測位航法学会 平成23年度全国大会 セミナー②

GNSS Precise Positioning with RTKLIB Part 2

2011-4-25,26 @東京海洋大学品川 楽水会館

東京海洋大学　高須 知二

Timetable

1.	GPS/GNSS	April 25	9:30-10:40
2.	Signal and Receiver		10:50-12:00
3.	Standard Positioning		13:00-15:10
4.	RTKLIB		15:30-16:40
5.	**RTK**	April 26	9:30-10:30
6.	**PPP**		10:40-11:50
7.	**RTK System**		13:00-14:20
8.	**Advanced Topics**		14:40-16:10

5. RTK

Precise 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, ...

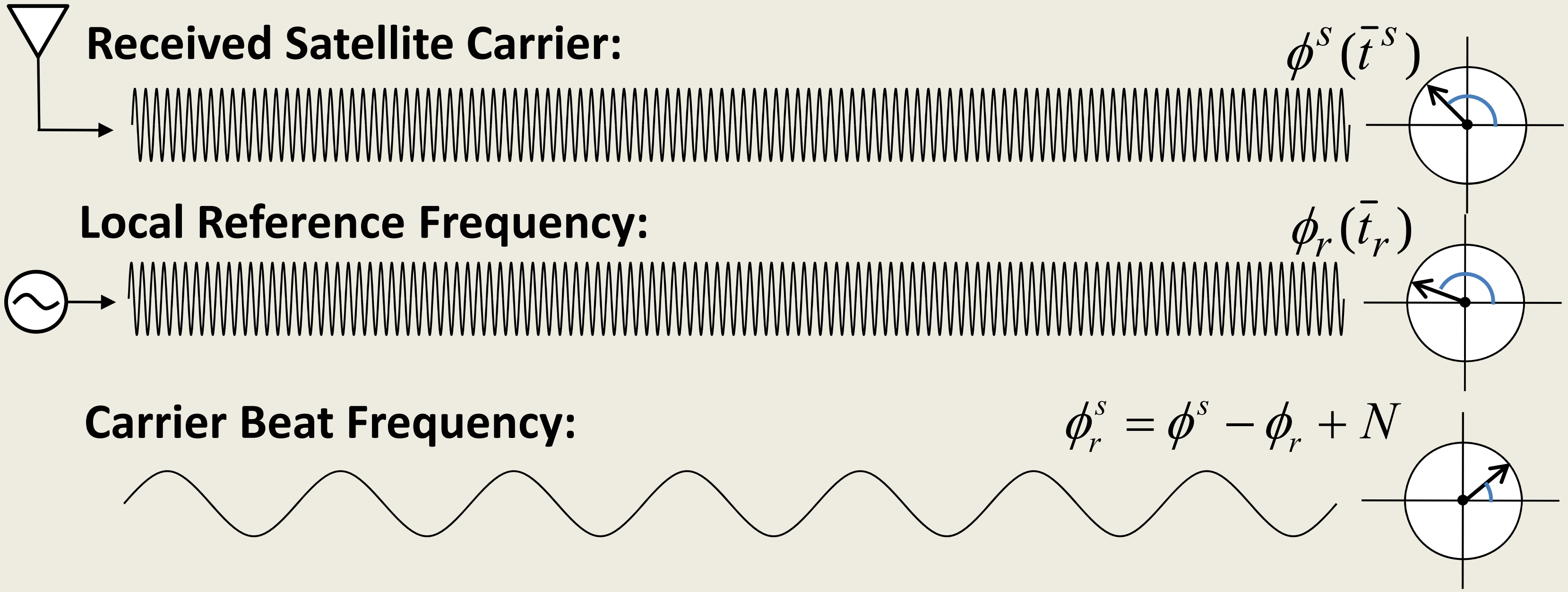
Carrier-Phase

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)*



Carrier-Phase Model (1)

Carrier-Phase:

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

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

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

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

$$= \underline{\rho_r^s + c(dt_r - dT^s) - I_r^s + T_r^s} + \underbrace{\lambda B_r^s}_{\text{Carrier-Phase Bias}} + \underbrace{d_r^s}_{\text{Other Correction Terms}} + \varepsilon_\Phi \qquad \text{(m)}$$

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:

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

$\boldsymbol{d}_{r,pco}$: 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

DD (Double Difference)

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

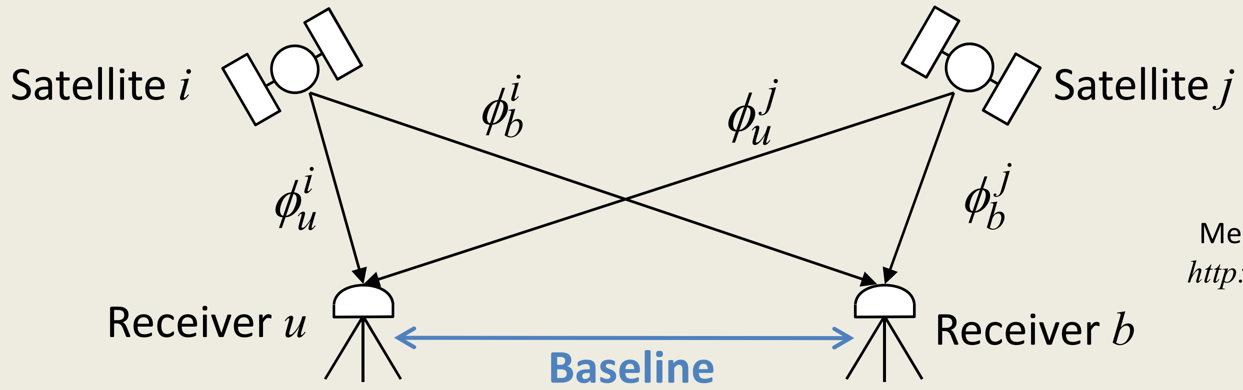
$$dt_{ub}^{ij} = dt_u^{ij} - dt_b^{ij} = 0,\ dT_{ub}^{ij} = dT_{ub}^i - dT_{ub}^j \approx 0$$

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

(short Baseline and same antenna type)

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

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



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

Carrier-based Relative Positioning

Nonlinear-LSE:

Parameter Vector:

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

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):

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

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

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

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

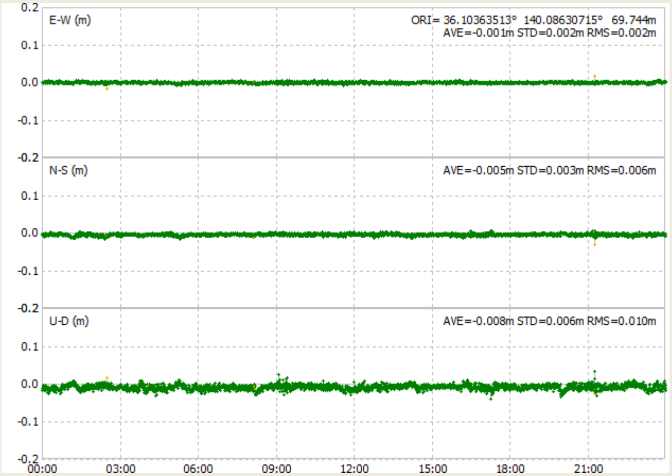
$$\boldsymbol{R}_{t_k} = \begin{pmatrix} 4\sigma_\Phi{}^2 & 2\sigma_\Phi{}^2 & \cdots & 2\sigma_\Phi{}^2 \\ 2\sigma_\Phi{}^2 & 4\sigma_\Phi{}^2 & \cdots & 2\sigma_\Phi{}^2 \\ \vdots & \vdots & \ddots & \vdots \\ 2\sigma_\Phi{}^2 & 2\sigma_\Phi{}^2 & \cdots & 4\sigma_\Phi{}^2 \end{pmatrix}$$

r_b : Fixed Base-Station Position

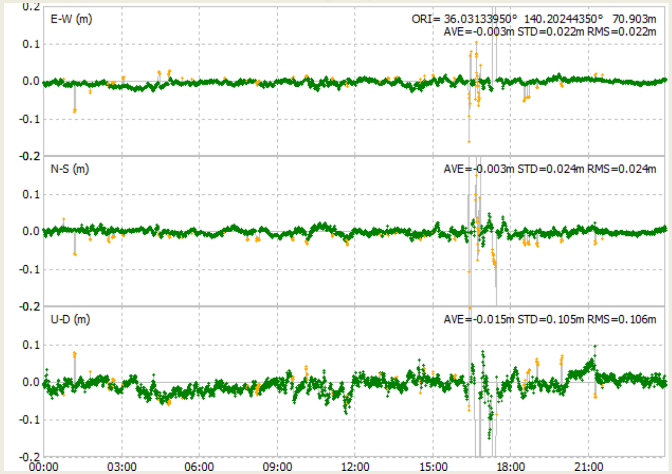
Effect of Baseline Length

BL=0.3 km

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



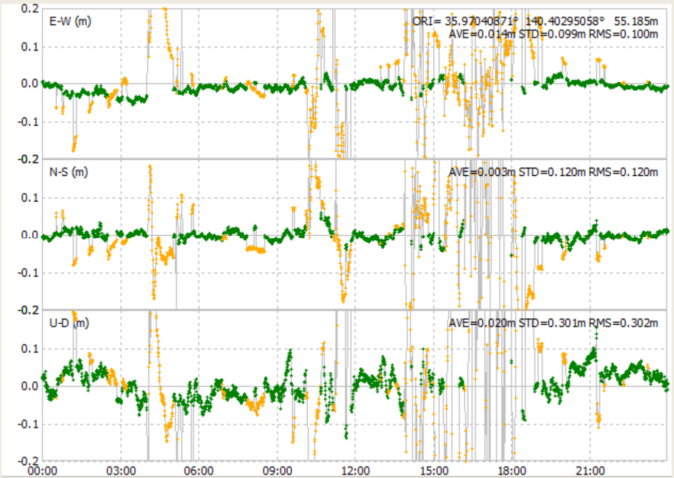
BL=13.3 km



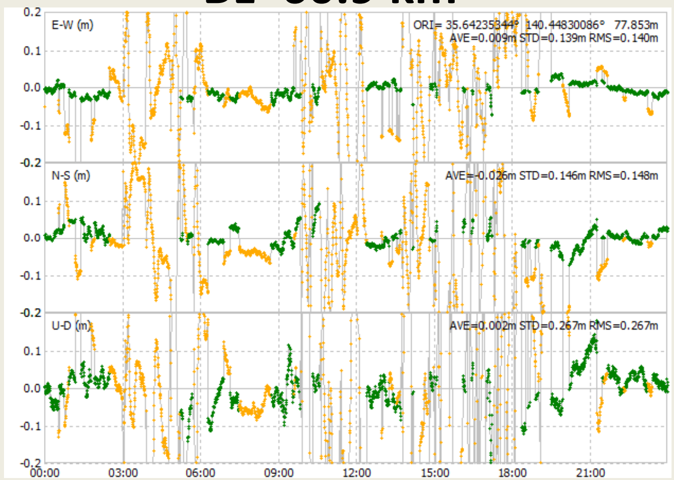
RMS Error:
E: 2.2cm
N: 2.4cm
U: 10.6cm
Fix Ratio:
94.2%

BL=32.2 km

RMS Error:
E: 10.0cm
N: 12.0cm
U: 30.2cm
Fix Ratio:
64.3%



BL=60.9 km



RMS Error:
E: 14.0cm
N: 14.8cm
U: 26.7cm
Fix Ratio:
44.4%

(24 hr Kinematic ●: Fixed Solution ●: Float Solution)

Integer Ambiguity Resolution

- **Objectives**
  - More accurate than float solutions
  - Fast converge of solutions
- **Many AR Strategies**
  - Simple Integer rounding
  - Multi-frequency wide-lane and narrow-lane generation
  - Search in coordinate domain
  - Search in ambiguity domain
  - AFM, FARA, LSAST, LAMBDA, ARCE, HB-L^3, Modified Cholesy Decomposition, Null Space, FAST, OMEGA, ...

ILS (Integer Least Square Estimation)

Problem:

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

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

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

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

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

(3) Improve solution

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

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

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

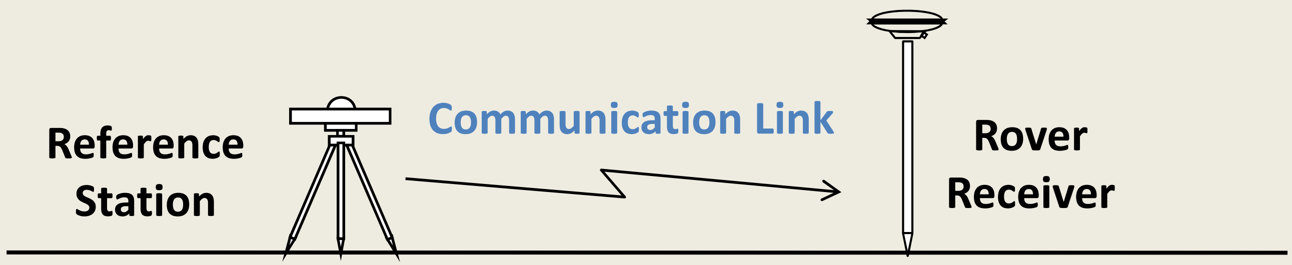
$$\hat{\boldsymbol{z}} = \boldsymbol{Z}^T \hat{\mathbf{a}},\ \mathbf{Q}_z = \boldsymbol{Z}^T \mathbf{Q}_a \boldsymbol{Z}$$

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

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

RTK (Real-time Kinematic)

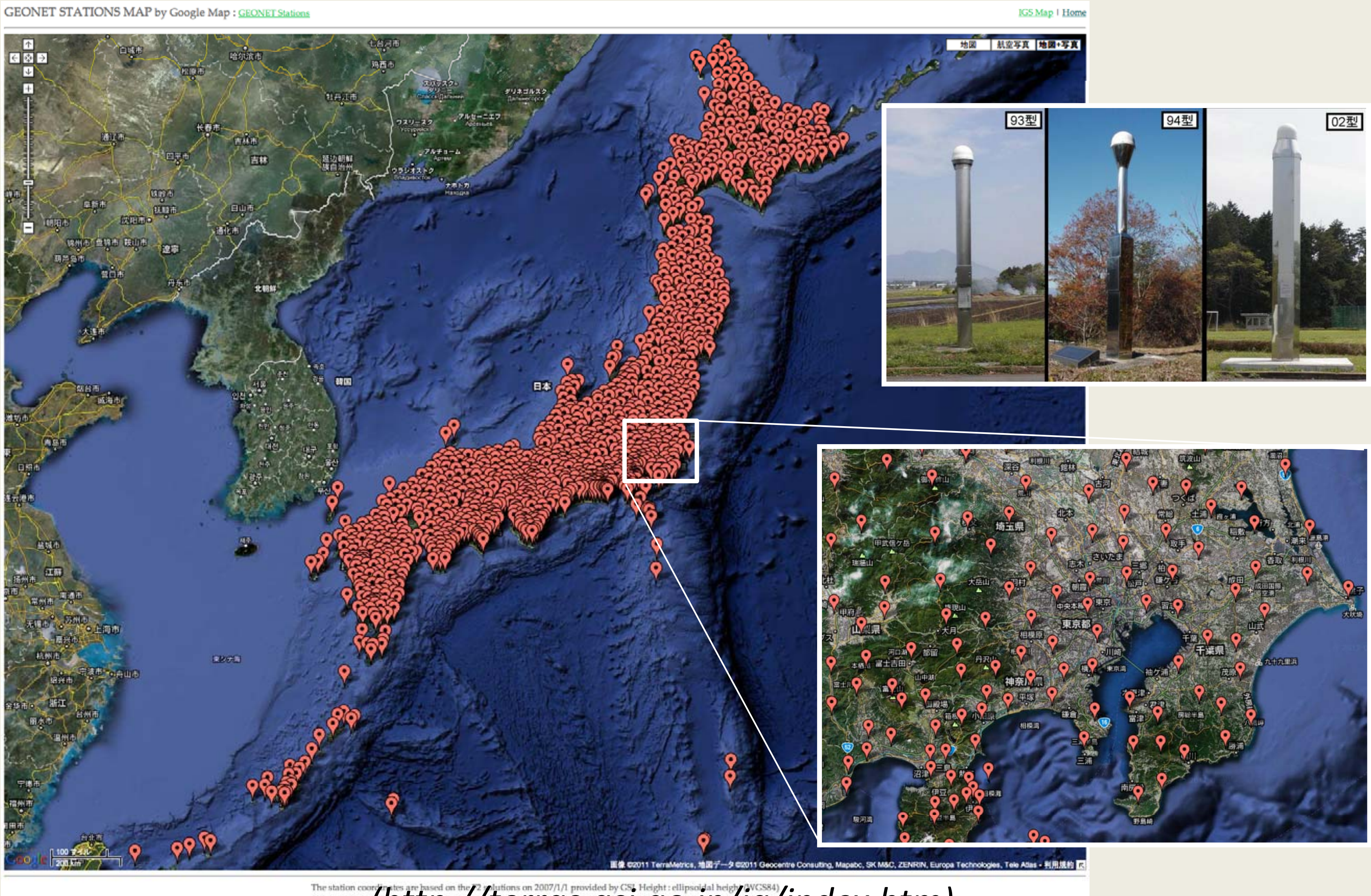
- **Technique with Carrier-based Relative Positioning**
  - Real-time Position of Rover Antenna
  - Transmit Reference Station Data to Rover via Comm. Link
  - **OTF** (On-the-Fly) Integer Ambiguity Resolution
  - Typical Accuracy: 1 cm + 1ppm x BL RMS (Horizontal)
  - Applications:
    Land Survey,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



NRTK (Network RTK)

- **Extension of RTK**
  - RTK without User Reference Station
  - Sparse Networked Reference Stations
  - Correction Messages via Mobile-Phone Network
  - Format: **VRS**, **FKP**, MAC, RTCM 2.3, RTCM 3.1
  - Server S/W: Trimble GPSNet, GEO++ GNSMART, ...
  - NTRIP Networked Transport of RTCM via Internet Protocol
- **NRTK Service in Japan**
  - GEONET: ~1200 Reference Stations by GSI
  - NGDS (www.gpsdata.co.jp), JENOBA (www.jenoba.jp)

GEONET



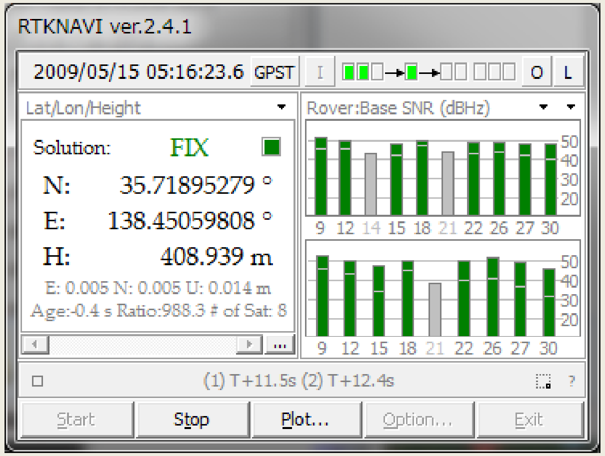
(http://terras.gsi.go.jp/ja/index.htm)

5. RTK:
Exercise

RTK of Driving Vehicle

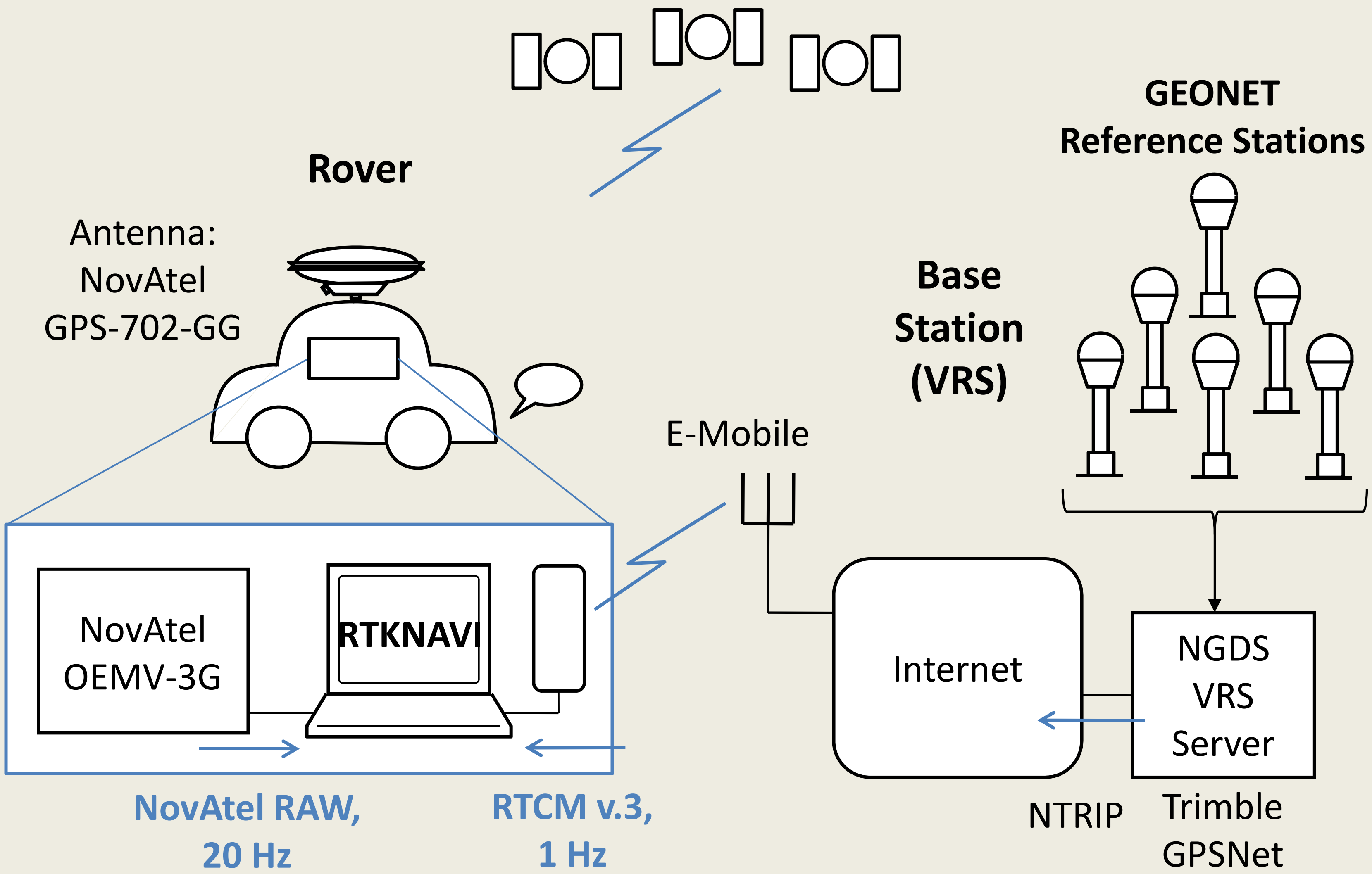
- **Objective**
  RTK of Driving Vehicle
- **Program**
  ...¥rtklib_2.4.0¥bin¥rtknavi.exe
  ...¥rtklib_2.4.1b¥bin¥rtknavi.exe
- **Data**
  ...¥seminar¥sample2¥
  oemv_2009515c.gps (NovAtel)
  0263_20090515c.rtcm3 (VRS)

RTKNAVI



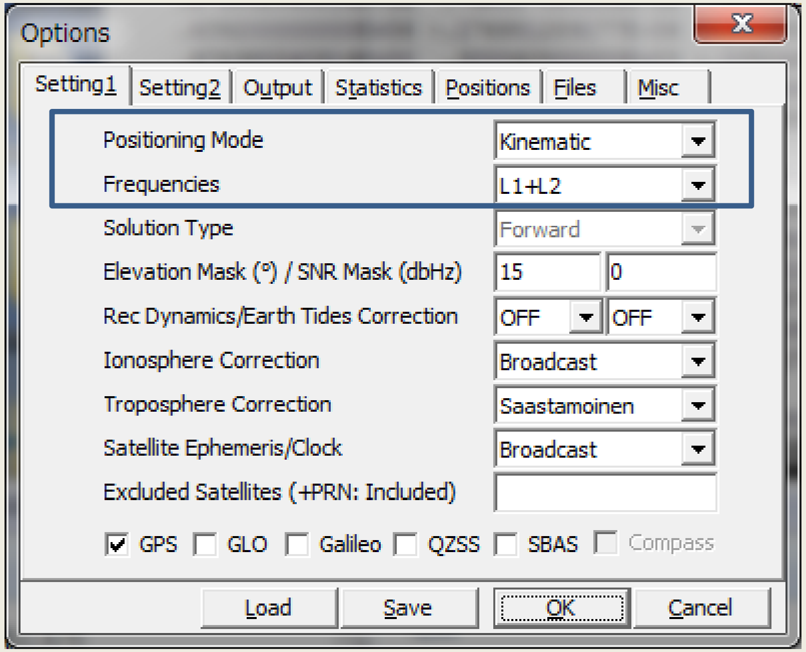
NovAtel OEMV-3G, GPS-702-GG

RTK Configuration

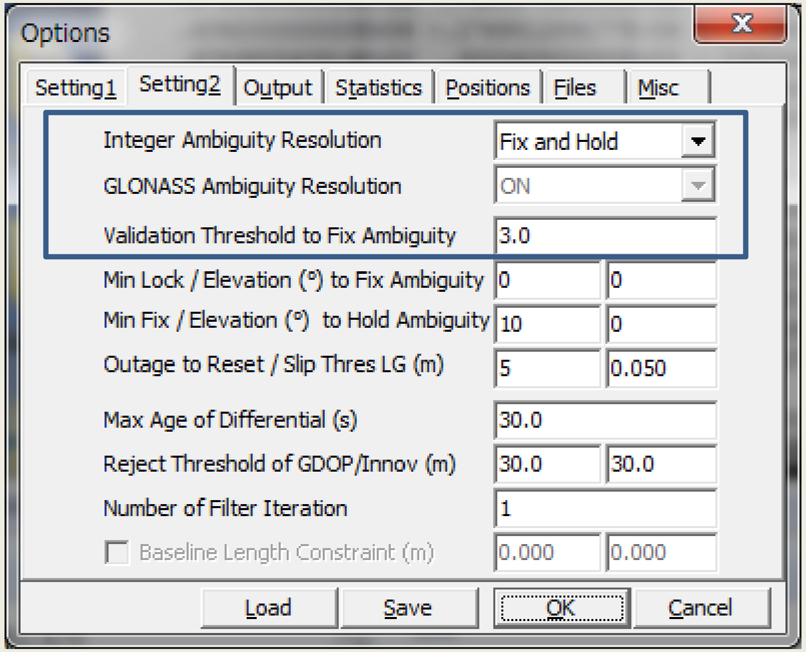


RTKNAVI - Options

Setting1

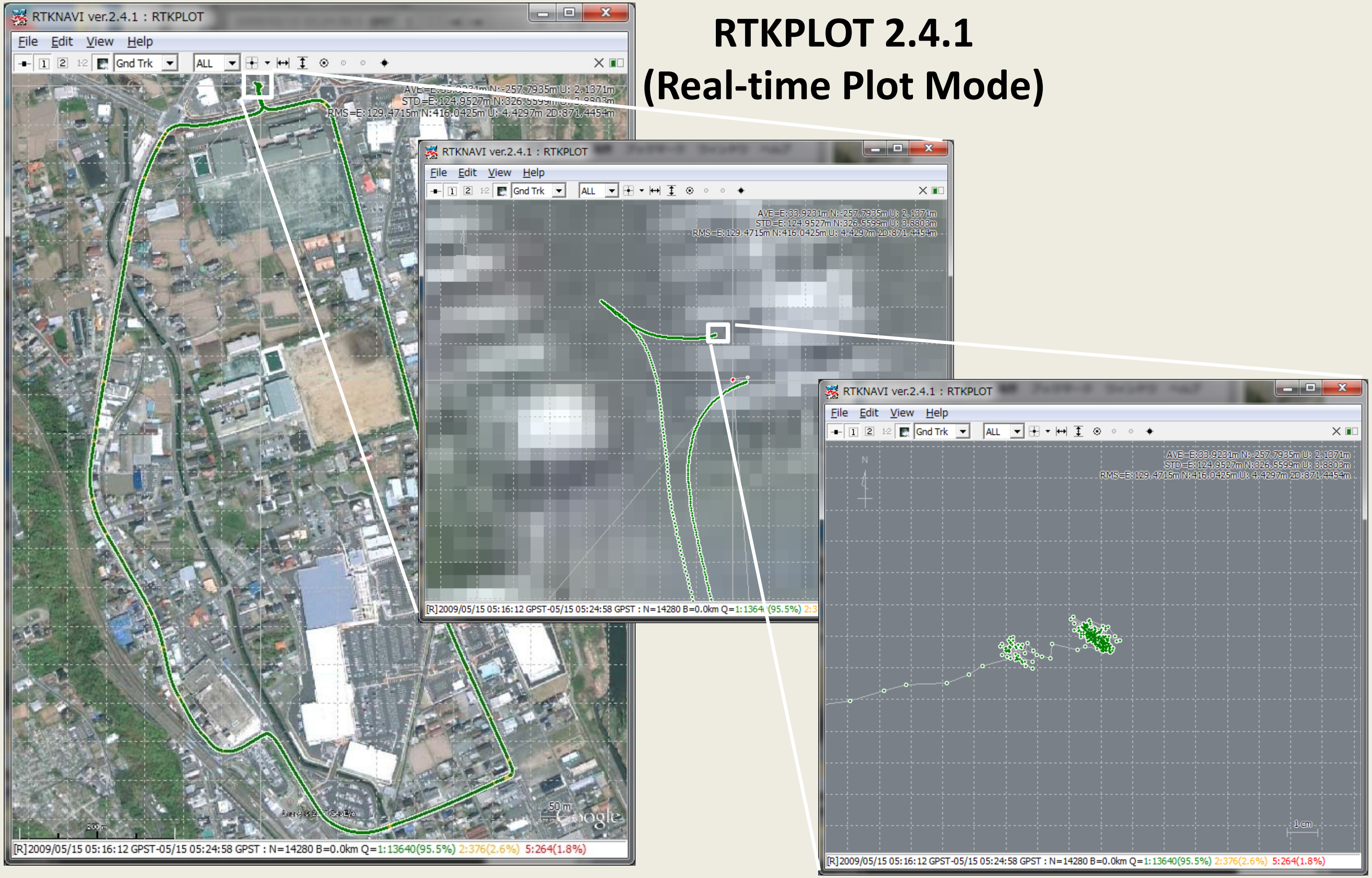


Setting2



RTK Solutions

RTKPLOT 2.4.1
(Real-time Plot Mode)



6. PPP

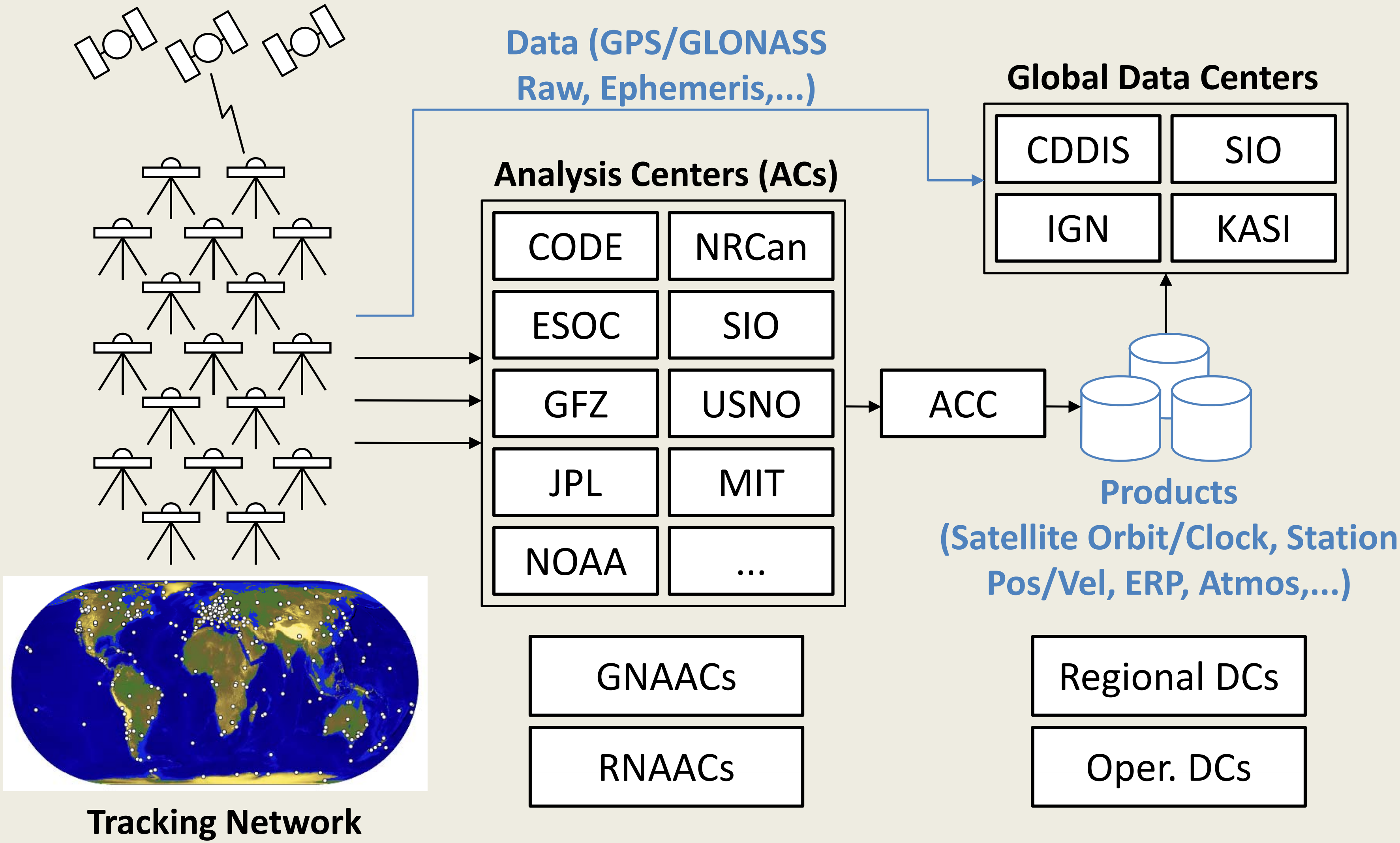
PPP (Precise Point Positioning)

- **Feature**
  - with Single Receiver (No Reference Station)
  - Efficient Analysis for Many Receivers
  - Precise Ephemeris
  - Conventionally Post-Processing
- **Applications**
  - GPS Seismometer
  - GPS Meteorology
  - POD (Precise Orbit Determination) of LEO Satellite
  - Precise Time Transfer

Precise Ephemeris

- **Precise Satellite Orbit and Clock**
  - By Post-Processing or in Real-time
  - Observation Data of Tracking Stations World-Wide
- **Data Format**
  - Orbit: NGS SP3
  - Clock: NGS SP3 or RINEX Clock Extension
- **Contents**
  - Orbit: ECEF-Positions of Satellite Mass Center
  - Clock: Clock-biases wrt Time Scale Aligned to GPS Time

IGS (International GNSS Service)



IGS Products

Product		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/)*

Iono-free LC (Linear Combination)

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

	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

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

Tropospheric Model

Tropospheric Delay:

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

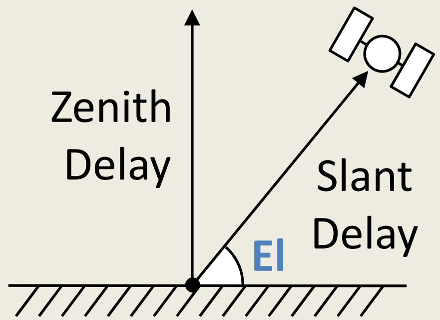
$$ZHD = \frac{0.0022768\,p}{1 - 0.00266\cos 2\phi - 2.8\times 10^{-7} H}$$

: 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):

$$T_m = 70.2 + 0.72T$$

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

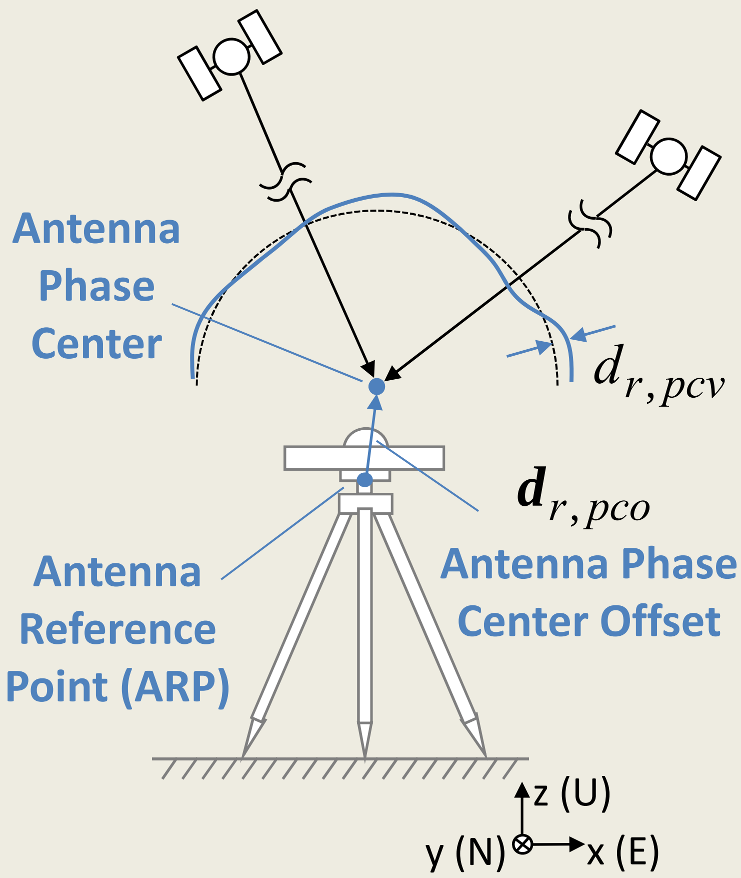
$R_v = 461, k_1 = 77.6,$

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

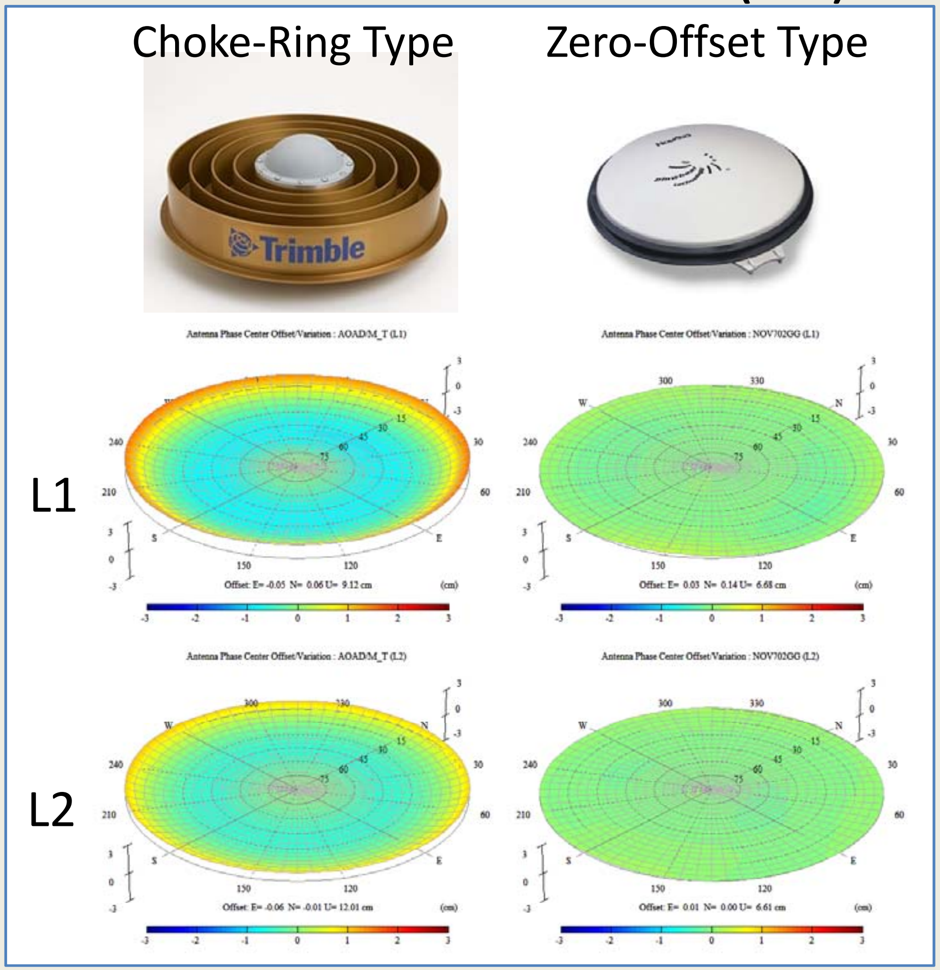
$m_v = 18.0152, m_d = 28.9644$

Antenna PCV (Phase Center Variation)

Receiver Antenna Phase Center:



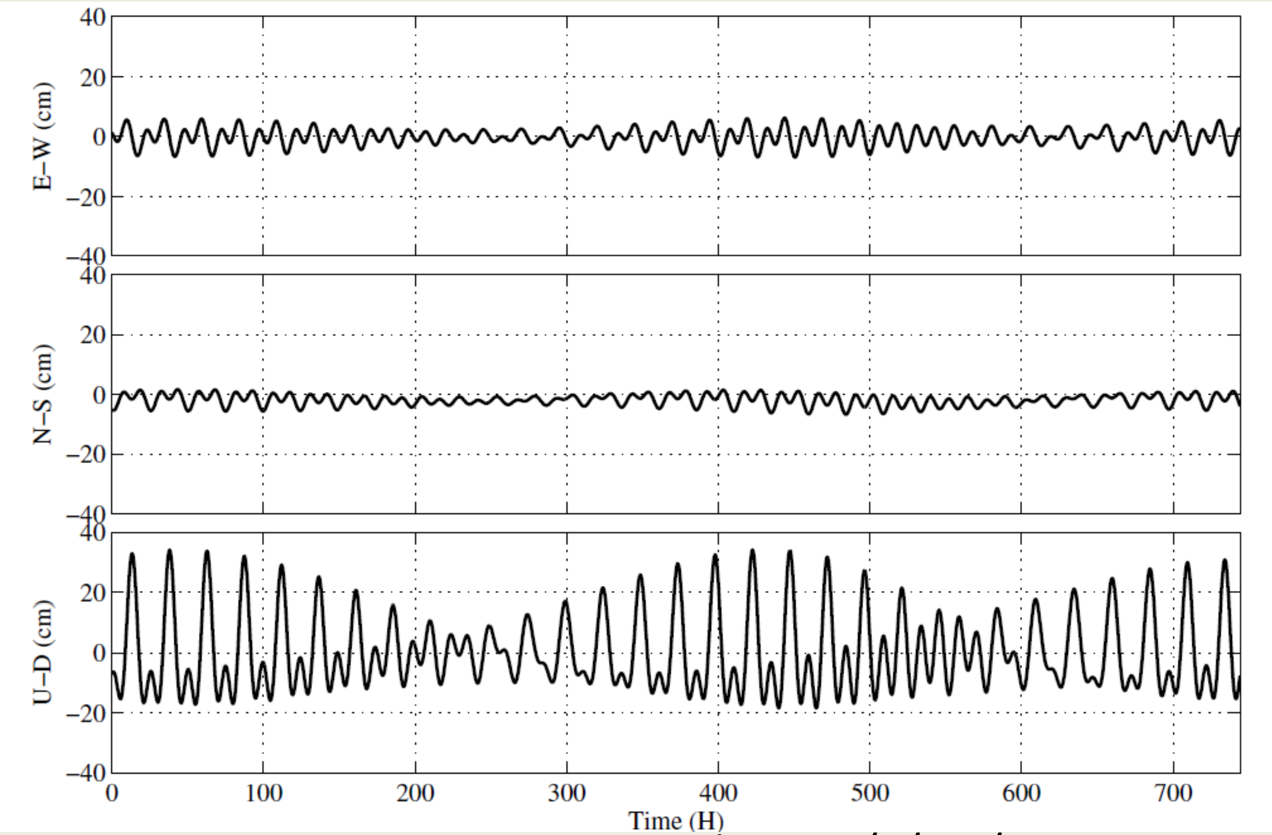
Antenna Phase Center Variation (PCV)



IGS Absolute Antenna Model (IGS05.PCV)

Earth Tides

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

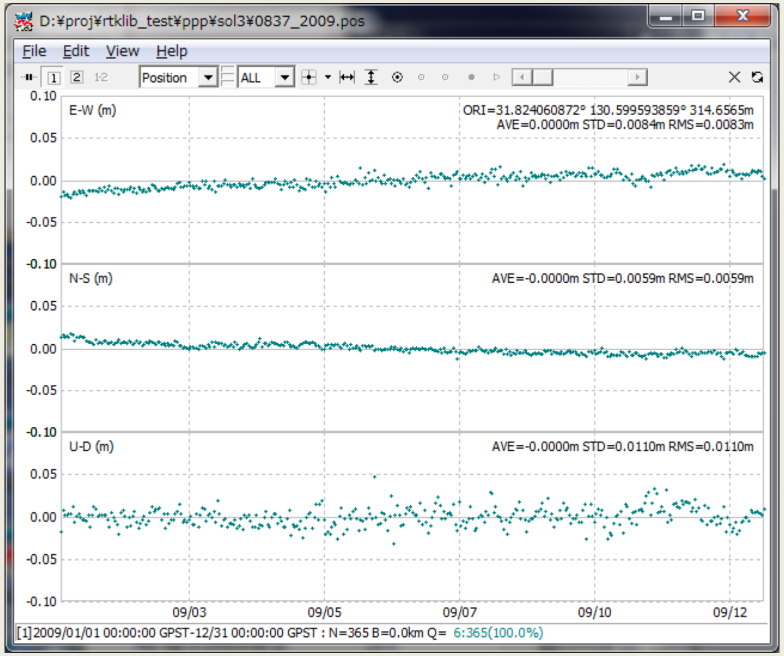


IERS Conventions 1996 + NAO99.b, 2007/1/1-1/31, TSKB

Static PPP vs Kinematic PPP

Static PPP Results

Station: GEONET 0837

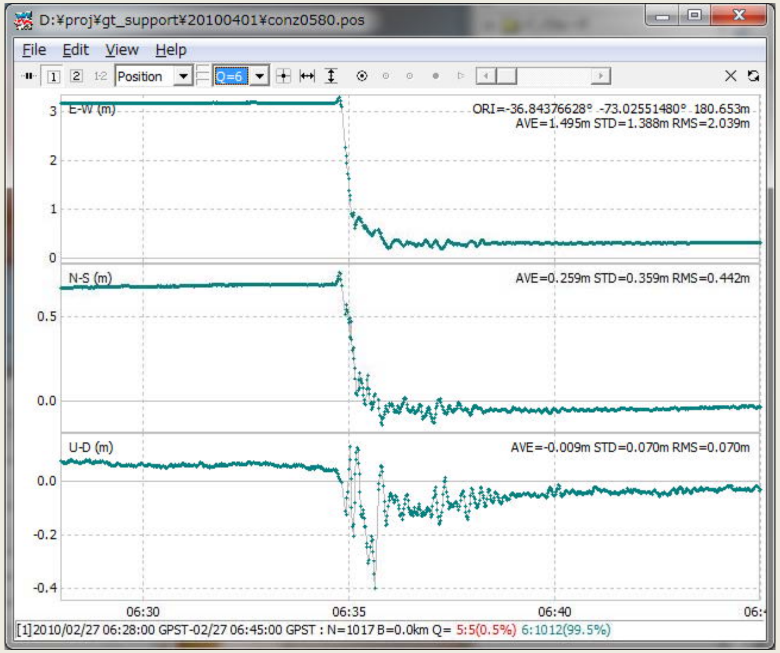


2009/1/1-2009/12/31

Interval: 1day

Kinematic PPP Results

Station: IGS CONZ



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

Interval: 1 s

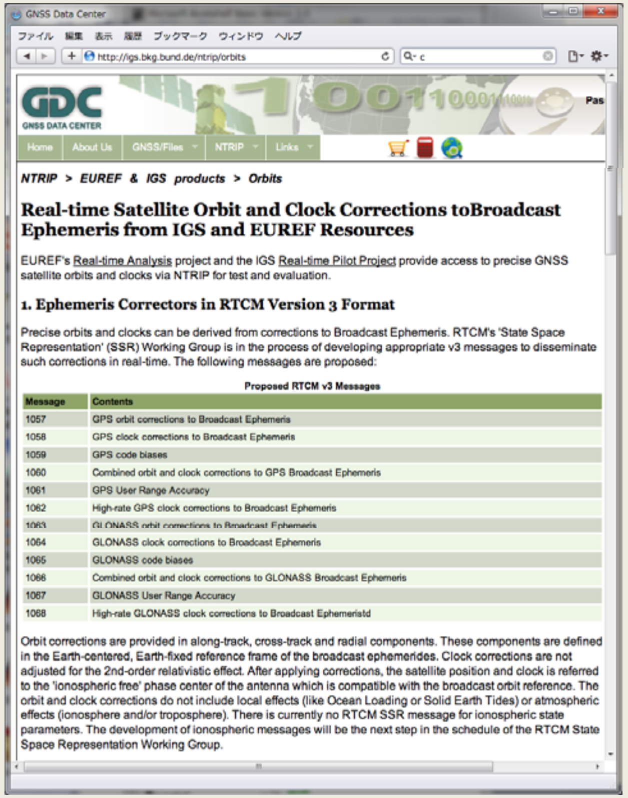
Real-time PPP

Commercial RT-PPP/GDPS Services

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

IGS Real-time Ephemeris

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


GNSS Data Center
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://igs.bkg.bund.de/ntrip/orbits
GDC GNSS DATA CENTER
Home About Us GNSS/Files NTRIP Links

NTRIP > EUREF & IGS products > Orbits

Real-time Satellite Orbit and Clock Corrections toBroadcast Ephemeris from IGS and EUREF Resources

EUREF's Real-time Analysis project and the IGS Real-time Pilot Project provide access to precise GNSS satellite orbits and clocks via NTRIP for test and evaluation.

1. Ephemeris Correctors in RTCM Version 3 Format

Precise orbits and clocks can be derived from corrections to Broadcast Ephemeris. RTCM's 'State Space Representation' (SSR) Working Group is in the process of developing appropriate v3 messages to disseminate such corrections in real-time. The following messages are proposed:

Proposed RTCM v3 Messages

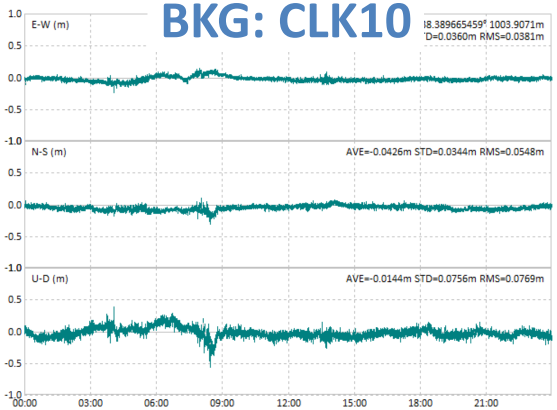
Message	Contents
1057	GPS orbit corrections to Broadcast Ephemeris
1058	GPS clock corrections to Broadcast Ephemeris
1059	GPS code biases
1060	Combined orbit and clock corrections to GPS Broadcast Ephemeris
1061	GPS User Range Accuracy
1062	High-rate GPS clock corrections to Broadcast Ephemeris
1063	GLONASS orbit corrections to Broadcast Ephemeris
1064	GLONASS clock corrections to Broadcast Ephemeris
1065	GLONASS code biases
1066	Combined orbit and clock corrections to GLONASS Broadcast Ephemeris
1067	GLONASS User Range Accuracy
1068	High-rate GLONASS clock corrections to Broadcast Ephemeristd

Orbit corrections are provided in along-track, cross-track and radial components. These components are defined in the Earth-centered, Earth-fixed reference frame of the broadcast ephemerides. Clock corrections are not adjusted for the 2nd-order relativistic effect. After applying corrections, the satellite position and clock is referred to the 'ionospheric free' phase center of the antenna which is compatible with the broadcast orbit reference. The orbit and clock corrections do not include local effects (like Ocean Loading or Solid Earth Tides) or atmospheric effects (ionosphere and/or troposphere). There is currently no RTCM SSR message for ionospheric state parameters. The development of ionospheric messages will be the next step in the schedule of the RTCM State Space Representation Working Group.

http://igs.bkg.bund.de

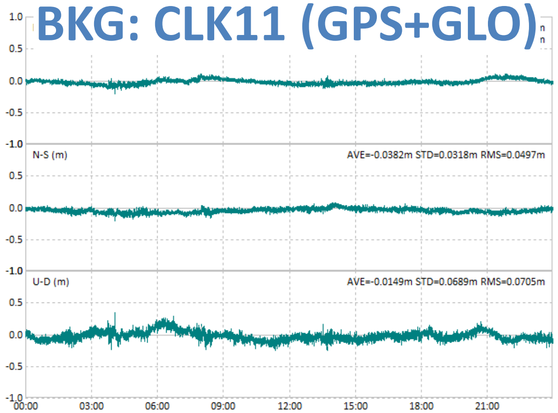
RT-PPP Performance with IGS

BKG: CLK10



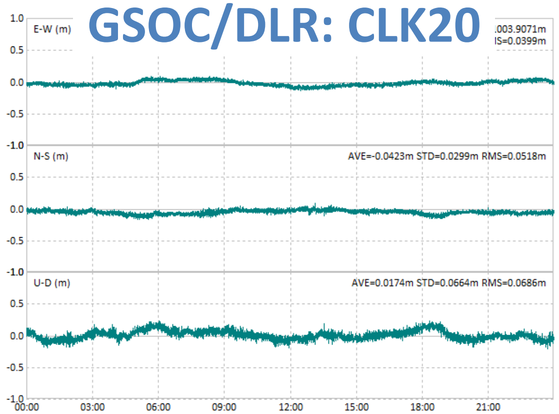
RMS: 3.8, 5.5, 7.7cm

BKG: CLK11 (GPS+GLO)



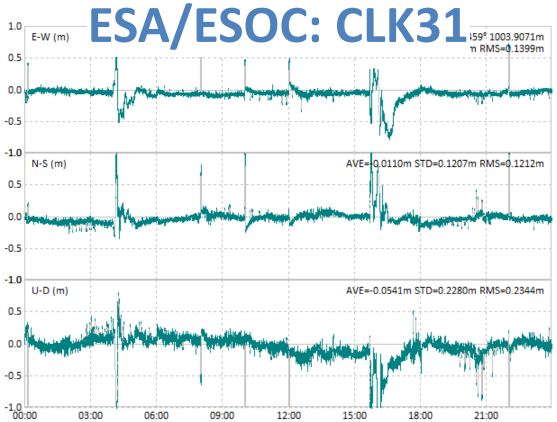
RMS: 3.8, 5.0, 7.1cm

GSOC/DLR: CLK20



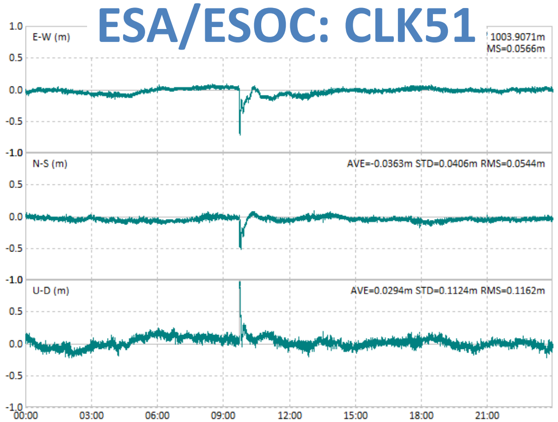
RMS: 4.0, 5.2, 6.9cm

ESA/ESOC: CLK31



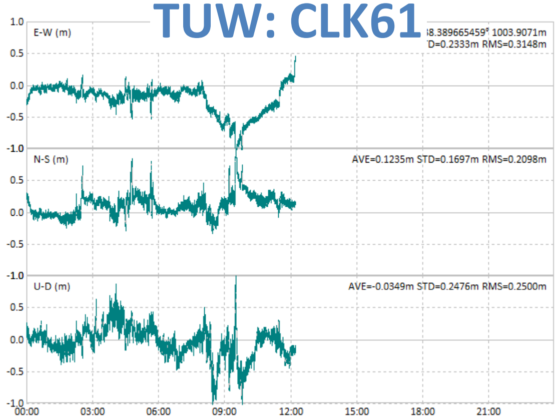
RMS: 14.0, 12.1, 23.4cm

ESA/ESOC: CLK51



RMS: 5.7, 5.4, 11.6cm

TUW: CLK61



RMS: 23.3, 21.0, 25.0cm

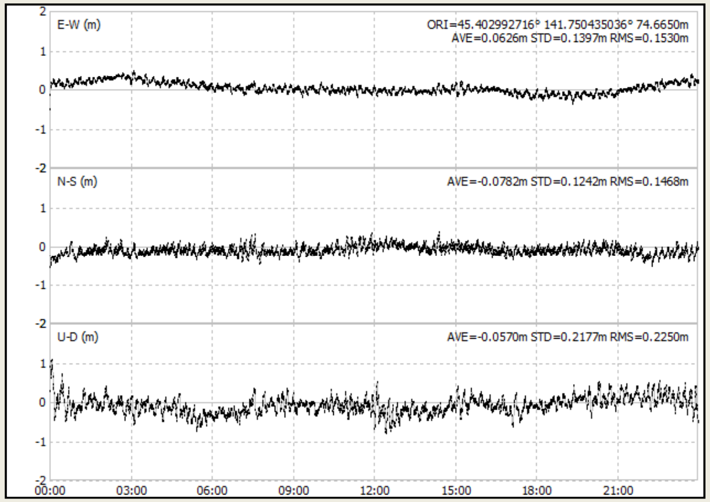
2010/9/18 0:00-23:59, 1Hz, Kinematic PPP, NovAtel OEMV-3+GPS-702, RTKLIB 2.4.1

JAXA QZSS LEX-PPP Experiment

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

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

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



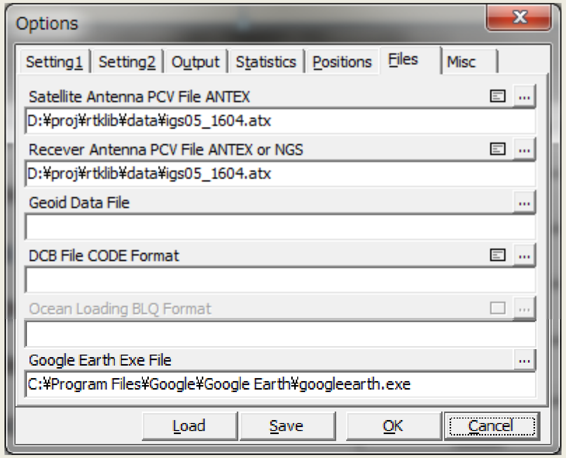
(T.Takasu, Space Sciences and Technology Conference , 2011)

6. PPP:
Exercise

PPP Analysis for Reference Point

- **Objective**
  PPP Analysis for Reference Point
- **Program**
  ...¥rtklib_2.4.0¥bin¥rtkpost.exe
  ...¥rtklib_2.4.1b¥bin¥rtkpost.exe
- **Data**
  ...¥seminar¥sample4¥
  09160700.11o, 09160700.11n (RINEX)
  21100700.11o, 21100700.11n (RINEX)
  igs16265.sp3 (Precise Orbit)
  igs16265.clk_30s (Precise Clock)

RTKPOST

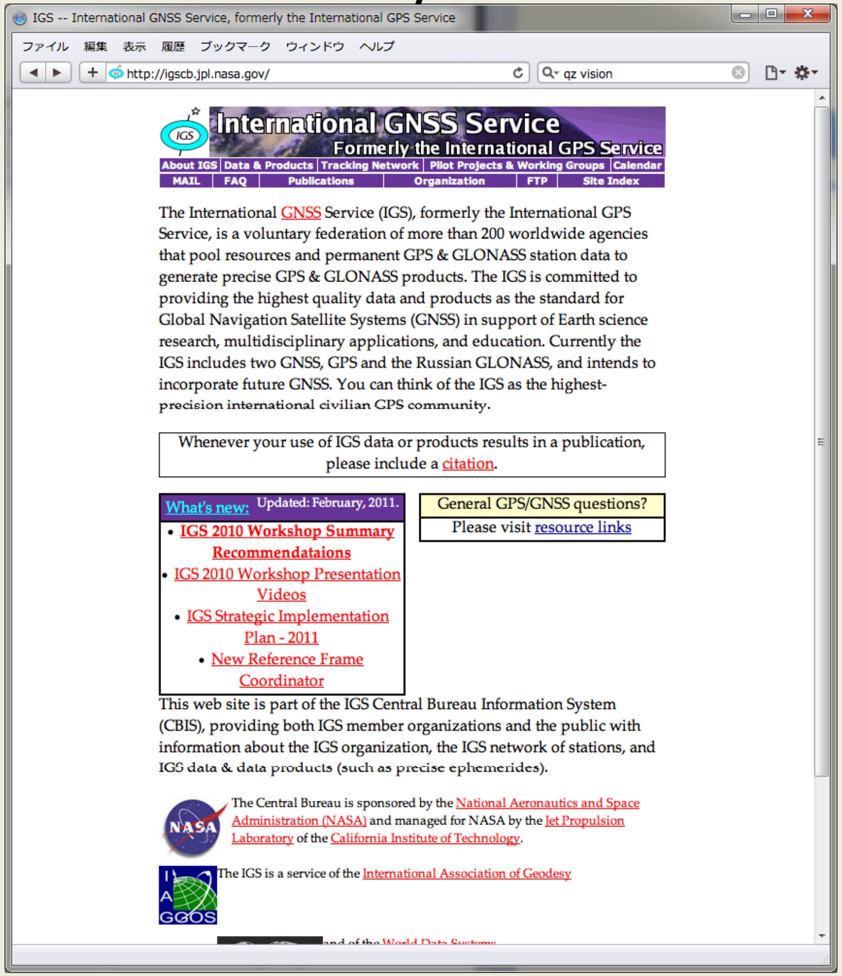


Date:
2011/3/11 GPST
(GPS week 1626-5, DOY 070)
GEONET Station:
020916: Minamikata
92110: Tsukuba

Acknowledgment: Sample Data are provided by GSI and IGS

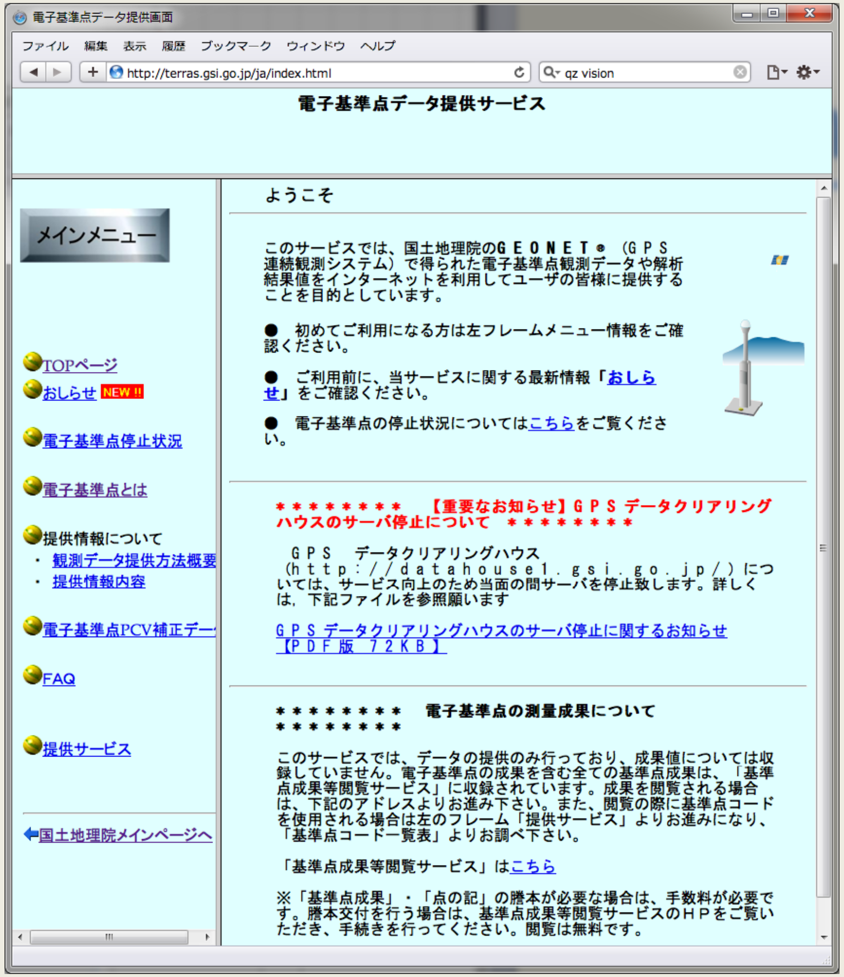
Online GNSS Data Sources

IGS Data/Products



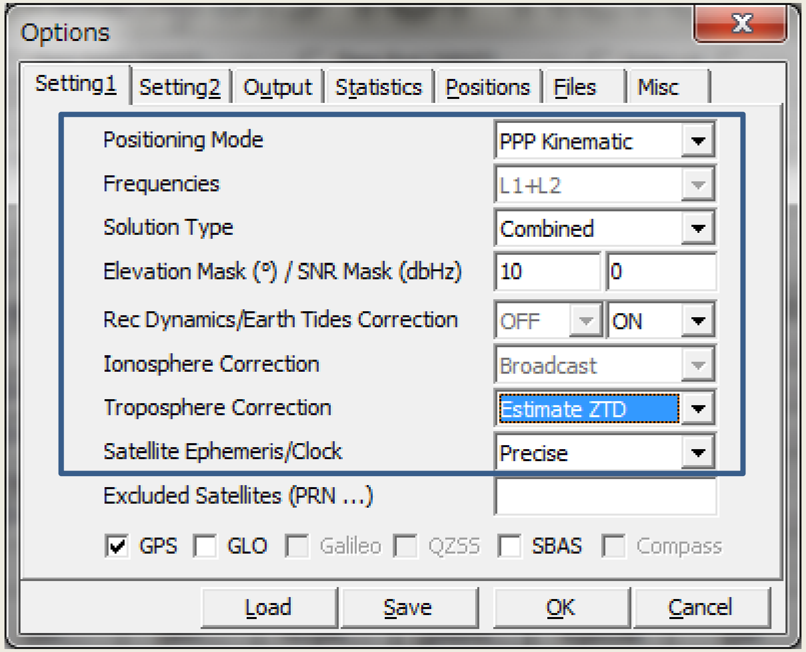
http://igscb.jpl.nasa.gov

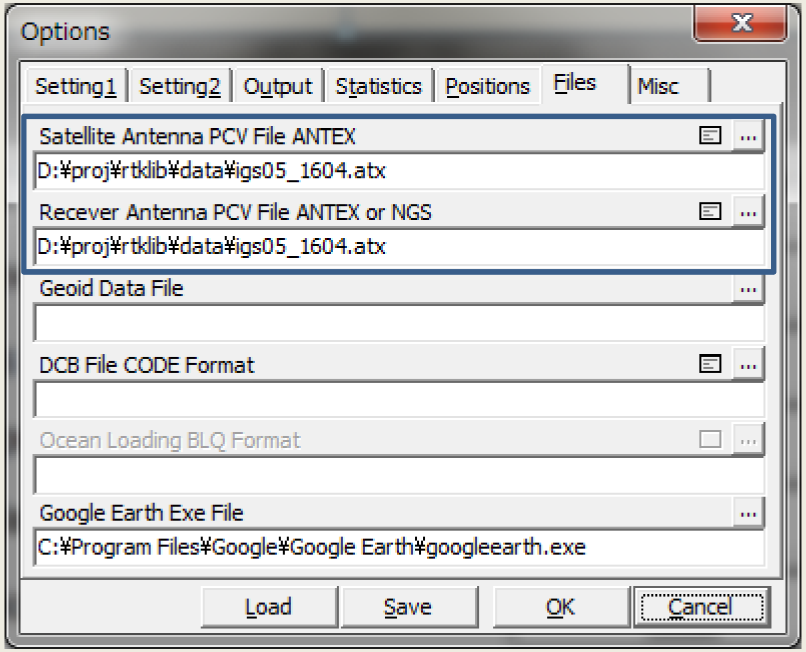
GEONET Data



http://terras.gsi.go.jp/ja/index.html

RTKPOST - Options





7. RTK System

RTK Application

Geodetic Survey

Construction Machine Control

Precision Agriculture

ITS (Intelligent Transport System)

Mobile Mapping System

Sports

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

Considerations for RTK System

- **Rover**
  - Single vs. Dual-freq, Update Rate, GNSS, Receiver-cost
  - CPU Power for external processing
  - INS-integration for obstacles
- **Reference Station**
  - Baseline-Length vs. Performance
  - Self-provided vs. NRTK Service
  - Coverage, Receiver-cost, Operational-cost, Service-fee
- **Communication Link**
  - Coverage, Band-width, Latency, Link-cost

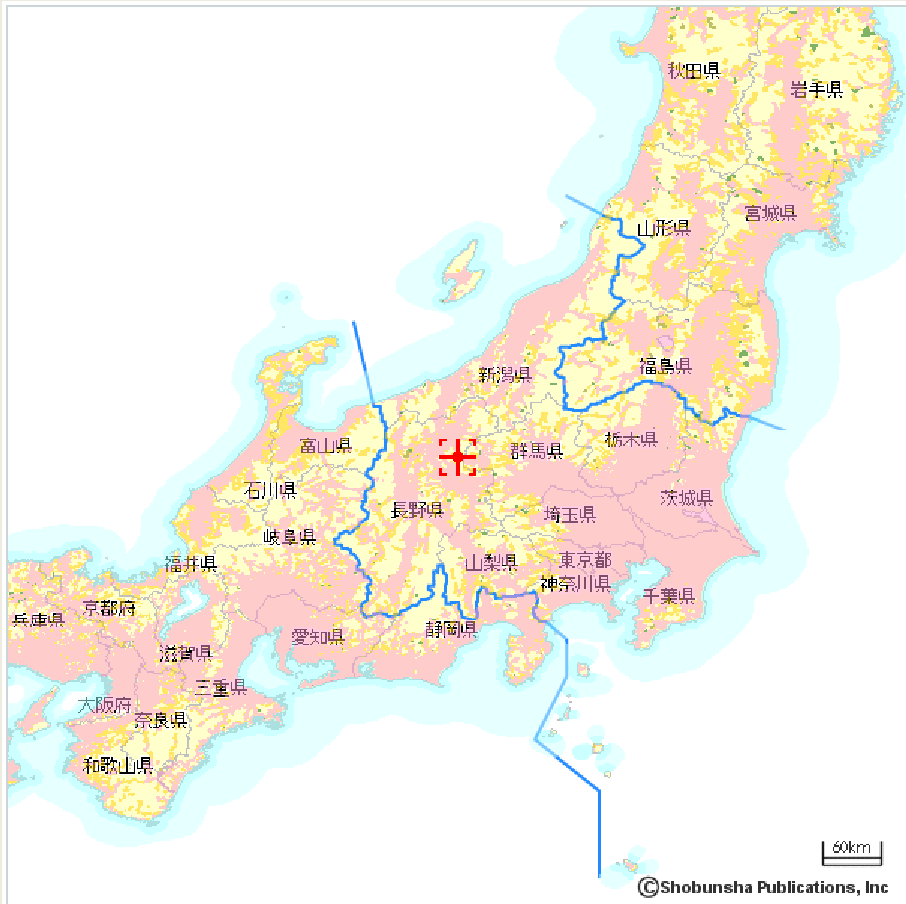
CPU-power, Bandwidth, Latency

- **CPU-power**
  - ~2 ms/epoch for dual-freq RTK on Intel Core 2 Q 2.4 GHz
  - ~20ms/epoch for single-freq RTK on ARM 600 MHz
  - H/W DP floating-point is necessary
- **Bandwidth**
  - ~3 kbps for 1 Hz GPS only, RTCM 3
  - ~20 kbps for 1 Hz GPS+GLO+QZS+SBAS, JAVAD GREIS
- **Latency**
  - > 5 s Latency degrades RTK performance
  - "Low-latency" vs. "Matched" Solution

Communication Link for RTK

- **Local (<300 m)**
  - Serial, USB, LAN, ... (wired)
  - Radio Modem, WiFi, ZigBee, DSRC, ... (wireless)
- **Regional (<1,000 km)**
  - Analog-phone, ISDN, Dedicated Link, ... (wired)
  - Mobile-phone (Analog, 2G, 3G, …), ... (wireless)
- **Global (<10,000 km)**
  - Internet
  - GEO Satellite Link (Inmarsat, WideStar II, ...)
  - LEO Satellite Link (Iridum, Orbicom, …)

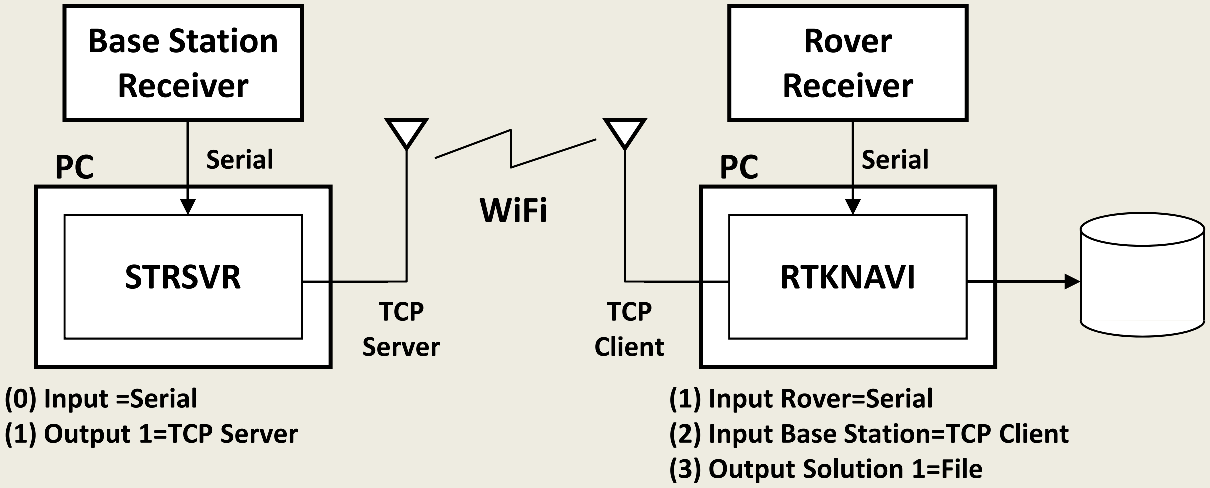
Coverage by Mobile-phone N/W

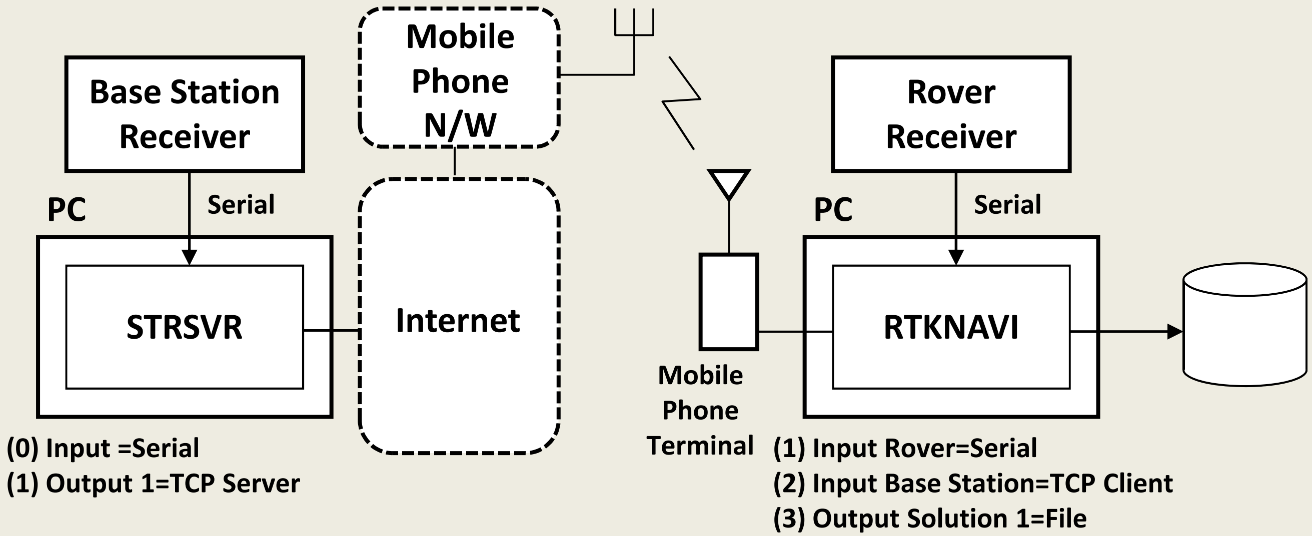


NTT docomo FOMA (2008/9)

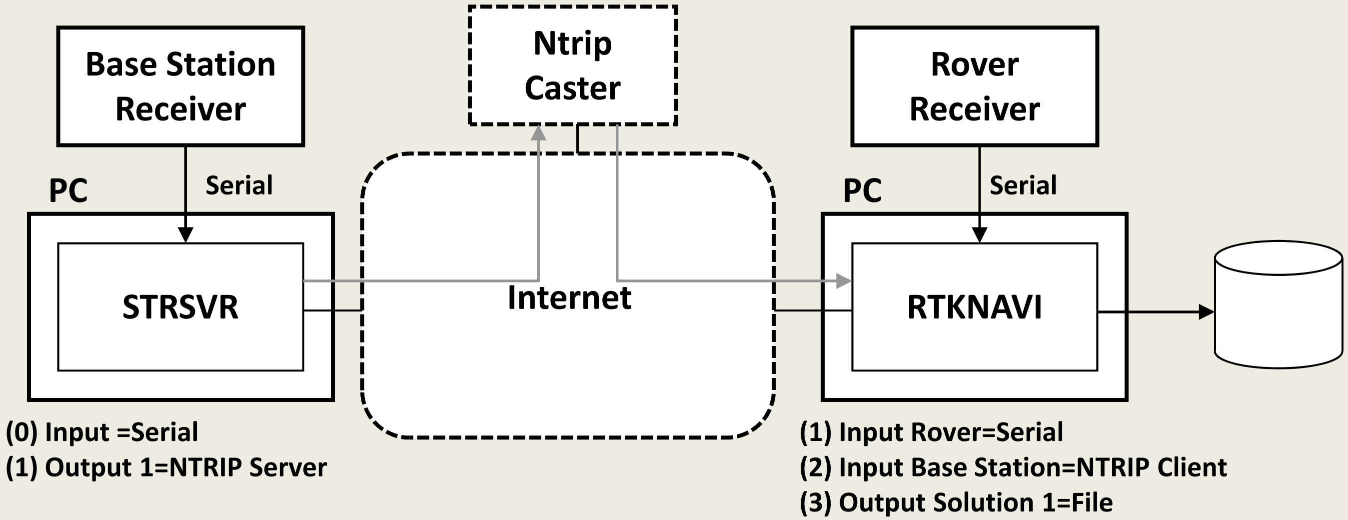
(http://servicearea.nttdocomo.co.jp)

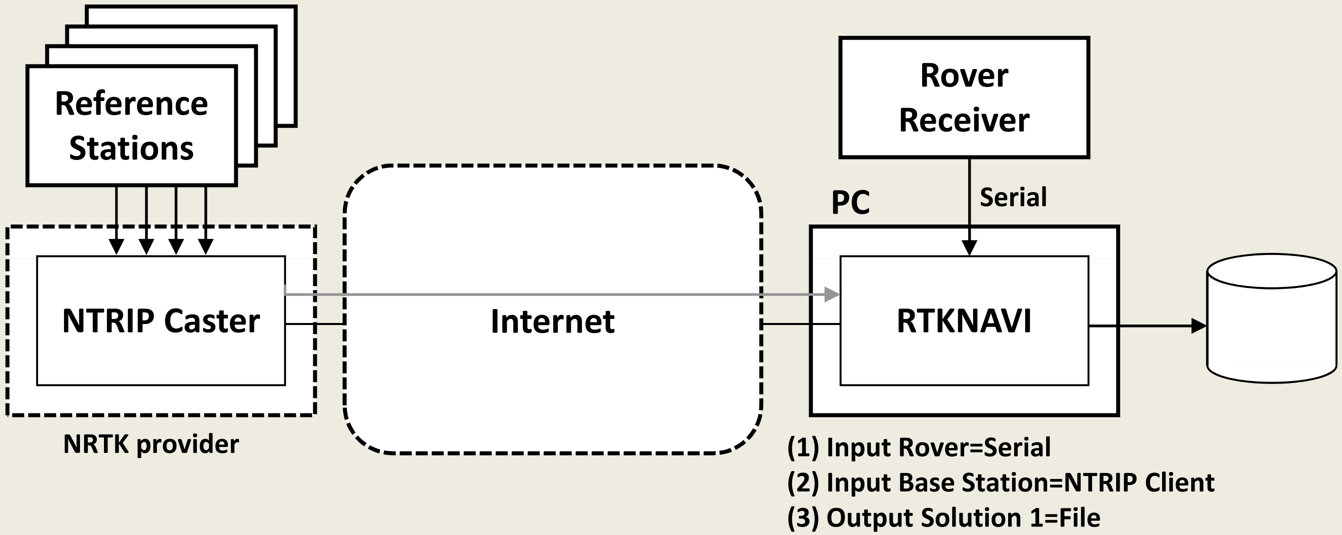
RTK Configurations (1)



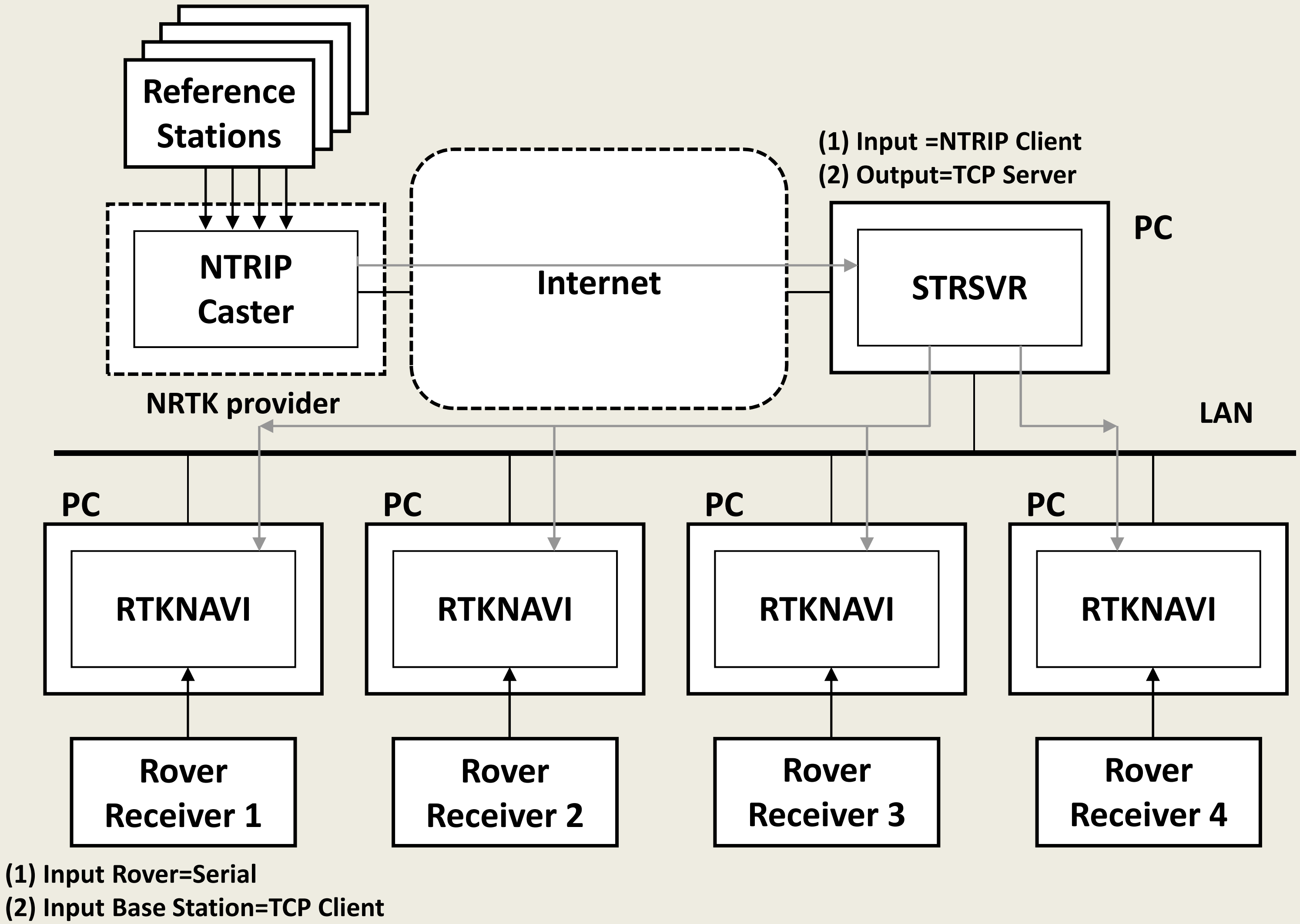


RTK Configuration (2)





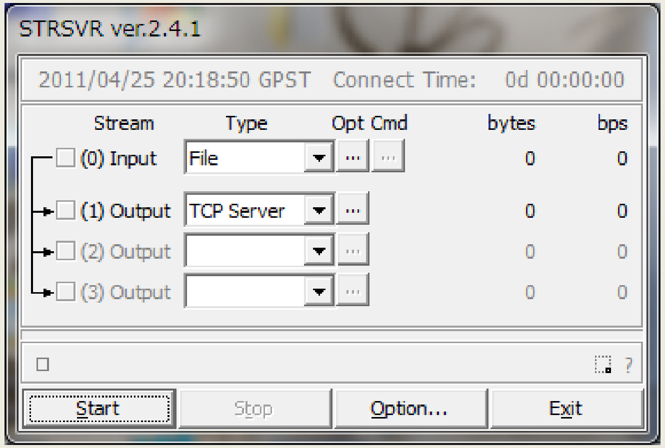
RTK Configuration (3)



7. RTK System: Exercise

Communication Link for RTK

- **Objective**
  Network Connection for RTK
- **Program**
  ...¥rtklib_2.4.1b¥bin¥rtknavi.exe
  ...¥rtklib_2.4.1b¥bin¥strsvr.exe
- **Stream (TCP Client)**
  JAV1: 192.168.1.173: 2101 (Format: Javad)
  JAV2: 192.168.1.173: 2102 (Format: Javad)



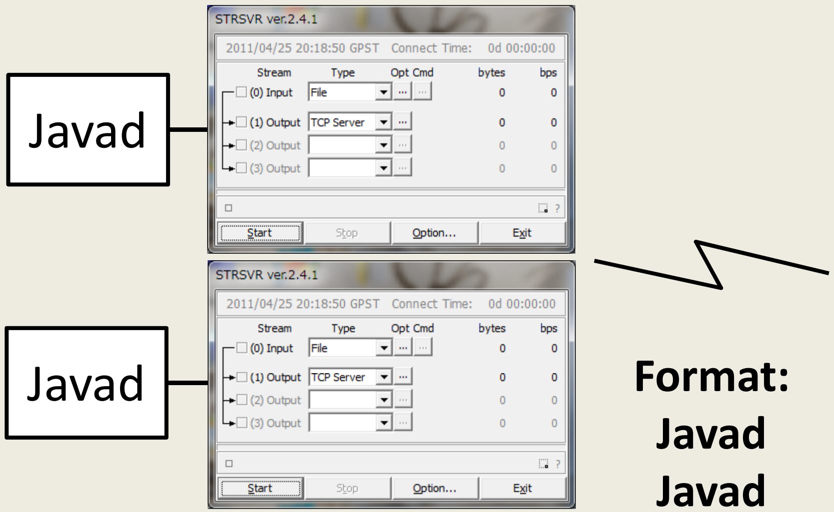
STRSVR

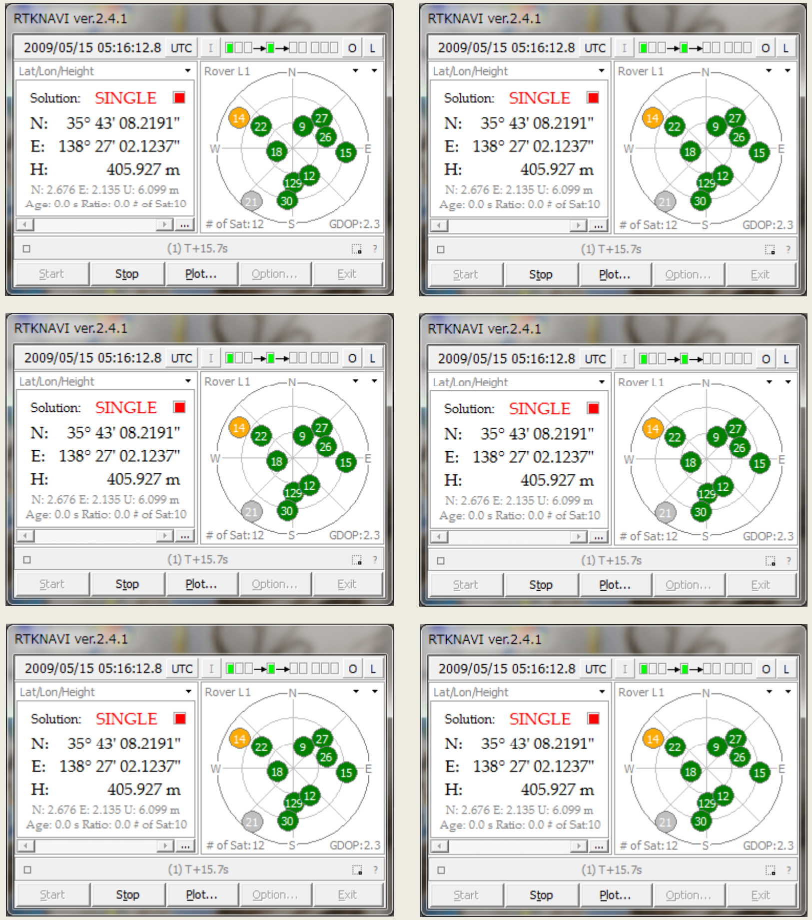
Acknowledgment:
Sample data were captured by JAVAD DELTA and FURUNO LPY-10000 receiver provided by JAXA

Network Configuration

RTKNAVI 2.4.1b (TCP Client)

STRSVR (TCP server)





Format:
Javad
Javad

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

Javad2: 35.666496867 139.792366358 59.3696

8. Advanced Topics

Advanced Topics

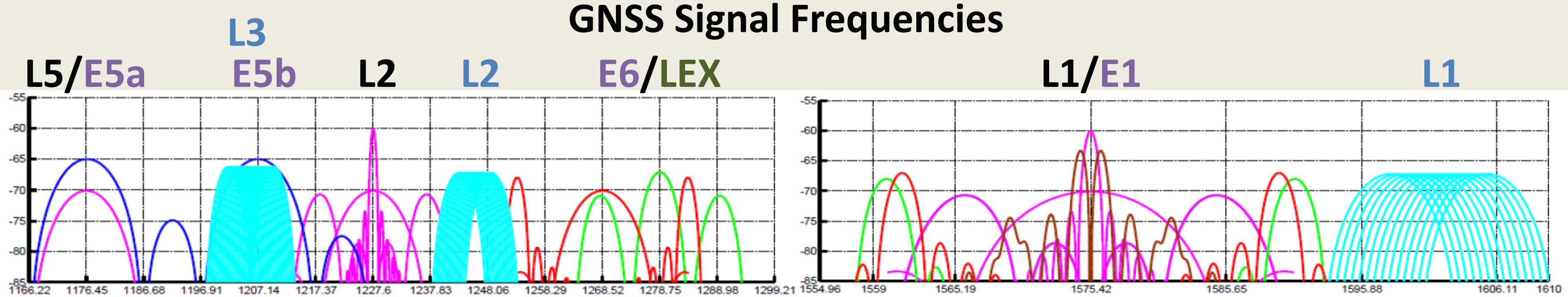
- **Multi-GNSS RTK**
- **Long-Baseline RTK**
- **INS-Aided RTK**
- **Ambiguity Resolution for PPP**
- **"CM-Accuracy Anywhere"**

GNSS Evolution

Number of Planned GNSS Satellites

System	2010	2013	2016	2019
GPS	**31**	32	32	32
GLONASS	23 (+2)	24 (+3)	24 (+3)	24 (+3)
Galileo	0	4	18	27 (+3)
Compass	6	12	30	32 (+3)
QZSS	1	1	7	7
IRNSS	0	7	7	7
SBAS	7	8	11	11
Total	**68**	**88**	**129**	**140**

GNSS Signal Frequencies



(Y.Yang, COMPASS: View on Compatibility and Interoperability, 2009)

Multi-GNSS RTK Performance

RTK Performance: Baseline 13.3 km, Instantaneous AR

		El Mask=15°				El Mask=30°			
GPS	Galileo	Fixing Ratio	RMS Error (cm)			Fixing Ratio	RMS Error (cm)		
			E-W	N-S	U-D		E-W	N-S	U-D
L1	-	49.7%	4.6	8.1	19.0	23.3%	71.4	115.0	289
L1,L2	-	99.0%	1.4	1.3	1.9	87.6%	3.4	10.5	15.5
L1,L2,L5	-	99.0%	1.4	1.3	1.9	87.3%	3.4	10.5	15.6
L1	E1	98.8%	1.3	1.2	1.9	90.1%	1.2	2.1	2.7
L1,L2	E1	98.9%	1.4	1.2	1.7	98.7%	1.2	1.0	1.6
L1,L2,L5	E1,E5a, E5b	98.9%	1.5	1.3	2.0	98.9%	1.3	1.1	1.8

GPS L1+L2

GPS+GAL L1

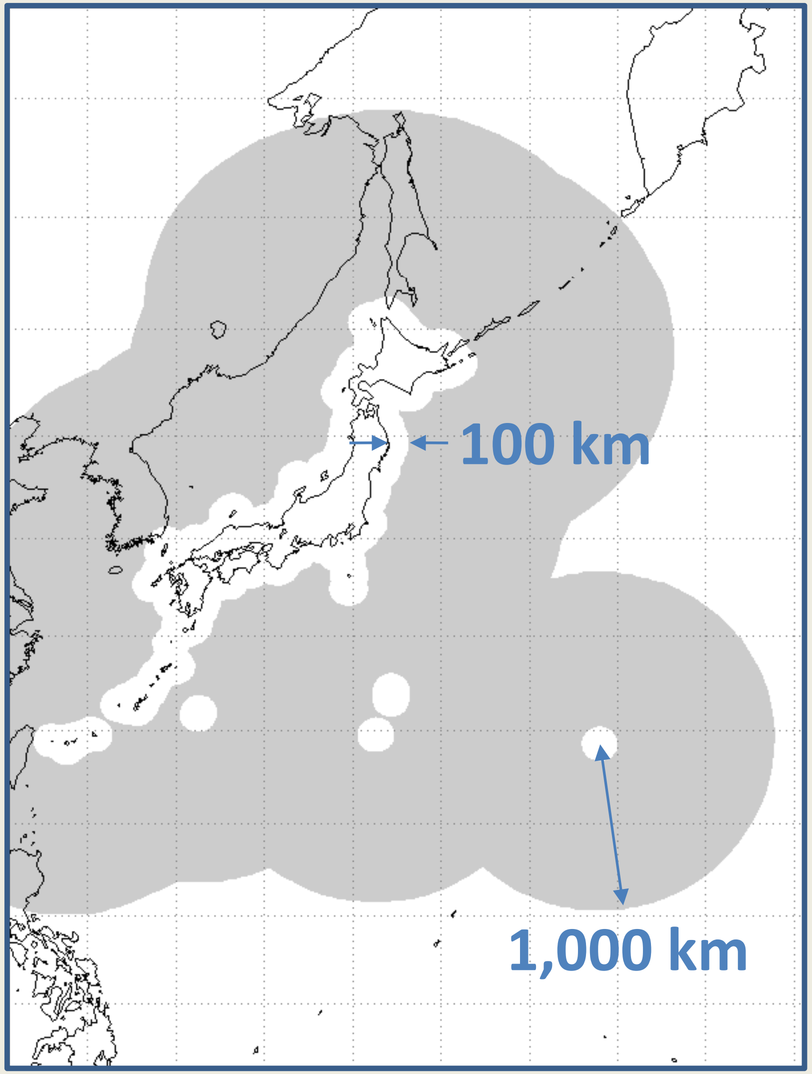
Multi-GNSS Receiver

- **Moore's Law**
  - More correlators
  - More tracking channels
  - More powerful embedded CPU
- **Consumer-grade Multi-GNSS Receiver**
  - SkyTraq: GPS + GLONASS
  - STMicro: GPS + GLONASS
  - Broadcom: GPS + GLONASS + QZSS
  - u-blox: GPS + Galileo

Issues for Multi-GNSS RTK

- **Multi-GNSS Integration Issue**
  - Time-system, Coordinate-system
  - Receiver H/W Biases
- **Multi-code System Issue**
  - L1C/A-L1P(Y)-L1Cd-L1Cp, L2P(Y)-L2C, L5I-L5Q
  - Quarter cycle phase-shift problem
- **GLONASS FDMA Issue**
  - Receiver Inter-channel biases (Receiver Interoperability)
  - Calibration Message Standard
  - Antenna Calibration

Long-Baseline RTK



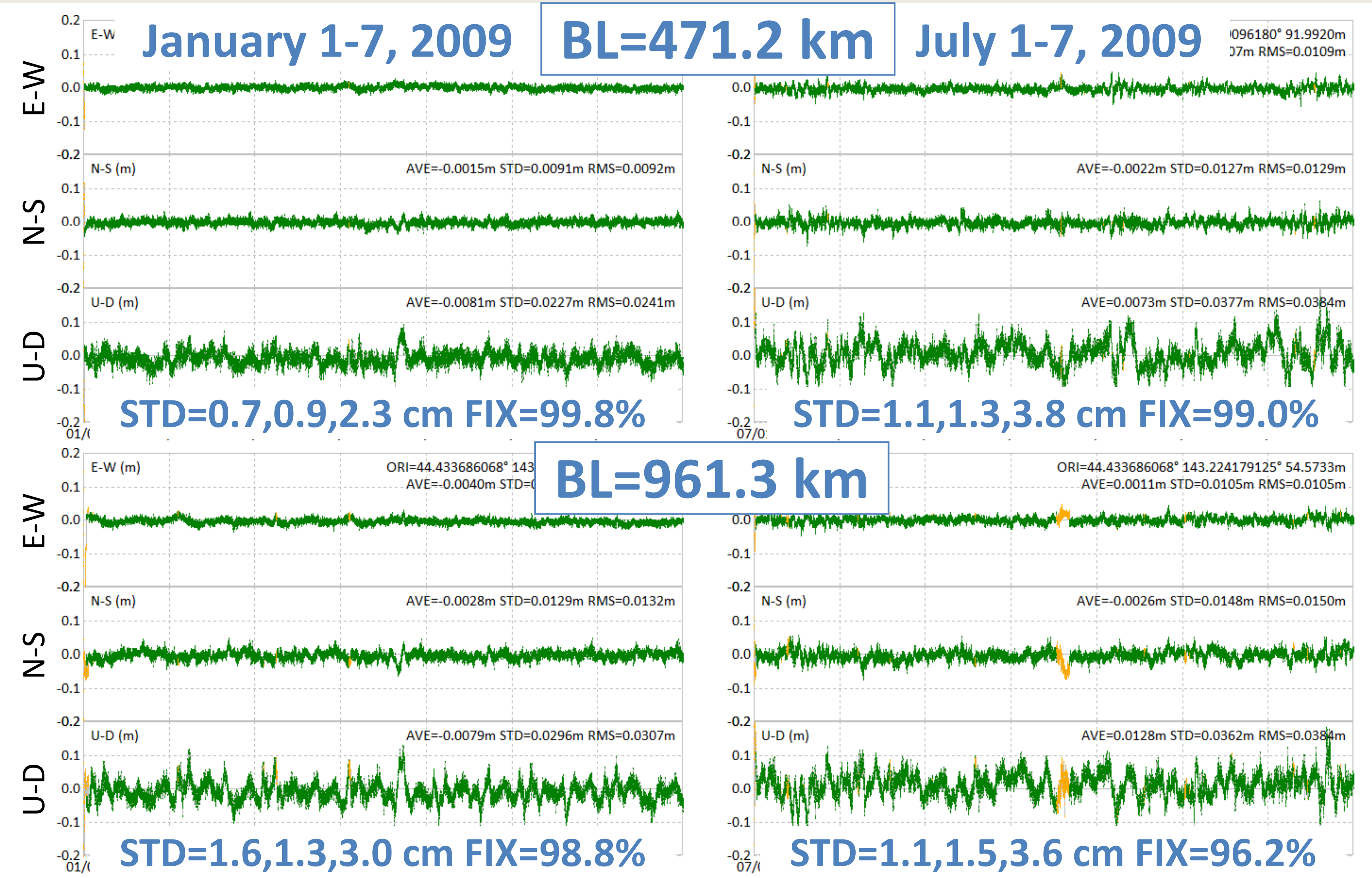
GPS Tsunami Monitoring System (Currently ~15 km off-shore)

http://www.tsunamigps.com

Long-Baseline RTK Strategy

	BL (km)	Error Elimination				Strategy
		Ephem	Ionos	Tropos	Others	
S	0 – 10	Broadcast	-	-	-	Conventional RTK
M	10 – 100	Broadcast	Dual-Freq	-	-	Conventional RTK
			Interpolation		-	Network RTK
L	100 – 1,000	Real-time Precise (IGU)	Dual-Freq	Estimate ZTD + MF	Earth Tides	Long-Baseline RTK
VL	>1,000	Non-RT Precise (IGR, IGS)	Dual-Freq	Estimate ZTD + MF	Earth Tides, Ph-WU	Post-Processing or PPP

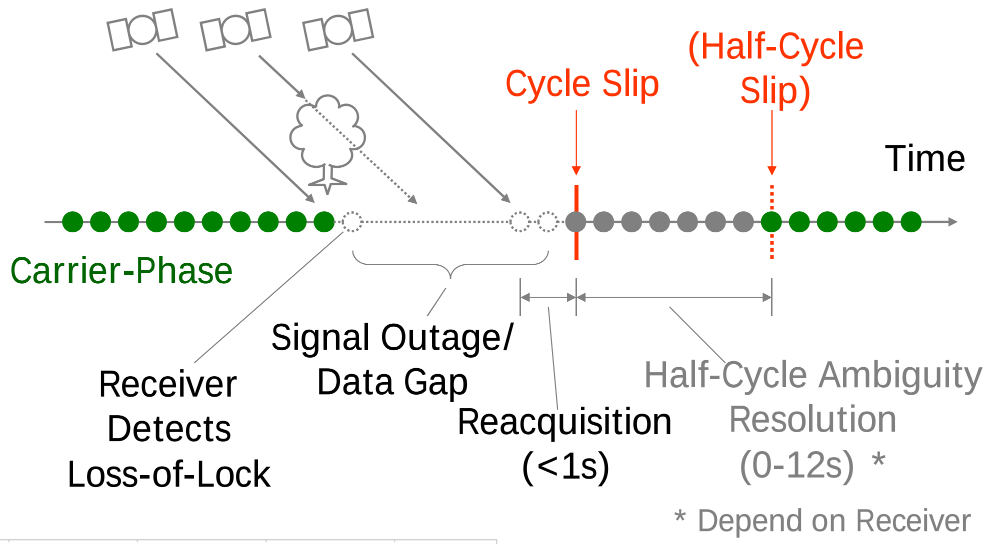
Long-Baseline RTK with RTKLIB



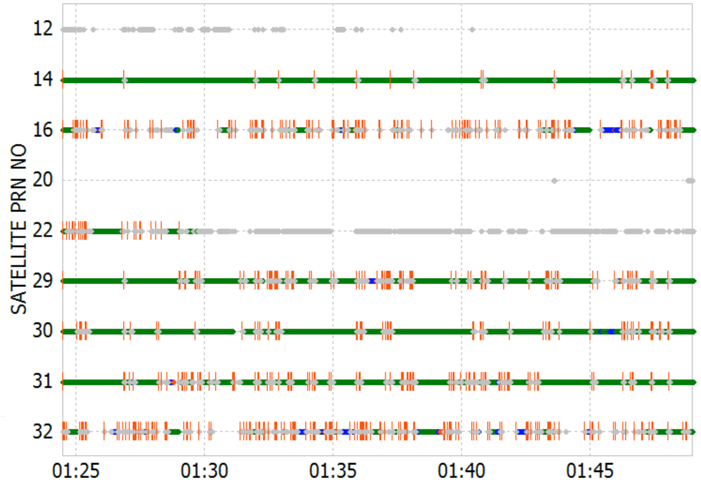
Mobile AP issues for RTK

- **Cycle-Slips**
  - Frequent cycle-slip with around obstacles
  - Miss-detection of cycle-slip
- **Low Solution Availability**
  - Long acquisition time by weak signal (Low C/N0)
  - Half-cycle ambiguity resolution with Costas-PLL
  - Low fixing ratio
- **High Noise Level**
  - High multipath level even in carrier-phase
  - Jamming by RFI

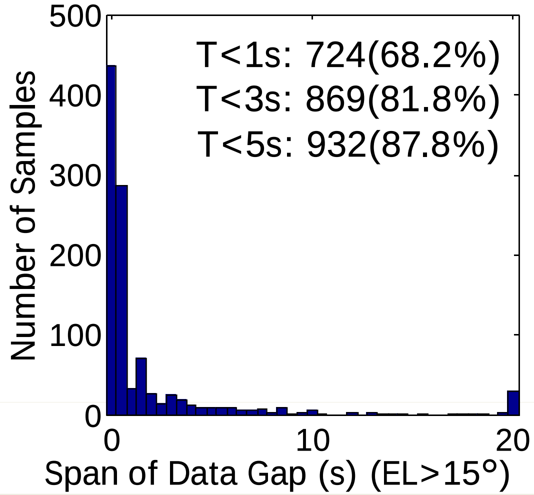
Cycle-Slips



Cycle Slip
(Half-Cycle Slip)
Time
Carrier-Phase
Signal Outage/ Data Gap
Receiver Detects Loss-of-Lock
Reacquisition (<1s)
Half-Cycle Ambiguity Resolution (0-12s) *
* Depend on Receiver

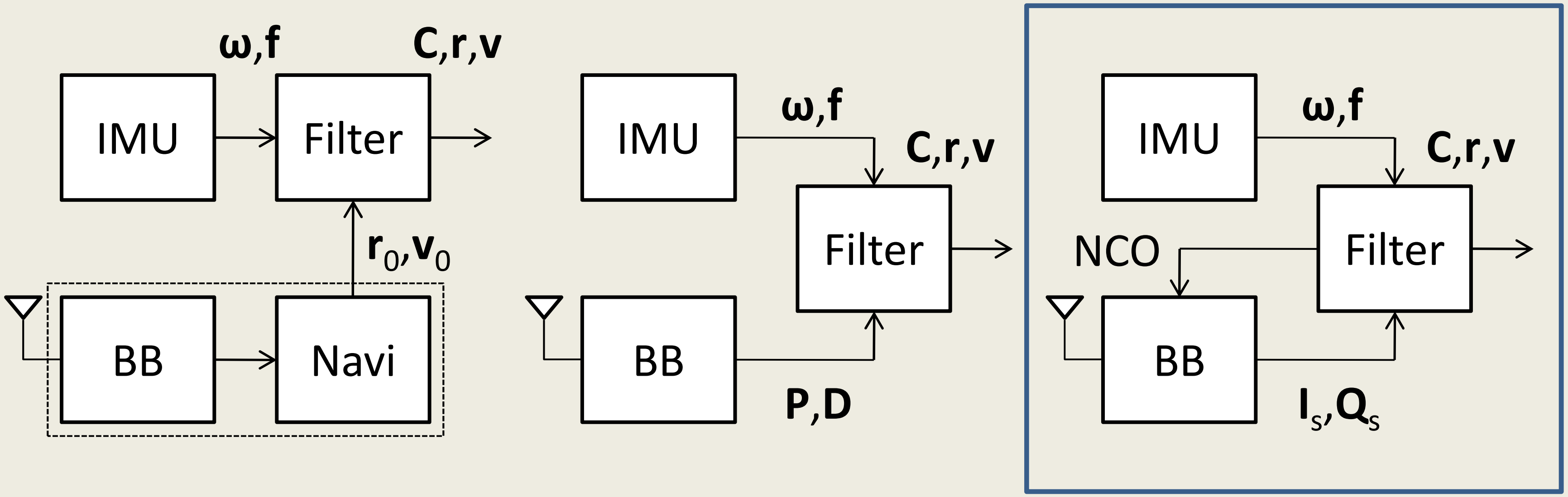


SATELLITE PRN NO
12
14
16
20
22
29
30
31
32
01:25
01:30
01:35
01:40
01:45



T<1s: 724(68.2%)
T<3s: 869(81.8%)
T<5s: 932(87.8%)
Number of Samples
Span of Data Gap (s) (EL>15°)
0
100
200
300
400
500
10
20

INS-Aided RTK



Loosely-Coupled Integration

Tightly-Coupled Integration

Deep Integration (Ultra-Tightly)

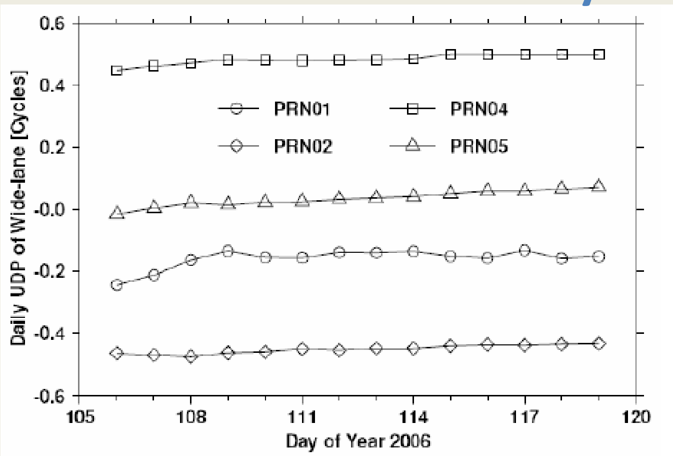
High sensitivity
(DLL, PLL)
Slip resistance

Ambiguity Resolution for PPP

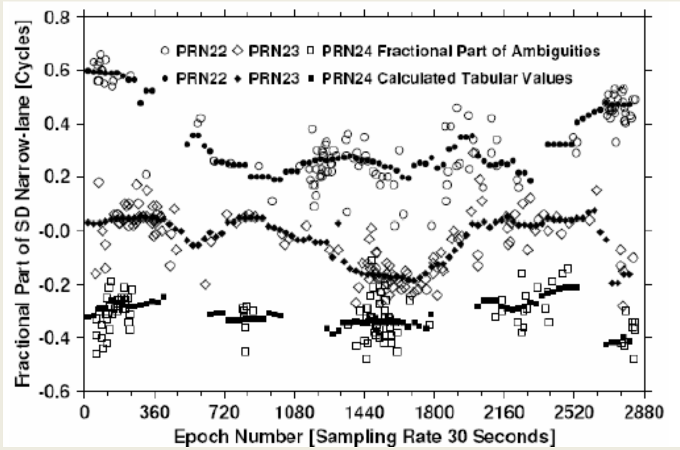
- with AR for PPP
  - Improve Convergence Time
  - Improve Accuracy of Static Solution (EW, UD)
  - Improve Stability of Kinematic Solution
- Difficulties of AR for PPP
  - Unknown Satellite Initial Phase Biases
  - Effect of Precise Orbit/Clock Error
  - Effect of Ionospheric Delay
  - Code/Phase Bias Instability
  - Multipath Effect at Reference Station Network

M.Ge et al., EGU 2007

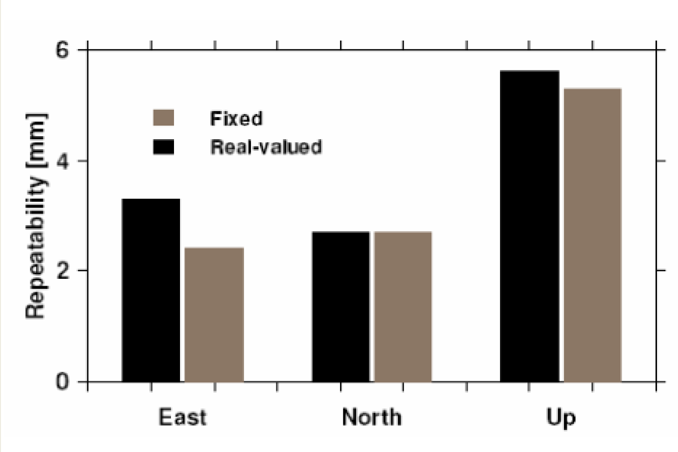
WL Phase Bias Stability



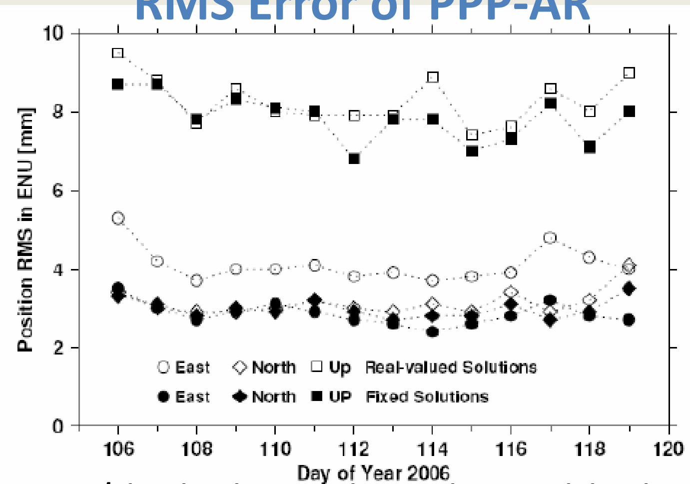
NL Phase Bias Stability



Repeatability of PPP-AR



RMS Error of PPP-AR



M.Ge et al., Resolution of GPS carrier-phase ambiguity in precise point positioning, EGU Assembly 2007

D.Laurichesse, ION 2010

- Real-Time Implementation of PPP-AR
  - Network WL ambiguity fixing
  - Parameter estimation by EKF with iono-free code/phase: phase-clock, code-phase-bias, ZTD, station position, orbit correction to IGU, phase ambiguity
  - Orbit construction + high-rate clock generation
- Evaluation of Accuracy
  - Orbit: 4cm, code-clock: 5 cm, phase-clock: 1cm
- RT-PPP with AR ("CNES Integer PPP")
  - 1 cm HRMS

"CM-Accuracy Anywhere"

Requirement	Target in 2020	Developing/Future Technologies
Coverage	Global (world-wide)	Precise Ephemeris with AR, Broadcast via GEO/QZSS Satellite
Latency	Real-time (1 s)	Real-time Multi-GNSS Orbit/Clock Estimation
Accuracy	1 cm (HRMS) 2 cm (VRMS)	Local iono/tropos corrections (land) Iono estimation by triple-freq (sea)
Availability	99 % (open-sky)	Multi-GNSS 30 Sats + triple-freq
	95 % (urban)	Multi-GNSS 30 Sats + INS-aided PLL, slip-resistant
TTFF	10 s (land)	Local iono/tropos corrections
	1 min (sea)	Iono estimation by triple-freq
User Cost	< $100	No patent problem, **need killer-AP**

8. Advanced Topics: Q & A