精密単独測位の技術動向と応用
Precise Point Positioning (PPP) and Its Applications
Precise Point Positioning (PPP)

• Typical Analysis Strategy
  – Zero-Differenced (ZD) Measurement Equations
  – Precise Satellite Orbit/Clock: IGS or Others
  – Ionosphere: Eliminated by Ionosphere-Free LC
  – Troposphere: ZTD or ZWD Estimation + Mapping Function
  – Antenna Model, Earth-Tides, Phase Wind-up Corrections
  – Float Estimation of Carrier-Phase Ambiguity

• Reference
  – J.F. Zumberge et al., Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks", JGR, Vol. 102, No. B3, 1997

Features and Applications

• Feature
  – with Single Receiver (No Reference Station)
  – Efficient Analysis for Many Receivers
  – Absolute Position in ITRF Frame

• Applications
  – Crustal Deformation Monitoring
  – GPS Seismometer
  – GPS Meteorology
  – POD (Precise Orbit Determination) of LEO Satellite
  – Precise Time Transfer
Limitations of Conventional PPP

- Accuracy/Precision
  - Depend on Quality of Precise Satellite Orbit/Clock
  - Satellite Clock Interpolation Error/Day-Boundary Problem
  - Solution Drift by Float Ambiguity and Imperfect Correction
- Real-time Processing
  - Lack of Real-time Precise Satellite Clock
- Long Convergence Time
  - Due to Float Ambiguity Estimation
- Inaccurate with Single-Freq Receiver
  - Poor Ionospheric Correction Model

KGPS vs Kinematic-PPP

Displacement by Iwate-Miyagi EQ

2008/6/13 22:00-6/14 0:30, GSI 0193 Minase

KGPS (BL=219 km) by RTKPOST 2.2.1

Kinematic-PPP IGS Final Orbit/30-s Clock by GT 0.6.4

△ Day-Boundary

20cm
**IGS Orbit/Clock**

**IGS Product Table**

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>Final (IGS)</th>
<th>Rapid (IGR)</th>
<th>Ultra-Rapid (IGU)</th>
<th>Broadcast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>~2.5cm</td>
<td>~2.5cm</td>
<td>~3cm</td>
<td>~5cm</td>
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<tr>
<td>Clock</td>
<td>~75ps RMS</td>
<td>~75ps RMS</td>
<td>~150ps RMS</td>
<td>~5ns RMS</td>
</tr>
<tr>
<td></td>
<td>~20ps STD</td>
<td>~25ps STD</td>
<td>~50ps STD</td>
<td>~2.5ns STD</td>
</tr>
<tr>
<td></td>
<td>~20ps STD</td>
<td>~25ps STD</td>
<td>~50ps STD</td>
<td>~2.5ns STD</td>
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<table>
<thead>
<tr>
<th>Latency</th>
<th>Updates</th>
<th>Sample Interval</th>
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<tbody>
<tr>
<td>12-18 days</td>
<td>every Thursday</td>
<td>Orbit 15min, Clock Sat: 30s, Stn: 5min</td>
</tr>
<tr>
<td>17-41 hours</td>
<td>at 17 UTC daily</td>
<td>15min, 5min, 15min, 15min</td>
</tr>
<tr>
<td>3-9 hours</td>
<td>at 03, 09, 15, 21 UTC</td>
<td>daily</td>
</tr>
<tr>
<td>realtime</td>
<td>at 03, 09, 15, 21 UTC</td>
<td>daily</td>
</tr>
<tr>
<td>realtime</td>
<td>-</td>
<td></td>
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</table>


**Day-Boundary Problem**

**Static-PPP Residuals**

2009/2/1-2/4, PRN19 - TSKB, IGS Final Orbit/Clock

![Graphs showing static-PPP residuals for different days and PRNs](image-url)
Anomaly of IGS 30-s Clock

**Static-PPP Residuals**
2008/3/30 5:35-9:30, PRN26 - TSKB
IGS Final Orbit/30-s Clock

![Image showing static-PPP residuals with large bias between 300-s clock and others, marked as 2cm]

**IGS AC Orbit/Clock**

<table>
<thead>
<tr>
<th>AC</th>
<th>Final Orbit</th>
<th>Clock</th>
<th>Rapid Orbit</th>
<th>Clock</th>
<th>Ultra-Rapid Orbit</th>
<th>Clock</th>
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<tbody>
<tr>
<td>CODE</td>
<td>15min</td>
<td>5s/30s</td>
<td>15min</td>
<td>5min</td>
<td>15min</td>
<td>15min</td>
</tr>
<tr>
<td>ESOC</td>
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<td>5min</td>
<td>15min</td>
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<td>15min</td>
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<td>GFZ</td>
<td>15min</td>
<td>5min</td>
<td>15min</td>
<td>5min</td>
<td>15min</td>
<td>15min</td>
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<tr>
<td>JPL</td>
<td>15min</td>
<td>5min</td>
<td>15min</td>
<td>5min</td>
<td>-</td>
<td>-</td>
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<tr>
<td>NOAA</td>
<td>15min</td>
<td>5min</td>
<td>15min</td>
<td>15min</td>
<td>15min</td>
<td>15min</td>
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<tr>
<td>NRCan</td>
<td>15min</td>
<td>30s</td>
<td>15min</td>
<td>5min</td>
<td>15min</td>
<td>15min</td>
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<tr>
<td>SIO</td>
<td>15min</td>
<td>-</td>
<td>15min</td>
<td>-</td>
<td>15min</td>
<td>15min</td>
</tr>
<tr>
<td>USNO</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15min</td>
<td>15min</td>
</tr>
<tr>
<td>MIT</td>
<td>15min</td>
<td>30s</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GRG</td>
<td>15min</td>
<td>5min</td>
<td>-</td>
<td>-</td>
<td>-</td>
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<td>-</td>
<td>15min</td>
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<tr>
<td>GOU</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>15min</td>
<td>15min</td>
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Interpolation Error of Clock

Satellite Clock Stability

<table>
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<tr>
<th></th>
<th>5s</th>
<th>30s</th>
<th>300s</th>
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<tbody>
<tr>
<td>Block II/IIA Cs</td>
<td>&lt;4 x 10^{-12}</td>
<td>&lt;3 x 10^{-12}</td>
<td>&lt;2 x 10^{-12}</td>
</tr>
<tr>
<td>Block II/IIA Rb</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Block IIR Rb</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\( \text{Averaging Time } \tau \text{ (sec)} \)

\( \sigma_c (s) \)

\( (2004/12) \)

CODE 5-s Clock

H. Bock et. al., High-rate GPS clock correction from CODE: support of 1Hz applications, *J Geod.*, 2009

**1Hz Kinematic-PPP** 2008/4/27 6:00-9:00 IGS USUD
with CODE Orbit/CODE 5s Clock

RMSE: E: 2.78cm N: 1.18cm U: 2.26cm

with IGS Final Orbit/30s Clock

RMSE: E: 3.05cm N: 1.42cm U: 2.75cm
Real-Time PPP

- **Strategy 1:**
  - Orbit/Clock: Estimated in Real-Time
  - Need World-Wide Station Network (>50 Stations)
  - Complicated Processing Process
  - CPU Load Restriction

- **Strategy 2:**
  - Orbit: Fixed to IGU-Predicted
  - Clock: Estimated in Real-Time
  - Regional Station Network
  - Simple Processing Process
StarFire™

• Features
  – Commercial Service by NavCom
  – Broadcast Real-Time Orbit/Clock via Satellite (Inmarsat)
  – JPL RTG (Real-time GIPSY) Processing Engine (GDGPS)
  – World Wide Station Network (72 Stn in 2006)
  – Ionosphere: L1/L2 Dual-Freq
  – Troposphere: WAAS Model
  – QC by Real-Time Monitor for Satellite Anomaly

• Accuracy/Precision
  – Horizontal Position RMS: <10 cm

Improvement of IGU Orbit

(1.Ray et. al., Status of IGS Ultra-Rapid Products for Real-Time Applications, 2008 AGU Fall Meeting)
IGU Orbit + Clock Est + PPP

• RTnet
  – Developed by GPS Solutions (http://www.gps-solutions.com)

• CDAAC
  – Near Real-Time POD of LEO Satellites (COSMIC ...)
  – Bernese 5.0

• EUREF NRTK Service
  – Use RTnet
  – Provide Real-Time Orbit/Clock via Internet (NTRIP)

• JMA
  – Near Real-Time GEONET PWV for NWM
Convergence Time of PPP

Kinematic Solution
2009/7/1 0:00-2:00, GSI 2110
KGPS with AR (BL=13.3km)

Kinematic-PPP

by RTKPOST 2.2.1
by GT 0.6.4,
IGS Final Orbit/CODE 5-s Clock

PPP-AR

• with AR for PPP
  – Improve Convergence Time
  – Improve Accuracy of Static Solution (EW, UD)
  – Improve Stability of Kinematic Solution

• Difficulties of AR for PPP
  – Unknown Satellite Initial Phase Biases
  – Effect of Precise Orbit/Clock Error
  – Effect of Ionospheric Delay
  – Code/Phase Bias Instability
  – Multipath Effect at Reference Station Network
Research

• M. Ge et al., Resolution of GPS carrier-phase ambiguities in Precise Point Positioning (PPP) with daily observations, Journal of Geodesy, 2007
• D. Laurichesse et al., Integer ambiguity resolution on undifferenced GPS phase measurements and its application to PPP, ION GNSS 2007
• G. Weber et al., Real-time Clock and Orbit Corrections for Improved Point Positioning via NTRIP, ION GNSS 2007
• D. Laurichesse et al., Real Time Zero-difference Ambiguities Fixing and Absolute RTK, ION NTM 2008
• P. Collins, Isolating and Estimating Undifferenced GPS Integer Ambiguity, ION NTM 2008
• J. Geng et al., Performance of Hourly Precise Point Positioning with Ambiguity Resolution, ION GNSS 2008
• P. Collins et al., Precise Point Positioning with Ambiguity Resolution using the Decoupled Clock Model, ION GNSS 2008
• D. Laurichesse et al., Zero-difference Ambiguity Fixing for Spaceborne GPS Receivers, ION GNSS 2008
• L. Mervart et al., Precise Point Positioning With Ambiguity Resolution In Real-Time, ION GNSS 2008
• C. Rocken et al., Precise Positioning of Ships and Buoys in the Open Ocean - Result from a 3-month Indian Ocean Cruise, and Tsunami Buoy Off Japan's Coast, ION GNSS 2008
• T. Iwabuchi et al., Deformation Monitoring with Single Frequency L1 Receivers, ION GNSS 2008

PPP-AR Strategy/Application

• Typical Strategy
  – Post Processing, Few Research for in Real-Time
  – Use Global Reference Stations Network
  – Fix Narrow-Lane Ambiguity with Iono-Free LC after Fixing Wide-Lane MW LC
  – Estimate Satellite Initial Phase Bias Assuming its Stability
  – PPP with Initial Phase Bias Correction

• Application
  – Precise Network Coordinates by Static-PPP
  – LEO Satellite POD, ...
M. Ge et al., Resolution of GPS carrier-phase ambiguity in precise point positioning, EGU Assembly 2007

WL Phase Bias Stability

NL Phase Bias Stability

Repeatability of PPP-AR

RMS Error of PPP-AR

M. Ge et al., EGU 2007

PPP-RTK
PPP-RTK

• Two View Points
  – Widely Extended NRTK (Network RTK)
  – Real-Time Kinematic PPP with AR

• Feature
  – State Space Correction Data
  – Satellite Code/Phase Bias Corrections for AR
  – Ionospheric Model for Single-Freq Users
  – Minimum Band-Width for Broadcast Communication Link

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PPP-RTK via QZS LEX

<table>
<thead>
<tr>
<th>Corrections</th>
<th>Bits</th>
<th>LSB</th>
<th>Range</th>
<th># Sat</th>
<th># Grid</th>
<th>Interval</th>
<th>bps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sat Orbit</td>
<td>15×3</td>
<td>2mm</td>
<td>-33-33m</td>
<td>12</td>
<td>-</td>
<td>30s</td>
<td>18</td>
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<tr>
<td></td>
<td>15×3</td>
<td>0.02mm/s</td>
<td>-.3-.3m/s</td>
<td>12</td>
<td>-</td>
<td>30s</td>
<td>18</td>
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<tr>
<td>Sat Clock</td>
<td>15</td>
<td>0.006ns</td>
<td>-98-98ns</td>
<td>12</td>
<td>-</td>
<td>3s</td>
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<td>Ionos Delay</td>
<td>15</td>
<td>2mm</td>
<td>0-66m</td>
<td>12</td>
<td>70</td>
<td>30s</td>
<td>420</td>
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<tr>
<td></td>
<td>13</td>
<td>2mm</td>
<td>-8-8m</td>
<td>12</td>
<td>210</td>
<td>30s</td>
<td>1092</td>
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<tr>
<td>Tropos Delay</td>
<td>11</td>
<td>0.5mm</td>
<td>0-1m</td>
<td>-</td>
<td>70</td>
<td>30s</td>
<td>26</td>
</tr>
<tr>
<td>Phase Bias</td>
<td>11×3</td>
<td>0.01cyc</td>
<td>-10-10cyc</td>
<td>12</td>
<td>-</td>
<td>30s</td>
<td>13</td>
</tr>
<tr>
<td>Code Bias</td>
<td>8×3</td>
<td>0.1m</td>
<td>-13-13m</td>
<td>12</td>
<td>-</td>
<td>30s</td>
<td>10</td>
</tr>
<tr>
<td>Sat ID+IOD</td>
<td>8+8</td>
<td>-</td>
<td>-</td>
<td>12</td>
<td>-</td>
<td>30s</td>
<td>6</td>
</tr>
<tr>
<td>Others</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1-30s</td>
<td>32</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1695</td>
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</table>

26
Correction Grid

Message Format

Sub Frame
1
2
3
4
5
...
30
Message Header (10)

Minor Frame
1
2
3
4
5
6
7
8
9
10

1695
5055

Sat Orbit Correction
Sat Clock Correction
Tropos Delay Correction
Ionospheric Delay Correction
Correction Generation

(1) Orbit/Clock/Tropos Estimation (Iono-Free LC)

(2) Ionos/Tropos Estimation, Fix Integer Ambiguities

(3) Orbit/Clock/Tropos/Ionos/Bias Re-Estimation

(4) Interpolate Ionos/Tropos Deley to Grids

GT 0.6.4
GT 0.6.4

- 2009/5/1 Release
  - Open Source License (GPLv3)
  - Matlab 7.3 (R2006b) or Higher, 32bit or 64bit
- GT 0.6.3 -> 0.6.4
  - Support High Rate Analysis up to 100 Hz
  - Support Long Continuous Session up to 1 year
  - Support IGS 30-S, CODE 5-s, IGS/CODE 5-s Clock
  - Support IGS05, ITRF2005 Frame
  - Support VMF1 and GPT Meteo Model
  - Support Az Term of Receiver Antenna PCV

Stability of Kinematic-PPP

2007/1/1-3/31 IGS ALGO

RMS Error:
E: 1.16cm
N: 1.07cm
U: 2.60cm

with IGS Final Orbit/Clock
Long Session ZTD

2009/5/1-5/31 GSI 940003

Less Day-Boundary Discontinuity

with IGS Final Orbit/Clock

NMF vs VMF1

Sonde PWV - GPS PWV: GSI 19 Stns, 2004/1/1-12/31

NMF

MEAN: 0.2mm
STD: 2.2mm

VMF1

MEAN: 0.2mm
STD: 2.2mm

with IGS Final Orbit/Clock