IPNTJ Summer School on GNSS 2016

GNSS Precise Positioning and RTKLIB

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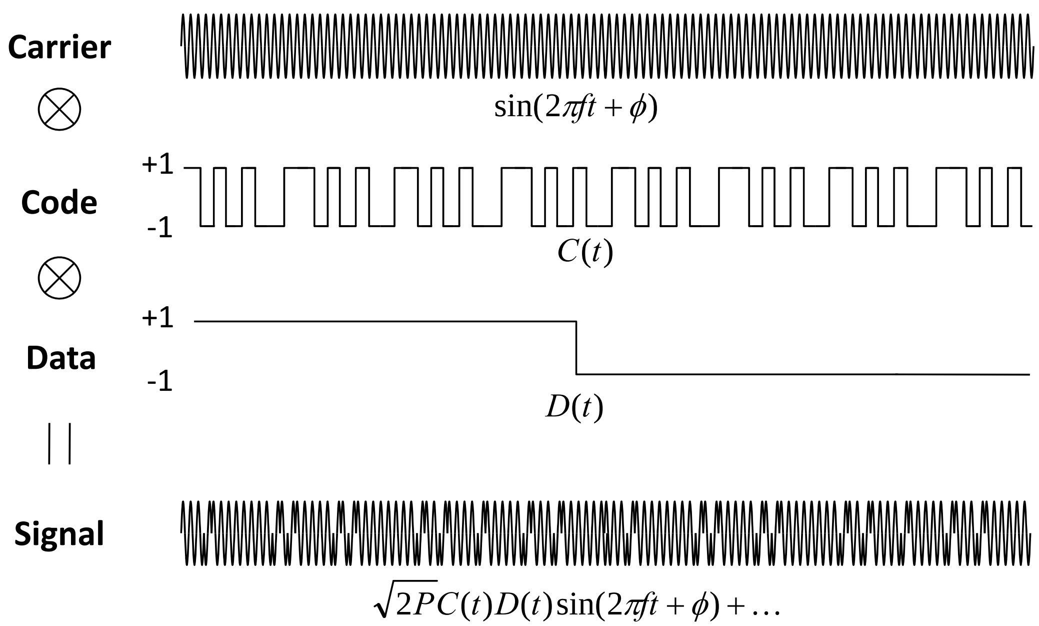
2016-08-01 ~ 2016-08-06 @Tokyo, Japan

Timetable

		Aug 4, 2016
B-5	Carrier-Phase-Based Positioning with GNSS	8:30-10:00
B-6	RTKLIB Practice (1)	10:10-11:40
	Lunch Break	11:40-12:30
B-7a	RTK-Demo Port Cruise (G-I) AIS/ECDIS (G-II)	12:30-14:00
B-7b	AIS/ECDIS (G-I) RTK-Demo Port Cruise (G-II)	14:10-15:40
B-8	RTKLIB Practice (2)	15:50-17:20

B-5
Carrier-Phase-Based Positioning with GNSS

GNSS Signal Structure

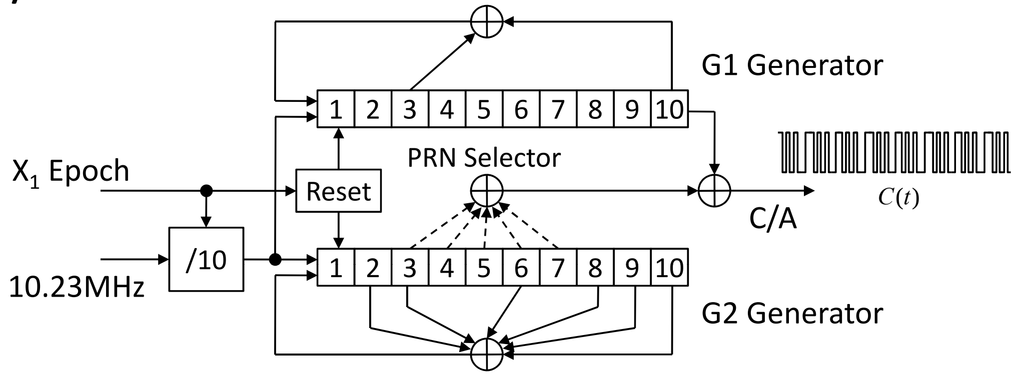


GNSS Signal Specifications

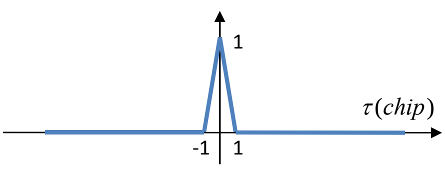
Carrier Freq (MHz)		Code	Modulation	Data Rate	GNSS
L1/E1	**1575.42**	**C/A**	**BPSK (1)**	**50 bps**	**GPS**, QZSS
				250 bps	QZSS (L1-SAIF), SBAS
		P(Y)	BPSK (10)	50 bps	GPS
		L1C-d/p	MBOC (6,1,1/11)	-/100 bps	GPS (III-), Galileo
		L1C-d/p	BOC (1,1)	-/100 bps	QZSS
L1	1602+0.5625K	C/A	BPSK	50 bps	GLONASS
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

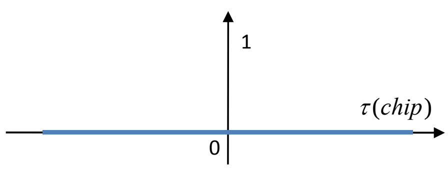


Auto-correlation function



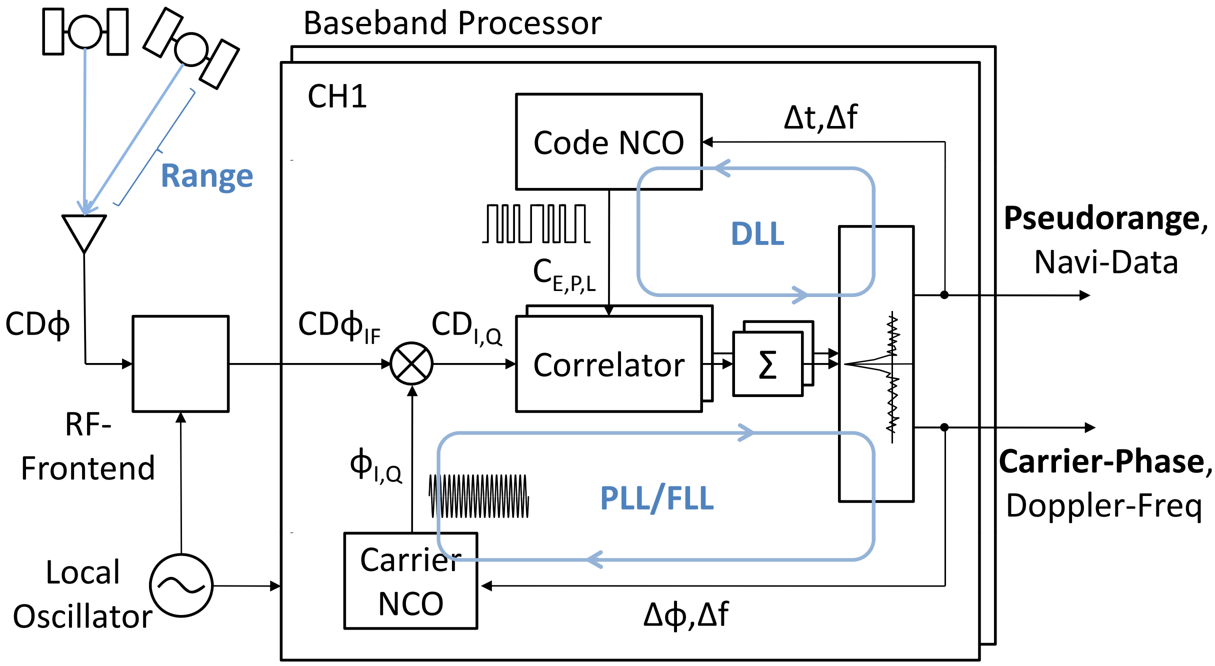
$$R(\tau) = \frac{1}{T}\int_0^T C^i(t)C^i(t-\tau)dt$$

Cross-correlation function



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

Carrier/Code Tracking in Receiver



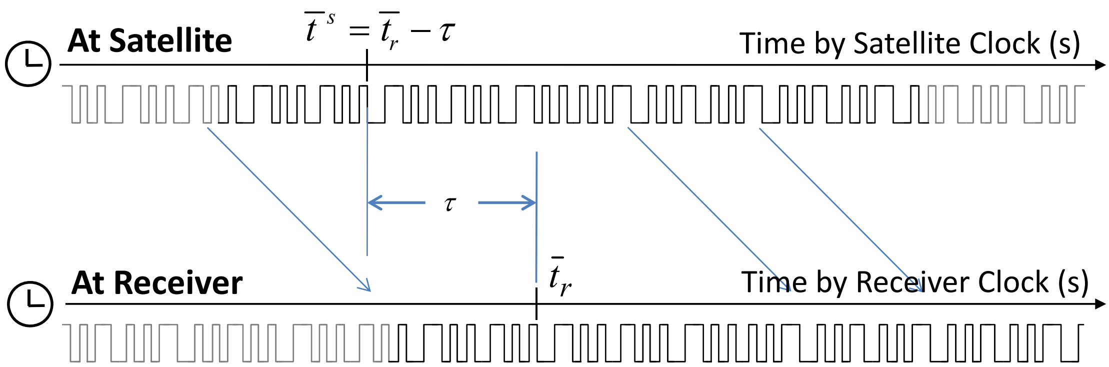
Pseudorange

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)*



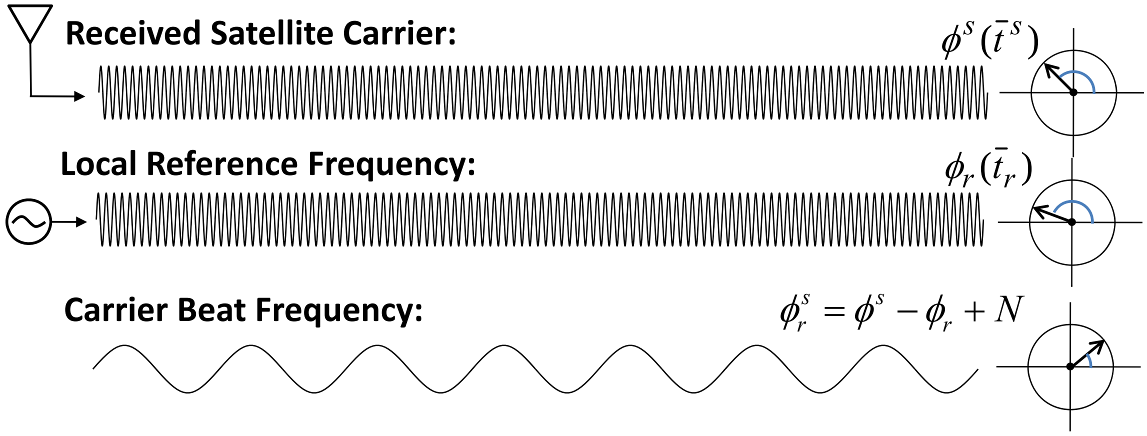
Carrier-Phase

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)*

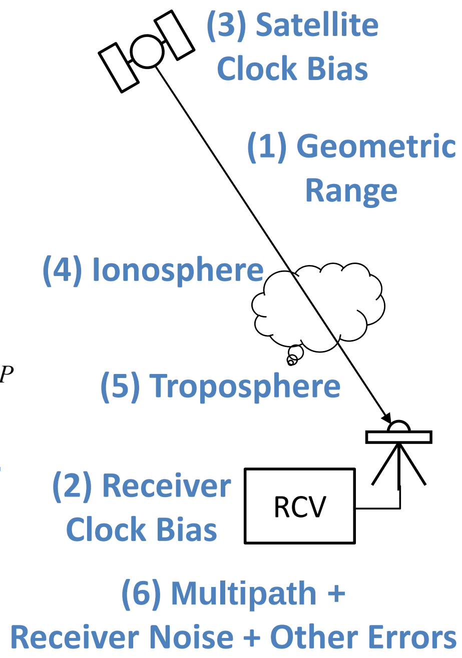


Code vs Carrier-Based Positioning

	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:

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

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

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

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

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

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:

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

$\mathbf{d}_{r,pco}$: Receiver Antenna Phase Center Offset
$d_{r,pcv}$: Receiver Antenna Phase Center Variation
$\mathbf{d}_{pco}^s$: Satellite Antenna Phase Center Offset
d_{pcv}^s : Satellite Antenna Phase Center Variation
$\mathbf{d}_{disp}$: Site Displacement
d_{pw} : Phase Wind-up Effect
d_{rel} : Relativistic Effect

DD (Double Difference)

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

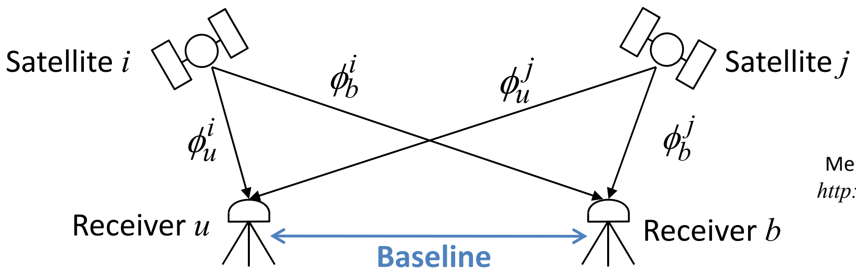
$$dt_{ub}^{ij} = dt_u^{ij} - dt_b^{ij} = 0,\ dT_{ub}^{ij} = dT_{ub}^i - dT_{ub}^j \approx 0$$

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

(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

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:

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

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

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

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

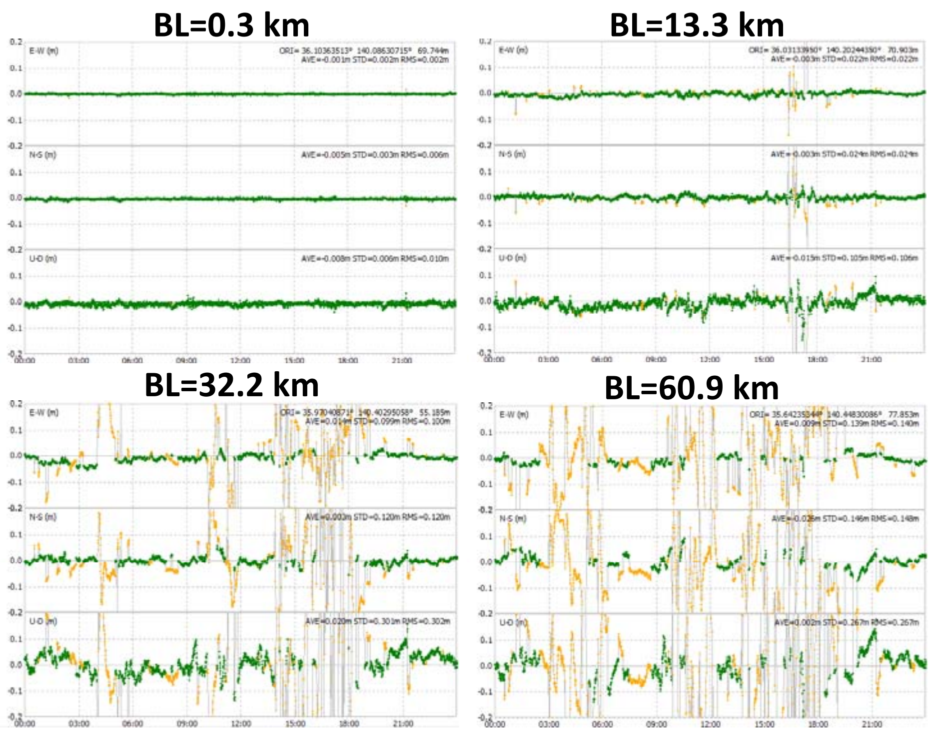
$$\boldsymbol{R}_{t_k} = \begin{pmatrix} 4\sigma_\Phi{}^2 & 2\sigma_\Phi{}^2 & \cdots & 2\sigma_\Phi{}^2 \\ 2\sigma_\Phi{}^2 & 4\sigma_\Phi{}^2 & \cdots & 2\sigma_\Phi{}^2 \\ \vdots & \vdots & \ddots & \vdots \\ 2\sigma_\Phi{}^2 & 2\sigma_\Phi{}^2 & \cdots & 4\sigma_\Phi{}^2 \end{pmatrix}$$

Solution (Static/Float):

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

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

Effect of Baseline Length



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

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

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

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

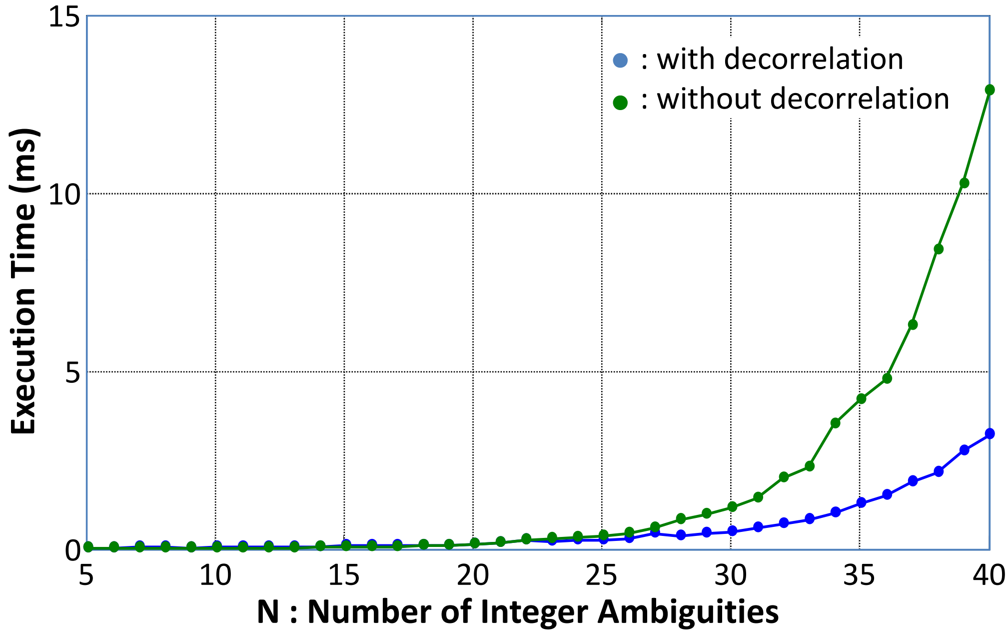
$$\breve{\boldsymbol{a}} = \arg\min_{\boldsymbol{a} \in \boldsymbol{Z}^n} (\hat{\boldsymbol{a}} - \boldsymbol{a})^T \boldsymbol{Q}_a^{-1} (\hat{\boldsymbol{a}} - \boldsymbol{a}) \Leftrightarrow$$

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

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

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

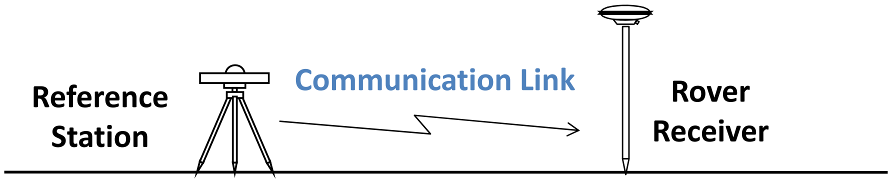
Performance of LAMBDA



(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

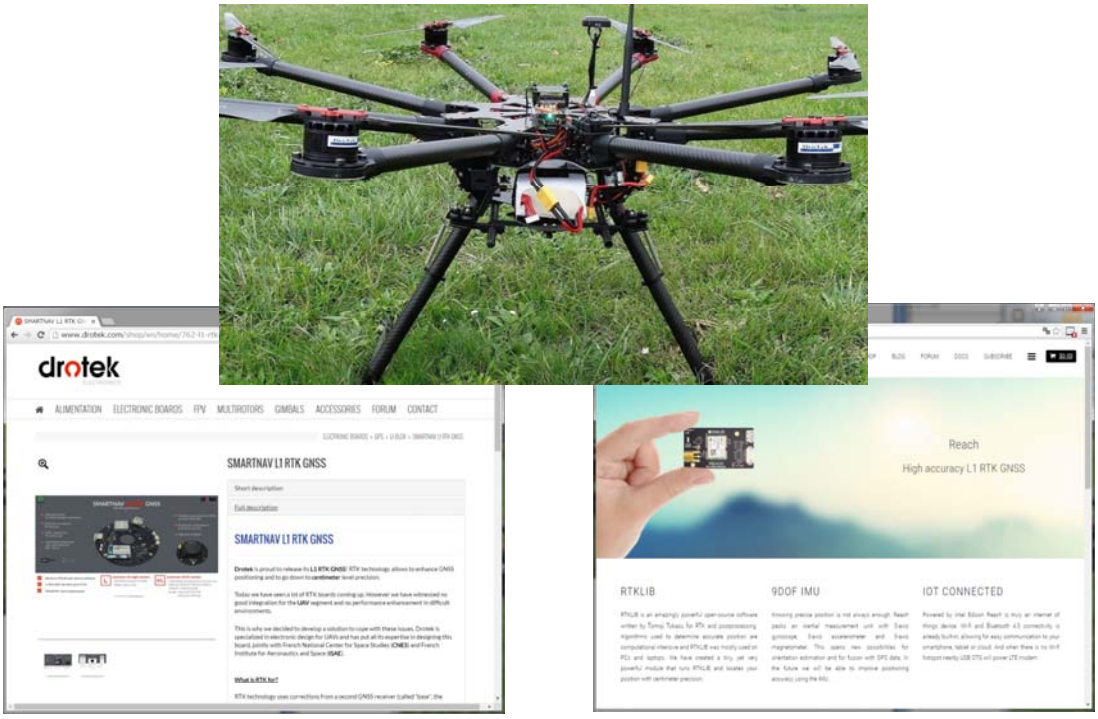
ITS (Intelligent Transport System)

Mobile Mapping System

Sports

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

RTK Application (2)

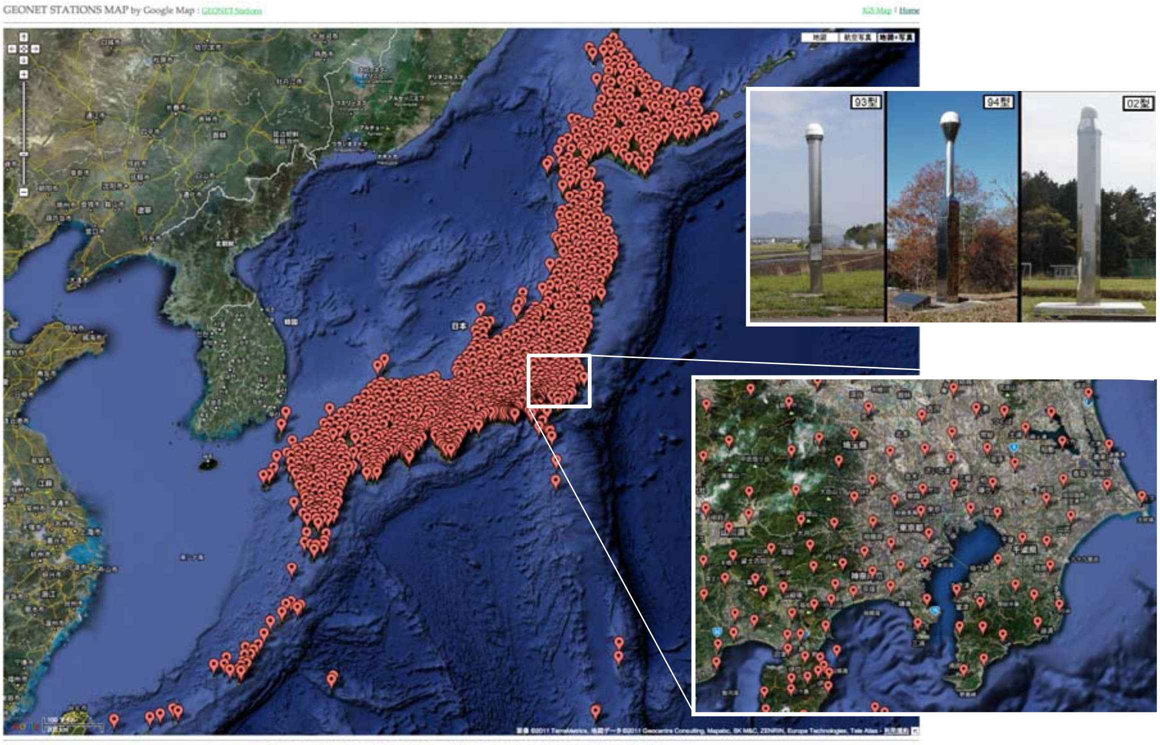


http://www.drotek.com http://www.emlid.com

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 (www.gpsdata.co.jp), JENOBA (www.jenoba.jp)

Japanese GEONET



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

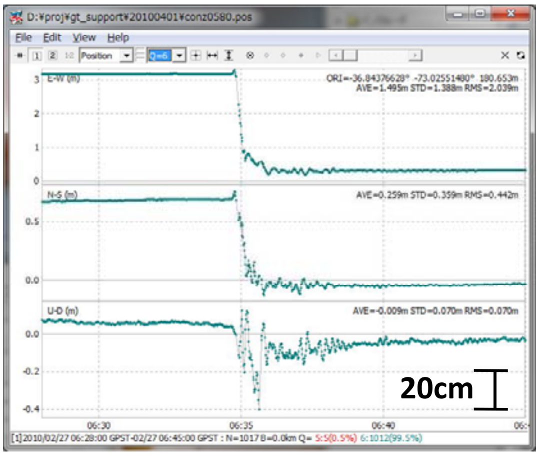
PPP (Precise Point Positioning)

- **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

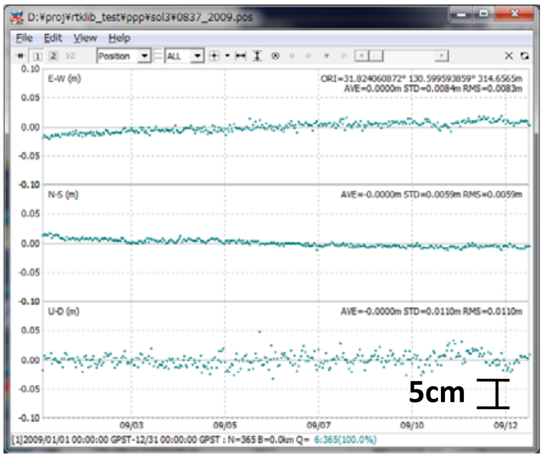


2010/2/27 6:28-6:45 GPST

Interval: 1 s

Static PPP

Station: GEONET 0837



2009/1/1-2009/12/31

Interval: 1day

PPP Applications

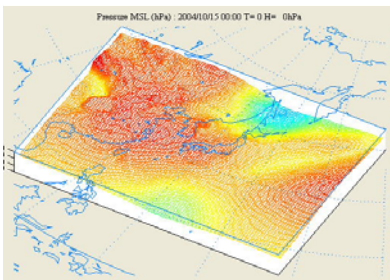
Automated Farming

Tsunami Warning

Mining Machine Control

Offshore Construction

Autonomous Driving



Weather Forecast

RTK vs. PPP

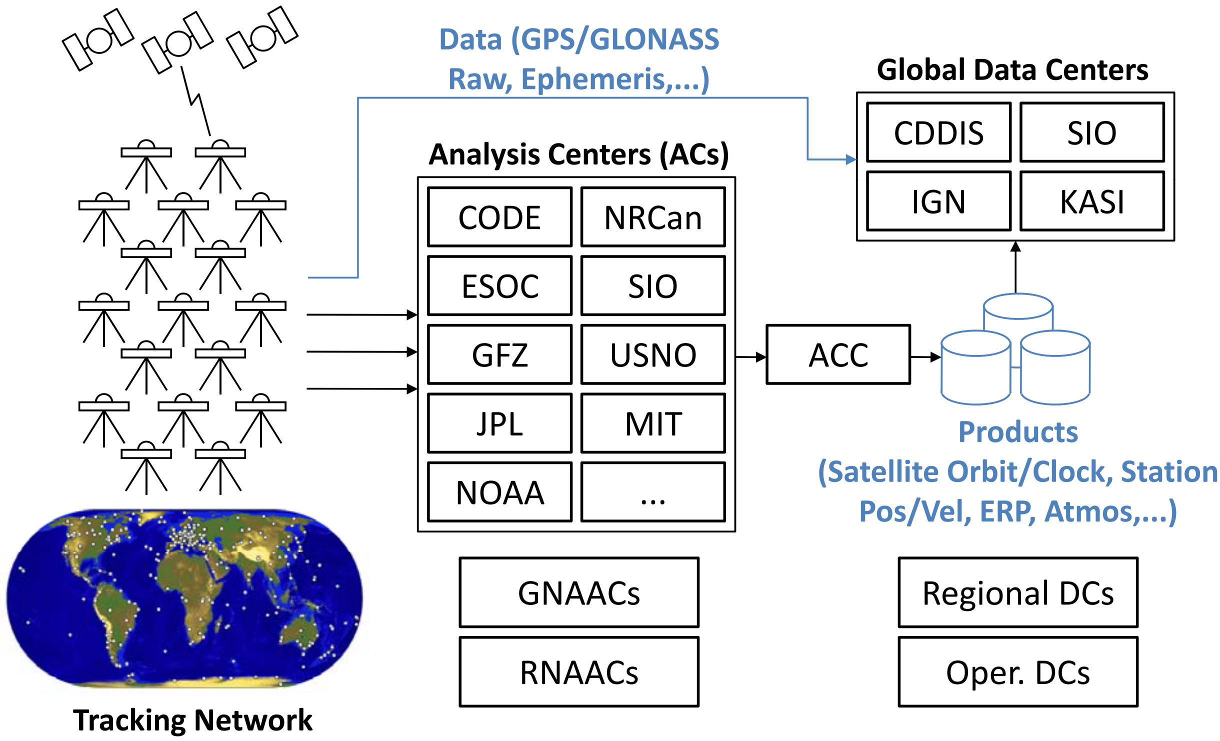
	RTK	Real-Time PPP
Coverage	Local/Regional (< 1000km)	Global
Typical Accuracy	1-3 cm HRMS	2-10 cm, much depending on orbit/clock quality
Effect of Ref Movement	Hard to separate ref and user movement	Less effect by distributed ref stations
System Complexity	Simple, at least one ref station	Complicated, 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.

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

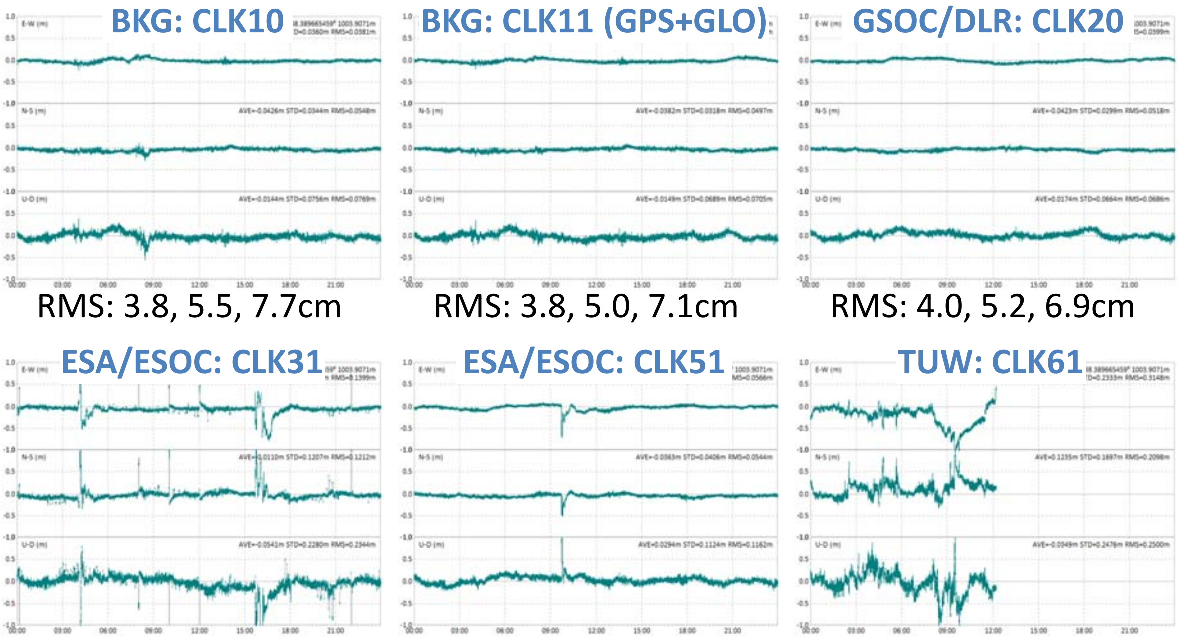
(2009/8, http://igscb.jpl.nasa.gov/)

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



RMS: 3.8, 5.5, 7.7cm | RMS: 3.8, 5.0, 7.1cm | RMS: 4.0, 5.2, 6.9cm

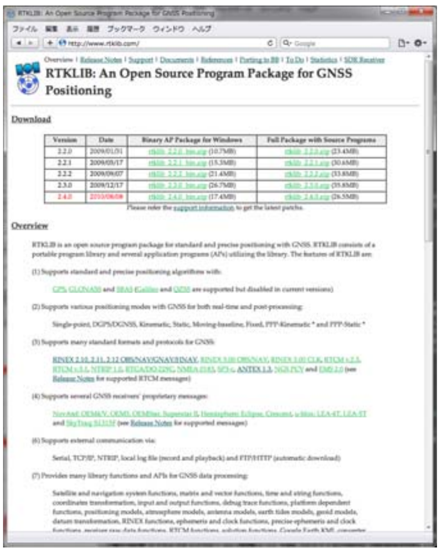
RMS: 14.0, 12.1, 23.4cm | RMS: 5.7, 5.4, 11.6cm | RMS: 23.3, 21.0, 25.0cm

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

B-6
RTKLIB Practice (1)

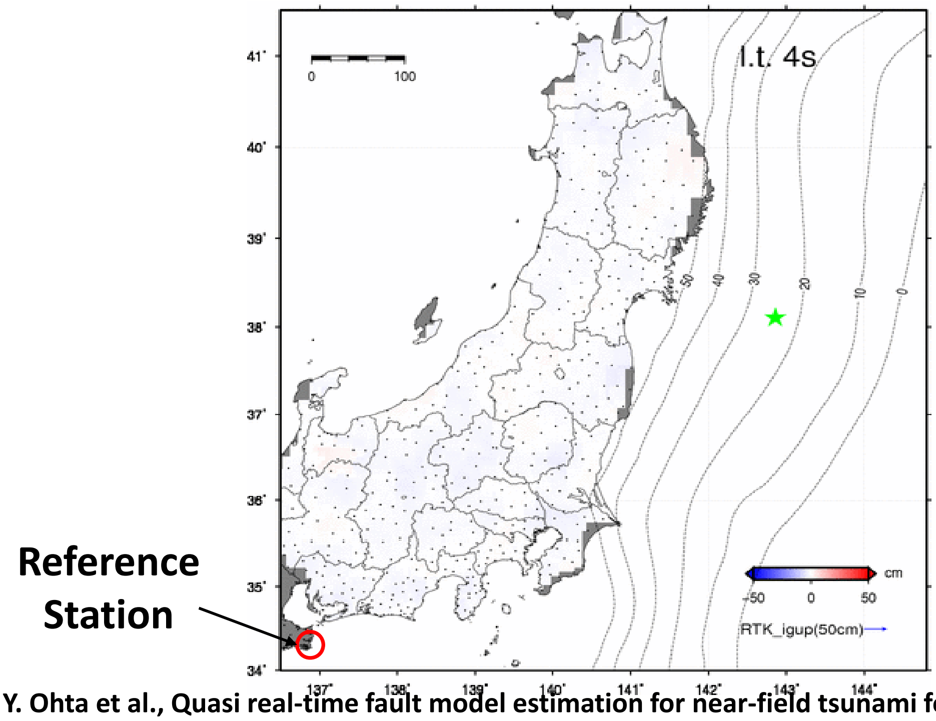
RTKLIB

- **An Open Source Software Package for GNSS Positioning**
  - Has been developed since 2006
  - The latest version 2.4.2 p11 distributed under BSD license
- **Portable APIs and Useful APs**
  - "All-in-one" package for Windows
  - CLI APs for any environments



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

RTKLIB: Application



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

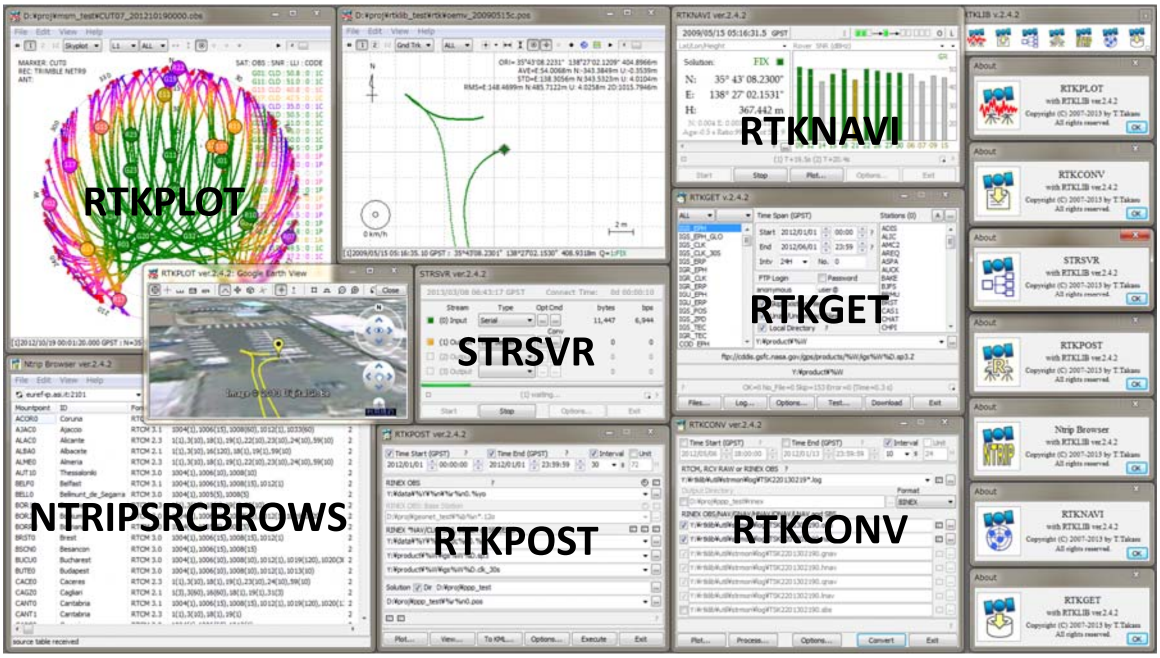
RTKLIB: History

- 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

OPTIONS

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
```

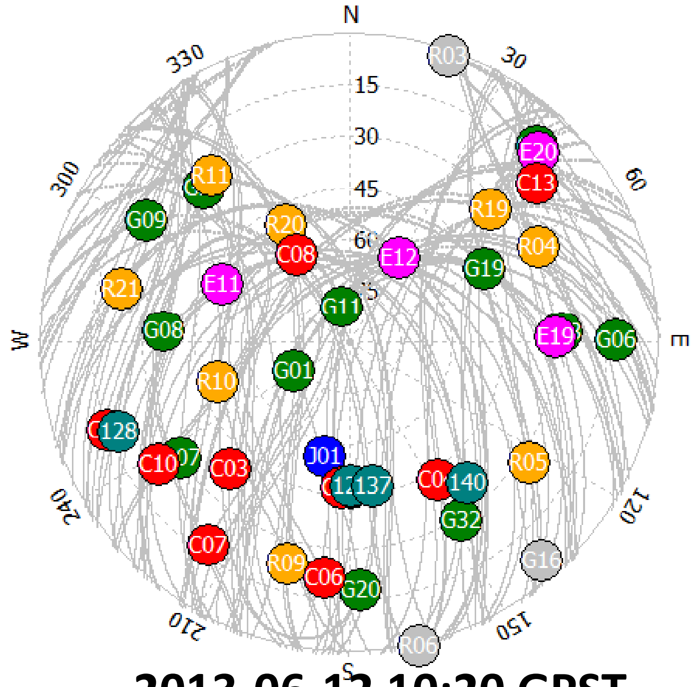
RTKLIB: APIs

```
/* 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

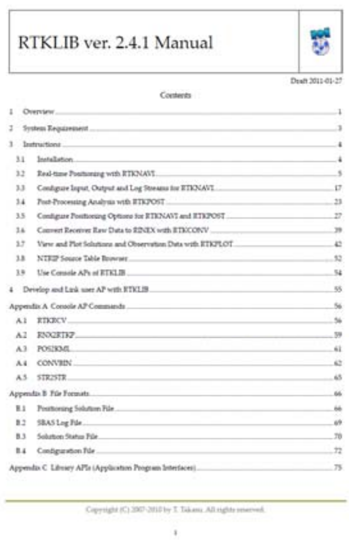


- GPS (12)
- GLONASS (8)
- Galileo (4)
- QZSS (1)
- BeiDou (10)
- SBAS (4)

 # Total (39)
(El>10deg)

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

RTKLIB: References



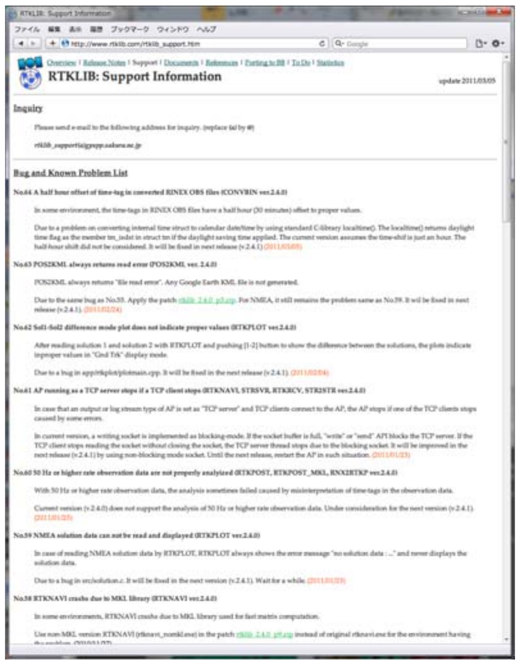
RTKLIB ver. 2.4.1 Manual

Draft 2011-01-27

Contents

Copyright (C) 2007-2010 by T. Takasu, All rights reserved.

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**
- **Use RTKLIB in Real-Time Mode**

Install RTKLIB

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

school_2016

¥rtklib_2.4.2p11

¥rtklib_2.4.3b15

¥sample1

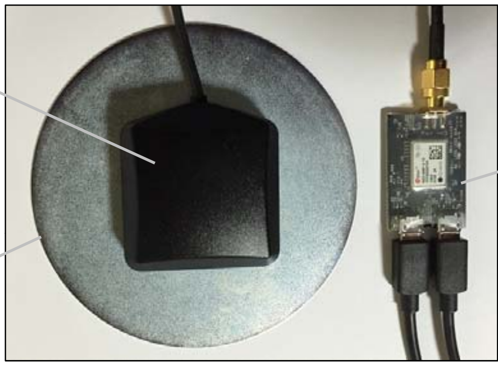
...

¥ublox

¥googleearth

Receivers and Antennas

- **Receiver**
  - u-blox NEO-M8P-2 (GPS, GLO/BDS, L1/B1)
- **Antenna**
  - INPAQ B3G02G-S3-01-A (GPS, GLO, BDS, L1/B1)



INPAQ B3G02G-S3-01-A

Ground Plane 10 cm Φ

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

Receiver Module, Antenna and Ground Plane are provided by u-blox .

u-blox NEO-M8P

NEO-M8P

u-blox M8 high precision GNSS modules

u-blox

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

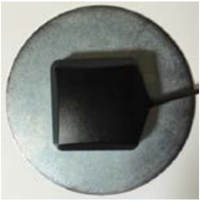
Model	Category				GNSS					Supply	Interfaces				Features								Grade		
	Standard Precision GNSS	High Precision GNSS	Dead Reckoning	Timing	GPS / QZSS	GLONASS	Galileo	BeiDou	Number of Concurrent GNSS	2.7 V – 3.6 V	UART	USB	SPI	DDC (I²C compliant)	Programmable (Flash)	Data logging	Carrier phase output	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**
    (school_2016¥ublox¥u-center_v8.22_B03.zip)

INPAQ B3G02G-S3-01-A



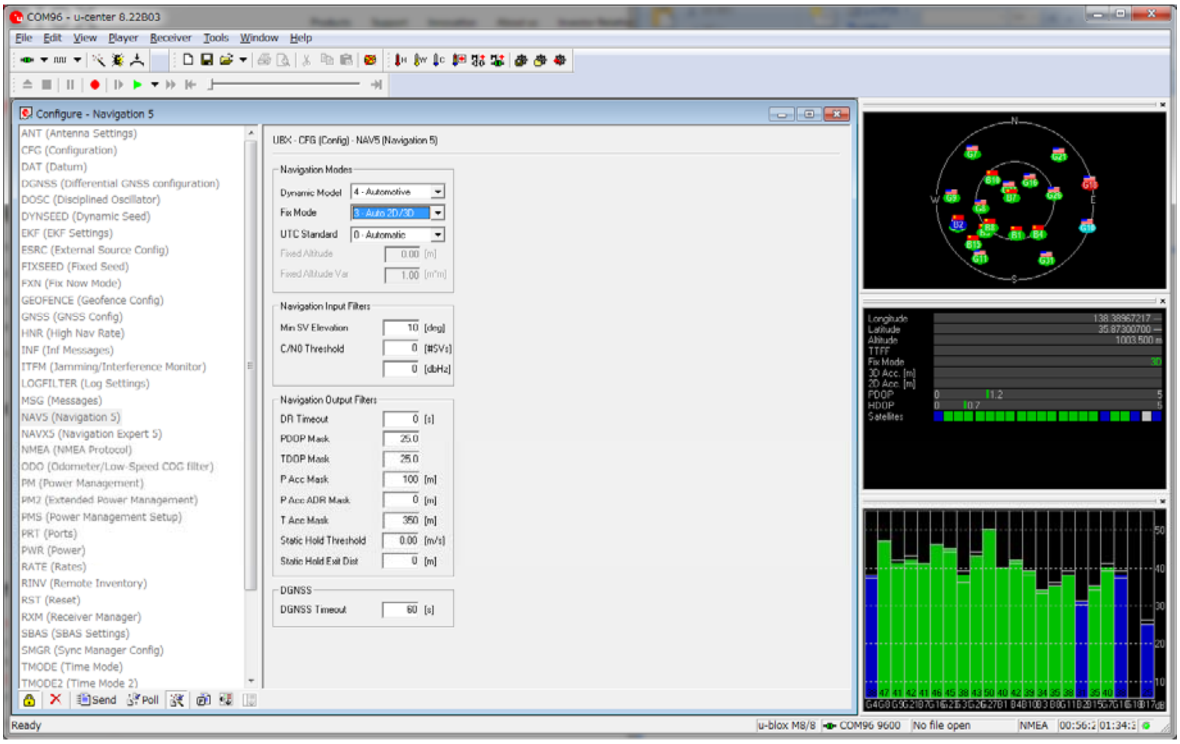
u-blox NEO-M8P-2 Mini-EVK Card

micro USB

u-blox u-center v8.22_B03

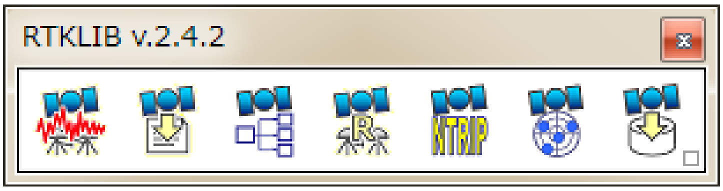
your Laptop PC

u-center



Use RTKLIB (1)

- **Execute RTKLAUNCH.**
  school¥rtklib_2.4.3b15¥bin¥rtklaunch.exe



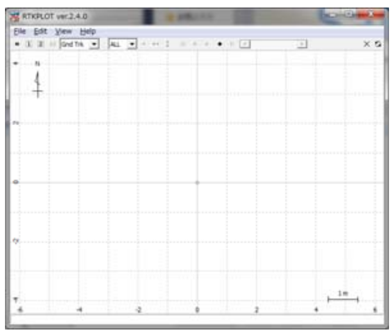
RTKPLOT STRSVR NTRIPBRS RTEGET

RTKCONV RTKPOST RTKNAVI

Use RTKLIB (2)

- **Execute RTKPLOT by RTKLAUNCH**
- **Execute Menu of RTKPLOT: File - Open Obs Data...**
  school¥sample1¥
  javad1_201102030000.obs

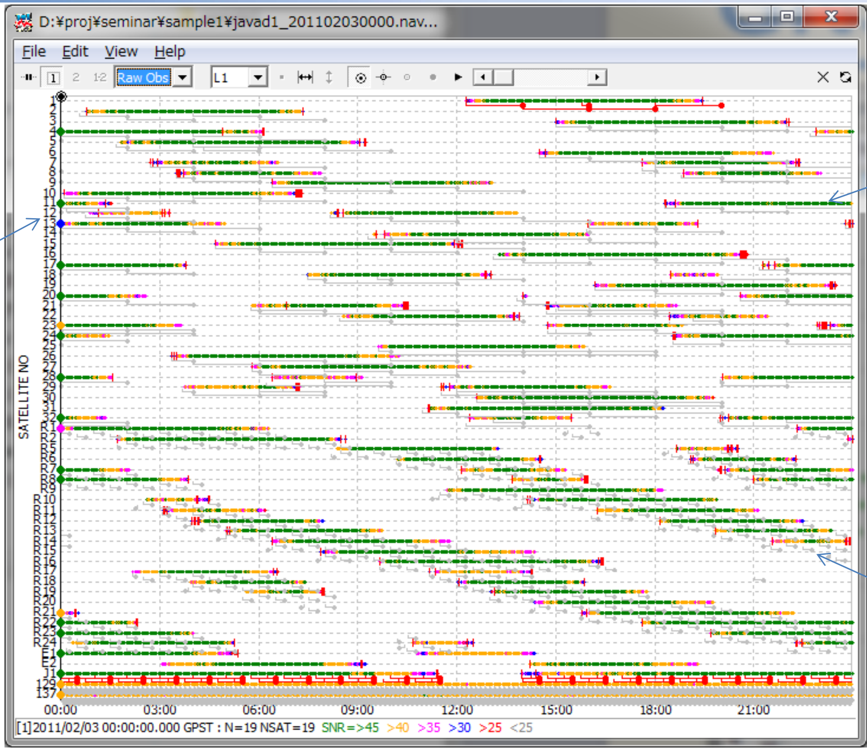
RTKLIB - RTKPLOT



JAVAD DELTA Receiver

Acknowledgment:
Sample data were captured by JAVAD DELTA receiver provided by JAXA

Use RTKLIB (3)



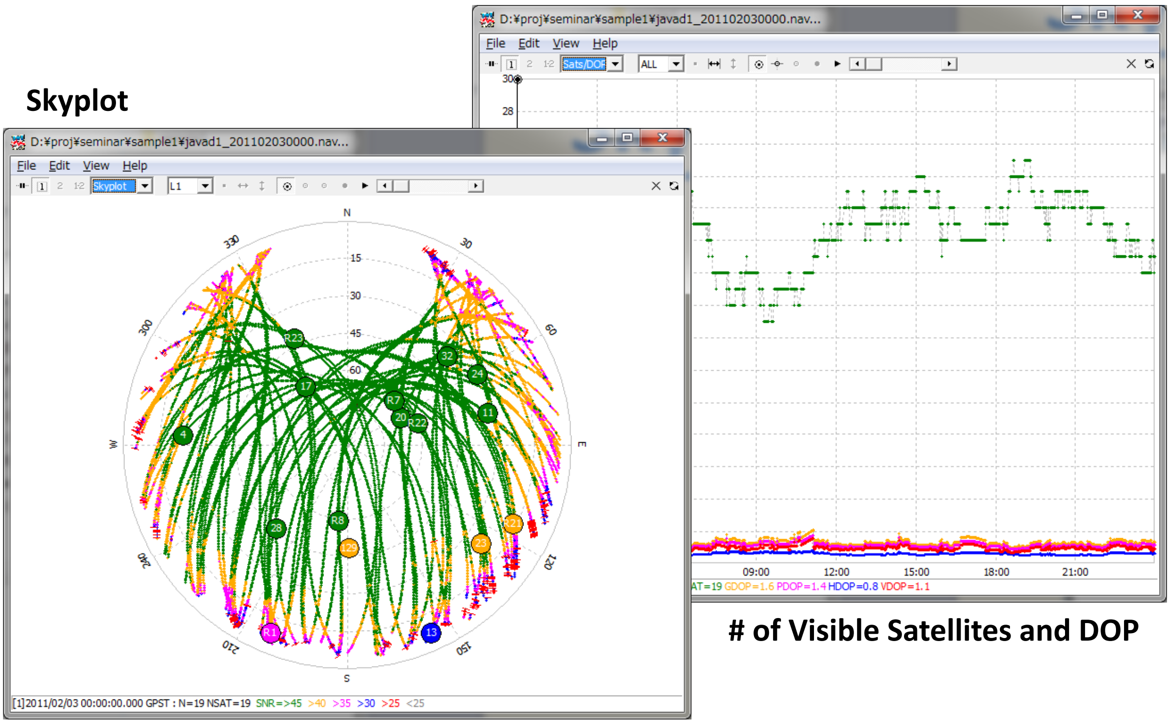
Tracking Data
|: Cycle-Slip
|: Parity Unknown

Satellite ID
Gnn: GPS
Rnn: GLO
Enn: GAL
Jnn: QZS
1nn: SBAS

Ephemeris
●: Toe
Red: unhealthy

Use RTKLIB (4)

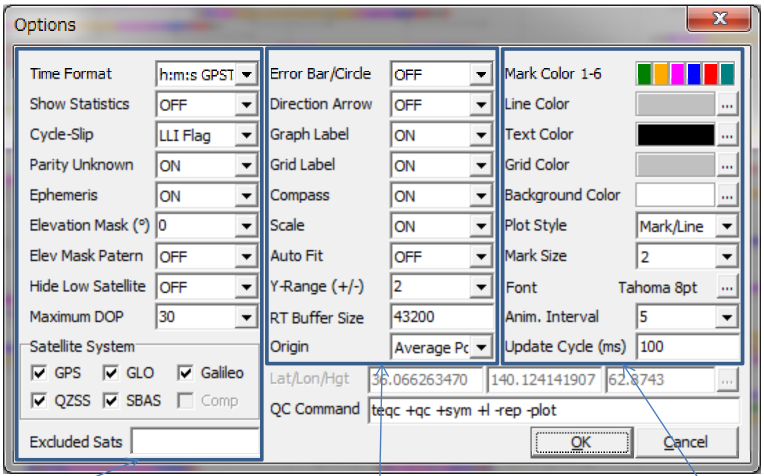
Skyplot



# of Visible Satellites and DOP

Use RTKLIB (5)

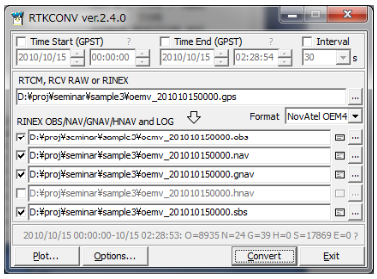
RTKPLOT - Options



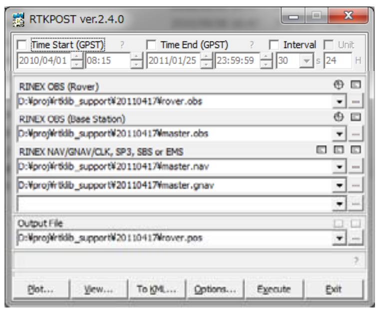
OBS Data Options **Solution Data Options** **Common Options**

Use RTKLIB (6)

- **Execute RTKCONV by RTKLAUNCH**
- **Set Input Data**
  school¥sample3¥
  oemv_201010150000.gps
- **Push Convert... Button**
- **Check RINEX Data**
- **Push Process... Button to Launch RTKPOST**



RTKCONV

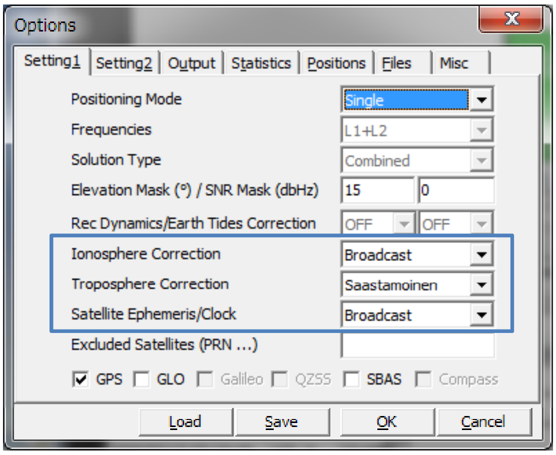


RTKPOST

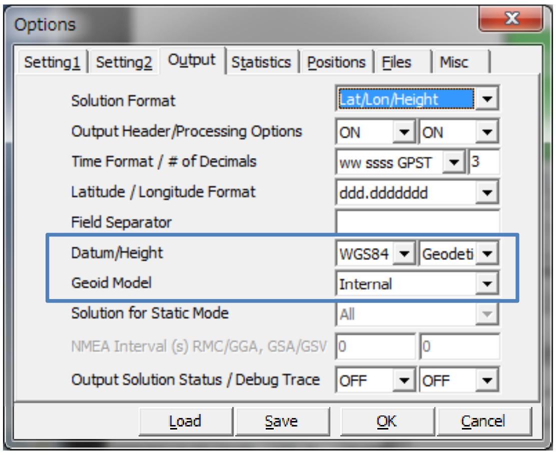
Use RTKLIB (7)

RTKPOST - Options

Setting1



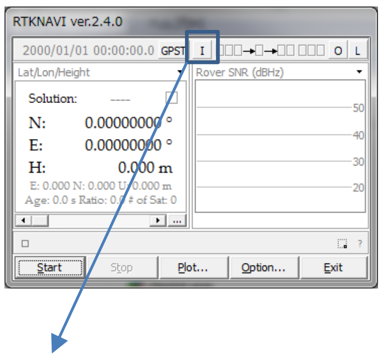
Output



Use RTKLIB in RT Mode (1)

- **Execute RTKNAVI by RTKLAUNCH**
- **Set Input Data Input Stream**
  Serial
- **Format**
  NovAtel OEM6 or Javad

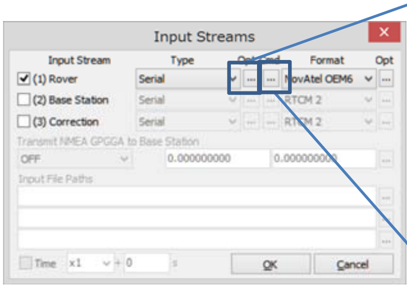
RTKLIB - RTKNAVI



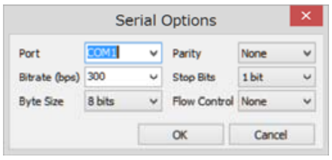
RTKLIB - RTKNAVI - Input Streams

Use RTKLIB in RT Mode (2)

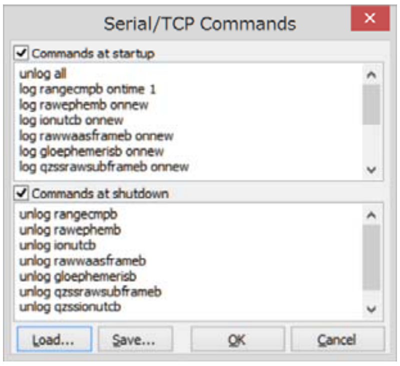
RTKLIB - RTKNAVI - Input Streams



RTKLIB - RTKNAVI - Input Streams - Serial Options

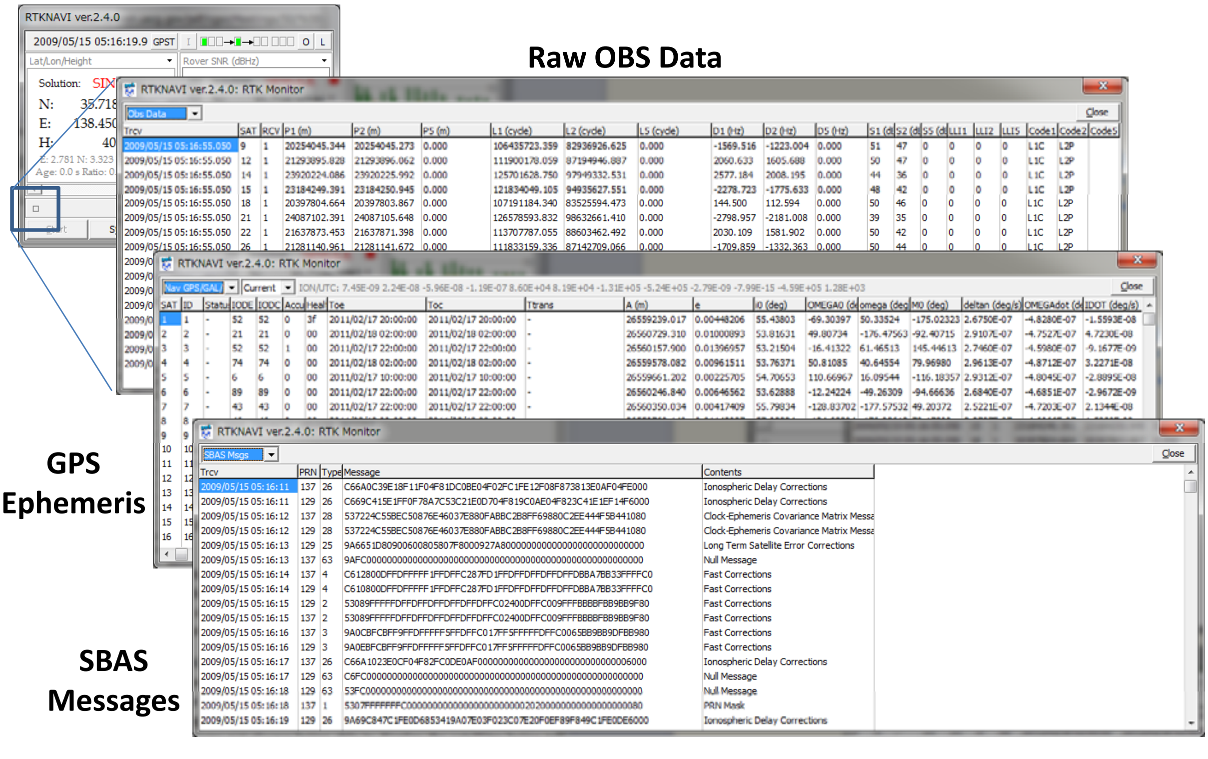


RTKLIB - RTKNAVI - Input Streams - Serial/TCP Commands



Use RTKLIB in RT Mode (3)

Raw OBS Data



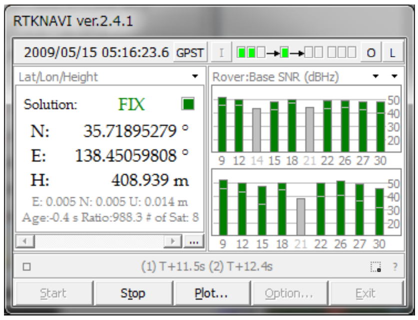
GPS Ephemeris

SBAS Messages

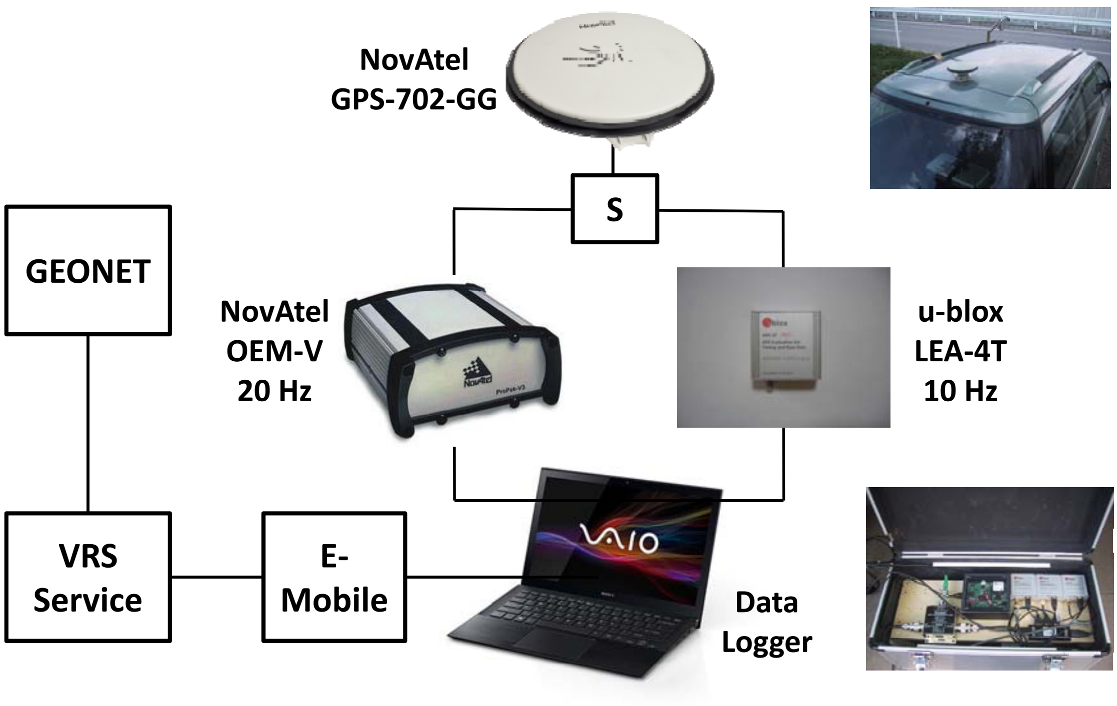
RTK by Playback Data

- **Objective**
  RTK of by Playback Data
- **Program**
  rtklib_2.4.2p11¥bin¥rtknavi.exe
- **Data**
  sample2¥
   oemv_2009515c.gps (NovAtel)
   ubx_20090515c.ubx (u-blox)
   0263_20090515c.rtcm3 (VRS)

RTKNAVI

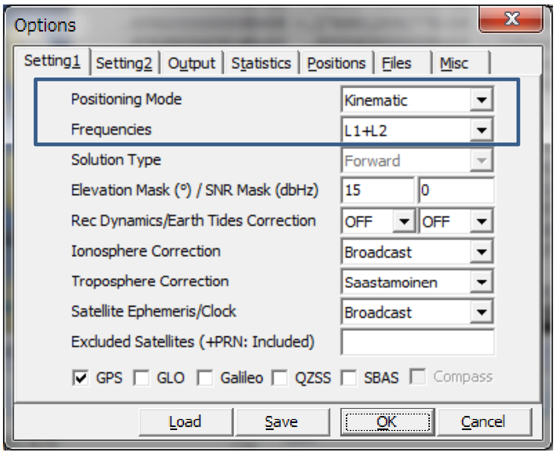


Playback Data

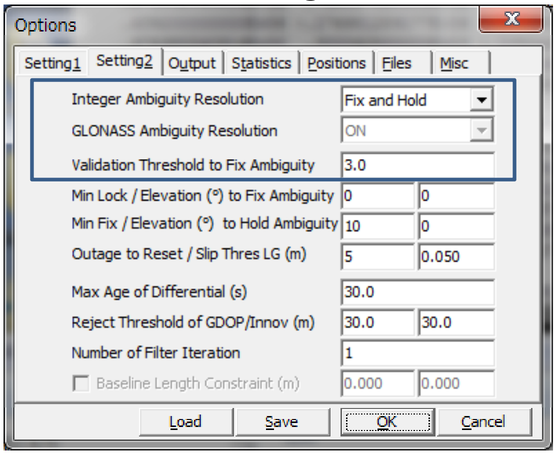


RTKNAVI - Options

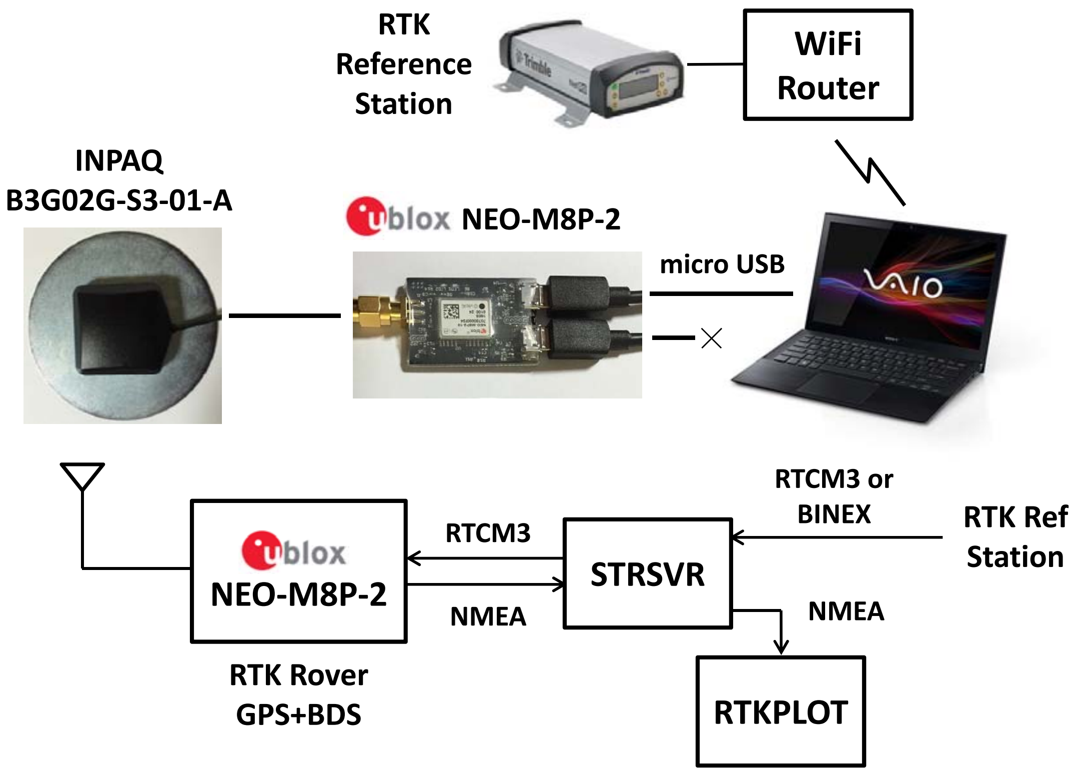
Setting1



Setting2



RTK Setup for Port Cruise

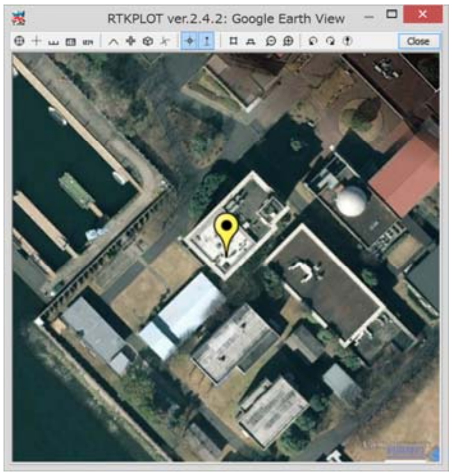


RTK Reference Station

Receiver:
Trimble NetR9

IP-Addr	: 192.244.***.***
Port	: 2101
MountP	: RTCM3
USER-ID	: ***
PW	: ***
Data	: RTCM 3, GPS+GLO

IP-Addr	: 192.244.***.***
Port	: 2102
MountP	: BINEX
USER-ID	: ***
PW	: ***
Data	: BINEX, GPS+GLO+GAL+QZS+BDS



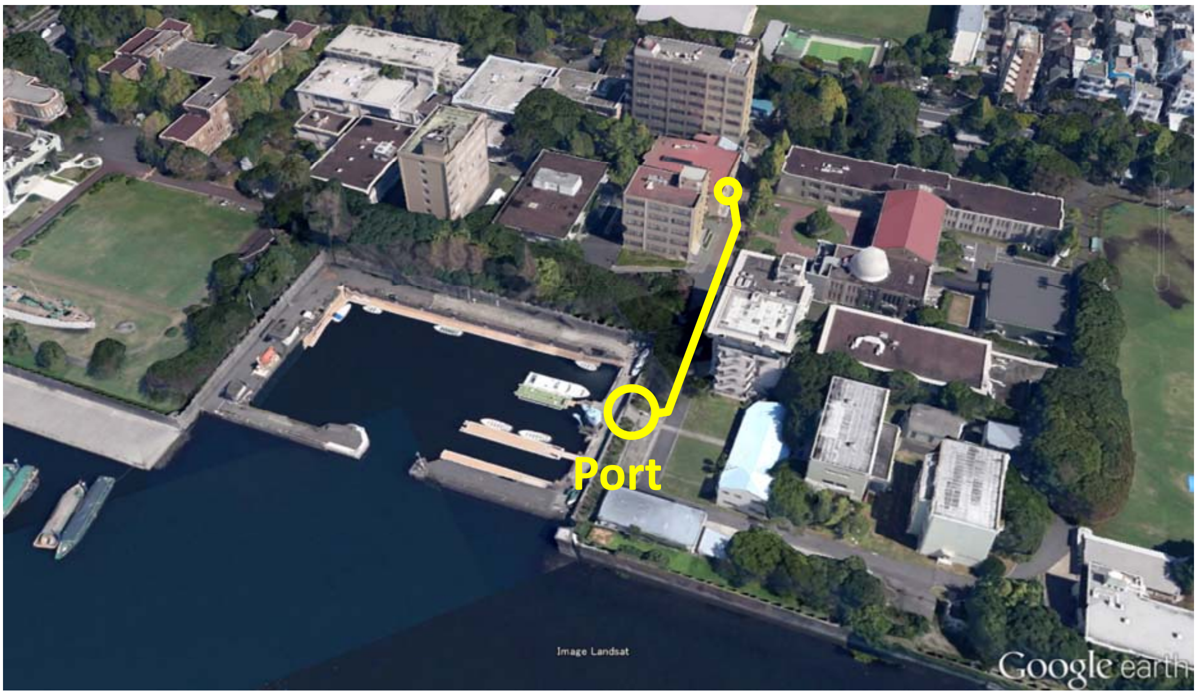
Lat: 35.666243069
Lon: 139.792308111
Height: 59.8700

B-7a/7b
RTK-Demo Port Cruise

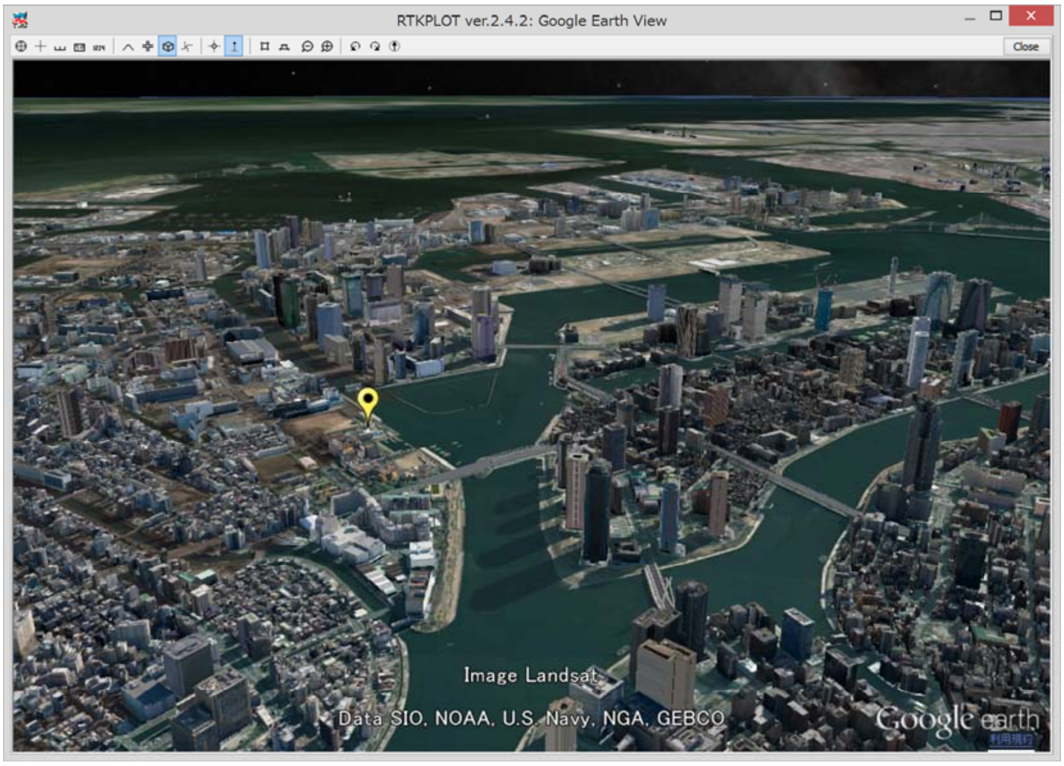
Port Cruise Schedule

- **Group I (G-I)**
  - **Loading : 12:30**
  - **Start : 12:40**
  - **Return : 14:00**
- **Group II (G-II)**
  - **Loading : 14:10**
  - **Start : 14:20**
  - **Return : 15:40**
- **Waiting Group**
  - AIS/ECDIS Demo (lead by Yasuda-sensei)

Loading of Boat



Port Cruise with RTK



Summer School 2014

News Letter of IPNTJ, Vol.IV No.3, 2014

B-8
RTKLIB Practice (2)

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

TAI to UTC:

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

UTC to UT1:

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

UT1 to GMST:

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

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

$$r = 1.0027379093\,50795 + 5.9006\times10^{-11}\,T'_u - 5.9\times10^{-15}\,T'^2_u$$

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

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-

GPS Time to TAI:

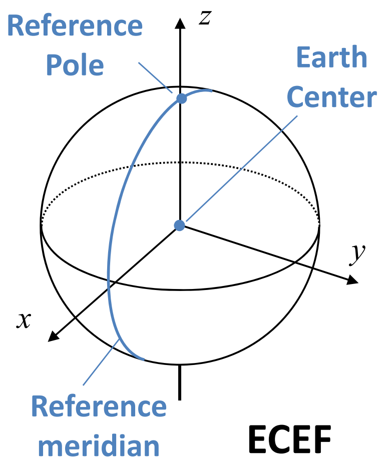
$$t_{TAI} \approx t_{GPST} + 19\,s$$

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



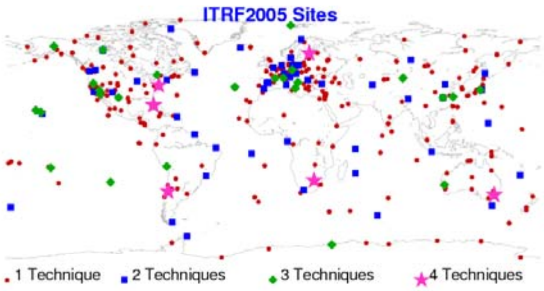
ECEF

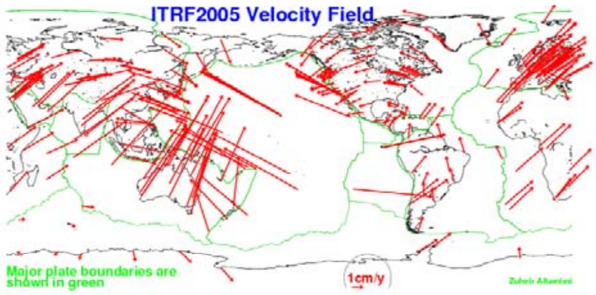
ITRF

- **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

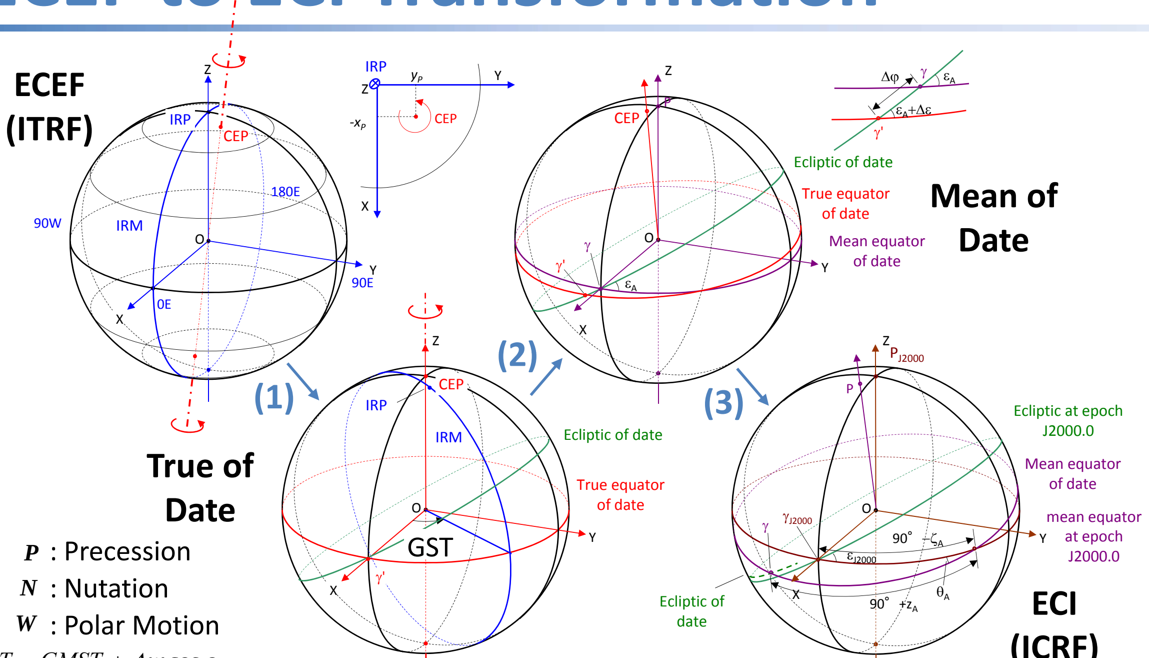
ITRS: International Terrestrial Reference System
IERS: International Earth Rotation Service





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

ECEF to ECI Transformation



P : Precession
N : Nutation
W : Polar Motion

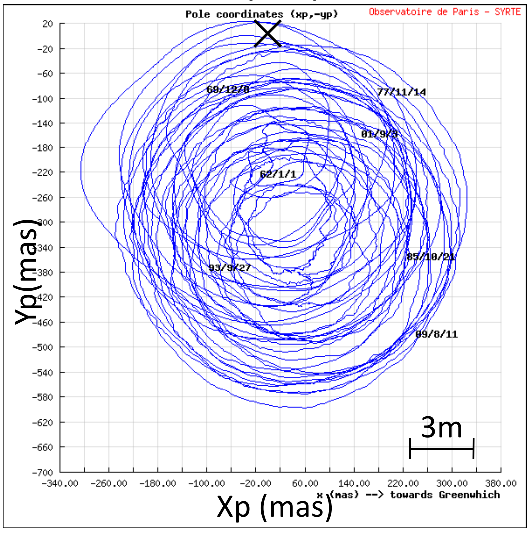
$$GST = GMST + \Delta\psi\cos\varepsilon_A + 0''.00264\sin\Omega + 0''.000063\sin 2\Omega$$

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

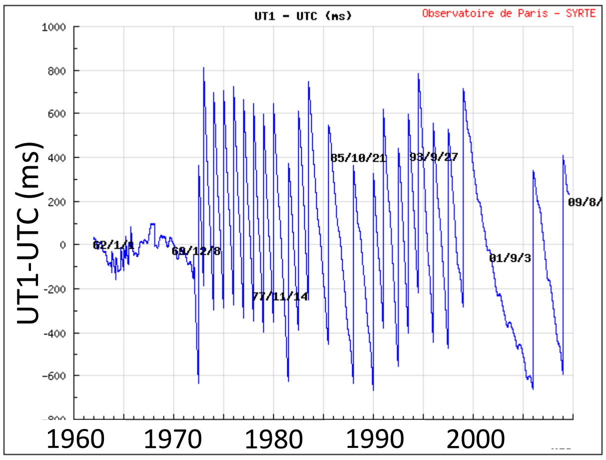
$$= \underbrace{\boldsymbol{R}_Z(\zeta_A)\boldsymbol{R}_Y(-\theta_A)\boldsymbol{R}_Z(z_A)}_{(3)}\underbrace{\boldsymbol{R}_X(-\varepsilon_A)\boldsymbol{R}_Z(\Delta\varphi)\boldsymbol{R}_X(\varepsilon_A+\Delta\varepsilon)}_{(2)}\underbrace{\boldsymbol{R}_Z(-GST)}_{}\underbrace{\boldsymbol{R}_X(y_P)\boldsymbol{R}_Y(x_P)}_{(1)}\boldsymbol{r}_{ecef}$$

EOP: Earth Orientation Parameters

Polar Motion:
Xp, Yp



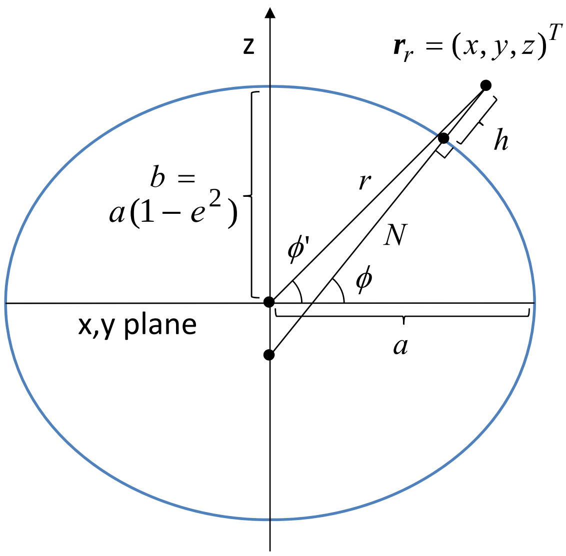
Earth Rotation Angle:
UT1-UTC



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	1/298.257222 101	1/298.257223 563
GM (m^3/s^2)	3986005.000 x 10^8	3986004.418 x 10^8

Lat/Lon/Height to ECEF:

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

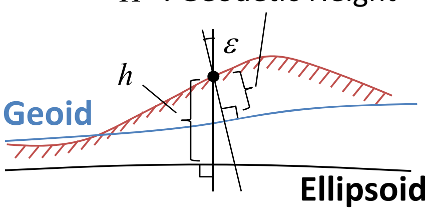
$$N = \frac{a}{\sqrt{1 - e^2 \sin^2 \phi}}$$

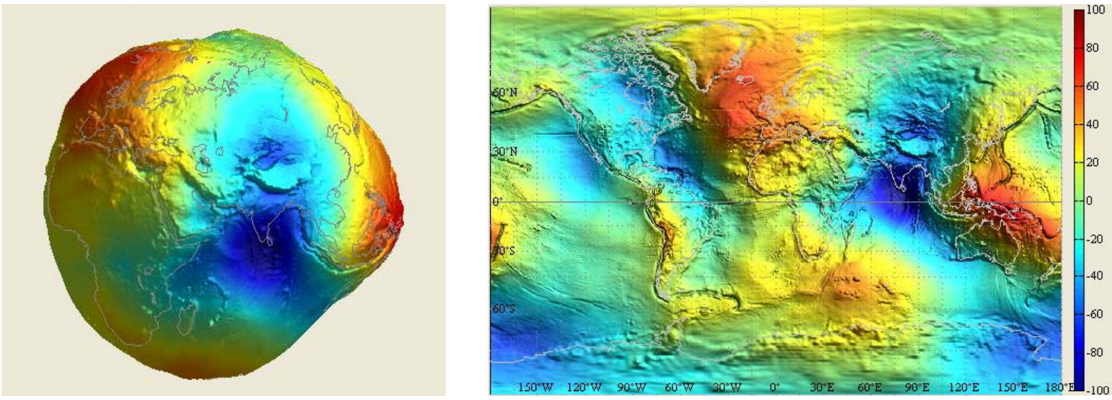
$$\mathbf{r}_r = \begin{pmatrix} (N+h)\cos\phi\cos\lambda \\ (N+h)\cos\phi\sin\lambda \\ (N(1+e^2)+h)\sin\phi \end{pmatrix}$$

Geoid

Geopotential:

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





EGM96 Geoid Model

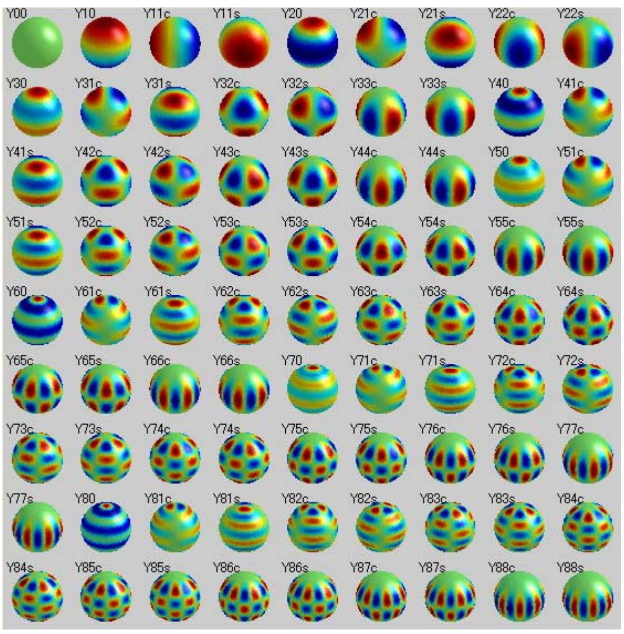
Spherical Harmonics

Spherical harmonic functions:

$$Y_{n0} = Y_{n0c}$$
$$Y_{nmc} = \bar{P}_{nm}(\sin\phi')\cos m\lambda$$
$$Y_{nms} = \bar{P}_{nm}(\sin\phi')\sin m\lambda$$

Legendre function:

$$\bar{P}_{nm} = N_{nm}P_{nm},\ P_{00}(x)=1, P_{10}(x)=x$$
$$P_{n-1,n}(x)=0,$$
$$P_{nn}(x)=(2n-1)(1-x^2)^{1/2}P_{n-1,n-1}(x)$$
$$P_{nm}(x)=\frac{(2n-1)xP_{n-1,m}(x)-(n+m-1)P_{n-2,m}(x)}{n-m}$$
$$N_{nm}=\begin{cases}\sqrt{2n+1} & (m=0)\\ \sqrt{\dfrac{2(2n+1)(n-m)!}{(n+m)!}} & (m>0)\end{cases}$$



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:

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

: Appleton-Hartree Formula

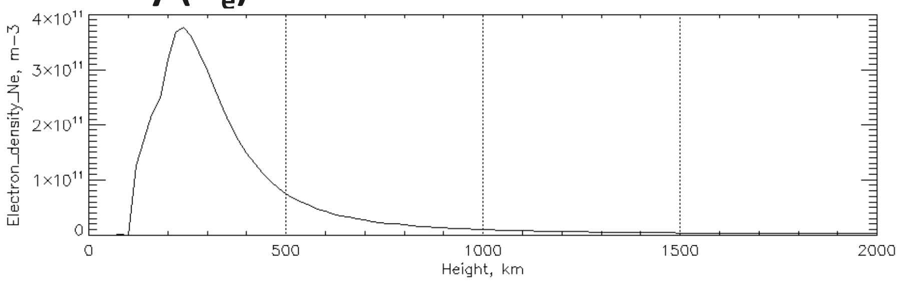
$$n = \sqrt{1 - f_N^2/f^2} \approx 1 - f_N^2/2f^2 = 1 - 40.30N_e/f^2$$

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

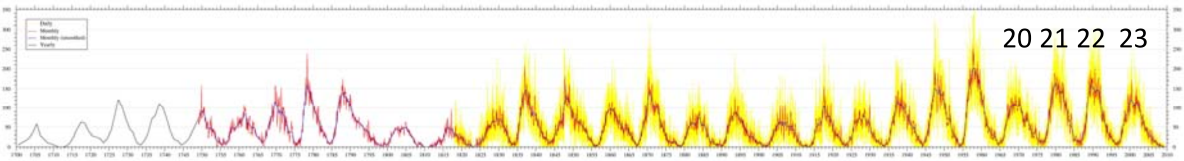
Electron Density (N_e):



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

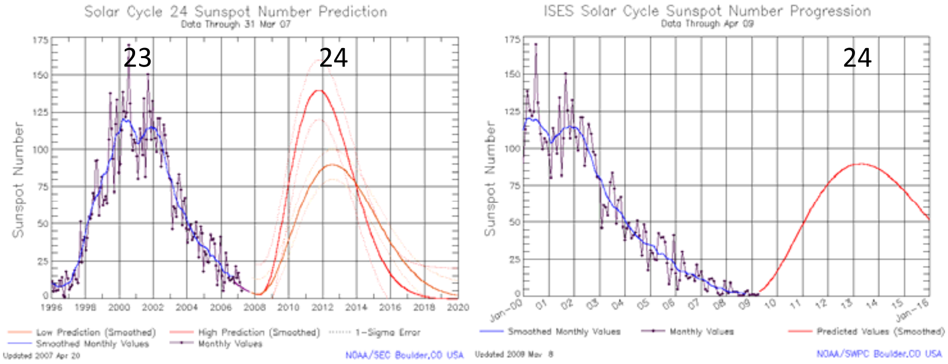
Solar Cycle

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:

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

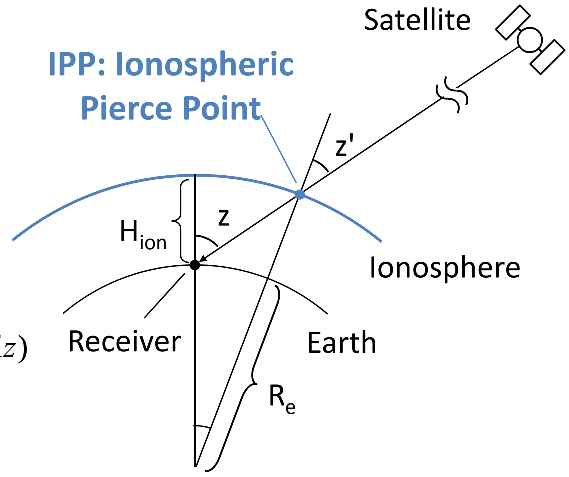
IPP Position/Slant Factor:

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

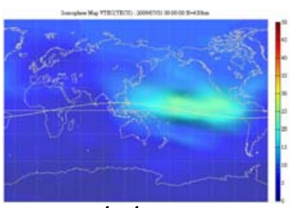
$$z' = \arcsin \frac{R_e \sin z}{R_e + H_{ion}}, \alpha = z - z'$$

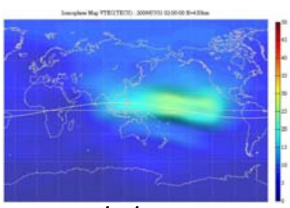
$$\phi_{pp} = \arcsin(\cos\alpha \sin\phi + \sin\alpha \cos\phi \cos Az)$$

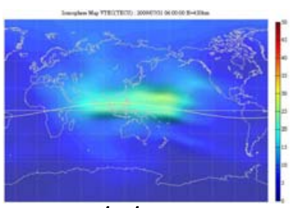
$$\lambda_{pp} = \lambda + \arcsin \frac{\sin\alpha \sin Az}{\phi_{pp}}$$

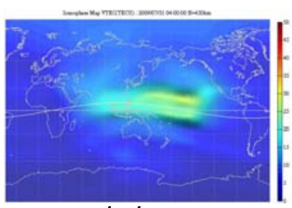


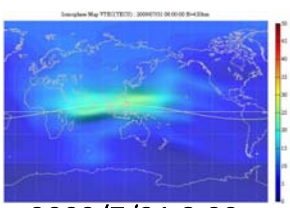
Ionospheric TEC Grid

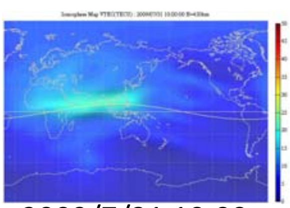

2009/7/31 0:00

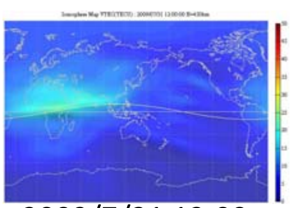

2009/7/31 2:00

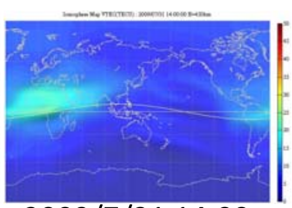

2009/7/31 4:00

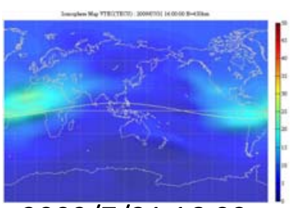

2009/7/31 6:00

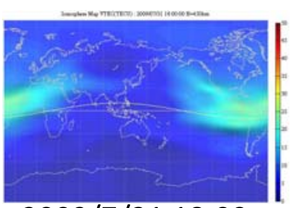

2009/7/31 8:00

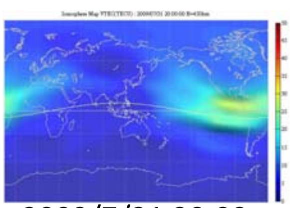

2009/7/31 10:00

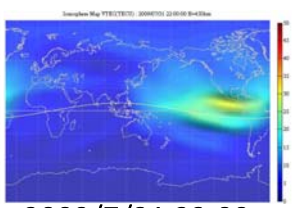

2009/7/31 12:00


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:

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

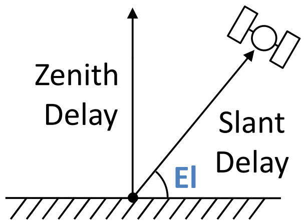
$$ZHD = \frac{0.0022768\,p}{1-0.00266\cos 2\phi - 2.8\times10^{-7}H}$$

: 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):

$$T_m = 70.2 + 0.72T$$

$$PWV = \frac{1\times10^5}{R_v\left(k_2 - k_1\frac{m_v}{m_d} + \frac{k_3}{T_m}\right)}ZWD$$

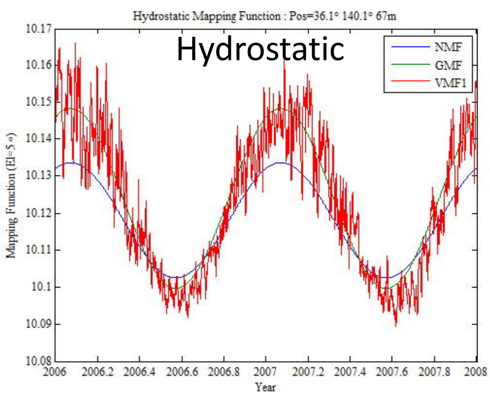
$R_v = 461, k_1 = 77.6,$
$k_2 = 71.98, k_3 = 3.754\times10^5$
$m_v = 18.0152, m_d = 28.9644$

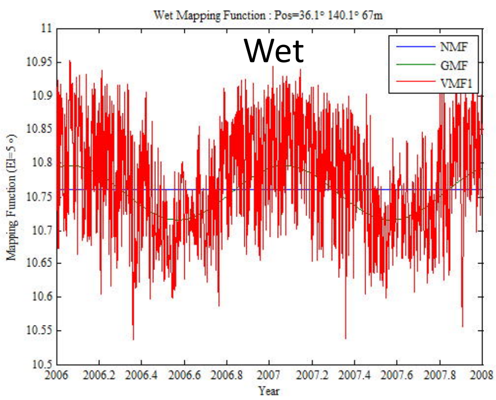
Mapping Function

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

a,b,c : Mapping Function Coefficients

NMF, GMF, VMF1

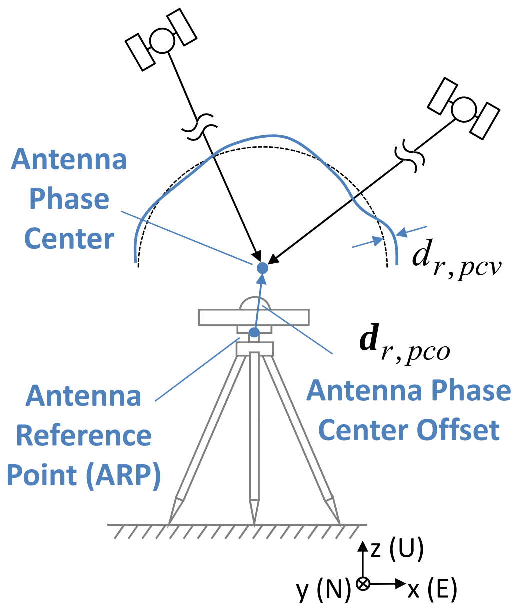




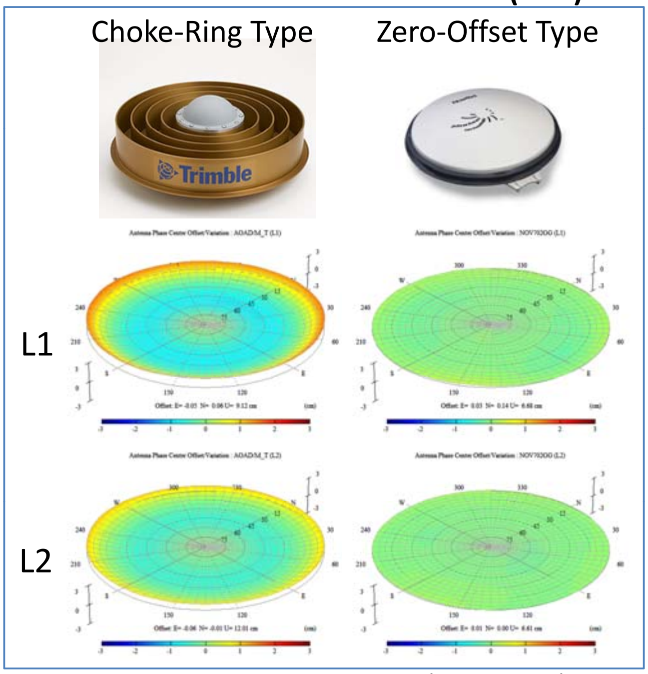
(2006/1/1-2007/12/31, TSKB, El=5deg)

Antenna Phase Center 1

Receiver Antenna Phase Center:



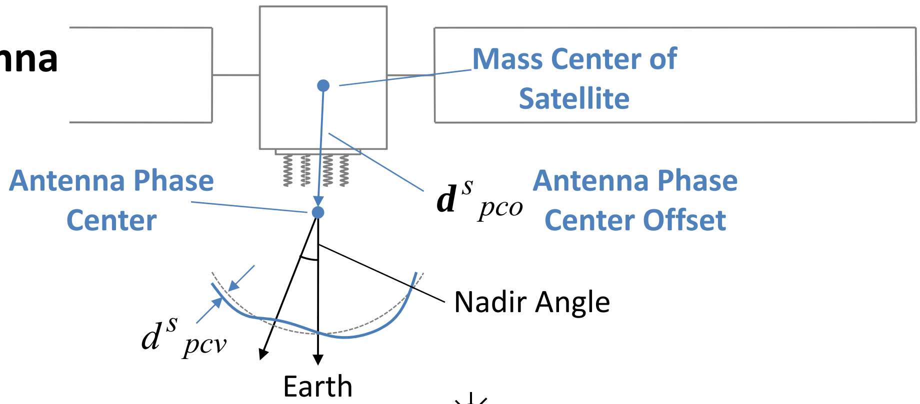
Antenna Phase Center Variation (PCV)



IGS Absolute Antenna Model (IGS05.PCV)

Antenna Phase Center 2

Satellite Antenna Phase Center:

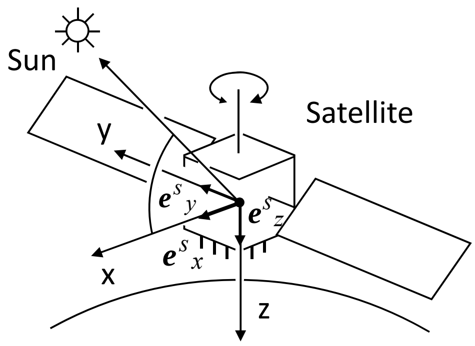


Satellite Coordinate to ECEF:

$$\boldsymbol{E}_{sat \to ecef} = (\boldsymbol{e}^s{}_x, \boldsymbol{e}^s{}_y, \boldsymbol{e}^s{}_z)$$

$$\boldsymbol{e}^s{}_z = -\frac{\boldsymbol{r}^s}{\left\| \boldsymbol{r}^s \right\|}, \boldsymbol{e}_s = \frac{\boldsymbol{r}_{sun} - \boldsymbol{r}^s}{\left\| \boldsymbol{r}_{sun} - \boldsymbol{r}^s \right\|}$$

$$\boldsymbol{e}^s{}_y = \frac{\boldsymbol{e}^s{}_z \times \boldsymbol{e}^s{}_s}{\left\| \boldsymbol{e}^s{}_z \times \boldsymbol{e}_s \right\|}, \boldsymbol{e}^s{}_x = \boldsymbol{e}^s{}_y \times \boldsymbol{e}^s{}_z$$

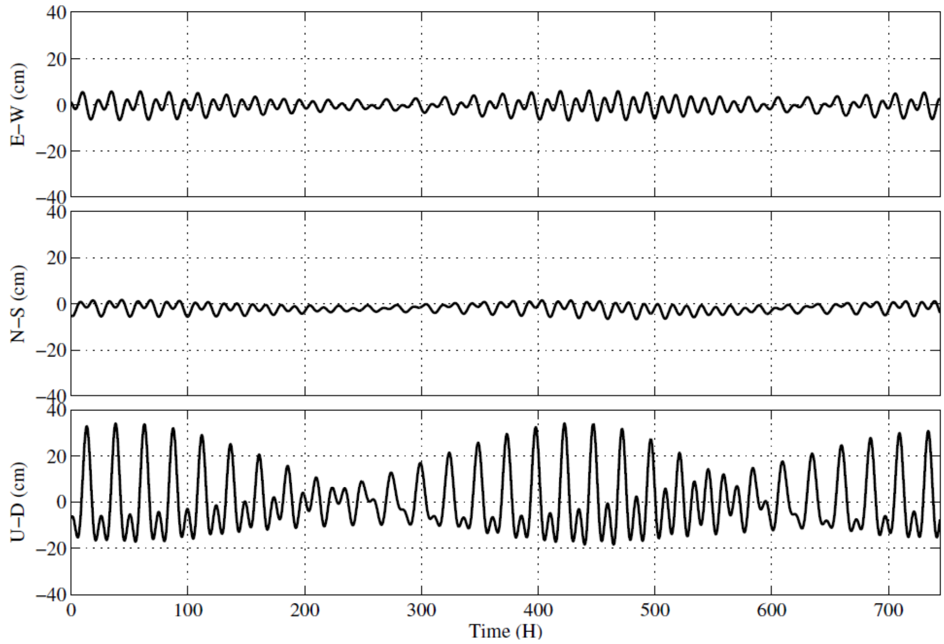


Site Displacement

- **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

Earth Tides Model



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

Phase Wind-up Effect

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

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

$\boldsymbol{D}^s = \boldsymbol{e}_x^s - \boldsymbol{e}_u^s(\boldsymbol{e}_u^s \cdot \boldsymbol{e}_x^s) - \boldsymbol{e}_u^s \times \boldsymbol{e}_y^s$: 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

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

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

N : Integer Ambiguity

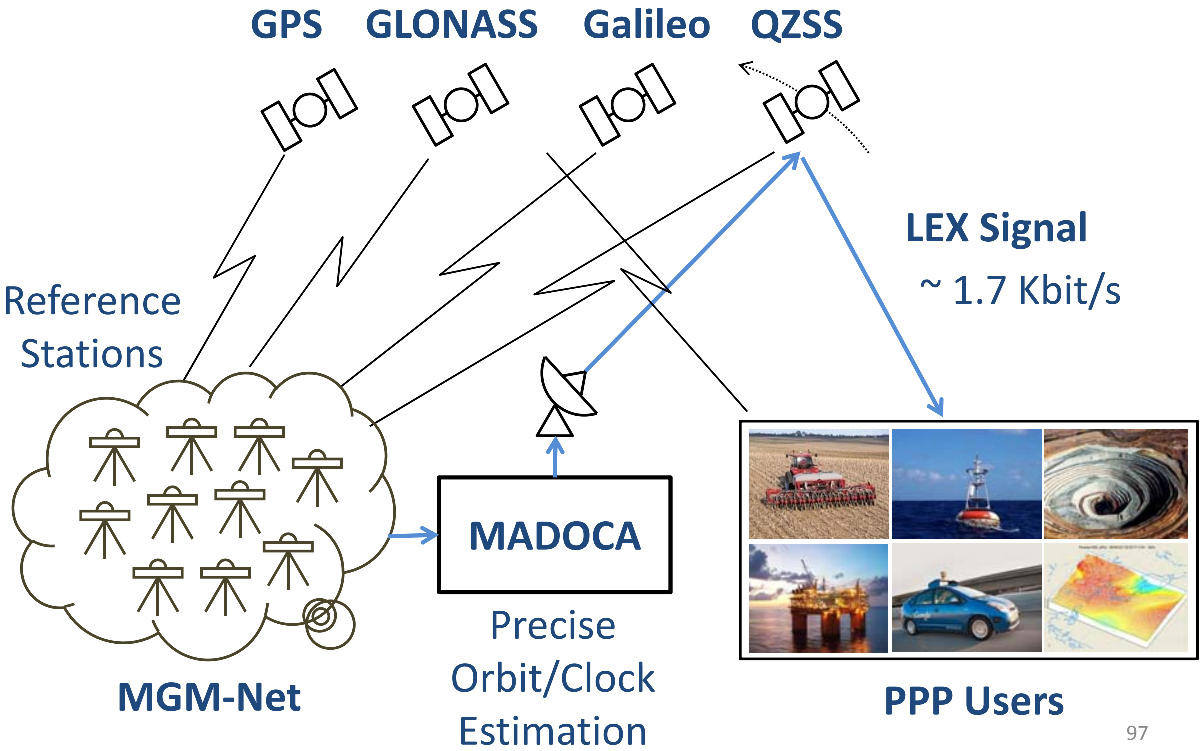
Relativistic Effects

- **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

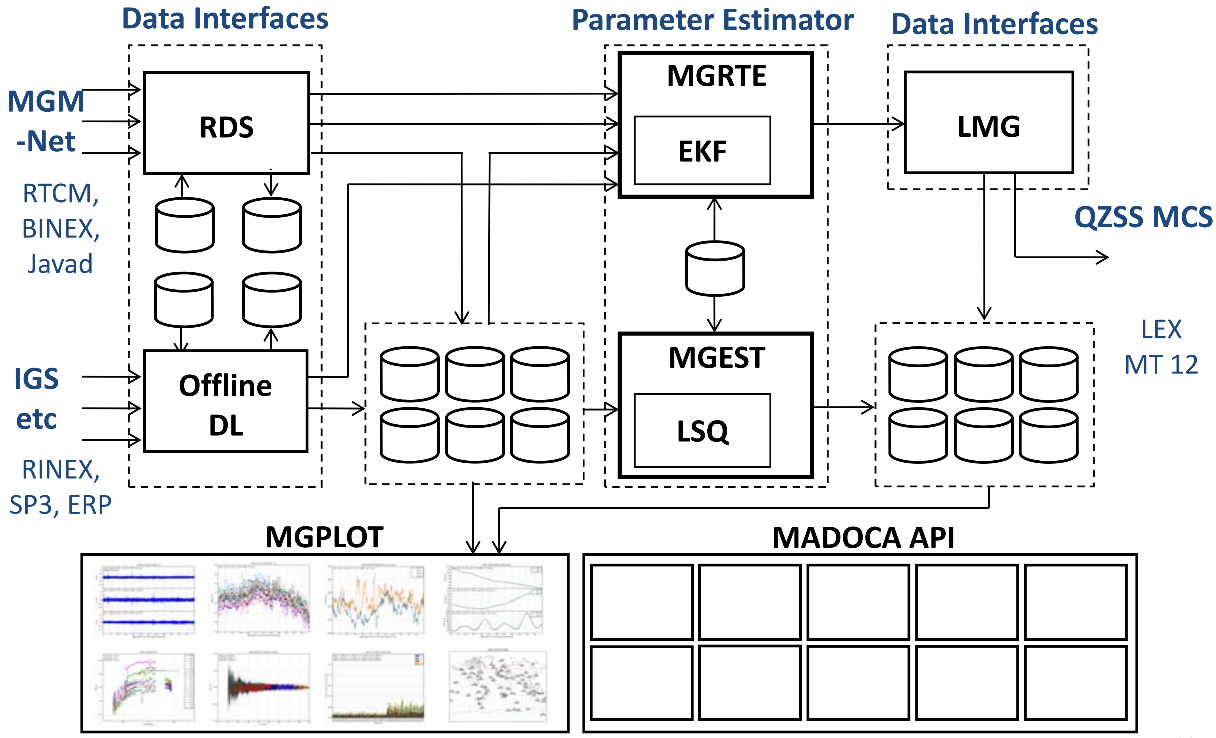


MADOCA (1)

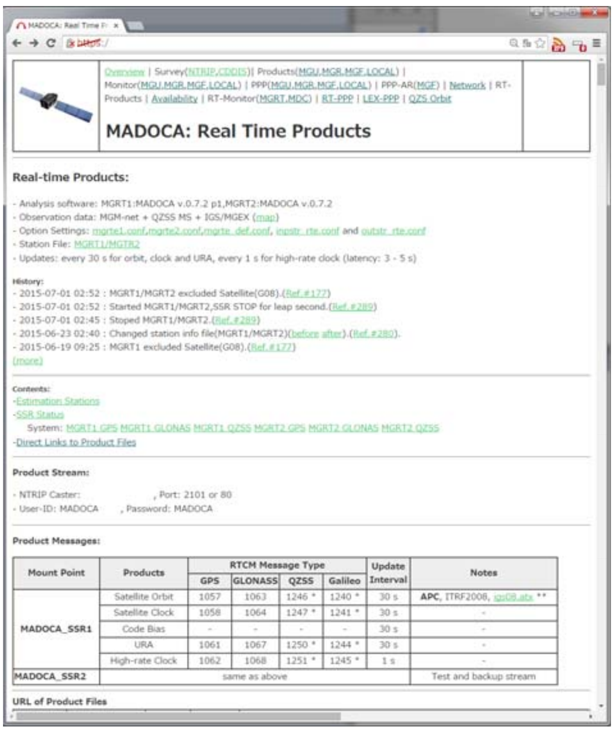
Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis

- **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

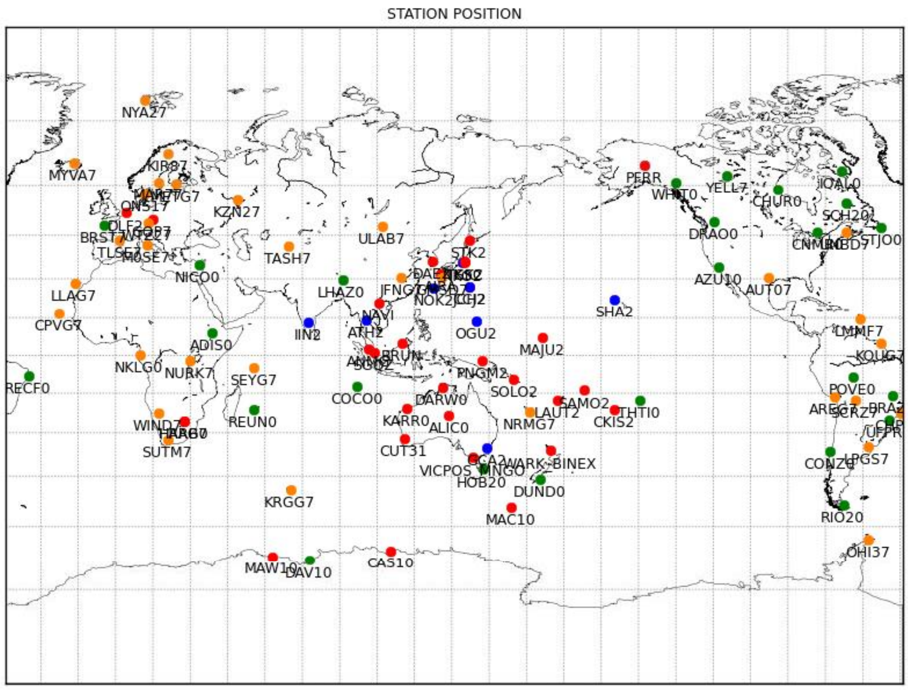
MADOCA (2)



MADOCA (3)

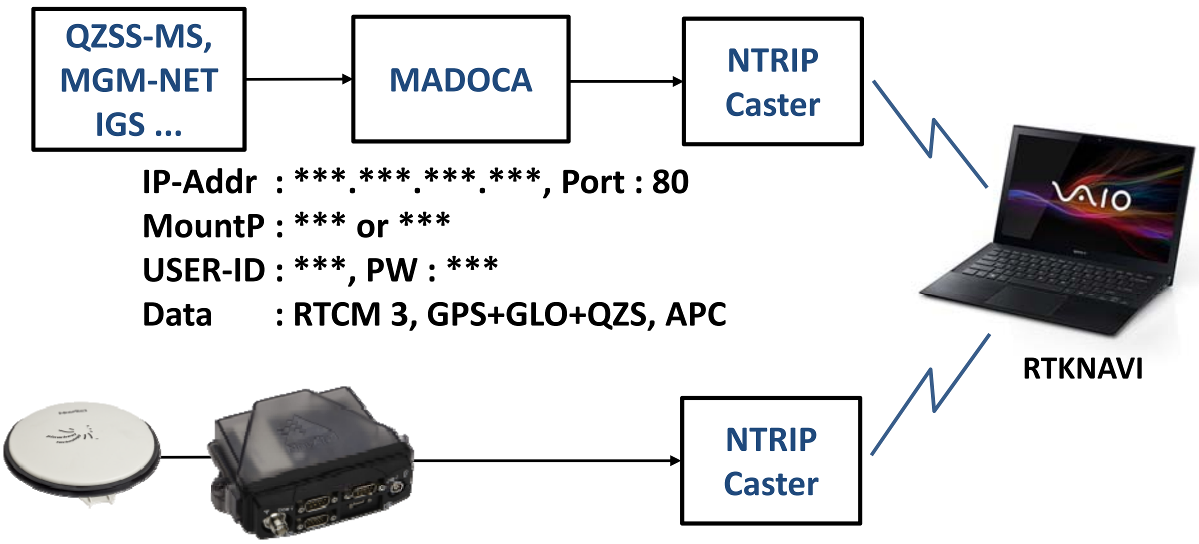


MADOCA (4)



- QZSS-MS • MGM-Net • IGS • MGEX

PPP Setup (1)



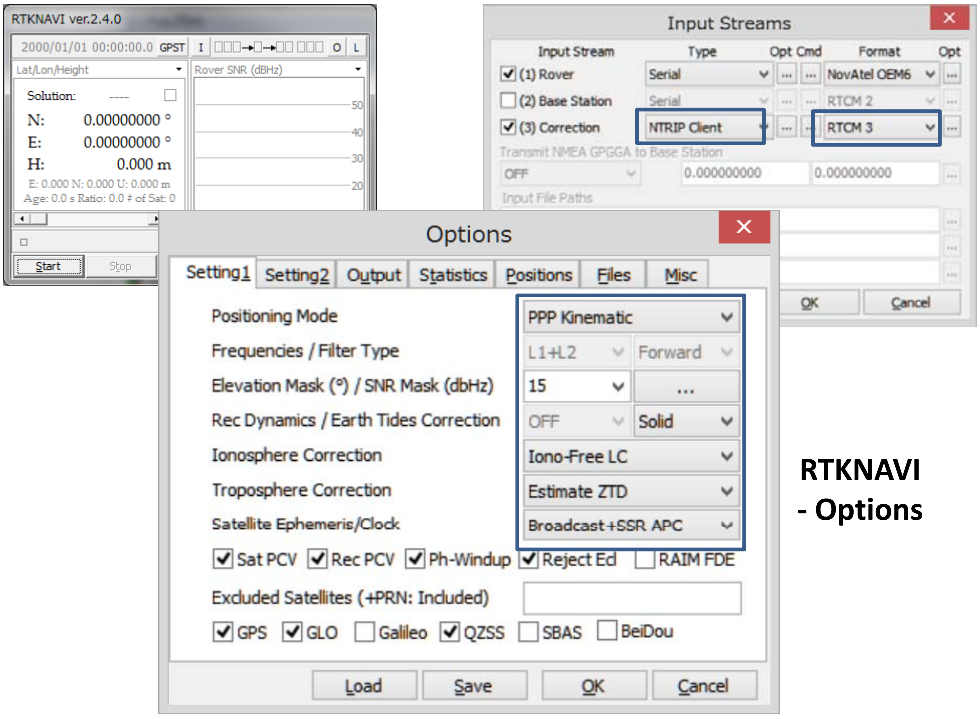
IP-Addr : *.***.***.***, Port : 80**
MountP : * or *****
USER-ID : *, PW : *****
Data : RTCM 3, GPS+GLO+QZS, APC

IP-Addr : *.***.***.***, Port : 80**
MountP : ***
USER-ID : *, PW : *****
Data : NovAtel OEM6

PPP Setup (2)

RTKNAVI

RTKNAVI - Input Streams



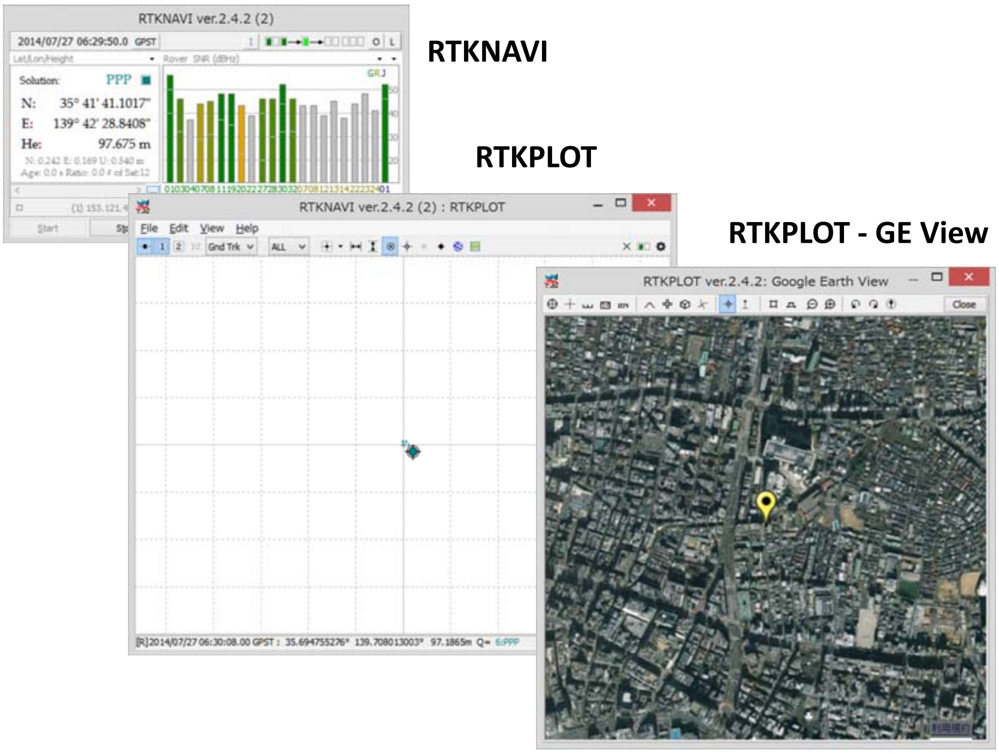
RTKNAVI - Options

PPP Setup (3)

RTKNAVI

RTKPLOT

RTKPLOT - GE View



RTKLIB Practice (MADOCA-PPP)