GNSS Precise Positioning with RTKLIB
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<td>9:30-10:40</td>
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<td>10:50-12:00</td>
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5. RTK
## Precise Positioning

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<tr>
<td><strong>Observables</strong></td>
<td>Pseudorange (Code)</td>
<td>Carrier-Phase + Pseudorange</td>
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<tr>
<td><strong>Receiver Noise</strong></td>
<td>30 cm</td>
<td>3 mm</td>
</tr>
<tr>
<td><strong>Multipath</strong></td>
<td>30 cm - 30 m</td>
<td>1 - 3 cm</td>
</tr>
<tr>
<td><strong>Sensitivity</strong></td>
<td>High (&lt;20dBHz)</td>
<td>Low (&gt;35dBHz)</td>
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<tr>
<td><strong>Discontinuity</strong></td>
<td>No Slip</td>
<td>Cycle-Slip</td>
</tr>
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<td><strong>Ambiguity</strong></td>
<td>-</td>
<td>Estimated/Resolved</td>
</tr>
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<td><strong>Receiver</strong></td>
<td>Low-Cost (~$100)</td>
<td>Expensive (~$20,000)</td>
</tr>
<tr>
<td><strong>Accuracy (RMS)</strong></td>
<td>3 m (H), 5 m (V) (Single)</td>
<td>5 mm (H), 1 cm (V) (Static)</td>
</tr>
<tr>
<td></td>
<td>1 m (H), 2 m (V) (DGPS)</td>
<td>1 cm (H), 2 cm (V) (RTK)</td>
</tr>
<tr>
<td><strong>Application</strong></td>
<td>Navigation, Timing, SAR,...</td>
<td>Survey, Mapping, ...</td>
</tr>
</tbody>
</table>
Carrier-Phase

Definition:

\[ \phi_r^s = \phi^s - \phi_r + N \]

... actually being a measurement on the beat frequency between the received carrier of the satellite signal and a receiver-generated reference frequency. (*RINEX 2.10*)

Received Satellite Carrier:

\[ \phi^s (t^s) \]

Local Reference Frequency:

\[ \phi_r (t_r) \]

Carrier Beat Frequency:

\[ \phi_r^s = \phi^s - \phi_r + N \]
Carrie-Phase Model (1)

**Carrier-Phase:**

\[ \phi_r^s = \phi_r(t_r) - \phi^s(t^s) + N_r^s + \varepsilon_\phi \quad (\phi_{r,0} = \phi_r(t_0), \phi_0^s = \phi^s(t_0)) \]

\[ = (f(t_r + dt_r - t_0) + \phi_{r,0}) - (f(t^s + dT^s - t_0) + \phi_0^s) + N_r^s + \varepsilon_\phi \]

\[ = \frac{c}{\lambda}(t_r - t^s) + \frac{c}{\lambda}(dt_r - dT^s) + (\phi_{r,0} - \phi_0^s + N_r^s) + \varepsilon_\phi \quad \text{(cycle)} \]

\[ \Phi_r^s \equiv \lambda \phi_r^s = c(t_r - t^s) + c(dt_r - dT^s) + \lambda(\phi_{r,0} - \phi_0^s + N_r^s) + \lambda \varepsilon_\phi \]

\[ = \rho_r^s + c(dt_r - dT^s) - I_r^s + T_r^s + \lambda B_r^s + d_r^s + \varepsilon_{\Phi} \quad \text{(m)} \]

**Pseudorange:**

\[ P_r^s = \rho_r^s + c(dt_r - dT^s) + I_r^s + T_r^s + \varepsilon_P \]
Carrier-Phase Model (2)

Carrier-Phase Bias:

\[ B_r^s = \phi_{r,0} - \phi_0^s + N_r^s \quad \text{(cycle)} \]

- \( N_r^s \): Integer Ambiguity
- \( \phi_{r,0} \): Receiver Initial Phase
- \( \phi_0^s \): Satellite Initial Phase

Other Correction Terms:

\[
d_r^s = -d_{r,pco}^T e_{r,enu}^s + \left( E_{sat \rightarrow ecef} d_{pco}^s \right)^T e_r^s + d_{r,pcv} + d_{pcv}^s - d_{disp}^T e_{r,enu}^s + d_{pw} + d_{rel} \quad \text{(m)}
\]

- \( d_{r,pco} \): Receiver Antenna Phase Center Offset
- \( d_{r,pcv} \): Receiver Antenna Phase Center Variation
- \( d_{pco}^s \): Satellite Antenna Phase Center Offset
- \( d_{pcv}^s \): Satellite Antenna Phase Center Variation
- \( d_{disp} \): Site Displacement
- \( d_{pw} \): Phase Wind-up Effect
- \( d_{rel} \): Relativistic Effect
\[ \Phi_{ub}^{ij} \equiv \lambda((\phi_u^i - \phi_b^i) - (\phi_u^j - \phi_b^j)) \]

\[ = \rho_{ub}^{ij} + c(dt_{ub}^{ij} - dT_{ub}^{ij}) - I_{ub}^{ij} + T_{ub}^{ij} + \lambda B_{ub}^{ij} + d_{ub}^{ij} + \varepsilon_{\Phi} \]

\[ = \rho_{ub}^{ij} - I_{ub}^{ij} + T_{ub}^{ij} + \lambda N_{ub}^{ij} + d_{ub}^{ij} + \varepsilon_{\Phi} \]

\[ dt_{ub}^{ij} = dt_u^{ij} - dt_b^{ij} = 0, \quad dT_{ub}^{ij} = dT_u^{ij} - dT_b^{ij} \approx 0 \]

\[ B_{ub}^{ij} = (\phi_{u,0}^i - N_u^i) - (\phi_{b,0}^i - N_b^i) - (\phi_{u,0}^j - N_u^j) + (\phi_{b,0}^j - N_b^j) = N_{ub}^{ij} \]

(short Baseline and same antenna type)

\[ \Phi_{ub}^{ij} \approx \rho_{ub}^{ij} + \lambda N_{ub}^{ij} + \varepsilon_{\Phi} \]

\[ I_{ub}^{ij} = I_{ub}^{i} - I_{ub}^{j} \approx 0, T_{ub}^{ij} = T_{ub}^{i} - T_{ub}^{j} \approx 0, d_{ub}^{ij} = d_{ub}^{i} - d_{ub}^{j} \approx 0 \]

Memo for Misra & Enge: http://gpspp.sakura.ne.jp/diary200608.htm
Carrier-based Relative Positioning

Nonlinear-LSE:

Parameter Vector:
\[ \mathbf{x} = (r_u^T, N_{ub}^{s_2 s_1}, N_{ub}^{s_3 s_1}, ..., N_{ub}^{s_m s_1})^T \]

Measurement Vector:
\[ \mathbf{y} = (y_{t_1}^T, y_{t_1}^T, ..., y_{t_n}^T)^T \]

Meas Model, Design Matrix:
\[ \mathbf{h}(\mathbf{x}) = \left( h_{t_1}(\mathbf{x})^T, h_{t_2}(\mathbf{x})^T, ..., h_{t_n}(\mathbf{x})^T \right)^T \]
\[ \mathbf{H} = \left( \mathbf{H}_{t_1}^T, \mathbf{H}_{t_2}^T, ..., \mathbf{H}_{t_n}^T \right)^T \]

Meas Error Covariance:
\[ \mathbf{R} = \text{blkdiag}(\mathbf{R}_{t_1}, \mathbf{R}_{t_2}, ..., \mathbf{R}_{t_n}) \]

Solution (Static/Float):
\[ \hat{\mathbf{x}} = \mathbf{x}_0 + (\mathbf{H}^T \mathbf{R}^{-1} \mathbf{H})^{-1} \mathbf{H}^T \mathbf{R}^{-1} (\mathbf{y} - \mathbf{h}(\mathbf{x}_0)) \]

\[ \mathbf{y}_{t_k} = (\Phi_{ub,t_k}^{s_2 s_1}, \Phi_{ub,t_k}^{s_3 s_1}, ..., \Phi_{ub,t_k}^{s_m s_1})^T \]
\[ \mathbf{h}_{t_k}(\mathbf{x}) = \begin{pmatrix} \rho_{u,t_k}^{s_2 s_1} - \rho_{b,t_k}^{s_2 s_1} + \lambda N_{ub}^{s_2 s_1} \\ \rho_{u,t_k}^{s_3 s_1} - \rho_{b,t_k}^{s_3 s_1} + \lambda N_{ub}^{s_3 s_1} \\ \vdots \\ \rho_{u,t_k}^{s_m s_1} - \rho_{b,t_k}^{s_m s_1} + \lambda N_{ub}^{s_m s_1} \end{pmatrix} \]
\[ \mathbf{H}_{t_k} = \begin{pmatrix} -\mathbf{e}_{u,t_k}^{s_2 s_1}^T & \lambda & 0 & \cdots & 0 \\ -\mathbf{e}_{u,t_k}^{s_3 s_1}^T & 0 & \lambda & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -\mathbf{e}_{u,t_k}^{s_m s_1}^T & 0 & 0 & \cdots & \lambda \end{pmatrix} \]
\[ \mathbf{R}_{t_k} = \begin{pmatrix} 4\sigma_\phi^2 & 2\sigma_\phi^2 & \cdots & 2\sigma_\phi^2 \\ 2\sigma_\phi^2 & 4\sigma_\phi^2 & \cdots & 2\sigma_\phi^2 \\ \vdots & \vdots & \ddots & \vdots \\ 2\sigma_\phi^2 & 2\sigma_\phi^2 & \cdots & 4\sigma_\phi^2 \end{pmatrix} \]

\( r_b \): Fixed Base-Station Position
Effect of Baseline Length

BL=0.3 km
RMS Error:
E: 0.2cm
N: 0.6cm
U: 1.0cm
Fix Ratio: 99.9%

BL=13.3 km
RMS Error:
E: 2.2cm
N: 2.4cm
U: 10.6cm
Fix Ratio: 94.2%

BL=32.2 km
RMS Error:
E: 10.0cm
N: 12.0cm
U: 30.2cm
Fix Ratio: 64.3%

BL=60.9 km
RMS Error:
E: 14.0cm
N: 14.8cm
U: 26.7cm
Fix Ratio: 44.4%

(24 hr Kinematic •: Fixed Solution ○: Float Solution)
Integer Ambiguity Resolution

• Objectives
  – More accurate than float solutions
  – Fast converge of solutions

• Many AR Strategies
  – Simple Integer rounding
  – Multi-frequency wide-lane and narrow-lane generation
  – Search in coordinate domain
  – Search in ambiguity domain
  – AFM, FARA, LSAST, LAMBDA, ARCE, HB-L³, Modified Cholesy Decomposition, Null Space, FAST, OMEGA, ...
**ILS (Integer Least Square Estimation)**

**Problem:**

\[
x = (a^T, b^T)^T, \quad H = (A, B)
\]
\[
y = Hx + v = Aa + Bb + v
\]
\[
\tilde{x} = \arg \min_{a \in \mathbb{Z}^n, b \in \mathbb{R}^m} (y - Hx)^T Q_y^{-1} (y - Hx)
\]

**Strategy:**

1. Conventional LSE

\[
\hat{x} = \begin{bmatrix} \hat{a} \\ \hat{b} \end{bmatrix} = Q_x H^T Q_y^{-1} y, \quad Q_x = \begin{pmatrix} Q_a & Q_{ab} \\ Q_{ba} & Q_b \end{pmatrix} = (H^T Q_y H)^{-1}
\]

2. **Search Integer Vector** with Minimum Squared Residuals

\[
\tilde{a} = \arg \min_{a \in \mathbb{Z}^n} (\hat{a} - a)^T Q_a^{-1} (\hat{a} - a)
\]

3. Improve solution

\[
\tilde{b} = \hat{b} - Q_{ba} Q_a^{-1} (\hat{a} - \tilde{a})
\]

**• ILS Estimation with:**

- Shrink Integer Search Space with "Decorrelation"
- Efficient Tree Search Strategy
- Similar to *Closest Point Search with LLL Lattice Basis Reduction* Algorithm

\[
\tilde{a} = \arg \min_{a \in \mathbb{Z}^n} (\hat{a} - a)^T Q_a^{-1} (\hat{a} - a)
\]

\[
\tilde{z} = Z^T \hat{a}, \quad Q_z = Z^T Q_a Z
\]

\[
\tilde{z} = \arg \min_{z \in \mathbb{Z}^n} (\tilde{z} - z)^T Q_z^{-1} (\tilde{z} - z)
\]

\[
\tilde{a} = Z^{-T} \tilde{z}
\]
RTK (Real-time Kinematic)

- Technique with Carrier-based Relative Positioning
  - Real-time Position of Rover Antenna
  - Transmit Reference Station Data to Rover via Comm. Link
  - **OTF** (On-the-Fly) Integer Ambiguity Resolution
  - Typical Accuracy: $1 \text{ cm} + 1 \text{ppm} \times \text{BL RMS (Horizontal)}$
  - Applications:
    Land Survey, Construction Machine Control, Precision Agriculture etc.

![Diagram of RTK setup with Reference Station, Communication Link, and Rover Receiver]
NRTK (Network RTK)

• Extension of RTK
  – RTK without User Reference Station
  – Sparse Networked Reference Stations
  – Correction Messages via Mobile-Phone Network
  – Format: VRS, FKP, MAC, RTCM 2.3, RTCM 3.1
  – Server S/W: Trimble GPSNet, GEO++ GNSMART, ...
  – NTRIP Networked Transport of RTCM via Internet Protocol

• NRTK Service in Japan
  – GEONET: ~1200 Reference Stations by GSI
  – NGDS (www.gpsdata.co.jp), JENOBABA (www.jenoba.jp)
GEONET

GEONET STATIONS MAP by Google Map - GEONET Stations

(http://terras.gsi.go.jp/ja/index.htm)
5. RTK:
Exercise
RTK of Driving Vehicle

• **Objective**
  RTK of Driving Vehicle

• **Program**
  ...tklib_2.4.0\bin\rtknavi.exe
  ...tklib_2.4.1b\bin\rtknavi.exe

• **Data**
  ...sample2\sem\l2\oemv_2009515c.gps (NovAtel)
  0263_20090515c.rtc3m3 (VRS)
RTK Configuration

- **Antenna:** NovAtel GPS-702-GG

- **Base Station (VRS):**
  - **Internet**
  - **NTRIP**
  - **Trimble GPSNet**

- **GEONET Reference Stations**

- **Rover**
  - **NovAtel OEMV-3G**
  - **RTKNAVI**

- **E-Mobile**

- **Data Flow:**
  - **NovAtel RAW, 20 Hz**
  - **RTCM v.3, 1 Hz**
RTKNAVI - Options

Setting 1

Setting 2

- Integer Ambiguity Resolution: Fix and Hold
- GLONASS Ambiguity Resolution: ON
- Validation Threshold to Fix Ambiguity: 3.0
RTK Solutions

RTK PLOT 2.4.1
(Real-time Plot Mode)
6. PPP
**PPP (Precise Point Positioning)**

**Feature**
- with Single Receiver (No Reference Station)
- Efficient Analysis for Many Receivers
- Precise Ephemeris
- Conventionally Post-Processing

**Applications**
- GPS Seismometer
- GPS Meteorology
- POD (Precise Orbit Determination) of LEO Satellite
- Precise Time Transfer
Precise Ephemeris

• Precise Satellite Orbit and Clock
  – By Post-Processing or in Real-time
  – Observation Data of Tracking Stations World-Wide

• Data Format
  – Orbit: NGS SP3
  – Clock: NGS SP3 or RINEX Clock Extension

• Contents
  – Orbit: ECEF-Positions of Satellite Mass Center
  – Clock: Clock-biases wrt Time Scale Aligned to GPS Time
IGS (International GNSS Service)

Data (GPS/GLONASS Raw, Ephemeris,...)

Analysis Centers (ACs)

- CODE
- ESOC
- GFZ
- JPL
- NOAA
- NRCan
- SIO
- USNO
- MIT
- ...

Global Data Centers

- CDDIS
- SIO
- IGN
- KASI

Products
(Satellite Orbit/Clock, Station Pos/Vel, ERP, Atmos,...)

Regional DCs

Oper. DCs

Tracking Network
## IGS Products

<table>
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<tr>
<th>Product</th>
<th>Final (IGS)</th>
<th>Rapid (IGR)</th>
<th>Ultra-Rapid (IGU)</th>
<th>Broadcast</th>
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<td><strong>Accuracy</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orbit</td>
<td>~2.5cm</td>
<td>~2.5cm</td>
<td>~3cm</td>
<td>~5cm</td>
</tr>
<tr>
<td>Clock</td>
<td>~75ps RMS</td>
<td>~75ps RMS</td>
<td>~150ps RMS</td>
<td>~3ns RMS</td>
</tr>
<tr>
<td></td>
<td>~20ps STD</td>
<td>~25ps STD</td>
<td>~50ps STD</td>
<td>~1.5ns STD</td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12-18 days</td>
<td>17-41 hours</td>
<td>3-9 hours</td>
<td>realtime</td>
</tr>
<tr>
<td><strong>Updates</strong></td>
<td>every Thursday</td>
<td>at 17 UTC daily</td>
<td>at 03, 09, 15, 21 UTC</td>
<td>at 03, 09, 15, 21 UTC</td>
</tr>
<tr>
<td><strong>Sample Interval</strong></td>
<td>Orbit</td>
<td>15min</td>
<td>15min</td>
<td>15min</td>
</tr>
<tr>
<td></td>
<td>Clock</td>
<td>Sat: 30s Stn: 5min</td>
<td>5min</td>
<td>15min</td>
</tr>
</tbody>
</table>

Iono-free LC (Linear Combination)

\[ C = a \Phi_1 + b \Phi_2 + cP_1 + dP_2 (\Phi_1 = \lambda_1 \phi_1, \Phi_2 = \lambda_2 \phi_2) \]

<table>
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<tr>
<th>LC</th>
<th>Coefficients</th>
<th>Wave Length (cm)</th>
<th>Ionos Effect wrt L1</th>
<th>Typical Noise (cm)</th>
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<tr>
<td>L1 Carrier-Phase</td>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
</tr>
<tr>
<td>L2 Carrier-Phase</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LC/L3 Iono-Free Phase</td>
<td>( C_1 )</td>
<td>( C_2 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Geometry-Free Phase</td>
<td>1</td>
<td>-1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Wide-Lane Phase</td>
<td>( \lambda_W / \lambda_1 )</td>
<td>( -\lambda_W / \lambda_2 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Narrow-Lane Phase</td>
<td>( \lambda_N / \lambda_1 )</td>
<td>( \lambda_N / \lambda_2 )</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Melbourne-Wübbena</td>
<td>( \lambda_W / \lambda_1 )</td>
<td>( -\lambda_W / \lambda_2 )</td>
<td>( \lambda_N / \lambda_1 )</td>
<td>( \lambda_N / \lambda_2 )</td>
</tr>
<tr>
<td>L1-Multipath</td>
<td>( 2C_2 - 1 )</td>
<td>( -2C_2 )</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>L2-Multipath</td>
<td>( -2C_1 )</td>
<td>( 2C_1 - 1 )</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

\[ C_1 = f_1^2 / (f_1^2 - f_2^2), \quad C_2 = -f_2^2 / (f_1^2 - f_2^2), \quad \lambda_W = 1 / (1/ \lambda_1 - 1/ \lambda_2), \quad \lambda_N = 1 / (1/ \lambda_1 + 1/ \lambda_2) \]
Tropospheric Model

Tropospheric Delay:

\[ T = m_h(El)ZHD + m_w(El)ZWD \]

\[ ZHD = \frac{0.0022768 \times \rho}{1 - 0.00266 \cos 2\phi - 2.8 \times 10^{-7} H} \]

- \( ZHD \): Zenith Hydrostatic Delay (m)
- \( ZWD \): Zenith Wet Delay (m)
- \( m_h(El) \): Hydrostatic Mapping Function
- \( m_w(El) \): Wet Mapping Function

ZWD to PWV (Precipitable Water Vapor):

\[ T_m = 70.2 + 0.72T \]

\[ PWV = \frac{1 \times 10^5}{R_v \left( k_2 - k_1 \frac{m_v}{m_d} + \frac{k_3}{T_m} \right) ZWD} \]

- \( R_v = 461, k_1 = 77.6, k_2 = 71.98, k_3 = 3.754 \times 10^5 \)
- \( m_v = 18.0152, m_d = 28.9644 \)
Antenna PCV (Phase Center Variation)

Receiver Antenna Phase Center:

\[ d_{r, pcv} \]

\[ d_{r, pco} \]

Antenna Reference Point (ARP)

Antenna Phase Center Offset

\[ z (U) \]

\[ y (N) \]

\[ x (E) \]

Antenna Phase Center Variation (PCV)

Choke-Ring Type

Zero-Offset Type

IGS Absolute Antenna Model (IGS05.PCV)
Earth Tides

Solid Earth Tide, Ocean Tide Loading, Pole Tide, Atmospheric Loading

IERS Conventions 1996 + NAO99.b, 2007/1/1-1/31, TSKB
Static PPP vs Kinematic PPP

Static PPP Results
Station: GEONET 0837
2009/1/1-2009/12/31
Interval: 1 day

Kinematic PPP Results
Station: IGS CONZ
2010/2/27 6:28-6:45 GPST
Interval: 1 s
# Real-time PPP

## Commercial RT-PPP/GDPS Services

<table>
<thead>
<tr>
<th>Service</th>
<th>Provider</th>
<th>Communication Coverage</th>
<th>Link</th>
<th>Ref. Stations</th>
<th>Orbit/Clock</th>
<th>Engine</th>
<th>Accuracy</th>
</tr>
</thead>
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<tr>
<td><strong>StarFire</strong></td>
<td>NavCom</td>
<td>World-wide</td>
<td>3 GEO L-band</td>
<td>60</td>
<td>1 min/1-2 s</td>
<td>JPL RTG</td>
<td>&lt;10 cm H &lt;15 cm V (1 sigma)</td>
</tr>
<tr>
<td><strong>OmniSTAR XP/HP+</strong></td>
<td>Fuguro</td>
<td>World-wide (Land)</td>
<td>6 GEO L-band</td>
<td>100</td>
<td>1 min/10 s</td>
<td>Fuguro</td>
<td>dm-class</td>
</tr>
<tr>
<td><strong>SeaSTAR XP/G2</strong></td>
<td>Fuguro</td>
<td>World-wide (Sea)</td>
<td>6 GEO L-band</td>
<td>100</td>
<td>1 min/10 s</td>
<td>Fuguro/ESOC (G2)</td>
<td>dm-class</td>
</tr>
<tr>
<td><strong>VERIPOS Ultra/Apex</strong></td>
<td>VERIPOS</td>
<td>World-wide</td>
<td>7 GEO L-band</td>
<td>80</td>
<td>30 s/30 s</td>
<td>JPL/ESOC</td>
<td>10 cm H 20 cm V (95%)</td>
</tr>
</tbody>
</table>
IGS Real-time Ephemeris

- Developed by IGS-RTPP
  - RTCM v.3 MT1057-1068 (SSR)
  - Corrections to broadcast ephemeris
  - Real-time NTRIP stream
  - Interval: 10 s, Latency: 5 - 10 s
  - GPS and GLONASS

- Analysis Strategy
  - Orbit: fixed to IGU or estimated
  - Clock: estimated with IGS real-time tracking network

http://igs.bkg.bund.de
RT-PPP Performance with IGS

**BKG: CLK10**
- RMS: 3.8, 5.5, 7.7cm

**BKG: CLK11 (GPS+GLO)**
- RMS: 3.8, 5.0, 7.1cm

**GSOC/DLR: CLK20**
- RMS: 4.0, 5.2, 6.9cm

**ESA/ESOC: CLK31**
- RMS: 14.0, 12.1, 23.4cm

**ESA/ESOC: CLK51**
- RMS: 5.7, 5.4, 11.6cm

**TUW: CLK61**
- RMS: 23.3, 21.0, 25.0cm

2010/9/18 0:00-23:59, 1Hz, Kinematic PPP, NovAtel OEMV-3+GPS-702, RTKLIB 2.4.1
JAXA QZSS LEX-PPP Experiment

• Implementation for LEX-PPP user algorithm
  – Based on Real-time PPP by RTKLIB 2.4.1
  – Support QZSS LEX Message Type 10, 11
  – Support LEX-Receiver (Furuno LPY-10000) Message

• Preliminary Evaluation

  GEONET 0001 Wakkanai, 2010/8/3 0:00:00-23:59:30

  RMS Error E/N/U:
  15.2, 14.2, 21.6 cm (Dual Frequency)

  (T.Takasu, Space Sciences and Technology Conference, 2011)
6. PPP:
Exercise
PPP Analysis for Reference Point

• **Objective**
  PPP Analysis for Reference Point

• **Program**
  ...\rtklib_2.4.0\bin\rtkpost.exe
  ...

• **Data**
  ...
  09160700.11o, 09160700.11n (RINEX)
  21100700.11o, 21100700.11n (RINEX)
  igs16265.sp3 (Precise Orbit)
  igs16265.clk_30s (Precise Clock)

**Acknowledgment:** Sample Data are provided by GSI and IGS
Online GNSS Data Sources

IGS Data/Products

GEONET Data

http://igscb.jpl.nasa.gov

http://terras.gsi.go.jp/ja/index.html
RTKPOST - Options
7. RTK System
RTK Application

- Geodetic Survey
- Construction Machine Control
- Precision Agriculture
- ITS (Intelligent Transport System)
- Mobile Mapping System
- Sports

Considerations for RTK System

• **Rover**
  – Single vs. Dual-freq, Update Rate, GNSS, Receiver-cost
  – CPU Power for external processing
  – INS-integration for obstacles

• **Reference Station**
  – Baseline-Length vs. Performance
  – Self-provided vs. NRTK Service
  – Coverage, Receiver-cost, Operational-cost, Service-fee

• **Communication Link**
  – Coverage, Band-width, Latency, Link-cost
CPU-power, Bandwidth, Latency

• CPU-power
  – ~2 ms/epoch for dual-freq RTK on Intel Core 2 Q 2.4 GHz
  – ~20 ms/epoch for single-freq RTK on ARM 600 MHz
  – H/W DP floating-point is necessary

• Bandwidth
  – ~3 kbps for 1 Hz GPS only, RTCM 3
  – ~20 kbps for 1 Hz GPS+GLO+QZS+SBAS, JAVAD GREIS

• Latency
  – > 5 s Latency degrades RTK performance
  – "Low-latency" vs. "Matched" Solution
Communication Link for RTK

• **Local (<300 m)**
  – Serial, USB, LAN, ... (wired)
  – Radio Modem, WiFi, ZigBee, DSRC, ... (wireless)

• **Regional (<1,000 km)**
  – Analog-phone, ISDN, Dedicated Link, ... (wired)
  – Mobile-phone (Analog, 2G, 3G, ...), ... (wireless)

• **Global (<10,000 km)**
  – Internet
  – GEO Satellite Link (Inmarsat, WideStar II, ...)
  – LEO Satellite Link (Iridum, Orbicom, ...)
Coverage by Mobile-phone N/W

NTT docomo FOMA (2008/9)
(http://servicearea.nttdocomo.co.jp)
RTK Configurations (1)
RTK Configuration (2)

- **Base Station Receiver**
  - Input: Serial
  - Output: Serial
  - PC
  - STRSVR

- **Ntrip Caster**
  - Internet

- **Rover Receiver**
  - Input: Serial
  - Output: Solution 1=File
  - PC
  - RTKNAVI

- **Reference Stations**
  - NTRIP Caster
  - NRTK provider

- **RTKNAVI**
  - Internet

- **Ntrip Caster**
  - Internet

(0) Input = Serial
(1) Output 1 = NTRIP Server
(1) Input Rover = Serial
(2) Input Base Station = NTRIP Client
(3) Output Solution 1 = File
RTK Configuration (3)

Reference Stations

NTRIP Caster

(1) Input = NTRIP Client
(2) Output = TCP Server

RTKNAVI

Rover Receiver 1

PC

INTERNET

NRTK provider

STRSVR

PC

LAN

RTKNAVI

Rover Receiver 2

PC

RTKNAVI

Rover Receiver 3

PC

RTKNAVI

Rover Receiver 4

(1) Input Rover = Serial
(2) Input Base Station = TCP Client
7. RTK System: Exercise
Communication Link for RTK

- **Objective**
  Network Connection for RTK

- **Program**
  ...

- **Stream (TCP Client)**
  JAV1: 192.168.1.173: 2101 (Format: Javad)
  JAV2: 192.168.1.173: 2102 (Format: Javad)

Acknowledgment:
Sample data were captured by JAVAD DELTA and FURUNO LPY-10000 receiver provided by JAXA
Network Configuration

RTKNAVI 2.4.1b (TCP Client)

STRSVR (TCP server)

Format: Javad

192.168.1.173:2101 (Javad1)
192.168.1.173:2102 (Javad2)

Javad2: 35.666496867 139.792366358 59.3696
8. Advanced Topics
Advanced Topics

- Multi-GNSS RTK
- Long-Baseline RTK
- INS-Aided RTK
- Ambiguity Resolution for PPP
- "CM-Accuracy Anywhere"
## GNSS Evolution

### Number of Planned GNSS Satellites

<table>
<thead>
<tr>
<th>System</th>
<th>2010</th>
<th>2013</th>
<th>2016</th>
<th>2019</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>31</td>
<td>32</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>GLONASS</td>
<td>23 (+2)</td>
<td>24 (+3)</td>
<td>24 (+3)</td>
<td>24 (+3)</td>
</tr>
<tr>
<td>Galileo</td>
<td>0</td>
<td>4</td>
<td>18</td>
<td>27 (+3)</td>
</tr>
<tr>
<td>Compass</td>
<td>6</td>
<td>12</td>
<td>30</td>
<td>32 (+3)</td>
</tr>
<tr>
<td>QZSS</td>
<td>1</td>
<td>1</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>IRNSS</td>
<td>0</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>SBAS</td>
<td>7</td>
<td>8</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>68</strong></td>
<td><strong>88</strong></td>
<td><strong>129</strong></td>
<td><strong>140</strong></td>
</tr>
</tbody>
</table>

### GNSS Signal Frequencies

(Y. Yang, COMPASS: View on Compatibility and Interoperability, 2009)
## Multi-GNSS RTK Performance

### RTK Performance: Baseline 13.3 km, Instantaneous AR

<table>
<thead>
<tr>
<th></th>
<th>El Mask=15°</th>
<th></th>
<th>El Mask=30°</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fixing Ratio</td>
<td>RMS Error (cm) E-W</td>
<td>N-S</td>
<td>U-D</td>
</tr>
<tr>
<td><strong>GPS</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1</td>
<td>-</td>
<td>49.7%</td>
<td>4.6</td>
<td>8.1</td>
</tr>
<tr>
<td><strong>GPS L1+L2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1,L2</td>
<td>-</td>
<td>99.0%</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>L1,L2,L5</td>
<td>-</td>
<td>99.0%</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td><strong>GPS+GAL L1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L1,L2</td>
<td>E1</td>
<td>98.8%</td>
<td>1.3</td>
<td>1.2</td>
</tr>
<tr>
<td>L1,L2,L5</td>
<td>E1,E5a, E5b</td>
<td>98.9%</td>
<td>1.5</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Multi-GNSS Receiver

• Moore's Law
  – More correlators
  – More tracking channels
  – More powerful embedded CPU

• Consumer-grade Multi-GNSS Receiver
  – SkyTraq: GPS + GLONASS
  – STMicro: GPS + GLONASS
  – Broadcom: GPS + GLONASS + QZSS
  – u-blox: GPS + Galileo
Issues for Multi-GNSS RTK

• **Multi-GNSS Integration Issue**
  – Time-system, Coordinate-system
  – Receiver H/W Biases

• **Multi-code System Issue**
  – L1C/A-L1P(Y)-L1Cd-L1Cp, L2P(Y)-L2C, L5I-L5Q
  – Quarter cycle phase-shift problem

• **GLONASS FDMA Issue**
  – Receiver Inter-channel biases (Receiver Interoperability)
  – Calibration Message Standard
  – Antenna Calibration
Long-Baseline RTK

GPS Tsunami Monitoring System
(Currently ~15 km off-shore)

http://www.tsunamigps.com
## Long-Baseline RTK Strategy

<table>
<thead>
<tr>
<th>BL (km)</th>
<th>Error Elimination</th>
<th>Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ephem</td>
<td>Ionos</td>
</tr>
<tr>
<td>S</td>
<td>0 – 10</td>
<td>Broadcast</td>
</tr>
<tr>
<td>M</td>
<td>10 – 100</td>
<td>Broadcast</td>
</tr>
<tr>
<td>L</td>
<td>100 – 1,000</td>
<td>Real-time Precise (IGU)</td>
</tr>
<tr>
<td>VL</td>
<td>&gt;1,000</td>
<td>Non-RT Precise (IGR, IGS)</td>
</tr>
</tbody>
</table>
Long-Baseline RTK with RTKLIB

January 1-7, 2009  
BL=471.2 km  
July 1-7, 2009  

**E-W**
- STD=0.7, 0.9, 2.3 cm  
- FIX=99.8%

**N-S**
- STD=0.7, 0.9, 2.3 cm  
- FIX=99.8%

**U-D**
- STD=0.7, 0.9, 2.3 cm  
- FIX=99.8%

---

**BL=961.3 km**

**E-W**
- STD=1.1, 1.3, 3.8 cm  
- FIX=99.0%

**N-S**
- STD=1.1, 1.3, 3.8 cm  
- FIX=99.0%

**U-D**
- STD=1.1, 1.3, 3.8 cm  
- FIX=99.0%

---

BL=961.3 km

**E-W**
- STD=1.6, 1.3, 3.0 cm  
- FIX=98.8%

**N-S**
- STD=1.6, 1.3, 3.0 cm  
- FIX=98.8%

**U-D**
- STD=1.6, 1.3, 3.0 cm  
- FIX=98.8%
Mobile AP issues for RTK

- **Cycle-Slips**
  - Frequent cycle-slip with around obstacles
  - Miss-detection of cycle-slip

- **Low Solution Availability**
  - Long acquisition time by weak signal (Low C/N0)
  - Half-cycle ambiguity resolution with Costas-PLL
  - Low fixing ratio

- **High Noise Level**
  - High multipath level even in carrier-phase
  - Jamming by RFI
Cycle-Slips

- Cycle Slips
- Half-Cycle Slip
- Time
- Receiver
- Data Gap
- Loss-of-Lock
- Reacquisition (<1s)
- Half-Cycle Ambiguity Resolution (0-12s)

* Depend on Receiver

Number of Samples

- T<1s: 724 (68.2%)
- T<3s: 869 (81.8%)
- T<5s: 932 (87.8%)

Span of Data Gap (s) (EL>15°)
INS-Aided RTK

Loosely-Coupled Integration

Tightly-Coupled Integration

Deep Integration (Ultra-Tightly)
High sensitivity (DLL, PLL)
Slip resistance
Ambiguity Resolution for PPP

• 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
M.Ge et al., Resolution of GPS carrier-phase ambiguity in precise point positioning, EGU Assembly 2007
Real-Time Implementation of PPP-AR

- Network WL ambiguity fixing
- Parameter estimation by EKF with iono-free code/phase: phase-clock, code-phase-bias, ZTD, station position, orbit correction to IGU, phase ambiguity
- Orbit construction + high-rate clock generation

Evaluation of Accuracy

- Orbit: 4cm, code-clock: 5 cm, phase-clock: 1cm

RT-PPP with AR ("CNES Integer PPP")

- 1 cm HRMS
# CM-Accuracy Anywhere

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Target in 2020</th>
<th>Developing/Future Technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coverage</strong></td>
<td>Global (world-wide)</td>
<td>Precise Ephemeris with AR, Broadcast via GEO/QZSS Satellite</td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td>Real-time (1 s)</td>
<td>Real-time Multi-GNSS Orbit/Clock Estimation</td>
</tr>
<tr>
<td><strong>Accuracy</strong></td>
<td>1 cm (HRMS) / 2 cm (VRMS)</td>
<td>Local iono/tropos corrections (land) / Iono estimation by triple-freq (sea)</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>99 % (open-sky) / 95 % (urban)</td>
<td>Multi-GNSS 30 Sats + triple-freq</td>
</tr>
<tr>
<td><strong>TTFF</strong></td>
<td>10 s (land) / 1 min (sea)</td>
<td>Local iono/tropos corrections / Iono estimation by triple-freq</td>
</tr>
<tr>
<td><strong>User Cost</strong></td>
<td>&lt; $100</td>
<td>No patent problem, <strong>need killer-AP</strong></td>
</tr>
</tbody>
</table>
8. Advanced Topics:
Q & A