GNSS stations track a combination of Galileo, Beidou, QZSS, in addition to GPS and GLONASS (from Steigenberger & Montenbruck (2017)).
MGEX Analysis

MGEX Analysis Centers (ACs) and products (orbits, clocks, coordinates of ground tracking network, Earth rotation parameters, intersystem biases); from Montenbuck et al (2017a)

<table>
<thead>
<tr>
<th>Institution</th>
<th>Abbr.</th>
<th>Constellations</th>
<th>SP3</th>
<th>CLK</th>
<th>SNX</th>
<th>ERP</th>
<th>BSX</th>
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<tr>
<td>CNES/CLS</td>
<td>GRM</td>
<td>GPS+GLO+GAL</td>
<td>15 min</td>
<td>30 s</td>
<td>x</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CODE</td>
<td>COM</td>
<td>GPS+GLO+GAL+BDS+QZS</td>
<td>15 min</td>
<td>5 min</td>
<td>-</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>GFZ</td>
<td>GBM</td>
<td>GPS+GLO+GAL+BDS+QZS</td>
<td>5 min</td>
<td>30 s</td>
<td>-</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>JAXA</td>
<td>QZF</td>
<td>GPS+QZS</td>
<td>5 min</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TUM</td>
<td>TUM</td>
<td>GAL+QZS</td>
<td>5 min</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Wuhan Univ.</td>
<td>WUM</td>
<td>GPS+GLO+GAL+BDS+QZS</td>
<td>15 min</td>
<td>5 min</td>
<td>-</td>
<td>x</td>
<td>-</td>
</tr>
</tbody>
</table>
MGEX Analysis

Orbit and Clock Products

<table>
<thead>
<tr>
<th>Agency</th>
<th>ID</th>
<th>GNSS</th>
<th>Sampl (O/C)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNES/CLS</td>
<td>grm</td>
<td>GRE</td>
<td>15 min/30 s</td>
<td>+ SNX for ~120 stations</td>
</tr>
<tr>
<td>CODE</td>
<td>com</td>
<td>GRECJ</td>
<td>15 min/5 min</td>
<td>+ BSX</td>
</tr>
<tr>
<td>GFZ</td>
<td>gbm</td>
<td>GRECJ</td>
<td>5 min/30 s</td>
<td>+ ERP, + BSX</td>
</tr>
<tr>
<td>JAXA</td>
<td>JAX</td>
<td>GRJ</td>
<td>5 min/30 s</td>
<td>+ SNX for ~140 stations</td>
</tr>
<tr>
<td>TUM</td>
<td>tum</td>
<td>EJ</td>
<td>5 min/(5 min)</td>
<td>SP3-only, no CLK</td>
</tr>
<tr>
<td>WU</td>
<td>wum</td>
<td>GRECJ</td>
<td>15 min/5 min</td>
<td>+ ERP</td>
</tr>
</tbody>
</table>

From Steigenberger & Montenbruck (2017)

International Association of Geodesy

26-Jun-17
### MGEX Analysis

Table 9: RMS values derived from orbit comparisons for the time period 1 January – 30 June 2016. All values are given in cm.

<table>
<thead>
<tr>
<th></th>
<th>GPS</th>
<th>GLONASS</th>
<th>Galileo</th>
<th>MEO</th>
<th>BeiDou</th>
<th>IGSO</th>
<th>GEO</th>
<th>YS</th>
<th>ON</th>
</tr>
</thead>
</table>

**MGEX Analysis Website**
- Signal Transmissions
- Product Availability
- Clock time series
- SLR Residuals
- Orbit Comparisons

[http://mgex.igs.org/analysis/](http://mgex.igs.org/analysis/)

MGEX, SLR Validation

Table 10: SLR residual offsets and standard deviations for the time period 1 January – 30 June 2016. All values are given in cm.

<table>
<thead>
<tr>
<th></th>
<th>GLONASS</th>
<th>Galileo</th>
<th>MEO</th>
<th>BeiDou</th>
<th>QZSS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>IOV</td>
<td>FOC</td>
<td></td>
<td>IGSO</td>
<td>GEO</td>
</tr>
<tr>
<td>COM</td>
<td>0.5 ± 5.0</td>
<td>−4.3 ± 4.5</td>
<td>−3.5 ± 4.3</td>
<td>−3.4 ± 6.5</td>
<td>−2.8 ± 14.5</td>
</tr>
<tr>
<td>GBM</td>
<td>1.0 ± 5.5</td>
<td>−1.7 ± 8.0</td>
<td>−3.0 ± 8.2</td>
<td>−0.3 ± 3.5</td>
<td>−1.1 ± 6.5</td>
</tr>
<tr>
<td>GRM</td>
<td>0.2 ± 5.2</td>
<td>−0.3 ± 4.5</td>
<td>−1.3 ± 4.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>QZF</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>−13.8 ± 16.2</td>
</tr>
<tr>
<td>TUM</td>
<td></td>
<td>−6.1 ± 8.8</td>
<td>−4.6 ± 8.6</td>
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<td></td>
</tr>
<tr>
<td>WUM</td>
<td>1.0 ± 5.4</td>
<td>−2.0 ± 4.2</td>
<td>−6.2 ± 9.0</td>
<td>−2.5 ± 4.2</td>
<td>−3.4 ± 8.2</td>
</tr>
</tbody>
</table>

SLR is the only independent validation technique for GNSS- and RNSS-derived orbits. All, except the GPS satellites, have SLR reflectors! Offsets indicate orbit model deficiencies!

From Montenbuck et al. (2017a)
Ultra-Rapid solutions are available four times/day with a latency of three hours, rapid solutions once per day with a latency of about half a day, final solution once per week with a latency < 1 week, MGEX solution once per week, with a latency < 1 week
CODE participates as COM Analysis Center in the IGS MGEX (Multi-GNSS Experiment and Pilot Project).

COM regularly analyzes five systems, namely

- GPS (G), GLONASS (R), Galileo (E), Beidou (C), QZSS (J)

About 80 satellites and 140 permanent sites of the MGEX network contribute to the COM solutions.

COM solutions include satellite orbits, satellite clock correction, ERPs, inter-system biases

In the long term CODE plans to incorporate all GNSS into its routine solutions.

In the framework of the COM solutions CODE contributes to implementing “exotic” satellite attitude/SRP models

Public access to MGEX monitoring results via FTP:
=> ftp://ftp.unibe.ch/aiub/CODE_MGEX/
Satellite-fixed Cartesian coordinate system \((x,y,z)\), unit vector \(e_{\text{sun}}\) pointing from satellite to Sun is perpendicular to solar panels under Yaw-steering, where \(z\)-axis points to Earth, \(y\)-axis is perpendicular to \(e_{\text{sun}}\).

QZS-1 and most BeiDou satellites switch to orbit normal (ON) steering mode, when the Sun is close to the satellites’ orbital planes.

CODE developed purely empirical models ECOM, ECOM2, ECOM-N for motion under orbit normal mode.
MGEX@CODE

SLR residuals of QZS-1 with SRP models (1 day solutions)

Yaw-Steering SRP (red) is not sufficient for ON mode
Experimental ECOM-N... models (green, blue) better represent SRP
Additional Challenge: switching epochs between YS and ON are unknown
Satellite orbits may also be validated by satellite clock corrections for those satellites which have high-accuracy oscillators. Figure shows the median of the daily RMS of clock estimates w.r.t. linear clock models for different satellite types. Large values indicate modeling problems and/or actual clock quality problems (Prange et al. (2017))
QZS-1 moving under ON-Mode from MJD=57256 onwards, Sun in orbital plane for MJD=57275, 1-, 3-, and 5-day solutions. Left: ECOM-2, Right: modified ECOM-N. Median of clock-RMS is < 1 ns (~30cm) for all solutions. The solutions are remarkable in so far, as no a priori models were needed/used; only definition of ON- and YS-modes required.
Semi-analytical solar radiation pressure modeling for QZS-1
orbit-normal and yaw-steering attitude

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\textsuperscript{b}Università degli Studi di Padova, Department of Industrial Engineering, Via Gradenigo 6/a, 35131 Padova, Italy

Received 24 December 2016; received in revised form 26 January 2017; accepted 28 January 2017
Available online 10 February 2017

SRP-model for QZS-1, based on sparse available information. Strong motivation to have \textit{as accurate as possible} satellite metadata available.