GNSS Training 2018

GNSS Precise Positioning and RTKLIB

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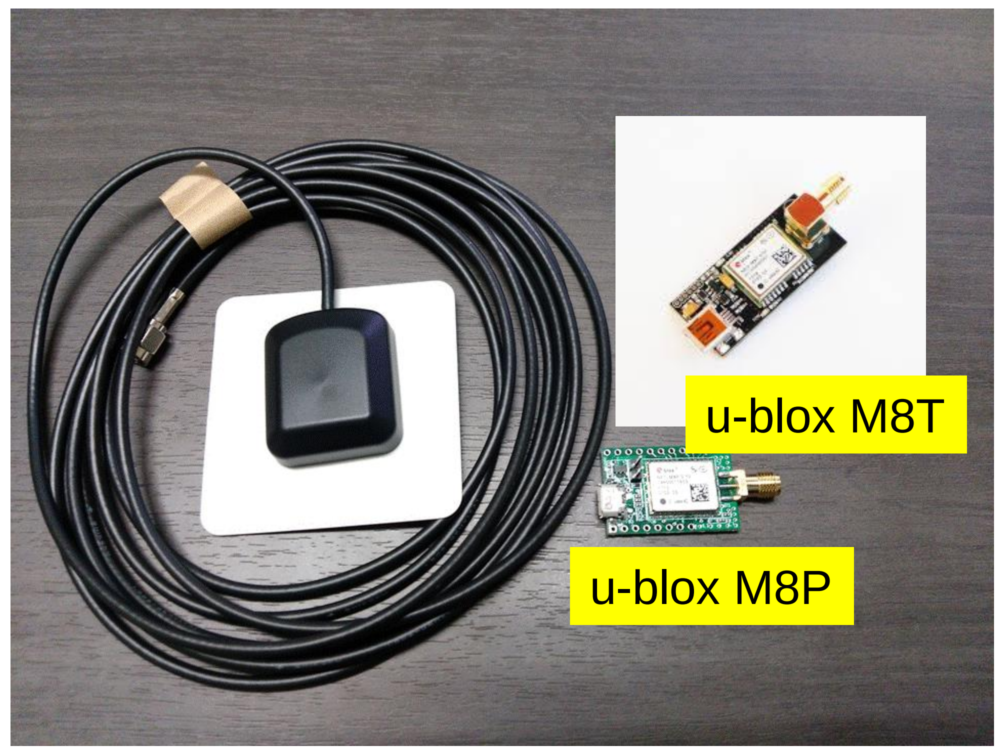
2018-01-23 ~ 2018-01-26 @AIT, Thailand

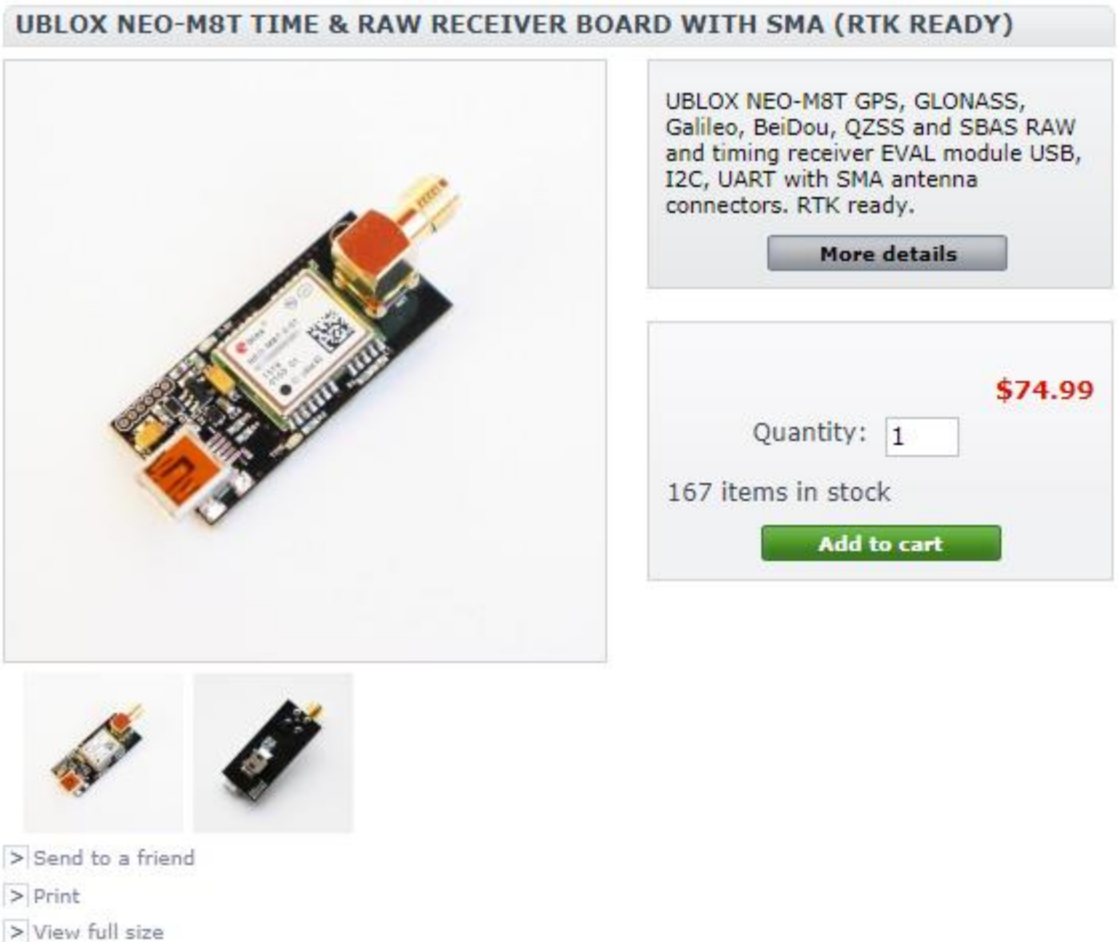
Receiver used in this training

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



You can purchase M8T

- http://www.csgshop.com/product.php?id_product=205



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)

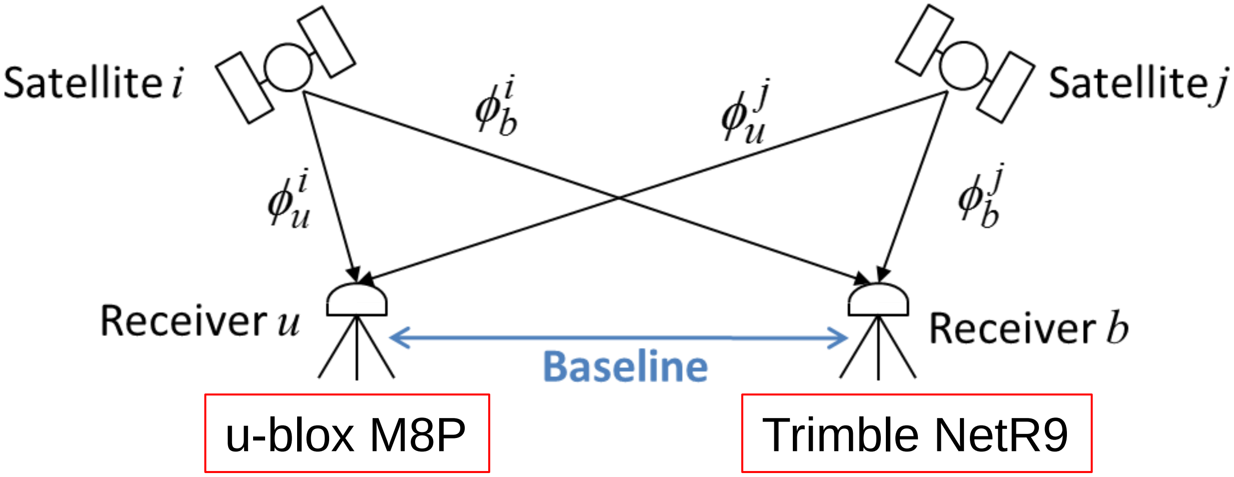
- u-blox M8P (ref/rover) + Trimble/NovAtel ant.
- Trimble NetR9 (ref/rover) + Trimble/NovAtel ant.

Kinematic raw data set (0.5h)

- u-blox M8T (ref/rover) + Trimble/NovAtel ant.
- Trimble NetR9 (ref/rover) + Trimble/NovAtel ant.

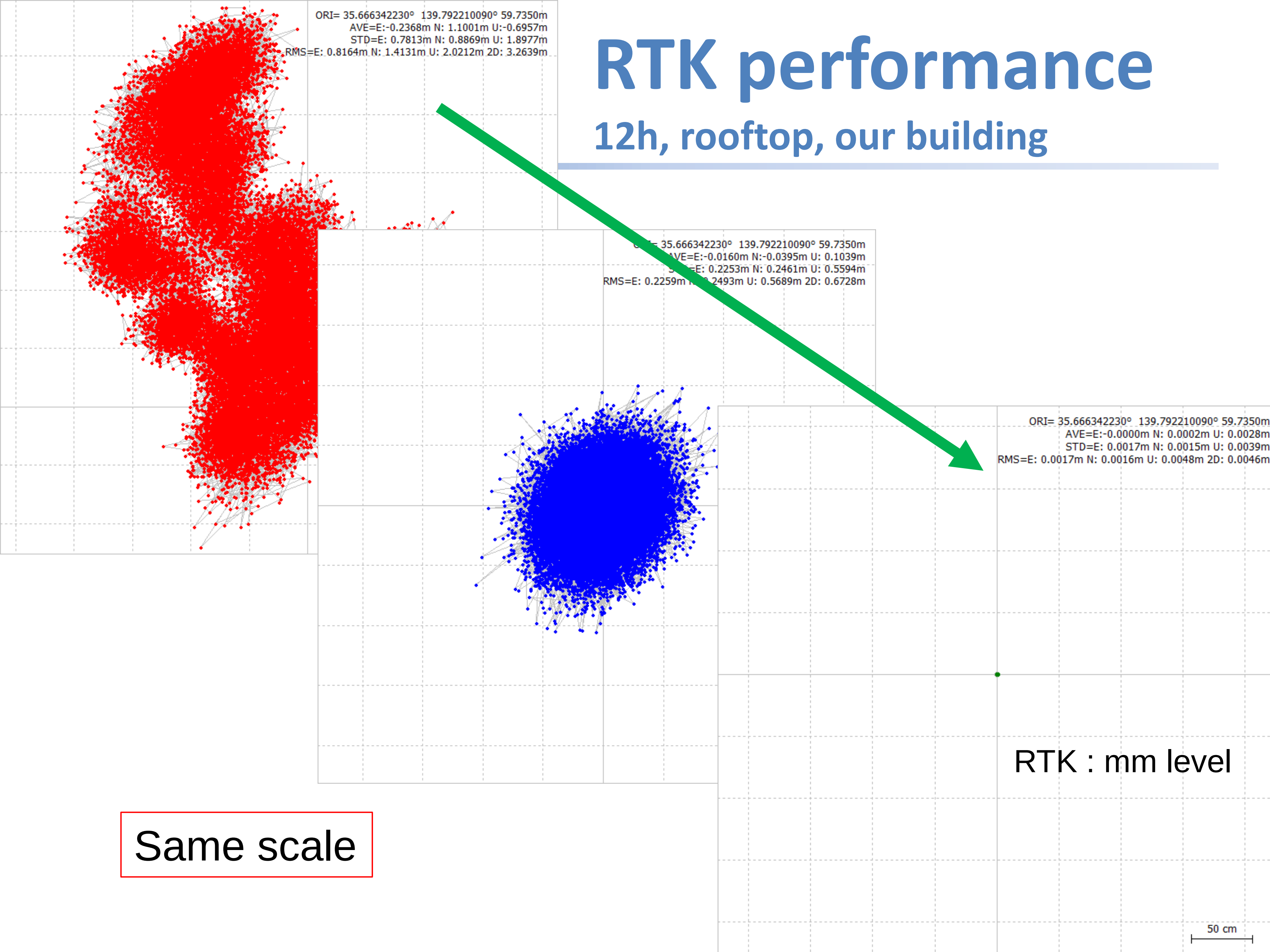
RTK DEMO

- 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.



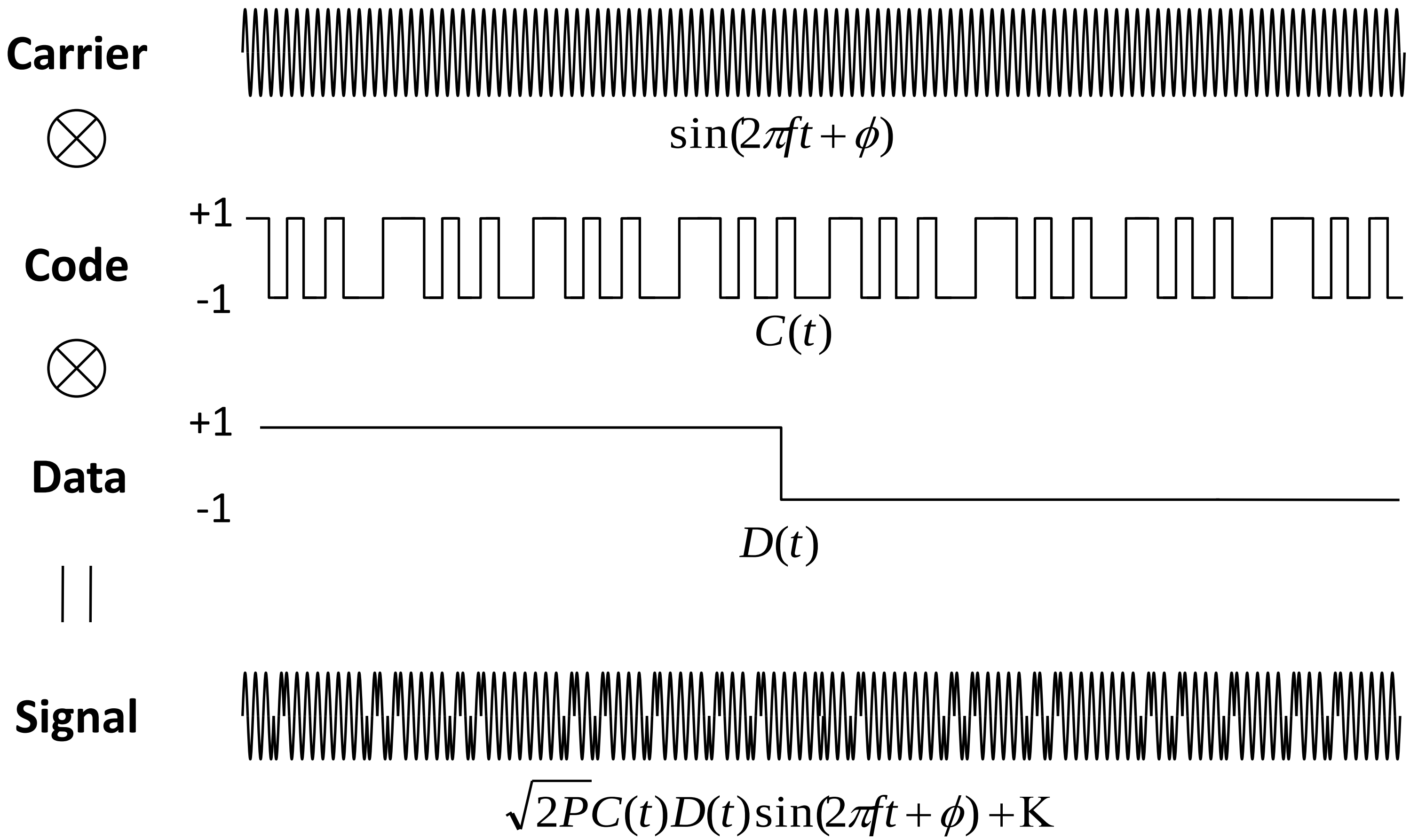
RTK performance

12h, rooftop, our building



Carrier-Phase-Based Positioning with GNSS

GNSS Signal Structure

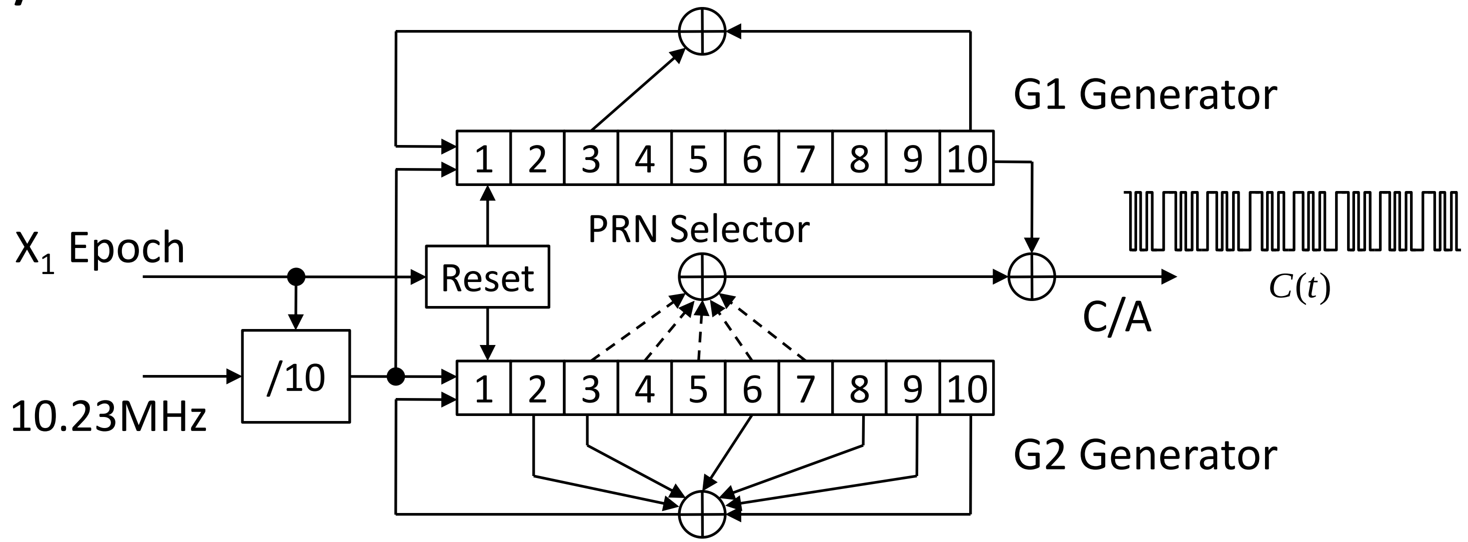


GNSS Signal Specifications

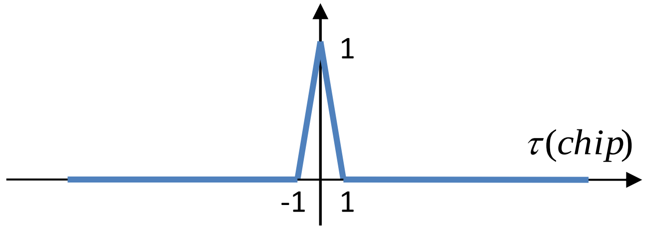
Carrier Freq (MHz)		Code	Modulation	Data Rate	GNSS
L1/E1	1575.42	C/A	BPSK (1)	50 bps	GPS, QZSS
				250 bps	QZSS (L1-SAIF), SBAS
		P(Y)	BPSK (10)	50 bps	GPS
		L1C-d/p	MBOC (6,1,1/11)	-/100 bps	GPS (III-), Galileo
		L1C-d/p	BOC (1,1)	-/100 bps	QZSS
L1	1602+0.5625K	C/A	BPSK	50 bps	GLONASS
L2	1227.60	P(Y)	BPSK (10)	50 bps	GPS
		L2C	BPSK (1)	25 bps	GPS (IIRM-), QZSS
L2	1246+0.4375K	C/A	BPSK	50 bps	GLONASS
L5/E5a	1176.45	L5-I/Q	BPSK (10)	-/100 bps	GPS (IIF-), QZSS
		E5a-I/Q	BPSK (10)	-/50 bps	Galileo
E5b	1207.14	E5b-I/Q	BPSK (10)	-/250 bps	Galileo
E6/LEX	1278.75	E6-I/Q	BPSK (5)	-/1000 bps	Galileo
		LEX	BPSK (5)	2000 bps	QZSS

Spreading (PRN) Code

GPS C/A Code Generator

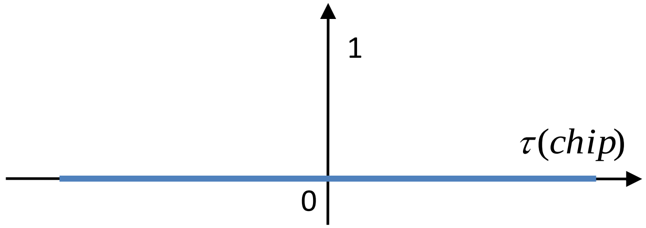


Auto-correlation function



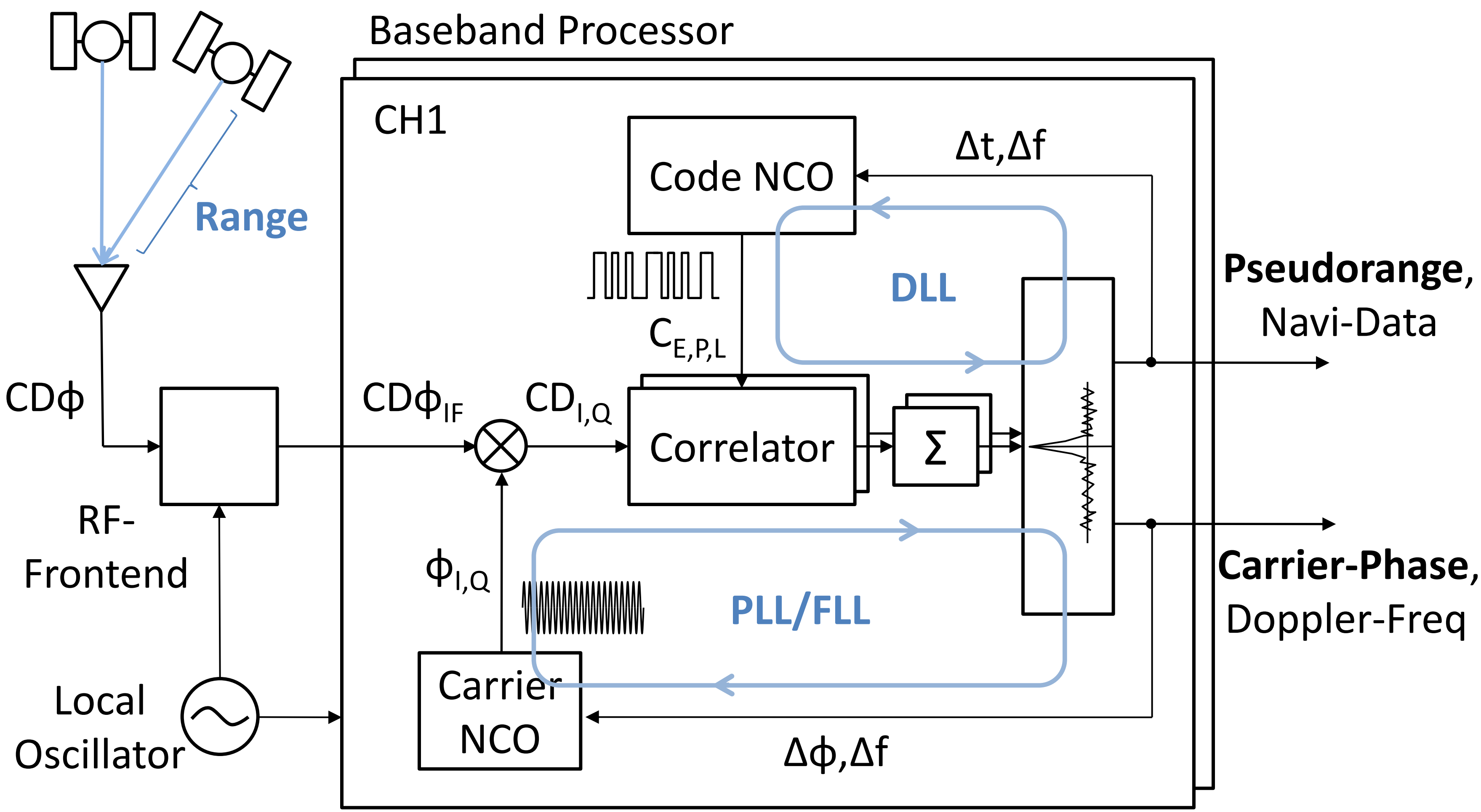
$$R(\tau) = \frac{1}{T}\int_0^T C^i(t)C^i(t-\tau)dt$$

Cross-correlation function



$$R(\tau) = \frac{1}{T}\int_0^T C^i(t)C^j(t-\tau)dt \ \ (i \neq j)$$

Carrier/Code Tracking in Receiver



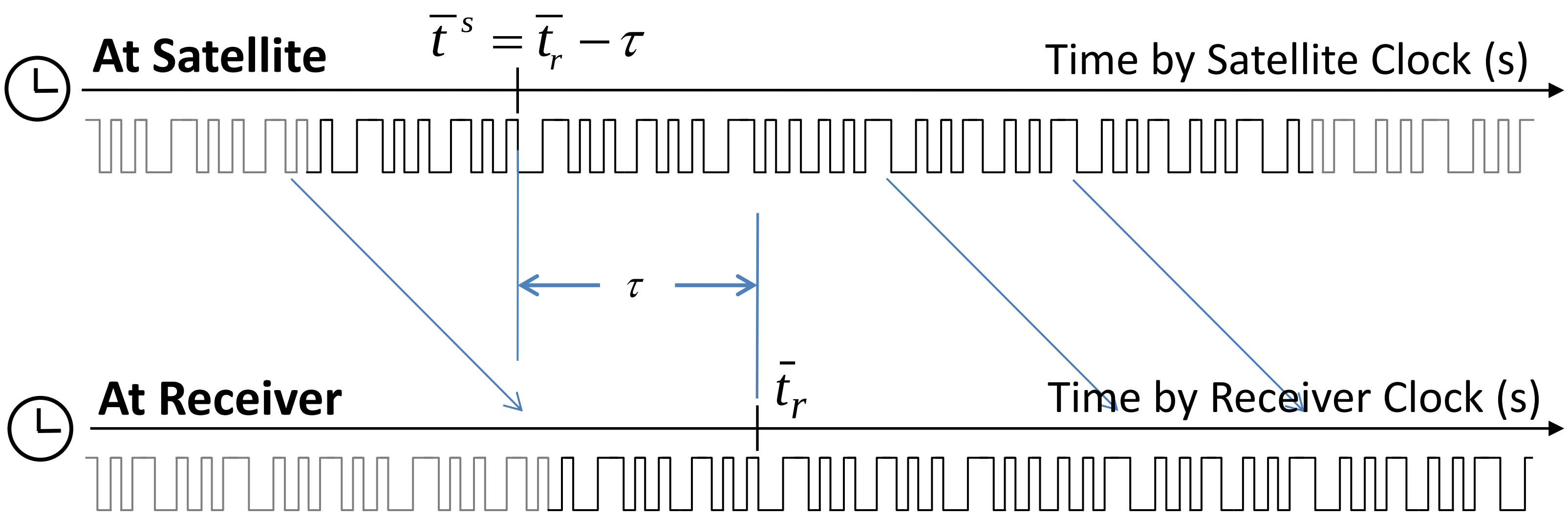
Pseudo-range (Code-phase)

Definition:

$$P_r^s \equiv c\tau = c(\bar{t}_r - \bar{t}^s)$$

(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)*



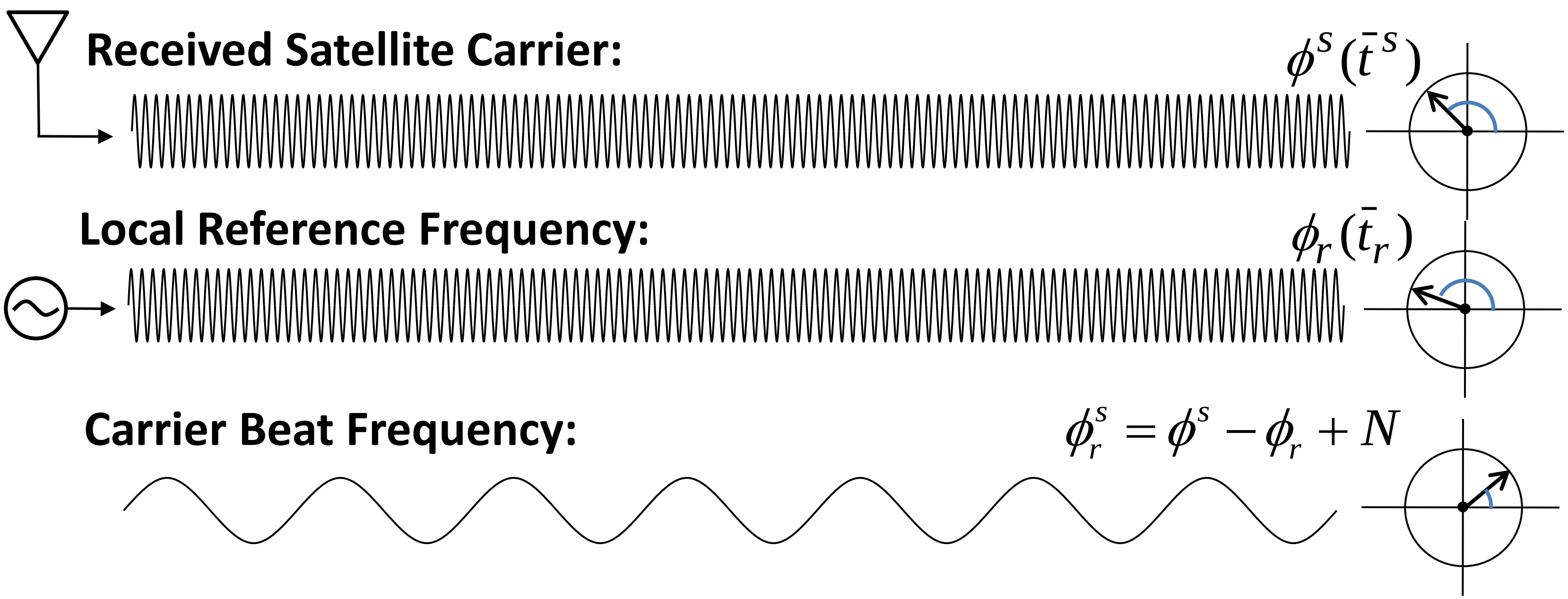
Carrier-Phase

Definition:

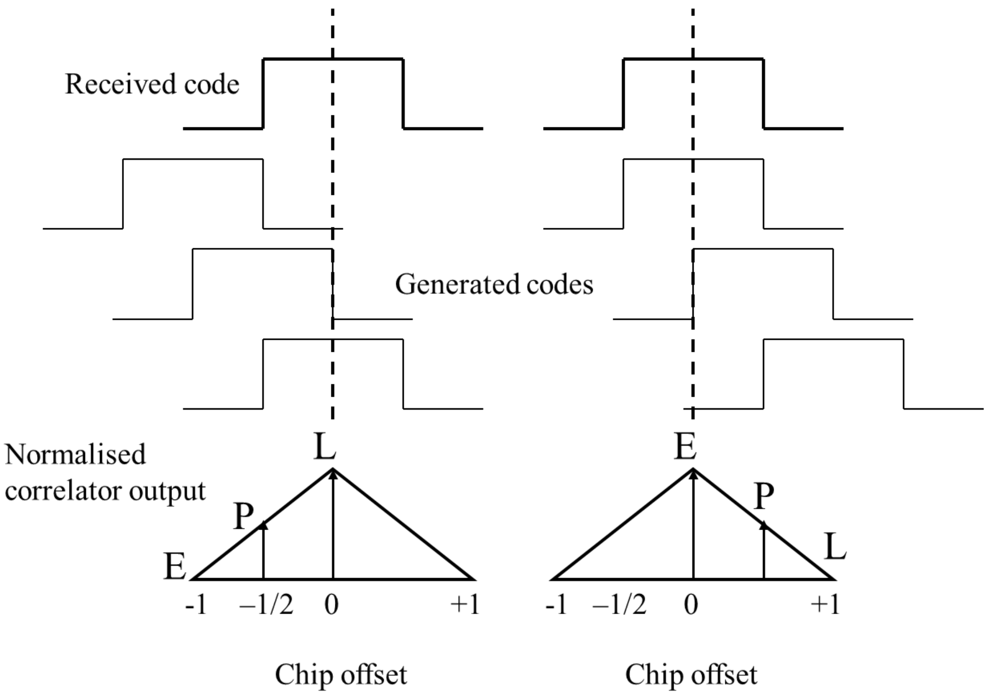
$$\phi_r^s = \phi^s - \phi_r + N$$

(cycle)

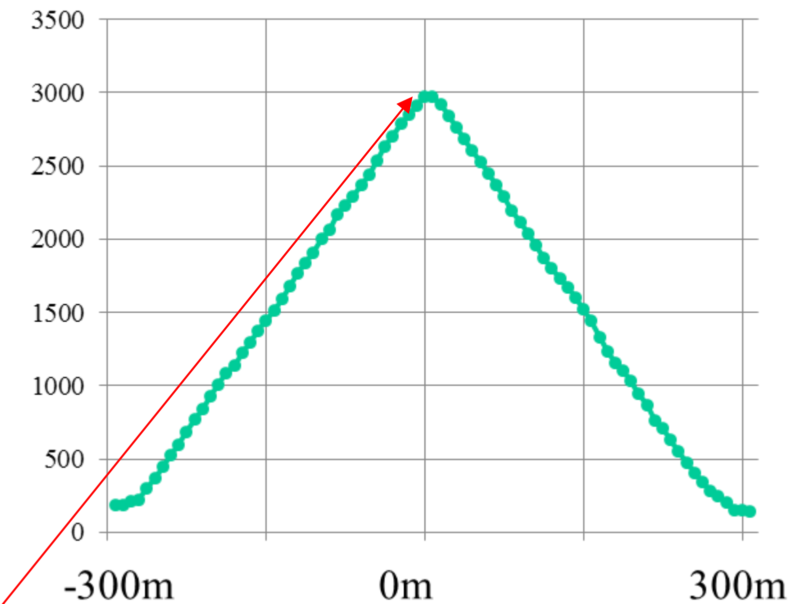
... actually being a measurement on the beat frequency between the received carrier of the satellite signal and a receiver-generated reference frequency. *(RINEX 2.10)*



How about accuracy (Code) ?

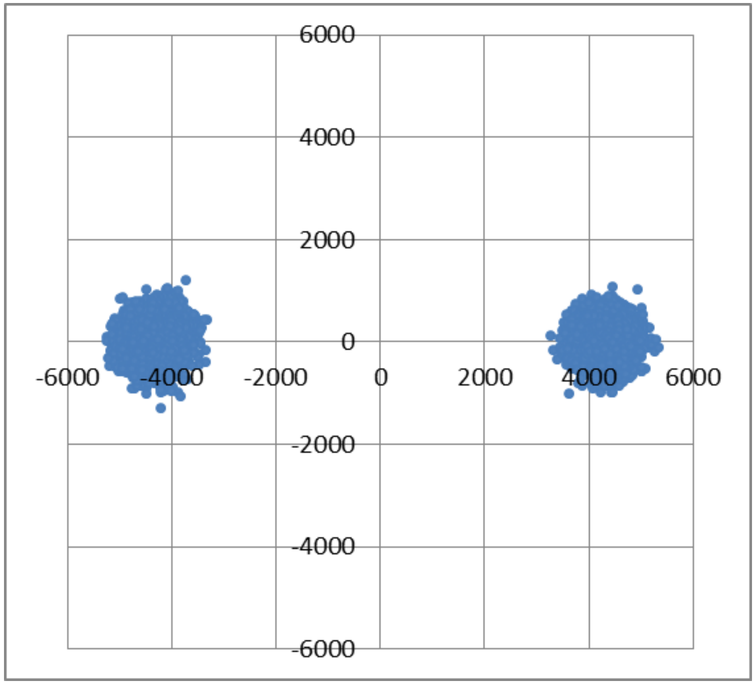


Real correlator samples (40MHz)
GPS L1-C/A : 1chip (293m)

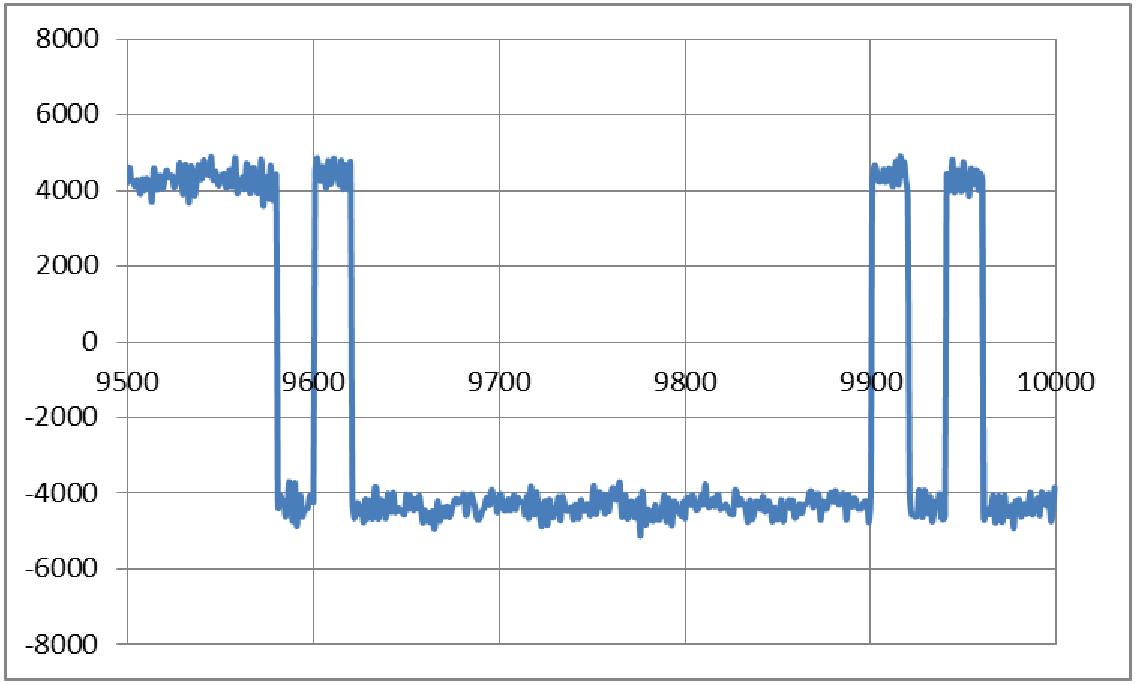


With the aid of “loop filtering + correlator characteristic”, we try to estimate the code measurements approximately desi-meter level (- 1m).

How about accuracy (Carrier) ?



I phase and Q phase (GPS L1-C/A)



I phase correlation value → Navigation data

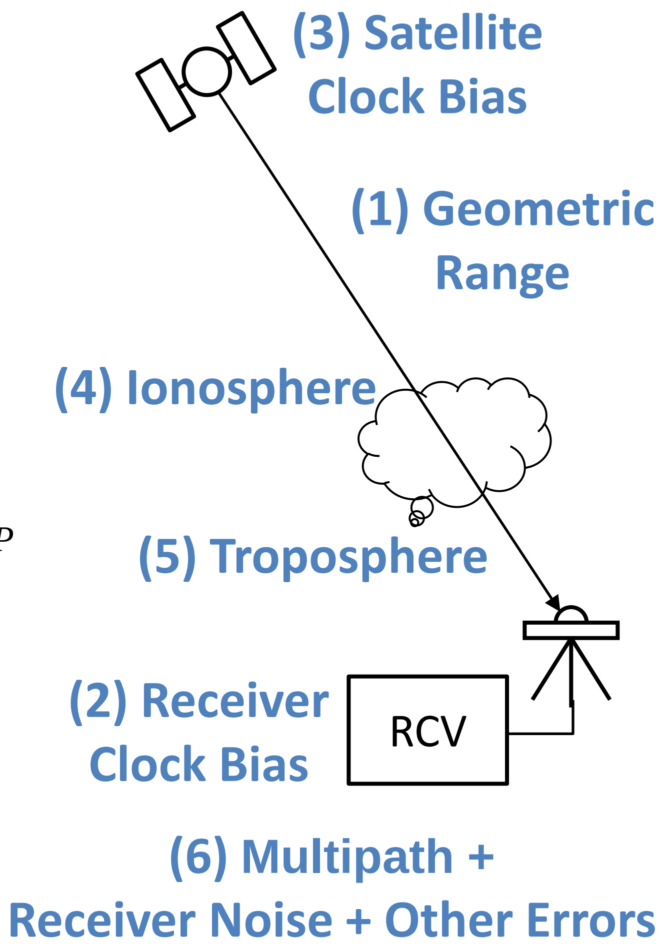
With the aid of "loop filtering + correlator characteristic", we try to estimate the carrier-phase measurements approximately mm meter level.

Code vs Carrier-Based Positioning

	Standard Positioning (code-based)	**Precise Positioning (carrier-based)**
Observables	Pseudorange (Code)	**Carrier-Phase + Pseudorange**
Receiver Noise	30 cm	3 mm
Multipath	30 cm - 30 m	1 - 3 cm
Sensitivity	High (<20dBHz)	Low (>35dBHz)
Discontinuity	No Slip	Cycle-Slip
Ambiguity	-	Estimated/Resolved
Receiver	Low-Cost (~$100)	**Expensive (~$20,000)**
Accuracy (RMS)	3 m (H), 5 m (V) (Single) 1 m (H), 2 m (V) (DGPS)	**5 mm (H), 1 cm (V) (Static) 1 cm (H), 2 cm (V) (RTK)**
Application	Navigation, Timing, SAR,...	Survey, Mapping, ...

Pseudorange Model

$$
\begin{aligned}
P_r^s &\equiv c\tau \\
&= c(\bar{t}_r - \bar{t}^s) \\
&= c((t_r + dt) - (t^s + dT^s)) + \varepsilon_P \\
&= c(t_r - t^s) + c(dt_r - dT^s) + \varepsilon_P \\
&= (\rho_r^s + I_r^s + T_r^s) + c(dt_r - dT^s) + \varepsilon_P \\
&= \underbrace{\rho_r^s}_{(1)} + c(\underbrace{dt_r}_{(2)} - \underbrace{dT^s}_{(3)}) + \underbrace{I_r^s}_{(4)} + \underbrace{T_r^s}_{(5)} + \underbrace{\varepsilon_P}_{(6)}
\end{aligned}
$$



Carrier-Phase Model (1)

Carrier-Phase:

Carrier phase measurement is accumulated Doppler frequency.

$$\phi_r^s = \phi_r(t_r) - \phi^s(t^s) + N_r^s + \varepsilon_\varphi \qquad (\phi_{r,0} = \phi_r(t_0), \phi_0^s = \phi^s(t_0))$$

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

$$= \frac{c}{\lambda}(t_r - t^s) + \frac{c}{\lambda}(dt_r - dT^s) + (\phi_{r,0} - \phi_0^s + N_r^s) + \varepsilon_\varphi \qquad \text{(cycle)}$$

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

$$= \underline{\rho_r^s + c(dt_r - dT^s) - I_r^s + T_r^s} + \lambda \underline{B_r^s} + \underline{d_r^s} + \varepsilon_\Phi \qquad \text{(m)}$$

Carrier-Phase Bias **Other Correction Terms**

Pseudorange:

$$P_r^s = \underline{\rho_r^s + c(dt_r - dT^s) + I_r^s + T_r^s} + \varepsilon_P$$

Carrier-Phase Model (2)

Carrier-Phase Bias:

$$B_r^s = \phi_{r,0} - \phi_0^s + N_r^s \qquad \text{(cycle)}$$

N_r^s : **Integer Ambiguity**

$\phi_{r,0}$: Receiver Initial Phase

ϕ_0^s : Satellite Initial Phase

Other Correction Terms:

$$d_r^s = -\boldsymbol{d}_{r,pco}{}^T \boldsymbol{e}_{r,enu}^s + \left(\boldsymbol{E}_{sat\to ecef}\boldsymbol{d}_{pco}^s\right)^T \boldsymbol{e}_r^s + d_{r,pcv} + d_{pcv}^s - \boldsymbol{d}_{disp}{}^T \boldsymbol{e}_{r,enu}^s$$

$$+ d_{pw} + d_{rel} \qquad \text{(m)}$$

$\boldsymbol{d}_{r,pco}$: Receiver Antenna Phase Center Offset

$d_{r,pcv}$: Receiver Antenna Phase Center Variation

$\boldsymbol{d}_{pco}^s$: Satellite Antenna Phase Center Offset

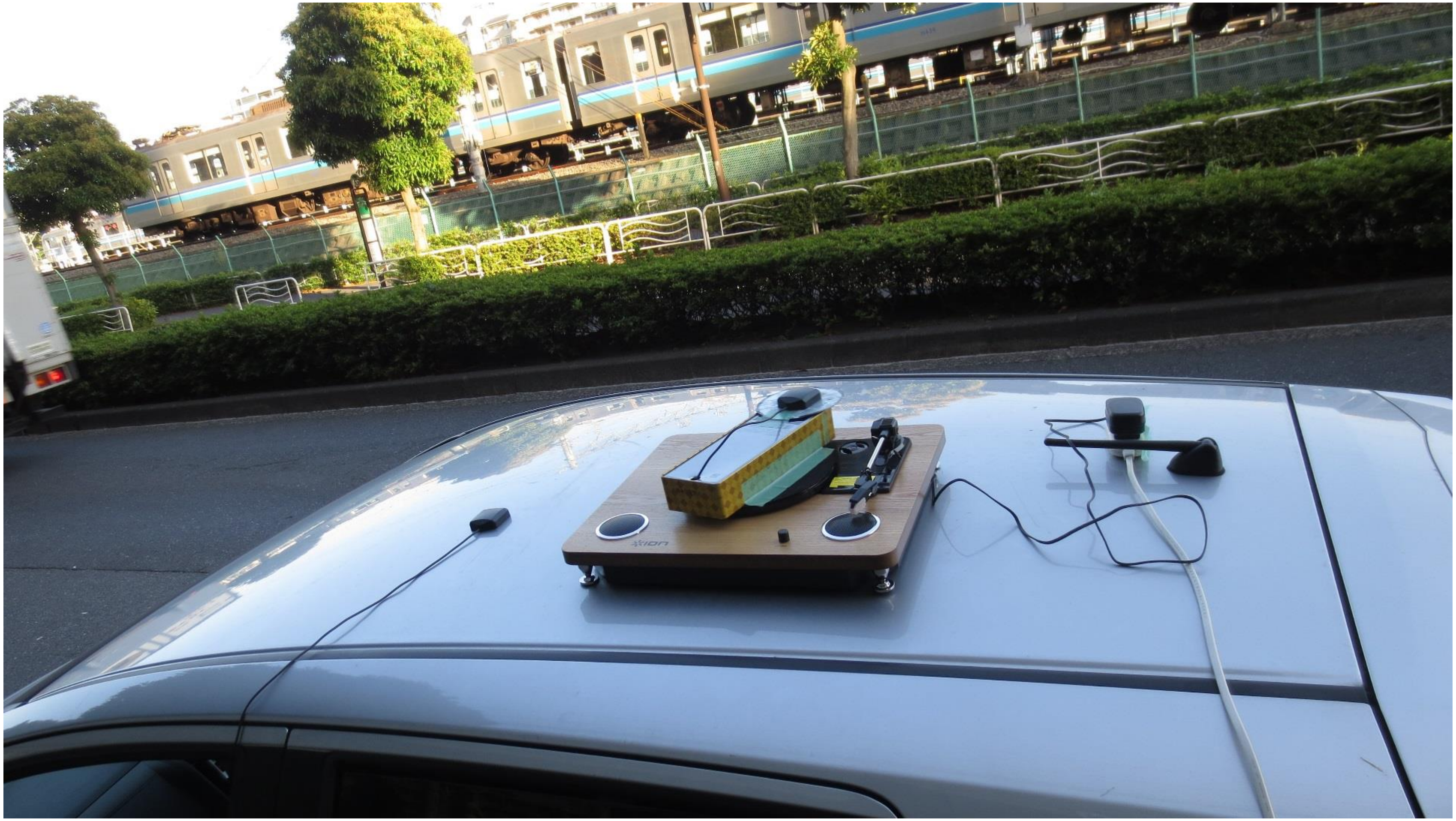
d_{pcv}^s : Satellite Antenna Phase Center Variation

$\boldsymbol{d}_{disp}$: Site Displacement

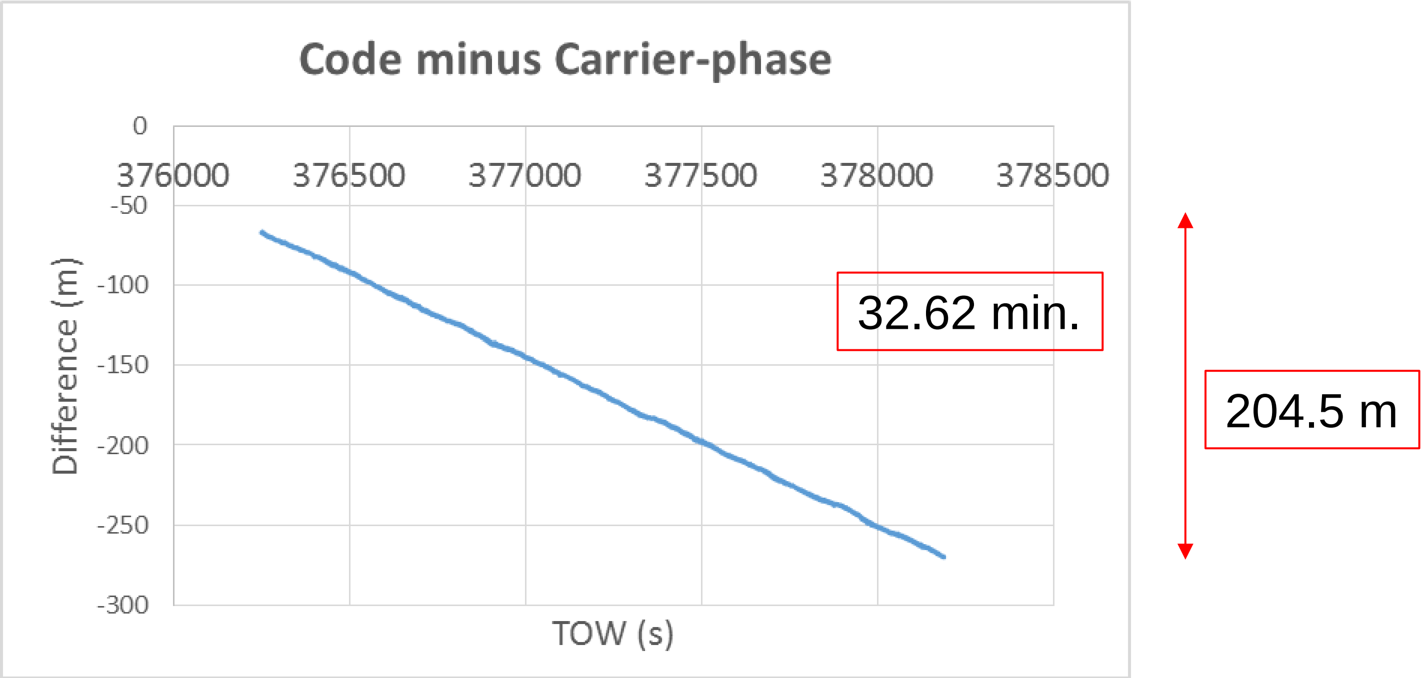
d_{pw} : Phase Wind-up Effect

d_{rel} : Relativistic Effect

Phase Wind-up Effect

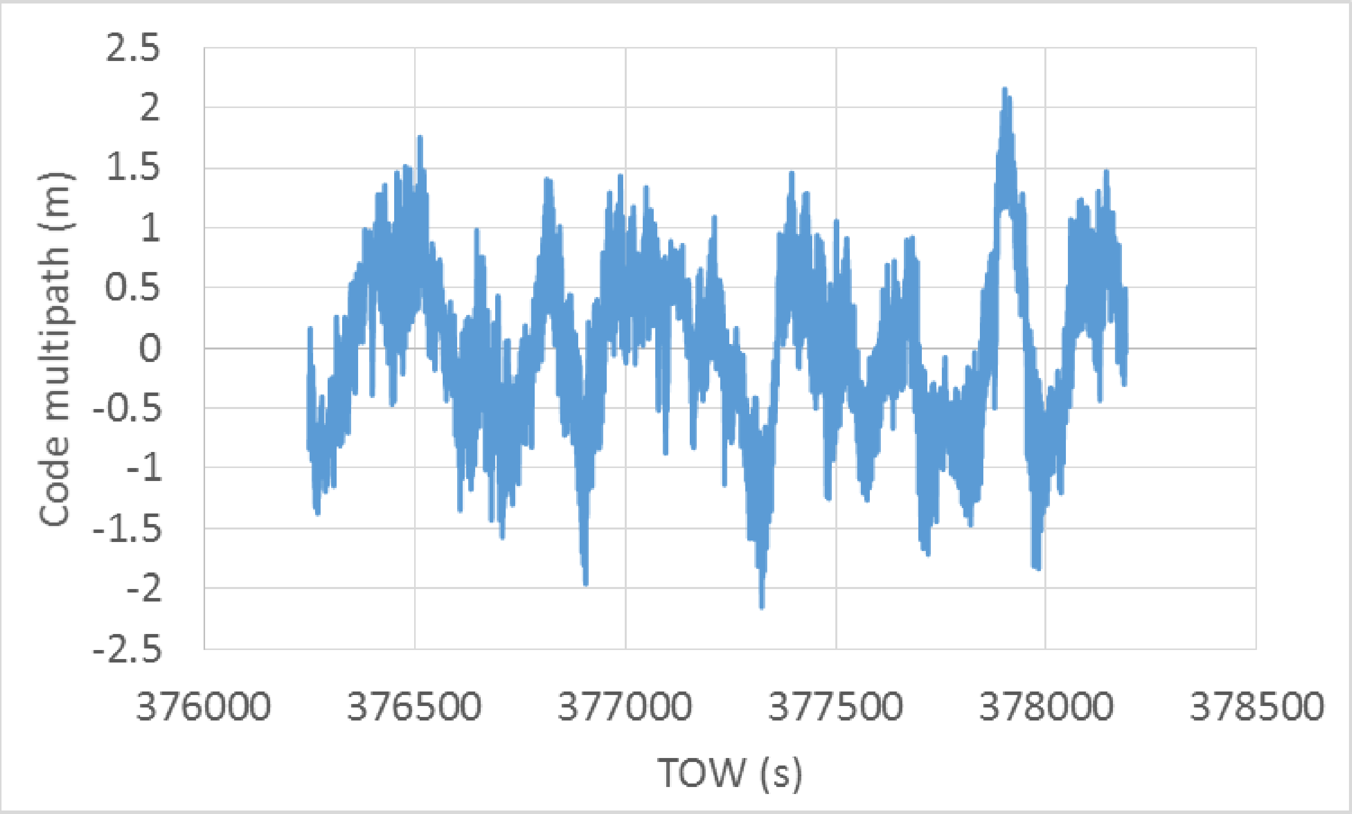


What happens in carrier-phase ?



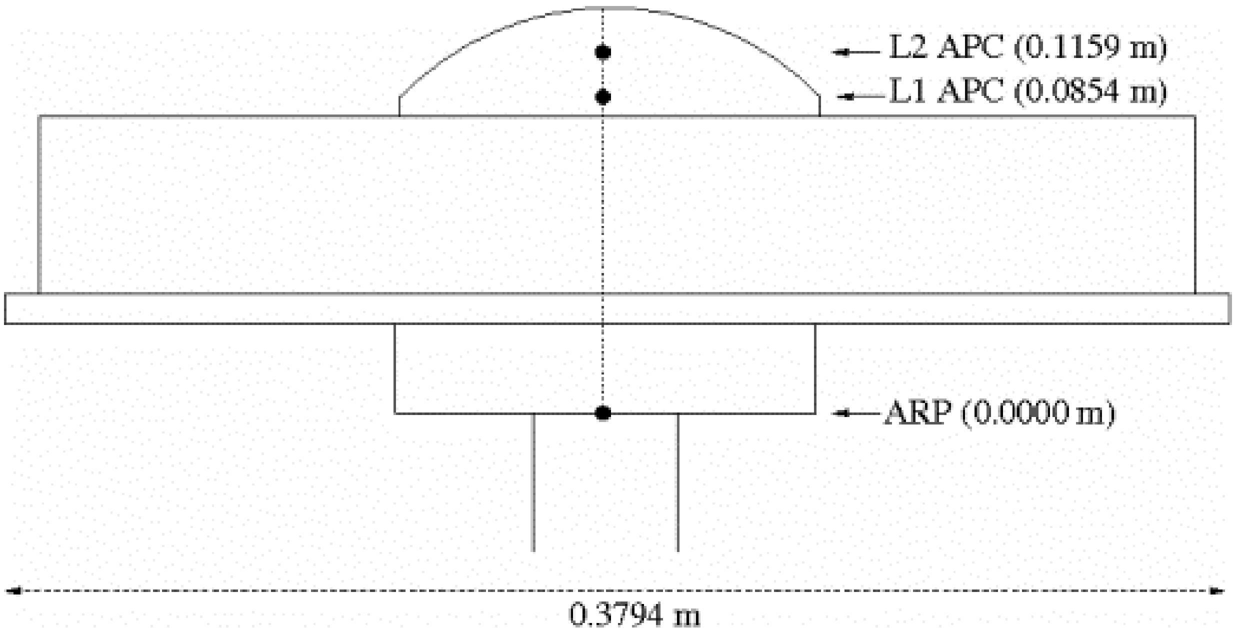
Basically, “code-carrier” indicates the code multipath errors (+ionosphere effect)
Turn table rotates 33.3333…/min.
It means that the number of rotation was 1077.22.
Converting to “meter” of L1-C/A, 1077.22*0.19… = 204.98 m
204.98/1939 s = 0.1057m / turn have to be compensated in carrier-phase.

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)

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

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

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

$$dt_{ub}^{ij} = dt_u^{ij} - dt_b^{ij} = 0, \quad dT_{ub}^{ij} = dT_{ub}^i - dT_{ub}^j \approx 0$$

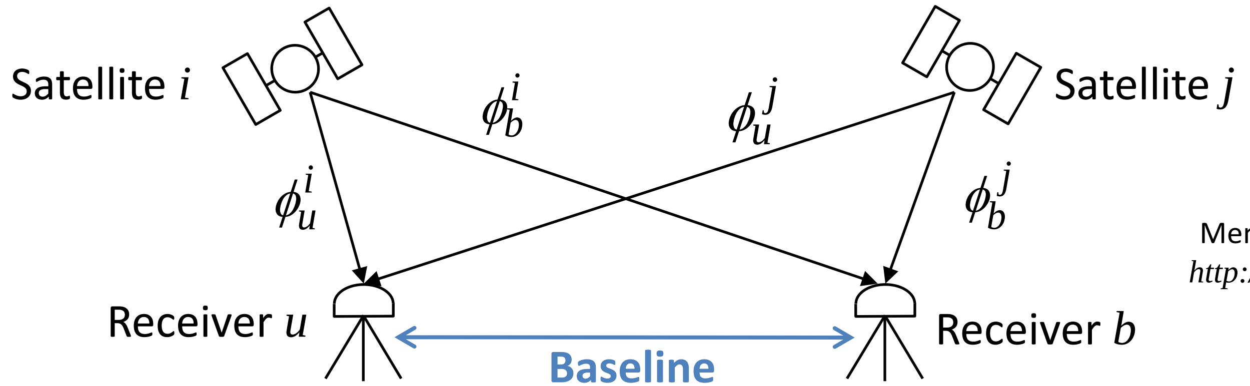
time difference between u and b satellite clock changes…

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

(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

Baseline Processing

Nonlinear-LSE:

Parameter Vector:

$$\boldsymbol{x} = (\boldsymbol{r}_u{}^T, N_{ub}^{s_2 s_1}, N_{ub}^{s_3 s_1}, \dots, N_{ub}^{s_m s_1})^T$$

Measurement Vector:

$$\boldsymbol{y} = (\boldsymbol{y}_{t_1}{}^T, \boldsymbol{y}_{t_1}{}^T, \dots, \boldsymbol{y}_{t_n}{}^T)^T$$

Meas Model, Design Matrix:

$$\boldsymbol{h}(\boldsymbol{x}) = \left(\boldsymbol{h}_{t_1}(\boldsymbol{x})^T, \boldsymbol{h}_{t_2}(\boldsymbol{x})^T, \dots, \boldsymbol{h}_{t_n}(\boldsymbol{x})^T\right)^T$$

$$\boldsymbol{H} = \left(\boldsymbol{H}_{t_1}{}^T, \boldsymbol{H}_{t_2}{}^T, \dots, \boldsymbol{H}_{t_n}{}^T\right)^T$$

Meas Error Covariance:

$$\boldsymbol{R} = blkdiag\left(\boldsymbol{R}_{t_1}, \boldsymbol{R}_{t_2}, \dots, \boldsymbol{R}_{t_n}\right)$$

Solution (Static/Float):

$$\hat{\boldsymbol{x}} = \boldsymbol{x}_0 + (\boldsymbol{H}^T \boldsymbol{R}^{-1} \boldsymbol{H})^{-1} \boldsymbol{H}^T \boldsymbol{R}^{-1} (\boldsymbol{y} - \boldsymbol{h}(\boldsymbol{x}_0))$$

$$\boldsymbol{y}_{t_k} = (\Phi_{ub,t_k}^{s_2 s_1}, \Phi_{ub,t_k}^{s_3 s_1}, \dots, \Phi_{ub,t_k}^{s_m s_1})^T$$

$$\boldsymbol{h}_{t_k}(\boldsymbol{x}) = \begin{pmatrix} \rho_{u,t_k}^{s_2 s_1} - \rho_{b,t_k}^{s_2 s_1} + \lambda N_{ub}^{s_2 s_1} \\ \rho_{u,t_k}^{s_3 s_1} - \rho_{b,t_k}^{s_3 s_1} + \lambda N_{ub}^{s_m s_1} \\ \vdots \\ \rho_{u,t_k}^{s_m s_1} - \rho_{b,t_k}^{s_m s_1} + \lambda N_{ub}^{s_m s_1} \end{pmatrix}$$

$$\boldsymbol{H}_{t_k} = \begin{pmatrix} -\boldsymbol{e}_{u,t_k}^{s_2 s_1 \, T} & \lambda & 0 & \cdots & 0 \\ -\boldsymbol{e}_{u,t_k}^{s_3 s_1 \, T} & 0 & \lambda & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ -\boldsymbol{e}_{u,t_k}^{s_m s_1 \, T} & 0 & 0 & \cdots & \lambda \end{pmatrix}$$

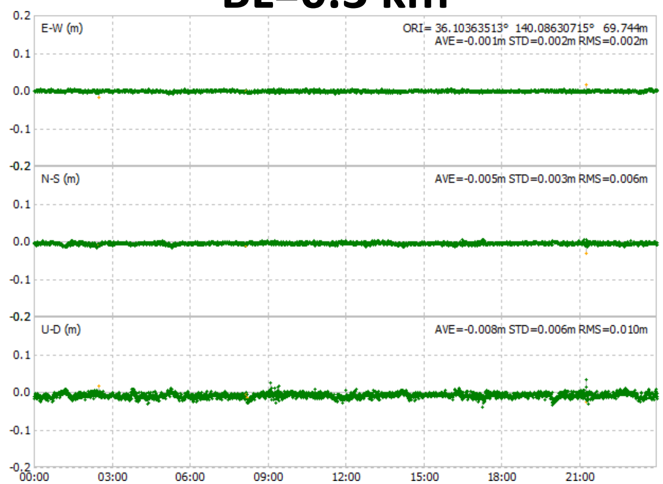
$$\boldsymbol{R}_{t_k} = \begin{pmatrix} 4\sigma_\Phi{}^2 & 2\sigma_\Phi{}^2 & \cdots & 2\sigma_\Phi{}^2 \\ 2\sigma_\Phi{}^2 & 4\sigma_\Phi{}^2 & \cdots & 2\sigma_\Phi{}^2 \\ \vdots & \vdots & \ddots & \vdots \\ 2\sigma_\Phi{}^2 & 2\sigma_\Phi{}^2 & \cdots & 4\sigma_\Phi{}^2 \end{pmatrix}$$

$\boldsymbol{r}_b$: Fixed Base-Station Position

It is similar to the single point positioning except for KF

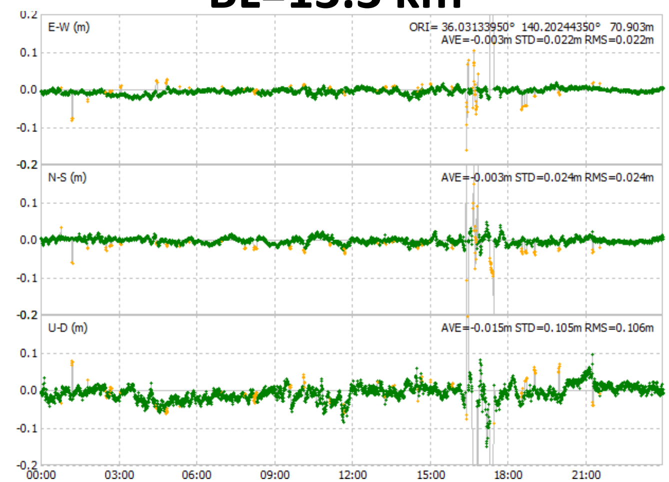
Effect of Baseline Length

BL=0.3 km



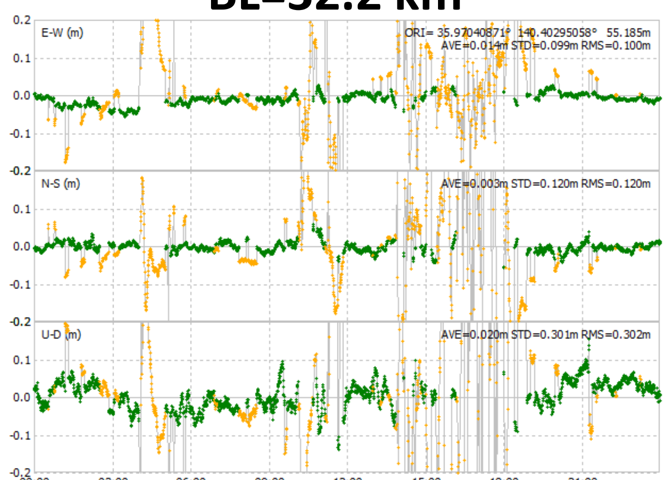
RMS Error:
E: 0.2cm
N: 0.6cm
U: 1.0cm
Fix Ratio:
99.9%

BL=13.3 km



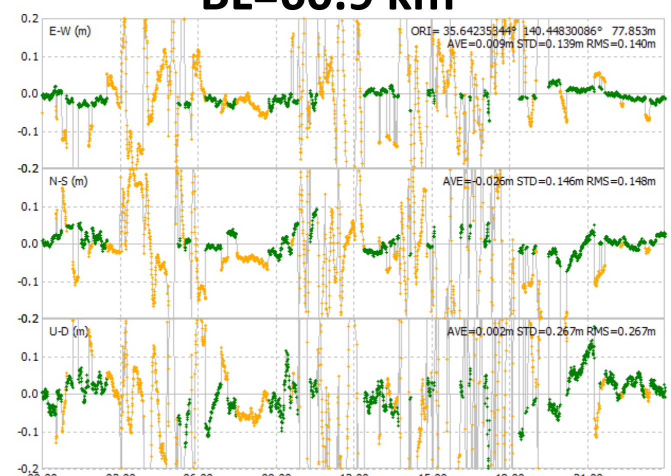
RMS Error:
E: 2.2cm
N: 2.4cm
U: 10.6cm
Fix Ratio:
94.2%

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-L^3, Modified Cholesy Decomposition, Null Space, FAST, OMEGA, ...

ILS (Integer Least Square Estimation)

Problem:

$$\boldsymbol{x} = (\boldsymbol{a}^T, \boldsymbol{b}^T)^T,\ \boldsymbol{H} = (\boldsymbol{A}, \boldsymbol{B})$$

$$\boldsymbol{y} = \boldsymbol{H}\boldsymbol{x} + \boldsymbol{v} = \boldsymbol{A}\boldsymbol{a} + \boldsymbol{B}\boldsymbol{b} + \boldsymbol{v}$$

$$\check{\boldsymbol{x}} = \underset{\boldsymbol{a}\in \boldsymbol{Z}^n, \boldsymbol{b}\in \boldsymbol{R}^m}{\arg\min} (\boldsymbol{y} - \boldsymbol{H}\boldsymbol{x})^T \boldsymbol{Q}_y^{-1} (\boldsymbol{y} - \boldsymbol{H}\boldsymbol{x})$$

Strategy:

(1) Conventional LSE

$$\hat{\boldsymbol{x}} = \begin{pmatrix} \hat{\boldsymbol{a}} \\ \hat{\boldsymbol{b}} \end{pmatrix} = \boldsymbol{Q}_x \boldsymbol{H}^T \boldsymbol{Q}_y^{-1} \boldsymbol{y},\ \boldsymbol{Q}_x = \begin{pmatrix} \boldsymbol{Q}_a & \boldsymbol{Q}_{ab} \\ \boldsymbol{Q}_{ba} & \boldsymbol{Q}_b \end{pmatrix} = (\boldsymbol{H}^T \boldsymbol{Q}_y \boldsymbol{H})^{-1}$$

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

$$\check{\boldsymbol{a}} = \underset{\boldsymbol{a}\in \boldsymbol{Z}^n}{\arg\min} (\hat{\boldsymbol{a}} - \boldsymbol{a})^T \boldsymbol{Q}_a^{-1} (\hat{\boldsymbol{a}} - \boldsymbol{a})$$

(3) Improve solution

$$\check{\boldsymbol{b}} = \hat{\boldsymbol{b}} - \boldsymbol{Q}_{ba} \boldsymbol{Q}_a^{-1} (\hat{\boldsymbol{a}} - \check{\boldsymbol{a}})$$

LAMBDA

Teunissen, P.J.G. (1995)
The least-squares ambiguity decorrelation adjustment: a method for fast GPS integer ambiguity estimation. *Journal of Geodesy,* Vol. 70, No. 1-2, pp. 65-82.

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

$$\breve{\boldsymbol{a}} = \arg\min_{\boldsymbol{a} \in \boldsymbol{Z}^n} (\hat{\boldsymbol{a}} - \boldsymbol{a})^T \boldsymbol{Q}_a^{-1} (\hat{\boldsymbol{a}} - \boldsymbol{a})$$

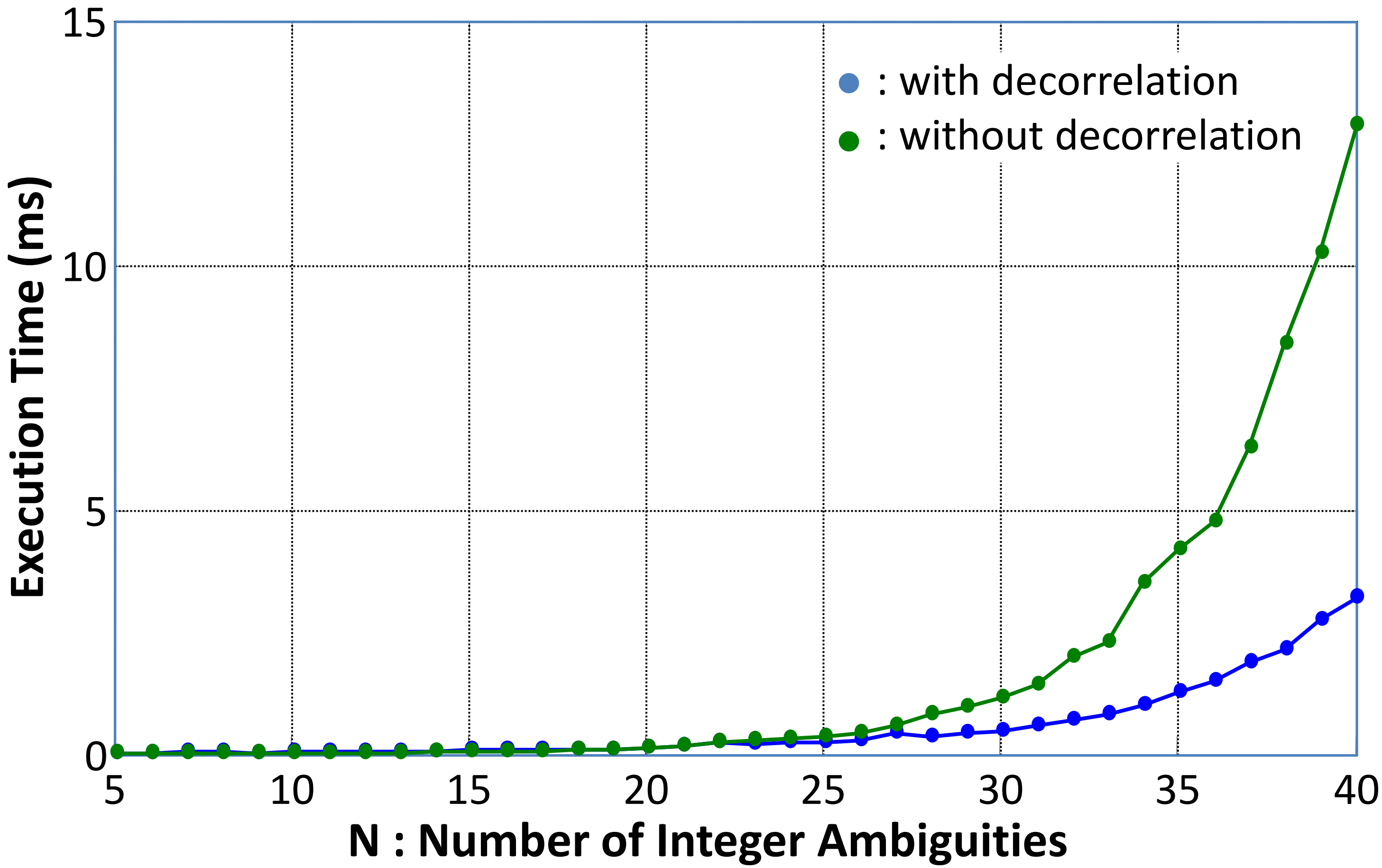
$\Leftrightarrow$

$$\hat{\boldsymbol{z}} = \boldsymbol{Z}^T \hat{\boldsymbol{a}},\ \boldsymbol{Q}_z = \boldsymbol{Z}^T \boldsymbol{Q}_a \boldsymbol{Z}$$

$$\breve{\boldsymbol{z}} = \arg\min_{\boldsymbol{z} \in \boldsymbol{Z}^n} (\hat{\boldsymbol{z}} - \boldsymbol{z})^T \boldsymbol{Q}_z^{-1} (\hat{\boldsymbol{z}} - \boldsymbol{z})$$

$$\breve{\boldsymbol{a}} = \boldsymbol{Z}^{-T} \breve{\boldsymbol{z}}$$

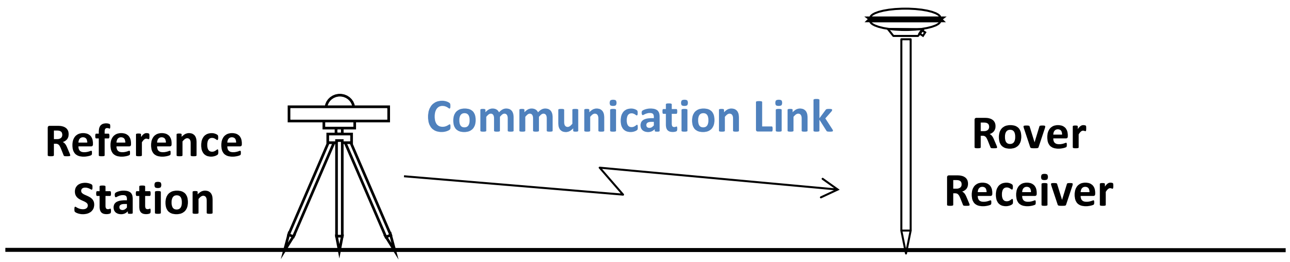
Performance of LAMBDA



(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.



RTK Application (1)

Geodetic Survey

Construction Machine Control

Precision Agriculture

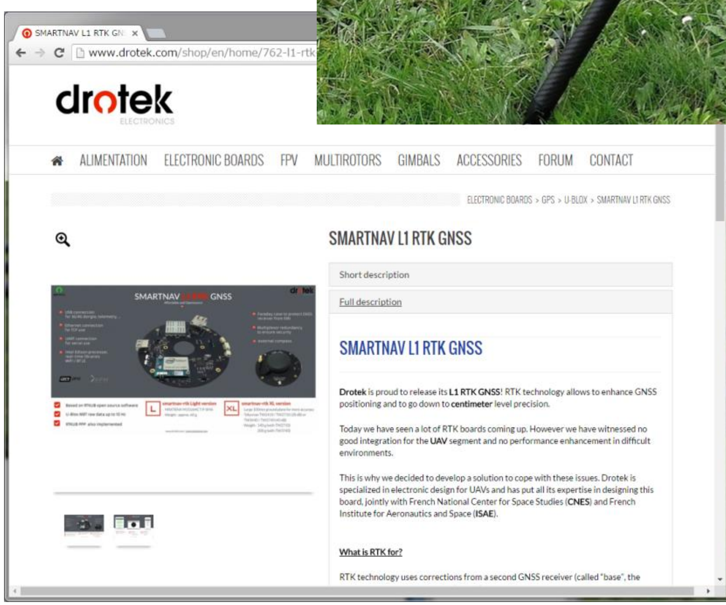
ITS (Intelligent Transport System)

Mobile Mapping System

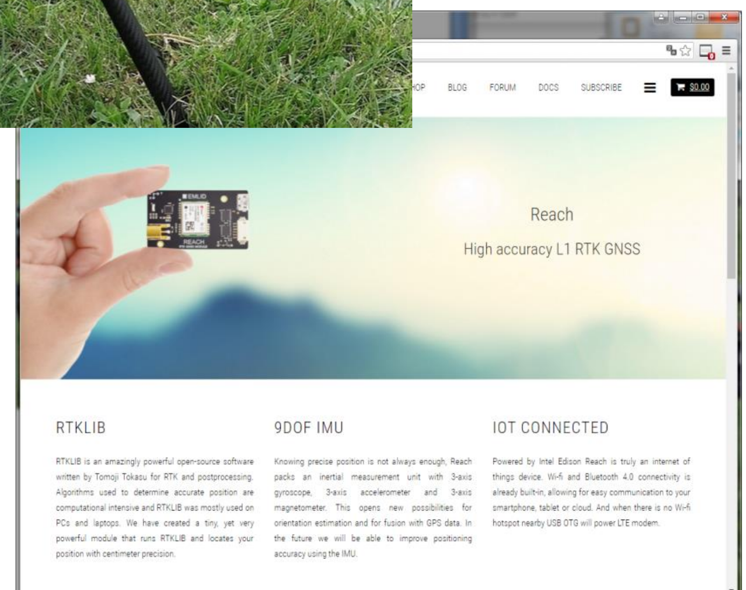
Sports

http://www.trimble.com, http://www.leica-geosystems.com, http://www.gpsworld.com

RTK Application (2)

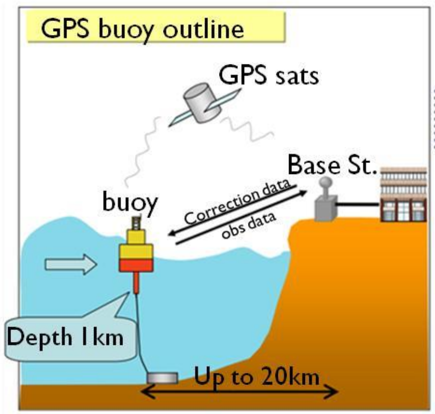


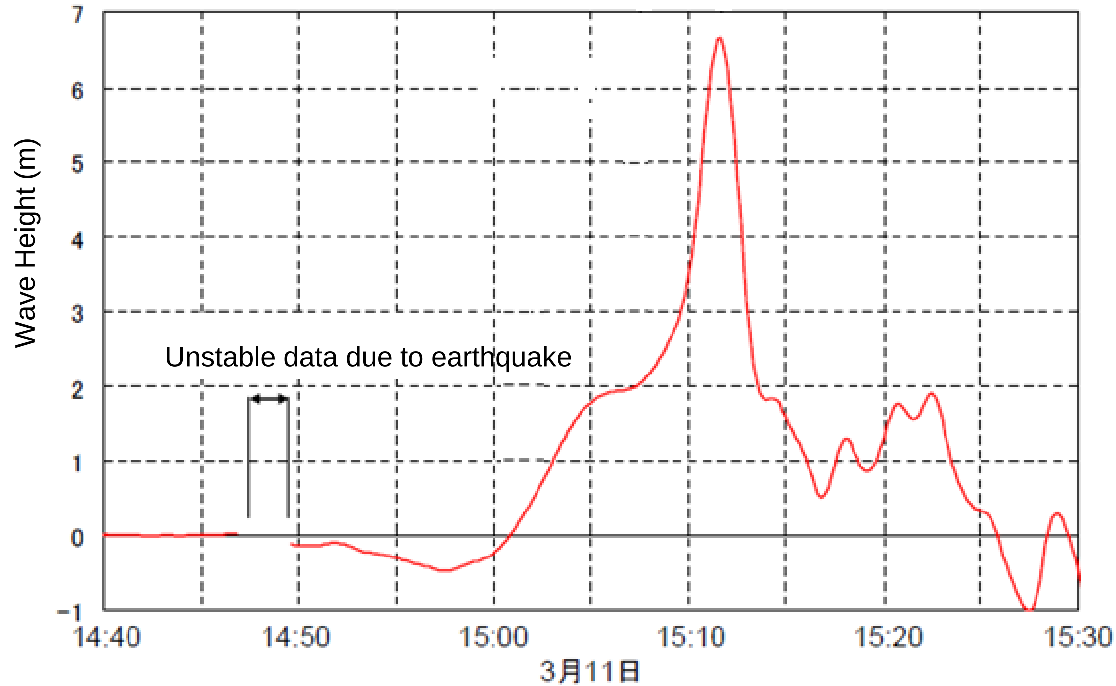
http://www.drotek.com



http://www.emlid.com

GNSS TSUNAMI BUOY





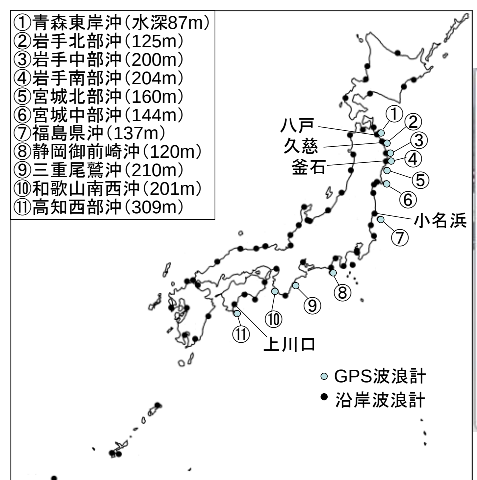
South *Iwate* buoy

- 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**

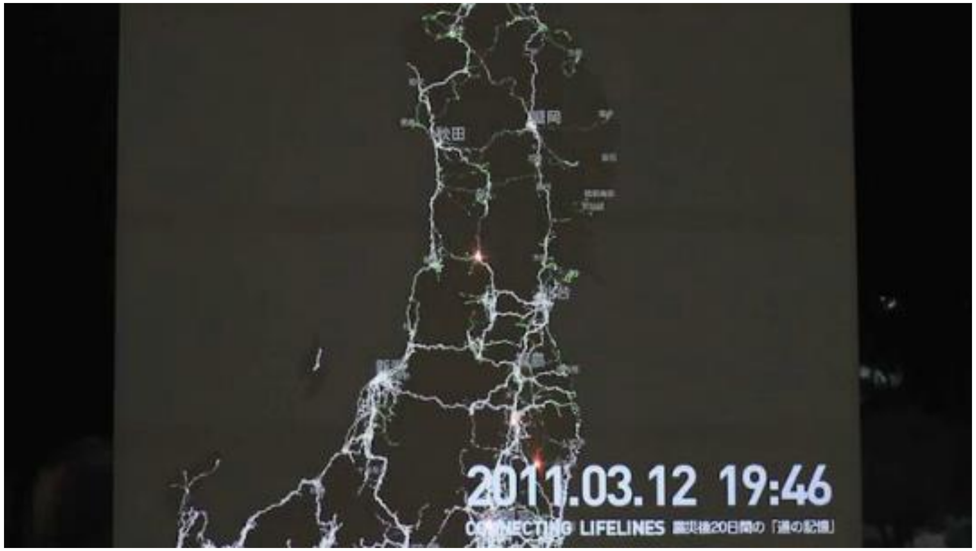
Precision Farming

- **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**



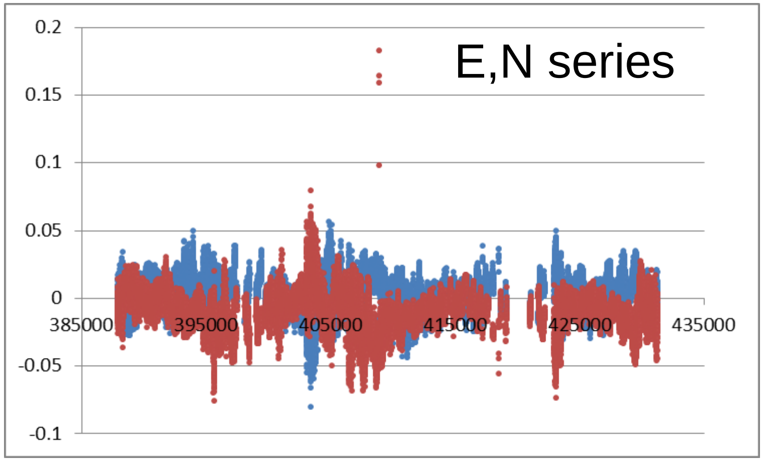
Accuracy improves the quality of Big data

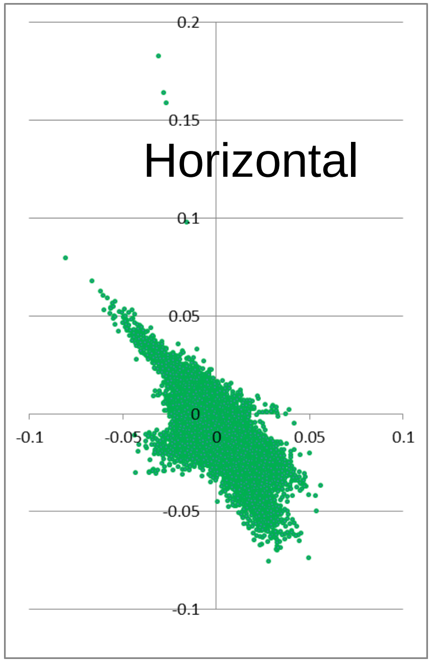
Autonomous car with precise map

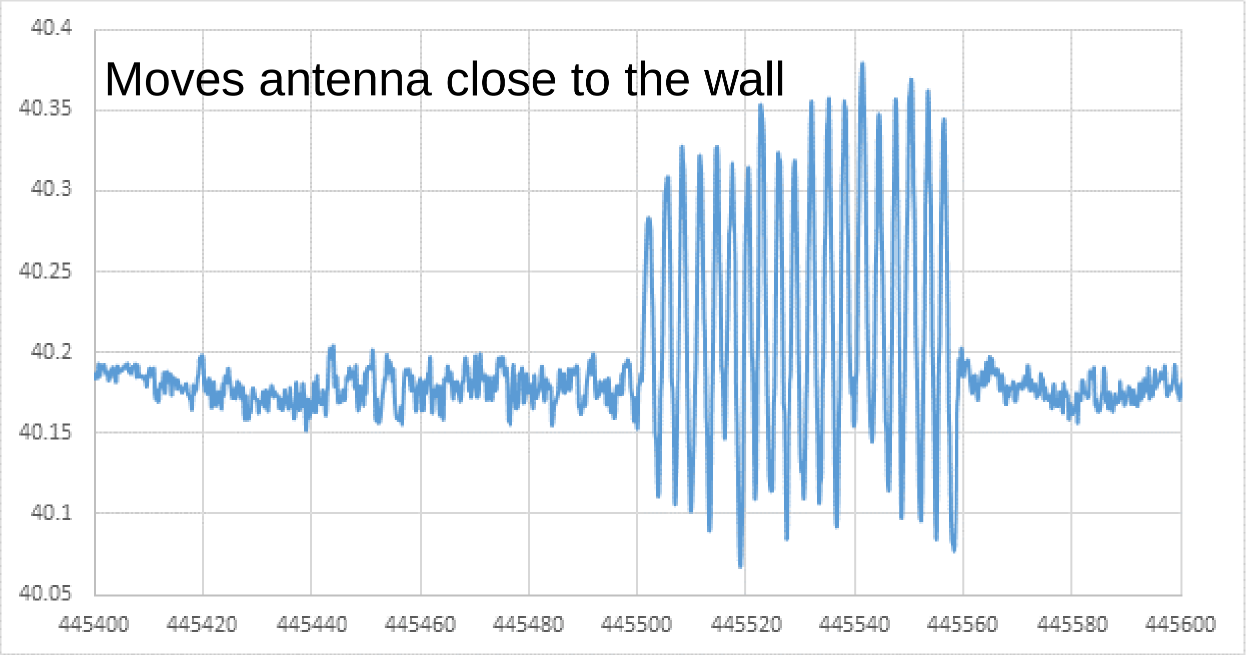
* Autonomous car
* Smart control

Recent Test : RTK on the wall

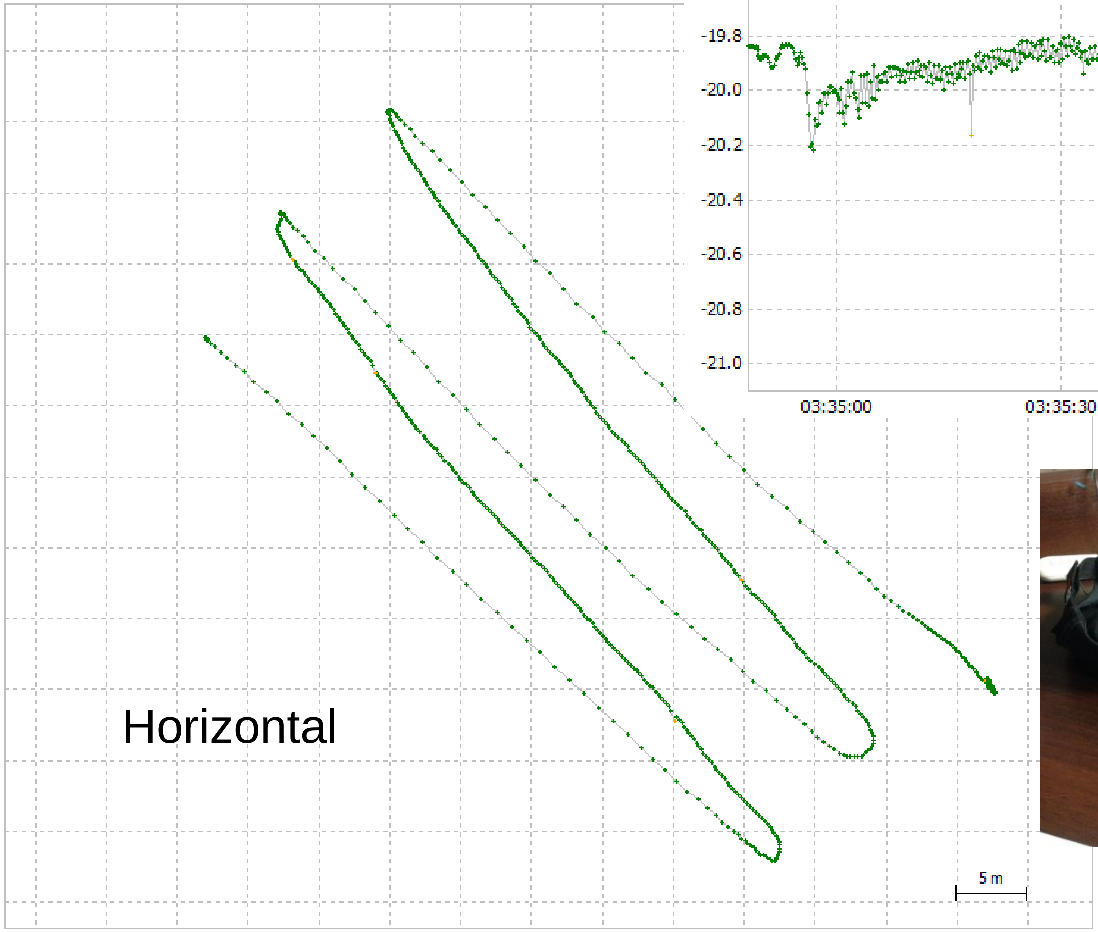
Monitoring for structure deformations







Recent Test : Running



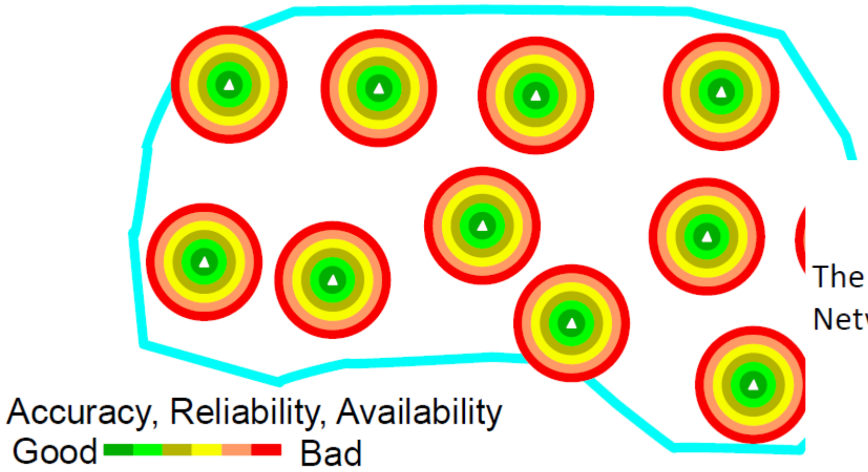
Network RTK (NRTK)

- **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

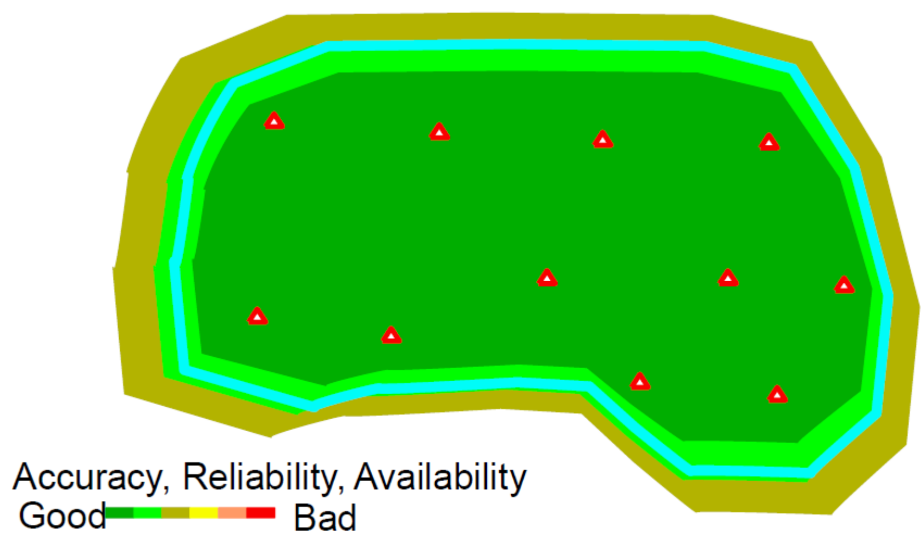
Network of Individual Reference Stations

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.



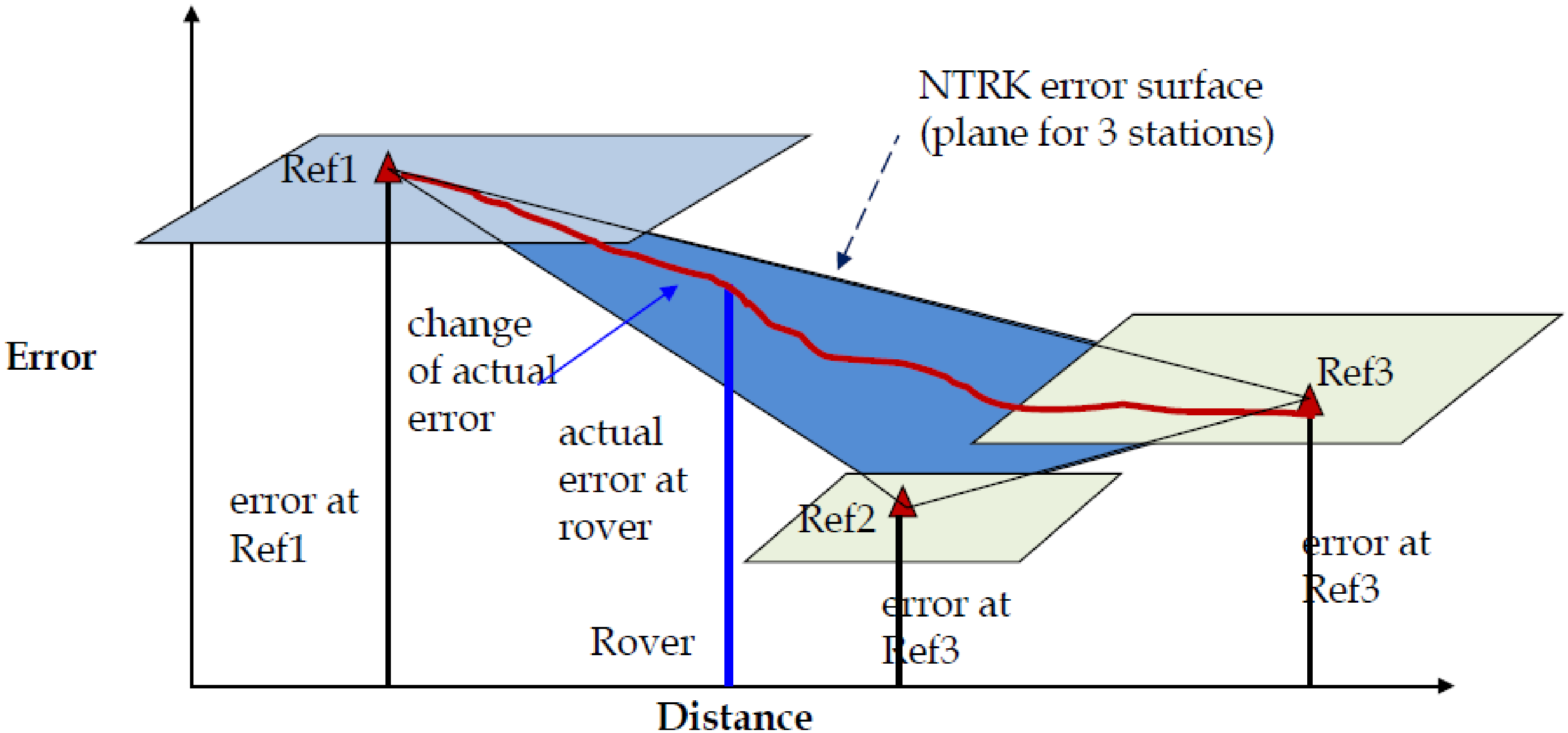
The Solution is Network RTK (NRTK)!

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



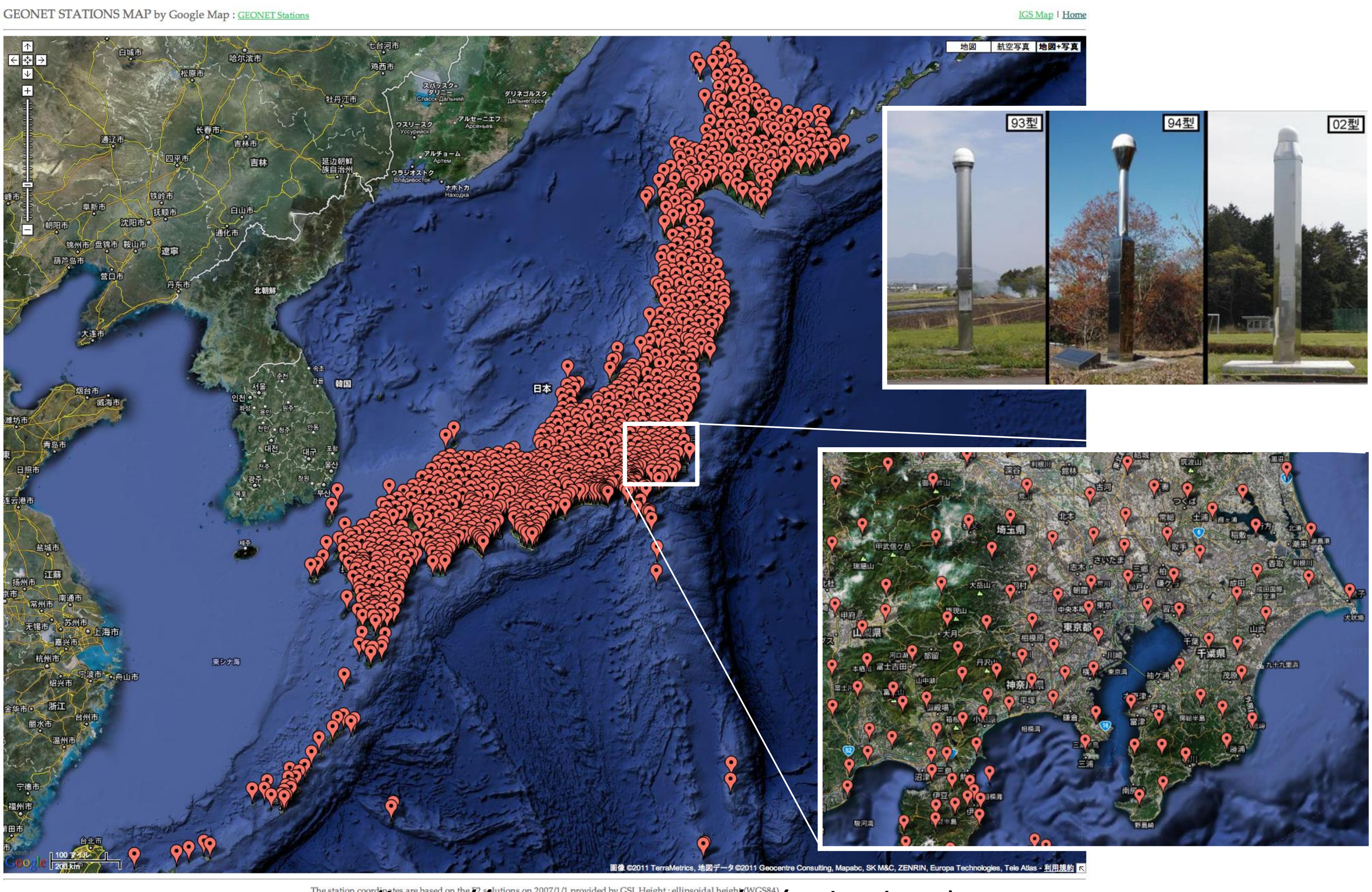
Source: GEO++

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)

$$\Phi_{ub}^{ij} \equiv \lambda((\phi_u^i - \phi_b^i) - (\phi_u^j - \phi_b^j))$$
$$= \rho_{ub}^{ij} + c(dt_{ub}^{ij} - dT_{ub}^{ij}) - I_{ub}^{ij} + T_{ub}^{ij} + \lambda N_{ub}^{ij} + d_{ub}^{ij} + \varepsilon_\Phi$$
$$= \rho_{ub}^{ij} - I_{ub}^{ij} + T_{ub}^{ij} + \lambda N_{ub}^{ij} + d_{ub}^{ij} + \varepsilon_\Phi$$

$$dt_{ub}^{ij} = dt_u^{ij} - dt_b^{ij} = 0, \quad dT_{ub}^{ij} = dT_{ub}^i - dT_{ub}^j \approx 0$$

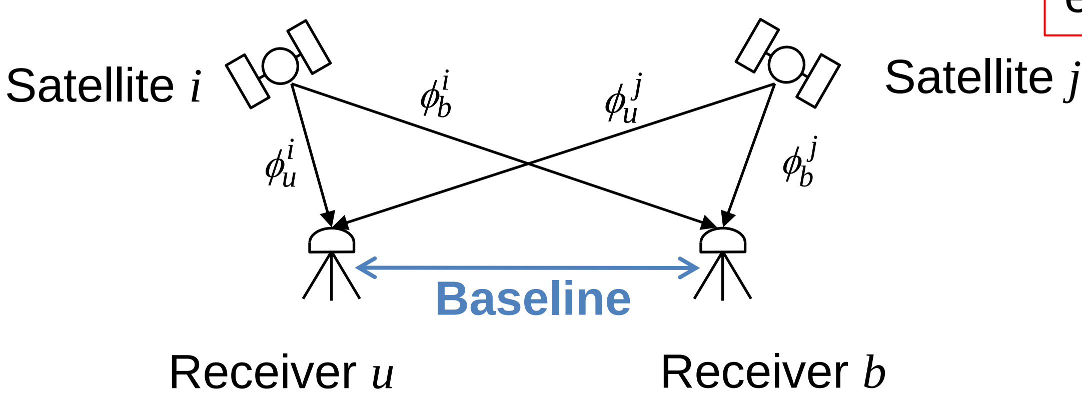
$$B_{ub}^{ij} = (\phi_{u,0} - \phi_0^i + N_u^i) - (\phi_{b,0} - \phi_0^i + N_b^i) - (\phi_{u,0} - \phi_0^j + N_u^j) + (\phi_{b,0} - \phi_0^j + N_b^j) = N_{ub}^{ij}$$

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

(short Baseline and same antenna type)

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

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

2. Integer Ambiguity Resolution

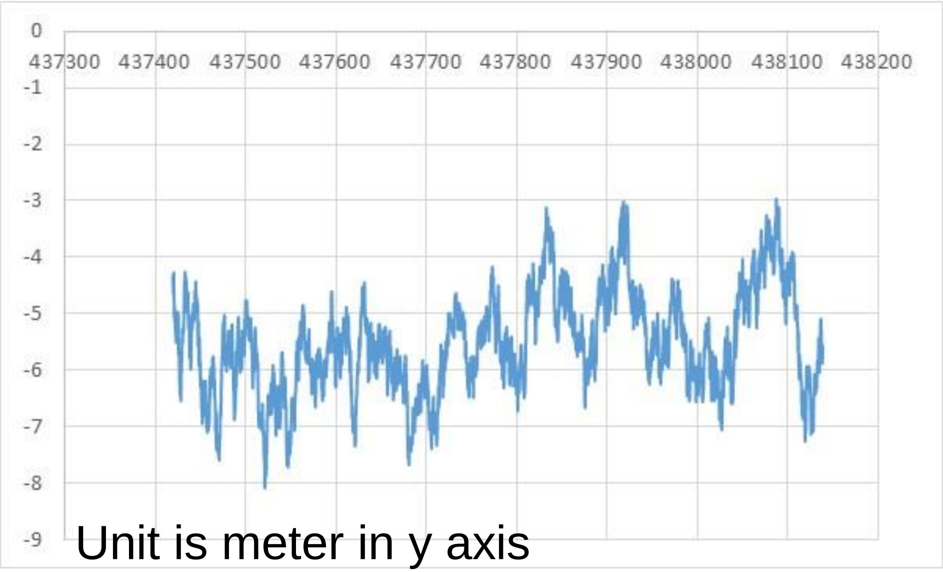
$$P_{rov\_ref}^{sv1\_sv2} = r_{rov\_ref}^{sv1\_sv2} + \varepsilon_{p,rov\_ref}^{sv1\_sv2}$$

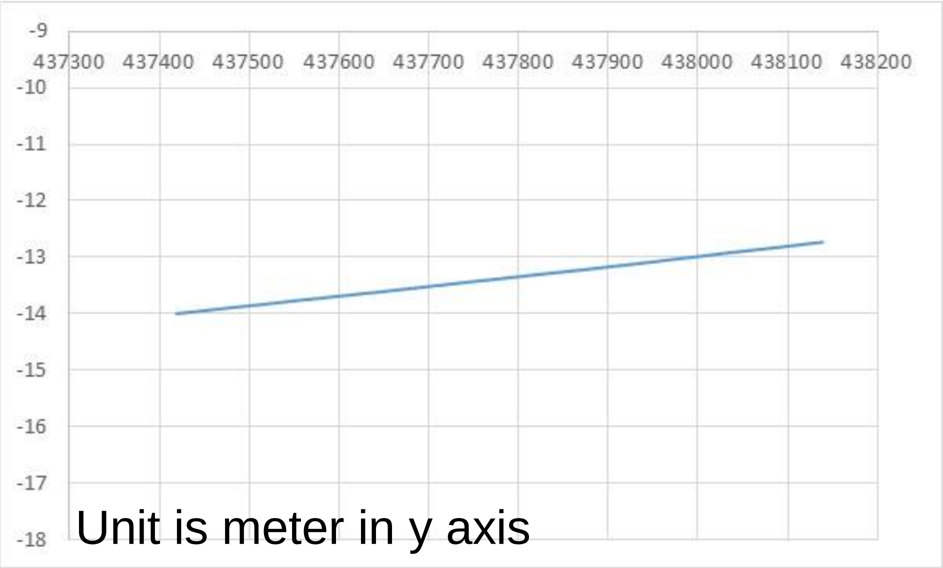
$$\phi_{rov\_ref}^{sv1\_sv2} = r_{rov\_ref}^{sv1\_sv2} + N_{rov\_ref}^{sv1\_sv2} + \varepsilon_{\phi,rov\_ref}^{sv1\_sv2}$$

- 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

3. Test results on the rooftop

- double difference of 10 m baseline-



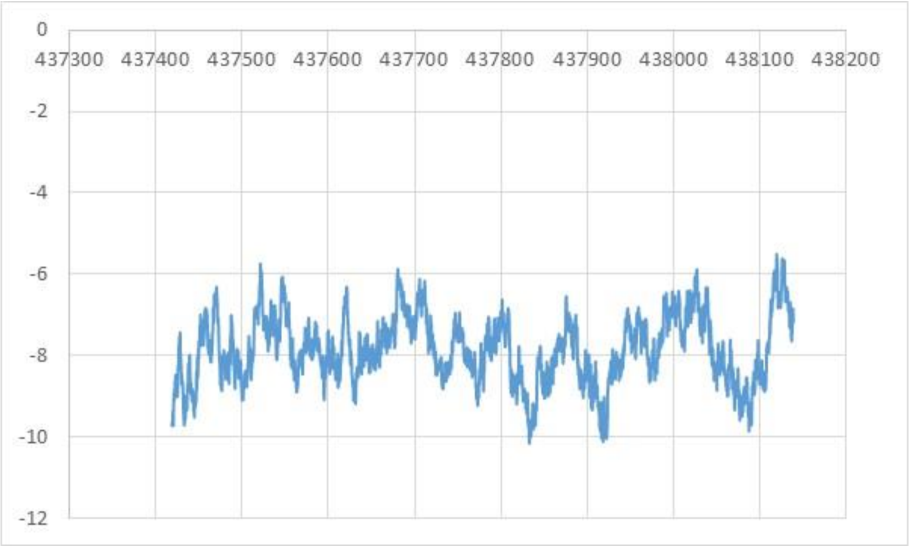


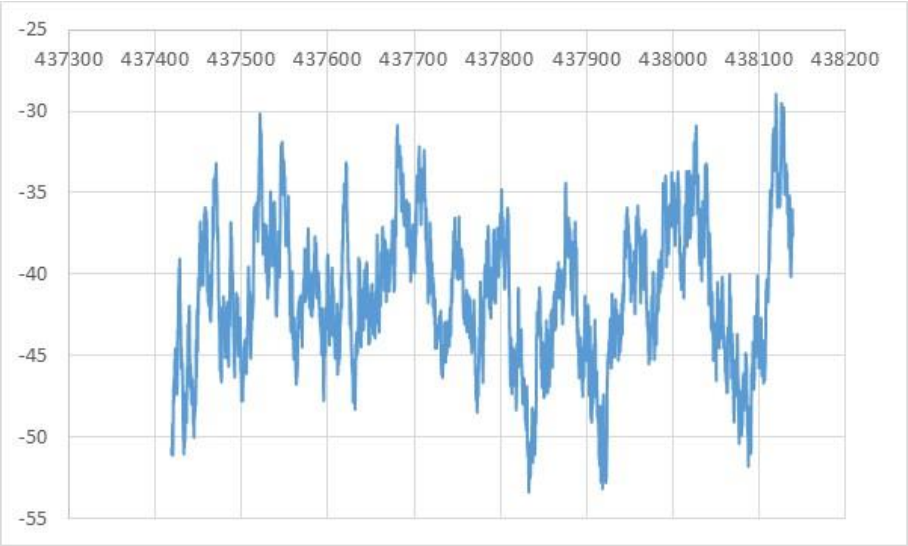
1. Reference satellite GPS PRN 16
   and target satellite is GPS PRN 8
2. Which is code-phase double difference ?
3. If you subtract from right to left, what happen ?

$$P_{rov\_ref}^{sv1\_sv2} = r_{rov\_ref}^{sv1\_sv2} + \varepsilon_{p,rov\_ref}^{sv1\_sv2}$$

$$\phi_{rov\_ref}^{sv1\_sv2} = r_{rov\_ref}^{sv1\_sv2} + N_{rov\_ref}^{sv1\_sv2} + \varepsilon_{\phi,rov\_ref}^{sv1\_sv2}$$

4. (Carrier DD) - (Code DD)





The unit is meter

Divided by wavelength
0.19029 m… (L1)

The unit is cycle

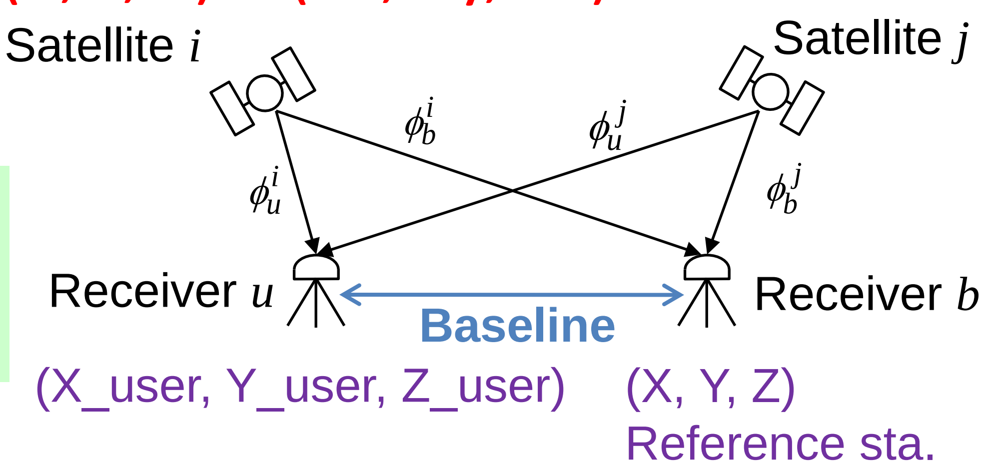
Probably, we guess the integer ambiguity between PRN16 and PRN8 is about - 40 ?
In fact, the average of this right results was - 41.3

5. What is the correct ambiguity ?

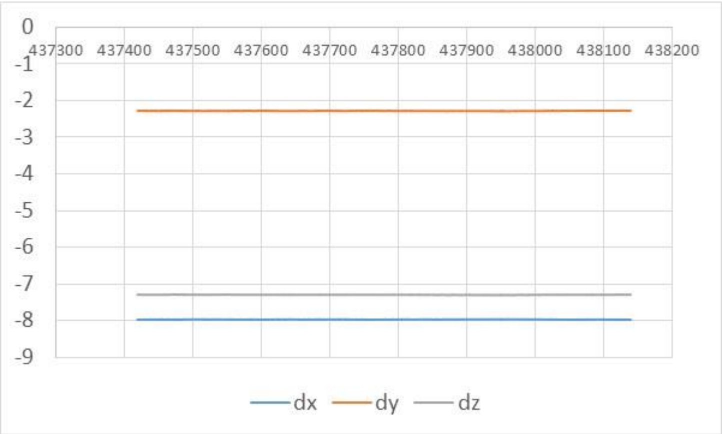
- “Integer least square method” tells us “– 42” in a single epoch !
- If you know the 3 or more ambiguities, you can estimate the user position with the level of carrier phase because only 3 unknowns remains.
- Then, (dx, dy, dz) can be estimated and finally,
- (X_user, Y_user, Z_user) = (X, Y, Z) +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

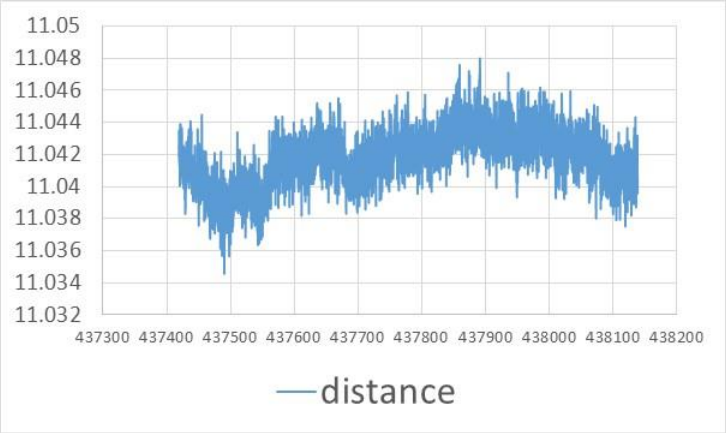
$$P_{rov\_ref}^{sv1\_sv2} = r_{rov\_ref}^{sv1\_sv2} + \varepsilon_{p,rov\_ref}^{sv1\_sv2}$$

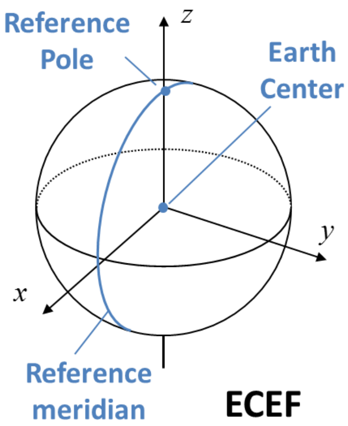
$$\phi_{rov\_ref}^{sv1\_sv2} = r_{rov\_ref}^{sv1\_sv2} + N_{rov\_ref}^{sv1\_sv2} + \varepsilon_{\phi,rov\_ref}^{sv1\_sv2}$$

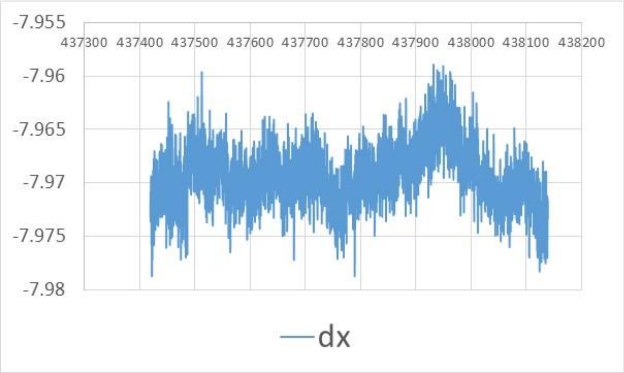


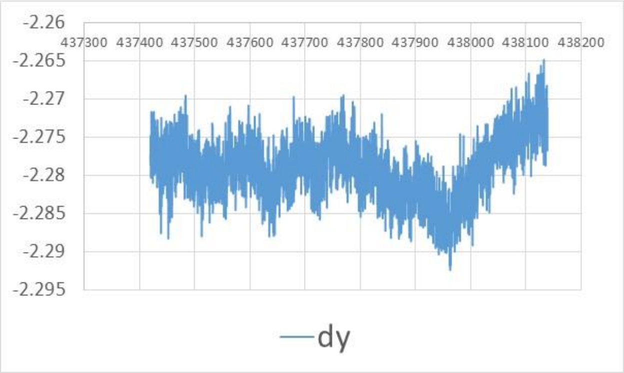
6. Test results (dx, dy, dz)

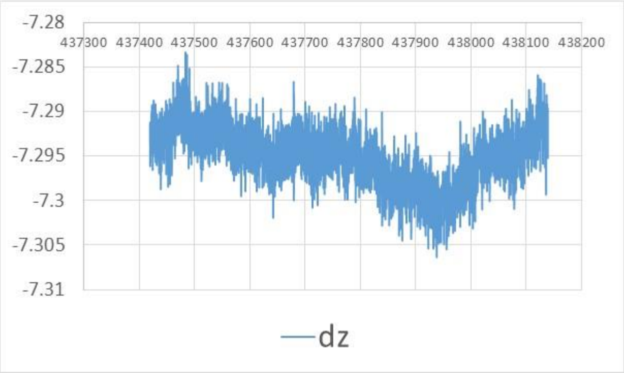










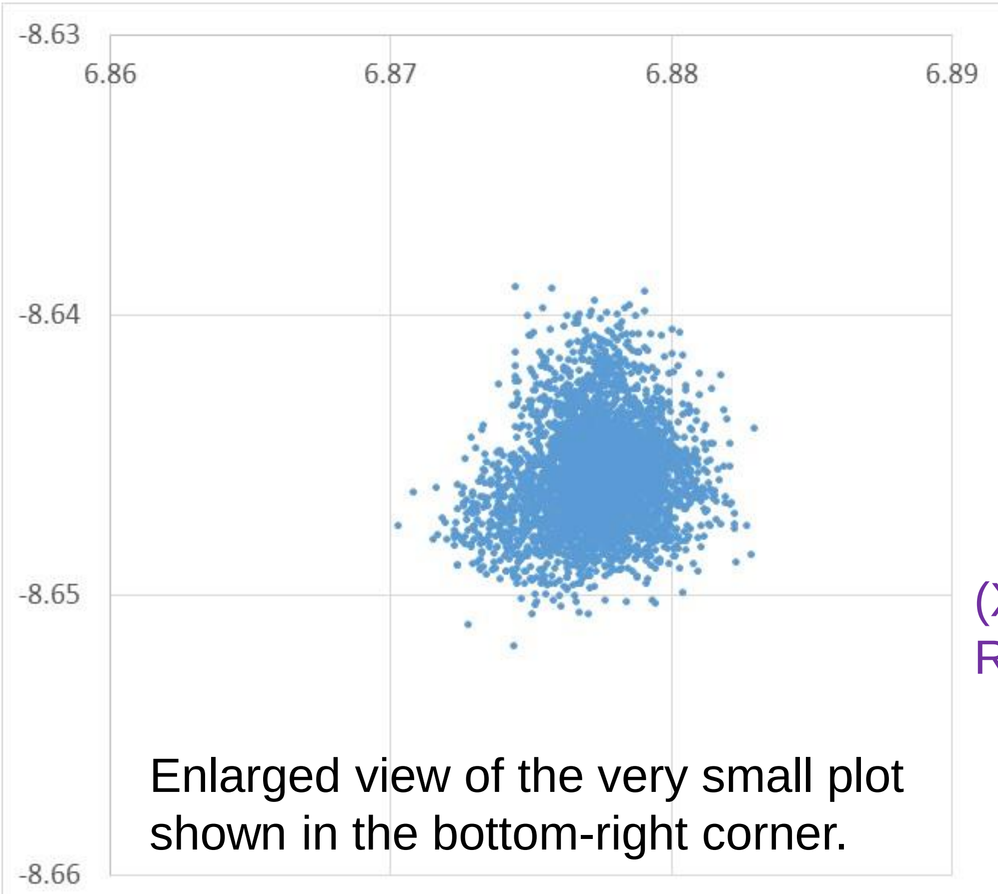


Std. = 2.8 mm

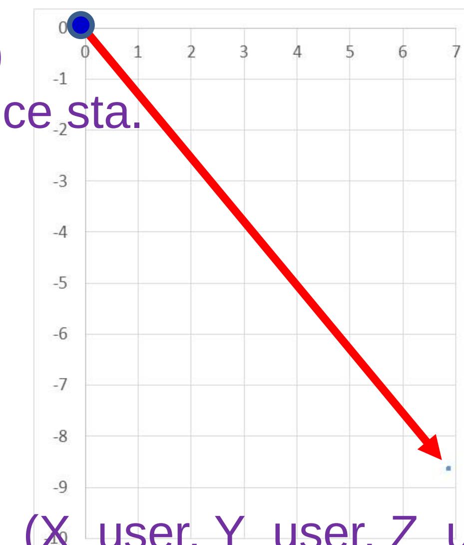
Std. = 4.0 mm

Std. = 3.4 mm

7. Convert to horizontal positions



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



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

Difference between expensive and low-cost receiver

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

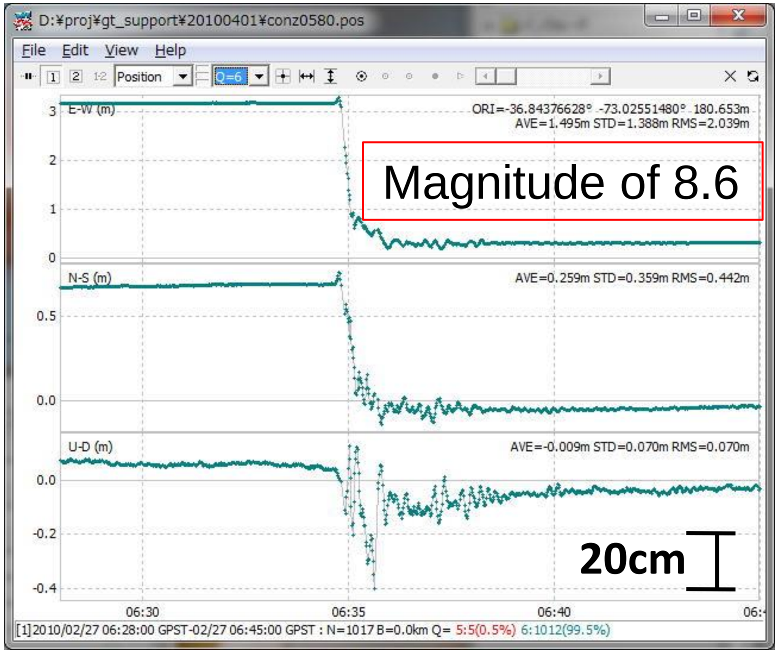
PPP (Precise Point Positioning)

- **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)

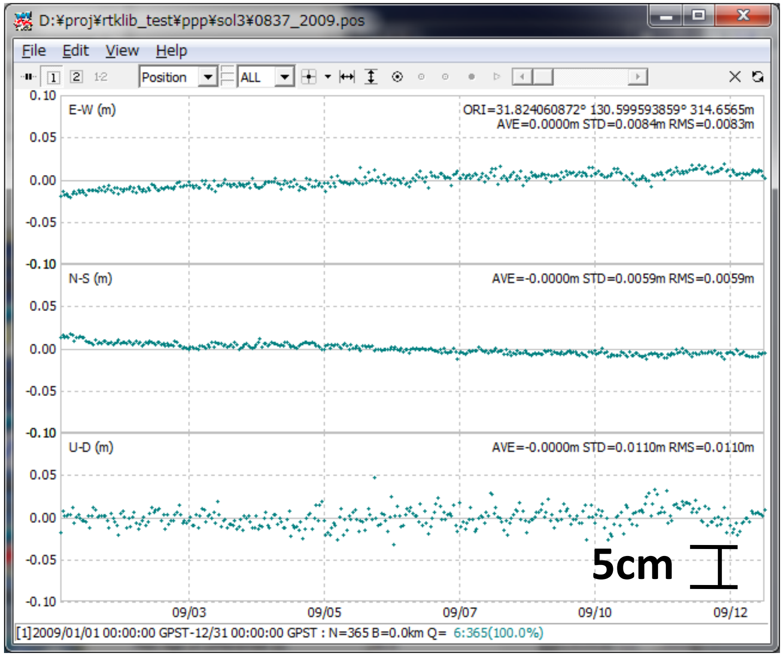


2010/2/27 6:28-6:45 GPST

Interval: 1 s

Static PPP

Station: GEONET 0837



2009/1/1-2009/12/31

Interval: 1day

PPP Applications

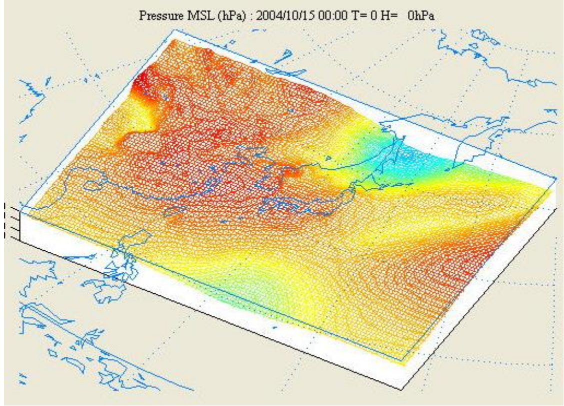
Automated Farming

Tsunami Warning

Mining Machine Control

Offshore Construction

Autonomous Driving



Weather Forecast

RTK vs. PPP

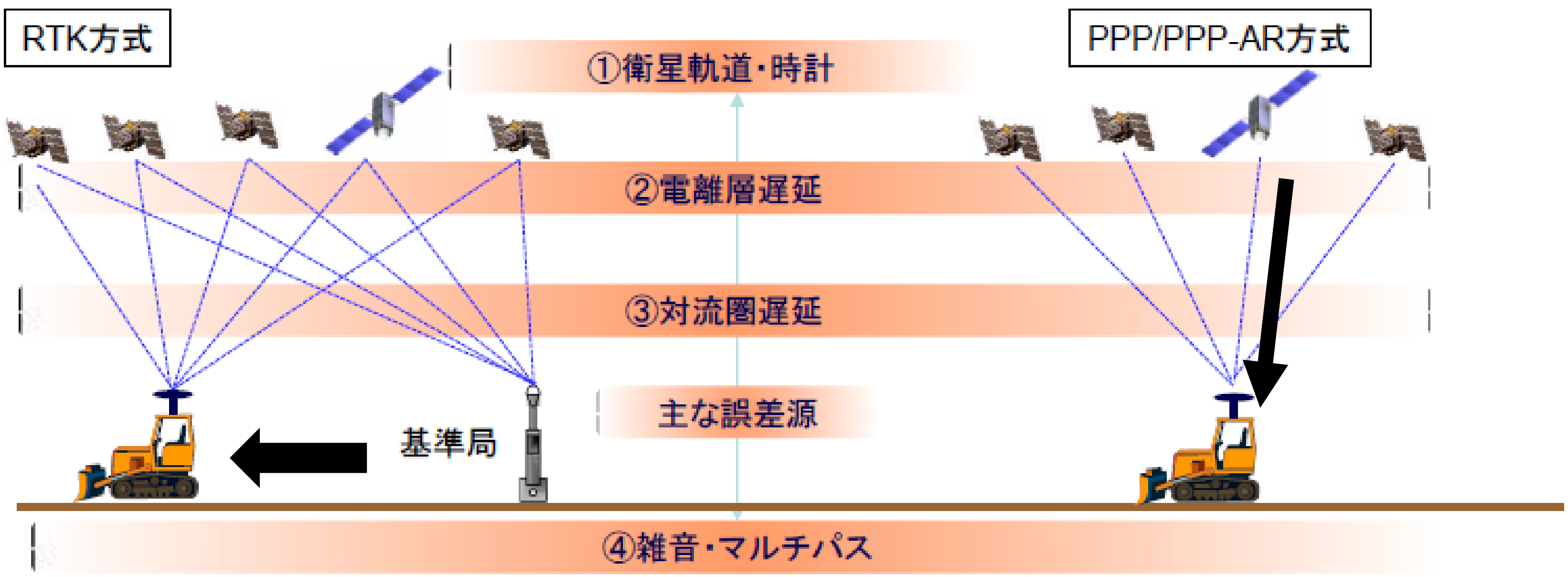
	RTK	Real-Time PPP
Coverage	Local/Regional (< 1000km)	Global
Typical Accuracy	1-3 cm HRMS	2-10 cm, much depending on orbit/clock quality
Effect of Ref Movement	Hard to separate ref and user movement	Less effect by distributed ref stations
System Complexity	Simple, at least one ref station	Complicated,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

Which is better depends on AP requirement and technology level.
RTKLIB offers both. They are user-selectable by option settings.

Error source mitigation (Typical)

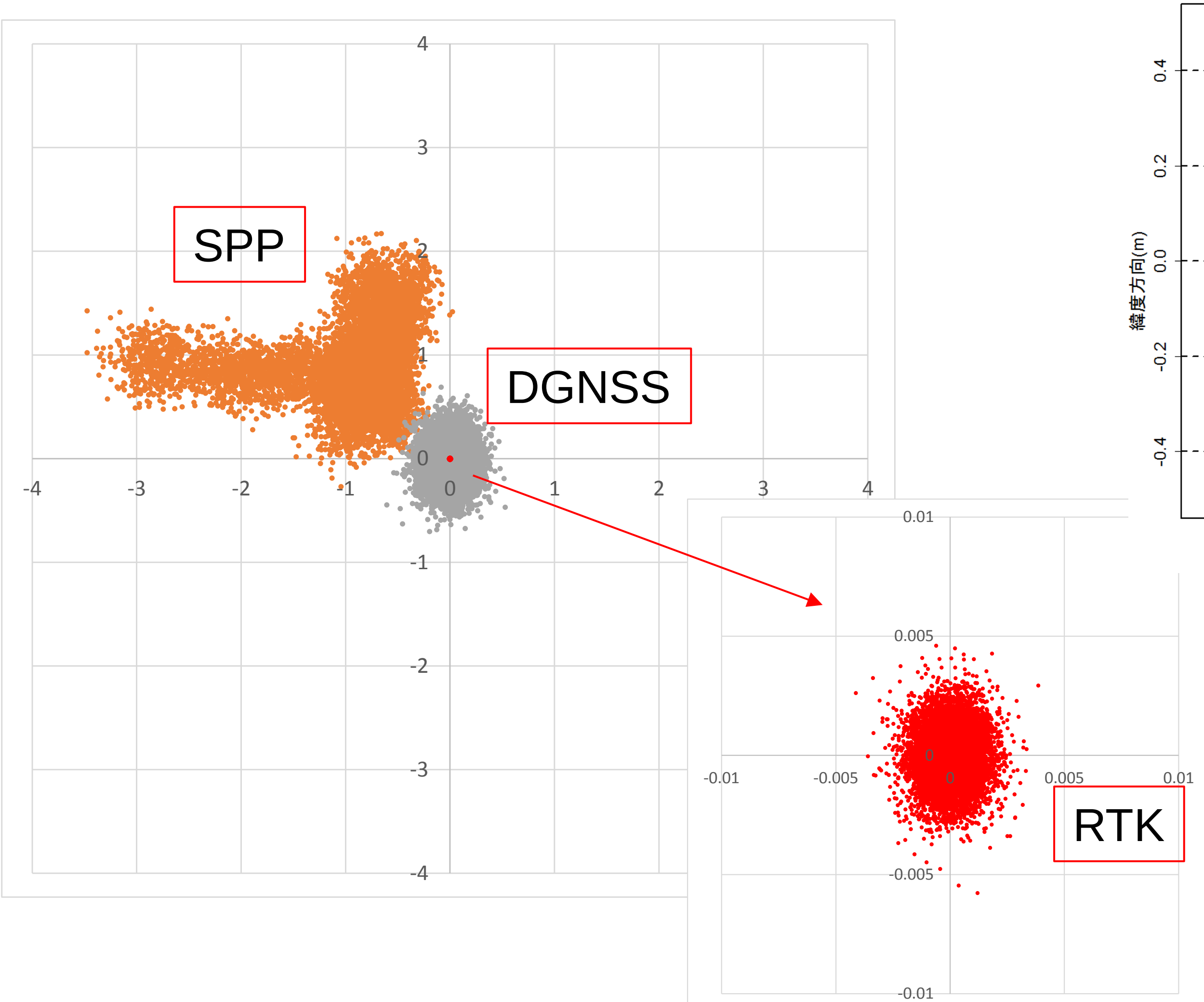
Source/Error	SPP	DGNSS	RTK	PPP
Satellite clock model 1 m (rms)	→	0.0 m	0.0 m	0.01 – 0.1 m
Satellite ephemeris 1 m (rms)	→	0.0 m	0.0 m	0.01 - 0.1 m
Ionospheric delay 2-10 m (zenith) × 3 at 5°	1 - 2 m (zenith)	0.1 - 0.2 m	0.01 m	0.01 m
Tropospheric delay 2.3-2.5m (zenith) × 10 at 5°	0.1 - 0.5 m (zenith)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

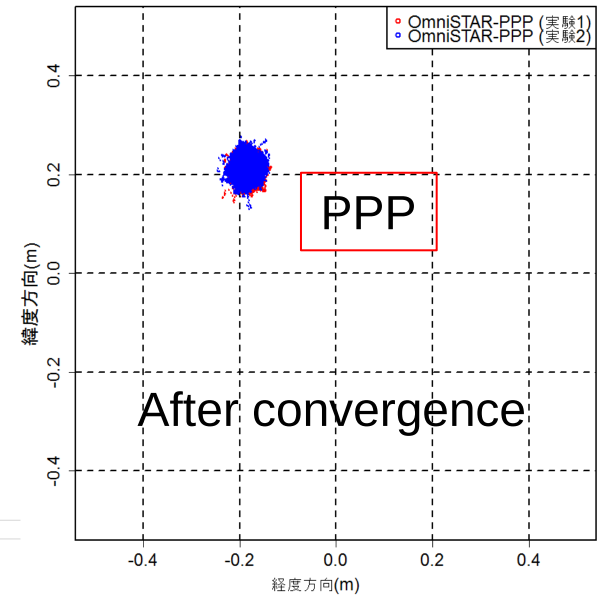
RTK and PPP



RTK	PPP
Reference station	Continuous communication through satellite
Continuous communication	Wait for 5-30 minutes
Instantaneous position	No limitation
10-100km limitation	

Actual performance…





<u>Accuracy (95%)</u>

SPP ： 1.36m

DGNSS ： 0.44m

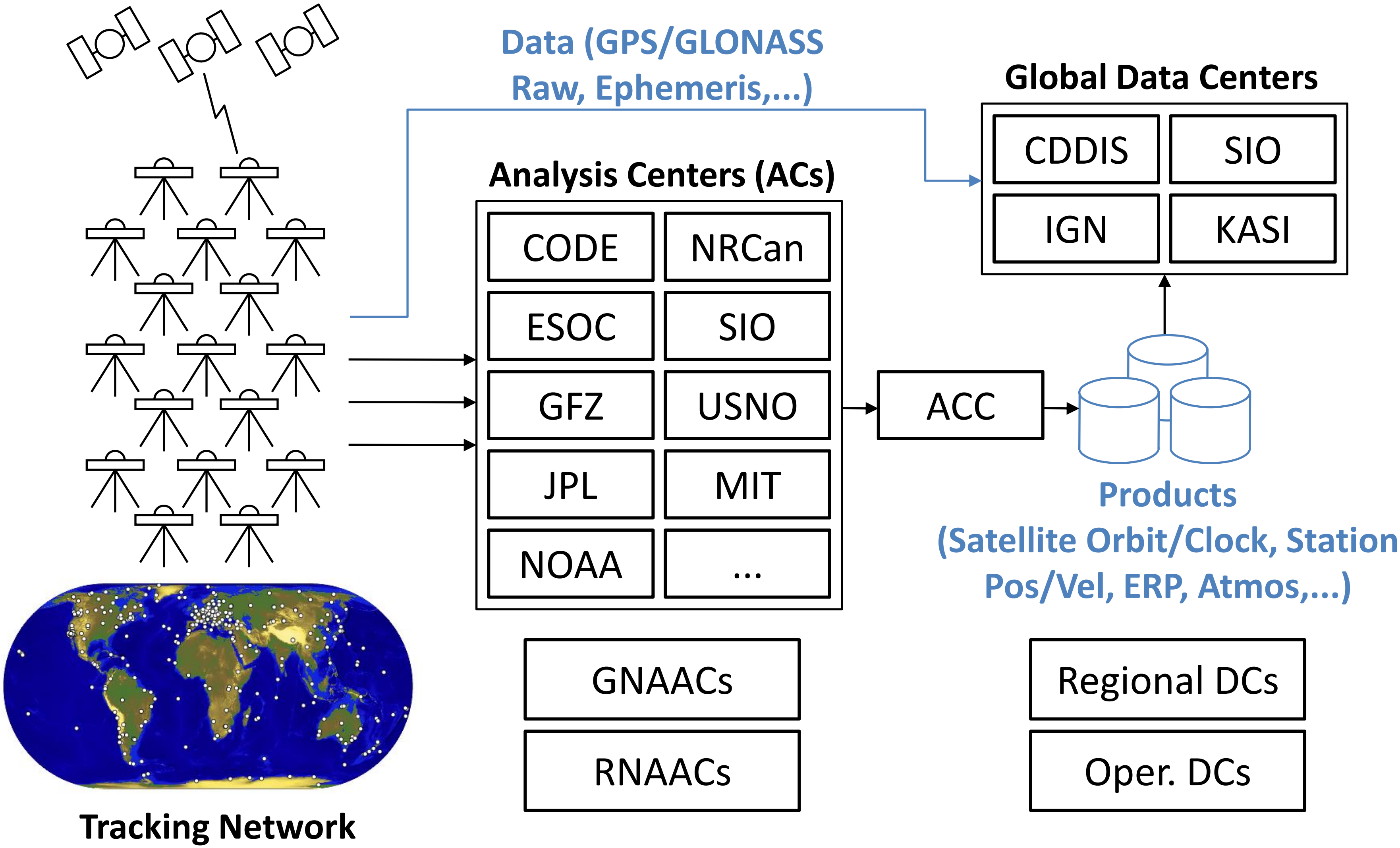
RTK ： 3 mm

PPP ： 3.4 cm

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



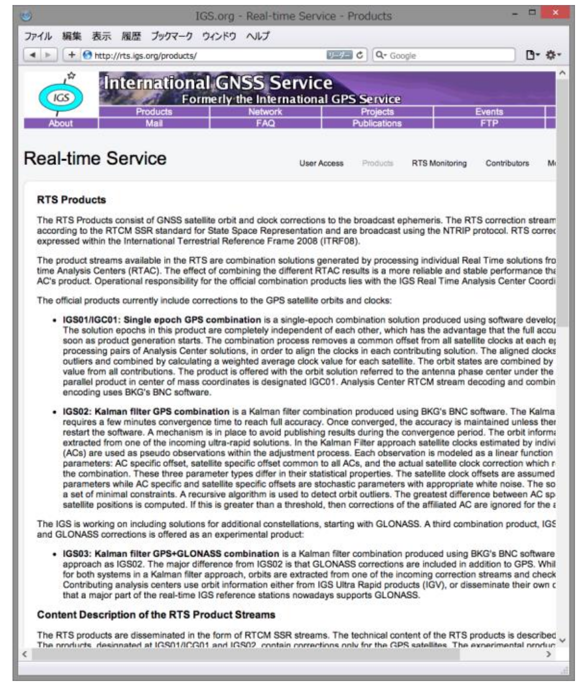
IGS Products

		Final (IGS)	Rapid (IGR)	Ultra-Rapid (IGU)		Broadcast
				Observed	Predicted	
Accuracy	Orbit	~2.5cm	~2.5cm	~3cm	~5cm	~100cm
	Clock	~75ps RMS ~20ps STD	~75ps RMS ~25ps STD	~150ps RMS ~50ps STD	~3ns RMS ~1.5ns STD	~5ns RMS ~2.5ns STD
Latency		12-18 days	17-41 hours	3-9 hours	realtime	realtime
Updates		every Thursday	at 17 UTC daily	at 03, 09, 15, 21 UTC	at 03, 09, 15, 21 UTC	-
Sample Interval	Orbit	15min	15min	15min	15min	daily
	Clock	Sat: 30s Stn: 5min	5min	15min	15min	daily

(2009/8, http://igscb.jpl.nasa.gov/)

IGS Real-time Service

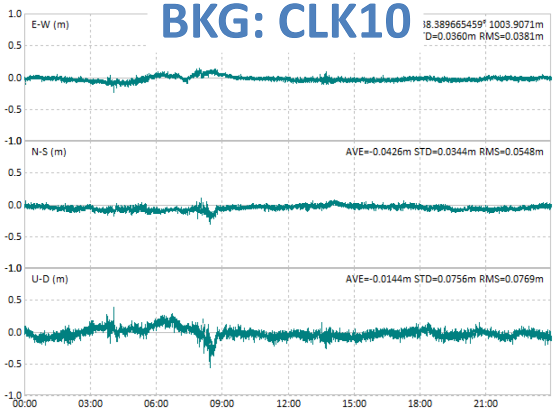
- **Developed by IGS-RTPP**
  - RTCM v.3 MT1057-1068 (SSR)
  - Corrections to broadcast ephemeris
  - Real-time NTRIP stream
  - Interval: 10 s, Latency: 5 - 10 s
  - GPS and GLONASS
- **Analysis Strategy**
  - Orbit: fixed to IGU or estimated
  - Clock: estimated with IGS real-time tracking network



http://rts.igs.org

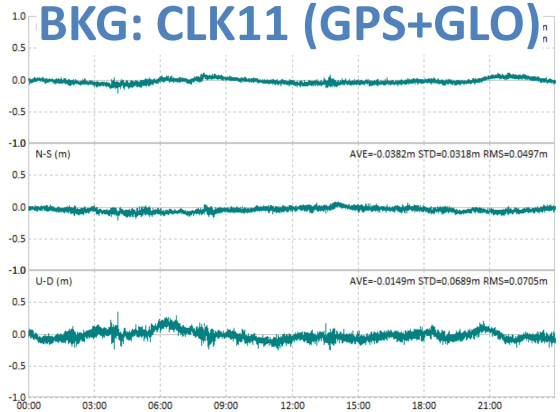
RT-PPP Performance with IGS

BKG: CLK10



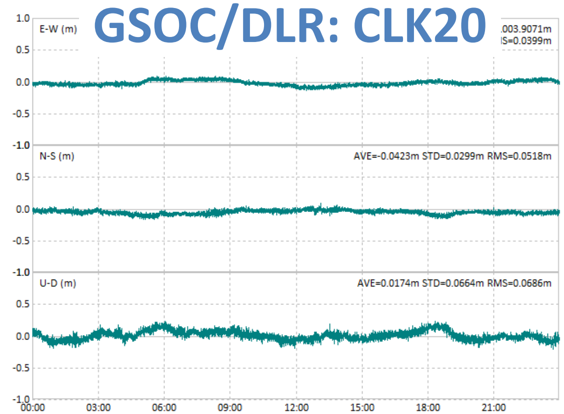
RMS: 3.8, 5.5, 7.7cm

BKG: CLK11 (GPS+GLO)



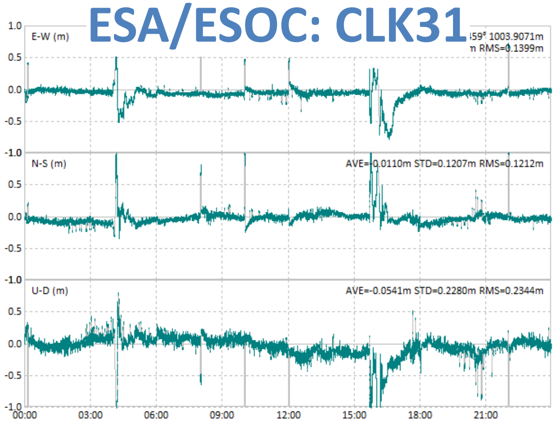
RMS: 3.8, 5.0, 7.1cm

GSOC/DLR: CLK20



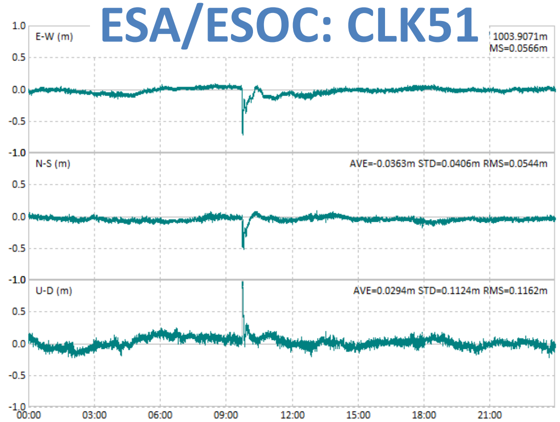
RMS: 4.0, 5.2, 6.9cm

ESA/ESOC: CLK31



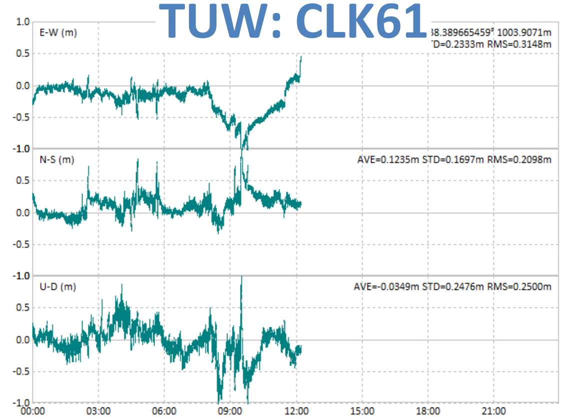
RMS: 14.0, 12.1, 23.4cm

ESA/ESOC: CLK51



RMS: 5.7, 5.4, 11.6cm

TUW: CLK61



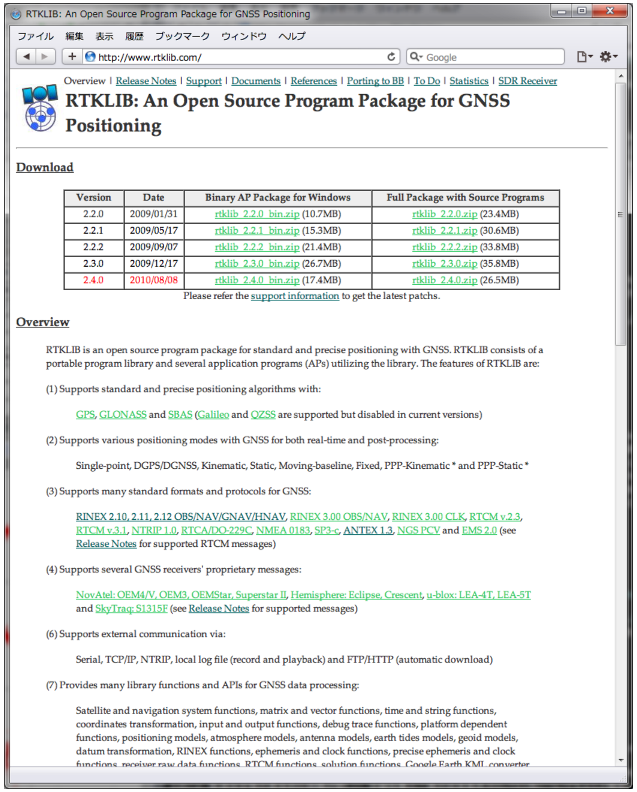
RMS: 23.3, 21.0, 25.0cm

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

RTKLIB Practice (1)

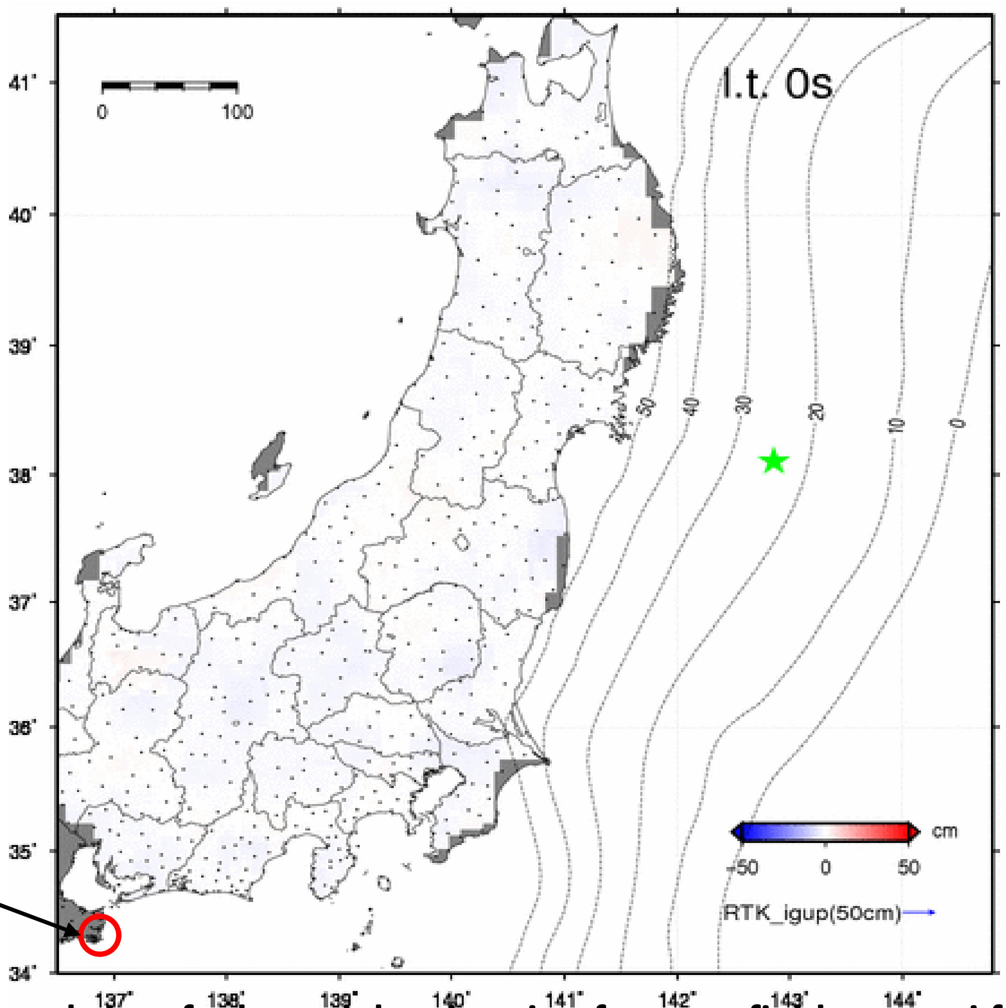
RTKLIB

- **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



Reference Station

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

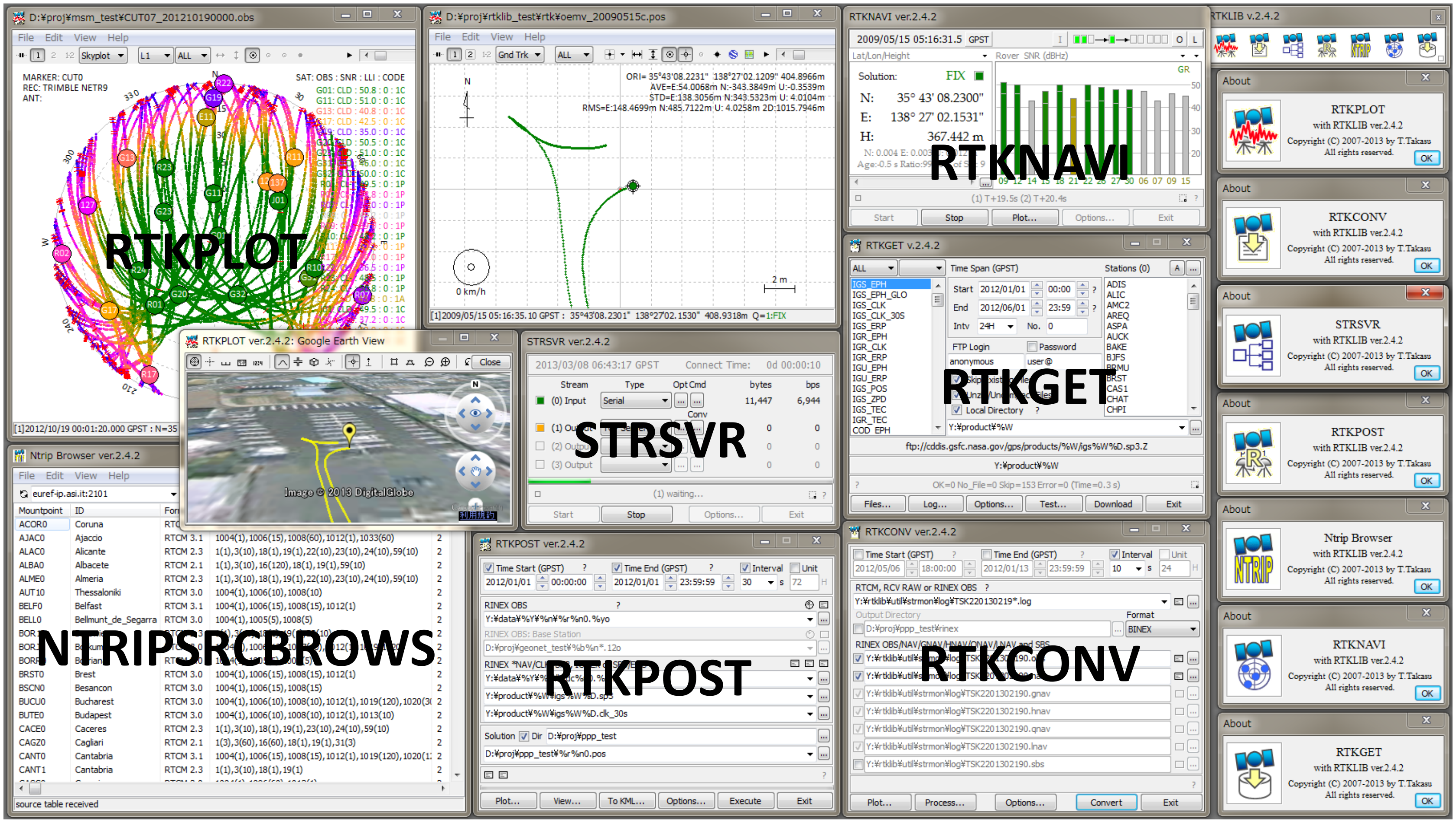
RTKLIB: History

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

RTKLIB: Features

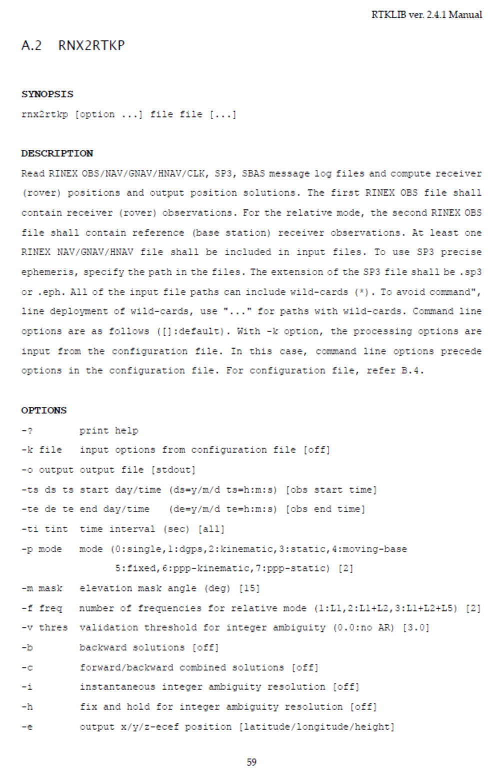
- **Standard and precise positioning algorithms with**:
  - GPS, GLONASS, QZSS, Galileo, BeiDou and SBAS
- **Real-time and post-processing by various modes**:
  - Single, SBAS, DGPS, RTK, Static, Moving-base and PPP
- **Supports many formats/protocols and receivers**:
  - RINEX 2/3, RTCM 2/3, BINEX, 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: 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 ver. 2.4.1 Manual

A.2 RNX2RTKP

SYNOPSIS

```
rnx2rtkp [option ...] file file [...]
```

DESCRIPTION

Read RINEX OBS/NAV/GNAV/HNAV/CLK, SP3, SBAS message log files and compute receiver (rover) positions and output position solutions. The first RINEX OBS file shall contain receiver (rover) observations. For the relative mode, the second RINEX OBS file shall contain reference (base station) receiver observations. At least one RINEX NAV/GNAV/HNAV file shall be included in input files. To use SP3 precise ephemeris, specify the path in the files. The extension of the SP3 file shall be .sp3 or .eph. All of the input file paths can include wild-cards (*). To avoid command", line deployment of wild-cards, use "..." for paths with wild-cards. Command line options are as follows ([]:default). With -k option, the processing options are input from the configuration file. In this case, command line options precede options in the configuration file. For configuration file, refer B.4.

OPTIONS

```
-?        print help
-k file   input options from configuration file [off]
-o output output file [stdout]
-ts ds ts start day/time (ds=y/m/d ts=h:m:s) [obs start time]
-te de te end day/time   (de=y/m/d te=h:m:s) [obs end time]
-ti tint  time interval (sec) [all]
-p mode   mode (0:single,1:dgps,2:kinematic,3:static,4:moving-base
                5:fixed,6:ppp-kinematic,7:ppp-static) [2]
-m mask   elevation mask angle (deg) [15]
-f freq   number of frequencies for relative mode (1:L1,2:L1+L2,3:L1+L2+L5) [2]
-v thres  validation threshold for integer ambiguity (0.0:no AR) [3.0]
-b        backward solutions [off]
-c        forward/backward combined solutions [off]
-i        instantaneous integer ambiguity resolution [off]
-h        fix and hold for integer ambiguity resolution [off]
-e        output x/y/z-ecef position [latitude/longitude/height]
```

59

CLI Command Reference

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
```

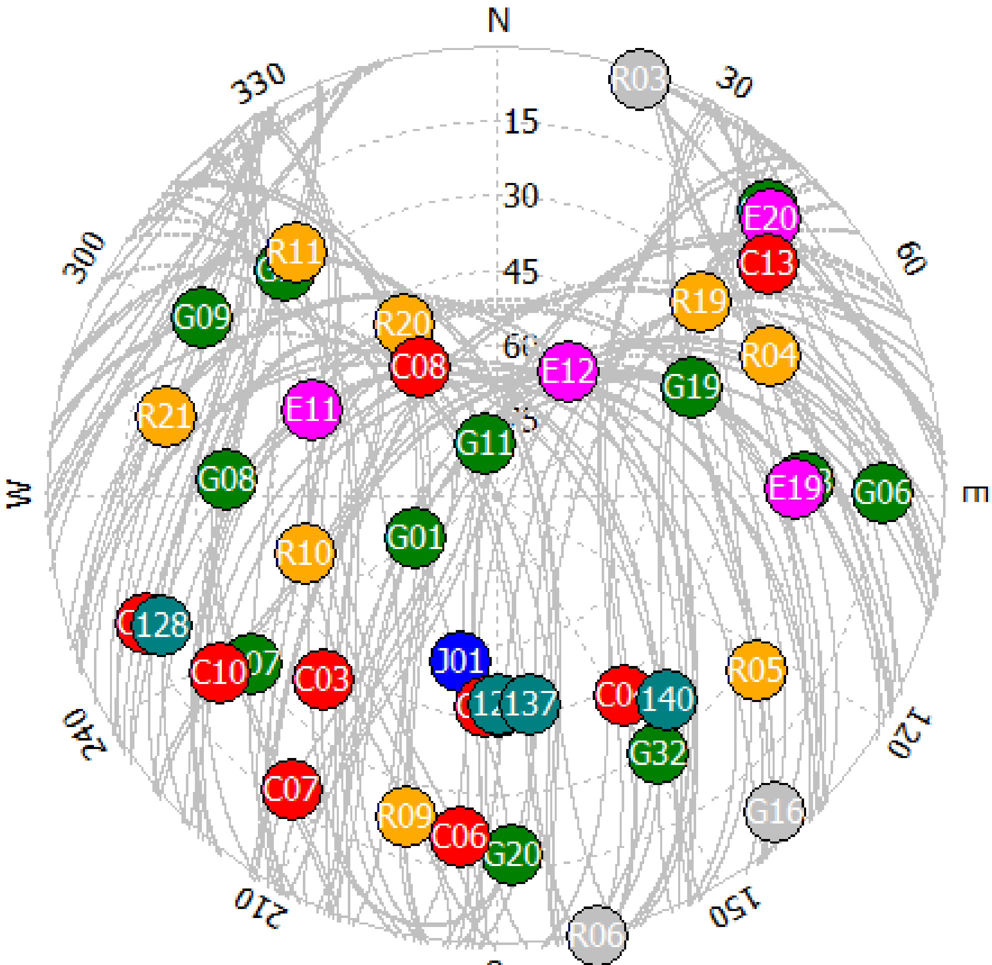
RTKLIB: APIs

```
/* 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(),covenu(),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(),readrnxt(),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_oem3f(),input_ubxf(),input_ss2f(),input_cresf()
/* rtcm functions */
init_rtcm(),free_rtcm(),input_rtcm2(),input_rtcm3(),input_rtcm2f(),input_rtcm3f()
/* solution functions */
readsol(),readsolt(),outsolheads(),outsols(),outsolexs(),outsolhead(),outsol(),outsolex(),setsolopt(),setsolformat(),
outnmea_rmc(),outnmea_gga(),outnmea_gsa(),outnmea_gsv(),
/* SBAS functions */
sbsreadmsg(),sbsreadmsgt(),sbsoutmsg(),sbsupdatestat(),sbsdecodemsg(),sbssatpos(),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(),strstat(),strsum(), strsetopt(),
strgettime()
/* stream server functions */
strsvrinit(),strsvrstart(),strsvrstop(),strsvrstat()
/* rtk server functions */
rtksvrinit(),rtksvrstart(),rtksvrstop(),rtksvrlock(),rtksvrunlock(),rtksvrostat(),rtksvrsstat() ...
```

RTKLIB: Supported Receivers

Format	Data Message Types							
	GPS Raw Meas Data	GLONASS Raw Meas	GPS Ephemeris	GLONASS Ephemeris	ION/UTC Parameters	Antenna Info	SBAS Messages	Others
RTCM v.2.3	Type 18, 19	Type 18, 19	Type 17	-	-	Type 3, 22	-	Type 1, 9, 14, 16
RTCM v.3.1	Type 1002, 1004	Type 1010, 1012	Type 1019	Type 1020	-	Type 1005, 1006, 1007, 1008, 1033	-	SSR corrections
NovAtel OEM4/V, OEMStar	RANGEB, RANGECMPB	RANGEB, RANGECMPB	RAWEPHEMB	GLO-EPHEMERISB	IONUTCB	-	RAWWAAS-FRAMEB	-
NovAtel OEM3	RGEB, RGED	-	REPB	-	IONB, UTCB	-	FRMB	-
NovAtel Superstar II	ID#23	-	ID#22	-	-	-	ID#67	ID#20, #21
u-blox LEA-4T, LEA-5T	UBX RXM-RAW	-	UBX RXM-SFRB	-	UBX RXM-SFRB	-	UBX RXM-SFRB	-
Hemisphere Crescent, Eclipse	bin 96	-	bin 95	-	bin 94	-	bin 80	-
SkyTraq S1315F	msg 0xDD (221)	-	msg 0xE0 (224)	-	msg 0xE0 (224)	-	-	msg 0xDC (220)
JAVAD (GRIL/GREIS)	[R*],[r*],[*R],[*r],[P*],[p*],[*p],[D*],[*d],[E*],[*E],[F*]	[R*],[r*],[*R],[*r],[P*],[p*],[*p],[D*],[*d],[E*],[*E],[F*]	[GE],[GD],[gd]	[NE],[LD]	[IO],[UO],[GD]	-	[WD]	[~~],[::],[RD],[SI],[NN],[TC], QZSS Data, Galileo Data
Furuno GW10 II	msg 0x08	-	msg 0x24	-	msg 0x26	-	msg 0x03	msg 0x20

Multi-GNSS Support

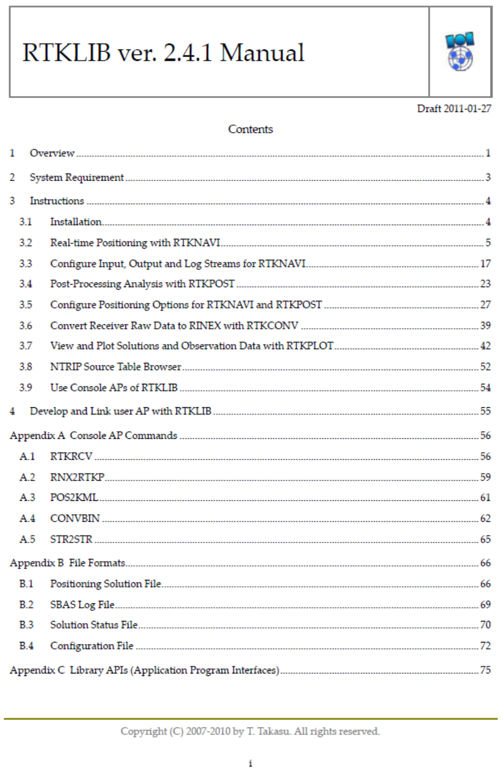


2013-06-12 10:20 GPST
Visibility at Tokyo by RTKPLOT

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

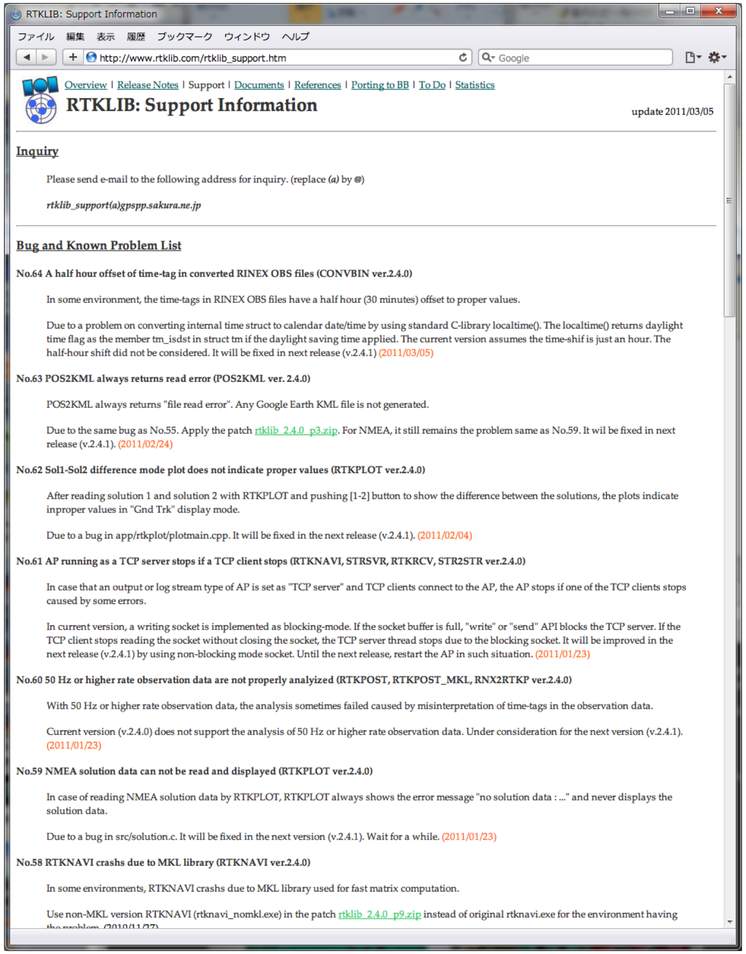
 # Total (39)
(El>10deg)

RTKLIB: References


RTKLIB ver. 2.4.1 Manual

Draft 2011-01-27

Contents


RTKLIB: Support Information

ファイル 編集 表示 履歴 ブックマーク ウィンドウ ヘルプ

http://www.rtklib.com/rtklib_support.htm

Overview | Release Notes | Support | Documents | References | Porting to BB | To Do | Statistics

RTKLIB: Support Information

update 2011/03/05

Inquiry

Please send e-mail to the following address for inquiry. (replace *(a)* by @)

rtklib_support(a)gpspp.sakura.ne.jp

Bug and Known Problem List

No.64 A half hour offset of time-tag in converted RINEX OBS files (CONVBIN ver.2.4.0)

In some environment, the time-tags in RINEX OBS files have a half hour (30 minutes) offset to proper values.

Due to a problem on converting internal time struct to calendar date/time by using standard C-library localtime(). The localtime() returns daylight time flag as the member tm_isdst in struct tm if the daylight saving time applied. The current version assumes the time-shif is just an hour. The half-hour shift did not be considered. It will be fixed in next release (v.2.4.1) (2011/03/05)

No.63 POS2KML always returns read error (POS2KML ver. 2.4.0)

POS2KML always returns "file read error". Any Google Earth KML file is not generated.

Due to the same bug as No.55. Apply the patch rtklib_2.4.0_p3.zip. For NMEA, it still remains the problem same as No.59. It wil be fixed in next release (v.2.4.1). (2011/02/24)

No.62 Sol1-Sol2 difference mode plot does not indicate proper values (RTKPLOT ver.2.4.0)

After reading solution 1 and solution 2 with RTKPLOT and pushing [1-2] button to show the difference between the solutions, the plots indicate inproper values in "Gnd Trk" display mode.

Due to a bug in app/rtkplot/plotmain.cpp. It will be fixed in the next release (v.2.4.1). (2011/02/04)

No.61 AP running as a TCP server stops if a TCP client stops (RTKNAVI, STRSVR, RTKRCV, STR2STR ver.2.4.0)

In case that an output or log stream type of AP is set as "TCP server" and TCP clients connect to the AP, the AP stops if one of the TCP clients stops caused by some errors.

In current version, a writing socket is implemented as blocking-mode. If the socket buffer is full, "write" or "send" API blocks the TCP server. If the TCP client stops reading the socket without closing the socket, the TCP server thread stops due to the blocking socket. It will be improved in the next release (v.2.4.1) by using non-blocking mode socket. Until the next release, restart the AP in such situation. (2011/01/23)

No.60 50 Hz or higher rate observation data are not properly analyized (RTKPOST, RTKPOST_MKL, RNX2RTKP ver.2.4.0)

With 50 Hz or higher rate observation data, the analysis sometimes failed caused by misinterpretation of time-tags in the observation data.

Current version (v.2.4.0) does not support the analysis of 50 Hz or higher rate observation data. Under consideration for the next version (v.2.4.1). (2011/01/23)

No.59 NMEA solution data can not be read and displayed (RTKPLOT ver.2.4.0)

In case of reading NMEA solution data by RTKPLOT, RTKPLOT always shows the error message "no solution data : ..." and never displays the solution data.

Due to a bug in src/solution.c. It will be fixed in the next version (v.2.4.1). Wait for a while. (2011/01/23)

No.58 RTKNAVI crashes due to MKL library (RTKNAVI ver.2.4.0)

In some environments, RTKNAVI crashs due to MKL library used for fast matrix computation.

Use non-MKL version RTKNAVI (rtknavi_nomkl.exe) in the patch rtklib_2.4.0_p9.zip instead of original rtknavi.exe for the environment having

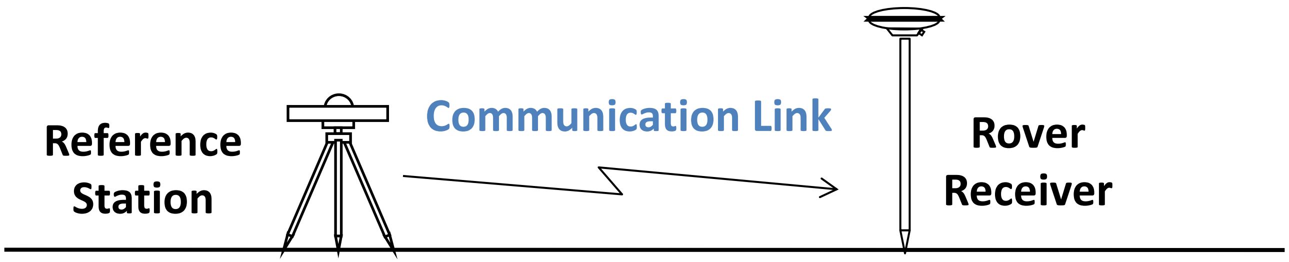
rtklib_2.4.2/doc/manual_2.4.2.pdf

http://www.rtklib.com

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).

RTCM

- 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.

NTRIP

- 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

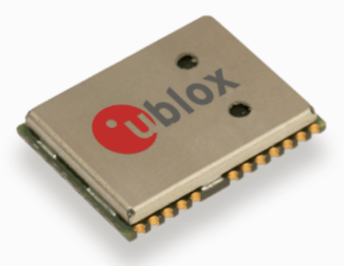
NEO-M8P

u-blox M8 high precision GNSS modules

Standard | Professional | Automotive

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



NEO-M8P
12.2 x 16 x 2.4 mm

Product variants

NEO-M8P-0	u-blox M8 high precision module with rover functionality
NEO-M8P-2	u-blox M8 high precision module with rover and base station functionality

Order online | Evaluation Kit

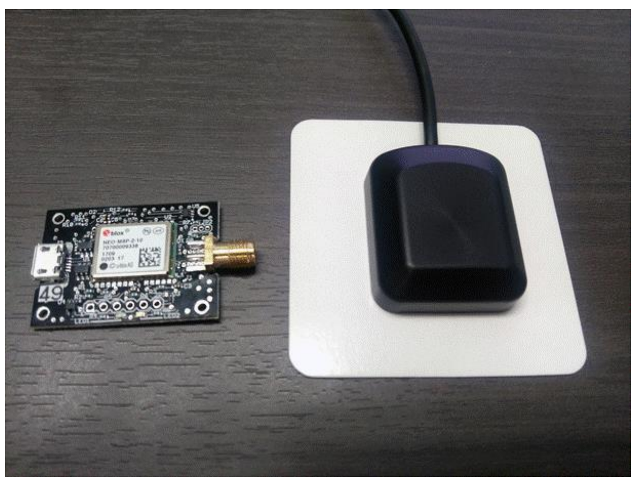
Model	Category				GNSS					Supply	Interfaces				Features								Grade		
	Standard Precision GNSS	High Precision GNSS	Dead Reckoning	Timing	GPS / QZSS	GLONASS	Galileo	BeiDou	Number of Concurrent GNSS	2.7 V – 3.6 V	UART	USB	SPI	DDC (I^2C compliant)	Programmable (Flash)	Data logging	Carrier phase output	Additional SAW	Additional LNA	RTK rover	Base station with survey-in	Timepulse	Standard	Professional	Automotive
NEO-M8P-0		•			•	•		•	2	•	•	•	•	•	•	•	•	•	•	•		1			
NEO-M8P-2		•			•	•		•	2	•	•	•	•	•	•	•	•	•	•	•	•	1			

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



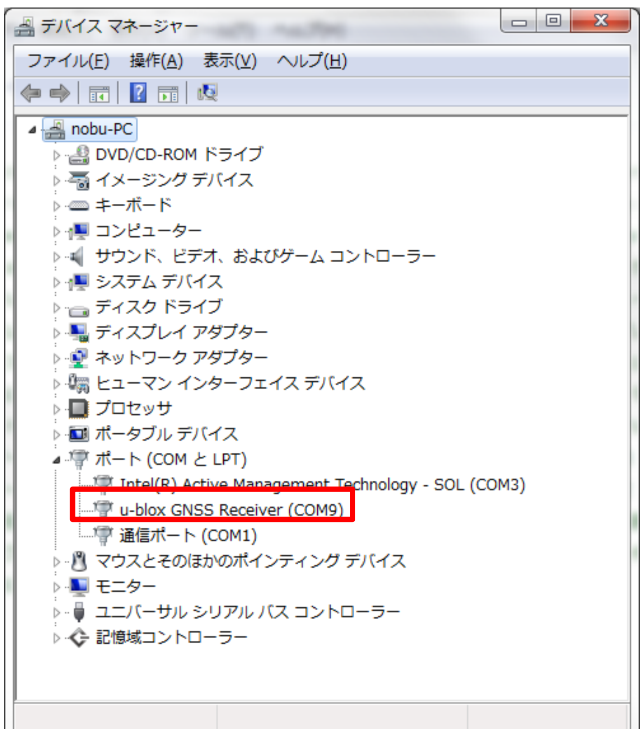
micro USB

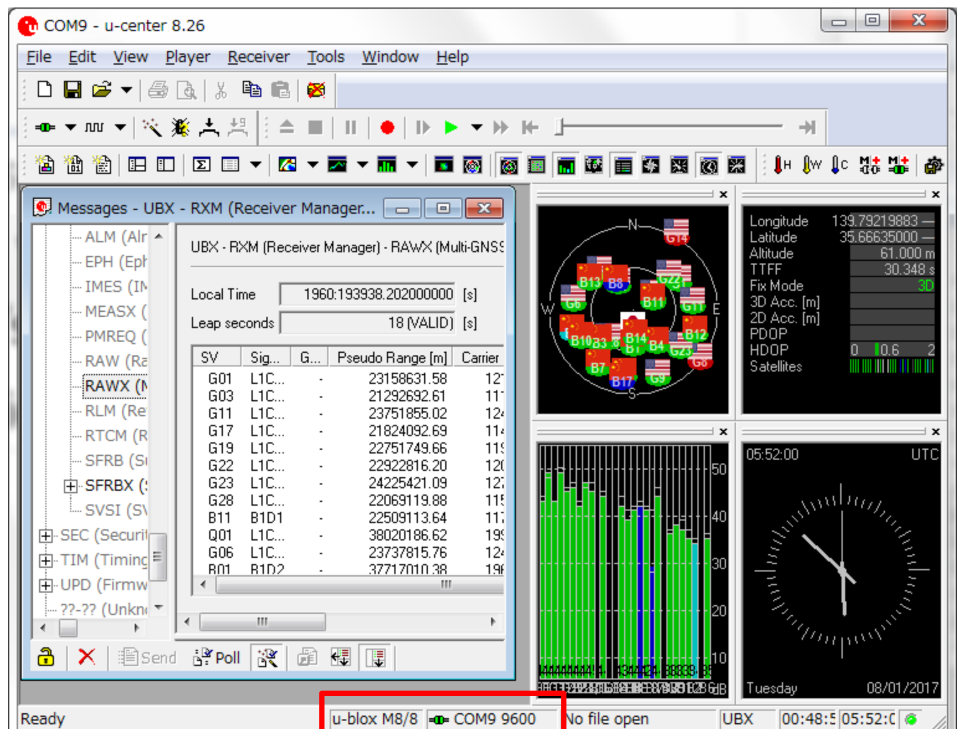
u-blox
u-center v8.26

your Laptop PC

Connection

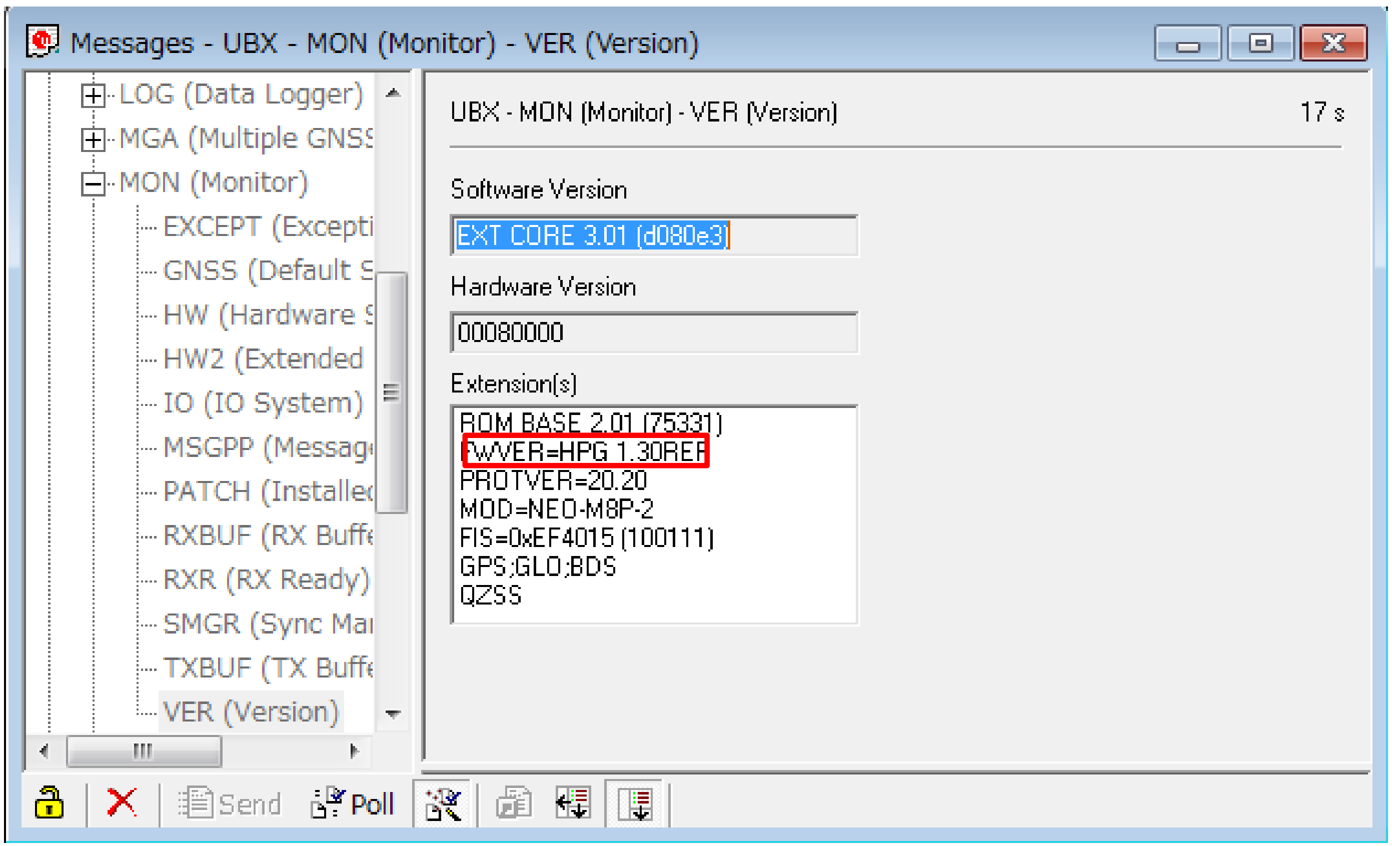
- Start u-center and select Receiver->Port
- You will see COM*. You can check your COM port in your laptop’s devise manager
- If you have any difficulties(win10), please catch us.





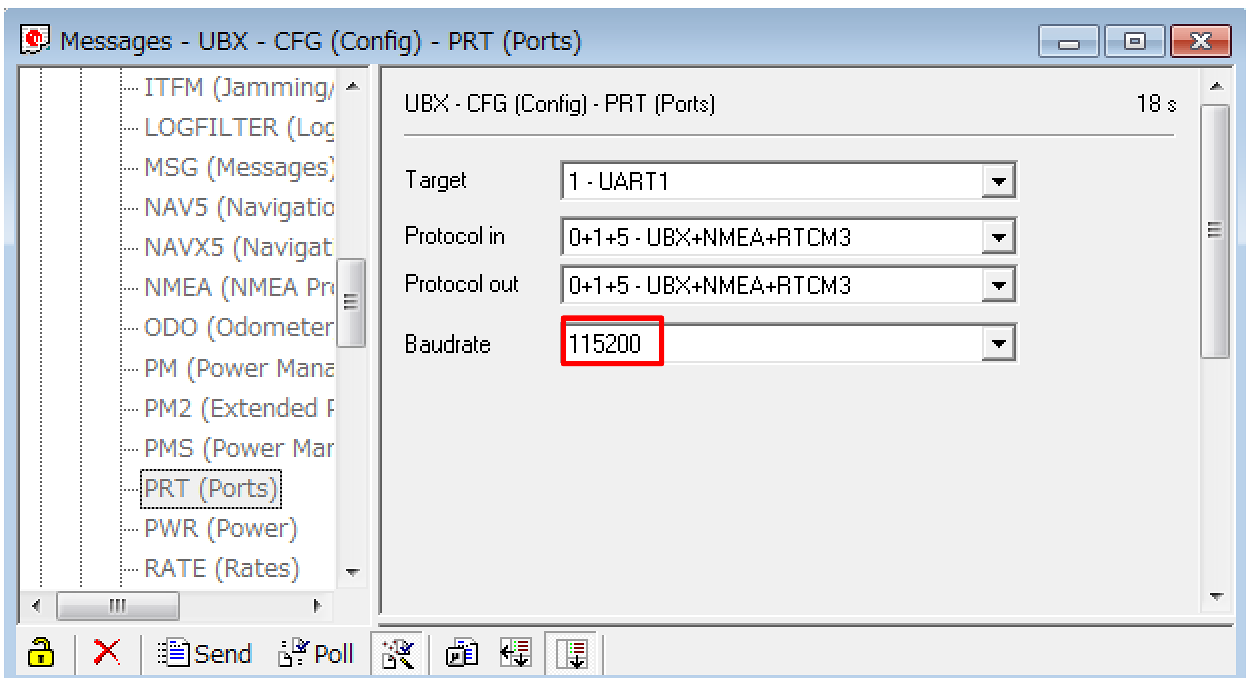
Firmware Check

- View->Message View->UBX->MON->VER



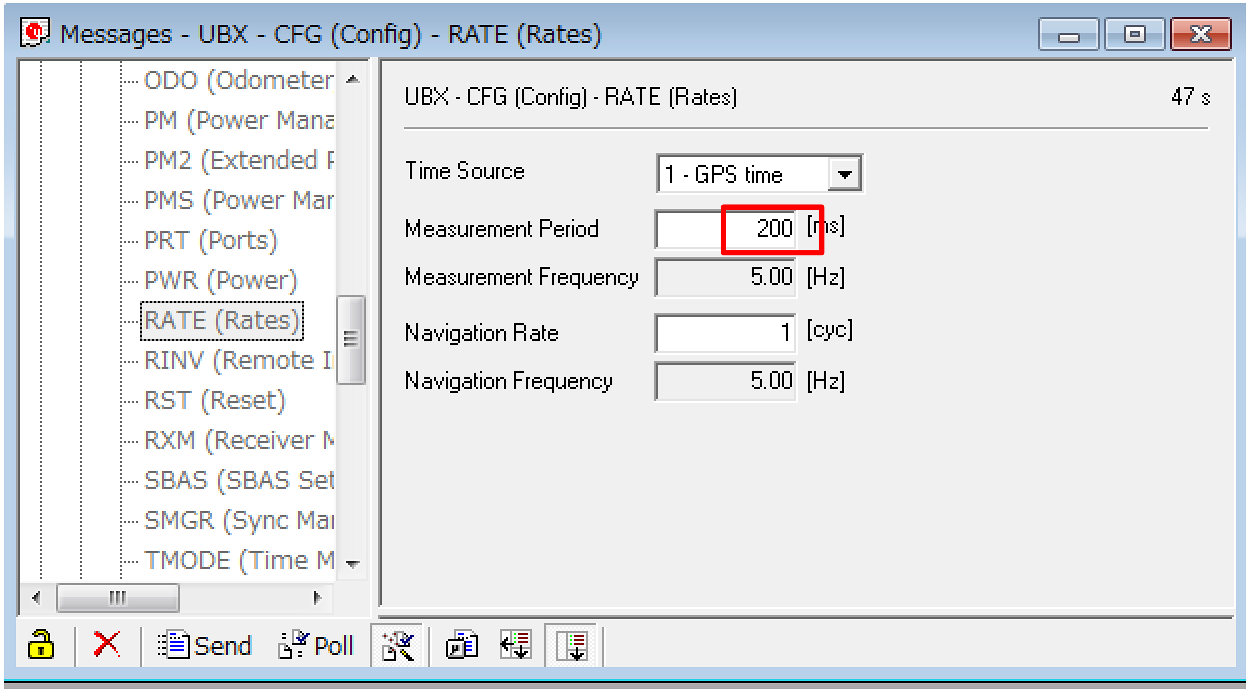
Baud rate Check

- View->Message View->UBX->CFG->PRT
- Please change from 9600 to 115200



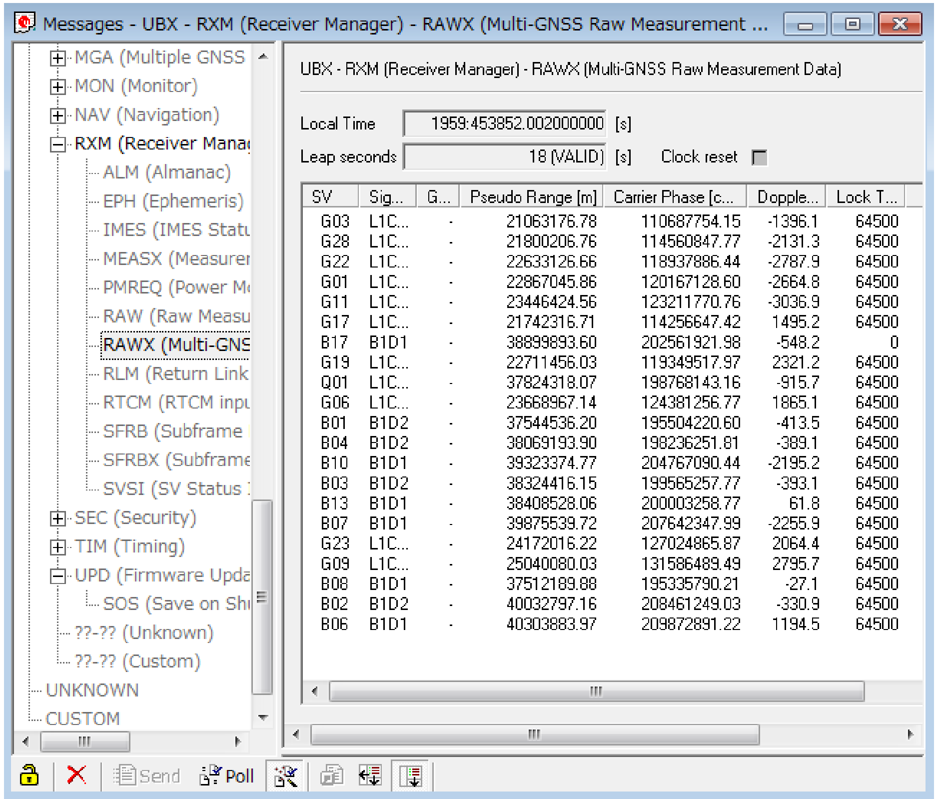
If you want to change the rate…

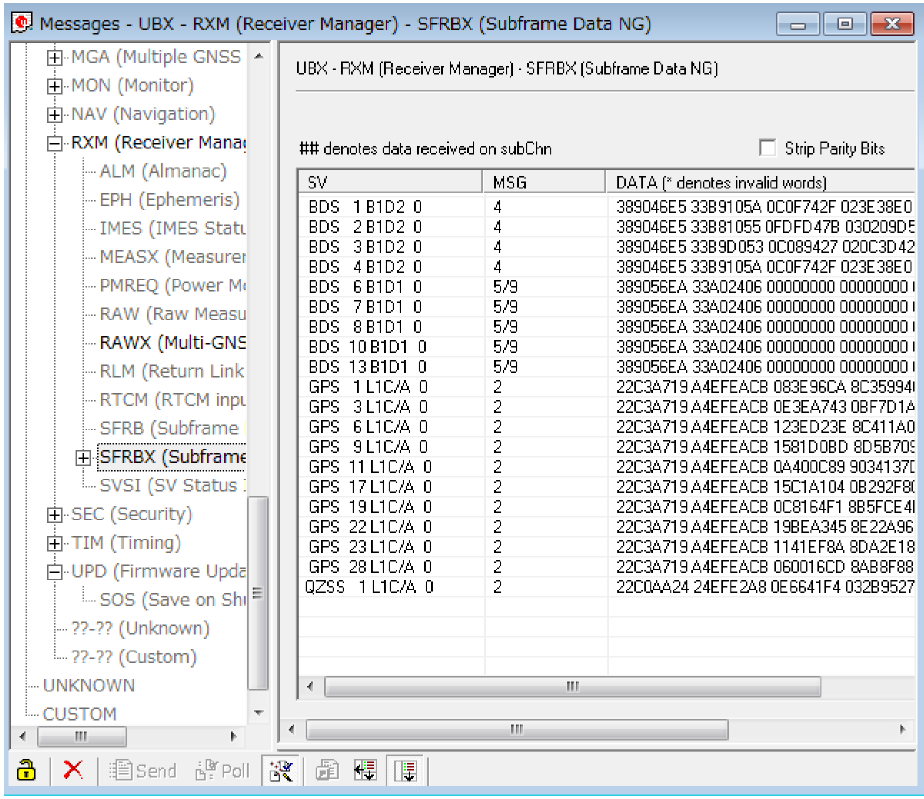
- View->Message View->UBX->CFG->RATE
- Please change the measurement period



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,

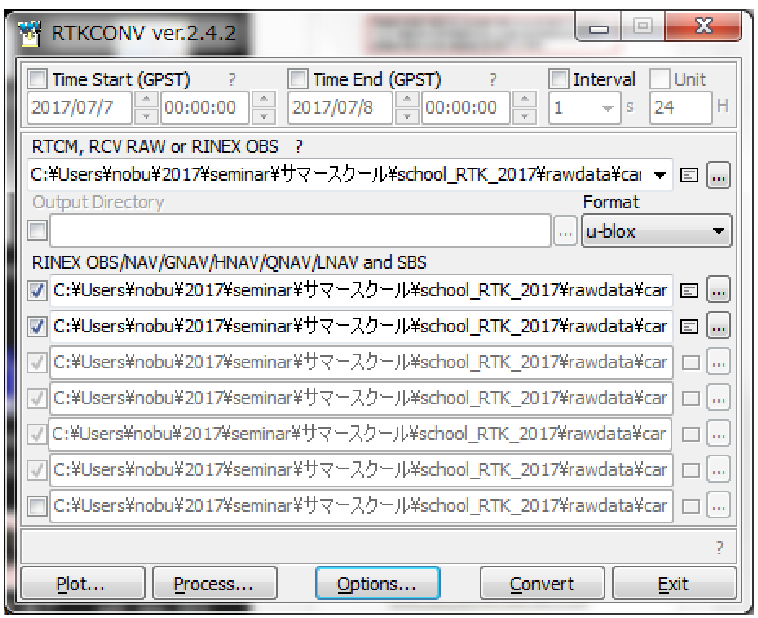
  (via same antenna, perfect condition)
- Switch from GPS/QZS/GLO to GPS/QZS/BEI

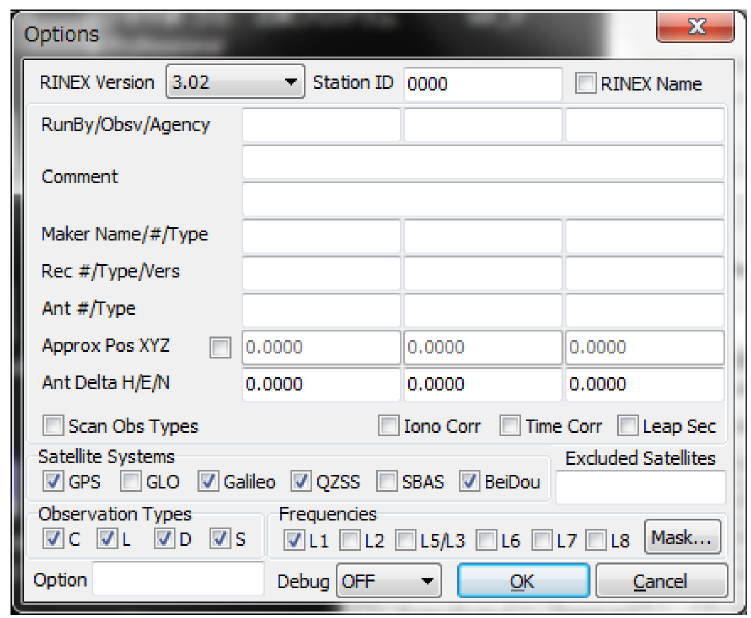
Please check them by yourself after you go back to home.
If you need an information how to set the reference station,
please refer to the website (GNSS TUTOR).

http://www.denshi.e.kaiyodai.ac.jp/gnss_tutor/experiment.html

RTKCONV

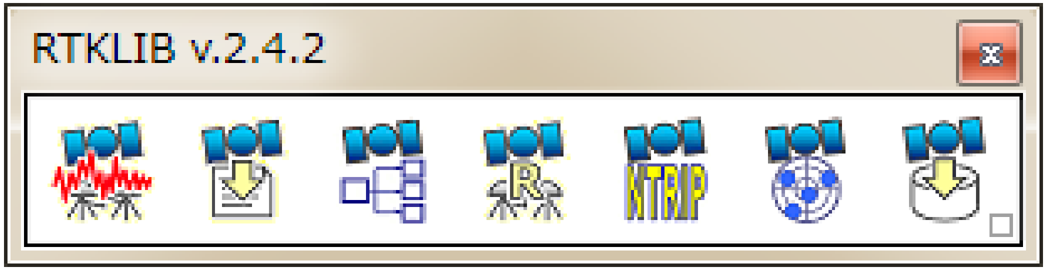
- When you post-process of GNSS raw data, RINEX format is quite popular.
- You can convert u-blox/SkyTraq raw data to RINEX format using rtkconv.exe.
- In the case of Trimble T02 file, you can use “Convert To RINEX” which is available in the Trimble website.





Use RTKLIB (1)

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

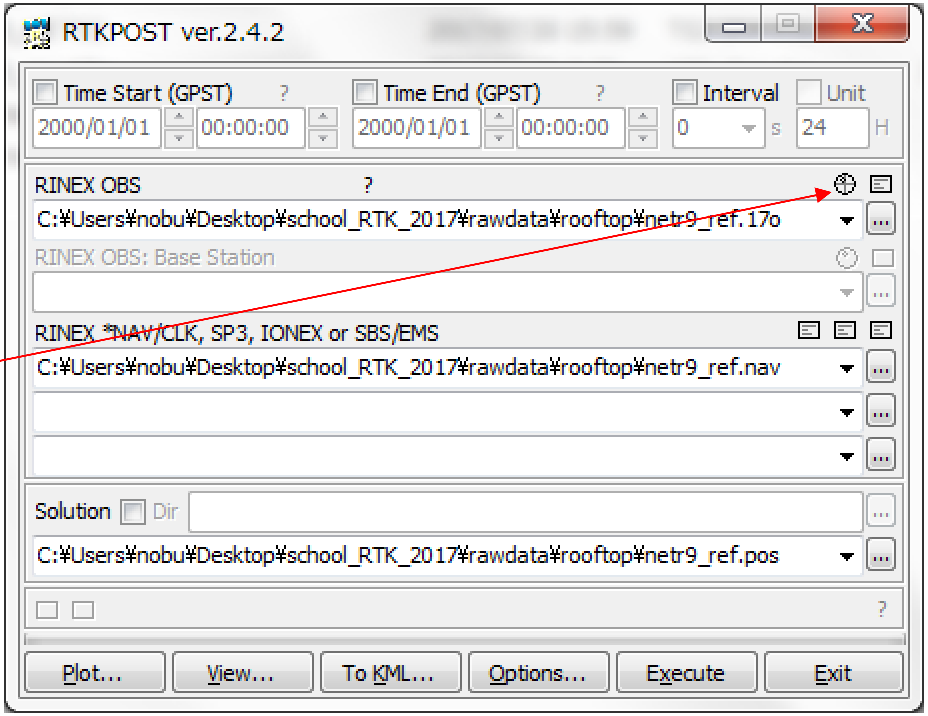


RTKPLOT STRSVR NTRIPBRS RTEGET

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

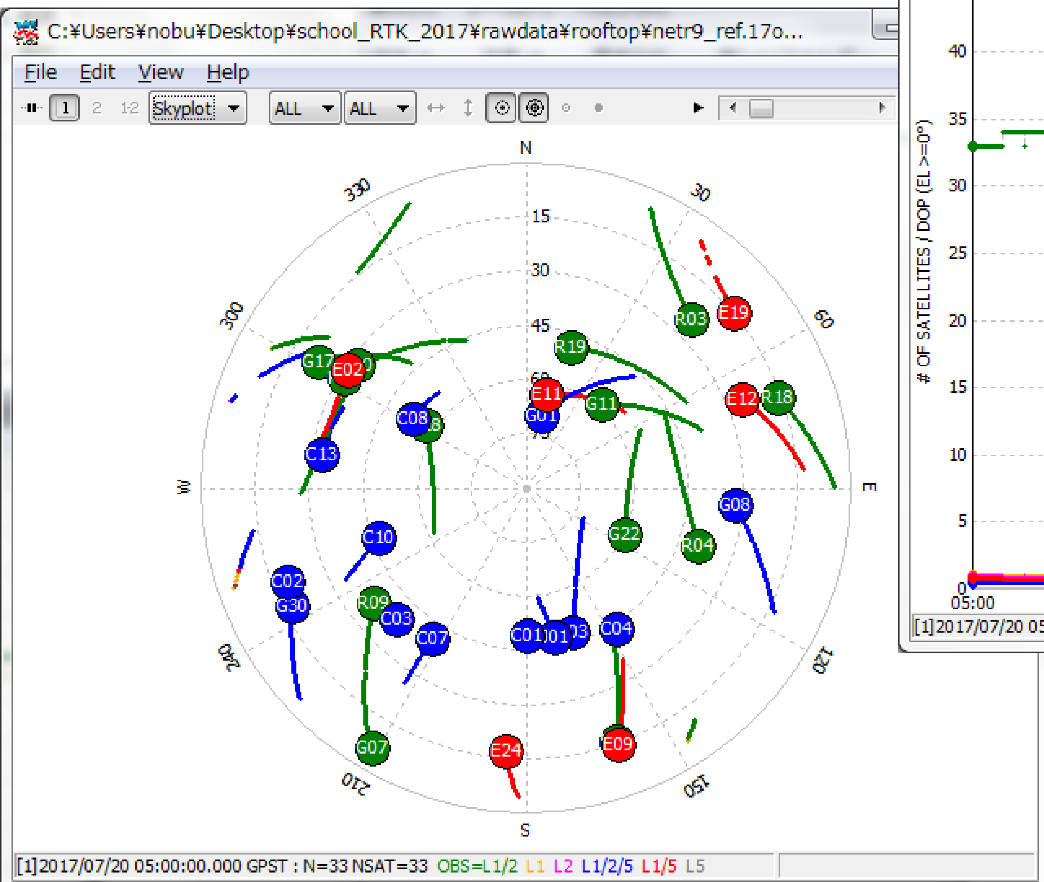
E: GAL

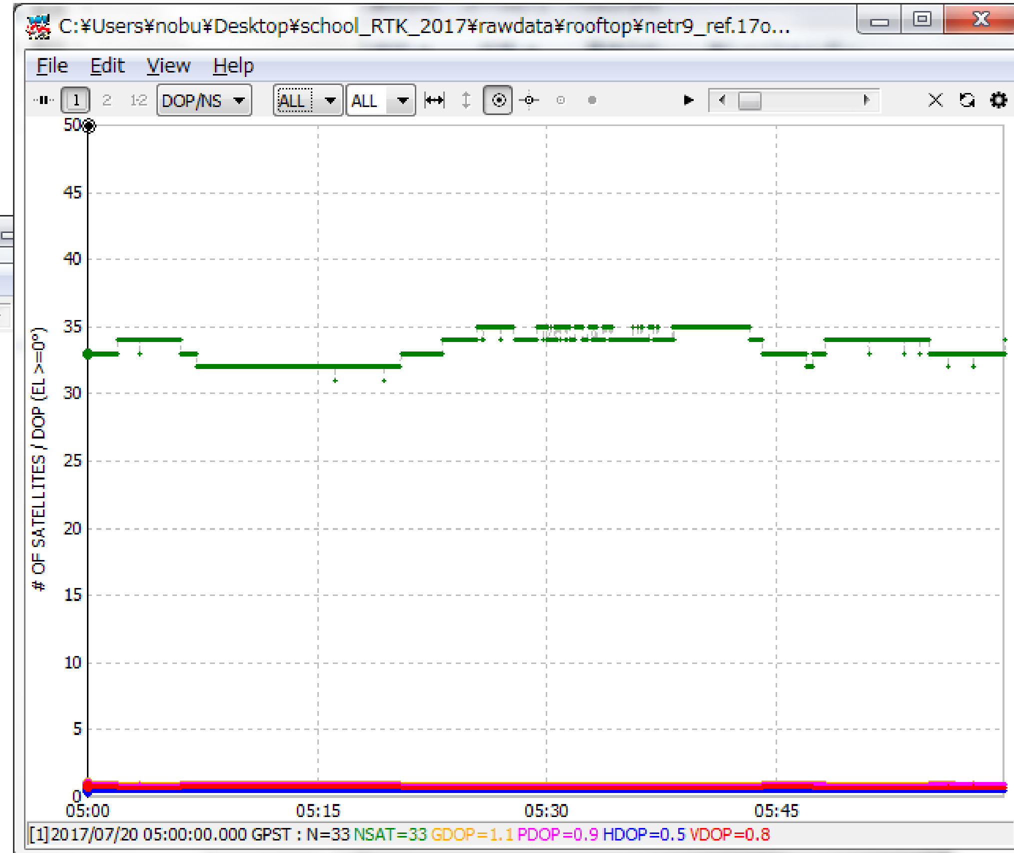
J: QZS

C: BEI

Use RTKLIB (4)

Skyplot

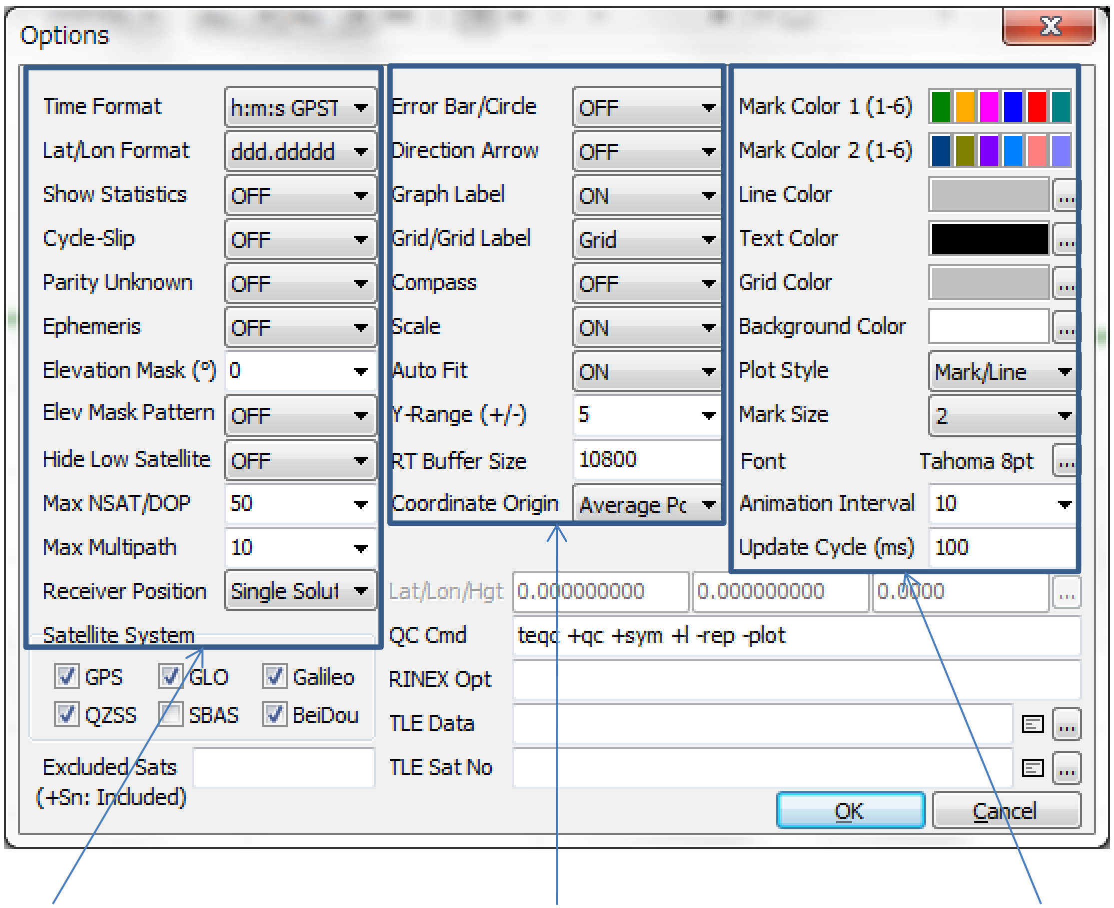




# of Visible Satellites and DOP

Use RTKLIB (5)

RTKPLOT - Options

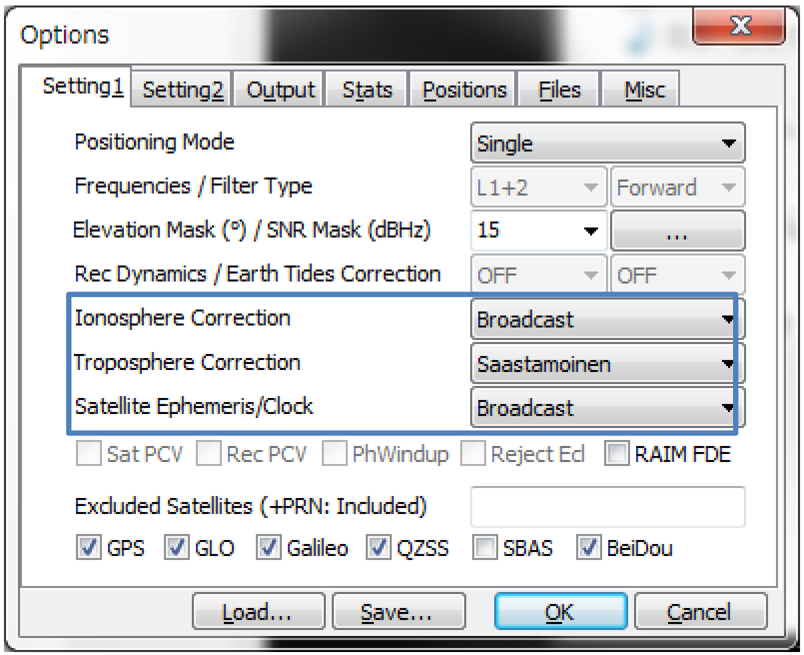


OBS Data Options **Solution Data Options** **Common Options**

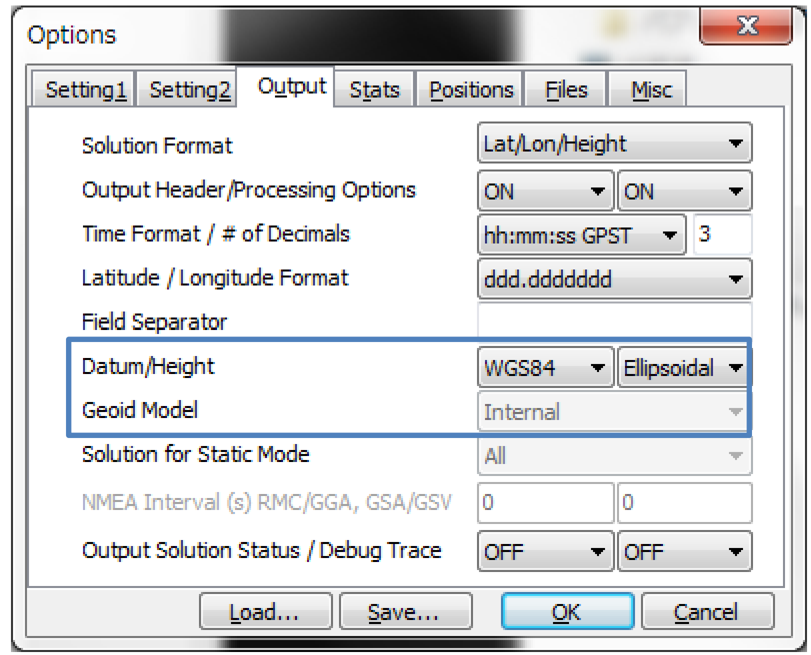
Use RTKLIB (6)

RTKPOST - Options

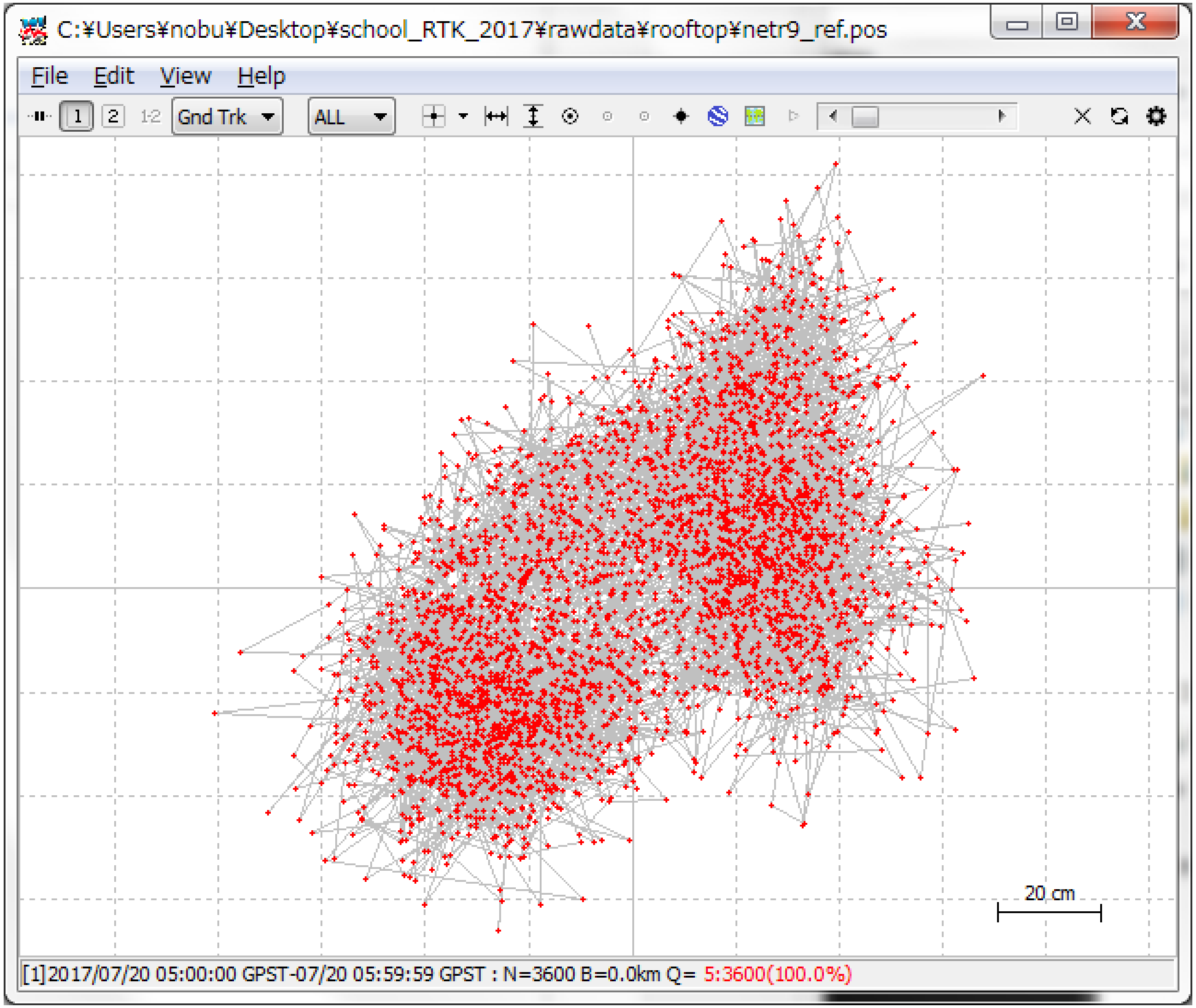
Setting1



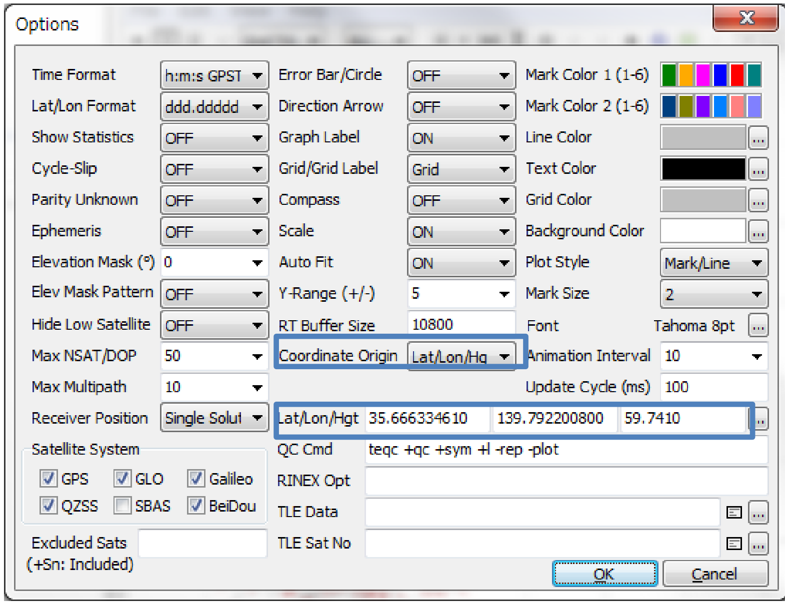
Output



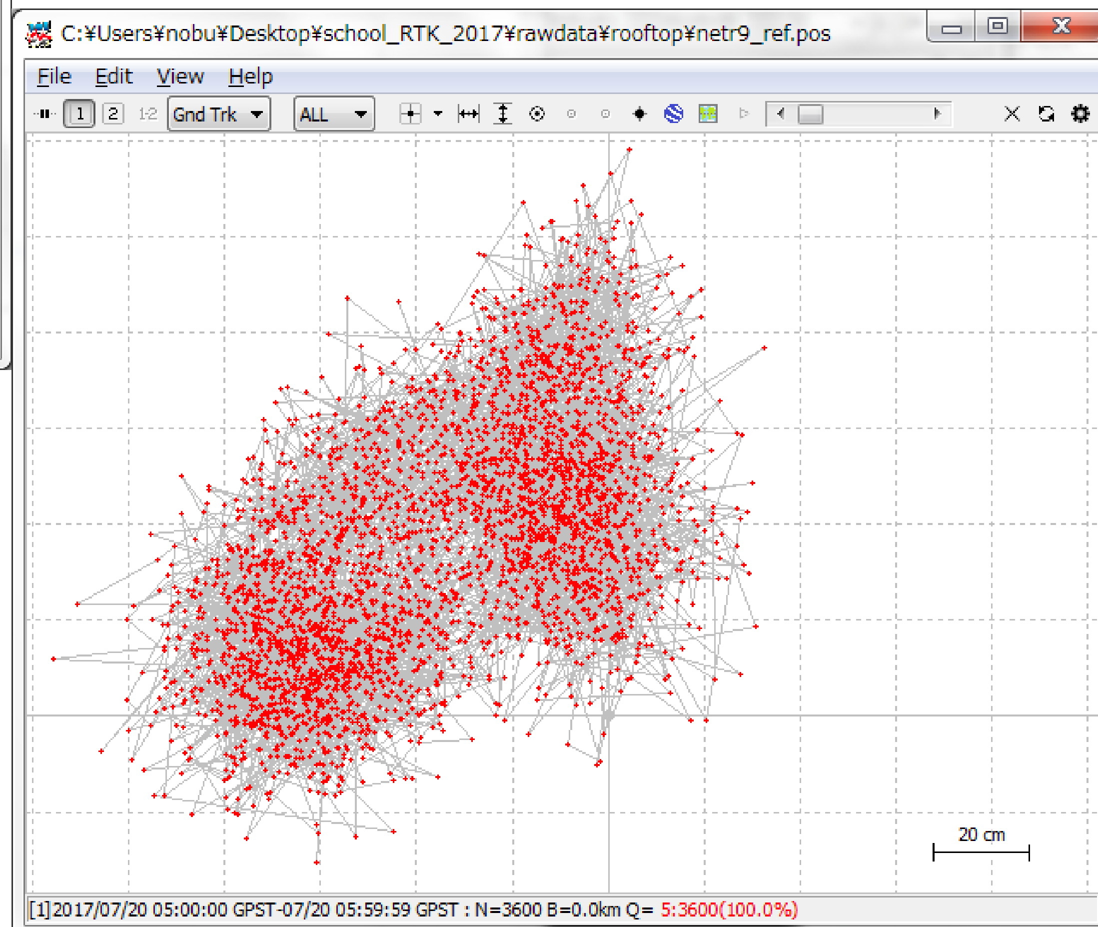
Single Point Positioning



Coordinate Origin



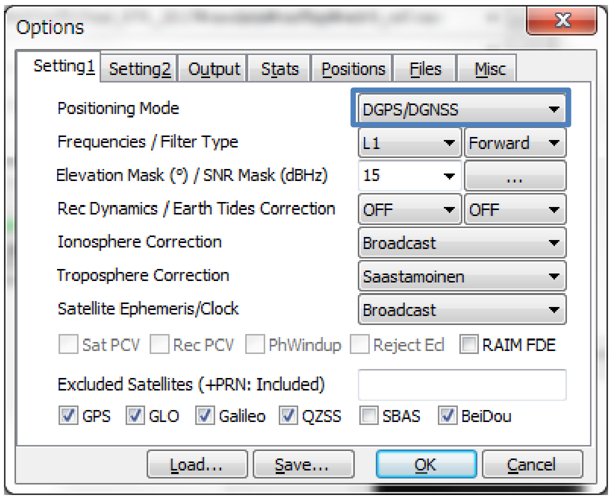
If you change the coordinate origin as a precise reference position, (35.66633461, 139.7922008, 59.741) you see bias like below.

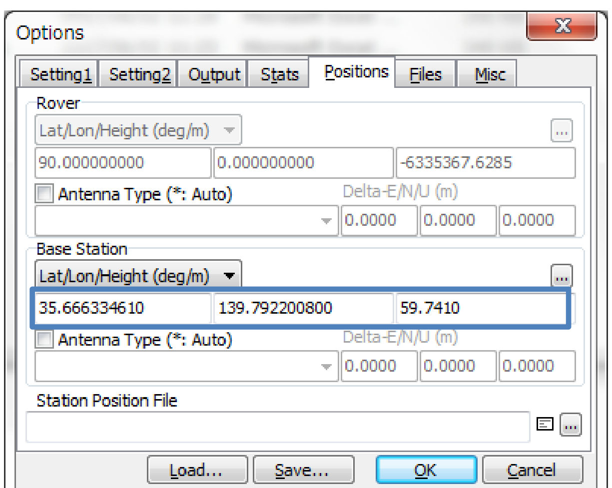


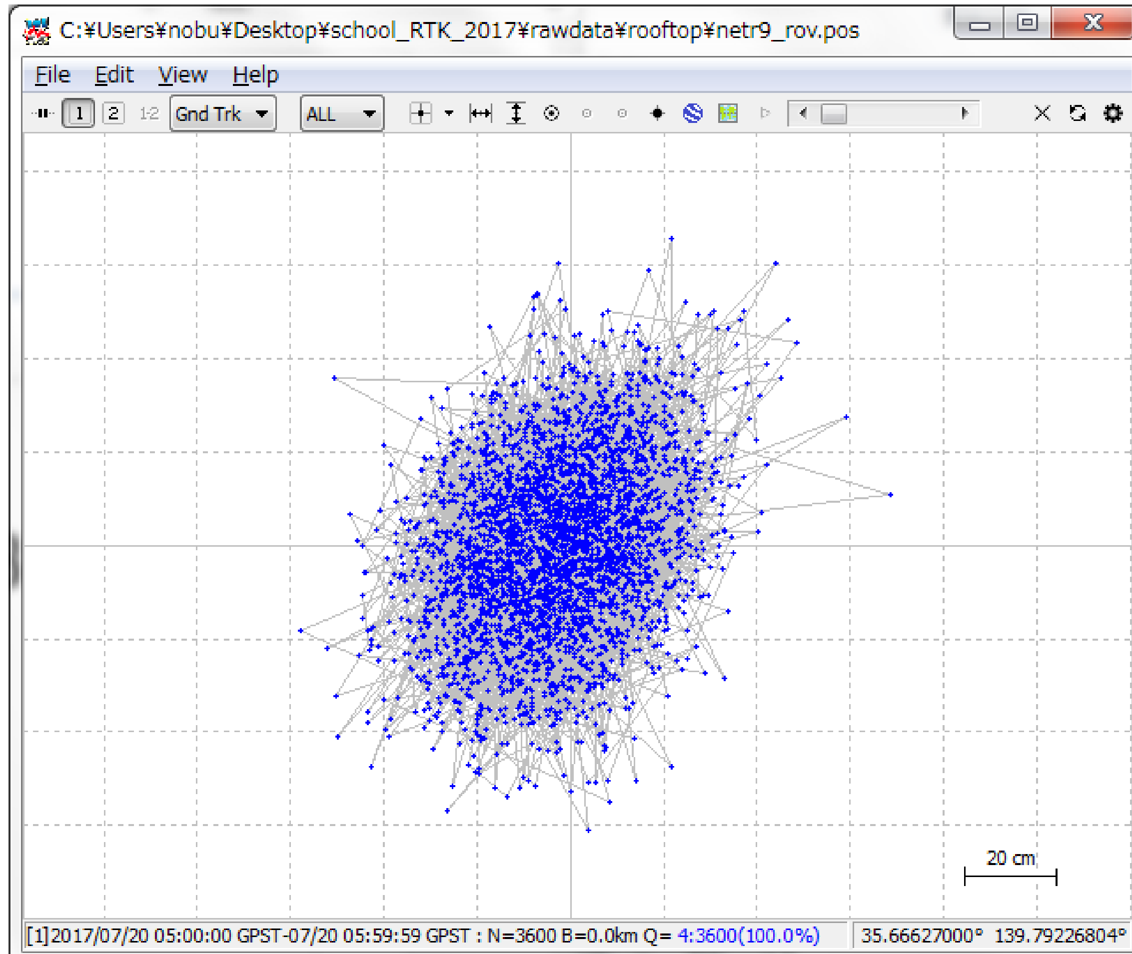
DGNSS

- Precise rover position(LAT/LON/HGT):

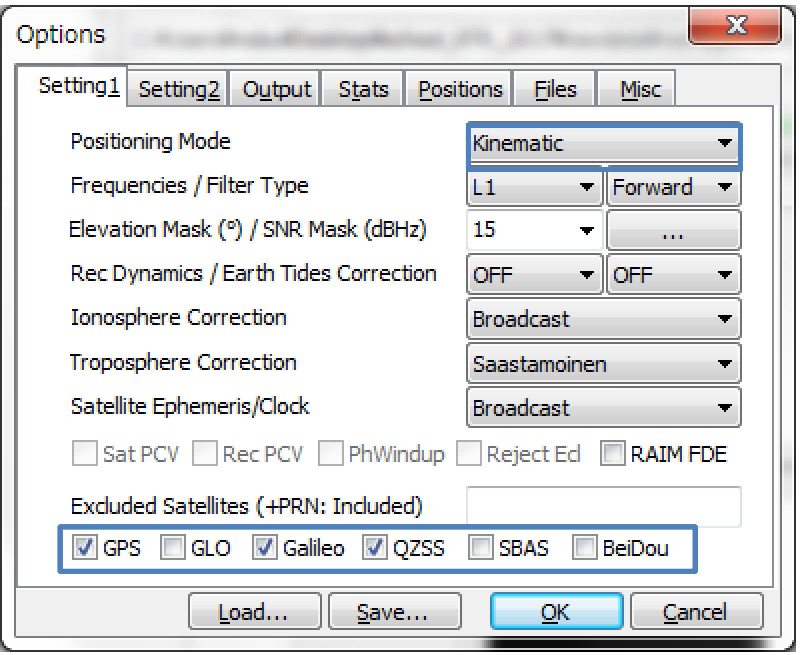
  35.66627025 139.79226723 59.33

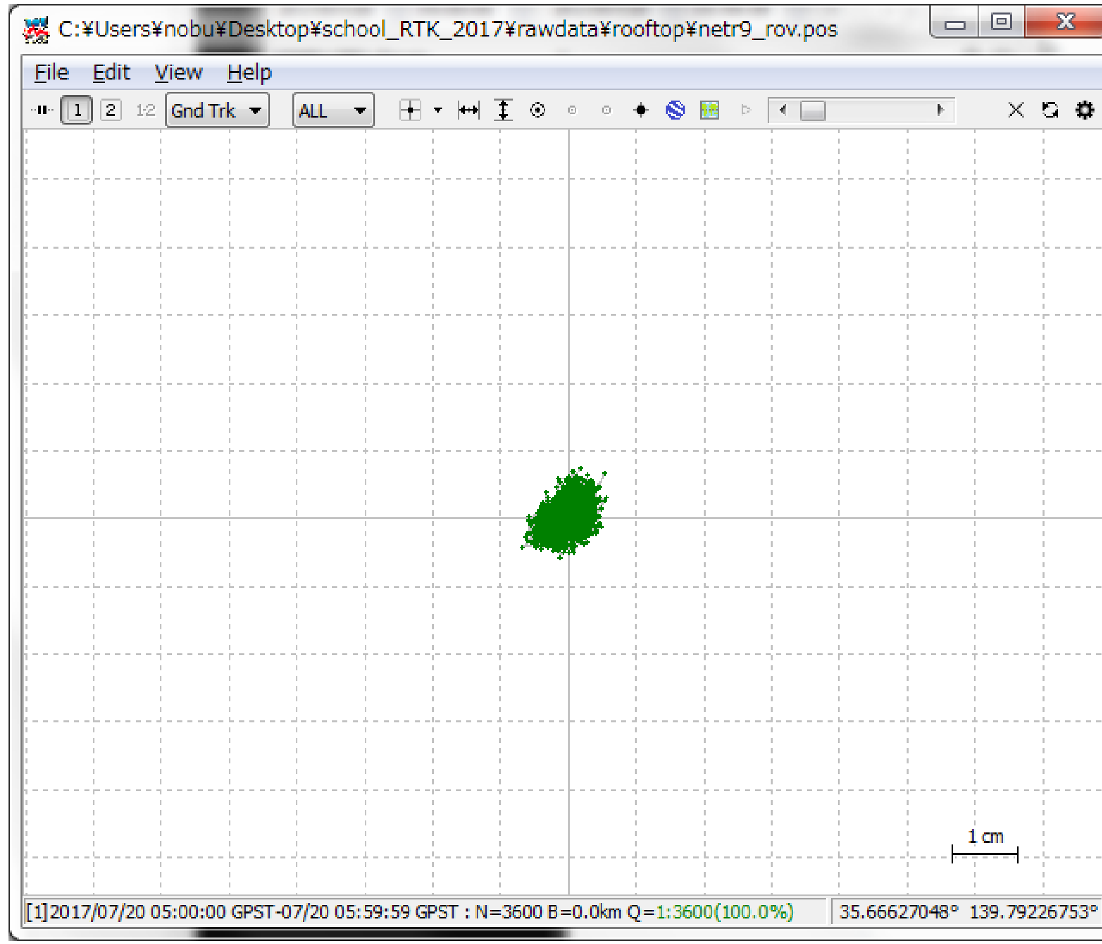






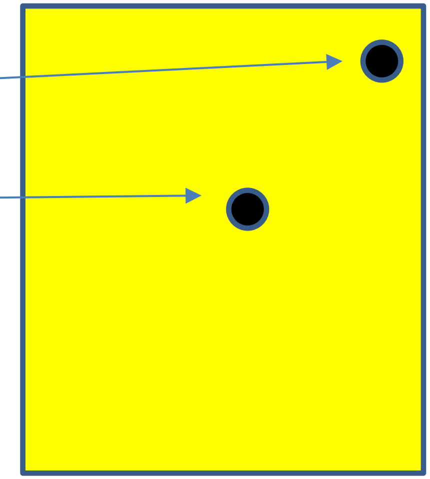
RTK-GNSS


Options
Setting1
Setting2
Output
Stats
Positions
Files
Misc
Positioning Mode
Kinematic
Frequencies / Filter Type
L1
Forward
Elevation Mask (°) / SNR Mask (dBHz)
15
...
Rec Dynamics / Earth Tides Correction
OFF
OFF
Ionosphere Correction
Broadcast
Troposphere Correction
Saastamoinen
Satellite Ephemeris/Clock
Broadcast
Sat PCV
Rec PCV
PhWindup
Reject Ecl
RAIM FDE
Excluded Satellites (+PRN: Included)
GPS
GLO
Galileo
QZSS
SBAS
BeiDou
Load...
Save...
OK
Cancel


C:¥Users¥nobu¥Desktop¥school_RTK_2017¥rawdata¥rooftop¥netr9_rov.pos
File
Edit
View
Help
1
2
1-2
Gnd Trk
ALL
1 cm
[1]2017/07/20 05:00:00 GPST-07/20 05:59:59 GPST : N=3600 B=0.0km Q=1:3600(100.0%)
35.66627048° 139.79226753°

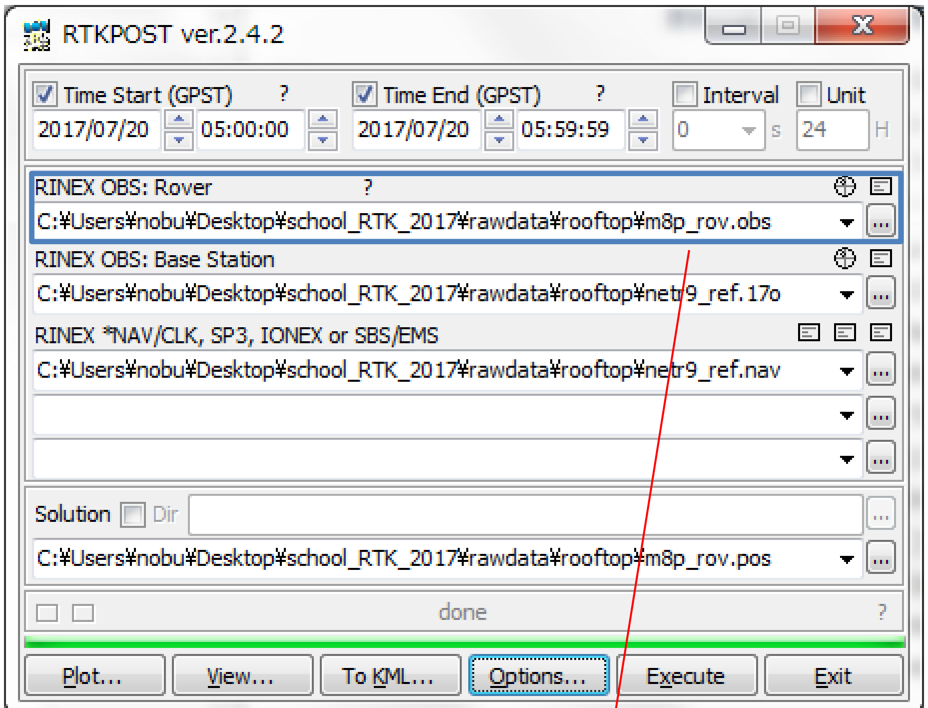
2 receivers were set simultaneously

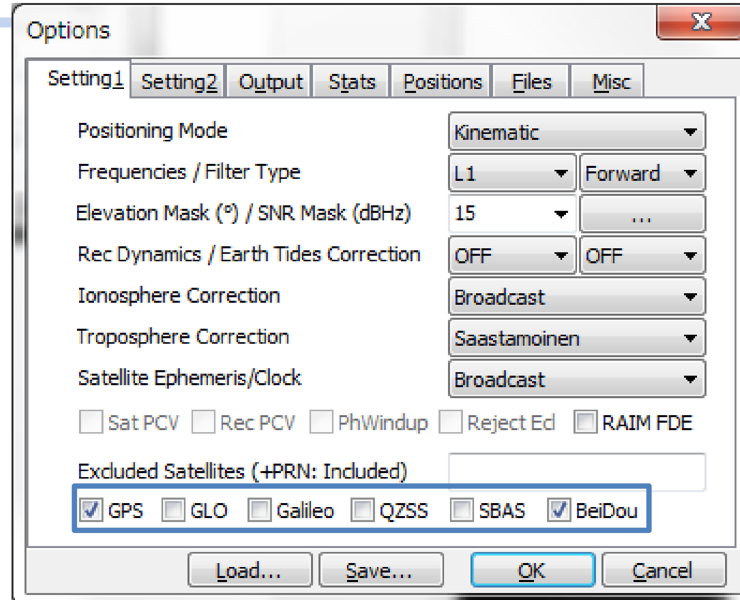
- Trimble **NetR9** with Trimble antenna
- **u-blox M8P** with YOKOWO antenna

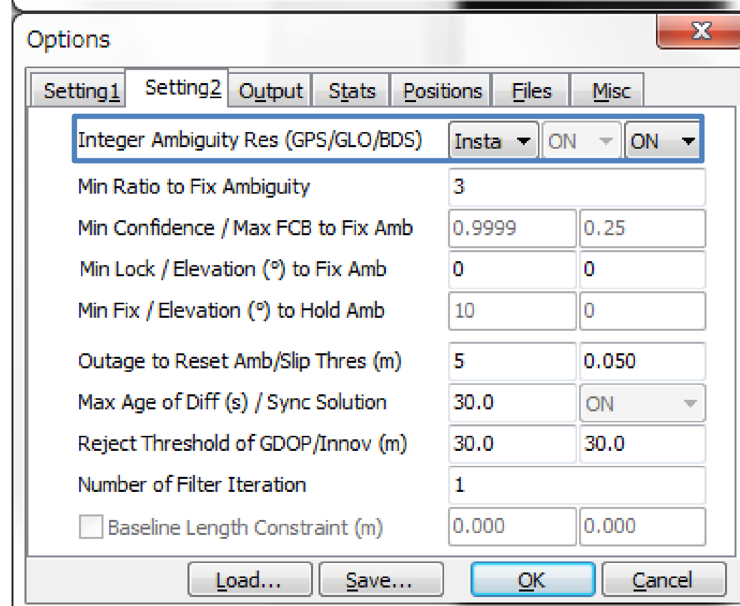


- For the equal comparison, same settings were applied.
- GPS/BEI + Instantaneous.

Similar test using u-blox

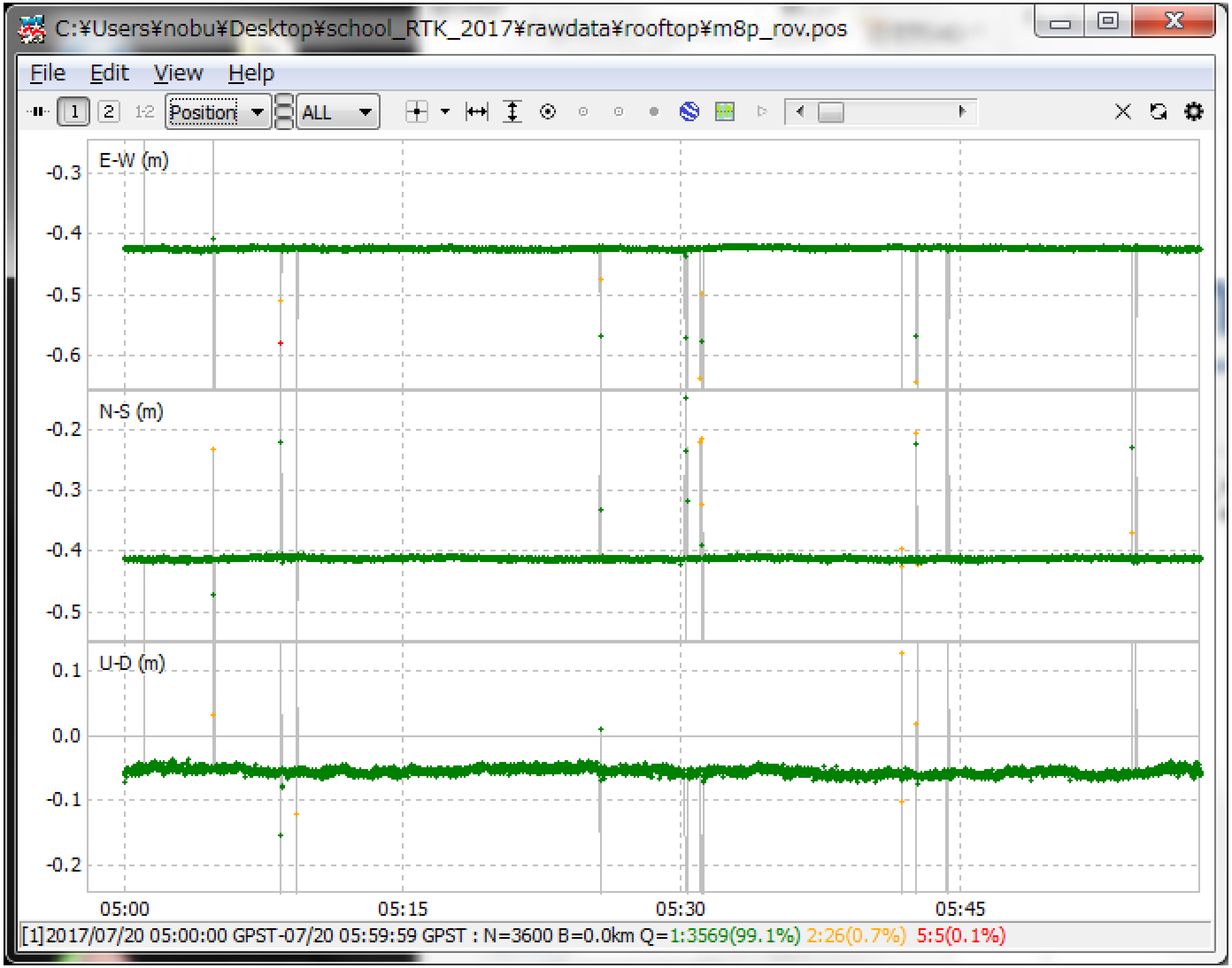




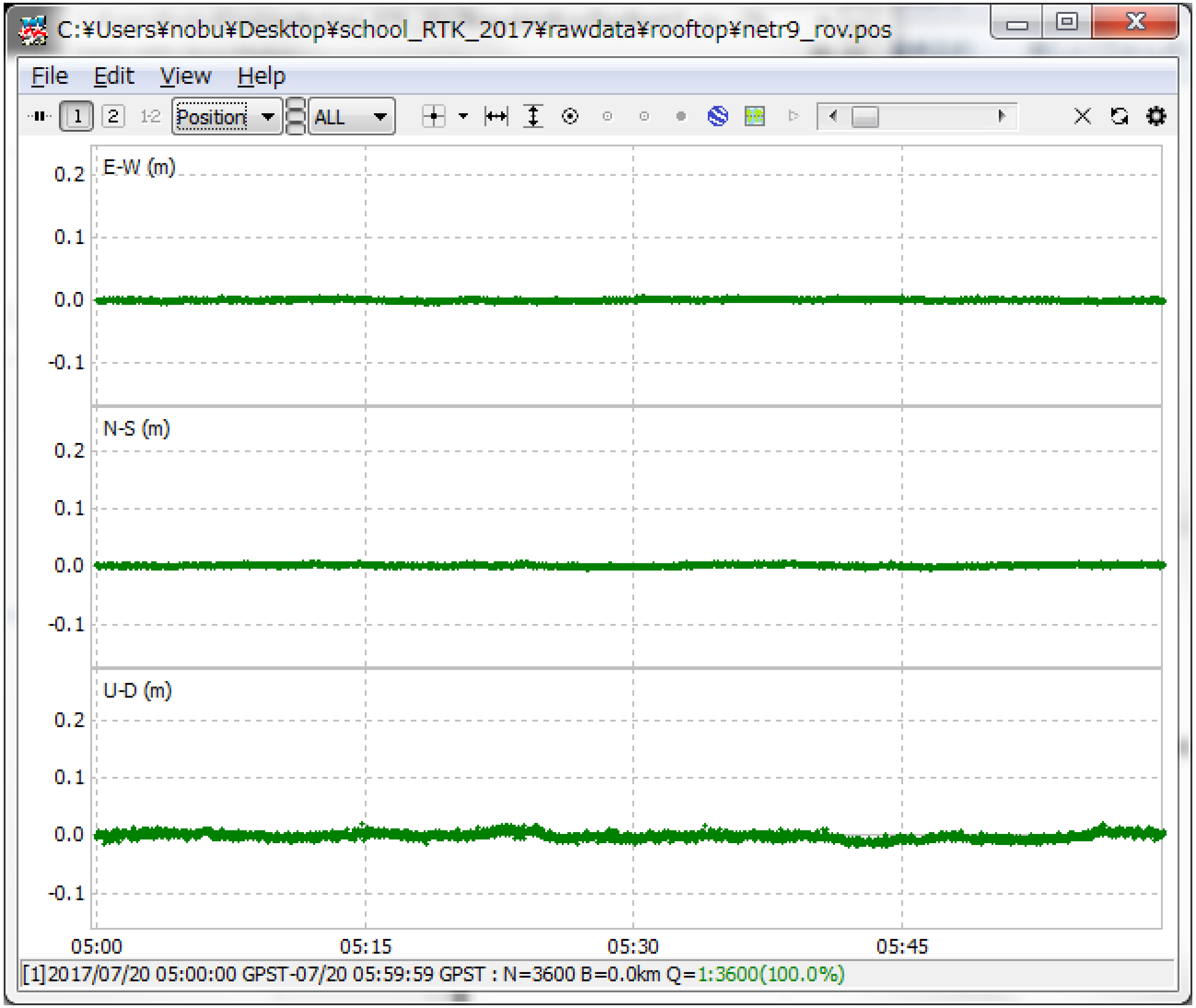


Or, netr9_rov.17o

u-blox M8P results



NetR9 results



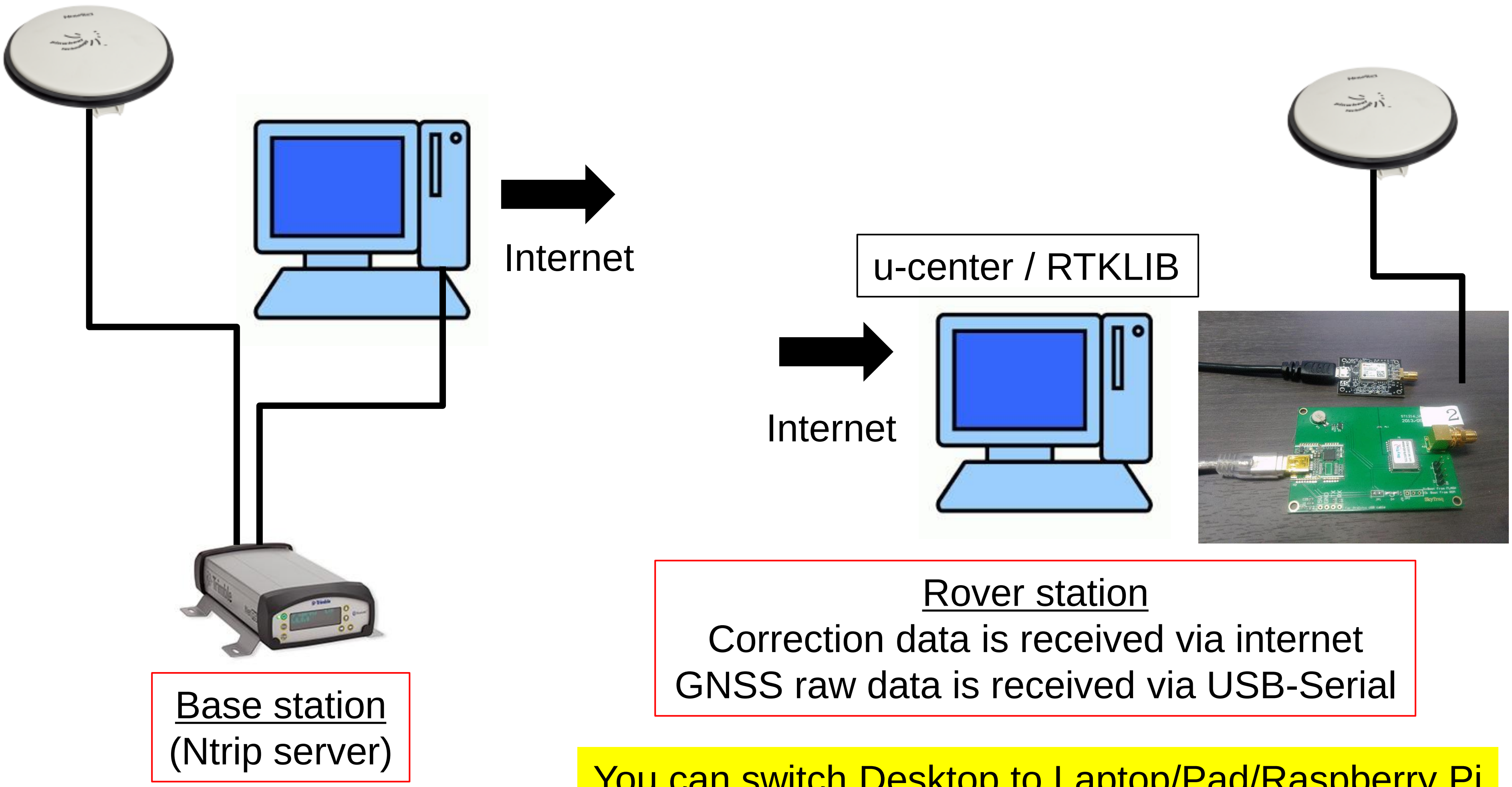
RTKLIB (my desktop movie)

- **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).

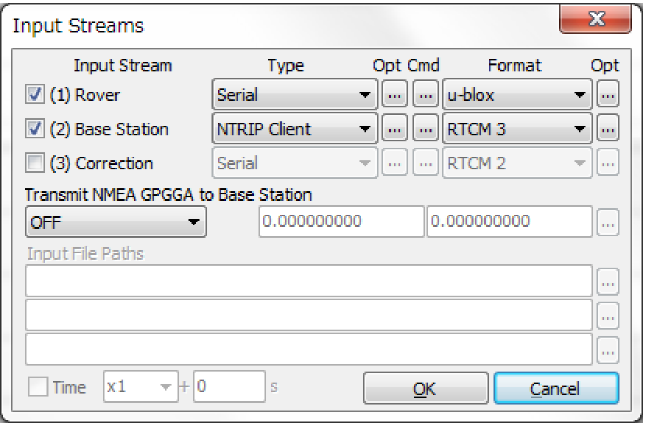
http://www.denshi.e.kaiyodai.ac.jp/gnss_tutor/experiment.html

How to connect (my desktop)

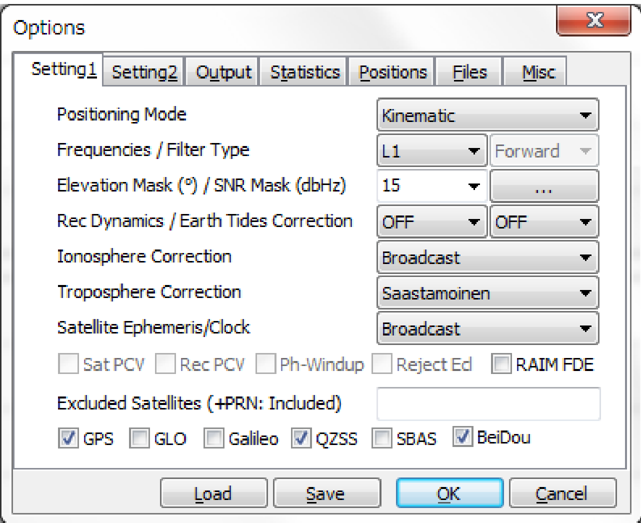


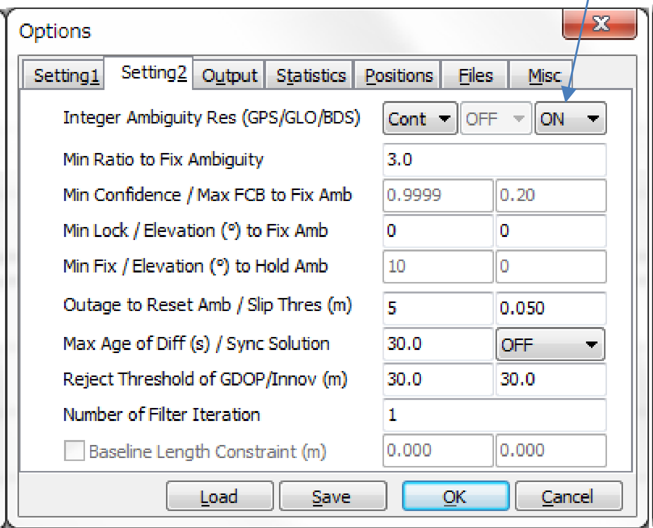
You can switch Desktop to Laptop/Pad/Raspberry Pi

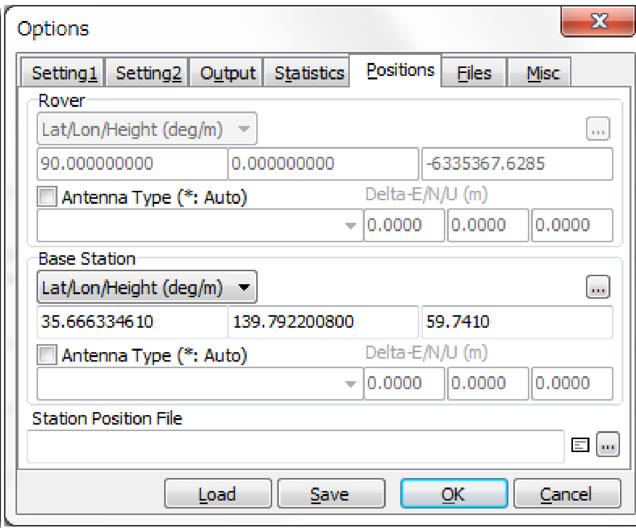
RTKNAVI - Options



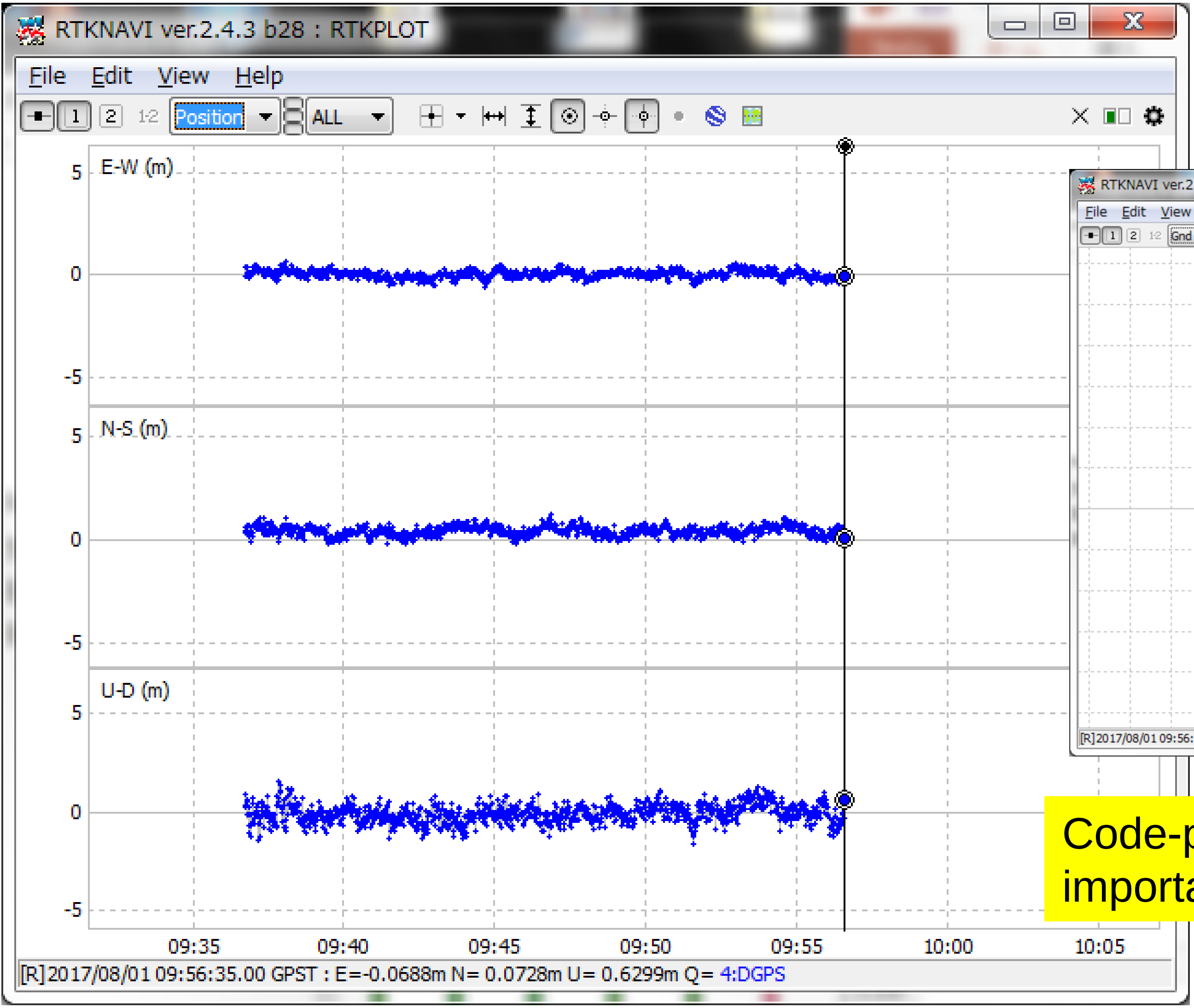
If you set GQR and it doesn’t fix, please try it again by changing the setting of Integer Ambiguity Res “OFF”.

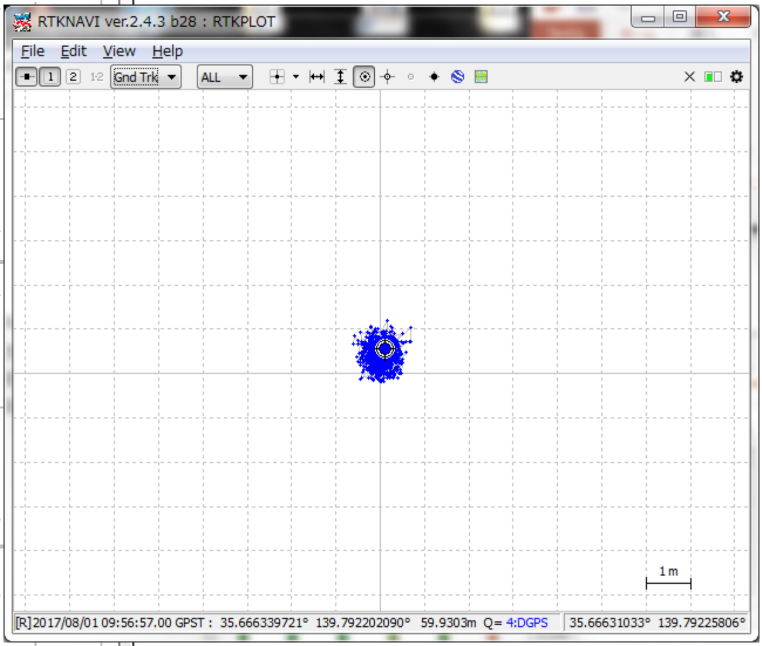






u-blox M8P DGNSS (GB)





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)

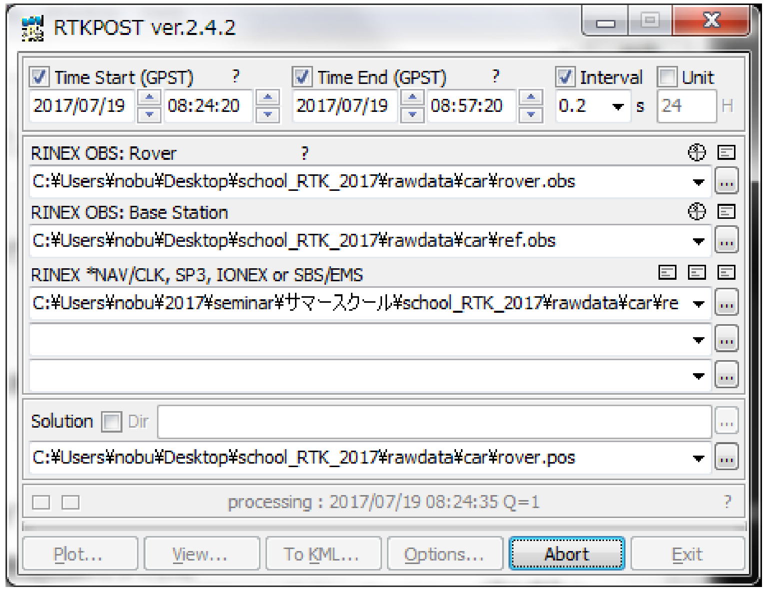
Car data and field test

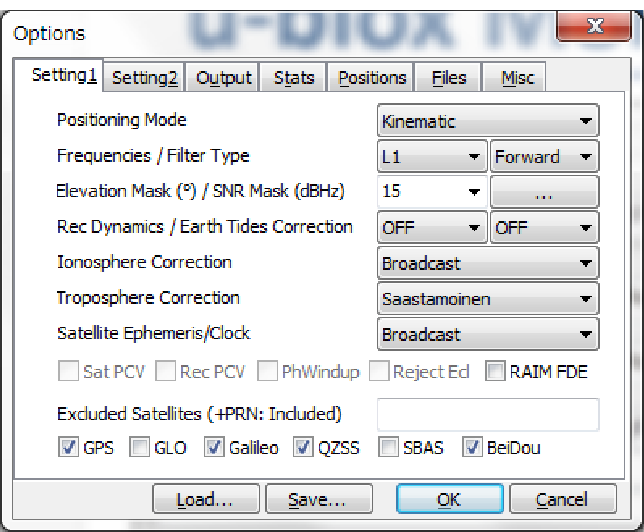
- Car data is post-processed using RTKLIB
- Homework
- RTK field test using u-blox M8P (8 groups)

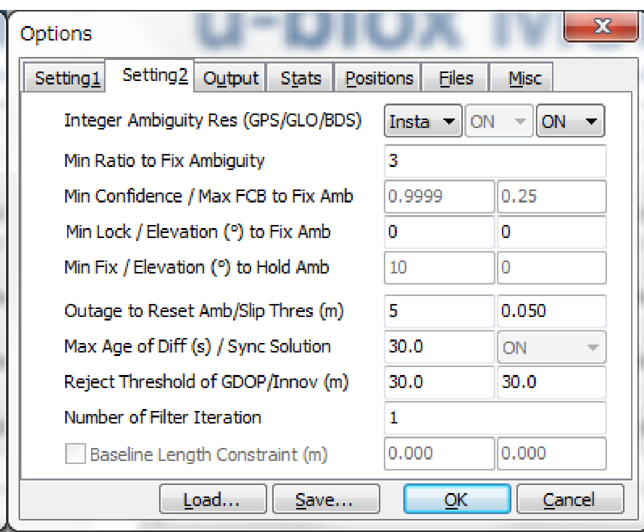
Car data

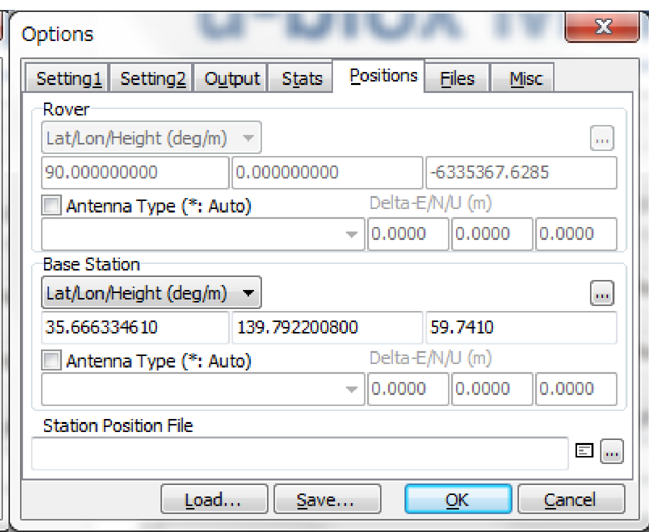
- 2017/7/19 8:24:20 – 8:57:20 (GPST)
- Total 9900 epochs in 5Hz
- Near university campus (normal urban)
- u-blox M8T and Trimble NetR9 for both Rover and reference station
- You can compare these two receivers
- Single-frequency or dual-frequency ?
- What is the best setting ?

Settings of u-blox M8P

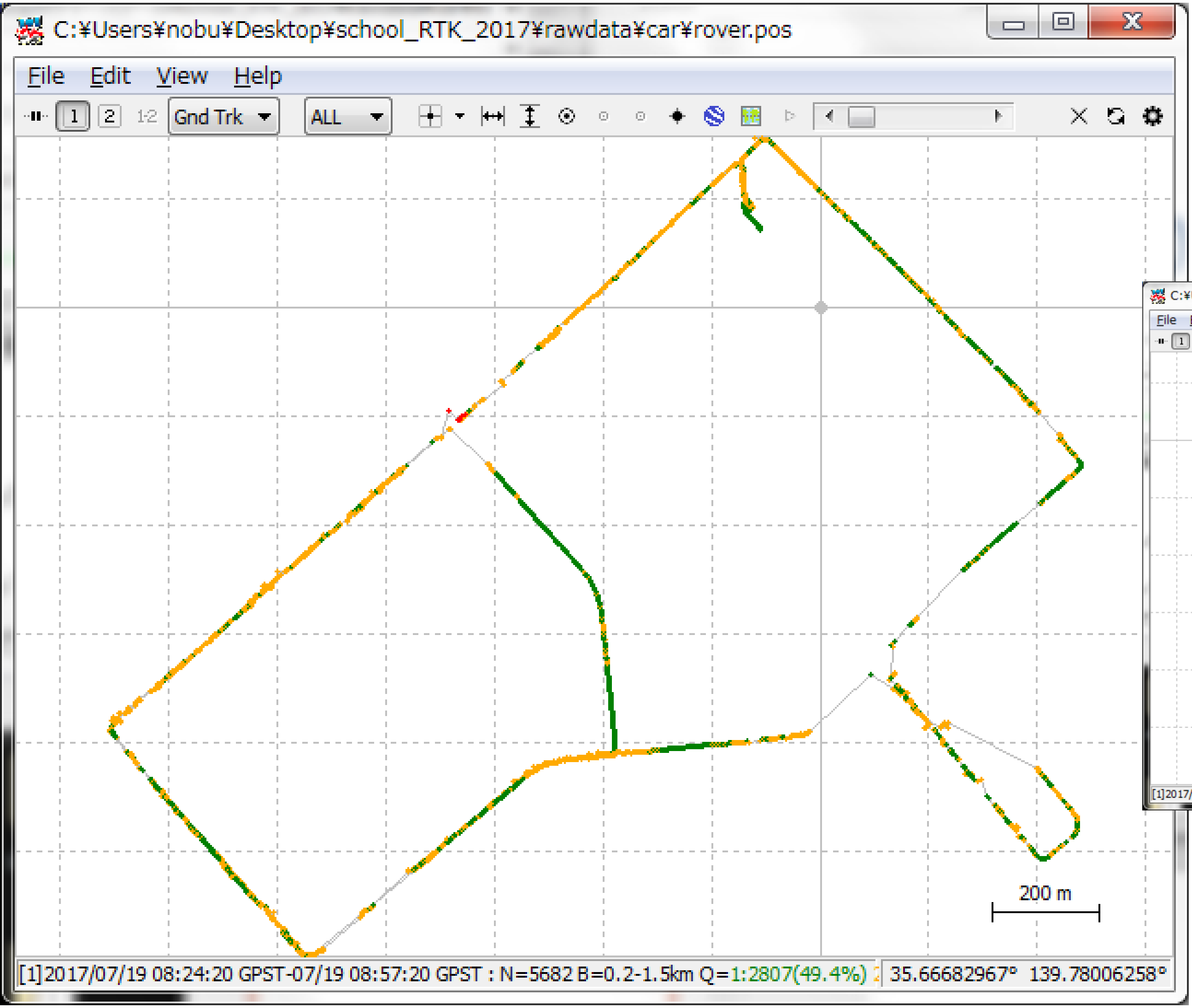




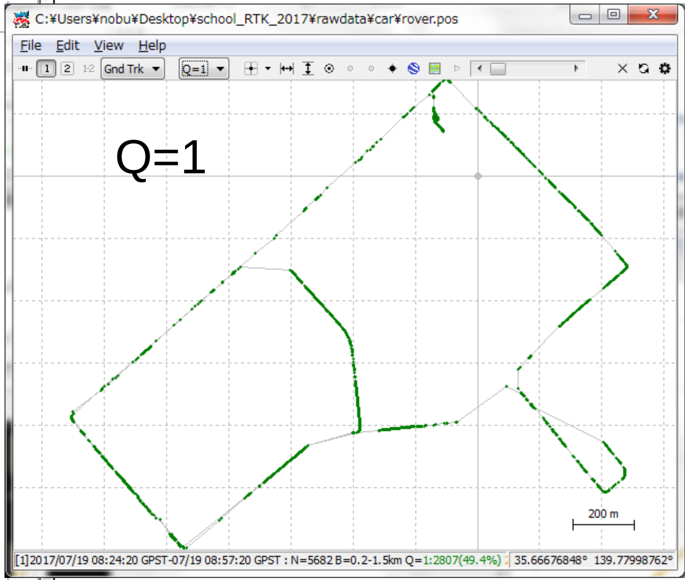




PLOT

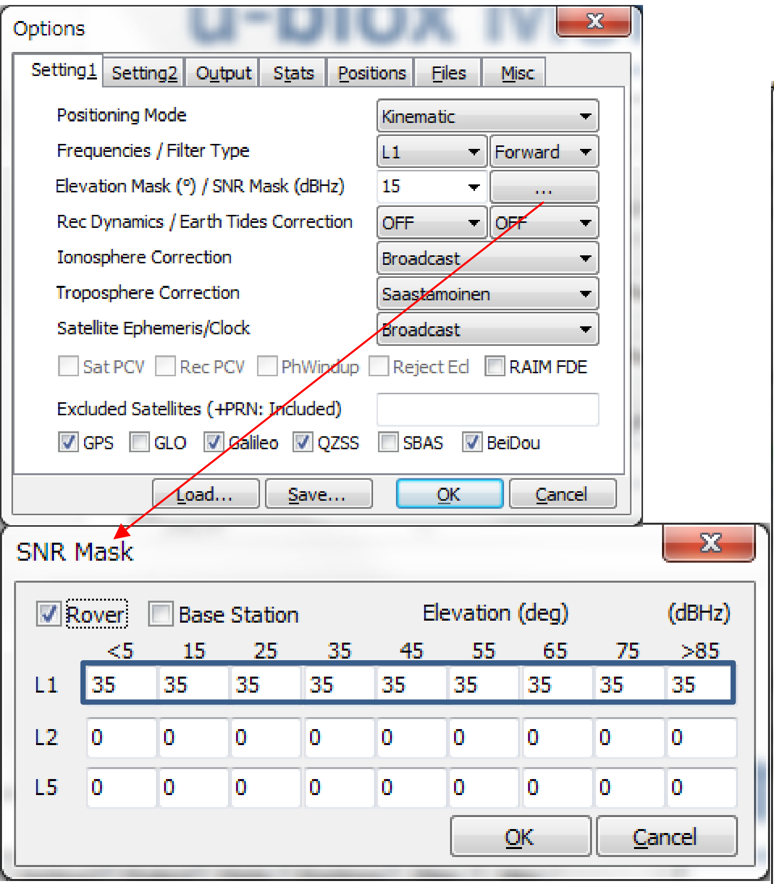


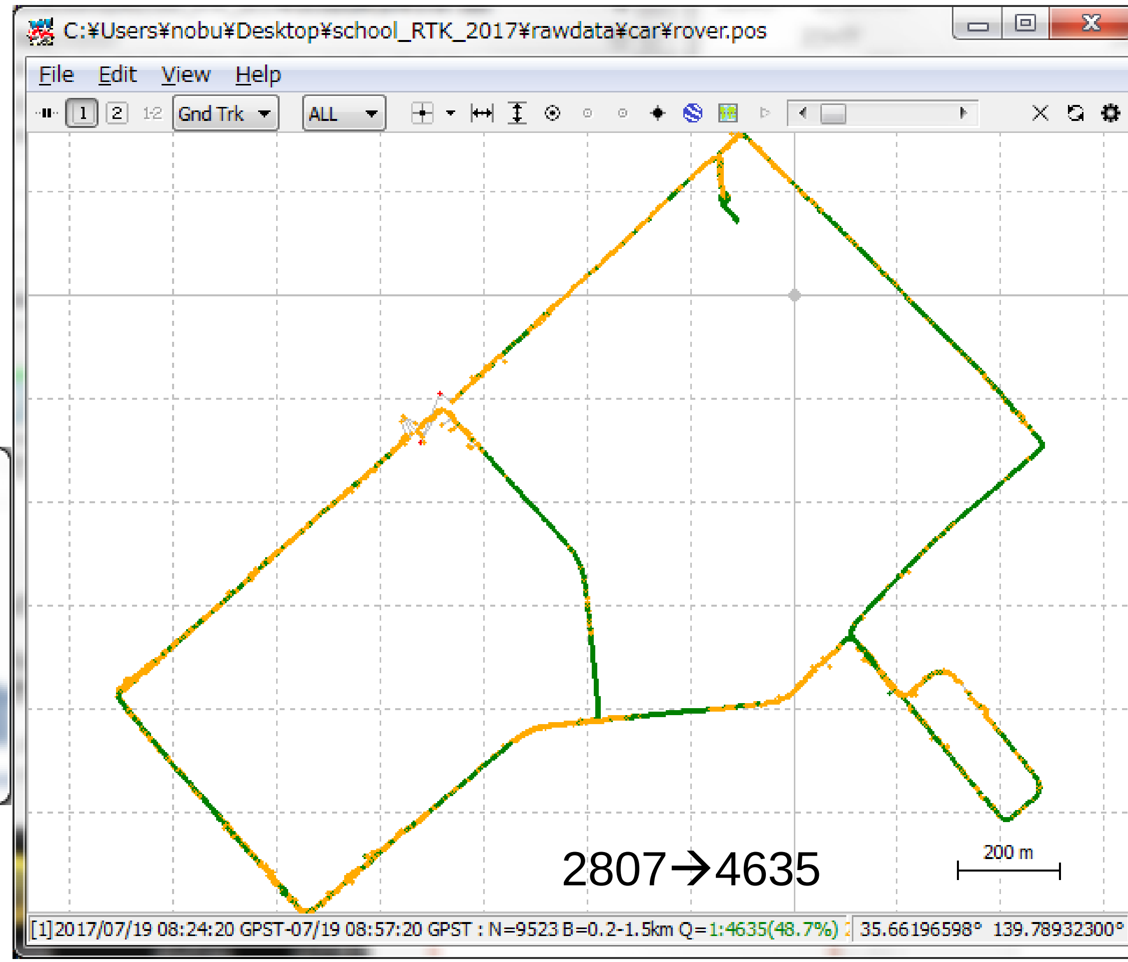
C:¥Users¥nobu¥Desktop¥school_RTK_2017¥rawdata¥car¥rover.pos
File Edit View Help
Gnd Trk
ALL
200 m
[1]2017/07/19 08:24:20 GPST-07/19 08:57:20 GPST : N=5682 B=0.2-1.5km Q=1:2807(49.4%)
35.66682967° 139.78006258°



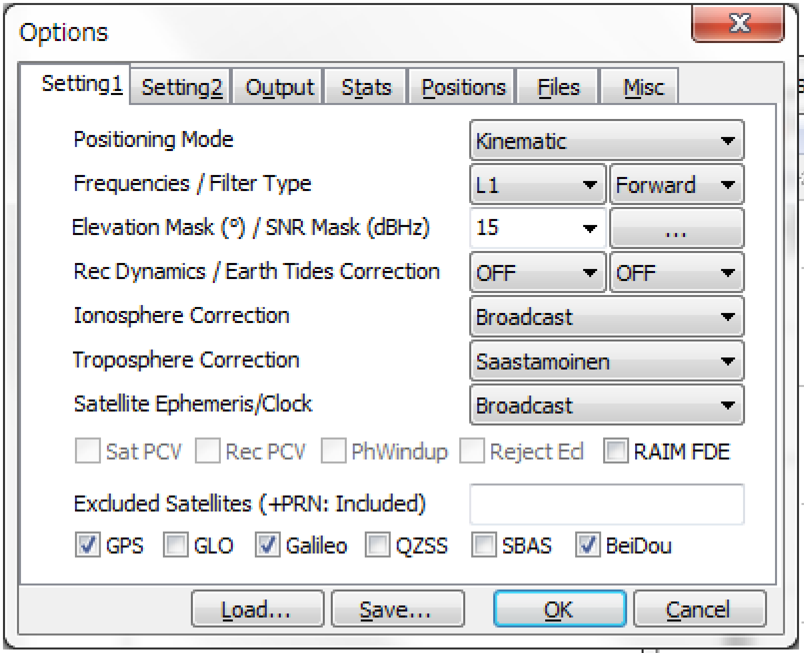
C:¥Users¥nobu¥Desktop¥school_RTK_2017¥rawdata¥car¥rover.pos
File Edit View Help
Gnd Trk
Q=1
Q=1
200 m
[1]2017/07/19 08:24:20 GPST-07/19 08:57:20 GPST : N=5682 B=0.2-1.5km Q=1:2807(49.4%)
35.66676848° 139.77998762°

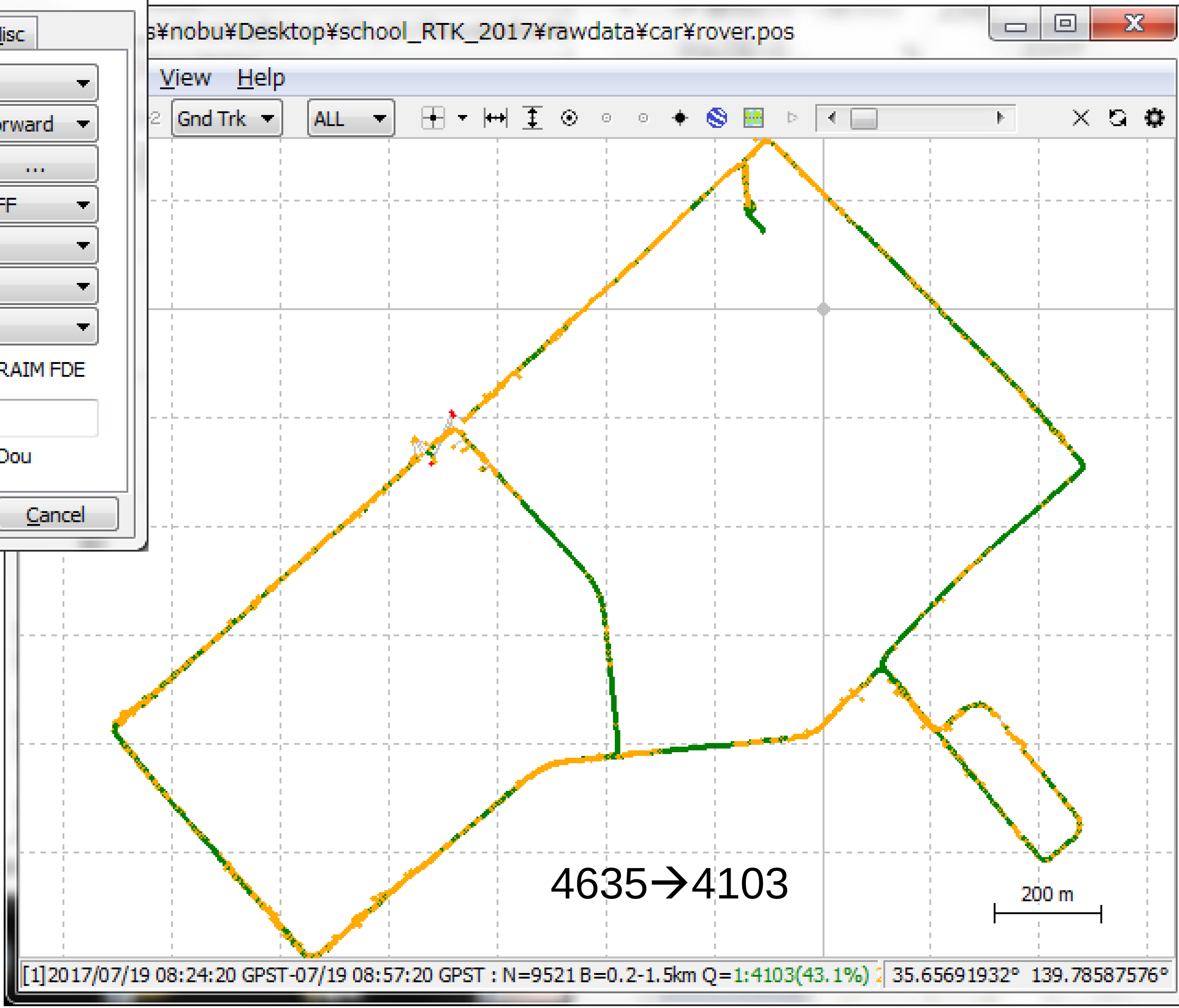
If you set minimum C/N_0 ,



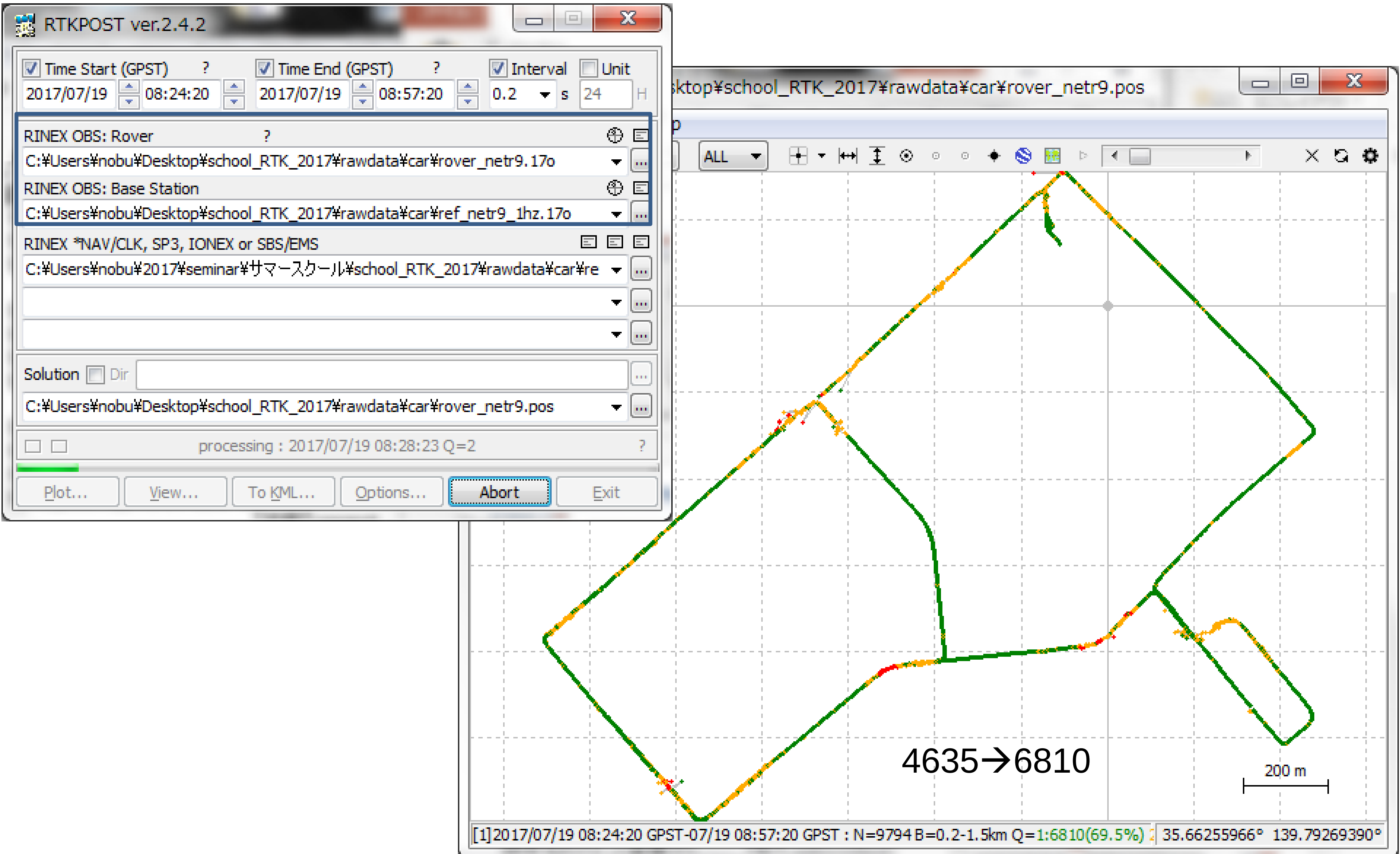


If you remove QZS ,

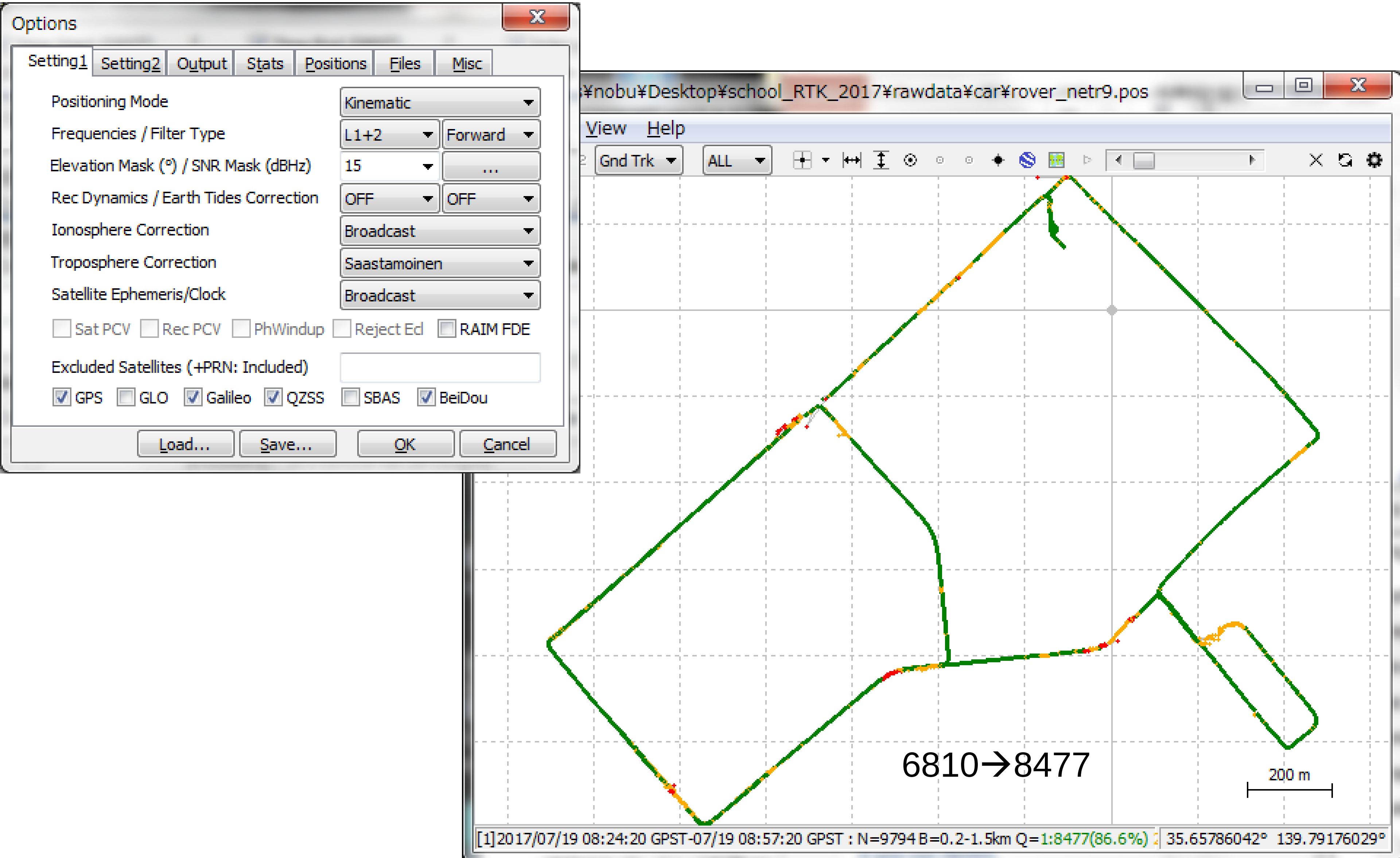




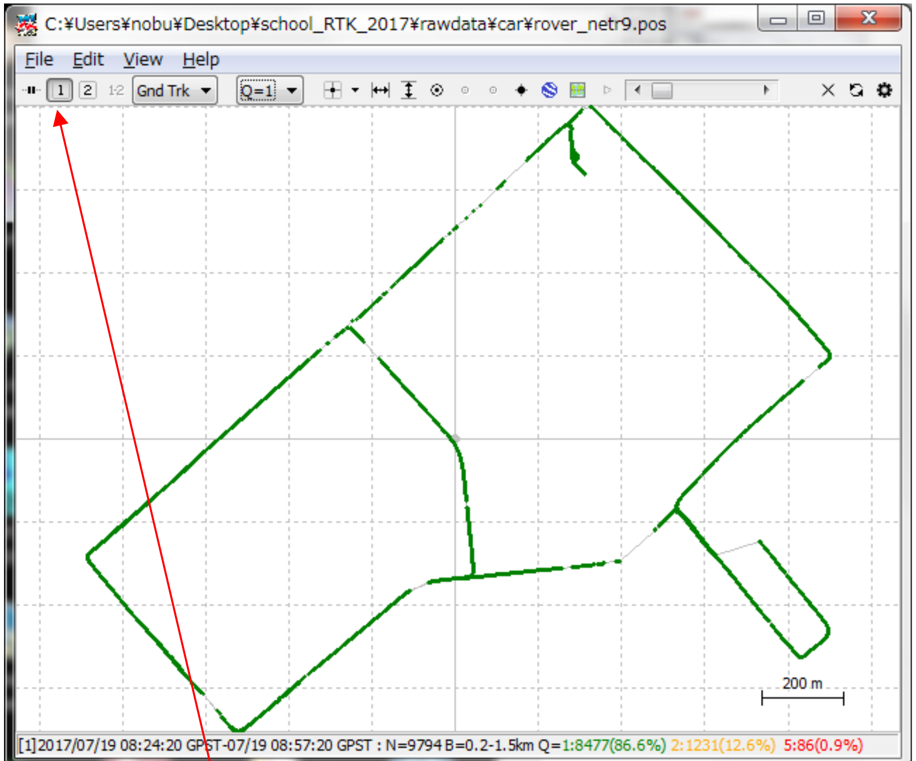
If you use NetR9 ,

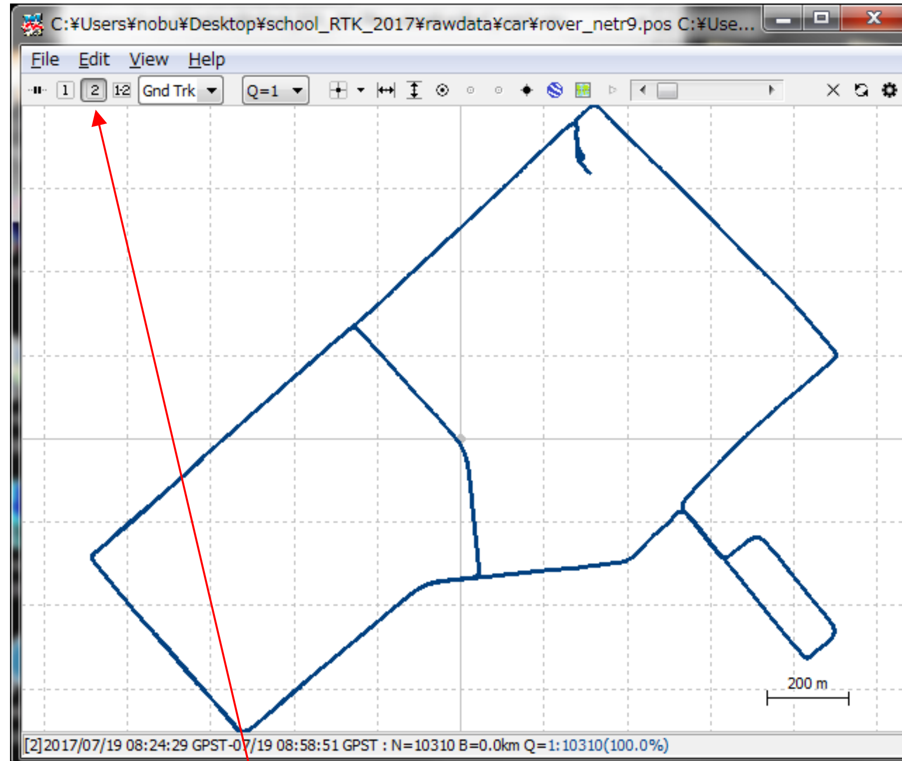


If you use dual-frequency ,



Comparing two POS files (RTKPLOT)





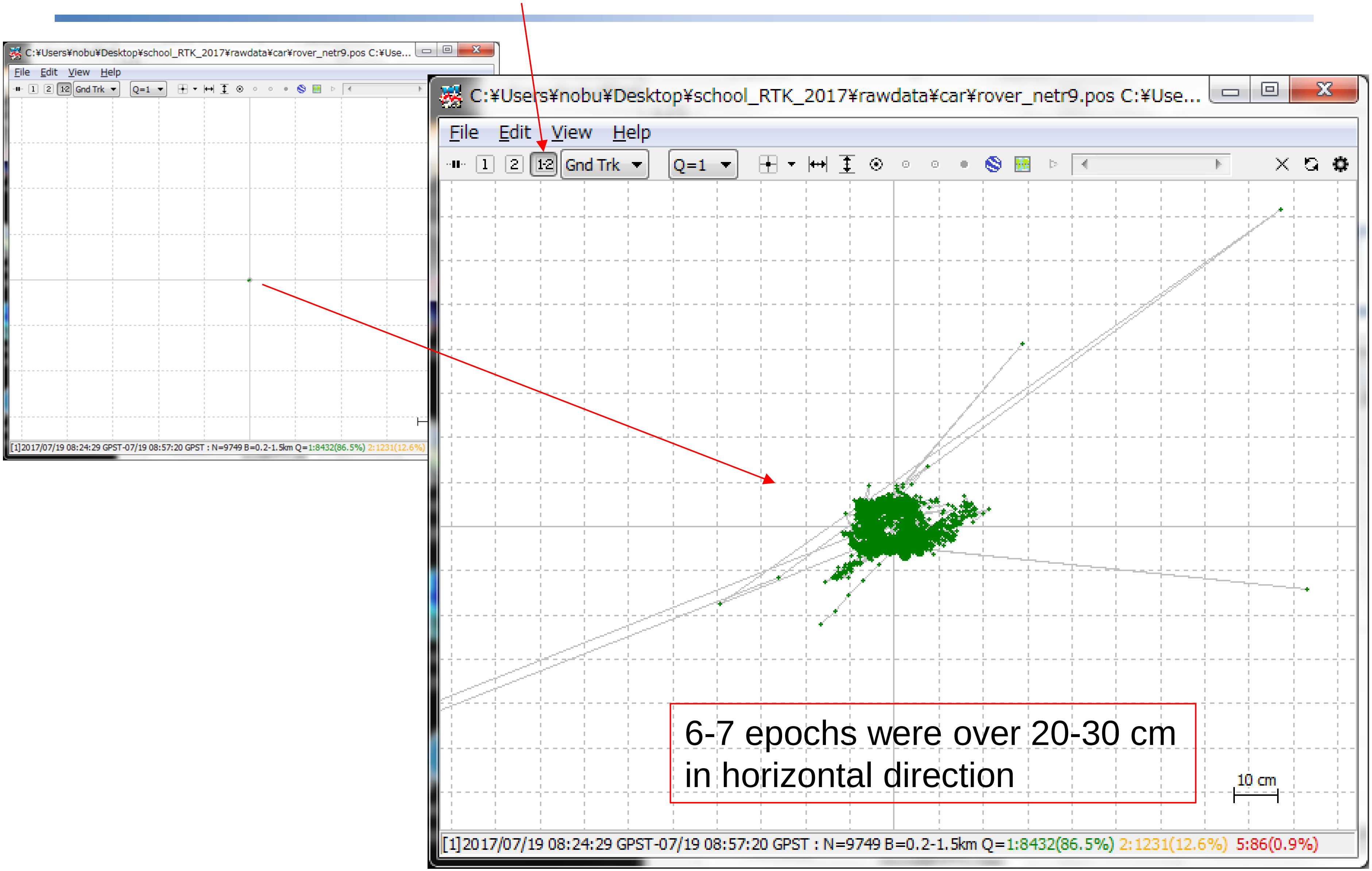
Previous test result

POSLVX result
(Post-processed RTK/IMU/Speed)

Just drug and drop of "poslvx.pos" into RTKPLOT

What happens if you click "1-2" ?

RTKPLOT 1-2


C:¥Users¥nobu¥Desktop¥school_RTK_2017¥rawdata¥car¥rover_netr9.pos C:¥Use...
File Edit View Help
1 2 1-2 Gnd Trk Q=1
[1]2017/07/19 08:24:29 GPST-07/19 08:57:20 GPST : N=9749 B=0.2-1.5km Q=1:8432(86.5%) 2:1231(12.6%)
C:¥Users¥nobu¥Desktop¥school_RTK_2017¥rawdata¥car¥rover_netr9.pos C:¥Use...
File Edit View Help
1 2 1-2 Gnd Trk Q=1
6-7 epochs were over 20-30 cm
in horizontal direction
10 cm
[1]2017/07/19 08:24:29 GPST-07/19 08:57:20 GPST : N=9749 B=0.2-1.5km Q=1:8432(86.5%) 2:1231(12.6%) 5:86(0.9%)

Homework

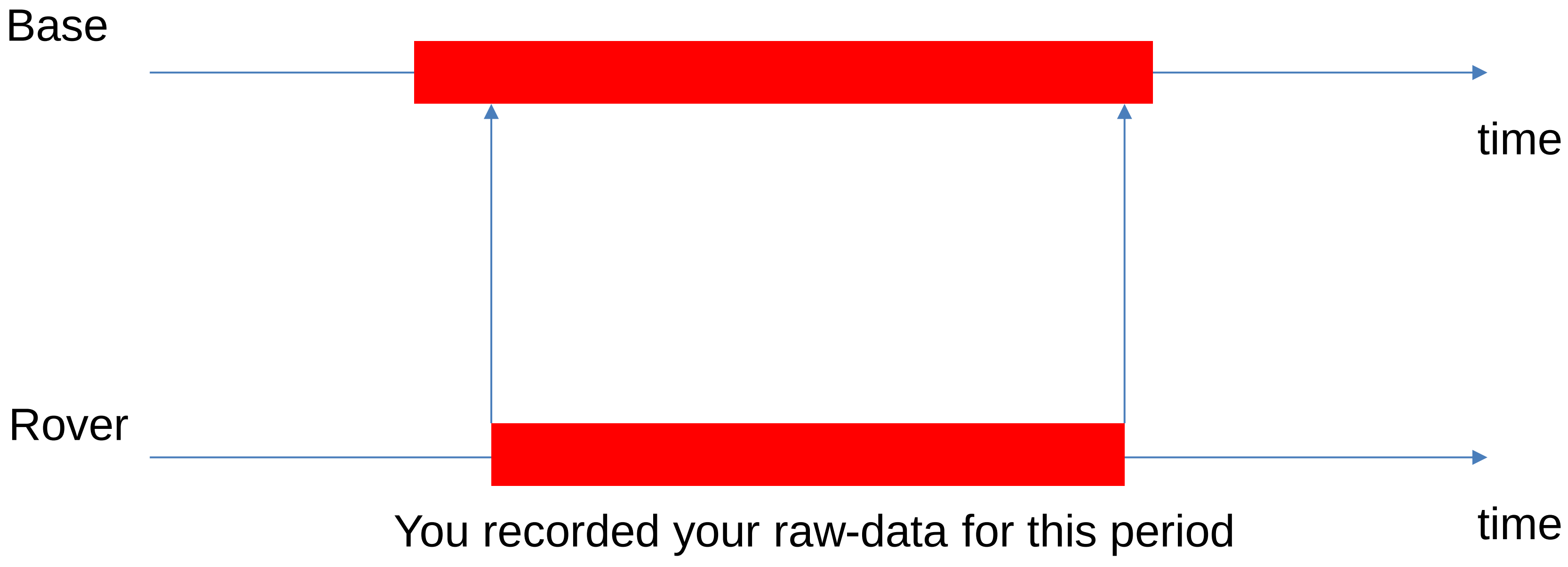
- Please try to find the best setting of RTKLIB using the u-blox data (both ref and rover).
- “Best” means highest number of fixes within 30cm based on POSLVX file.

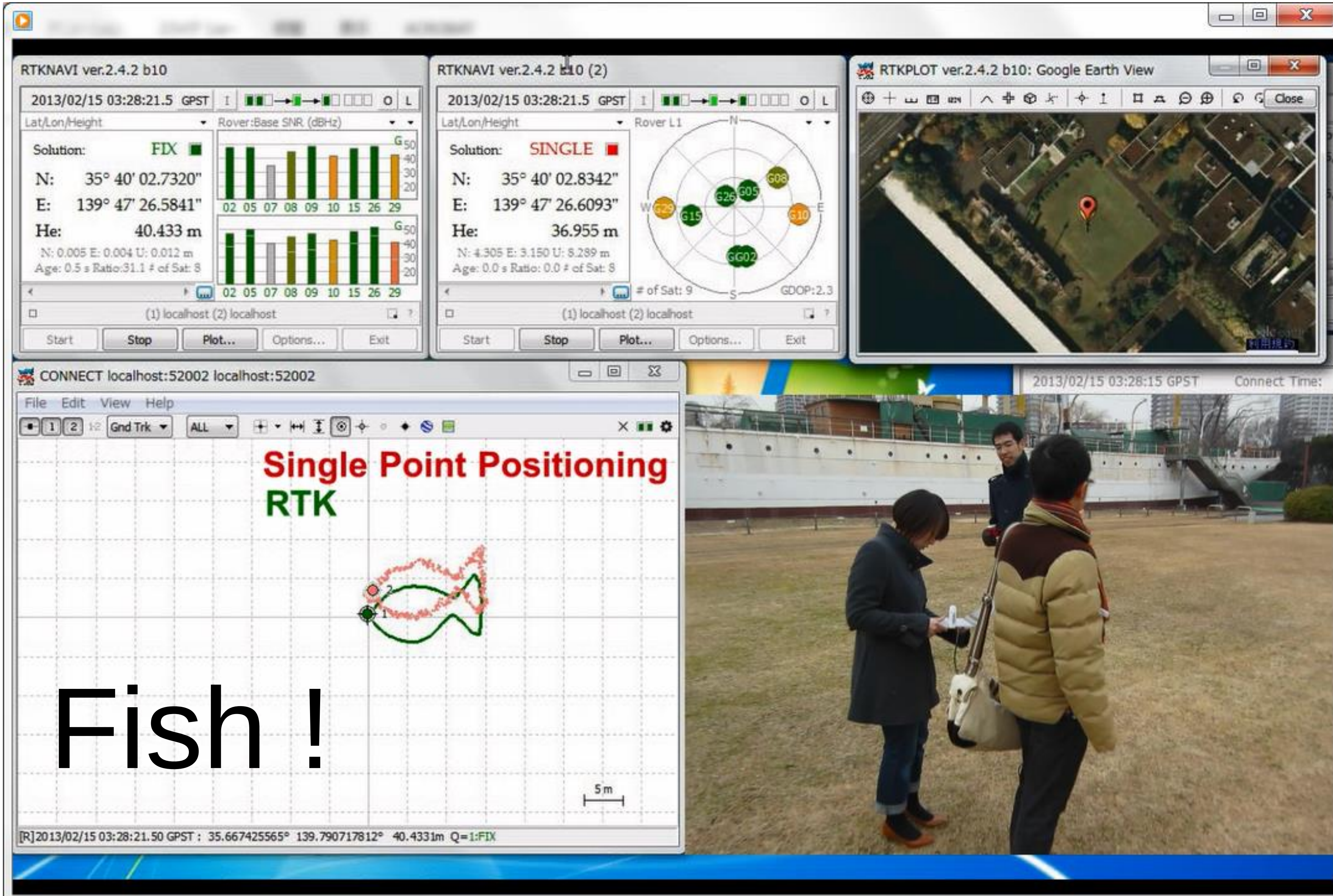
RTK field test using M8P/M8T (Post-processed)

- 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.




RTKNAVI ver.2.4.2 b10
2013/02/15 03:28:21.5 GPST
Solution: FIX
N: 35° 40' 02.7320"
E: 139° 47' 26.5841"
He: 40.433 m
N: 0.005 E: 0.004 U: 0.012 m
Age: 0.5 s Ratio:31.1 # of Sat: 8
Rover:Base SNR (dBHz)
RTKNAVI ver.2.4.2 b10 (2)
2013/02/15 03:28:21.5 GPST
Solution: SINGLE
N: 35° 40' 02.8342"
E: 139° 47' 26.6093"
He: 36.955 m
N: 4.305 E: 3.150 U: 8.289 m
Age: 0.0 s Ratio: 0.0 # of Sat: 8
# of Sat: 9
GDOP:2.3
RTKPLOT ver.2.4.2 b10: Google Earth View
CONNECT localhost:52002 localhost:52002
Single Point Positioning
RTK
Fish !
5 m
[R]2013/02/15 03:28:21.50 GPST : 35.667425565° 139.790717812° 40.4331m Q=1:FIX
2013/02/15 03:28:15 GPST
Connect Time:

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

UTC-TAI (s)			
-25	1990/1/1-	-30	1996/1/1-
-26	1991/1/1-	-31	1997/7/1-
-27	1992/7/1-	-32	1999/1/1-
-28	1993/7/1-	-33	2006/1/1-
-29	1994/7/1-	-34	2009/1/1-

TAI to UTC:

$$t_{UTC} = t_{TAI} + (UTC - TAI)$$

UTC to UT1:

$$t_{UT1} = t_{UTC} + (UT1 - UTC)$$

UT1 to GMST:

$$GMST_{0h\,UT1} = 24110.54841 + 8640184.812866\,T'_u + 0.093104\,T'^2_u - 6.2\times10^{-6}\,T'^3_u$$

$$GMST = GMST_{0h\,UT1} + r(t_{UT1} - t_{0h\,UT1})$$

$$r = 1.002737909350795 + 5.9006\times10^{-11}\,T'_u - 5.9\times10^{-15}\,T'^2_u$$

$T'_u = d'_u / 36525$ d'_u : number of days elapsed since 2000 Jan 1, 12h UT1

GPS Time to TAI:

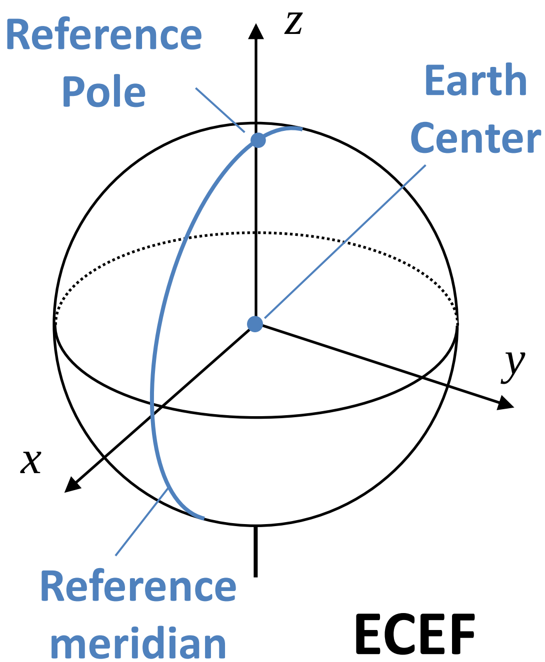
$$t_{TAI} \approx t_{GPST} + 19s$$

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

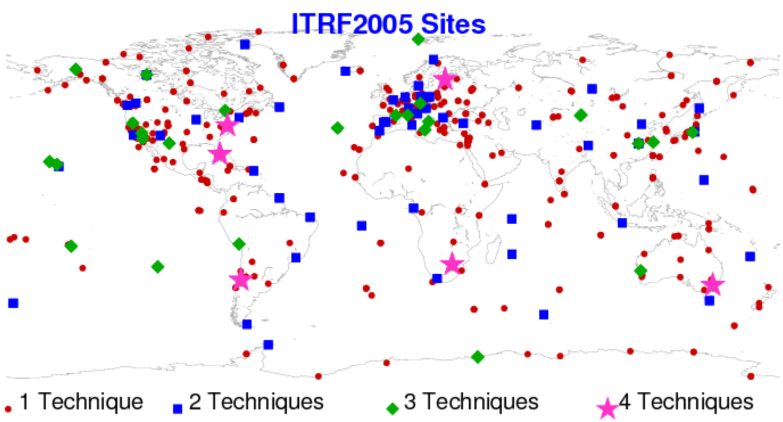


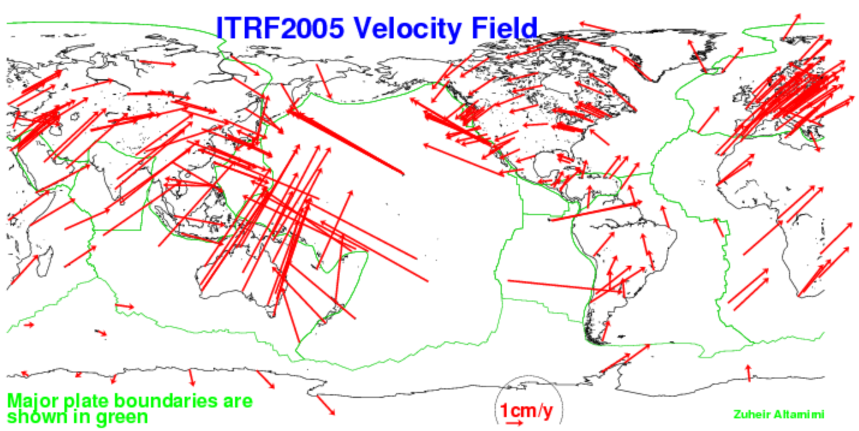
ITRF

- **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

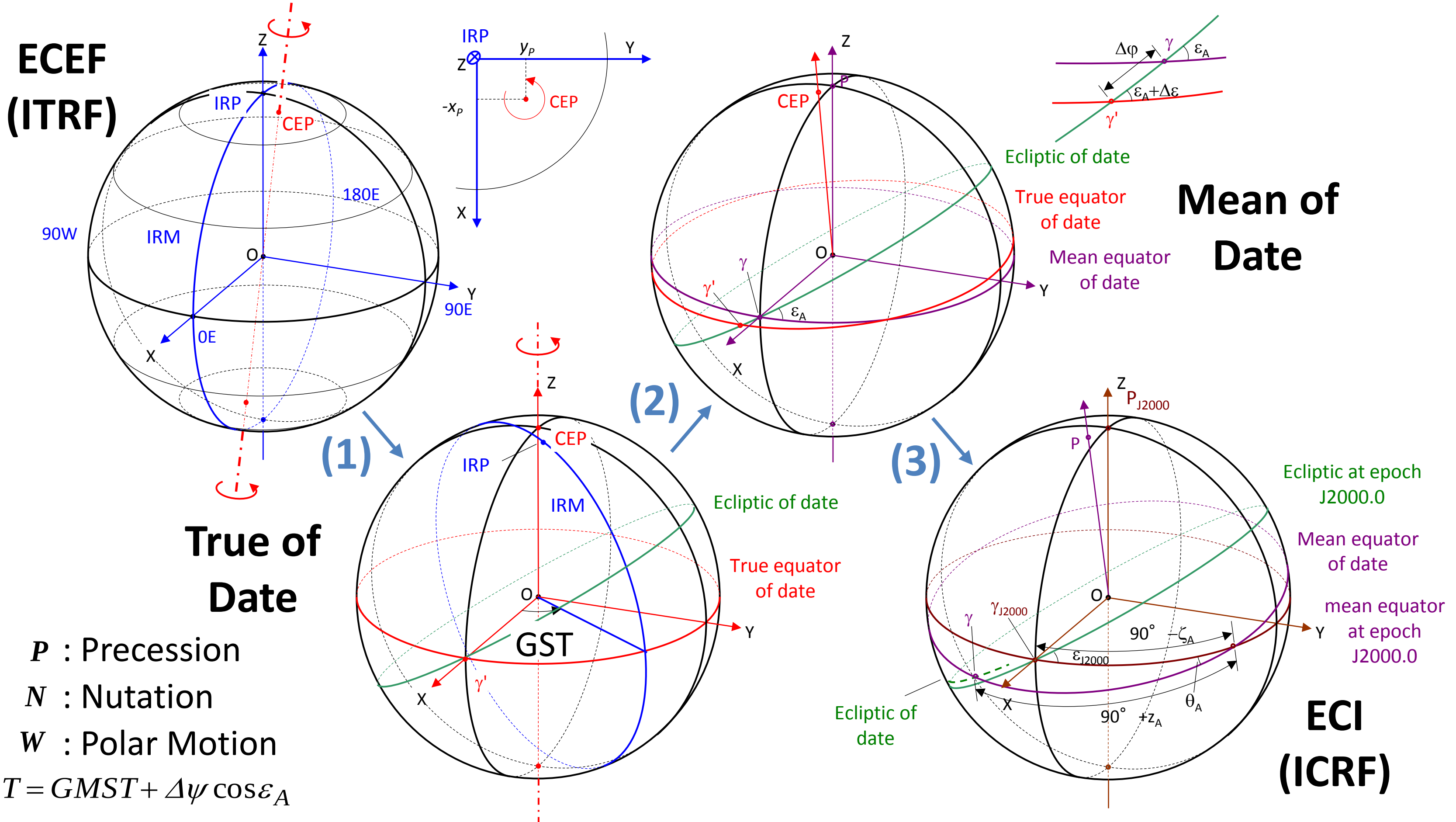
ITRS: International Terrestrial Reference System
IERS: International Earth Rotation Service





http://itrf.ensg.ign.fr/ITRF_solutions/2005/ITRF2005.php

ECEF to ECI Transformation



$\boldsymbol{P}$: Precession

$\boldsymbol{N}$: Nutation

$\boldsymbol{W}$: Polar Motion

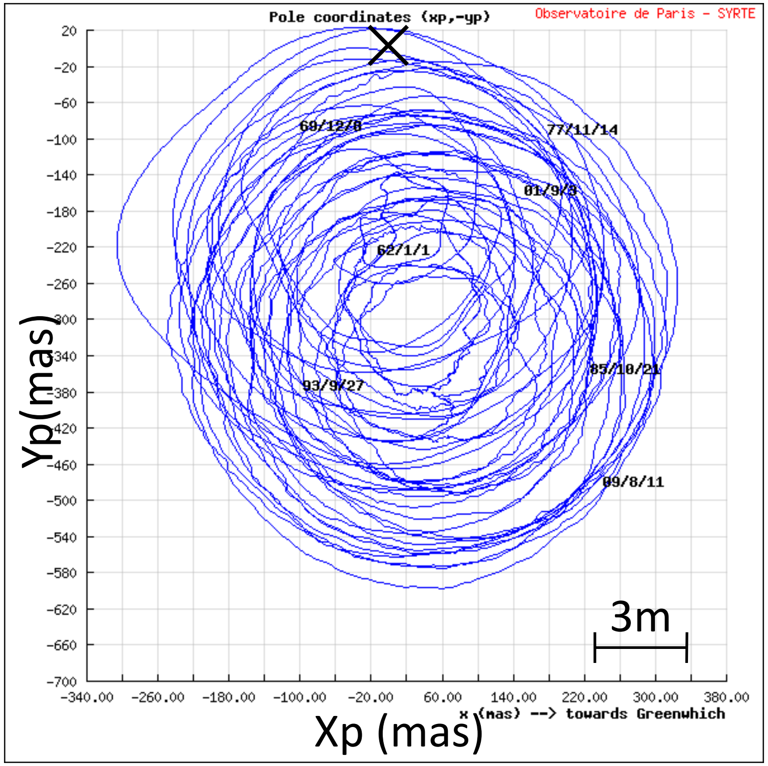
$$GST = GMST + \Delta\psi \cos\varepsilon_A + 0''.00264 \sin\Omega + 0''.000063 \sin 2\Omega$$

$$\boldsymbol{r}_{eci} = \boldsymbol{P}\boldsymbol{N}\boldsymbol{R}_z(-GST)\boldsymbol{W}\boldsymbol{r}_{ecef}$$

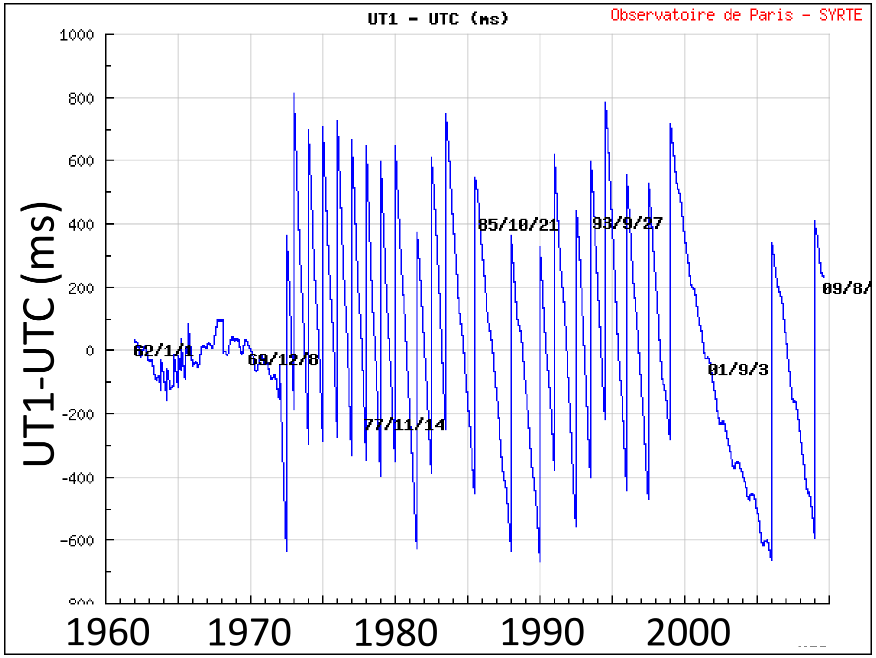
$$= \underbrace{\boldsymbol{R}_Z(\zeta_A)\boldsymbol{R}_Y(-\theta_A)\boldsymbol{R}_Z(z_A)}_{(3)}\underbrace{\boldsymbol{R}_X(-\varepsilon_A)\boldsymbol{R}_Z(\Delta\varphi)\boldsymbol{R}_X(\varepsilon_A+\Delta\varepsilon)}_{(2)}\underbrace{\boldsymbol{R}_Z(-GST)}_{}\underbrace{\boldsymbol{R}_X(y_P)\boldsymbol{R}_Y(x_P)}_{(1)}\boldsymbol{r}_{ecef}$$

EOP: Earth Orientation Parameters

Polar Motion:
Xp, Yp



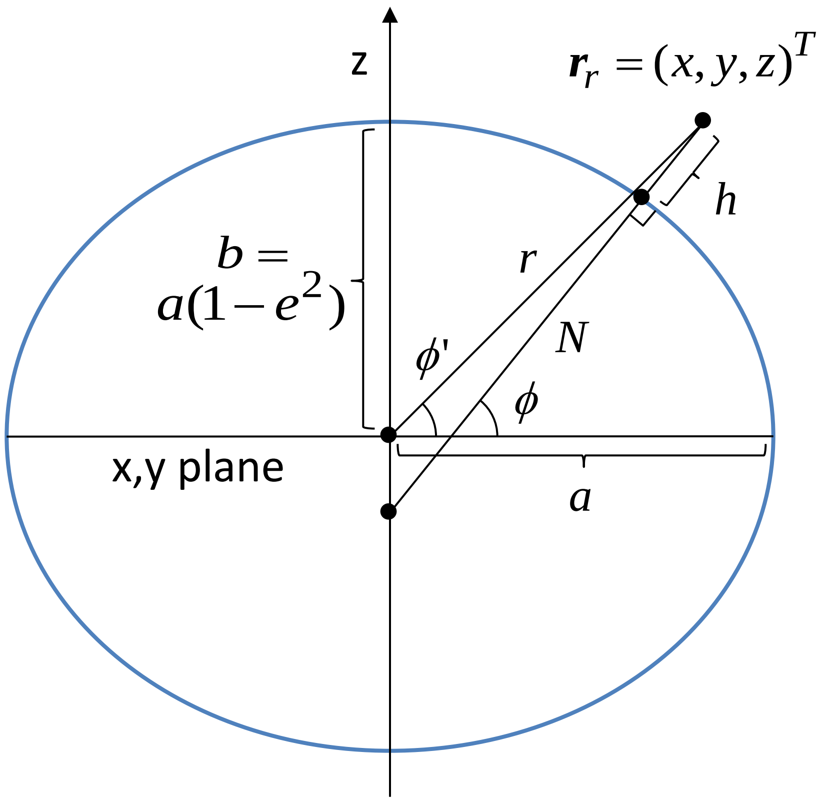
Earth Rotation Angle:
UT1-UTC



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

Ellipsoid and Datum

Ellipsoid:



ϕ' : Geocentric Latitude λ : Longitude

ϕ : Geodetic Latitude h : Ellipsoidal Height

	GRS 80	WGS 84
a (m)	6378137	6378137
f	1/298.257222101	1/298.257223563
GM (m^3/s^2)	3986005.000 x 10^8	3986004.418 x 10^8

Lat/Lon/Height to ECEF:

$$e^2 = f(2-f)$$

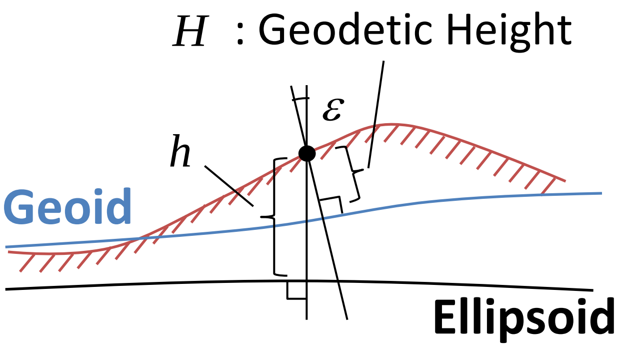
$$N = \frac{a}{\sqrt{1-e^2\sin^2\phi}}$$

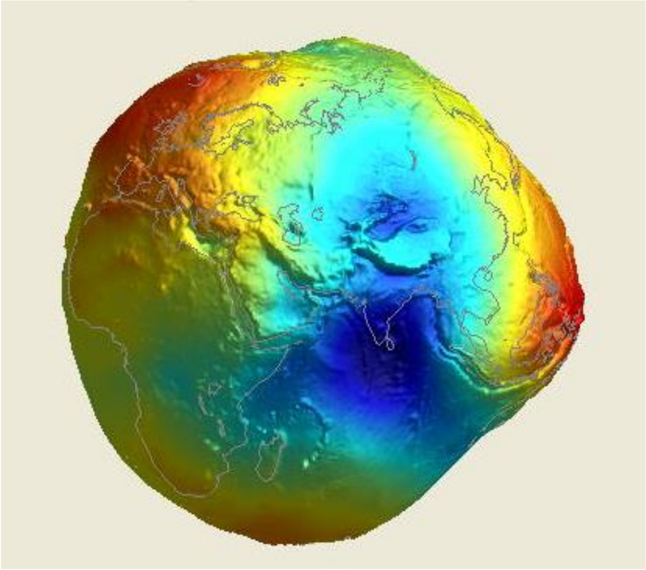
$$\boldsymbol{r}_r = \begin{pmatrix} (N+h)\cos\phi\cos\lambda \\ (N+h)\cos\phi\sin\lambda \\ (N(1+e^2)+h)\sin\phi \end{pmatrix}$$

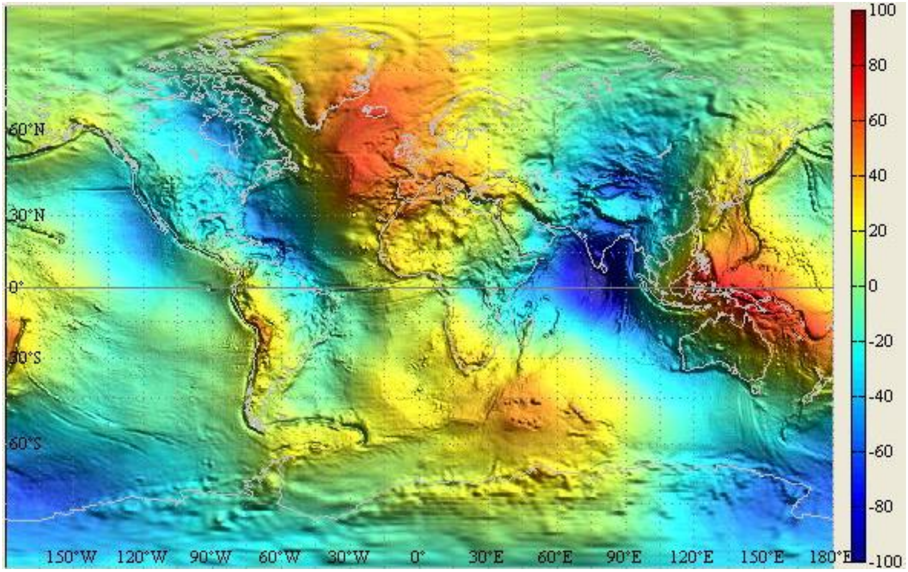
Geoid

Geopotential:

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







EGM96 Geoid Model

Spherical Harmonics

Spherical harmonic functions:

$$Y_{n0} = Y_{n0c}$$

$$Y_{nmc} = \overline{P}_{nm}(\sin\phi')\cos m\lambda$$

$$Y_{nms} = \overline{P}_{nm}(\sin\phi')\sin m\lambda$$

Legendre function:

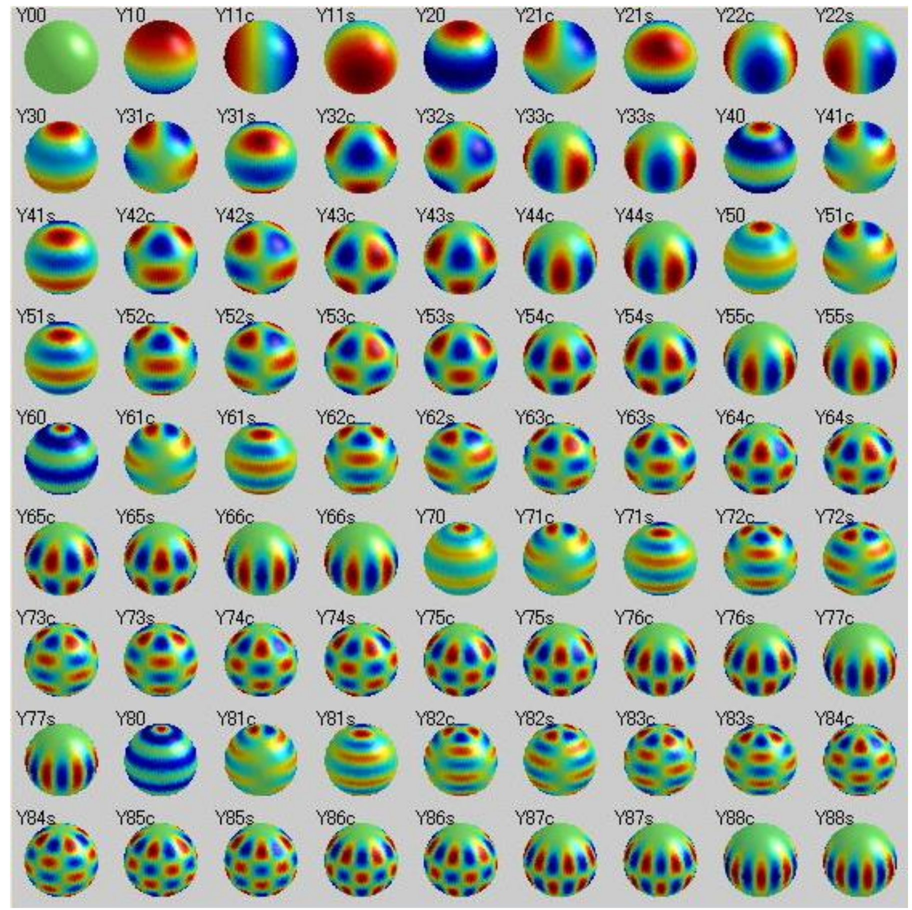
$$\overline{P}_{nm} = N_{nm}P_{nm},\ P_{00}(x) = 1, P_{10}(x) = x$$

$$P_{n-1,n}(x) = 0,$$

$$P_{nn}(x) = (2n-1)(1-x^2)^{1/2}P_{n-1,n-1}(x)$$

$$P_{nm}(x) = \frac{(2n-1)xP_{n-1,m}(x) - (n+m-1)P_{n-2,m}(x)}{n-m}$$

$$N_{nm} = \begin{cases} \sqrt{2n+1} & (m=0) \\ \sqrt{\dfrac{2(2n+1)(n-m)!}{(n+m)!}} & (m>0) \end{cases}$$



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

Coordinates		T1 (mm)	T2 (mm)	T3 (mm)	D (10^{-9})	R1 (mas)	R2 (mas)	R3 (mas)
A	B							
ITRF2005	ITRF2000	0.1	-0.8	-5.8	0.40	0.00	0.00	0.00
		-0.2/y	0.1/y	-1.8/y	0.08/y	0.00/y	0.00/y	0.00/y

(Epoch 2000.0)

Ionospheric Delay

Ionospheric Delay Model:

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

: Appleton-Hartree Formula

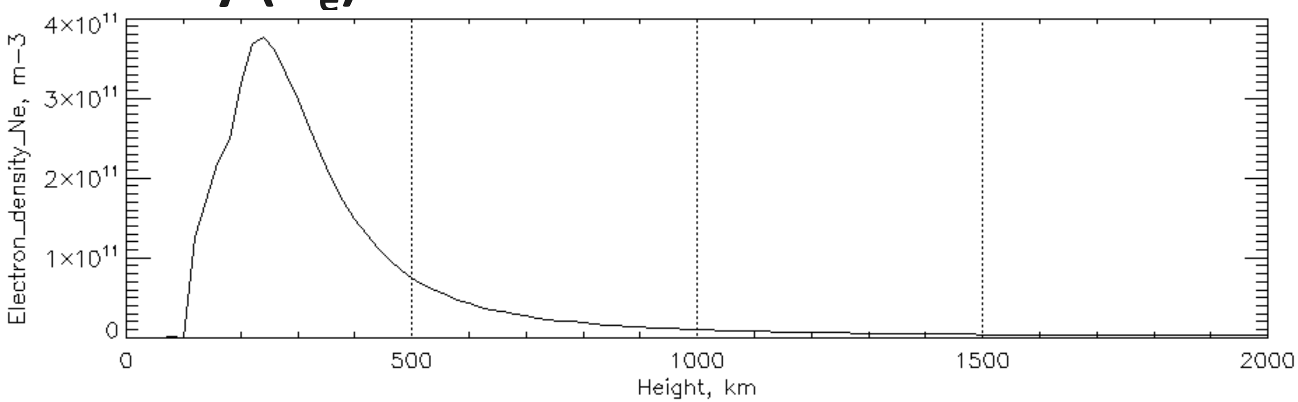
$$n = \sqrt{1 - f_N^2 / f^2} \approx 1 - f_N^2 / 2f^2 = 1 - 40.30 N_e / f^2$$

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

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

TEC: Total Electron Content

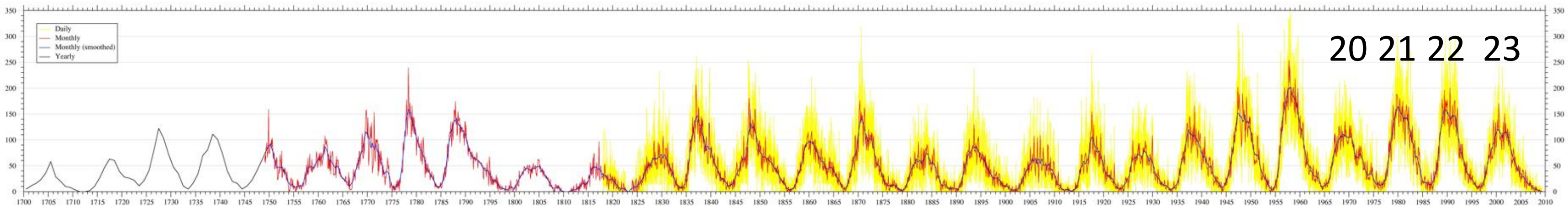
Electron Density (N_e):



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

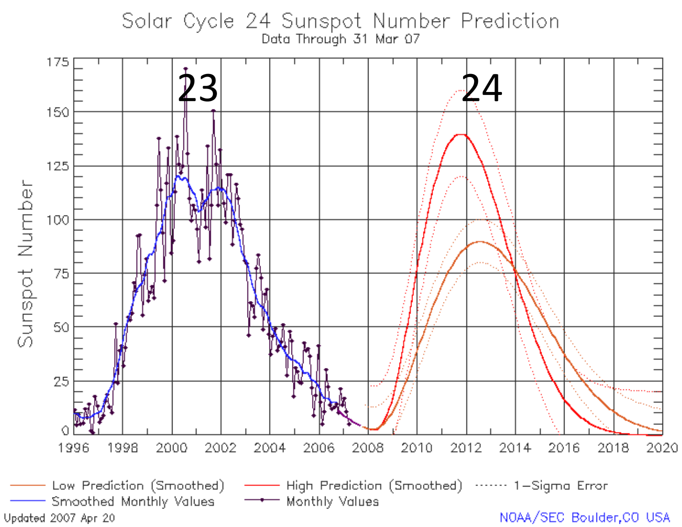
Solar Cycle

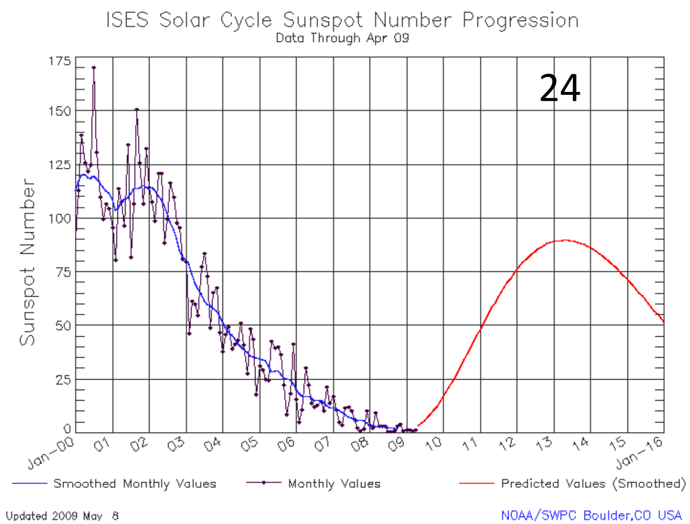
International Sunspot Number (ISN): 1700-2009



by SIDC (Solar Influences Data Analysis Center) in Belglum (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

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

	LC	Coefficients				Wave Length (cm)	Ionos Effect wrt L1	Typical Noise (cm)
		a	b	c	d			
L1	L1 Carrier-Phase	1	0	0	0	19.0	1.0	0.3
L2	L2 Carrier-Phase	0	1	0	0	24.4	1.6	0.3
LC/L3	Iono-Free Phase	C_1	C_2	0	0	-	0.0	0.9
LG/L4	Geometry-Free Phase	1	-1	0	0	-	0.6	0.4
WL	Wide-Lane Phase	λ_W / λ_1	$-\lambda_W / \lambda_2$	0	0	86.2	1.3	1.7
NL	Narrow-Lane Phase	λ_N / λ_1	λ_N / λ_2	0	0	10.7	1.3	1.7
MW	Melbourne-Wübbena	λ_W / λ_1	$-\lambda_W / \lambda_2$	λ_N / λ_1	λ_N / λ_2	86.2	0.0	21
MP1	L1-Multipath	$2C_2 - 1$	$-2C_2$	1	0	-	0.0	30
MP2	L2-Multipath	$-2C_1$	$2C_1 - 1$	0	1	-	0.0	30

$$C_1 = f_1^2/(f_1^2 - f_2^2),\ C_2 = -f_2^2/(f_1^2 - f_2^2),\ \lambda_W = 1/(1/\lambda_1 - 1/\lambda_2),\ \lambda_N = 1/(1/\lambda_1 + 1/\lambda_2)$$

Single Layer Model

Ionospheric Delay Model:

$$I = \frac{40.30\times10^{16}}{f^2}TEC \approx \frac{1}{\cos z'}\frac{40.30\times10^{16}}{f^2}\times VTEC(t,\phi_{pp},\lambda_{pp})$$

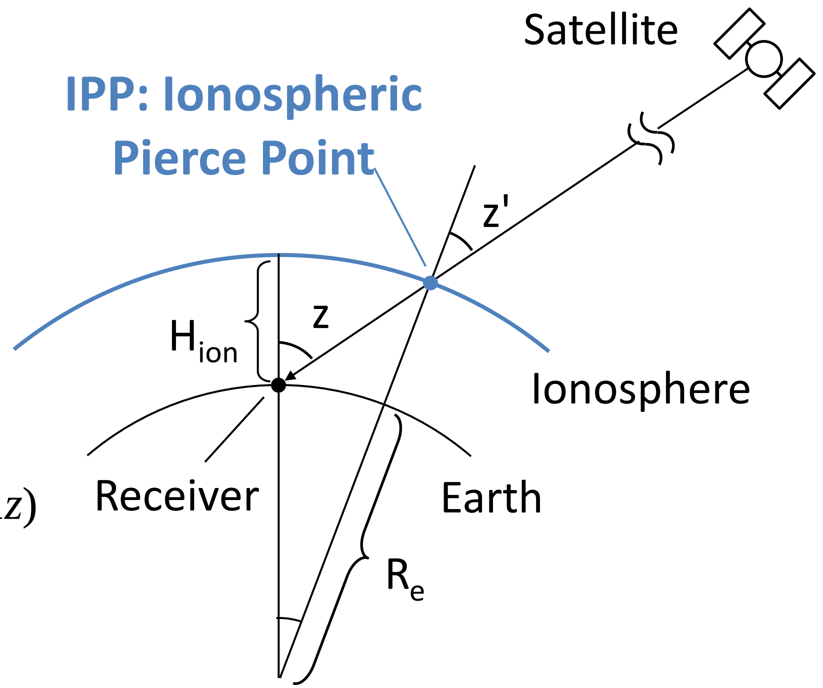
IPP Position/Slant Factor:

$$z = \pi/2 - El$$

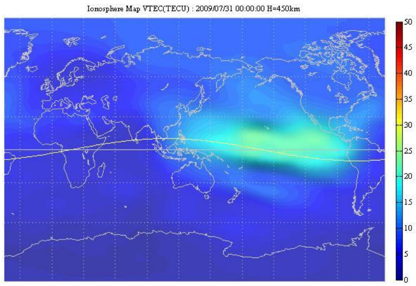
$$z' = \arcsin\frac{R_e \sin z}{R_e + H_{ion}}, \alpha = z - z'$$

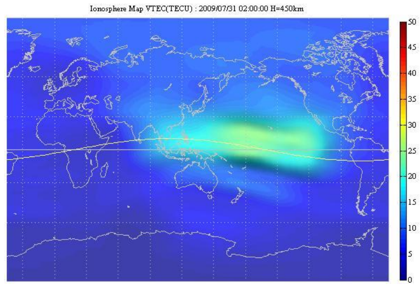
$$\phi_{pp} = \arcsin(\cos\alpha\sin\phi + \sin\alpha\cos\phi\cos Az)$$

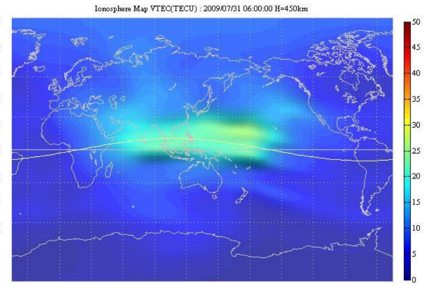
$$\lambda_{pp} = \lambda + \arcsin\frac{\sin\alpha\sin Az}{\phi_{pp}}$$

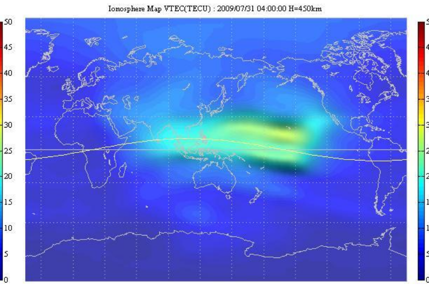


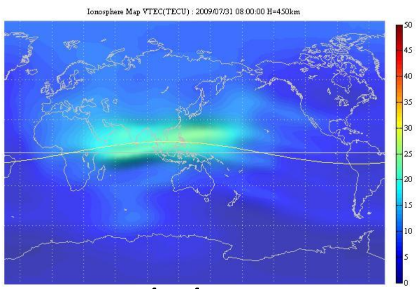
Ionospheric TEC Grid

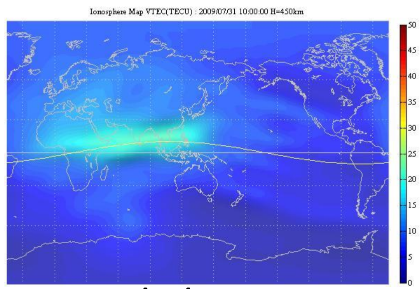

2009/7/31 0:00

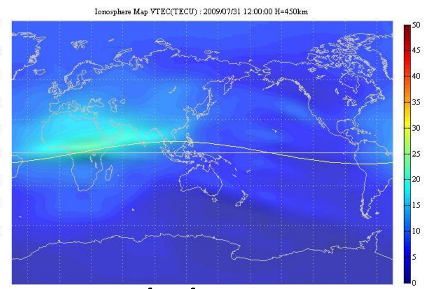

2009/7/31 2:00

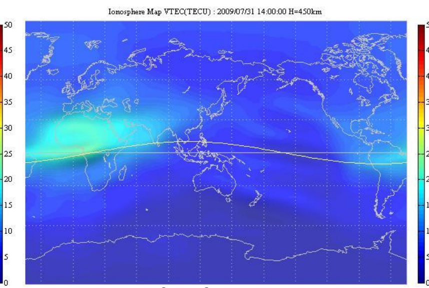

2009/7/31 4:00

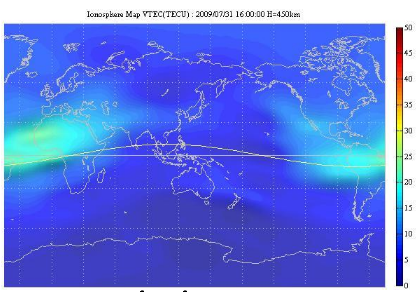

2009/7/31 6:00

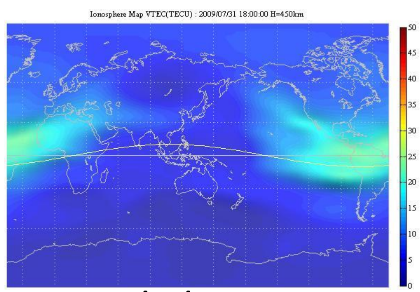

2009/7/31 8:00

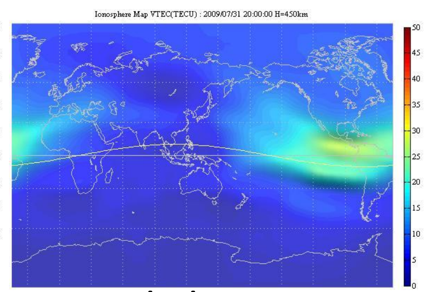

2009/7/31 10:00

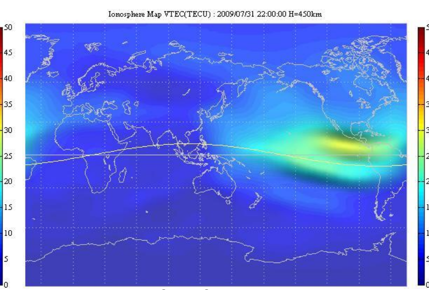

2009/7/31 12:00


2009/7/31 14:00


2009/7/31 16:00


2009/7/31 18:00


2009/7/31 20:00


2009/7/31 22:00

(IGS TEC Final, GPS Time)

Tropospheric Delay

Tropospheric Delay Model:

$$T = m_h(El)ZHD + m_w(El)ZWD$$

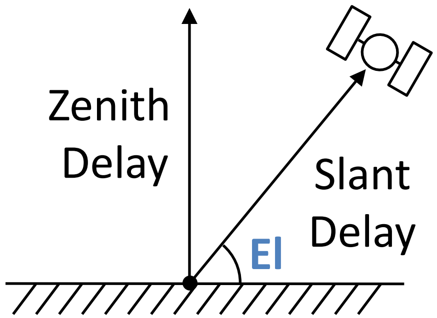
$$ZHD = \frac{0.0022768p}{1 - 0.00266\cos 2\phi - 2.8\times 10^{-7} H}$$

: 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):

$$T_m = 70.2 + 0.72T$$

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

$R_v = 461, k_1 = 77.6,$

$k_2 = 71.98, k_3 = 3.754\times 10^5$

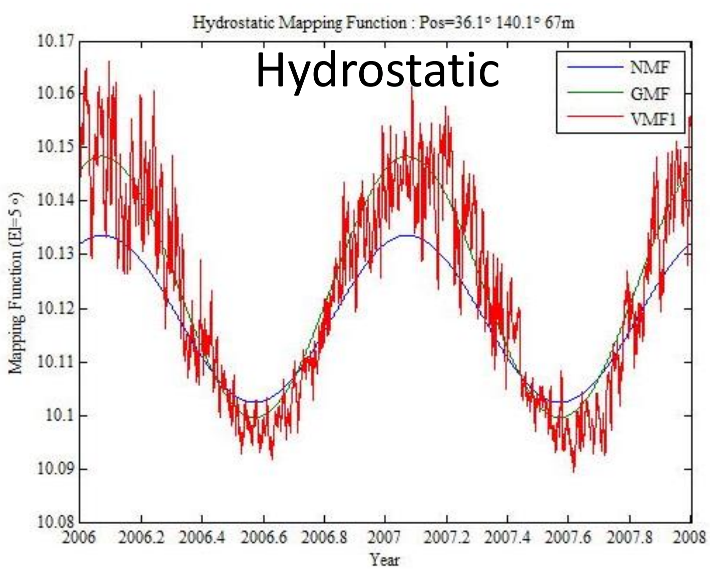
$m_v = 18.0152, m_d = 28.9644$

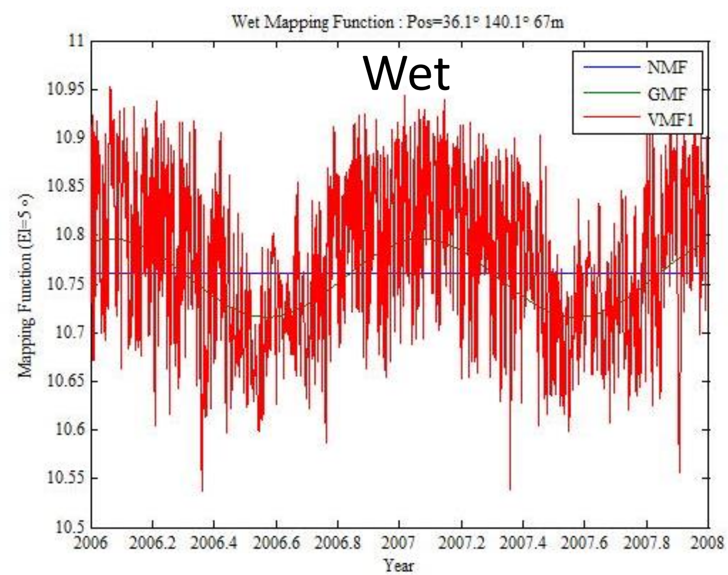
Mapping Function

$$m(El) = \frac{1 + \cfrac{a}{1 + \cfrac{b}{1 + c}}}{\sin(El) + \cfrac{a}{\sin(El) + \cfrac{b}{\sin(El) + c}}}$$

a, b, c : Mapping Function Coefficients

NMF, GMF, VMF1

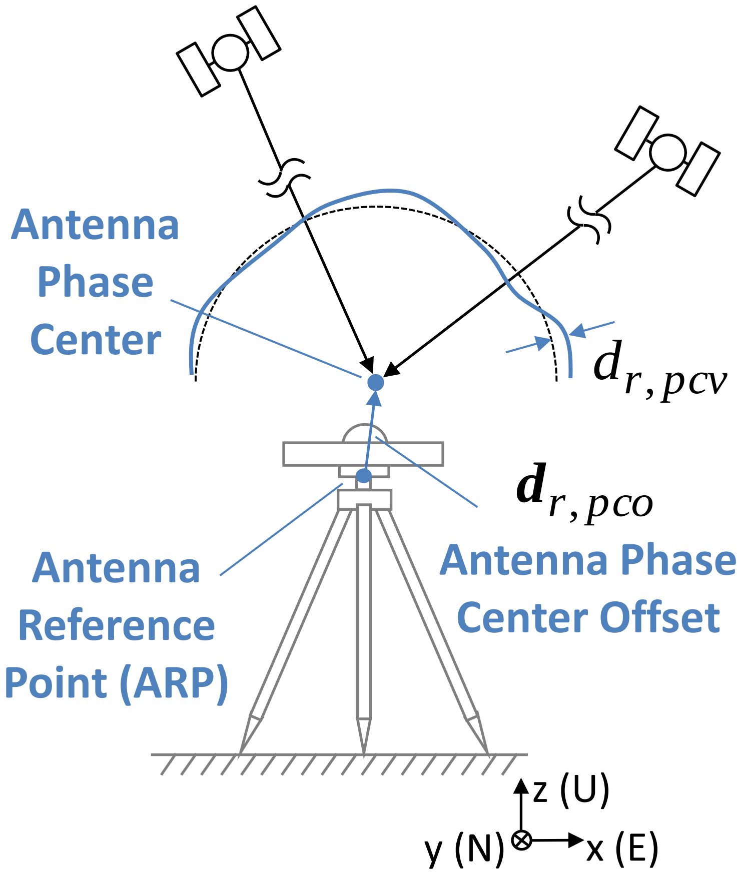




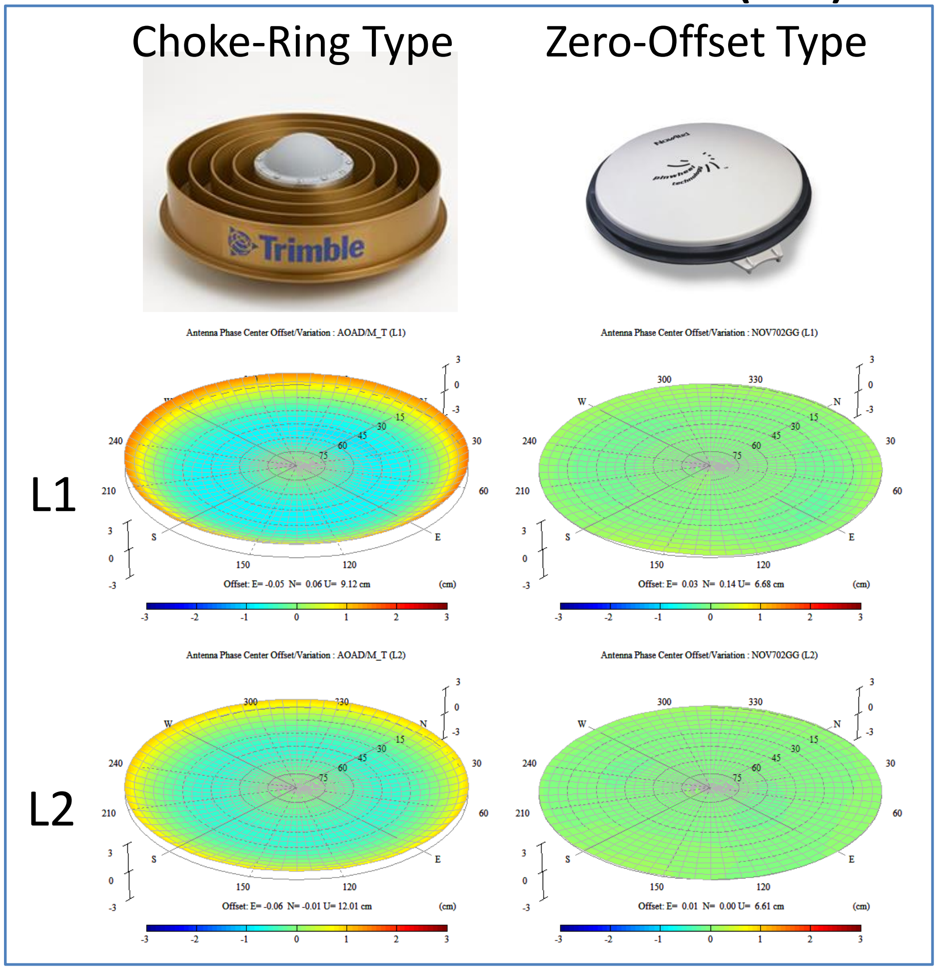
(2006/1/1-2007/12/31, TSKB, El=5deg)

Antenna Phase Center 1

Receiver Antenna Phase Center:



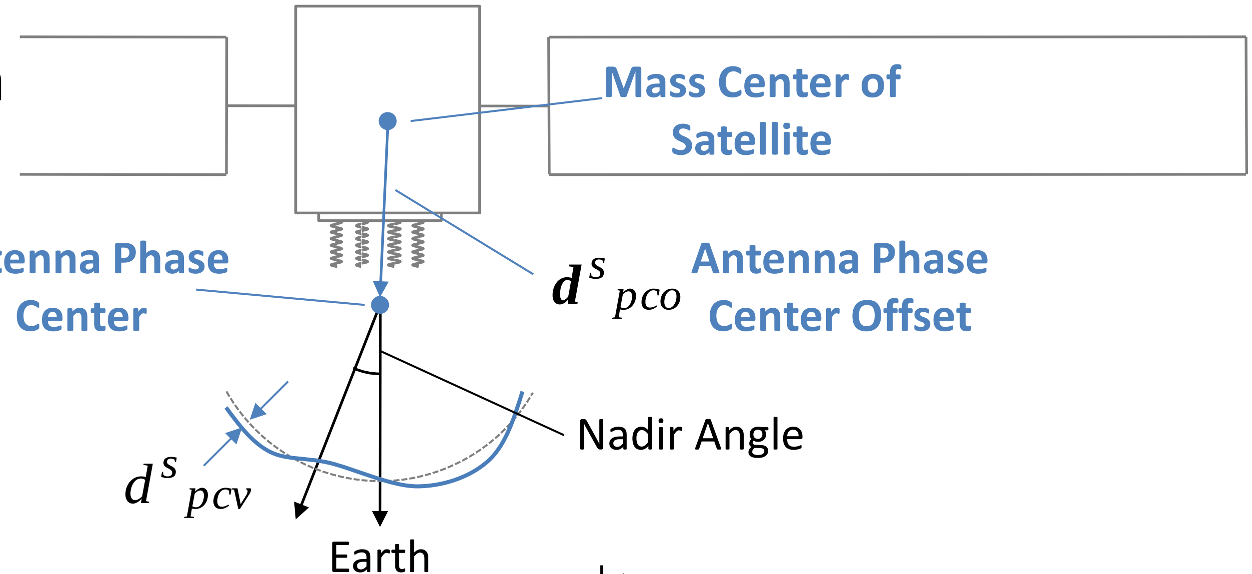
Antenna Phase Center Variation (PCV)



IGS Absolute Antenna Model (IGS05.PCV)

Antenna Phase Center 2

Satellite Antenna Phase Center:

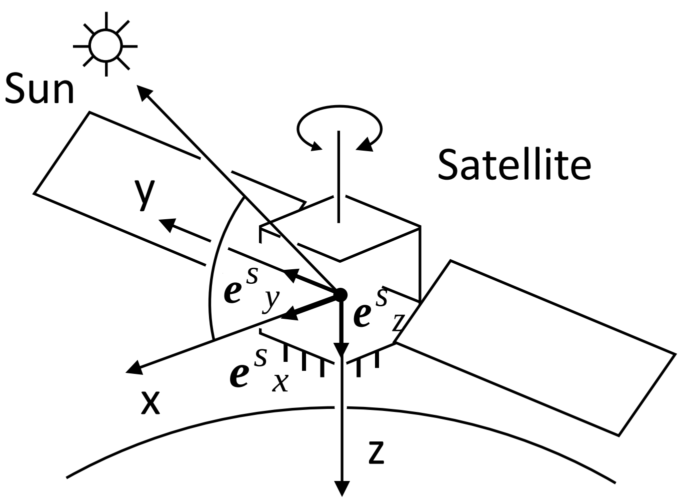


Satellite Coordinate to ECEF:

$$E_{sat \to ecef} = (e^{s}_{x}, e^{s}_{y}, e^{s}_{z})$$

$$e^{s}_{z} = -\frac{r^{s}}{\left\| r^{s} \right\|}, e_{s} = \frac{r_{sun} - r^{s}}{\left\| r_{sun} - r^{s} \right\|}$$

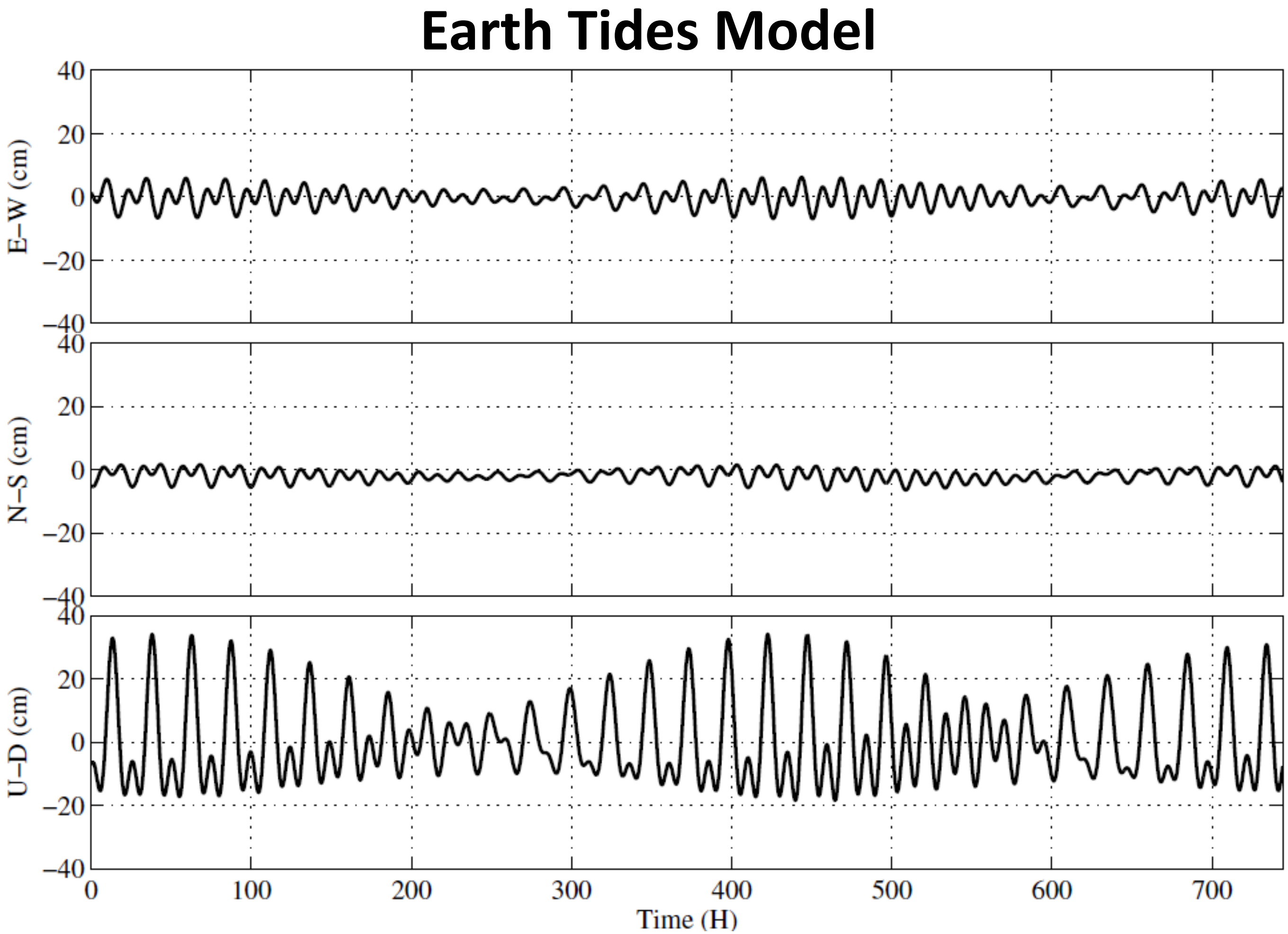
$$e^{s}_{y} = \frac{e^{s}_{z} \times e^{s}_{s}}{\left\| e^{s}_{z} \times e_{s} \right\|}, e^{s}_{x} = e^{s}_{y} \times e^{s}_{z}$$



Site Displacement

- **Displacement of Ground-Fixed Receiver**
  - Solid Earth Tide
  - Ocean Tide Loading (OTL)
  - Pole Tide
  - Atmospheric Loading
- **Tide Model**
  - IERS Conventions 1996/2003/2010
  - Ocean Loading: Schwiderski, GOT99.2/00.2, CSR 3.0/4.0, FES99/2004, NAO99.b
  - $M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_1, M_m, S_{sa}$

Earth Tides



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.

$$d_{pw} = \lambda \left\{ sign(\boldsymbol{e}_r^s \cdot (\boldsymbol{D}^s \times \boldsymbol{D}_r)) \arccos \frac{\boldsymbol{D}^s \cdot \boldsymbol{D}_r}{\left\| \boldsymbol{D}^s \right\| \left\| \boldsymbol{D}_r \right\|} / 2\pi + N \right\}$$

$\boldsymbol{D}^s = \boldsymbol{e}_x^s - \boldsymbol{e}_u^s(\boldsymbol{e}_u^s \cdot \boldsymbol{e}_x^s) - \boldsymbol{e}_u^s \times \boldsymbol{e}_y^s$: Dipole Vector of Satellite Antenna

$\boldsymbol{D}_r = \boldsymbol{e}_{r,x} - \boldsymbol{e}_r^s(\boldsymbol{e}_r^s \cdot \boldsymbol{e}_{r,x}) + \boldsymbol{e}_r^s \times \boldsymbol{e}_{r,y}$: Dipole Vector of Receiver Antenna

$\boldsymbol{E}_{ecef \rightarrow enu} = (\boldsymbol{e}_{r,x}{}^T, \boldsymbol{e}_{r,y}{}^T, \boldsymbol{e}_{r,z}{}^T)^T$: ECEF to ENU Transformation Matrix

$\boldsymbol{e}_r^s$: LOS Vector from Receiver to Satellite Antenna

N : Integer Ambiguity

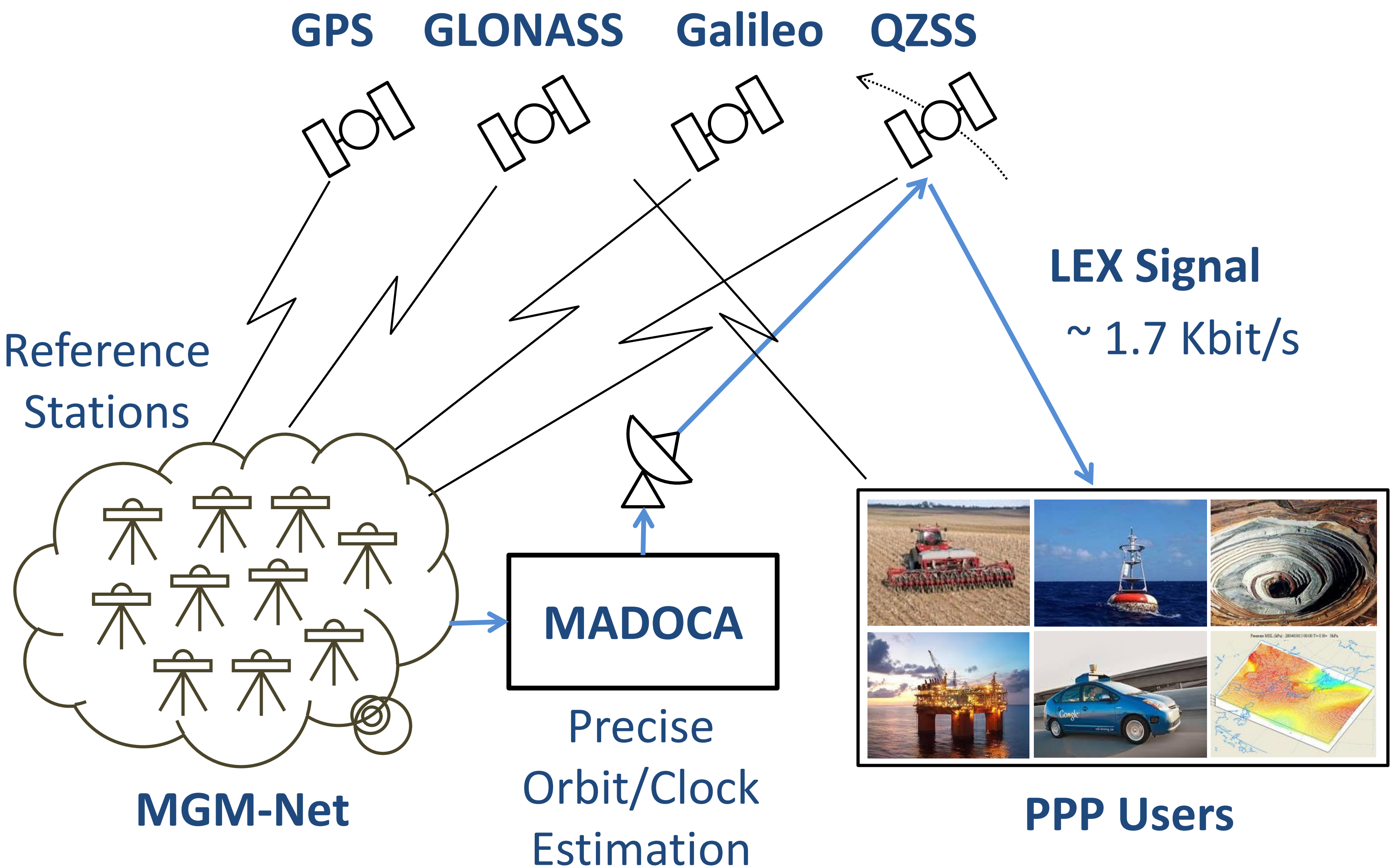
Relativistic Effects

- **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:

$$d_{rel} = -\frac{2\boldsymbol{r}^s \cdot \boldsymbol{v}^s}{c^2}$$

Real-Time PPP via QZSS LEX

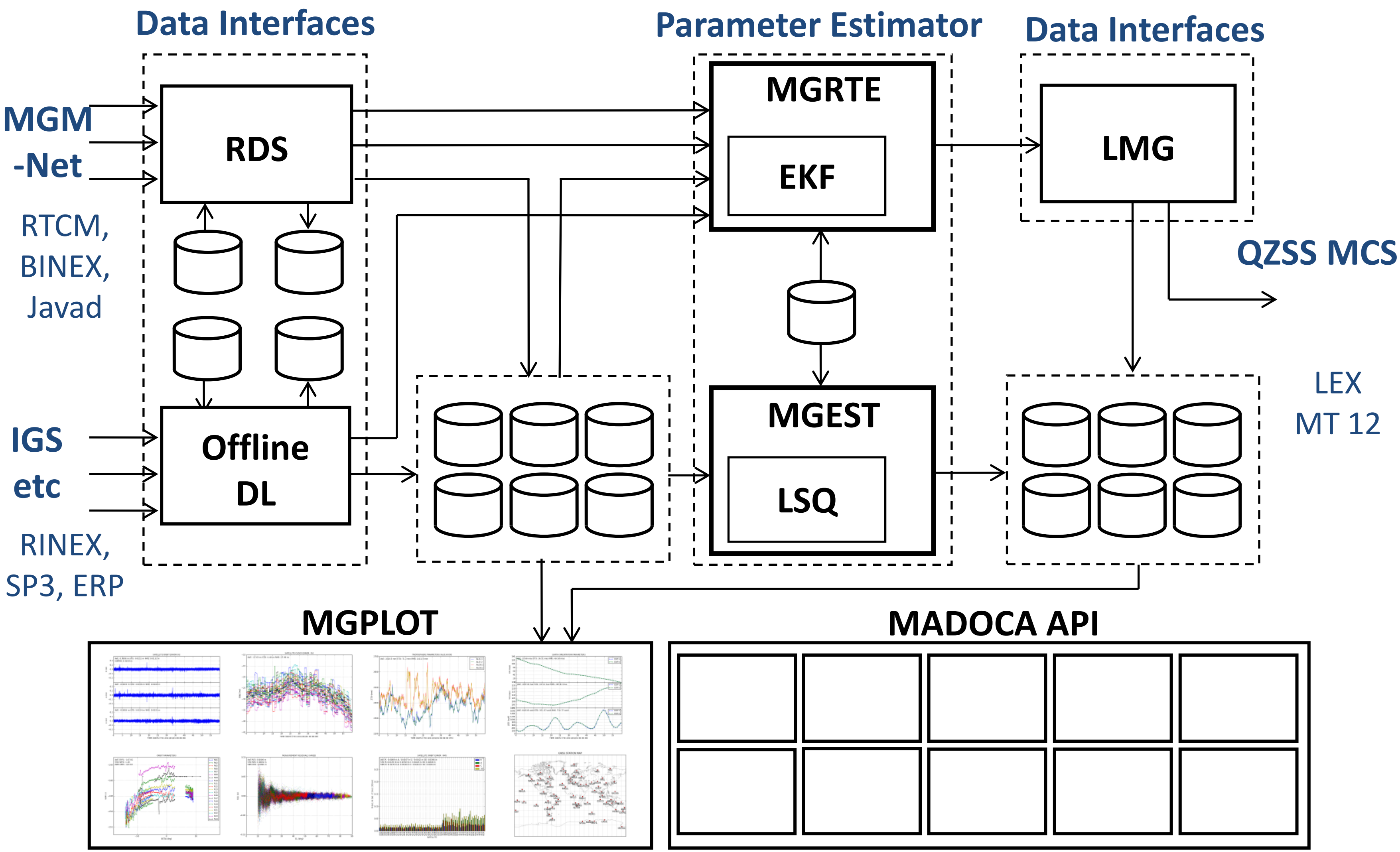


MADOCA (1)

Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis

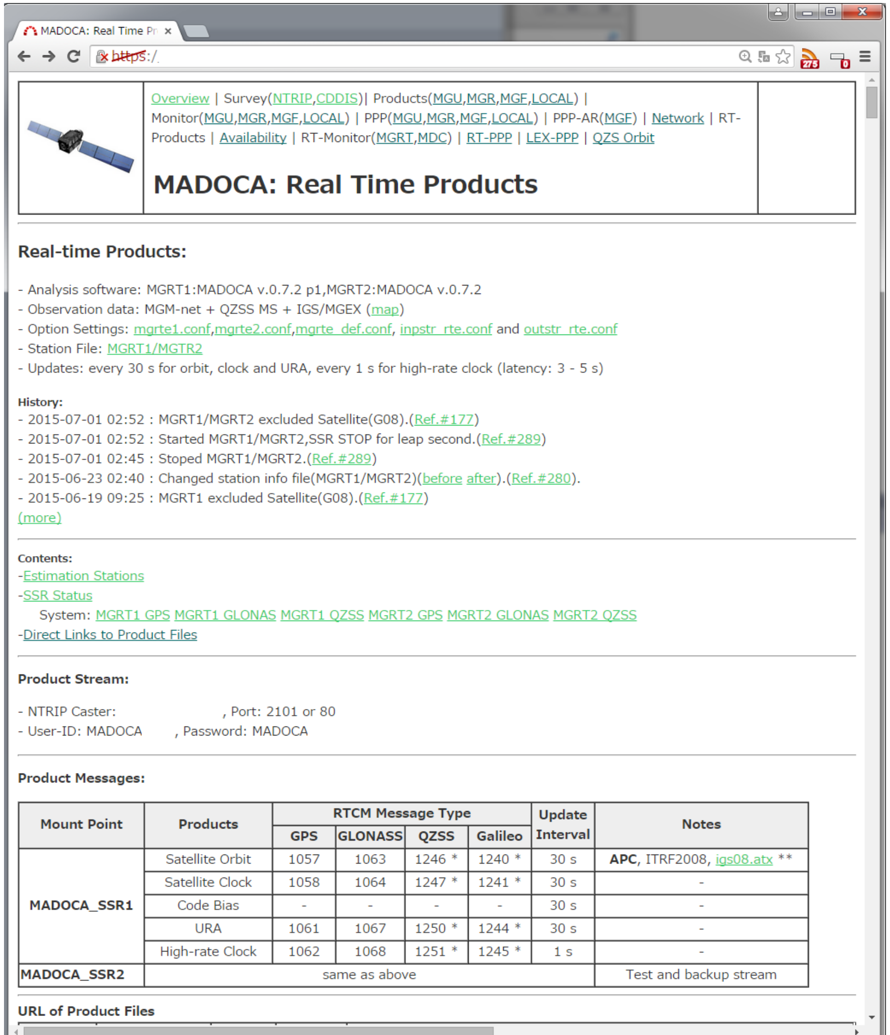
- **For real-time PPP service via QZSS LEX**
  - Many (potential) applications over global area
- **Precise orbit/clock for multi-GNSS constellation**
  - Key-technology for future cm-class positioning
- **Brand-new codes developed from scratch**
  - Optimized multi-threading design for recent CPU
 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

MADOCA (2)



Data Interfaces
Parameter Estimator
Data Interfaces
MGM
-Net
RTCM,
BINEX,
Javad
RDS
MGRTE
EKF
LMG
QZSS MCS
IGS
etc
RINEX,
SP3, ERP
Offline
DL
MGEST
LSQ
LEX
MT 12
MGPLOT
MADOCA API

MADOCA (3)



Overview | Survey(NTRIP,CDDIS)| Products(MGU,MGR,MGF,LOCAL) | Monitor(MGU,MGR,MGF,LOCAL) | PPP(MGU,MGR,MGF,LOCAL) | PPP-AR(MGF) | Network | RT-Products | Availability | RT-Monitor(MGRT,MDC) | RT-PPP | LEX-PPP | QZS Orbit

MADOCA: Real Time Products

Real-time Products:

- Analysis software: MGRT1:MADOCA v.0.7.2 p1,MGRT2:MADOCA v.0.7.2
- Observation data: MGM-net + QZSS MS + IGS/MGEX (map)
- Option Settings: mgrte1.conf,mgrte2.conf,mgrte_def.conf, inpstr_rte.conf and outstr_rte.conf
- Station File: MGRT1/MGTR2
- 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(G08).(Ref.#177)
- 2015-07-01 02:52 : Started MGRT1/MGRT2,SSR STOP for leap second.(Ref.#289)
- 2015-07-01 02:45 : Stoped MGRT1/MGRT2.(Ref.#289)
- 2015-06-23 02:40 : Changed station info file(MGRT1/MGRT2)(before after).(Ref.#280).
- 2015-06-19 09:25 : MGRT1 excluded Satellite(G08).(Ref.#177)

(more)

Contents:

-Estimation Stations
-SSR Status
System: MGRT1 GPS MGRT1 GLONAS MGRT1 QZSS MGRT2 GPS MGRT2 GLONAS MGRT2 QZSS
-Direct Links to Product Files

Product Stream:

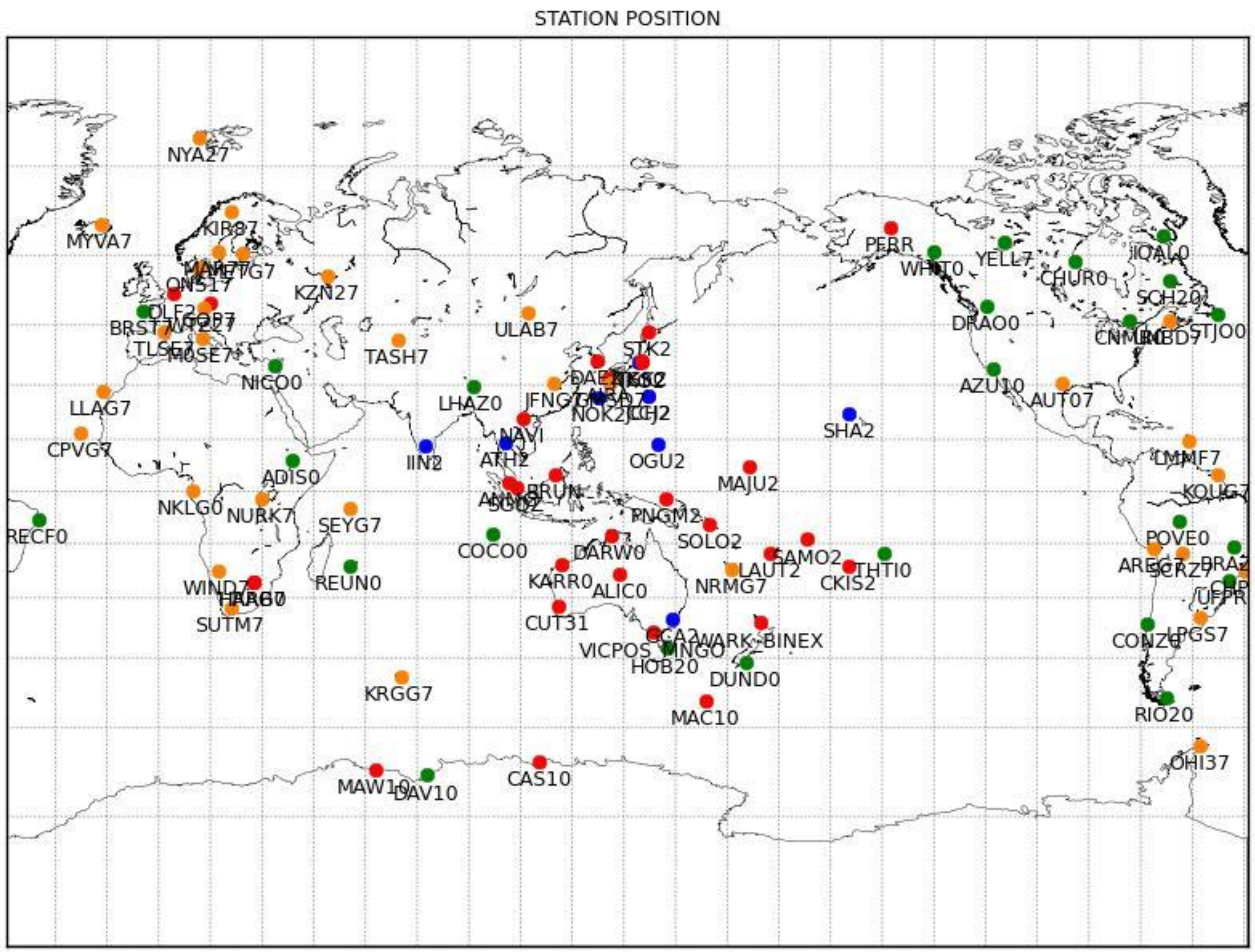
- NTRIP Caster: , Port: 2101 or 80
- User-ID: MADOCA , Password: MADOCA

Product Messages:

Mount Point	Products	RTCM Message Type				Update Interval	Notes
		GPS	GLONASS	QZSS	Galileo		
MADOCA_SSR1	Satellite Orbit	1057	1063	1246 *	1240 *	30 s	**APC**, ITRF2008, igs08.atx **
	Satellite Clock	1058	1064	1247 *	1241 *	30 s	-
	Code Bias	-	-	-	-	30 s	-
	URA	1061	1067	1250 *	1244 *	30 s	-
	High-rate Clock	1062	1068	1251 *	1245 *	1 s	-
MADOCA_SSR2	same as above						Test and backup stream

URL of Product Files

MADOCA (4)



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