Single-Frequency Multi-GNSS RTK Positioning for Moving Platform

ION ITM 2015
2015.1.27-29

Tokyo University of Marine Science and Technology
H. Sridhara, N. Kubo, R.Kikuchi
Motivation and Background
Single-epoch multi-GNSS RTK
Short baseline analysis
- Experiment and Results
5KM baseline analysis
- Experiment and Results
Crane motion
- Experiment and Results
Automobile test
- Experiment and Results
Summary
Future Direction
Motivation & Background

- Possible to achieve high precision positioning with RTK-GNSS
- Prospective accuracy for safety apps like lane recognition is to be under 1m with continuous positioning.

Low-cost precise position apps:

- UAV: Centimeter-level accuracy allows it to be used for precise map generation.
- Crane motion: Cost of precise verification of a large crane remains excessive.

GPS L1-only FIX: 24.1 %
Novatel OEM615 Receiver
Multi-GNSS Test (around Tokyo station)

GPS-only vs. GNSS:
- using only the GPS-L1 signal, the FIX rate of RTK can be low.
- Dual frequency still a necessity for reliability

Blue plots shows the horizontal plots at dense urban areas using GPS/QZS/BEIDOU of commercial high-sensitivity receiver.

On the other hand, red plots shows the results using only GPS.

The performance difference is clear.
BeiDou Satellite System (BDS) provides PNT services in the Asia-Pacific corridor.

Current constellation consists of fourteen: including five GEO, five IGSO and four MEO satellites.

They transmit on B1, B2 and B3 frequencies using QPSK modulation and utilize CDMA.

Current (Phase II) B1 civil signal with 4.092MHz bandwidth centered at 1561.098MHz.

Phase III plan: B1 shifted to GPS-L1 frequency with multiplex binary offset carrier (MBOC 6,1,1/11) modulation.

BDS should reach its full constellation of 35 satellites by 2020.

Focus on performance comparison between GPS-L1, GPS/QZS L1+ BeiDou B1 and GPS L1+L2 in Japan for moving platform in urban environment.

Cost for precision

- Current GNSS-RTK products are expensive – different reasons stable clocks, high-quality antenna, integrated RF front-ends, number of correlators in ASIC, patented algorithms etc.
- Push to support lower cost RTK products for safety applications or UAVs & applications
- When B1 civil signal uses L1 frequency, availability will increase multi-fold in Asia-Pacific

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>10m</th>
<th>5m</th>
<th>1m</th>
<th>10cm</th>
<th>1cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low cost product</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Target</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Survey-grade GNSS Quite expensive product</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Single epoch RTK-GNSS

- Double-differenced observations in each satellite system
- Signal quality check and ADOP
- LAMBDA method
- Ratio Test (>3)

It is expected that the multi-GNSS RTK will be improved by using many satellites
Algorithm

\[ E[\phi] = [A \ A][a \ b], V[\phi] = [Q_{\phi \phi} \ 0 \ 0 \ Q_{pp}] \]

\[ \{\tilde{a}, \tilde{b}\} = \arg \min_{a \in \mathbb{Z}^n, b \in \mathbb{R}^n} (\|\phi - \Lambda a - Ab\|^2_{Q_{\phi \phi}} + \|p - Ab\|^2_{Q_{pp}}) \]

\[ \tilde{b} = Q_{bb}A^TQ_{pp}^{-1}p \quad Q_{bb} = (A^TQ_{pp}^{-1}A)^{-1} \]

\[ \tilde{a} = \Lambda^{-1}(\phi - \Lambda \tilde{b}), Q_{aa} = \Lambda^{-1}(Q_{\phi \phi} + AQ_{bb}A^T)\Lambda^{-1} \quad Q_{bb} = (A^T(Q_{pp}^{-1} + Q_{\phi \phi}^{-1})A)^{-1} \]

\[ \tilde{a} = \arg \min_{z \in \mathbb{Z}^n}(\|z - \lambda\|^2_{Q_{aa}}) \]

\[ \tilde{b} = Q_{bb}A^T[Q_{pp}^{-1}p + Q_{\phi \phi}^{-1}(\phi - \Lambda \tilde{a})] \]

- respective reference satellites were selected for the BeiDou and GPS systems
- \( n_G + 1 \) and \( n_B + 1 \) are the number of GPS/QZS and BDS satellites tracked on L1 and B1 frequencies, a total of \( 2 \times (n_B + n_G) \) DD code and phase observables are available per epoch.
- redundancy in the model was calculated as \( (n_G + n_B) - \nu \)
- ILS-based estimators are not only optimal, but have the highest probability of fixing ambiguities among all the integer estimators.
- Empirical fix rate is ratio of the number of passed epochs determined by the ratio test to the total number of observations
- Reliability is equal to the number of correctly fixed epochs divided by the number of passed epochs determined in the ratio test
# Experimental Set-up

<table>
<thead>
<tr>
<th>RECEIVER (BASE STATION AND ROVER)</th>
<th>Trimble NetR9</th>
</tr>
</thead>
</table>
| ANTEENA                           | Base station: Trimble Zephyr Geodesic 2  
Rover: Novatel 703-GGG            |
| SOFTWARE                          | Laboratory developed RTK -GNSS engine |

<table>
<thead>
<tr>
<th>Constellation</th>
<th>Frequency</th>
<th>Code STD (cm)</th>
<th>Phase STD (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>L1</td>
<td>35</td>
<td>3.5</td>
</tr>
<tr>
<td>QZS</td>
<td>L1</td>
<td>35</td>
<td>3.5</td>
</tr>
<tr>
<td>BDS</td>
<td>B1</td>
<td>35</td>
<td>3.5</td>
</tr>
</tbody>
</table>
Experiment 1 -1m baseline

- Very short baseline analysis -1m
- Total period: 24 hours
- Different mask angles – 15 & 30 degrees
- Reference station on the rooftop of our building at Etchujima
- Data rate: 1Hz
- Average number of satellites – GPS L1 – 8.3 & 6.1
  GPS/QZS L1 and BeiDou B1 – 15.9 & 12

<table>
<thead>
<tr>
<th>Mask angle = 15 degrees</th>
<th>Combinations</th>
<th>Fix rate (%)</th>
<th>Reliability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPS</td>
<td>52.53</td>
<td>98.53</td>
</tr>
<tr>
<td></td>
<td>GPS+QZS</td>
<td>65.78</td>
<td>99.30</td>
</tr>
<tr>
<td></td>
<td>GPS+BDS</td>
<td>99.82</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>GPS/QZS/BDS</td>
<td>99.85</td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>GPS (L1+L2)</td>
<td>97.88</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mask angle = 30 degrees</th>
<th>Combinations</th>
<th>Fix rate (%)</th>
<th>Reliability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPS</td>
<td>18.59</td>
<td>91.72</td>
</tr>
<tr>
<td></td>
<td>GPS+QZS</td>
<td>28.46</td>
<td>95.35</td>
</tr>
<tr>
<td></td>
<td>GPS+BDS</td>
<td>90.85</td>
<td>99.87</td>
</tr>
<tr>
<td></td>
<td>GPS/QZS/BDS</td>
<td>92.30</td>
<td>99.90</td>
</tr>
<tr>
<td></td>
<td>GPS (L1+L2)</td>
<td>70.76</td>
<td>100</td>
</tr>
</tbody>
</table>
Without any kinds of smoothing technique, single-frequency RTK requires more than 10 satellites to achieve good Fix-rate.
Experiment 2 - 5KM baseline

- 5KM baseline analysis
- Total period: 18 hours
- Different mask angles – 15 & 30 degrees
- Frequency: 1Hz
- Reference station on the rooftop of our building at Etchujima
- QZSS ignored due to unstable and inconsistent data
- Average number of satellites used:
  - GPS L1 – 7.9 & 6.1
  - GPS/QZS L1 and BeiDou B1 – 15.8 & 11.7

<table>
<thead>
<tr>
<th>Mask angle = 15 degrees</th>
<th>Combinations</th>
<th>Fix rate (%)</th>
<th>Reliability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPS</td>
<td>27.2</td>
<td>95.71</td>
</tr>
<tr>
<td></td>
<td>GPS+ BDS</td>
<td>73.9</td>
<td>99.98</td>
</tr>
<tr>
<td></td>
<td>GPS (L1+L2)</td>
<td>79.7</td>
<td>100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mask angle = 30 degrees</th>
<th>Combinations</th>
<th>Fix rate (%)</th>
<th>Reliability (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GPS</td>
<td>14.0</td>
<td>92.73</td>
</tr>
<tr>
<td></td>
<td>GPS+ BDS</td>
<td>88.2</td>
<td>99.90</td>
</tr>
<tr>
<td></td>
<td>GPS (L1+L2)</td>
<td>50.1</td>
<td>100</td>
</tr>
</tbody>
</table>
• L1+B1 combination provides best availability for both mask angles.
• For successful fix rate, L1+B1’s performance comparable to L1+L2’s for 15 degrees mask angle and betters for 30 degree mask angle.
• L1+B1 has better reliability owing to this consistency.
• A mask angle 30 deg similar to may be necessary to keep multipath effects in check.
Experiment 3

- Crane motion analysis
- Moving reference station - Antenna & receiver at higher elevation on the crane
- Rover antenna placed on the blue side-post shown
- Single mask angle – 35 degrees
- Two tests carried out – closer & away from wall
- Each experiment lasted approximately 30 min.
Estimated Trajectories

Test#1

Dual GQB reference trajectory
Single GQB estimated trajectory
Single G estimated trajectory

Test#2

Dual GQB reference trajectory
Single GQB estimated trajectory
Single G estimated trajectory
Results

<table>
<thead>
<tr>
<th>Combinations</th>
<th>Test #1= Away from wall (over 30m)</th>
<th>Test #2= Closer to wall (approx. 15m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fix rate (%)</td>
<td>Reliability (%)</td>
</tr>
<tr>
<td>GPS</td>
<td>7.65</td>
<td>50.08</td>
</tr>
<tr>
<td>GPS+QZS</td>
<td>31.78</td>
<td>96.96</td>
</tr>
<tr>
<td>GPS+QZS+BDS</td>
<td>86.95</td>
<td>99.41</td>
</tr>
<tr>
<td>GPS+QZS+BDS (dual-frequency)</td>
<td>99.85</td>
<td>100</td>
</tr>
</tbody>
</table>

• Reason we chose “moving reference station” was so it would have open sky view.
• True reference positions of the crane motion unknown, hence dual frequency derived results used as a reference.
• If we set the mask angle below 30 degrees, the fix rate and reliability decreased dramatically for all combinations.
• Explained by vulnerability of single frequency RTK to small/medium multipath environment.
• The performance difference between test1 and test2 evident from estimated trajectories.
• The reliability of the only GPS case very poor at almost 0%.
• In test1, single GQB fares almost as well as dual GQB.
• In test2, single GQB combination does not fare as well but dual GQB presents an almost perfect result.
Experiment 4

- Automobile testing near university campus
- Urban environment with surrounding buildings
- Reference station on rooftop of building in Etchujima campus
- QZS was not available due to low elevation angle.
- Mask angle – 15 degrees
- Test duration - approximately 25 min.
Reference Positions by Multi-GNSS RTK

GPS+QZS+GLONASS+BEIDOU dual-frequency

84% reliable FIX and it was enough to evaluate single-frequency RTK solutions.
Number of used satellites

GPS and GPS+BEIDOU

- **GPS**: Average = approx. 6
- **GPS+BeiDou**: Average = approx. 12

25 minutes
### Results

<table>
<thead>
<tr>
<th>Ratio 2</th>
<th>Fix rate (%)</th>
<th>Reliability (%)</th>
<th>HDOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>13</td>
<td>27.8</td>
<td>4.3</td>
</tr>
<tr>
<td>GPS+BDS</td>
<td>28.2</td>
<td>85.9</td>
<td>1.3</td>
</tr>
<tr>
<td>GPS(L1/L2)</td>
<td>44.5</td>
<td>99.8</td>
<td>4.1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ratio 3</th>
<th>Fix rate (%)</th>
<th>Reliability (%)</th>
<th>HDOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>5.5</td>
<td>28.7</td>
<td>4.3</td>
</tr>
<tr>
<td>GPS+BDS</td>
<td>15.1</td>
<td>91.9</td>
<td>1.1</td>
</tr>
<tr>
<td>GPS(L1/L2)</td>
<td>35.2</td>
<td>100</td>
<td>3.9</td>
</tr>
</tbody>
</table>

**Ratio test threshold = 2**

- **L1**
- **L1+B1**
- **L1+L2**

**Ratio test threshold = 3**

- **L1**
- **L1+B1**
- **L1+L2**

**Reliability** means the percentage within 50cm of horizontal errors.
Comparisons
- GPS and GPS/BeiDou Ratio>2 1 Round-

GPS (L1)

GPS+BeiDou (L1/B1)
• Reference positions deduced from GPS/QZS/BeiDou/GLONASS with dual frequency @ 84% fix rate.
• Reliability % checked only if (result - reference position) = ~ 50 cm.
• Average HDOP for only GPS approximately 4.3 while for GPS/BeiDou was 1.3.
• Fix rates dropped significantly compared to stationary tests.
• Despite incorrect fixes, percentage of accurate results within 50 cm in horizontal direction jumped by adding BeiDou satellites.
• Similar tendency also observed for dual frequency case.
Low-cost receiver test using boat

-Single frequency GPS/QZS/BeiDou RTK-

Height Determination of Small Boat on the Sea (1hour)
• By adding QZS, BeiDou, or QZS/BeiDou to GPS only, fix rate and reliability of RTK improved significantly under various conditions.

• First reason: high satellite availability improves ambiguity resolution. Even under open sky conditions more than 8–9 satellites are generally required for only GPS constellation.

• Second reason: good selectability; set a high cut off angle if we have redundancies to result in good quality selection.

• For crane test, the mask angle was important for increasing fix rate.
• Avoiding the multipath reflections is quite important too.
Future Direction

• Ambiguity resolution with consideration of ISBs will be evaluated:
  Once correct ISBs are obtained, one reference satellite for multi-GNSS

• Autonomous UAV like waypoint-navigation is already available but it essentially does not need RTK:
  We are looking for the application using centimeter-accuracy RTK for small UAV
Thank you for your attention!