GNSS Training 2018

GNSS Precise Positioning and RTKLIB

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2018-01-23 ~ 2018-01-26 @AIT, Thailand
Receiver used in this training

1. u-blox GNSS receiver (M8P or M8T)
2. Trimble NetR9
You can purchase M8T


UBLOX NEO-M8T TIME & RAW RECEIVER BOARD WITH SMA (RTK READY)

UBLOX NEO-M8T GPS, GLONASS, Galileo, BeiDou, QZSS and SBAS RAW and timing receiver EVAL module USB, I2C, UART with SMA antenna connectors. RTK ready.

More details

$74.99

Quantity: 1

167 items in stock

Add to cart
Some Data used in Practice

Static raw data set (24h)
- u-blox M8T (ref/rover) + Trimble/NovAtel ant.
- Trimble NetR9 (ref) Trimble ant.

Static raw data set (1h)
- u-blox M8P (ref/rover) + Trimble/NovAtel ant.
- Trimble NetR9 (ref/rover) + Trimble/NovAtel ant.

Kinematic raw data set (0.5h)
- u-blox M8T (ref/rover) + Trimble/NovAtel ant.
- Trimble NetR9 (ref/rover) + Trimble/NovAtel ant.
Both reference station and rover station are installed on the rooftop of our building.

Using the “RTKLIB” and “internet”, we can check RTK.

You will learn why the cm-level navigation can be achieved by RTK-GNSS through this class.

[Diagram of satellite communication]
RTK performance
12h, rooftop, our building

RTK : mm level

Same scale
GNSS Signal Structure

$$\sqrt{2PC(t)D(t)\sin(2\pi ft + \phi)} + K$$
<table>
<thead>
<tr>
<th>Carrier Freq (MHz)</th>
<th>Code</th>
<th>Modulation</th>
<th>Data Rate</th>
<th>GNSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1/E1 1575.42</td>
<td>C/A</td>
<td>BPSK (1)</td>
<td>50 bps</td>
<td>GPS, QZSS</td>
</tr>
<tr>
<td></td>
<td>P(Y)</td>
<td>BPSK (10)</td>
<td>50 bps</td>
<td>GPS</td>
</tr>
<tr>
<td></td>
<td>L1C-d/p</td>
<td>MBOC (6,1,1/11)</td>
<td>-/100 bps</td>
<td>GPS (III-), Galileo</td>
</tr>
<tr>
<td></td>
<td>L1C-d/p</td>
<td>BOC (1,1)</td>
<td>-/100 bps</td>
<td>QZSS</td>
</tr>
<tr>
<td>L1 1602+0.5625K</td>
<td>C/A</td>
<td>BPSK</td>
<td>50 bps</td>
<td>GLONASS</td>
</tr>
<tr>
<td>L2 1227.60</td>
<td>P(Y)</td>
<td>BPSK (10)</td>
<td>50 bps</td>
<td>GPS</td>
</tr>
<tr>
<td>L2C</td>
<td>BPSK (1)</td>
<td>25 bps</td>
<td></td>
<td>GPS (IIRM-), QZSS</td>
</tr>
<tr>
<td>L2 1246+0.4375K</td>
<td>C/A</td>
<td>BPSK</td>
<td>50 bps</td>
<td>GLONASS</td>
</tr>
<tr>
<td>L5/E5a 1176.45</td>
<td>L5-I/Q</td>
<td>BPSK (10)</td>
<td>-/100 bps</td>
<td>GPS (IIF-), QZSS</td>
</tr>
<tr>
<td>E5a-I/Q</td>
<td>BPSK (10)</td>
<td>-/50 bps</td>
<td></td>
<td>Galileo</td>
</tr>
<tr>
<td>E5b 1207.14</td>
<td>E5b-I/Q</td>
<td>BPSK (10)</td>
<td>-/250 bps</td>
<td>Galileo</td>
</tr>
<tr>
<td>E6/LEX 1278.75</td>
<td>E6-I/Q</td>
<td>BPSK (5)</td>
<td>-/1000 bps</td>
<td>Galileo</td>
</tr>
<tr>
<td></td>
<td>LEX</td>
<td>BPSK (5)</td>
<td>2000 bps</td>
<td>QZSS</td>
</tr>
</tbody>
</table>
Spreading (PRN) Code

GPS C/A Code Generator

X₁ Epoch
10.23MHz

Auto-correlation function

\[ R(\tau) = \frac{1}{T} \int_{0}^{T} C^i(t)C^i(t-\tau)dt \]

Cross-correlation function

\[ R(\tau) = \frac{1}{T} \int_{0}^{T} C^i(t)C^j(t-\tau)dt \quad (i \neq j) \]
Carrier/Code Tracking in Receiver

CH1

- Code NCO
- Correlator
- DLL
- PLL/FLL

Baseband Processor

Δt, Δf

- Pseudorange, Navi-Data
- Carrier-Phase, Doppler-Freq

Δφ, Δf

- Carrier NCO
- Δφ
- CDφ
- CDφ_{IF}
- CD_{I,Q}
- C_{E,P,L}
- Δφ_{I,Q}
- PLL/FLL
- Range
- RF-Frontend
- Local Oscillator
**Pseudo-range (Code-phase)**

**Definition:**

\[ P_r^s \equiv c\tau = c(t_r - t^s) \]  
(m)

The pseudo-range (PR) is the distance from the receiver antenna to the satellite antenna including receiver and satellite clock offsets (and other biases, such as atmospheric delays) (*RINEX 2.10*)

At Satellite \[ \bar{t}^s = t_r - \tau \]  
Time by Satellite Clock (s)

At Receiver \[ \bar{t}_r \]  
Time by Receiver Clock (s)
Carrier-Phase

Definition:

\[ \phi^s_r = \phi^s - \phi_r + N \] (cycle)

... 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)

Receive Satellite Carrier:

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

Local Reference Frequency:

\[ \phi_r(t_r) \]

Carrier Beat Frequency:

\[ \phi^s_r = \phi^s - \phi_r + N \]
How about accuracy (Code)?

With the aid of “loop filtering + correlator characteristic”, we try to estimate the code measurements approximately desi-meter level (-1m).
How about accuracy (Carrier) ?

With the aid of “loop filtering + correlator characteristic”, we try to estimate the carrier-phase measurements approximately mm meter level.

I phase and Q phase (GPS L1-C/A)  I phase correlation value → Navigation data
# Code vs Carrier-Based Positioning

<table>
<thead>
<tr>
<th>Observables</th>
<th>Standard Positioning (code-based)</th>
<th>Precise Positioning (carrier-based)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall</td>
<td>Pseudorange (Code)</td>
<td>Carrier-Phase + Pseudorange</td>
</tr>
<tr>
<td>Observables</td>
<td>Pseudorange (Code)</td>
<td>Carrier-Phase + Pseudorange</td>
</tr>
<tr>
<td>Receiver Noise</td>
<td>30 cm</td>
<td>3 mm</td>
</tr>
<tr>
<td>Multipath</td>
<td>30 cm - 30 m</td>
<td>1 - 3 cm</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>High (&lt;20dBiHz)</td>
<td>Low (&gt;35dBiHz)</td>
</tr>
<tr>
<td>Discontinuity</td>
<td>No Slip</td>
<td>Cycle-Slip</td>
</tr>
<tr>
<td>Ambiguity</td>
<td>-</td>
<td>Estimated/Resolved</td>
</tr>
<tr>
<td>Receiver</td>
<td>Low-Cost (~$100)</td>
<td>Expensive (~$20,000)</td>
</tr>
<tr>
<td>Accuracy (RMS)</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>Application</td>
<td>Navigation, Timing, SAR,...</td>
<td>Survey, Mapping, ...</td>
</tr>
</tbody>
</table>
Pseudorange Model

\[ P^s_r \equiv c\tau \]

\[ = c(t_r - t^s) \]

\[ = c((t_r + dt) - (t^s + dT^s)) + \varepsilon_p \]

\[ = c(t_r - t^s) + c(dt_r - dT^s) + \varepsilon_p \]

\[ = (\rho_r^s + I_r^s + T_r^s) + c(dt_r - dT^s) + \varepsilon_p \]

\[ = \rho_r^s + c(dt_r - dT^s) + I_r^s + T_r^s + \varepsilon_p \]

\[ \text{(1)} \quad \text{(2)} \quad \text{(3)} \quad \text{(4)} \quad \text{(5)} \quad \text{(6)} \]
Carrier-Phase Model (1)

Carrier-Phase:

\[
\phi_r^s = \phi_r(t_r) - \phi_s(t_s) + N_r^s + \varepsilon_\phi
\]

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

\[
= \frac{c}{\lambda}(t_r - t_s) + \frac{c}{\lambda}(dt_r - dT_s) + (\phi_{r,0} - \phi_{0,0}^s + N_r^s) + \varepsilon_\phi
\]

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

\[
= \rho_r^s + c(dt_r - dT_s) - I_r^s + T_r^s + \lambda B_r^s + d_r^s + \varepsilon_\phi
\]

Pseudorange:

\[
P_r^s = \rho_r^s + c(dt_r - dT_s) + I_r^s + T_r^s + \varepsilon_P
\]

Carrier phase measurement is accumulated Doppler frequency.
Carrier-Phase Model (2)

Carrier-Phase Bias:

\[ B^S_r = \phi^s_{r,0} - \phi^0_s + N^S_r \] (cycle)

- \( N^S_r \): Integer Ambiguity
- \( \phi^s_{r,0} \): Receiver Initial Phase
- \( \phi^0_s \): Satellite Initial Phase

Other Correction Terms:

\[ d^S_r = -d^S_{r,pcoc} e^S_{r,enu} + (E_{sat\rightarrow ecef} d^S_{pcoc})^T e^S_r + d^S_{r,pccv} + d^S_{pccv} - d^T_{disp} e^S_{r,enu} \]

+ \( d^S_{pw} + d^S_{rel} \) (m)

- \( d^S_{r,pcoc} \): Receiver Antenna Phase Center Offset
- \( d^S_{r,pccv} \): Receiver Antenna Phase Center Variation
- \( d^S_{pcoc} \): Satellite Antenna Phase Center Offset
- \( d^S_{pccv} \): Satellite Antenna Phase Center Variation
- \( d^S_{disp} \): Site Displacement
- \( d^S_{pw} \): Phase Wind-up Effect
- \( d^S_{rel} \): Relativistic Effect
Phase Wind-up Effect
What happens in carrier-phase?

Basically, “code-carrier” indicates the code multipath errors (+ionosphere effect).
Turn table rotates 33.3333…/min. It means that the number of rotation was 1077.22.
Converting to “meter” of L1-C/A, 1077.22*0.19… = 204.98 m
204.98/1939 s = 0.1057m / turn have to be compensated in carrier-phase.
After compensation,

You see code multipath…
Antenna Phase Center

- The GNSS measurements are referred to the so-called antenna phase center. The position of the antenna phase center is not necessarily the geometric center of the antenna. Indeed, it is not constant, but it depends on the direction the radio signal coming in.

Source: Navipedia
**DD (Double Difference)**

\[ \Phi_{ub}^{ij} \equiv \lambda((\phi_u^i - \phi_b^i) - (\phi_u^j - \phi_b^j)) \]

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

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

\[ d_{ub}^{ij} = dt_{ub}^{ij} - dt_{ub}^{ij} = 0, \quad dT_{ub}^{ij} = dt_{ub}^{ij} - dT_{ub}^{ij} \approx 0 \]

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

**(short Baseline and same antenna type)**

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

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

**Memo for Misra & Enge:**

http://gpspp.sakura.ne.jp/diary200608.htm

*Baseline time difference between u and b satellite clock changes…*
Baseline Processing

Nonlinear-LSE:

Parameter Vector:
\[ x = (r_u^T, N_{ub}^{s_2s_1}, N_{ub}^{s_3s_1}, ..., N_{ub}^{s_ms_1})^T \]

Measurement Vector:
\[ y = (y_{t_1}^T, y_{t_2}^T, ..., y_{t_n}^T)^T \]

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

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

Solution (Static/Float):
\[ \hat{x} = x_0 + (H^T R^{-1} H)^{-1} H^T R^{-1} (y - h(x_0)) \]

\[ y_{t_k} = (\Phi_{ub,t_k}^{s_2s_1}, \Phi_{ub,t_k}^{s_3s_1}, ..., \Phi_{ub,t_k}^{s_ms_1})^T \]
\[ h_{t_k}(x) = \begin{pmatrix} \rho_{u,t_k}^{s_2s_1} - \rho_{b,t_k}^{s_2s_1} + \lambda N_{ub}^{s_3s_1} \\ \rho_{u,t_k}^{s_3s_1} - \rho_{b,t_k}^{s_3s_1} + \lambda N_{ub}^{s_ms_1} \\ \rho_{u,t_k}^{s_ms_1} - \rho_{b,t_k}^{s_ms_1} + \lambda N_{ub}^{s_ms_1} \end{pmatrix} \]
\[ H_{t_k} = \begin{pmatrix} -e_{u,t_k}^{s_2s_1}^T & \lambda & 0 & \Lambda & 0 \\ -e_{u,t_k}^{s_3s_1}^T & 0 & \lambda & \Lambda & 0 \\ M & M & M & O & M \\ -e_{u,t_k}^{s_ms_1}^T & 0 & 0 & \Lambda & \lambda \end{pmatrix} \]
\[ R_{t_k} = \begin{pmatrix} 4\sigma_{\phi}^2 & 2\sigma_{\phi}^2 & \Lambda & 2\sigma_{\phi}^2 \\ 2\sigma_{\phi}^2 & 4\sigma_{\phi}^2 & \Lambda & 2\sigma_{\phi}^2 \\ M & M & O & M \\ 2\sigma_{\phi}^2 & 2\sigma_{\phi}^2 & \Lambda & 4\sigma_{\phi}^2 \end{pmatrix} \]

\( r_b \) : Fixed Base-Station Position

It is similar to the single point positioning except for KF
Effect of Baseline Length

RMS Error:
- BL=0.3 km: E: 0.2cm, N: 0.6cm, U: 1.0cm, Fix Ratio: 99.9%
- BL=13.3 km: E: 2.2cm, N: 2.4cm, U: 10.6cm, Fix Ratio: 94.2%
- BL=32.2 km: E: 10.0cm, N: 12.0cm, U: 30.2cm, Fix Ratio: 64.3%
- BL=60.9 km: 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-L$^3$, Modified Cholesy Decomposition, Null Space, FAST, OMEGA, ...
**ILS (Integer Least Square Estimation)**

**Problem:**

\[
x = (a^T, b^T)^T, \ H = (A, B)
\]

\[
y = Hx + v = Aa + Bb + v
\]

\[
\hat{x} = \text{arg min}_{a \in \mathbb{Z}^n, b \in \mathbb{R}^m} (y - Hx)^T Q_y^{-1} (y - Hx)
\]

**Strategy:**

(1) Conventional LSE

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

(2) **Search Integer Vector** with Minimum Squared Residuals

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

(3) Improve solution

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

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

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

\[
\begin{align*}
\hat{z} &= Z^T \hat{a}, \quad Q_{\hat{z}} = Z^T Q_a Z \\
\hat{z} &= \arg\min_{z \in \mathbb{Z}^n} (\hat{z} - z)^T Q_{\hat{z}}^{-1} (\hat{z} - z) \\
\hat{a} &= Z^{-T}\hat{z}
\end{align*}
\]
Performance of LAMBDA

![Graph showing execution time vs number of integer ambiguities with and without decorrelation. The graph includes a legend indicating blue dots for with decorrelation and green dots for without decorrelation. The execution time is measured in milliseconds.](image)

(N : Number of Integer Ambiguities)

(Pentium 4 3.2GHz, Intel C/C++ 8.0)
RTK (Real-Time Kinematic)

- **Technique with Baseline Processing**
  - 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 cm + 1ppm x BL RMS (Horizontal)
  - Applications:
    - Land Survey, Construction Machine Control, Precision Agriculture etc.

![Diagram showing Reference Station, Communication Link, and Rover Receiver]
RTK Application (1)

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

RTK Application (2)

http://www.drotek.com

http://www.emlid.com
South *Iwate* buoy
- 10km offshore
- Depth 200m

14:46 Earthquake
14:53 First detected Tsunami motion
15:12 Tip of Tsunami wave

*Source: Port and Airport Research Institute*
Smart Construction

• Computer aided construction
Precision Farming

• Precision farming resolves the issue in decreasing farm family

* Agricultural management
* Low cost receiver
* Amateur can control
* Improvement of harvest
* Improvement of quality
* Autonomous helicopter
Quality of Big data

- Road condition monitoring
- Traffic information in big disaster

Accuracy improves the quality of Big data
Autonomous car with precise map

* Autonomous car
* Smart control
Recent Test: RTK on the wall

Monitoring for structure deformations

Moves antenna close to the wall
Recent Test: Running

Height series

Horizontal
Network RTK (NRTK)

• 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, JENOBa, Terasat
Concept of NRTK

Network of Individual Reference Stations

To cover a large area with single reference stations to run RTK, we need multitude of points and still we have huge gaps between the points.

The Solution is Network RTK (NRTK)!

The same area is covered with much less number of points using the Network RTK concept. All the area is covered with no gaps.

Source: GEO++
Relationship between Errors

Several interpolation algorithms
Japanese GEONET

(http://terras.gsi.go.jp/ja/index.htm)
Actual Steps of RTK

• After this summer school, please check the followings regarding the process of RTK to deepen your understanding!

1. Generating “double difference”
2. Finding “integer ambiguities”
3. Baseline processing
1. DD (Double Difference)

\[ \Phi_{ub}^{ij} = \lambda((\phi_u^i - \phi_b^i) - (\phi_u^j - \phi_b^j)) \]

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

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

\[ dt_{ub}^{ij} = dt_{u}^{ij} - dt_{b}^{ij} = 0, \quad dT_{ub}^{ij} = dT_{ub}^{i} - dT_{ub}^{j} \approx 0 \]

\[ B_{ub}^{ij} = (\phi_{u,0}^i - \phi_0^i + N_u^i) - (\phi_{b,0}^i - \phi_0^i + N_b^i) - (\phi_{u,0}^j - \phi_0^j + N_u^j) - (\phi_{b,0}^j - \phi_0^j + N_b^j) + (\phi_{b,0}^i - \phi_0^i + N_b^i) = N_{ub}^{ij} \]

(short Baseline and same antenna type)

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

Without reference station, it is impossible to remove “receiver and satellite clock error” completely! Generate new observation which means double difference.

Why do we say the baseline limitation of RTK? (10-100 km or more) It strongly depends on each RTK engine!

Memo for Misra & Enge:
http://gpspp.sakura.ne.jp/diary200608.htm

Without reference station, it is impossible to remove “receiver and satellite clock error” completely! Generate new observation which means double difference.
2. Integer Ambiguity Resolution

Once you can resolve integer N in carrier phase double difference, you get accurate position about 1 cm.

It can be imagine that the pseudo-range (code) accuracy is quite important.

Code-phase is noisy (1 m-) but absolute distance

Carrier-phase is accurate but includes integer ambiguity

\[
P_{sv1_{-}sv2_{rov\_ref}} = r_{sv1_{-}sv2_{rov\_ref}} + \epsilon_{p,rov\_ref}^{sv1_{-}sv2}
\]

\[
\phi_{sv1_{-}sv2_{rov\_ref}} = r_{sv1_{-}sv2_{rov\_ref}} + N_{sv1_{-}sv2_{rov\_ref}} + \epsilon_{\phi,rov\_ref}^{sv1_{-}sv2}
\]
3. Test results on the rooftop
- double difference of 10 m baseline-

1. Reference satellite GPS PRN 16 and target satellite is GPS PRN 8
2. Which is code-phase double difference?
3. If you subtract from right to left, what happen?

\[ P_{rov_{ref}}^{sv1_{sv2}} = r_{rov_{ref}}^{sv1_{sv2}} + \epsilon_{p,rov_{ref}}^{sv1_{sv2}} \]
\[ \phi_{rov_{ref}}^{sv1_{sv2}} = r_{rov_{ref}}^{sv1_{sv2}} + N_{rov_{ref}}^{sv1_{sv2}} + \epsilon_{\phi,rov_{ref}}^{sv1_{sv2}} \]

Unit is meter in y axis
4. (Carrier DD) - (Code DD)

The unit is **meter**  
Divided by wavelength  
0.19029 m… (L1)

The unit is **cycle**

Probably, we guess the integer ambiguity between PRN16 and PRN8 is about - 40 ?  
In fact, the average of this right results was - 41.3
5. What is the correct ambiguity?

- “Integer least square method” tells us “– 42” in a single epoch!
- If you know the 3 or more ambiguities, you can estimate the user position with the level of carrier phase because only 3 unknowns remains.
- Then, \((dx, dy, dz)\) can be estimated and finally,
- \((X_{user}, Y_{user}, Z_{user}) = (X, Y, Z) + (dx, dy, dz)\)
6. Test results \((dx, dy, dz)\)

- Std. = 2.8 mm
- Std. = 4.0 mm
- Std. = 3.4 mm
7. Convert to horizontal positions

I am repeating myself, RTK tells you only dx, dy, dz. You have to decide the precise reference positions!

Enlarged view of the very small plot shown in the bottom-right corner.

(X, Y, Z)
Reference sta.
## Difference between expensive and low-cost receiver

<table>
<thead>
<tr>
<th>Feature</th>
<th>Survey-grade receiver</th>
<th>Low-cost receiver</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost</td>
<td>$100,00〜</td>
<td>$100〜</td>
</tr>
<tr>
<td>Multiple GNSS</td>
<td>Perfect</td>
<td>BeiDou or Glonass Other are OK</td>
</tr>
<tr>
<td>Multiple Frequency</td>
<td>Perfect</td>
<td>L1/B1/E1/G1 only</td>
</tr>
<tr>
<td>Number of channel</td>
<td>400-500-</td>
<td>100</td>
</tr>
<tr>
<td>RTK (short baseline) + open sky</td>
<td>Perfect</td>
<td>Almost perfect</td>
</tr>
<tr>
<td>RTK (over 20 km baseline) + open sky</td>
<td>Almost perfect up to 100 km or more</td>
<td>Impossible</td>
</tr>
<tr>
<td>RTK under mid obstructed area (short)</td>
<td>Almost perfect</td>
<td>May be difficult</td>
</tr>
<tr>
<td>RTK under dense obstructed area (short)</td>
<td>Sometimes not good</td>
<td>Difficult</td>
</tr>
<tr>
<td>Accuracy of fixed position + open</td>
<td>mm</td>
<td>→</td>
</tr>
<tr>
<td>Accuracy of code position + open</td>
<td>Deci-meter</td>
<td>1-2 meter</td>
</tr>
</tbody>
</table>
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
Static PPP vs Kinematic PPP

Kinematic PPP
Station: IGS CONZ (Chile)
2010/2/27 6:28-6:45 GPST
Interval: 1 s
Magnitude of 8.6

Static PPP
Station: GEONET 0837
2009/1/1-2009/12/31
Interval: 1 day
20 cm ↔

20 cm ↔
## RTK vs. PPP

<table>
<thead>
<tr>
<th></th>
<th>RTK</th>
<th>Real-Time PPP</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coverage</strong></td>
<td>Local/Regional (&lt; 1000km)</td>
<td>Global</td>
</tr>
<tr>
<td><strong>Typical Accuracy</strong></td>
<td>1-3 cm HRMS</td>
<td>2-10 cm, much depending on orbit/clock quality</td>
</tr>
<tr>
<td><strong>Effect of Ref Movement</strong></td>
<td>Hard to separate ref and user movement</td>
<td>Less effect by distributed ref stations</td>
</tr>
<tr>
<td><strong>System Complexity</strong></td>
<td>Simple, at least one ref station</td>
<td>Complicated, need many ref stations</td>
</tr>
<tr>
<td><strong>Latency of Corrections</strong></td>
<td>~ 1 s</td>
<td>5 ~ 25 s</td>
</tr>
<tr>
<td><strong>Biases</strong></td>
<td>Basically cancelled by DD</td>
<td>Need careful handling</td>
</tr>
</tbody>
</table>

Which is better depends on AP requirement and technology level. RTKLIB offers both. They are user-selectable by option settings.
## Error source mitigation (Typical)

<table>
<thead>
<tr>
<th>Source/Error</th>
<th>SPP</th>
<th>DGNSS</th>
<th>RTK</th>
<th>PPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite clock model 1 m (rms)</td>
<td>→</td>
<td>0.0 m</td>
<td>0.0 m</td>
<td>0.01 – 0.1 m</td>
</tr>
<tr>
<td>Satellite ephemeris 1 m (rms)</td>
<td>→</td>
<td>0.0 m</td>
<td>0.0 m</td>
<td>0.01 - 0.1 m</td>
</tr>
<tr>
<td>Ionospheric delay 2-10 m (zenith) × 3 at 5°</td>
<td>1 - 2 m (zenith)</td>
<td>0.1 - 0.2 m</td>
<td>0.01 m</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Tropospheric delay 2.3-2.5m (zenith) × 10 at 5°</td>
<td>0.1 - 0.5 m (zenith)</td>
<td>0.1 - 0.2 m</td>
<td>0.01 m</td>
<td>0.01 m</td>
</tr>
<tr>
<td>Multipath (open sky) Code : 0.5-1 m Carrier : -1 cm</td>
<td>→ Code</td>
<td>→ Code</td>
<td>→ Carrier</td>
<td>→ Carrier</td>
</tr>
<tr>
<td>Receiver Noise Code : 0.1-0.5 m Carrier : 1-2 mm</td>
<td>→ Code</td>
<td>→ Code</td>
<td>→ Carrier</td>
<td>→ Carrier</td>
</tr>
<tr>
<td>Finally…</td>
<td>2-3 m</td>
<td>- 1 m</td>
<td>- 1 cm</td>
<td>- 10 cm</td>
</tr>
</tbody>
</table>
RTK and PPP

Reference station
Continuous communication
Instantaneous position
10-100km limitation

Continuous communication through satellite
Wait for 5-30 minutes
No limitation
Actual performance...

Accuracy (95%)
- SPP: 1.36m
- DGNSS: 0.44m
- RTK: 3 mm
- PPP: 3.4 cm

After convergence
Precise Ephemeris

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

• **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
- ...
## IGS Products

<table>
<thead>
<tr>
<th></th>
<th><strong>Final (IGS)</strong></th>
<th><strong>Rapid (IGR)</strong></th>
<th><strong>Ultra-Rapid (IGU)</strong></th>
<th><strong>Broadcast</strong></th>
</tr>
</thead>
<tbody>
<tr>
<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>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></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Orbit</td>
<td>15min</td>
<td>15min</td>
<td>15min</td>
<td>15min</td>
</tr>
<tr>
<td>Clock</td>
<td>Sat: 30s</td>
<td>5min</td>
<td>15min</td>
<td>15min</td>
</tr>
<tr>
<td></td>
<td>Stn: 5min</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

IGS Real-time Service

• 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://rts.igs.org
RT-PPP Performance with IGS

BKG: CLK10
18 300866439 1003.9071m
AVG=0.042m STD=0.056m RMS=0.076m
RMS: 3.8, 5.5, 7.7cm

BKG: CLK11 (GPS+GLO)
19 300866439 1003.9071m
AVG=0.018m STD=0.018m RMS=0.047m
RMS: 3.8, 5.0, 7.1cm

GSOC/DLR: CLK20
10 3009.9071m
AVG=0.023m STD=0.029m RMS=0.051m
RMS: 4.0, 5.2, 6.9cm

ESA/ESOC: CLK31
15 3009.9071m
AVG=0.014m STD=0.016m RMS=0.028m
RMS: 14.0, 12.1, 23.4cm

ESA/ESOC: CLK51
16 3009.9071m
AVG=0.014m STD=0.016m RMS=0.028m
RMS: 5.7, 5.4, 11.6cm

TUW: CLK61
16 3009.9071m
AVG=0.014m STD=0.016m RMS=0.028m
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
RTKLIB Practice (1)
• An Open Source Software Package for GNSS Positioning
  – Has been developed since 2006
  – The latest version 2.4.2 p12 distributed under BSD license
• Portable APIs and Useful APs
  – "All-in-one" package for Windows
  – CLI APs for any environments

http://www.rtklib.com or
https://github.com/tomojitakasu/RTKLIB
RTKLIB: Application

Y. Ohta et al., Quasi real-time fault model estimation for near-field tsunami forecasting base on RTK-GPS analysis: Application to the 2011 Tohoku-Oki earthquake (Mw 9.0), JGR-solid earth, 2012
## RTKLIB: History

<table>
<thead>
<tr>
<th>Year/Version</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006/4 v.0.0.0</td>
<td>First version for RTK+C program lecture</td>
</tr>
<tr>
<td>2007/1 v.1.0.0</td>
<td>Simple post processing AP</td>
</tr>
<tr>
<td>2008/7 v.2.1.0</td>
<td>Add APs, support medium-range</td>
</tr>
<tr>
<td>2009/1 v.2.2.0</td>
<td>Add real-time AP, support NTRIP, start to distribute as <strong>Open Source S/W</strong></td>
</tr>
<tr>
<td>2009/5 v.2.2.1</td>
<td>Support RTCM, NRTK, many receivers</td>
</tr>
<tr>
<td>2009/12 v.2.3.0</td>
<td>Support GLONASS, several receivers</td>
</tr>
<tr>
<td>2010/8 v.2.4.0</td>
<td>Support PPP Real-time/Post-processing PPP and Long-baseline RTK (&lt;1000 km)</td>
</tr>
<tr>
<td>2011/6 v.2.4.1</td>
<td>Support QZSS, JAVAD receiver, ...</td>
</tr>
<tr>
<td>2013/4 v.2.4.2</td>
<td>Support Galileo, Enable BeiDou, ...</td>
</tr>
<tr>
<td>2016/12 v.2.4.3</td>
<td>TBD</td>
</tr>
</tbody>
</table>
RTKLIB: Features

• Standard and precise positioning algorithms with:
  – GPS, GLONASS, QZSS, Galileo, BeiDou and SBAS

• Real-time and post-processing by various modes:
  – Single, SBAS, DGPS, RTK, Static, Moving-base and PPP

• Supports many formats/protocols and receivers:
  – RINEX 2/3, RTCM 2/3, BINEX, NTRIP 1.0, NMEA0183, SP3, RINEX CLK, ANTEX, NGS PCV, IONEX, RTCA-DO-229, EMS,
  – NovAtel, JAVAD, Hemisphere, u-blox, SkyTraq, NVS, …

• Supports real-time communication via:
  – Serial, TCP/IP, NTRIP and file streams
RTKLIB: GUI APs

RTKLIB

RTKNAVI

RTKGET

RTKPOST

RTKCONV

STRSVR

RTKPPLOT

NTRIPSRCBROWS
RTKLIB: CLI APs

- **RNX2RTKP (rnx2rtkp)**
  Post-processing Positioning

- **RTKRCV (rtkrcv)**
  Real-time Positioning

- **CONVBIN (convbin)**
  RINEX Translator

- **STR2STR (str2str)**
  Stream Server

- **POS2KML (pos2kml)**
  Google Earth Converter
RTKLIB: Package Structure

rtklib_2.4.2.zip

/src
  : Source programs of RTKLIB libraries
/rcv
  : Source programs depending on GPS/GNSS receiv.
/bin
  : Executable binary APs and DLLs for Windows
/data
  : Sample data for APs
/app
  : Build environment for APs

/rtknavi
  : RTKNAVI (GUI)
/strsvr
  : STRSVR (GUI)
/rtkpost
  : RTKPOST (GUI)
/rtkpost_mkl
  : RTKPOST_MKL (GUI)
/rtkplot
  : RTKPLOT (GUI)
/rtkconv
  : RTKCONV (GUI)
/srctblbrows
  : NTRIP source table browser (GUI)
/rtkrcv
  : RTKRCV (console)
/rnx2rtkp
  : RNX2RTKP (console)
/pos2kml
  : POS2KML (console)
/convbin
  : CONVBIN (console)
/str2str
  : STR2STR (console)
/appcmn
  : Common routines for GUI APs
/icon
  : Icon data for GUI APs
/mkl
  : Intel MKL libraries for Borland environment
/test
  : Test program and data
/util
  : Utilities
/doc
  : Document files
RTKLIB: APIs

/* matrix and vector functions */
mat(),imat(),zeros(),eye(),dot(),norm(),matcpy(),matmul(),matinv(),solve(),lsq(),filter(),smoother(),matprint(),matfprint()
/* time and string functions */
str2num(),str2time(),time2str(),epoch2time(),time2epoch(),gpst2time(),time2gpst(),timeadd(),timediff(),gpst2utc(),utc2gpst(),
timeget(),time2doy(),adjgpsweek(),tickget(),sleepms()
/* coordinates functions */
ecef2pos(),pos2ecef(),ecef2enu(),enu2ecef(),coven(),covecef(),xyz2enu(),geoidh(),loaddatump(),tokyo2jgd(),jgd2tokyo()
/* input/output functions */
readpcv(),readpos(),sortobs(),uniqeph(),screent()
/* positioning models */
eph2pos(),geph2pos(),satpos(),satposv(),satposiode(),satazel(),geodist(),dops(),ionmodel(),ionmapf(),tropmodel(),tropmapf(),
antmodel(),csmooth()
/* single-point positioning */
pntpos(),pntvel()
/* rinex functions */
readrnx(),readrnx(),outrnxobsh(),outrnxnavh(),outrnxnavb(),uncompress(),convrnx()
/* precise ephemeris functions */
readsp3(),readsap(),eph2posp(),satposp()
/* receiver raw data functions */
getbitu(),getbits(),crc32(),crc24q(),decode_word(),decode_frame(),init_raw(),free_raw(),input_raw(),input_rawf(),input_oem4(),
input_oem3(),input_ubx(),input_ss2(),input_cres(),input_oem4f(),input_om3f(),input_ubxf(),input_ss2f(),input_cresf()
/* rtcm functions */
init_rtcm(),free_rtcm(),input_rtcmt2(),input_rtcmt3(),input_rtcmt2f(),input_rtcmt3f()
/* solution functions */
readsol(),readsol(),outsolheads(),outsols(),outsolexs(),outsolexh(),outsol(),outsolex(),setsopt(),setsolformat(),
outnmea_rmc(),outnmea_gga(),outnmea_gsa(),outnmea_gsv()
/* SBAS functions */
sbssreadmsg(),sbsreadmsgt(),sbsoutmsg(),sbsupdatestat(),sbsdecode(),sbsatpos(),sbspntpos()
/* integer least-square estimation */
lambda()
/* realtime kinematic positioning */
rtkinit(),rtkfree(),rtkpos()
/* post-processing positioning */
postpos(),postposopt(),readopts(),writeopts()
/* stream data input/output */
strinitcom(),strinit(),strlock(),strunlock(),stropen(),strclose(),strread(),strwrite(),strsync(),stras(),strsum(),strsetopt(),
strgettime()
/* stream server functions */
strsvrinit(),strsvrstart(),strsvrstop(),strsvrstat()
/* rtk server functions */
rtksvrinit(),rtksvrstart(),rtksvrstop(),rtksvrstat() ...
# RTKLIB: Supported Receivers

<table>
<thead>
<tr>
<th>Format</th>
<th>Data Message Types</th>
<th>Antenna Info</th>
<th>SBAS Messages</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>RTCM v.2.3</strong></td>
<td>Type 18, 19</td>
<td>Type 3, 22</td>
<td>Type 1, 9, 14, 16</td>
<td></td>
</tr>
<tr>
<td><strong>RTCM v.3.1</strong></td>
<td>Type 1002, 1004</td>
<td>Type 1005, 1006, 1007, 1008, 1033</td>
<td>-</td>
<td>SSR corrections</td>
</tr>
<tr>
<td><strong>NovAtel OEM4/V, OEMStar</strong></td>
<td>RANGEB, RANGECMPB</td>
<td>RAWWAAS-FRAMEB</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td><strong>NovAtel OEM3</strong></td>
<td>RGEB, RGED</td>
<td>IONB, UTCB</td>
<td>-</td>
<td>FRMB</td>
</tr>
<tr>
<td><strong>NovAtel Superstar II</strong></td>
<td>ID#23</td>
<td>ID#20, ID#21</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>u-blox LEA-4T, LEA-5T</strong></td>
<td>UBX RXM-RAW</td>
<td>UBX RXM-SFRB</td>
<td>UBX RXM-SFRB</td>
<td>UBX RXM-SFRB</td>
</tr>
<tr>
<td><strong>Hemisphere Crescent, Eclipse</strong></td>
<td>bin 96</td>
<td>bin 94</td>
<td>bin 80</td>
<td></td>
</tr>
<tr>
<td><strong>SkyTraq S1315F</strong></td>
<td>msg 0xDD (221)</td>
<td>msg 0xE0 (224)</td>
<td>msg 0xDC (220)</td>
<td></td>
</tr>
<tr>
<td><strong>JAVAD (GRIL/GREIS)</strong></td>
<td>[R*],[r*],[R*],[r*]</td>
<td>[GE],[GD],[gd]</td>
<td>[WD]</td>
<td>QZSS Data, Galileo Data</td>
</tr>
<tr>
<td><strong>Furuno GW10 II</strong></td>
<td>msg 0x08</td>
<td>msg 0x26</td>
<td>msg 0x03</td>
<td>msg 0x20</td>
</tr>
</tbody>
</table>
Multi-GNSS Support

Visibility at Tokyo by RTKPLOT

2013-06-12 10:20 GPST

# Total (39) (El>10deg)

- GPS (12)
- GLONASS (8)
- Galileo (4)
- QZSS (1)
- BeiDou (10)
- SBAS (4)
RTKLIB Practice (1)

• Install RTKLIB
• Setup Receivers and Antennas
• Use RTKLIB in Post Processing Mode
• RTKLIB in Real-Time Mode (demo)
RTK Practice

- **Post processing**: Observation and Navigation data are required (RINEX).
- **Real-Time**: Communication link and differential data reception are required (RTCM/NTRIP).
The standard for differential global navigation satellite system was defined in RTCM Special Committee 104 and its current version is Version 3. RTCM standard for differential global navigation satellite services are communication protocols between reference stations and mobile receivers which allow very high accurate positioning, when compared with positioning system without augmentation.
The NTRIP was also defined in the RTCM Special Committee 104. NTRIP stands for “Networked Transport for RTCM via Internet Protocol”. It is based on Hypertext transfer Protocol version 1.1 and the intention is to disseminate differential correction data through the internet.

https://igs.bkg.bund.de/index/index
Install RTKLIB

• Copy the following directory and files in the USB memory to your laptop PC.

   School_RTK_2017
   \RTKLIB_bin-master.zip
   \u-centersetup_v8.26.zip
   \rawdata
     \car (u-blox, NetR9, POSLVX)
     \rooftop (u-blox, SkyTraq, NetR9)

You can refer to the latest update:
https://github.com/tomojitakasu/RTKLIB
u-blox NEO-M8P

Highlights
- Centimeter-level GNSS positioning for the mass market
- Integrated Real Time Kinematics (RTK) for fast time-to-market
- Smallest, lightest, and energy-efficient RTK module
- Complete and versatile solution due to base and rover variants
- World-leading GNSS positioning technology

Product variants

<table>
<thead>
<tr>
<th>Model</th>
<th>Category</th>
<th>GNSS</th>
<th>Supply</th>
<th>Interfaces</th>
<th>Features</th>
<th>Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEO-M8P-0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NEO-M8P-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

https://www.u-blox.com/en/product/neo-m8p
Setup u-blox Receiver/u-center

• Install Support S/W to your laptop PC
  – u-blox u-center
    (u-centersetup_v8.26.zip)

u-blox NEO-M8P-2
Mini-EVK Card + antenna

u-blox u-center v8.26
micro USB
your Laptop PC
Connection

• Start u-center and select Receiver->Port
• You will see COM*. You can check your COM port in your laptop’s devise manager
• If you have any difficulties(win10), please catch us.
Firmware Check

- View->Message View->UBX->MON->VER
Baud rate Check

- View->Message View->UBX->CFG->PRT
- Please change from 9600 to 115200
If you want to change the rate...

• View->Message View->UBX->CFG->RATE
• Please change the measurement period
If you want to save the raw-data...

- View->Message View->UBX->RXM->"RAWX" and "SFRBX"
- Right click->Enable Message
u-center (my desktop movie)

• Connection
• Single point positioning
• RTK was valid using NTRIP of base station, (via same antenna, perfect condition)
• Switch from GPS/QZS/GLO to GPS/QZS/BEI

Please check them by yourself after you go back to home. If you need an information how to set the reference station, please refer to the website (GNSS TUTOR).

http://www.denshi.e.kaiyodai.ac.jp/gnss_tutor/experiment.html
• When you post-process of GNSS raw data, RINEX format is quite popular.
• You can convert u-blox/SkyTraq raw data to RINEX format using rtkconv.exe.
• In the case of Trimble T02 file, you can use “Convert To RINEX” which is available in the Trimble website.
Use RTKLIB (1)

• **Execute RTKLAUNCH.**
  RTKLIB_bin-master\bin\rtklaunch.exe

![RTKLIB v.2.4.2](image)

RTKPLOT  STRSVR  NTRIPBRS  RTEGET
RTKCONV  RTKPOST  RTKNAVI
Use RTKLIB (2)

- Execute RTKPOST by RTKLAUNCH
- Execute Menu of RTKPLOT:
  rawdata\rooftop\netr9_ref.17o and netr9_ref.nav
- Click here

1h data was obtained on 20th July 2017 using NetR9 on the rooftop.
2017/7/20 5:00:00-5:59:59 (GPST)
Use RTKLIB (3)

Satellite ID
- G: GPS
- R: GLO
- E: GAL
- J: QZS
- C: BEI
Use RTKLIB (4)

Skyplot

# of Visible Satellites and DOP
Use RTKLIB (5)

RTKPLGOT - Options

- OBS Data Options
- Solution Data Options
- Common Options
Use RTKLIB (6)

RTKPOST - Options

Setting1

Output
Single Point Positioning
Coordinate Origin

If you change the coordinate origin as a precise reference position, (35.66633461, 139.7922008, 59.741) you see bias like below.
DGNSS

- Precise rover position (LAT/LON/HGT):
  35.66627025  139.79226723  59.33
RTK-GNSS

[Image of a software interface with options for GNSS settings and a graphical representation of a point on a map.]
2 receivers were set simultaneously

- Trimble **NetR9** with Trimble antenna
- **u-blox M8P** with YOKOWO antenna

- For the equal comparison, same settings were applied.
- GPS/BEI + Instantaneous.
Similar test using u-blox

Or, netr9_rov.170
u-blox M8P results
NetR9 results
RTKLIB (my desktop movie)

• Connect u-blox M8P
• Execute RTKNAVI
• RTK was valid using NTRIP of base station (NetR9) via the same antenna under perfect condition (GQB).
• GQR was also valid but GLONASS ambiguity resolution is set OFF.

Please check them by yourself after you go back to home.
If you need an information how to set the reference station, please refer to the website (GNSS TUTOR).

http://www.denshi.e.kaiyodai.ac.jp/gnss_tutor/experiment.html
How to connect (my desktop)

Base station (Ntrip server) → Internet

Internet → Rover station
Correction data is received via internet
GNSS raw data is received via USB-Serial

You can switch Desktop to Laptop/Pad/Raspberry Pi
If you set GQR and it doesn’t fix, please try it again by changing the setting of Integer Ambiguity Res “OFF”.
u-blox M8P DGNSS (GB)

Code-phase accuracy is quite important for RTK performance.
Limited Coverage of RTK

• Normally, the coverage of RTK is 10-20km. It strongly depends on the ionospheric activity.
• But, the recent commercial RTK engine can cover up to 50-100km.
• Also, you can use VRS/FKP correction service. The commercial company produces real-time correction data (Ntrip) using several base stations.
• QZSS will provide similar correction data through the L6 signal (inside Japan). It is challenging because message bit-rate is 2Kbps.
PPP does not have limitation in area

- PPP provides precise orbit and clock of GNSS.
- It means that you have to remove ionospheric/tropospheric errors as much as possible. It takes 5-30 minutes and depends on the ionosphere model you have.
- QZSS is going to test PPP correction data through the L6 signal. In fact, we have tested it for serval years by JAXA (MADOCA).
RTKLIB Practice (2)
Car data and field test

- Car data is post-processed using RTKLIB
- Homework
- RTK field test using u-blox M8P (8 groups)
Car data

- 2017/7/19 8:24:20 – 8:57:20 (GPST)
- Total 9900 epochs in 5Hz
- Near university campus (normal urban)
- u-blox M8T and Trimble NetR9 for both Rover and reference station
- You can compare these two receivers
- Single-frequency or dual-frequency?
- What is the best setting?
Settings of u-blox M8P
$Q = 1$
If you set minimum $C/N_0$,
If you remove QZS,
If you use NetR9,
If you use dual-frequency,
Comparing two POS files (RTKPLOT)

What happens if you click “1-2”?

Just drag and drop of “poslvx.pos” into RTKPLOT

Previous test result

POSLVX result
(Post-processed RTK/IMU/Speed)
6-7 epochs were over 20-30 cm in horizontal direction
Homework

• Please try to find the best setting of RTKLIB using the u-blox data (both ref and rover).

• “Best” means highest number of fixes within 30cm based on POSLVX file.
RTK field test using M8P/M8T (Post-processed)

• Please check your memory obtained through this class. It is not difficult.
• All you need is two observation files (base and rover) + navigation file.
• Probably, Netr9 can be used as a base station. You need to obtain the observation data at rover.
• You bring your laptop with ublox receiver and antenna. You need to check the configuration of your ublox. Then, please just click record in the u-center. Or you can also use RTKLIB to record the raw-data.
Simultaneous data is required

You need to prepare the raw-data at base station to include your period at rover.

You recorded your raw-data for this period
Any questions?

nkubo@kaiyodai.ac.jp
Following pages are complements of GNSS and more details about precise positioning especially PPP including MADOCA.
Time Systems

• **Time Systems**
  
  – TAI: International Atomic Time
  – UTC: Coordinated Universal Time
  – Local Time (JST, EDT, ...)
  – UT0, UT1, UT2: Universal Time
  – GMST: Greenwich Mean Sidereal Time
  – GPS Time
  – GLONASS Time
  – ...
Time System Conversion

<table>
<thead>
<tr>
<th>TAI to UTC:</th>
<th>UTC-TAI (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{UTC} = t_{TAI} + (UTC - TAI) )</td>
<td>\begin{array}{</td>
</tr>
</tbody>
</table>

| UTC to UT1: | \( t_{UT1} = t_{UTC} + (UT1 - UTC) \) |

| UT1 to GMST: | \( GMST_{0h UT1} = 2411054841 + 864018481286 T'_u + 0.093104 T'_u^2 - 6.2 \times 10^{-6} T'_u^3 \) |

\[ GMST = GMST_{0h UT1} + r(t_{UT1} - t_{0h UT1}) \]

\[ r = 1.00273790950795 + 5.9006 \times 10^{-11} T'_u - 5.9 \times 10^{-15} T'_u^2 \]

\[ T'_u = d'_u / 36525 \quad d'_u : \text{number of days elapsed since 2000 Jan 1, 12h UT1} \]

| GPS Time to TAI: | \( t_{TAI} \approx t_{GPST} + 19s \) |

| GPS Time to UTC: | \( t_{UTC} = t_{GPST} - (\Delta t_{LS} + A_0 + A_1(t_{GPST} - t_{ot})) \) |
Coordinate Systems

• **ECEF: Earth-Centered Earth-Fixed**
  – ITRF
  – WGS 84: US (GPS)
  – PZ90: Russia (GLONASS), ...

• **ECI: Earth-Centered Inertial**
  – ICRF: International Celestial Reference Frame

• **ECI-ECEF Connection**
  – Precession/Nutation Model
  – EOP: Earth Orientation Parameters
• **International Terrestrial Reference Frame**
  - A "Realization" of Maintained by IERS
  - GPS, VLBI, SLR, DORIS Site Position/Velocity List
  - ITRF2005, ITRF2000, ITRF97, ITRF96, ...

VLBI: Very Long Baseline Interferometry
SLR: Satellite Laser Ranging
DORIS: Doppler Orbit determination and Radiopositioning Integrated on Satellite

ITRS: International Terrestrial Reference System
IERS: International Earth Rotation Service

ECEF to ECI Transformation

**ECEF (ITRF)**

**Mean of Date**

- **P** : Precession
- **N** : Nutation
- **W** : Polar Motion

\[ \text{GST} = \text{GMST} + \Delta \psi \cos \epsilon_A + 0^\circ.00264 \sin \Omega + 0^\circ.00063 \sin 2\Omega \]

\[ r_{eci} = PNR_Z(-\text{GST})WR_{ecef} \]

\[ = R_Z(\zeta_A)R_Y(-\theta_A)R_Z(z_A)R_X(-\epsilon_A)R_Z(\Delta \varphi)R_X(\epsilon_A + \Delta \epsilon)R_Z(-\text{GST})R_X(y_P)R_Y(x_P)r_{ecef} \]

(1) (2) (3)
EOP: Earth Orientation Parameters

Polar Motion:
Xp, Yp

Earth Rotation Angle:
UT1-UTC

IERS C04 Series (1962/1/1-2009/8/11)
Ellipsoid and Datum

Ellipsoid:

\[ b = a(1 - e^2) \]

\[ r_r = (x, y, z)^T \]

\[ \phi' : \text{Geocentric Latitude} \]
\[ \phi : \text{Geodetic Latitude} \]
\[ \lambda : \text{Longitude} \]
\[ h : \text{Ellipsoidal Height} \]

Lat/Lon/Height to ECEF:

\[ e^2 = f (2 - f) \]

\[ N = \frac{a}{\sqrt{1 - e^2 \sin^2 \phi}} \]

\[ r_r = \begin{pmatrix}
(N + h) \cos \phi \cos \lambda \\
(N + h) \cos \phi \sin \lambda \\
(N(1 + e^2) + h) \sin \phi
\end{pmatrix} \]

Lat/Lon/Height to ECEF:

<table>
<thead>
<tr>
<th></th>
<th>GRS 80</th>
<th>WGS 84</th>
</tr>
</thead>
<tbody>
<tr>
<td>a (m)</td>
<td>6378137</td>
<td>6378137</td>
</tr>
<tr>
<td>f</td>
<td>1/298.257222 101</td>
<td>1/298.257223 563</td>
</tr>
<tr>
<td>GM (m^3/s^2)</td>
<td>3986005.000 x 10^8</td>
<td>3986004.418 x 10^8</td>
</tr>
</tbody>
</table>
Geoid

Geopotential:

\[ V(r, \phi', \lambda) = \frac{GM}{r} \left\{ 1 + \sum_{n=2}^{\infty} \sum_{m=0}^{n} \left( \frac{a}{r} \right)^n \left( \bar{C}_{nm} Y_{nmc} + \bar{S}_{nm} Y_{nms} \right) \right\} \]

\( H \) : Geodetic Height

EGM96 Geoid Model
Spherical Harmonics

**Spherical harmonic functions:**

\[ Y_{n0} = Y_{n0c} \]
\[ Y_{nm_{c}} = P_{nm}(\sin \phi') \cos m\lambda \]
\[ Y_{nm_{s}} = P_{nm}(\sin \phi') \sin m\lambda \]

**Legendre function:**

\[ P_{nm} = N_{nm}P_{nm}, \quad P_{00}(x) = 1, P_{10}(x) = x \]
\[ P_{n-1,n}(x) = 0, \]
\[ P_{nn}(x) = (2n - 1)(1 - x^2)^{1/2} P_{n-1,n-1}(x) \]
\[ P_{nm}(x) = \frac{(2n - 1)xP_{n-1,m}(x) - (n + m - 1)P_{n-2,m}(x)}{n - m} \]
\[ N_{nm} = \begin{cases} 
\sqrt{2n + 1} & (m = 0) \\
\sqrt{\frac{2(2n + 1)(n - m)!}{(n + m)!}} & (m > 0) 
\end{cases} \]
Coordinates Transformation

Helmert Transformation (A to B):

\[
\begin{pmatrix}
 x \\
 y \\
 z
\end{pmatrix}_B = \begin{pmatrix}
 T_1 \\
 T_2 \\
 T_3
\end{pmatrix} + (1 + D) \begin{pmatrix}
 1 & -R_3 & R_2 \\
 R_3 & 1 & -R_1 \\
 -R_2 & R_1 & 1
\end{pmatrix} \begin{pmatrix}
 x \\
 y \\
 z
\end{pmatrix}_A
\]

- T1, T2, T3 : Translation along coordinate axis
- D : Scale factor
- R1, R2, R3 : Rotation of coordinate axis

<table>
<thead>
<tr>
<th>Coordinates</th>
<th>T1 (mm)</th>
<th>T2 (mm)</th>
<th>T3 (mm)</th>
<th>D (10⁻⁹)</th>
<th>R1 (mas)</th>
<th>R2 (mas)</th>
<th>R3 (mas)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>B</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ITRF2005</td>
<td>ITRF2000</td>
<td>0.1</td>
<td>-0.8</td>
<td>-5.8</td>
<td>0.40</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-0.2/y</td>
<td>0.1/y</td>
<td>-1.8/y</td>
<td>0.08/y</td>
<td>0.00/y</td>
<td>0.00/y</td>
</tr>
</tbody>
</table>

(Epoch 2000.0)
Ionospheric Delay

Ionospheric Delay Model:

\[ n^2 = 1 - \frac{X}{1 - iZ - \frac{Y_T^2}{2(1 - X - iZ)}} \pm \sqrt{\frac{Y_T^4}{4(1 - X - iZ)^2} + Y_L^2} \approx 1 - X = 1 - \frac{f_N^2}{f^2} \text{ (L-band)} \]

: Appleton-Hartree Formula

\[ n = \sqrt{1 - \frac{f_N^2}{f^2}} \approx 1 - \frac{f_N^2}{2f^2} = 1 - 40.30N_e/f^2 \]

\[ f_N^2 = \frac{N_e e^2}{4\pi^2 \varepsilon_0 m_e} \text{ : plasma frequency} \]

\[ I_r^s \approx \int 40.30N_e/f^2 dl = 40.30 \times 10^{16} \text{TEC}/f^2 \]

TEC: Total Electron Content

Electron Density \((N_e)\):

IRI-2007 model: 2009/7/31 0:00 Tokyo (http://modelweb.gsfc.nasa.gov/models/iri.html)
Solar Cycle

International Sunspot Number (ISN): 1700-2009
by SIDC (Solar Influences Data Analysis Center) in Belgium (http://sidc.oma.be)

Solar Cycle Prediction: Cycle 24
by NOAA SWPC (Space Weather Prediction Center) (http://www.swpc.noaa.gov/SolarCycle)
## 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>
<thead>
<tr>
<th>LC</th>
<th>Coefficients</th>
<th>Wave Length (cm)</th>
<th>Ionos Effect wrt L1</th>
<th>Typical Noise (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LC</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a</td>
<td>b</td>
<td>c</td>
<td>d</td>
<td></td>
</tr>
<tr>
<td>L1 L1 Carrier-Phase</td>
<td>1 0 0 0</td>
<td>19.0</td>
<td>1.0</td>
<td>0.3</td>
</tr>
<tr>
<td>L2 L2 Carrier-Phase</td>
<td>0 1 0 0</td>
<td>24.4</td>
<td>1.6</td>
<td>0.3</td>
</tr>
<tr>
<td>LC/L3 Iono-Free Phase</td>
<td>( C_1 ) ( C_2 ) 0 0</td>
<td>-</td>
<td>0.0</td>
<td>0.9</td>
</tr>
<tr>
<td>LG/L4 Geometry-Free Phase</td>
<td>1 -1 0 0</td>
<td>-</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>WL Wide-Lane Phase</td>
<td>( \lambda_W/\lambda_1 ) (-\lambda_W/\lambda_2 ) 0 0</td>
<td>86.2</td>
<td>1.3</td>
<td>1.7</td>
</tr>
<tr>
<td>NL Narrow-Lane Phase</td>
<td>( \lambda_N/\lambda_1 ) ( \lambda_N/\lambda_2 ) 0 0</td>
<td>10.7</td>
<td>1.3</td>
<td>1.7</td>
</tr>
<tr>
<td>MW Melbourne-Wübben</td>
<td>( \lambda_W/\lambda_1 ) (-\lambda_W/\lambda_2 ) ( \lambda_N/\lambda_1 ) ( \lambda_N/\lambda_2 )</td>
<td>86.2</td>
<td>0.0</td>
<td>21.0</td>
</tr>
<tr>
<td>MP1 L1-Multipath</td>
<td>2( C_2 ) -1 (-2C_2 ) 1 0</td>
<td>-</td>
<td>0.0</td>
<td>30.0</td>
</tr>
<tr>
<td>MP2 L2-Multipath</td>
<td>(-2C_1 ) ( 2C_1 -1 ) 0 1</td>
<td>-</td>
<td>0.0</td>
<td>30.0</td>
</tr>
</tbody>
</table>

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

Ionospheric Delay Model:

\[ I = \frac{40.30 \times 10^{16}}{f^2} TEC \approx \frac{1}{\cos z'} \frac{40.30 \times 10^{16}}{f^2} \times VTEC(t, \phi_{pp}, \lambda_{pp}) \]

IPP Position/Slant Factor:

\[ z = \frac{\pi}{2} - El \]
\[ z' = \arcsin \frac{R_e \sin z}{R_e + H_{ion}}, \alpha = z - z' \]
\[ \phi_{pp} = \arcsin (\cos \alpha \sin \phi + \sin \alpha \cos \phi \cos Az) \]
\[ \lambda_{pp} = \lambda + \arcsin \frac{\sin \alpha \sin Az}{\phi_{pp}} \]
Ionospheric TEC Grid

(IGS TEC Final, GPS Time)
Tropospheric Delay

Tropospheric Delay Model:

\[ T = m_h(\text{El})ZHD + m_w(\text{El})ZW D \]

\[ ZHD = \frac{0.0022768p}{1 - 0.00266\cos2\phi - 2.8 \times 10^{-7} H} \]

- \( ZWD \): Zenith Hydrostatic Delay (m)
- \( ZW D \): Zenith Wet Delay (m)
- \( m_h(\text{El}) \): Hydrostatic Mapping Function
- \( m_w(\text{El}) \): Wet Mapping Function

ZWD to PWV (Precipitable Water Vapor):

\[ T_m = 70.2 + 0.72T \]

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

- \( R_v = 461, k_1 = 77.6, k_2 = 71.98, k_3 = 3.754 \times 10^5 \)
- \( m_v = 18.0152, m_d = 28.9644 \)
Mapping Function

\[
m(El) = \frac{1 + \frac{a}{b}}{1 + \frac{1 + c}{\sin(El)}} + \frac{\sin(El) + \frac{a}{b}}{\sin(El) + \frac{b}{\sin(El) + c}}
\]

\[a, b, c\] : Mapping Function Coefficients

NMF, GMF, VMF1

Hydrostatic

Wet

(2006/1/1-2007/12/31, TSKB, El=5deg)
Antenna Phase Center 1

Receiver Antenna Phase Center:

Antenna Phase Center

Antenna Reference Point (ARP)

Antenna Phase Center Offset

$d_{r, pco}$

$d_{r, pcv}$

Antenna Phase Center Variation (PCV)

Choke-Ring Type

Zero-Offset Type

L1

L2

IGS Absolute Antenna Model (IGS05.PCV)
**Antenna Phase Center 2**

**Satellite Antenna Phase Center:**

Satellite Antenna Phase Center:

- **Mass Center of Satellite**
- **Antenna Phase Center**
- **Antenna Phase Center Offset**
- **Nadir Angle**

**Satellite Coordinate to ECEF:**

\[
E_{sat\rightarrow ecef} = (e^s_x, e^s_y, e^s_z)
\]

\[
e^s_z = -\frac{r^s}{\|r^s\|}, e_s = \frac{r_{sun} - r^s}{\|r_{sun} - r^s\|}
\]

\[
e^s_y = \frac{e^s_z \times e^s_s}{\|e^s_z \times e_s\|}, e^s_x = e^s_y \times e^s_z
\]

- **Earth**
- **Sun**
- **Satellite**
Site Displacement

• Displacement of Ground-Fixed Receiver
  – Solid Earth Tide
  – Ocean Tide Loading (OTL)
  – Pole Tide
  – Atmospheric Loading

• Tide Model
  – $M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_1, M_m, S_{sa}$
Earth Tides

Earth Tides Model

IERS Conventions 1996 + NAO99.b, 2007/1/1-1/31, TSKB
Phase Wind-up Effect

- Relative rotation between satellite and receiver antennas effect to the measured phase of RHCP signal.

\[
d_{pw} = \lambda \left\{ \text{sign}(e_r \cdot (D_s \times D_r)) \arccos \left( \frac{D_s \cdot D_r}{\|D_s\| \|D_r\|} \right) / 2\pi + N \right\}
\]

\[
D_s = e_x^s - e_u^s(e_u^s \cdot e_x^s) - e_u^s \times e_y^s
\]

\[
D_r = e_{r,x} - e_r^s(e_r^s \cdot e_{r,x}) + e_{r,y}^s \times e_{r,y}
\]

\[
E_{ecef \rightarrow enu} = (e_{r,x}^T, e_{r,y}^T, e_{r,z}^T)^T
\]

- Dipole Vector of Satellite Antenna
- Dipole Vector of Receiver Antenna
- ECEF to ENU Transformation Matrix
- LOS Vector from Receiver to Satellite Antenna
- Integer Ambiguity
Relativistic Effects

• **Satellite/Receiver:**
  – Frequency Shift by Earth Gravity (General Rel.)
  – Frequency Shift by Sun/Moon Gravity (General Rel.)
  – Second-Order Doppler-Shift by Motion (Special Rel.)

• **Signal Propagation:**
  – Sagnac Correction (Rotating Coordinates)
  – Shapiro Time Delay Effect
  – Lense-Thirring Drag

Satellite Clock Bias/Rate Correction
+ Periodic Term:

\[ d_{rel} = -\frac{2r^s \cdot v^s}{c^2} \]
Real-Time PPP via QZSS LEX

GPS  GLONASS  Galileo  QZSS

Reference Stations

MGM-Net

MADOCA
Precise Orbit/Clock Estimation

LEX Signal
~ 1.7 Kbit/s

PPP Users
Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis

- For real-time PPP service via QZSS LEX
  - Many (potential) applications over global area
- Precise orbit/clock for multi-GNSS constellation
  - Key-technology for future cm-class positioning
- Brand-new codes developed from scratch
  - Optimized multi-threading design for recent CPU
  - As basis of future model improvements
MADOCA: Real Time Products

Real-time Products:
- Analysis software: MGRT1/MADOCA v.0.7.2 pl. MGRT2/MADOCA v.0.7.2
- Observation data: MGR/MG/M, QZSS M/G, IG/M/M (same)
- Option Settings: mngt1.conf, mg2t2.conf, mg2t1_def.conf, mg2t1_rte.conf, and outsrc_rte.conf
- Station File: MGRT1/MGRT2
- Updates: every 30 s for orbit, clock and URA, every 1 s for high-rate clock (latency: 3 - 5 s)

History:
- 2015-07-01 02:52 - MGRT1/MGRT2 excluded Satellite(008). (Ref. #123)
- 2015-07-01 03:54 - Started MGRT1/MGRT2, SSR STOP for leap second. (Ref. #289)
- 2015-07-01 03:54 - Stopped MGRT1/MGRT2. (Ref. #289)
- 2015-06-23 02:40 - Changed station info file (MGRT1/MGRT2) (before after). (Ref. #280).
- 2015-06-19 09:10 - MGRT1 excluded Satellite(008). (Ref. #123)

Contents:
- Estimation Stations
- SSR Status
- System: MGRT1 GPS MGRT1 QZSS MGRT2 GPS MGRT2 QZSS

Product Stream:
- INTRP Caster: , Port: 2101 or 80
- User-ID: MADOCA , Password: MADOCA

Product Messages:

<table>
<thead>
<tr>
<th>Mount Point</th>
<th>Products</th>
<th>RTCM Message Type</th>
<th>Update Interval</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>GPS</td>
<td>QZSS</td>
<td>Galileo</td>
</tr>
<tr>
<td>MADoca_SSR1</td>
<td>Satellite Orbit</td>
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URL of Product Files
MADOCA (4)

- QZSS-MS
- MGM-Net
- IGS
- MGEX