Accuracy Evaluation of QZS-1 Precise Ephemerides with Satellite Laser Ranging

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Introduction

Quasi-Zenith Satellite System (QZSS)

- QZSS is a Japanese navigation satellite system.
- QZSS improves positioning availability
  - GPS compatible signals from QZSS improve positioning availability in East Asia and Oceanian region.
- QZSS improves positioning accuracy
  - For the purpose of PPP (Precise Point Positioning) service provision, QZSS-LEX (L-Band Experiment) signals allow for precise orbits and clock data.

▼QZS-1 orbital elements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semi-major Axis</td>
<td>42,164 km (average)</td>
</tr>
<tr>
<td>Eccentricity</td>
<td>0.075 ± 0.015</td>
</tr>
<tr>
<td>Orbital Inclination</td>
<td>43° ± 4°</td>
</tr>
<tr>
<td>Argument of Perigee</td>
<td>270° ± 2°</td>
</tr>
<tr>
<td>Central Longitude of Ground Track</td>
<td>135° ± 5° East</td>
</tr>
</tbody>
</table>

▼Coverage of QZS-1

Visible rate of QZS-1 in 24 hours more than 10 degrees in elevation, indicated by percentage(%).
QZSS Final Products

- JAXA publishes precise ephemeris/clock of GPS/QZS-1. (since December 2012)
- The final products are to be released approximately 6 days later.

- Enhanced the accuracy of QZS-1 final products (QZF) lead to high accuracy PPP even in region where GPS signals are insufficient.
- JAXA have been working on improving the accuracy of QZF.
MADOCA QZSS Orbit via LEX Signal

MADOCA: Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis

- Multi-GNSS precise orbit/clock estimation tool that JAXA developed at 2011~2012.
- From April of 2014, JAXA is promoting Precise Point Positioning (PPP) experiments using MADOCA orbit/clock products transmitted via QZSS LEX channel.

Goal of orbit/clock accuracy:

- Batch: 3 cm/0.1 ns (GPS), 7 cm/0.25 ns (GLO/QZS)
- Real-time: 6 cm/0.15 ns (GPS), 9 cm/0.25 ns (GLO/QZS)

Enhanced the accuracy of the MADOCA QZS-1 Orbit

- For Batch and Real-time processes, same parameters and models used.
- Improve the accuracy of Batch products
- Improve the accuracy of Real-time products

High accuracy of Real-time PPP!
Real-Time PPP Service

GLONASS  GPS  Galileo  QZSS

MGM-net etc.

NTRIP Caster (provided by BKG)

Data interface

orbit & clock estimator

LEX message generator

RTCM, BINEX, JPS ...

Tracking & Control Station

@Okinawa

Master Control Station (MCS)

@Tsukuba

LEX signal

Target accuracy < 10cm (H/V RMS)
Accuracy evaluation of QZS-1 ephemerides

Accuracy evaluation of JAXA-processed QZS-1 ephemerides: MAD and QZF

① Cross validation with other QZS-1 orbits

<table>
<thead>
<tr>
<th>name</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAD</td>
<td>Orbit processed with MADOCA (Batch)</td>
</tr>
<tr>
<td>ESOC</td>
<td>Orbit processed with ESOC software</td>
</tr>
</tbody>
</table>

② SLR residual to QZS-1 orbits

Evaluation period
- June 16 (0:00 a.m.) - July 12 (0:00 a.m.) in 2013 (26 days)
- Attitude mode: Yaw-Steering (YS) Mode
Accuracy evaluation of QZS-1 ephemerides

Estimation Condition of MAD

- Estimation Parameters
  - QZS-1 orbit/clock, GPS clock
  - Station position/clock
  - Tropospheric delay
  - Earth orientation parameter
  - Ambiguity

- Solar Radiation Pressure Model
  - QZS-1: Modified-DBY (est 9 para. D,B,Y(const),D,B,Y(1/rev))
    +X,Y,Z (piece-wise const)

QZSS/GPS:
11 MGM-net sta +2 MGEX,
GPS: 9 IGS sta
Accuracy evaluation of QZS-1 ephemerides

- Solar Radiation Pressure (SRP) model
  
  **DBY model**
  
  D: toward the Sun direction  
  Y: along the spacecraft's solar panel axis  
  B: D × Y direction  
  
  $\mathbf{a}_{srp} = S \left( D \mathbf{e}_d + B \mathbf{e}_b + Y \mathbf{e}_y \right) \times 10^{-9} \left( m/s^2 \right)$  
  
  $D = D_0 + D_c \cos f + D_s \sin f$  
  $B = B_0 + B_c \cos f + B_s \sin f$  
  $Y = Y_0 + Y_c \cos f + Y_s \sin f$  

**Modified-DBY model**

- Enhanced DBY model in MADOCA  
- A-priori SRP coefficients made dependent on angle $\beta$
Accuracy evaluation of QZS-1 ephemerides

Estimation Condition of QZF

- Estimation Parameters
  - GPS/QZS-1 orbit/clock
  - Station position/clock
  - Tropospheric delay
  - Ambiguity

- Solar Radiation Pressure Model
  - GPS: CODE model
  - QZS-1: est 13 Para. D,B,Y(const),D,B,Z(1/rev),D,X(2/rev)
### Accuracy evaluation of QZS-1 ephemerides

#### Comparison of Estimation Conditions among Ephemerides

<table>
<thead>
<tr>
<th>case name</th>
<th>MAD</th>
<th>QZF</th>
<th>TUM</th>
<th>ESOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>System</td>
<td>GPS + QZS</td>
<td>GPS + QZS</td>
<td>GPS + Galileo + QZS</td>
<td>GPS + QZS</td>
</tr>
<tr>
<td>Frequencies</td>
<td>L1&amp;L2</td>
<td>L1&amp;L2</td>
<td>L1&amp;L5</td>
<td>L1&amp;L2</td>
</tr>
<tr>
<td>Arc</td>
<td>24H+48H+24H</td>
<td>7days</td>
<td>3days</td>
<td>2day</td>
</tr>
</tbody>
</table>
**Result : Difference between ephemerides**

<table>
<thead>
<tr>
<th>Mean Differences in Radial Direction (m)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MAD</td>
<td>QZF</td>
<td>TUM</td>
<td>ESOC</td>
</tr>
<tr>
<td>MAD</td>
<td>-</td>
<td>0.290</td>
<td>0.279</td>
</tr>
<tr>
<td>QZF</td>
<td>-</td>
<td>-</td>
<td>-0.010</td>
</tr>
<tr>
<td>TUM</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ESOC</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mean Differences in Along Track (m)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>MAD</td>
<td>QZF</td>
<td>TUM</td>
<td>ESOC</td>
</tr>
<tr>
<td>MAD</td>
<td>-</td>
<td>0.020</td>
<td>-0.135</td>
</tr>
<tr>
<td>QZF</td>
<td>-</td>
<td>-</td>
<td>-0.172</td>
</tr>
<tr>
<td>TUM</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ESOC</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- MAD seems to have around 30 cm bias in radial.
- Other ephemerides (QZF, TUM, and ESOC) matched with each other in radial.
- ESOC had larger bias in along track than other ephemerides.
## Result: Difference between ephemerides

### RMS in Cross Track (m)

<table>
<thead>
<tr>
<th></th>
<th>MAD</th>
<th>QZF</th>
<th>TUM</th>
<th>ESOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAD</td>
<td>-</td>
<td>0.139</td>
<td>0.311</td>
<td>0.602</td>
</tr>
<tr>
<td>QZF</td>
<td>-</td>
<td>-</td>
<td>0.328</td>
<td>0.499</td>
</tr>
<tr>
<td>TUM</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.672</td>
</tr>
<tr>
<td>ESOC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### Differences 3D-RMS (m)

<table>
<thead>
<tr>
<th></th>
<th>MAD</th>
<th>QZF</th>
<th>TUM</th>
<th>ESOC</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAD</td>
<td>-</td>
<td>0.386</td>
<td>0.685</td>
<td>1.492</td>
</tr>
<tr>
<td>QZF</td>
<td>-</td>
<td>-</td>
<td>0.663</td>
<td>1.041</td>
</tr>
<tr>
<td>TUM</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.689</td>
</tr>
<tr>
<td>ESOC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- ESOC had periodic variations of one-day cycle in cross track (about 0.6 m : 1σ).
  → Orbit determination in cross direction might have low accuracy.
- MAD most closely matched with QZF except for the bias in radial.
- QZF closely matched with TUM and ESOC in radial direction.
  - QZF evaluated to be a definitive ephemeris at present.
Result: MAD-QZF

SATELLITE ORBIT ERROR

- **A** (m) with:
  - AVE: 0.0048 m
  - STD: 0.1389 m
  - RMS: 0.1390 m

- **R** (m) with:
  - AVE: 0.2901 m
  - STD: 0.1162 m
  - RMS: 0.3125 m

- **A** (m) with:
  - AVE: 0.0203 m
  - STD: 0.1774 m
  - RMS: 0.1785 m

**Note:**
- About 30 cm bias in Radial
- Most closely matched in Along and Cross-track
Result: TUM-QZF

SATELLITE ORBIT ERROR

R (m)

\[ \text{AVE: } 0.0102 \text{ m STD: } 0.1283 \text{ m RMS: } 0.1287 \text{ m} \]

\[ \text{3DRMS: } 0.6629 \text{ m} \]

A (m)

\[ \text{AVE: } 0.1717 \text{ m STD: } 0.5345 \text{ m RMS: } 0.5614 \text{ m} \]

C (m)

\[ \text{AVE: } 0.1825 \text{ m STD: } 0.2728 \text{ m RMS: } 0.3283 \text{ m} \]

matched with each other in radial
Result: ESOC-QZF

- Matched with each other in radial
- Periodic variation in cross track (about 0.6m : 1σ)
Analysis of SLR residuals

ILRS Tracking Stations
- Tanegashima (7358)
- Koganei (7308)
- Yarragadee (7090)
- Changchun (7237)
- Beijing (7249)
- Shanghai (7821)
- Mount Stromlo (7825)
Result: SLR residuals

- MAD showed a large bias (30~40cm).
- Other ephemerides (QZF, TUM, and ESOC) also showed biases but their magnitudes were smaller than that of MAD.

<table>
<thead>
<tr>
<th></th>
<th>AVE(m)</th>
<th>STD(m)</th>
<th>RMS(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAD</td>
<td>-0.3558</td>
<td>0.0839</td>
<td>0.3655</td>
</tr>
<tr>
<td>QZF</td>
<td>-0.1391</td>
<td>0.0745</td>
<td>0.1578</td>
</tr>
<tr>
<td>TUM</td>
<td>-0.1218</td>
<td>0.0989</td>
<td>0.1569</td>
</tr>
<tr>
<td>ESOC</td>
<td>-0.0526</td>
<td>0.1090</td>
<td>0.1210</td>
</tr>
</tbody>
</table>
Conclusion

• SLR data and ephemerides of other systems allow reliable accuracy evaluations of JAXA QZS-1 ephemerides.

  ✷ QZF
    - SLR residuals: \(~20 \text{ cm RMS}\)
  ➢ QZF evaluated to be a definitive ephemeris in our analysis

  ✷ MAD processed with MADOCA
    - SLR residuals: \(~40 \text{ cm RMS}\)
    - Comparison with the other ephemerides shows 30~40 cm large bias in radial
  ➢ Eliminating the bias in radial direction will lead to a further improvement in accuracy.
Thank you for your attention.