The Possibility of Precise Automobile Navigation using GPS/QZS L5 and (Galileo E5) Pseudo-ranges

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Outline

• Background
• Objective
• Multipath error estimation methods
• Static and kinematic experiment
• Test results
• Conclusion
Background

- GPS L5 up to 24 by 2021
- L5 is broadcast from 3 satellites (PRN1/24/25)
- QZS L5 up to 4 by 2017

Galileo E5 AltBOC: cm level accuracy under open sky
L5 Signal Tracking by SDR (PRN1)

GPS PRN1
2012/8/16
Open-Sky
Elevation: 45 deg.
10ms Integration
FE: Fraunhofer
SF: 40.96MHz

![Graph showing L5 signal tracking](image.png)
Multipath Envelope

(hardware simulator check: MP is set 6dB lower than Direct)

Consumer receiver is vulnerable to multipath delay even over 100m
Multipath Envelope (close up)

small difference between L1 and L5
⇒ Multipath in L1 has been improved
Performance in Urban Areas

Vehicles in dense urban areas with geodetic receiver

Several applications require high accuracy (RTK) ⇒ far from perfect at present
Objective

• Pseudo-range observations from L5 in both GPS and QZS are basically robust against multipath.
• It can be used for high reliable and accurate application without Ambiguity Resolution.
• L5 performance has not been investigated because satellites with L5 are few.

The Question: Dose pseudo-ranges of new signals really work well in urban areas?
Estimation of Multipath Error

• Code-Carrier difference (cc-differnce)
  – Effective for static data
  – Cycle slip happens a lot for kinematic data
  ⇒ impossible to extract multipath for kinematic data

• Proposed method
  ⇒ Separating Multipath Errors for Vehicle
CC-difference

CC-difference L1 = P1 − 4.0915 x Φ1 + 3.0915 x Φ2
CC-difference L5 = P5 − 3.5212 x Φ5 + 3.5212 x Φ1

P : Pseudo-range measurement
Φ : Carrier phase measurement

• Dual-frequency receivers can effectively remove the ionospheric delay
• Offset average

- Use both Pseudo-range and Carrier phase
- Effective for only static data
Proposed Method
Separating Multipath Errors for Vehicle

- Higher Elevation SV
- Reference SV
- Precise Rover Position + Double Difference
- 4 Different Combinations of Multipath and Noise
- Code minus Carrier Difference
- Extraction of Target Multipath and Noise
- Target Multipath and Noise
- Precise Rover Position
- Rover
- Reference Receiver
Separating Multipath Errors for Vehicle

\[ \begin{align*}
P_{rov}_{ref}^{sv1_{-sv2}} &= \rho_{rov}^{sv1} + c(dt_{sv1} - dT_{rov}) + \text{ion}_{rov}^{sv1} + \text{tropo}_{rov}^{sv1} + mp_{rov}^{sv1} + noise_{rov}^{sv1} \\
&\quad - \left[ \rho_{ref}^{sv1} + c(dt_{sv1} - dT_{ref}) + \text{ion}_{ref}^{sv1} + \text{tropo}_{ref}^{sv1} + mp_{ref}^{sv1} + noise_{ref}^{sv1} \right] \\
&\quad - \left[ \rho_{rov}^{sv2} + c(dt_{sv2} - dT_{rov}) + \text{ion}_{rov}^{sv2} + \text{tropo}_{rov}^{sv2} + mp_{rov}^{sv2} + noise_{rov}^{sv2} \right] \\
&\quad + \left[ \rho_{ref}^{sv2} + c(dt_{sv2} - dT_{ref}) + \text{ion}_{ref}^{sv2} + \text{tropo}_{ref}^{sv2} + mp_{ref}^{sv2} + noise_{ref}^{sv2} \right] \\
&= \rho_{rov}^{sv1} - \rho_{ref}^{sv1} + \rho_{rov}^{sv2} - \rho_{ref}^{sv2} \\
&\quad + \left( mp_{rov}^{sv1} + noise_{rov}^{sv1} \right) - \left( mp_{ref}^{sv1} + noise_{ref}^{sv1} \right) \quad \text{(1)} \\
&\quad - \left( mp_{rov}^{sv2} + noise_{rov}^{sv2} \right) + \left( mp_{ref}^{sv2} + noise_{ref}^{sv2} \right) \quad \text{(2)} \quad \text{(3)}
\end{align*} \]

Target = Raw Data - Measurements + \text{Computed by each CC-Difference}

\text{sv1} : Target SV  \text{ sv2} : QZS (Elevation angle > 80)
Proposed Method
Separating Multipath Errors for Vehicle

Higher Elevation SV

Reference SV

Precise Rover Position + Double Difference

4 Different Combinations of Multipath and Noise

Code minus Carrier Difference

Cc-difference ①

Rover

Reference Receiver
Separating Multipath Errors for Vehicle

\[
P_{\text{rov\_ref}}^{sv_{1}\_sv_{2}} = (P_{\text{rov}}^{sv_{1}} - P_{\text{ref}}^{sv_{1}}) - (P_{\text{rov}}^{sv_{2}} - P_{\text{ref}}^{sv_{2}}) \\
= \rho_{\text{rov}}^{sv_{1}} + c(d_{\text{sv}_{1}} - d_{\text{rov}}) + \text{ion}_{\text{rov}}^{sv_{1}} + \text{tropo}_{\text{rov}}^{sv_{1}} + m_{\text{rov}}^{sv_{1}} + \text{noise}_{\text{rov}}^{sv_{1}} \\
- \left[ \rho_{\text{ref}}^{sv_{1}} + c(d_{\text{sv}_{1}} - d_{\text{ref}}) + \text{ion}_{\text{ref}}^{sv_{1}} + \text{tropo}_{\text{ref}}^{sv_{1}} + m_{\text{ref}}^{sv_{1}} + \text{noise}_{\text{ref}}^{sv_{1}} \right] \\
- \left[ \rho_{\text{rov}}^{sv_{2}} + c(d_{\text{sv}_{2}} - d_{\text{rov}}) + \text{ion}_{\text{rov}}^{sv_{2}} + \text{tropo}_{\text{rov}}^{sv_{2}} + m_{\text{rov}}^{sv_{2}} + \text{noise}_{\text{rov}}^{sv_{2}} \right] \\
+ \left[ \rho_{\text{ref}}^{sv_{2}} + c(d_{\text{sv}_{2}} - d_{\text{ref}}) + \text{ion}_{\text{ref}}^{sv_{2}} + \text{tropo}_{\text{ref}}^{sv_{2}} + m_{\text{ref}}^{sv_{2}} + \text{noise}_{\text{ref}}^{sv_{2}} \right] \\
= \rho_{\text{rov}}^{sv_{1}} - \rho_{\text{ref}}^{sv_{1}} + \rho_{\text{rov}}^{sv_{2}} - \rho_{\text{ref}}^{sv_{2}} \\
+ (m_{\text{rov}}^{sv_{1}} + \text{noise}_{\text{rov}}^{sv_{1}}) - (m_{\text{ref}}^{sv_{1}} + \text{noise}_{\text{ref}}^{sv_{1}}) \\
- (m_{\text{rov}}^{sv_{2}} + \text{noise}_{\text{rov}}^{sv_{2}}) + (m_{\text{ref}}^{sv_{2}} + \text{noise}_{\text{ref}}^{sv_{2}}) \\
\]

Target = Raw Data - Measurement + Computed by each CC-Difference

\( sv_{1} : \text{Target SV} \quad sv_{2} : \text{QZS (Elevation angle > 80)} \)
Proposed Method
Separating Multipath Errors for Vehicle

- Higher Elevation SV
- Reference SV
- Precise Rover Position + Double Difference
- 4 Different Combinations of Multipath and Noise
- Code minus Carrier Difference

Cc-difference ②
Separating Multipath Errors for Vehicle

\[ P_{\text{sv1-sv2}}^{\text{rov-ref}} = (P_{\text{rov}}^{\text{sv1}} - P_{\text{ref}}^{\text{sv1}}) - (P_{\text{rov}}^{\text{sv2}} - P_{\text{ref}}^{\text{sv2}}) \]

\[ = \rho_{\text{rov}}^{\text{sv1}} + c(dt_{\text{sv1}} - dT_{\text{rov}}) + \text{ion}_{\text{rov}}^{\text{sv1}} + \text{tropo}_{\text{rov}}^{\text{sv1}} + mp_{\text{rov}}^{\text{sv1}} + noise_{\text{rov}}^{\text{sv1}} \]

\[ - \left[ \rho_{\text{ref}}^{\text{sv1}} + c(dt_{\text{sv1}} - dT_{\text{ref}}) + \text{ion}_{\text{ref}}^{\text{sv1}} + \text{tropo}_{\text{ref}}^{\text{sv1}} + mp_{\text{ref}}^{\text{sv1}} + noise_{\text{ref}}^{\text{sv1}} \right] \]

\[ - \left[ \rho_{\text{rov}}^{\text{sv2}} + c(dt_{\text{sv2}} - dT_{\text{rov}}) + \text{ion}_{\text{rov}}^{\text{sv2}} + \text{tropo}_{\text{rov}}^{\text{sv2}} + mp_{\text{rov}}^{\text{sv2}} + noise_{\text{rov}}^{\text{sv2}} \right] \]

\[ + \left[ \rho_{\text{ref}}^{\text{sv2}} + c(dt_{\text{sv2}} - dT_{\text{ref}}) + \text{ion}_{\text{ref}}^{\text{sv2}} + \text{tropo}_{\text{ref}}^{\text{sv2}} + mp_{\text{ref}}^{\text{sv2}} + noise_{\text{ref}}^{\text{sv2}} \right] \]

\[ = \rho_{\text{rov}}^{\text{sv1}} - \rho_{\text{ref}}^{\text{sv1}} + \rho_{\text{rov}}^{\text{sv2}} - \rho_{\text{ref}}^{\text{sv2}} \]

\[ + (mp_{\text{rov}}^{\text{sv1}} + noise_{\text{rov}}^{\text{sv1}}) - (mp_{\text{ref}}^{\text{sv1}} + noise_{\text{ref}}^{\text{sv1}}) \]

\[ - (mp_{\text{rov}}^{\text{sv2}} + noise_{\text{rov}}^{\text{sv2}}) + (mp_{\text{ref}}^{\text{sv2}} + noise_{\text{ref}}^{\text{sv2}}) \]

\[ \text{Target} = \text{Raw Data - Measurements} + (\text{1}) + (\text{2}) - (\text{3}) \]

Computed by each CC-Difference

sv1 : Target SV  sv2 : QZS (Elevation angle > 80)
Proposed Method
Separating Multipath Errors for Vehicle

Higher Elevation SV

Reference SV

Precise Rover Position + Double Difference

4 Different Combinations of Multipath and Noise

Code minus Carrier Difference

Cc-difference ③
Separating Multipath Errors for Vehicle

\[ P_{rov \_ref}^{sv1 \_sv2} = (P_{rov}^{sv1} - P_{ref}^{sv1}) - (P_{rov}^{sv2} - P_{ref}^{sv2}) \]

\[ = \rho_{rov}^{sv1} + c(d_{sv1} - d_{rov}) + ion_{rov}^{sv1} + tropo_{rov}^{sv1} + mp_{rov}^{sv1} + noise_{rov}^{sv1} \]

\[ - \left[ \rho_{ref}^{sv1} + c(d_{sv1} - d_{ref}) + ion_{ref}^{sv1} + tropo_{ref}^{sv1} + mp_{ref}^{sv1} + noise_{ref}^{sv1} \right] \]

\[ - \left[ \rho_{rov}^{sv2} + c(d_{sv2} - d_{rov}) + ion_{rov}^{sv2} + tropo_{rov}^{sv2} + mp_{rov}^{sv2} + noise_{rov}^{sv2} \right] \]

\[ + \left[ \rho_{ref}^{sv2} + c(d_{sv2} - d_{ref}) + ion_{ref}^{sv2} + tropo_{ref}^{sv2} + mp_{ref}^{sv2} + noise_{ref}^{sv2} \right] \]

\[ = \rho_{rov}^{sv1} - \rho_{ref}^{sv1} + \rho_{rov}^{sv2} - \rho_{ref}^{sv2} \]

\[ + (mp_{rov}^{sv1} + noise_{rov}^{sv1}) - (mp_{ref}^{sv1} + noise_{ref}^{sv1}) \]

\[ - (mp_{rov}^{sv2} + noise_{rov}^{sv2}) + (mp_{ref}^{sv2} + noise_{ref}^{sv2}) \]

Target = Raw Data Measurements + ① + ② - ③

Computed by each CC-Difference

sv1 : Target SV  sv2 : QZS (Elevation angle > 80)
Proposed Method
Separating Multipath Errors for Vehicle

- Higher Elevation SV
- Reference SV (QZS is very useful)
- Precise Rover Position + Double Difference
  - 4 Different Combinations of Multipath and Noise
    - Code minus Carrier Difference
      - Extraction of Target Multipath and Noise

- Target Multipath and Noise
- Precise Rover Position
- Rover
- Reference Receiver
Test and Results

1. Static Test 1 (Toyosu, Tokyo)
   long distance (approx. 30m) from building

2. Static Test 2 (campas, Tokyo)
   short distance (<10m) from building

3. Kinematic Test 1 (tukishima, Tokyo)

4. Kinematic Test 2 (edagawa, Tokyo)

   Estimate multipath error using proposed method
   Target: GPS-PRN1 (transmitting both L1 and L5)
### Static Test 1 (Toyosu, Tokyo)

- **Date:** 12/13/2012 (GPSTIME) 0:30~
- **Receiver:**
  - Geodetic Receiver
  - Rover Receiver
- **Timing:**
  - 60 min 2 Hz
- **Satellites:**
  - 5-8 satellites in view over 15 degrees elevation
- **Targets:**
  - **Target SV:** GPS-PRN-1 (L1, L5)
  - **Reference SV:** QZS-1 (L1, L5)
- **Position:**
  - Precise position was computed by post processing

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**Diagram:**

- **Positioning:**
  - Rover Receiver
  - Building
  - 30m

**Legend:**

- **Long delay multipath**

**Notice:**

- Using proposed method to extraction the PRN-1 multipath
Static Test 1 Multipath Errors (no smoothing)

<table>
<thead>
<tr>
<th></th>
<th>$\sigma$ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5</td>
<td>0.37</td>
</tr>
<tr>
<td>L1</td>
<td>0.52</td>
</tr>
</tbody>
</table>

GPSTIME [s]
Static Test 1 Multipath Errors (100s smoothing)

We just set receiver parameter as 100s for smoothing

<table>
<thead>
<tr>
<th></th>
<th>σ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5</td>
<td>0.09</td>
</tr>
<tr>
<td>L1</td>
<td>0.12</td>
</tr>
</tbody>
</table>
**Static Test 2 (campas, Tokyo)**

<table>
<thead>
<tr>
<th><strong>Date and Time</strong></th>
<th>12/14/ 2012 (GPSTIME) 0:30~</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Receiver</strong></td>
<td>Geodetic Receiver</td>
</tr>
<tr>
<td><strong>Recording Duration</strong></td>
<td>60 min 2 Hz</td>
</tr>
<tr>
<td><strong>Visible Satellites</strong></td>
<td>5-9 satellites in view over 15 degrees elevation</td>
</tr>
<tr>
<td><strong>Target SV</strong></td>
<td>GPS-PRN-1 (L1,L5)</td>
</tr>
<tr>
<td><strong>Reference SV</strong></td>
<td>QZS-1 (L1,L5)</td>
</tr>
<tr>
<td><strong>Precise Position</strong></td>
<td>Precise position was computed by post processing</td>
</tr>
</tbody>
</table>

Precise position was computed by post processing using the proposed method to extract the PRN-1 multipath.
Static Test 2 Multipath Errors (no smoothing)

[m]

<table>
<thead>
<tr>
<th></th>
<th>σ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5</td>
<td>1.40</td>
</tr>
<tr>
<td>L1</td>
<td>1.74</td>
</tr>
</tbody>
</table>
We just set receiver parameter as 100s for smoothing.
Validation of Our Proposed Method

MP errors derived from cc-difference

MP errors derived from proposed method

Multipath for PRN-1 derived from cc-difference

Multipath for PRN-1 derived from Proposed Method
Another type of geodetic receiver shows almost same difference level (4-5dB) between L1 and L5 although the maximum level was different.
Kinematic Test 1  \textit{(tukishima, Tokyo)}

<table>
<thead>
<tr>
<th>Date</th>
<th>11/23/ 2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver</td>
<td>Geodetic</td>
</tr>
<tr>
<td>Duration</td>
<td>20 min 5 Hz</td>
</tr>
<tr>
<td>Satellites</td>
<td>4-8 satellites in view over 15 degrees elevation</td>
</tr>
<tr>
<td>Target SV</td>
<td>GPS-PRN-1 (L1,L5)</td>
</tr>
<tr>
<td>Reference SV</td>
<td>QZS-1 (L1,L5)</td>
</tr>
<tr>
<td>Precision</td>
<td>Precise position was computed by post processing</td>
</tr>
<tr>
<td>Smoothing</td>
<td>100s smoothing</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Fix rate [%]</th>
<th>74.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>RTK</td>
<td></td>
</tr>
</tbody>
</table>

(Post-Processed RTK Plots)
Kinematic Test 1  Multipath Errors

[m] 100
80
60
40
20
0
-20

GPSTIME[s]
438000 438300 438600 438900 439200

<table>
<thead>
<tr>
<th>Enabled percentage [%]</th>
<th>L5</th>
<th>49.6</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>59.3</td>
<td></td>
</tr>
</tbody>
</table>
Kinematic Test 1  Multipath Errors

<table>
<thead>
<tr>
<th>GPSTIME[s]</th>
<th>438000</th>
<th>438300</th>
<th>438600</th>
<th>438900</th>
<th>439200</th>
</tr>
</thead>
<tbody>
<tr>
<td>abs(MP) &lt; 25m</td>
<td>σ [m]</td>
<td>L5</td>
<td>0.82</td>
<td>L1</td>
<td>0.77</td>
</tr>
<tr>
<td>1_L5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1_L1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

abs(MP) < 25m

σ [m]

L5 0.82

L1 0.77
Kinematic Test 2  (edagawa, Tokyo)

12/27/2012
Geodetic Receiver
35min 5 Hz
4-9 satellites in view over 15 degrees elevation
Target SV : GPS-PRN-1 (L1,L5)
Reference SV : QZS-1 (L1,L5)
Precise position was computed by post processing

100s smoothing

<table>
<thead>
<tr>
<th>Fix rate[%]</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>RTK</td>
<td>94.1</td>
</tr>
</tbody>
</table>
Kinematic Test 2  Multipath Errors

<table>
<thead>
<tr>
<th>GPSTIME [s]</th>
<th>L5</th>
<th>L1</th>
</tr>
</thead>
<tbody>
<tr>
<td>430830</td>
<td></td>
<td></td>
</tr>
<tr>
<td>431130</td>
<td></td>
<td></td>
</tr>
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<td>431430</td>
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<tr>
<td>431730</td>
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<tr>
<td>432330</td>
<td></td>
<td></td>
</tr>
<tr>
<td>432630</td>
<td></td>
<td></td>
</tr>
<tr>
<td>432930</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Enabled percentage [%]

<table>
<thead>
<tr>
<th></th>
<th>L5</th>
<th>L1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>64.9</td>
<td>91.5</td>
</tr>
</tbody>
</table>

[Graph showing multipath errors with L5 and L1 data points]
Kinematic Test 2  Multipath Errors

abs(MP) < 25m

<table>
<thead>
<tr>
<th></th>
<th>σ [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>L5</td>
<td>1.93</td>
</tr>
<tr>
<td>L1</td>
<td>1.55</td>
</tr>
</tbody>
</table>
Conclusion

• Pseudo-range observables from L5 are basically robust against multipath.
• We were able to estimate multipath errors for moving targets by using the proposed method.
• The multipath mitigation performance between L1 and L5 was not so different at present.
• Using L5 instead of L1 will be practical in the future without special correlator.
Future work

• Further investigation for L5 signal is required because manufactures are still developing the tracking technique for new L5 signal.

• Software defined GNSS receiver can be used to evaluate it.
Thank you very much for your kind attention!