2019年度測位航法学会 全国大会 セミナー②

RTKおよびPPP技術の基礎と実習

Tokyo Univ. of Marine Science and Technology (TUMSAT)

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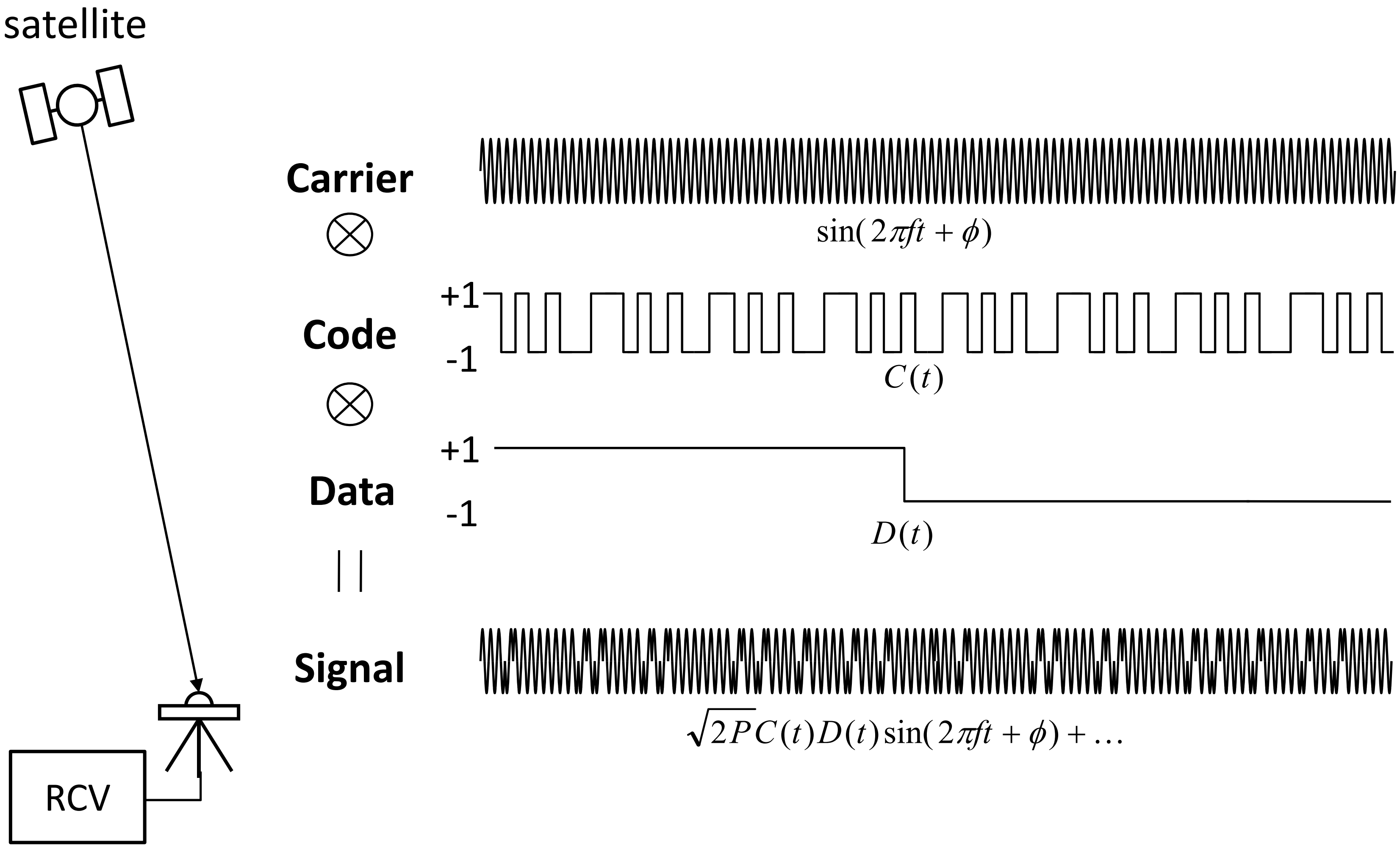
2019-05-15 @東京海洋大学 越中島

Timetable

		May 15, 2019
1	Theory of PP (precise positioning)	9:30-10:10
2	RTK Basics	10:10-10:50
3	RTK Practice	11:00-12:30
	Lunch Break	12:30-13:30
4	PPP Basics	13:30-14:10
5	PPP Practice	14:20-16:00
6	Advanced Topics of PP	16:10-16:30

1 Theory of PP
(precise positioning)

GNSS Signal Structure

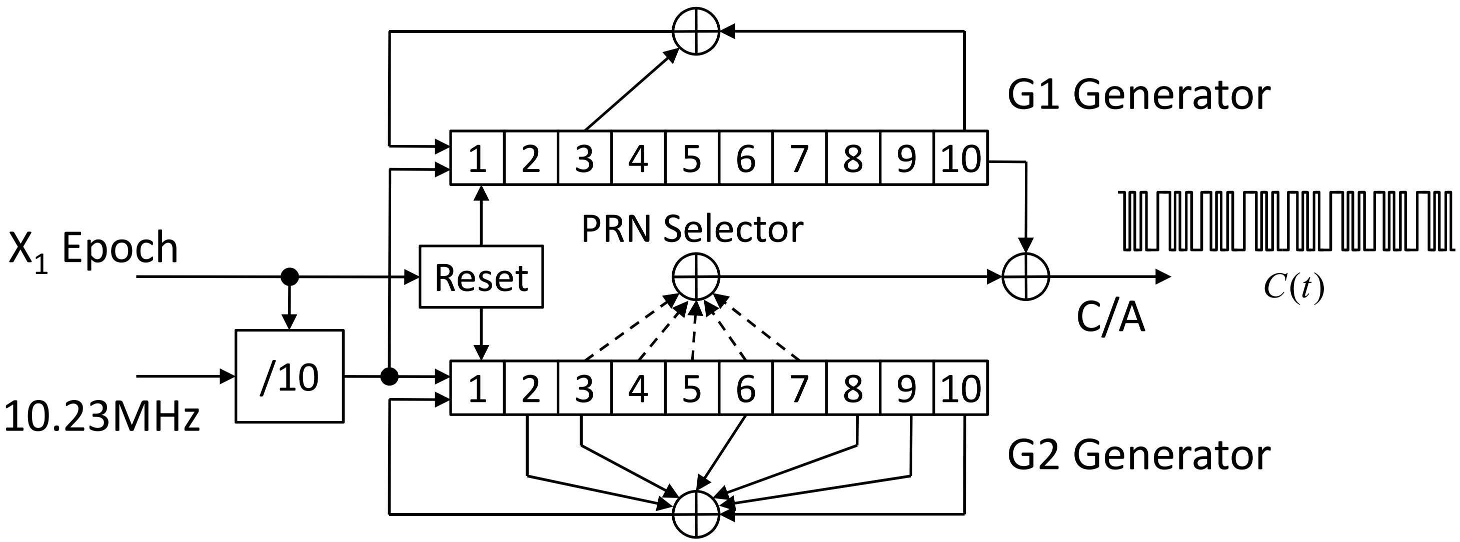


GNSS Signal Specifications

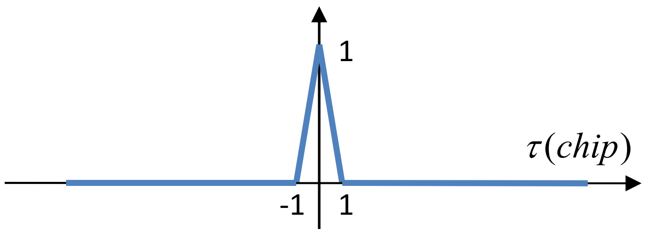
Carrier Freq (MHz)		Code	Modulation	Data Rate	GNSS
L1/E1	**1575.42**	**C/A**	**BPSK (1)**	**50 bps**	**GPS**, QZSS
				250 bps	QZSS (L1-SAIF), SBAS
		P(Y)	BPSK (10)	50 bps	GPS
		L1C-d/p	MBOC (6,1,1/11)	-/100 bps	GPS (III-), Galileo
		L1C-d/p	BOC (1,1)	-/100 bps	QZSS
L1	1602+0.5625K	C/A	BPSK	50 bps	GLONASS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

PRN Code Generator

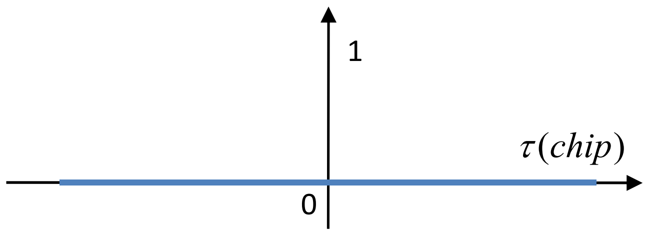


Auto-correlation function



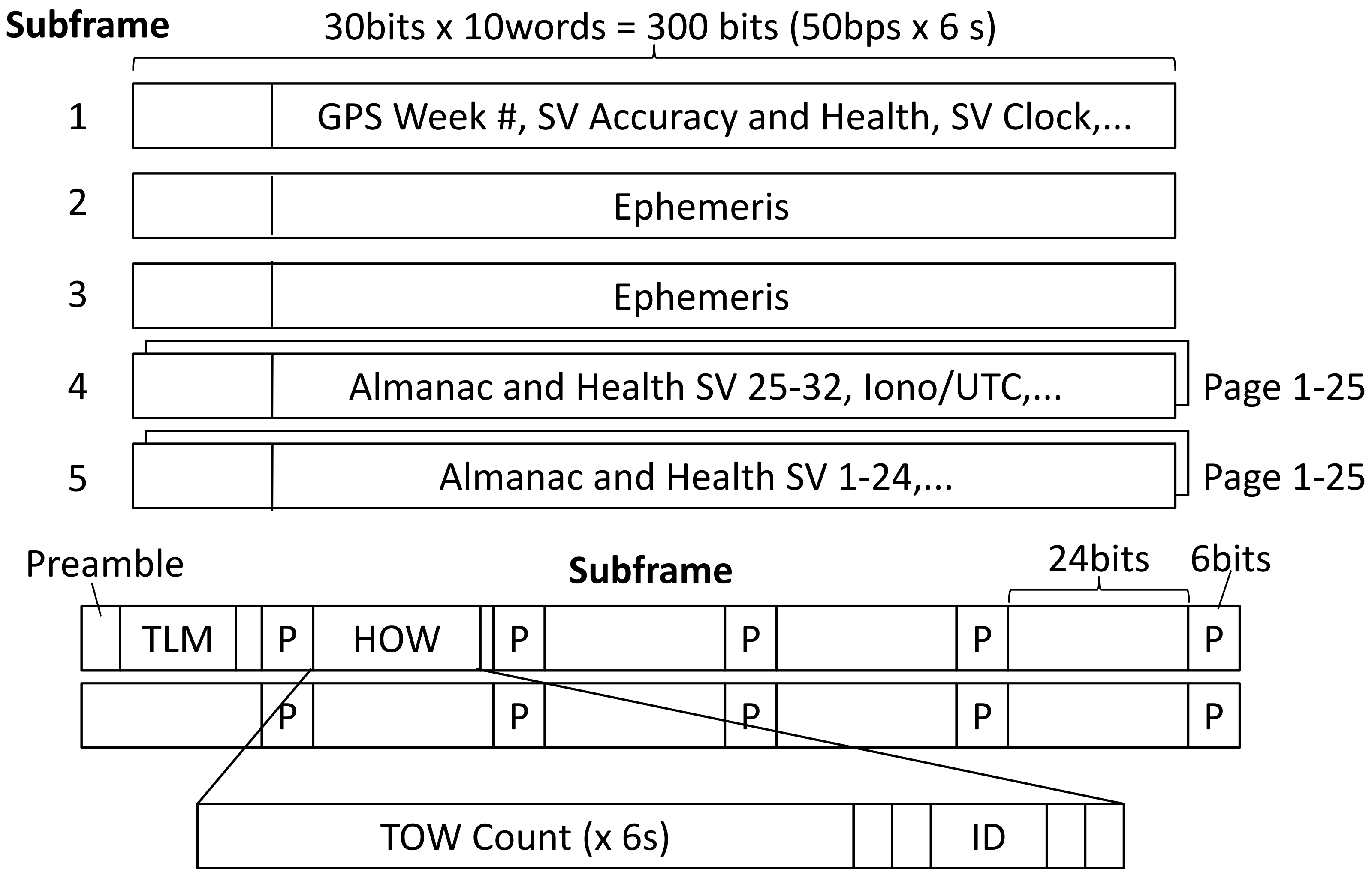
$$R(\tau) = \frac{1}{T}\int_0^T C^i(t)C^i(t-\tau)dt$$

Cross-correlation function

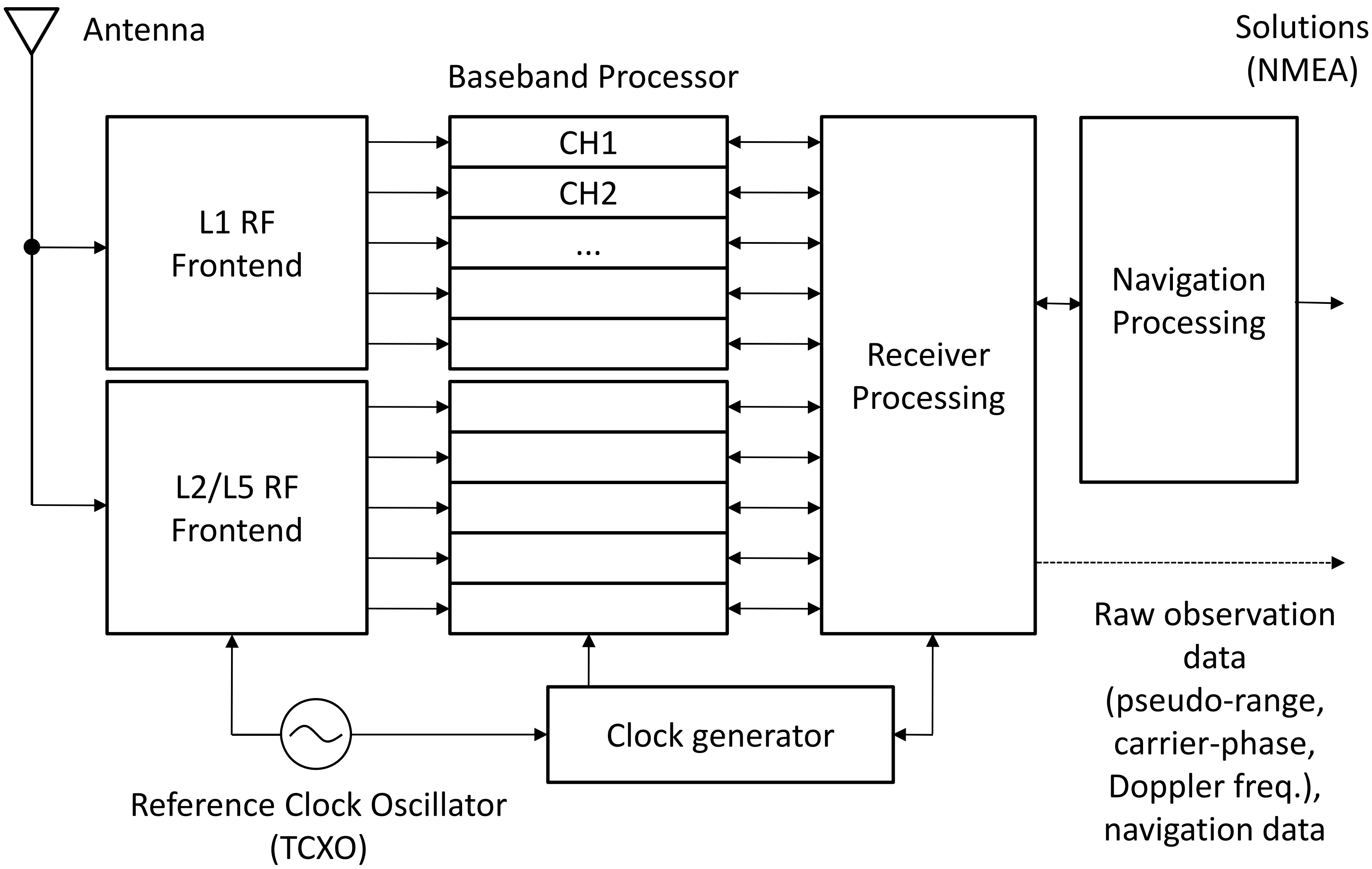


$$R(\tau) = \frac{1}{T}\int_0^T C^i(t)C^j(t-\tau)dt \quad (i \neq j)$$

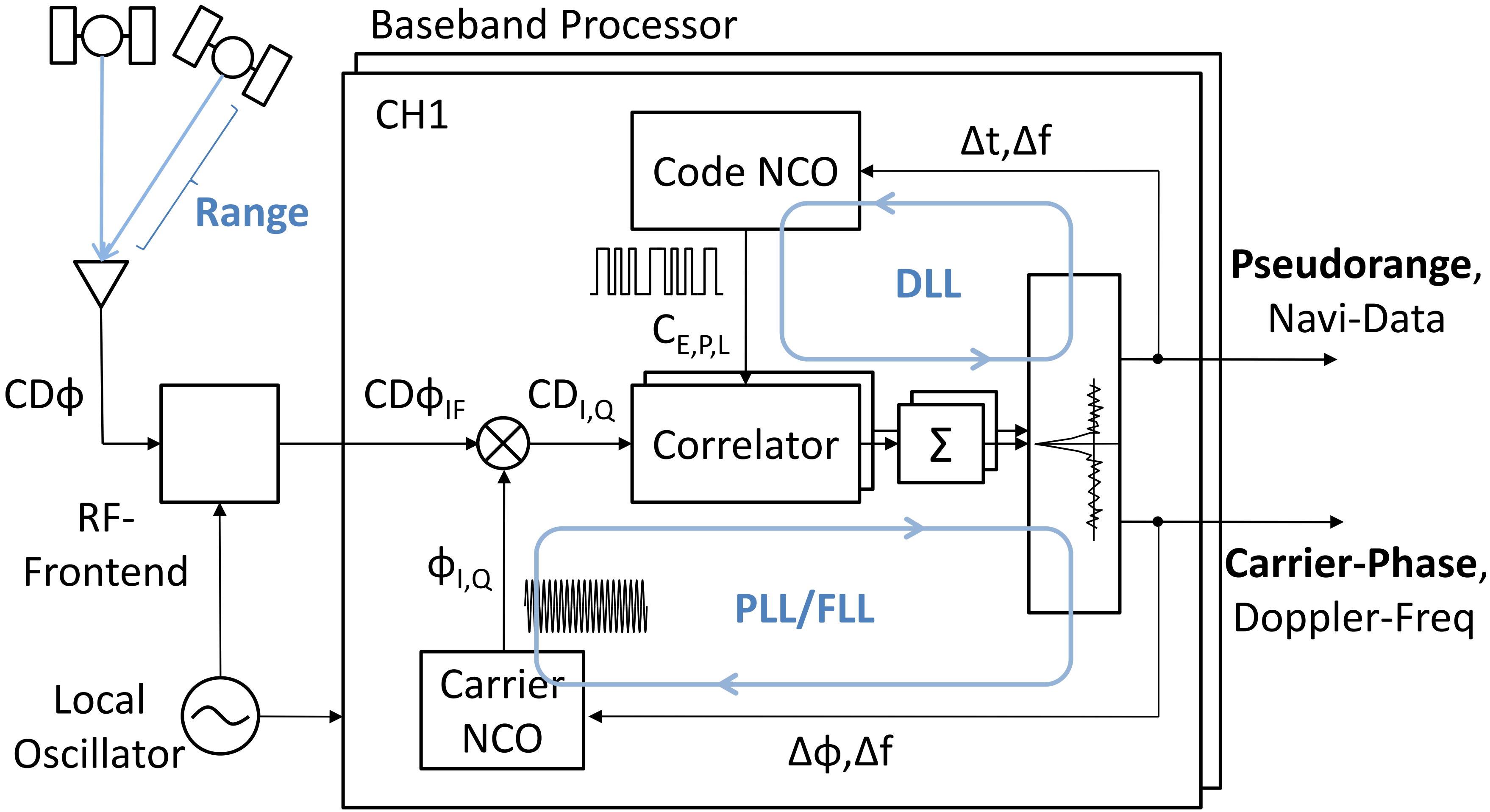
Navigation Data (GPS LNAV)



Receiver Functional Diagram



Carrier/Code Tracking in Receiver



Receiver and Navigation Processing

- **Receiver processing**
  - Acquisition : Doppler-freq/code-phase search
  - Code tracking : DLL (Delay Lock Loop)
  - Carrier tracking : PLL/FLL (Phase/Freq Lock Loop)
  - Decode navigation data
  - Generation of pseudorange and carrier-phase
- **Navigation processing**
  - Positioning algorithms (single, DGPS, RTK, ...)
  - Coordinates transformation
  - I/O message handling (NMEA, RTCM, ...)

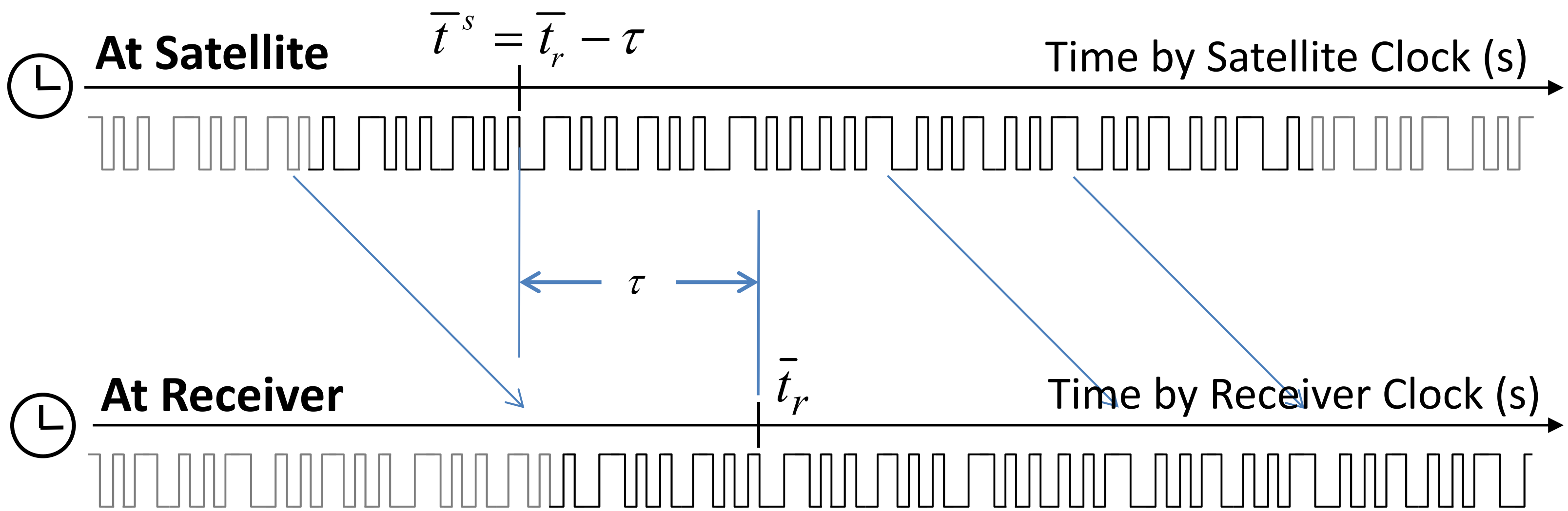
Pseudorange

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)*



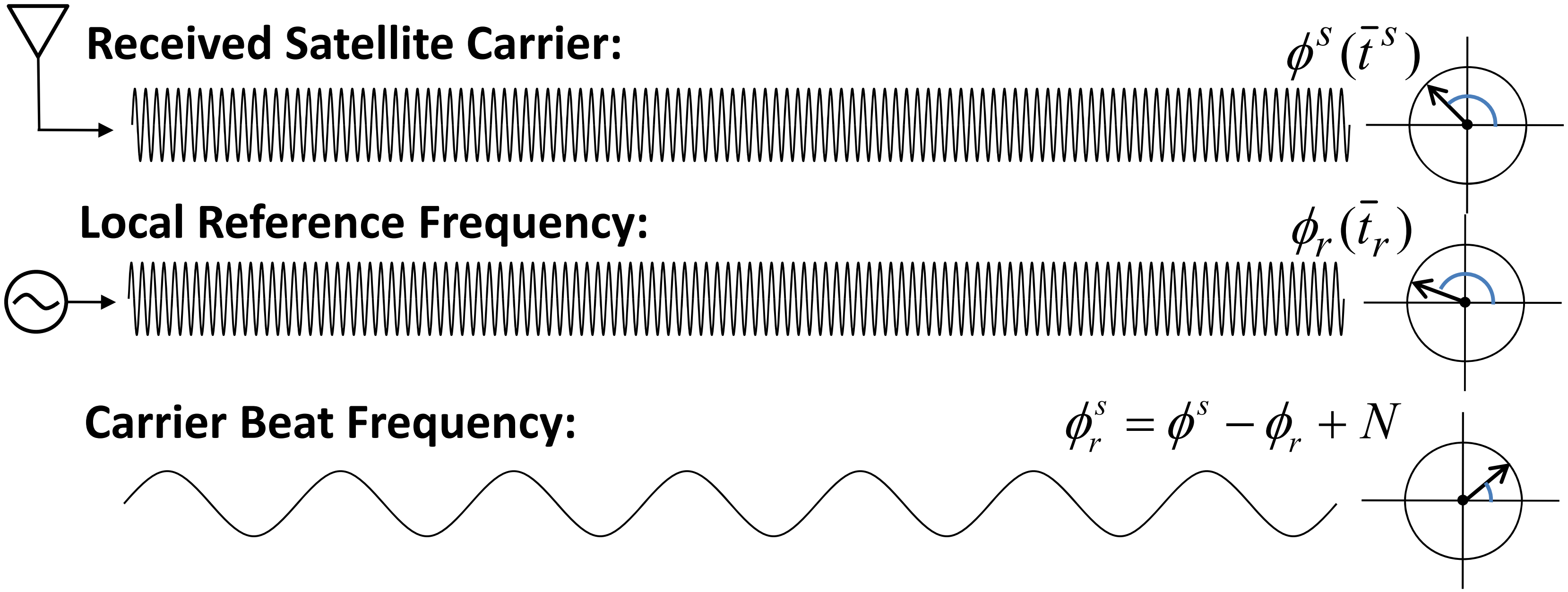
Carrier-Phase

Definition:

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

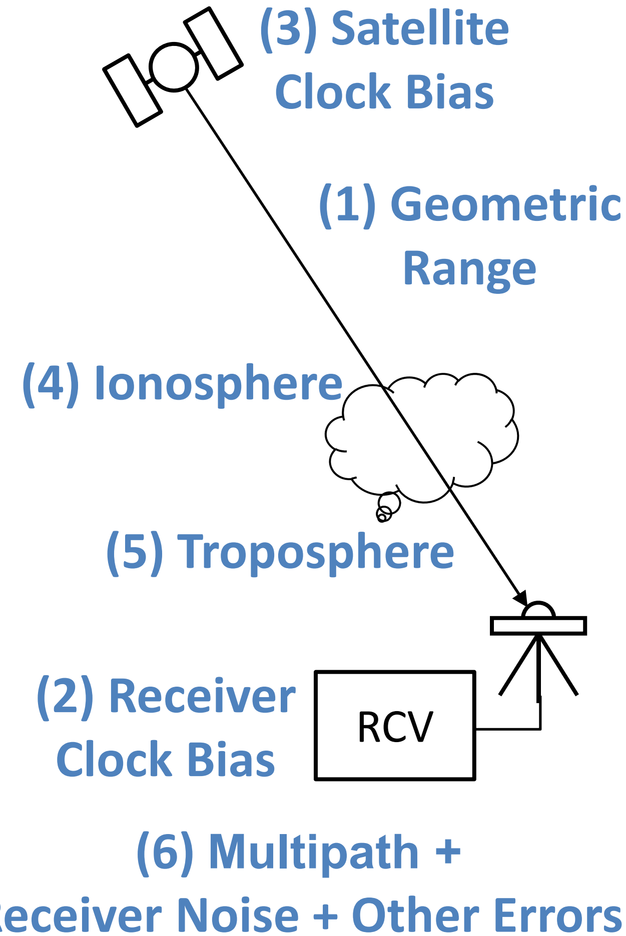
(cycle)

... 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)*



Pseudorange Model

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

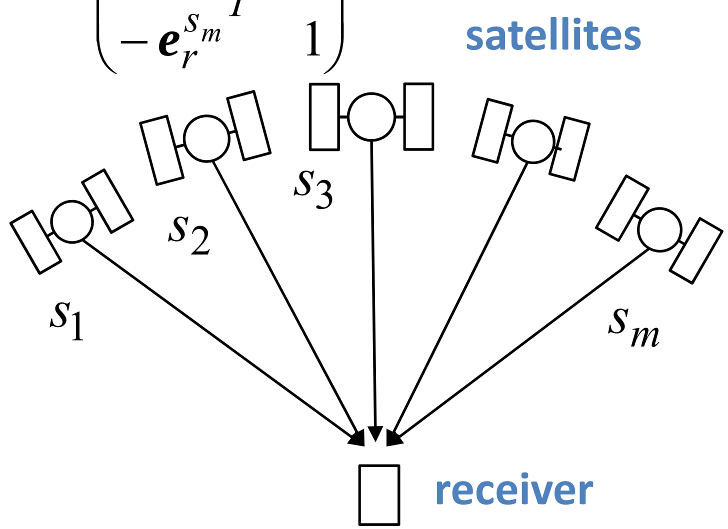


SD (standard positionig)

$$\boldsymbol{x} = (\boldsymbol{r}_r{}^T, cdt)^T, \quad \boldsymbol{y} = (P_r^{s_1}, P_r^{s_2}, P_r^{s_3}, \ldots, P_r^{s_m})^T$$ pseudo-ranges

$$\boldsymbol{h}(\hat{\boldsymbol{x}}) = \begin{pmatrix} \rho_r^{s_1} + c\hat{d}t - cdT^{s_1} + I_r^{s_1} + T_r^{s_1} \\ \rho_r^{s_2} + c\hat{d}t - cdT^{s_2} + I_r^{s_2} + T_r^{s_2} \\ \rho_r^{s_3} + c\hat{d}t - cdT^{s_3} + I_r^{s_3} + T_r^{s_3} \\ \vdots \\ \rho_r^{s_m} + c\hat{d}t - cdT^{s_m} + I_r^{s_m} + T_r^{s_m} \end{pmatrix} \quad \boldsymbol{H} = \begin{pmatrix} -\boldsymbol{e}_r^{s_1}{}^T & 1 \\ -\boldsymbol{e}_r^{s_2}{}^T & 1 \\ -\boldsymbol{e}_r^{s_3}{}^T & 1 \\ \vdots & \vdots \\ -\boldsymbol{e}_r^{s_m}{}^T & 1 \end{pmatrix}$$

range | receiver clock | satellite clock



$$\hat{\boldsymbol{x}} = (\hat{\boldsymbol{r}}_r{}^T, c\hat{d}t)^T$$ solution

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

Code vs Carrier-Based Positioning

	SD (standard positioning, code-based)	**PP (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 Model (1)

Carrier-Phase:

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

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

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

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

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

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:

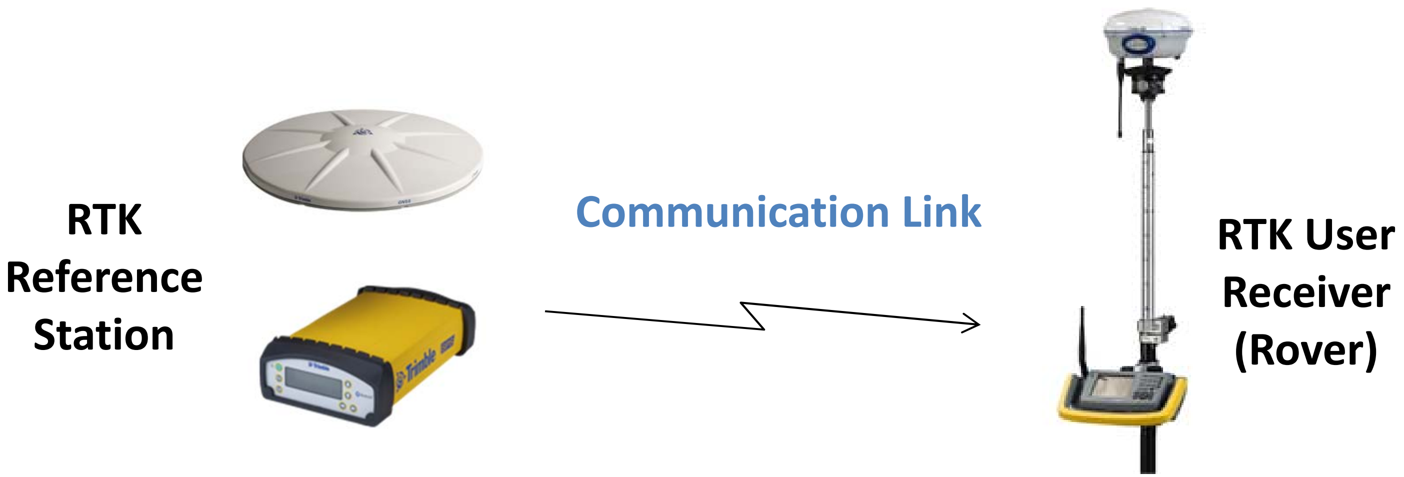
$$d_r^s = -\boldsymbol{d}_{r,pco}{}^T \boldsymbol{e}_{r,enu}^s + \left(\boldsymbol{E}_{sat \to ecef} \boldsymbol{d}_{pco}^s\right)^T \boldsymbol{e}_r^s + d_{r,pcv} + d_{pcv}^s - \boldsymbol{d}_{disp}{}^T \boldsymbol{e}_{r,enu}^s$$
$$+ d_{pw} + d_{rel} \qquad \text{(m)}$$

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

2 RTK Basics

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)



RTK Applications

Geodetic Survey

Construction Machine Control

Precision Agriculture

Self-driving Car

Mapping

UAV (Drone)

RTK Algorithm (1)

Carrier-Phase:

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

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

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

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

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

Carrier-Phase Bias (λB_r^s)   **Other Correction Terms** (d_r^s)

Carrier-Phase Bias:

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

N_r^s : **Integer Ambiguity**

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

ϕ_0^s : Satellite Initial Phase

RTK Algorithm (2)

DD (Double-difference) :

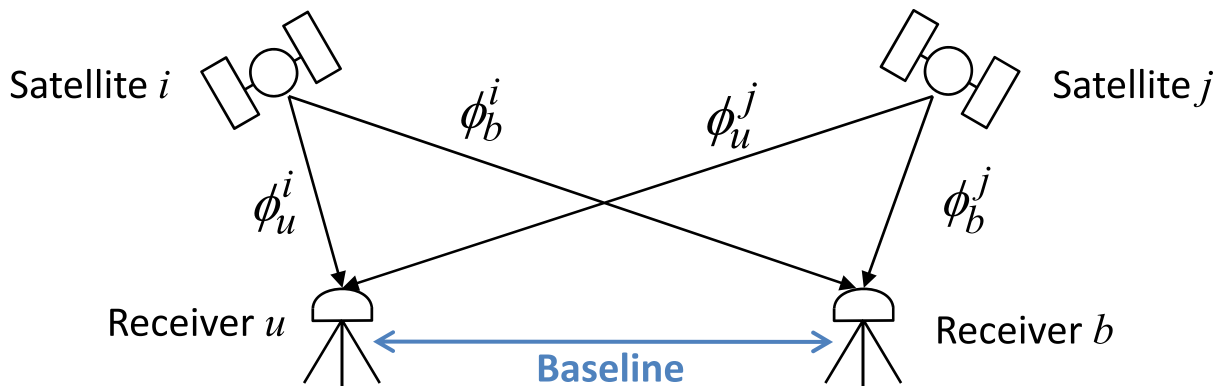
$$\begin{aligned}\Phi_{ub}^{ij} &\equiv \lambda((\phi_u^i - \phi_b^i) - (\phi_u^j - \phi_b^j)) \\ &= \rho_{ub}^{ij} + c(dt_{ub}^{ij} - dT_{ub}^{ij}) - I_{ub}^{ij} + T_{ub}^{ij} + \lambda B_{ub}^{ij} + d_{ub}^{ij} + \varepsilon_{\Phi} \\ &= \rho_{ub}^{ij} - I_{ub}^{ij} + T_{ub}^{ij} + \lambda N_{ub}^{ij}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

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

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

(short Baseline and same antenna type)

$$\Phi_{ub}^{ij} \approx \rho_{ub}^{ij} + \lambda N_{ub}^{ij} + \varepsilon_{\Phi} \quad I_{ub}^{ij} = I_{ub}^i - I_{ub}^j \approx 0, T_{ub}^{ij} = T_{ub}^i - T_{ub}^j \approx 0, d_{ub}^{ij} = d_{ub}^i - d_{ub}^j \approx 0$$



RTK Algorithm (3)

Nonlinear-LSE:

Parameter Vector:

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

Measurement Vector:

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

Meas Model, Design Matrix:

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

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

Meas Error Covariance:

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

Solution (Static/Float):

$$\hat{x} = x_0 + (H^T R^{-1} H)^{-1} H^T R^{-1} (y - h(x_0))$$

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

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

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

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

r_b : Fixed Base-Station Position

Integer Ambiguity Resolution

ILS problem:

$$x = (a^T, b^T)^T,\ H = (A, B)$$
$$y = Hx + v = Aa + Bb + v$$
$$\breve{x} = \underset{a \in Z^n, b \in R^m}{\arg\min}\ (y - Hx)^T Q_y^{-1} (y - Hx)$$

Strategy to solve it:

(1) Conventional LSE

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

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

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

(3) Improve solution

$$\breve{b} = \hat{b} - Q_{ba} Q_a^{-1} (\hat{a} - \breve{a})$$

ILS: Integer Least Square

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

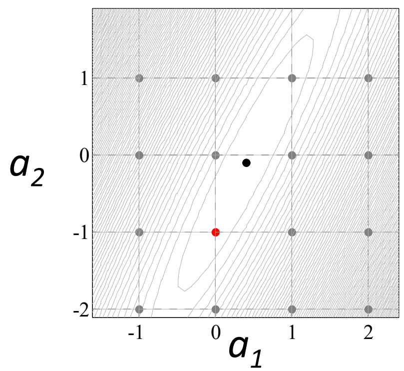
$$\breve{\boldsymbol{a}} = \underset{\boldsymbol{a}\in \boldsymbol{Z}^n}{\operatorname{argmin}} (\hat{\boldsymbol{a}} - \boldsymbol{a})^T \boldsymbol{Q}_a^{-1} (\hat{\boldsymbol{a}} - \boldsymbol{a})$$

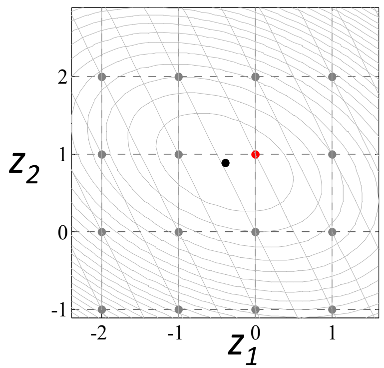
⇔

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

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

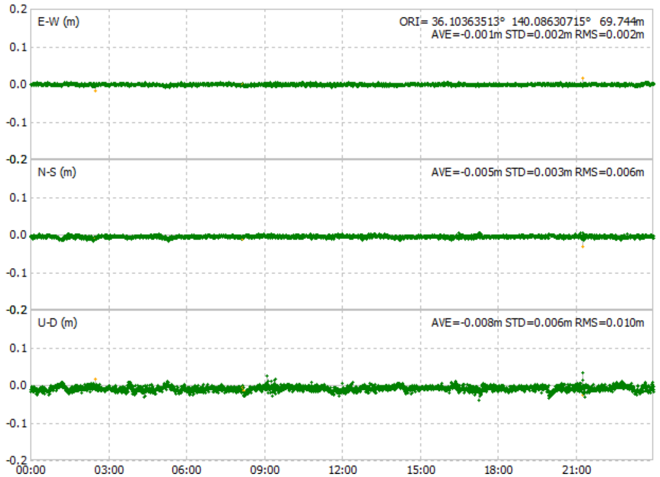
$$\breve{\boldsymbol{a}} = \boldsymbol{Z}^{-T} \breve{\boldsymbol{z}}$$





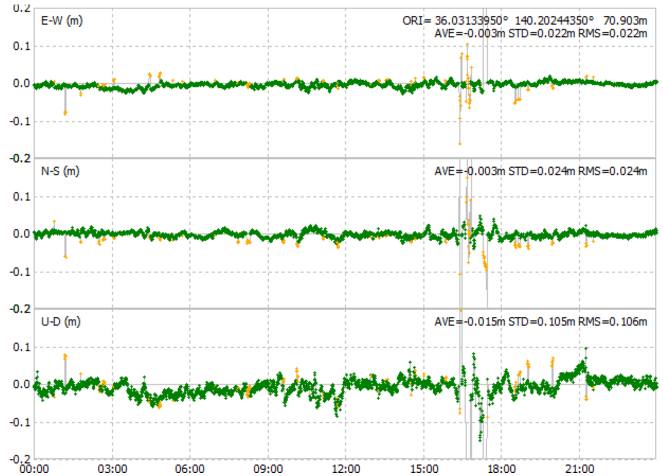
Effect of Baseline Length

BL=0.3 km



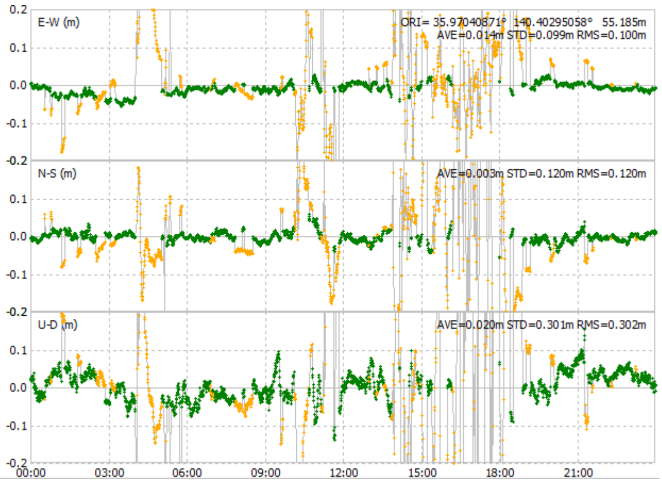
RMS Error:
E: 0.2cm
N: 0.6cm
U: 1.0cm
Fix Ratio:
99.9%

BL=13.3 km



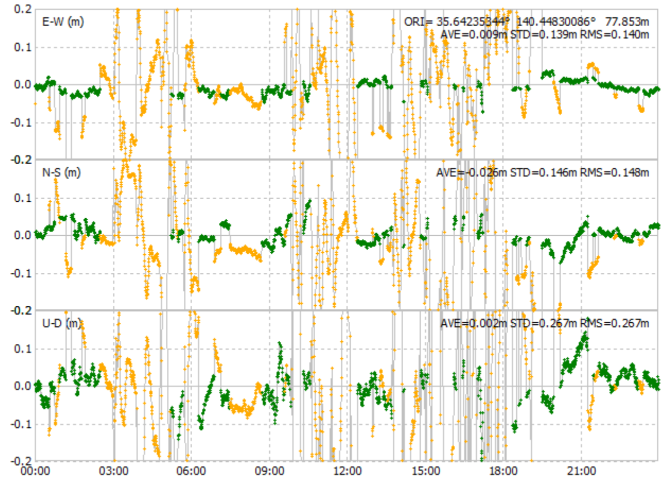
RMS Error:
E: 2.2cm
N: 2.4cm
U: 10.6cm
Fix Ratio:
94.2%

BL=32.2 km



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

BL=60.9 km



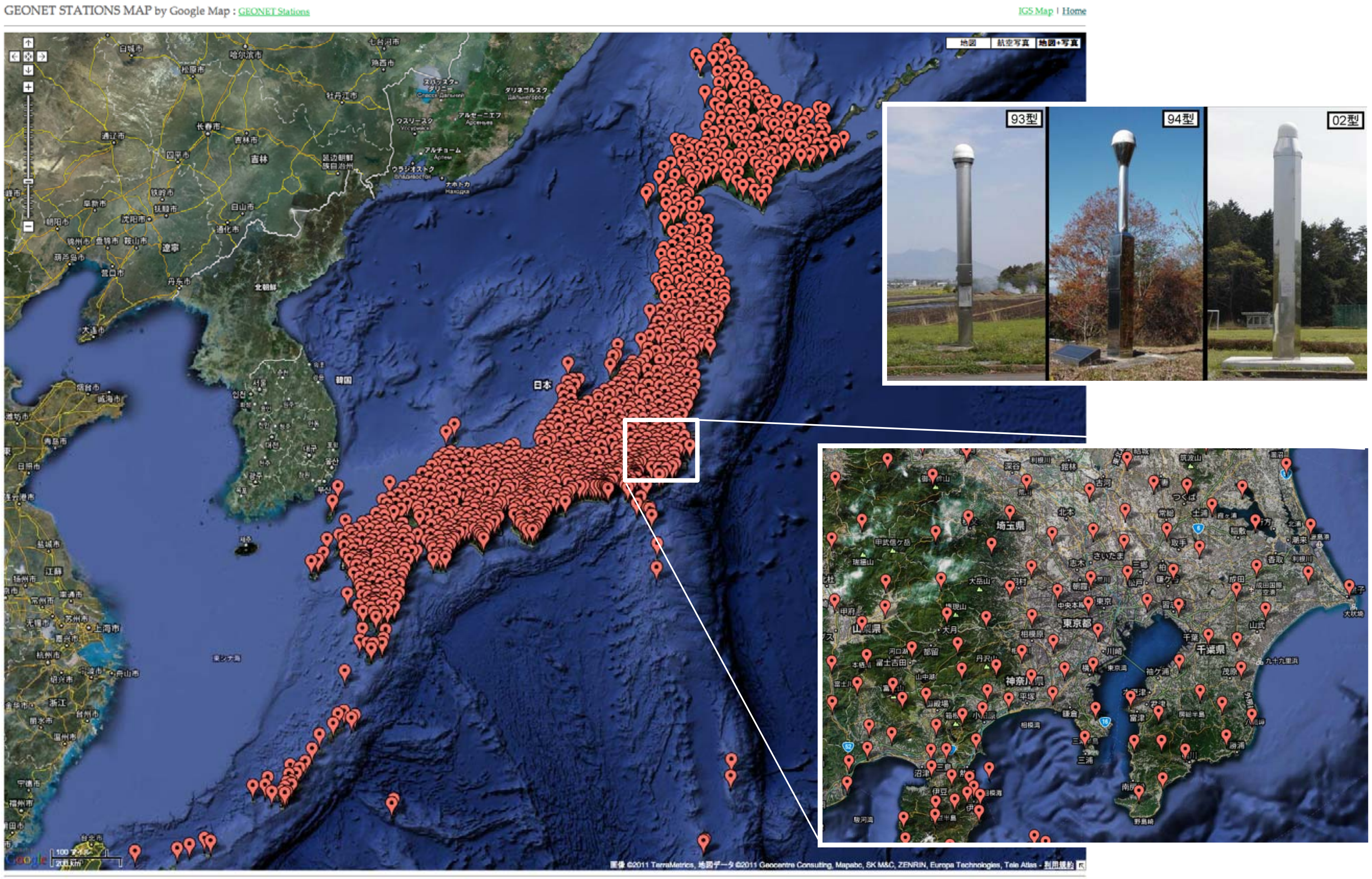
RMS Error:
E: 14.0cm
N: 14.8cm
U: 26.7cm
Fix Ratio:
44.4%

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

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 3.2
  - Server S/W: Trimble GPSNet, GEO++ GNSMART, ...
  - NTRIP Networked Transport of RTCM via Internet Protocol
- **NRTK Service in Japan**
  - GEONET: ~1300 Reference Stations by GSI
  - NGDS (www.gpsdata.co.jp), JENOBA (www.jenoba.jp), Nihon Terasat (www.terasat.co.jp)

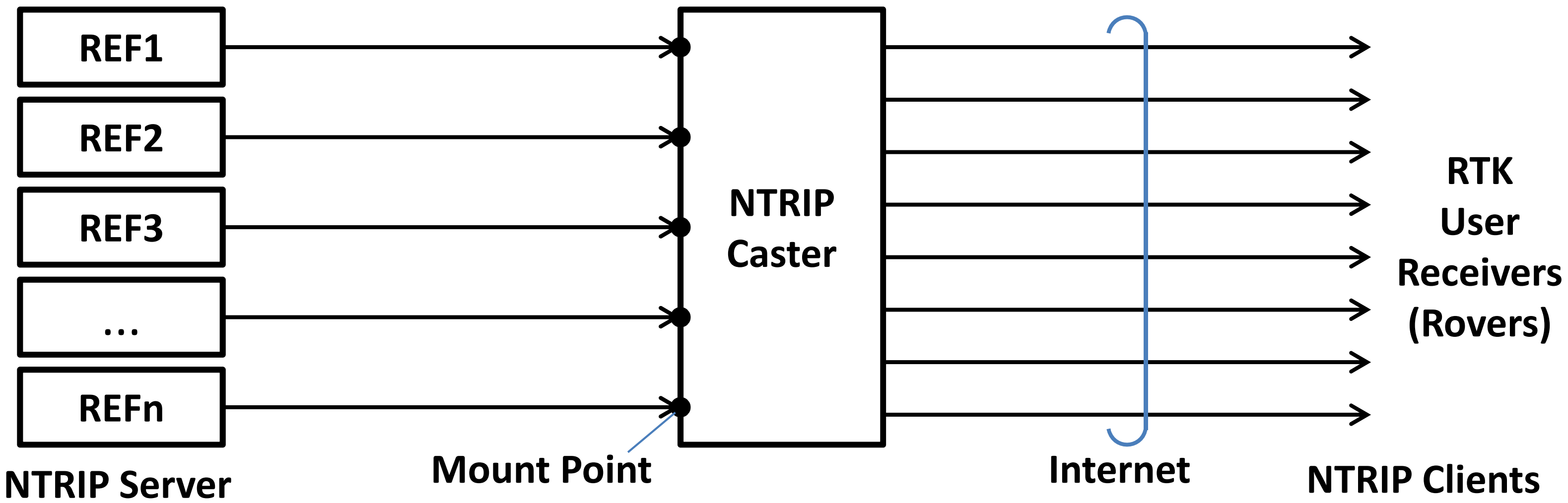
Japanese GEONET

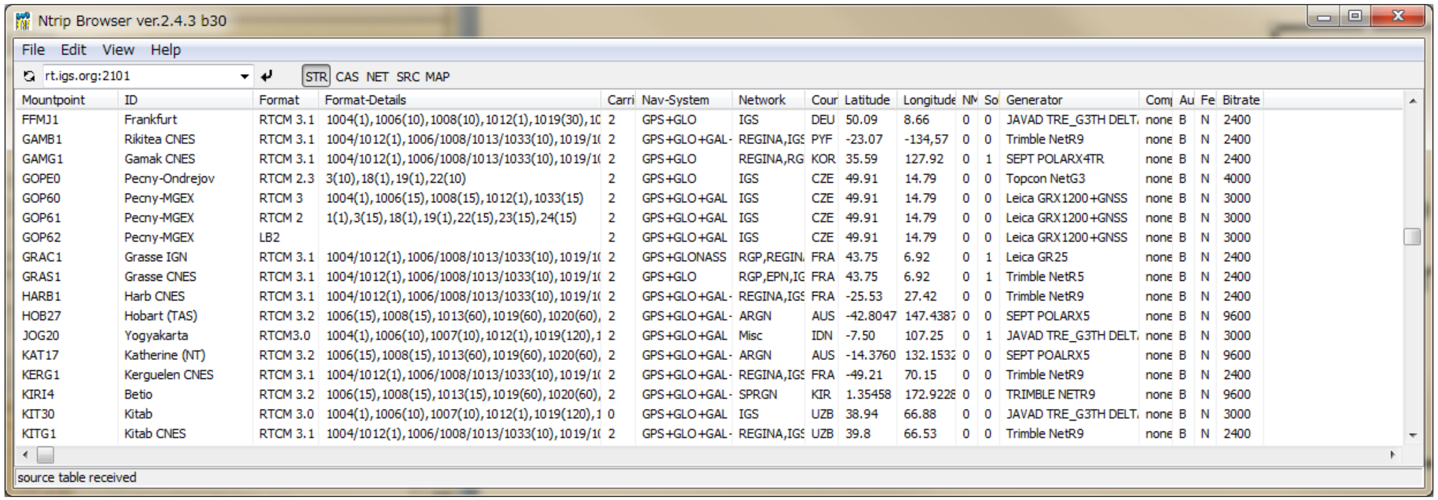


(http://terras.gsi.go.jp/ja/index.htm)

NTRIP

- **Networked Transport of RTCM via Internet Protocol**





Ntrip Browser ver.2.4.3 b30

File Edit View Help

rt.igs.org:2101 STR CAS NET SRC MAP

Mountpoint	ID	Format	Format-Details	Carri	Nav-System	Network	Cour	Latitude	Longitude	NM	So	Generator	Comp	Au	Fe	Bitrate
FFMJ1	Frankfurt	RTCM 3.1	1004(1),1006(10),1008(10),1012(1),1019(30),10	2	GPS+GLO	IGS	DEU	50.09	8.66	0	0	JAVAD TRE_G3TH DELT.	none	B	N	2400
GAMB1	Rikitea CNES	RTCM 3.1	1004/1012(1),1006/1008/1013/1033(10),1019/1	2	GPS+GLO+GAL-	REGINA,IGS	PYF	-23.07	-134,57	0	0	Trimble NetR9	none	B	N	2400
GAMG1	Gamak CNES	RTCM 3.1	1004/1012(1),1006/1008/1013/1033(10),1019/1	2	GPS+GLO	REGINA,RG	KOR	35.59	127.92	0	1	SEPT POLARX4TR	none	B	N	2400
GOPE0	Pecny-Ondrejov	RTCM 2.3	3(10),18(1),19(1),22(10)	2	GPS+GLO	IGS	CZE	49.91	14.79	0	0	Topcon NetG3	none	B	N	4000
GOP60	Pecny-MGEX	RTCM 3	1004(1),1006(15),1008(15),1012(1),1033(15)	2	GPS+GLO+GAL	IGS	CZE	49.91	14.79	0	0	Leica GRX1200+GNSS	none	B	N	3000
GOP61	Pecny-MGEX	RTCM 2	1(1),3(15),18(1),19(1),22(15),23(15),24(15)	2	GPS+GLO+GAL	IGS	CZE	49.91	14.79	0	0	Leica GRX1200+GNSS	none	B	N	3000
GOP62	Pecny-MGEX	LB2		2	GPS+GLO+GAL	IGS	CZE	49.91	14.79	0	0	Leica GRX1200+GNSS	none	B	N	3000
GRAC1	Grasse IGN	RTCM 3.1	1004/1012(1),1006/1008/1013/1033(10),1019/1	2	GPS+GLONASS	RGP,REGIN.	FRA	43.75	6.92	0	1	Leica GR25	none	B	N	2400
GRAS1	Grasse CNES	RTCM 3.1	1004/1012(1),1006/1008/1013/1033(10),1019/1	2	GPS+GLO	RGP,EPN,IG	FRA	43.75	6.92	0	1	Trimble NetR5	none	B	N	2400
HARB1	Harb CNES	RTCM 3.1	1004/1012(1),1006/1008/1013/1033(10),1019/1	2	GPS+GLO+GAL-	REGINA,IGS	FRA	-25.53	27.42	0	0	Trimble NetR9	none	B	N	2400
HOB27	Hobart (TAS)	RTCM 3.2	1006(15),1008(15),1013(60),1019(60),1020(60),	2	GPS+GLO+GAL-	ARGN	AUS	-42.8047	147.4387	0	0	SEPT POLARX5	none	B	N	9600
JOG20	Yogyakarta	RTCM3.0	1004(1),1006(10),1007(10),1012(1),1019(120),1	2	GPS+GLO+GAL	Misc	IDN	-7.50	107.25	0	1	JAVAD TRE_G3TH DELT.	none	B	N	3000
KAT17	Katherine (NT)	RTCM 3.2	1006(15),1008(15),1013(60),1019(60),1020(60),	2	GPS+GLO+GAL-	ARGN	AUS	-14.3760	132.1532	0	0	SEPT POALRX5	none	B	N	9600
KERG1	Kerguelen CNES	RTCM 3.1	1004/1012(1),1006/1008/1013/1033(10),1019/1	2	GPS+GLO+GAL-	REGINA,IGS	FRA	-49.21	70.15	0	0	Trimble NetR9	none	B	N	2400
KIRI4	Betio	RTCM 3.2	1006(15),1008(15),1013(15),1019(60),1020(60),	2	GPS+GLO+GAL-	SPRGN	KIR	1.35458	172.9228	0	0	TRIMBLE NETR9	none	B	N	9600
KIT30	Kitab	RTCM 3.0	1004(1),1006(10),1007(10),1012(1),1019(120),1	0	GPS+GLO+GAL	IGS	UZB	38.94	66.88	0	0	JAVAD TRE_G3TH DELT.	none	B	N	3000
KITG1	Kitab CNES	RTCM 3.1	1004/1012(1),1006/1008/1013/1033(10),1019/1	2	GPS+GLO+GAL-	REGINA,IGS	UZB	39.8	66.53	0	0	Trimble NetR9	none	B	N	2400

source table received

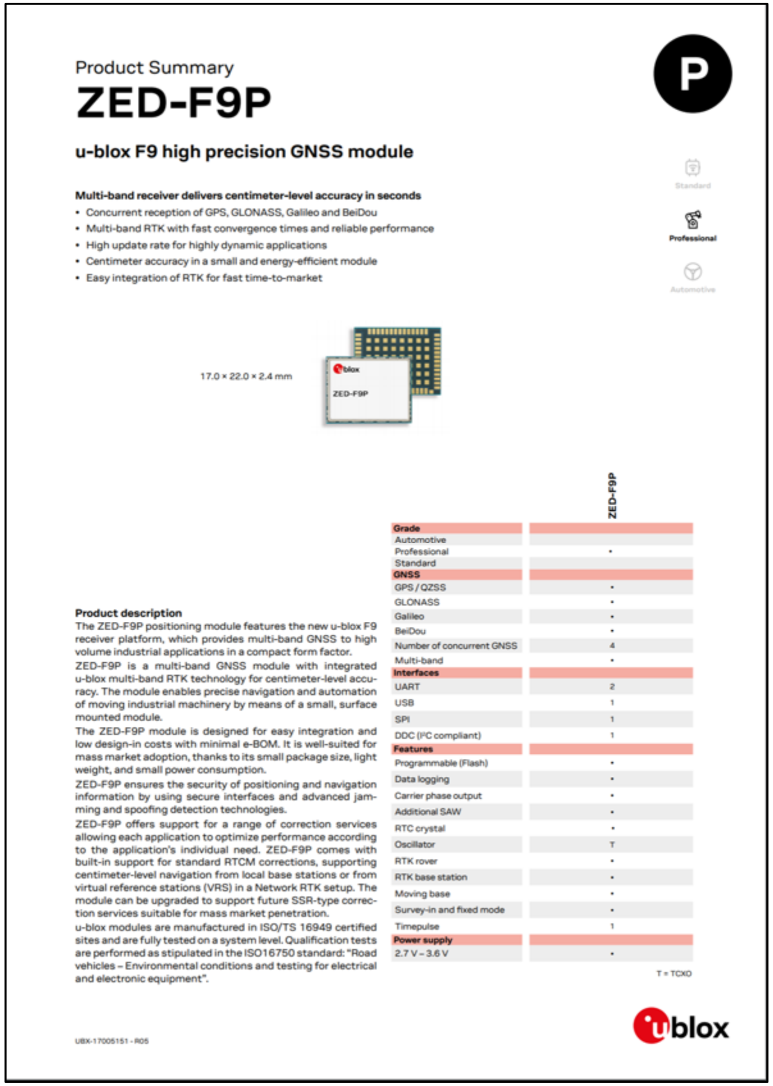
RTCM 3.3 OBS, MSM, NAV, ANT

Message		GPS	GLOASS	Galileo	QZSS	BeiDou	SBAS
OBS	Compact L1	1001	1009	-	-	-	-
	Full L1	1002	1010	-	-	-	-
	Compact L1/2	1003	1011	-	-	-	-
	Full L1/2	1004	1012	-	-	-	-
Ephemeris		1019	1020	1045/6	1044	1042	-
MSM	1	1071	1081	1091	1111	1121	1101
	2	1072	1082	1092	1112	1122	1102
	3	1073	1083	1093	1113	1123	1103
	4	1074	1084	1094	1114	1124	1104
	5	1075	1085	1095	1115	1125	1105
	6	1076	1086	1096	1116	1126	1106
	7	1077	1087	1097	1117	1127	1107
SSR	Orbit Corr.	1057	1063	1240*	1246*	1258*	1252*
	Clock Corr.	1058	1064	1241*	1247*	1259*	1253*
	Code Bias	1059	1065	1242*	1248*	1260*	1254*
	Combined	1060	1066	1243*	1249*	1261*	1255*
	URA	1061	1067	1244*	1250*	1262*	1256*
	HR-Clock	1062	1068	1245*	1251*	1263*	1257*
Antenna Info		1005 1006 1007 1008 1033					

* draft

3 RTK Practice

Receiver and Antenna



Product Summary

ZED-F9P

u-blox F9 high precision GNSS module

Multi-band receiver delivers centimeter-level accuracy in seconds

- Concurrent reception of GPS, GLONASS, Galileo and BeiDou
- Multi-band RTK with fast convergence times and reliable performance
- High update rate for highly dynamic applications
- Centimeter accuracy in a small and energy-efficient module
- Easy integration of RTK for fast time-to-market

17.0 × 22.0 × 2.4 mm

Product description

The ZED-F9P positioning module features the new u-blox F9 receiver platform, which provides multi-band GNSS to high volume industrial applications in a compact form factor.

ZED-F9P is a multi-band GNSS module with integrated u-blox multi-band RTK technology for centimeter-level accuracy. The module enables precise navigation and automation of moving industrial machinery by means of a small, surface mounted module.

The ZED-F9P module is designed for easy integration and low design-in costs with minimal e-BOM. It is well-suited for mass market adoption, thanks to its small package size, light weight, and small power consumption.

ZED-F9P ensures the security of positioning and navigation information by using secure interfaces and advanced jamming and spoofing detection technologies.

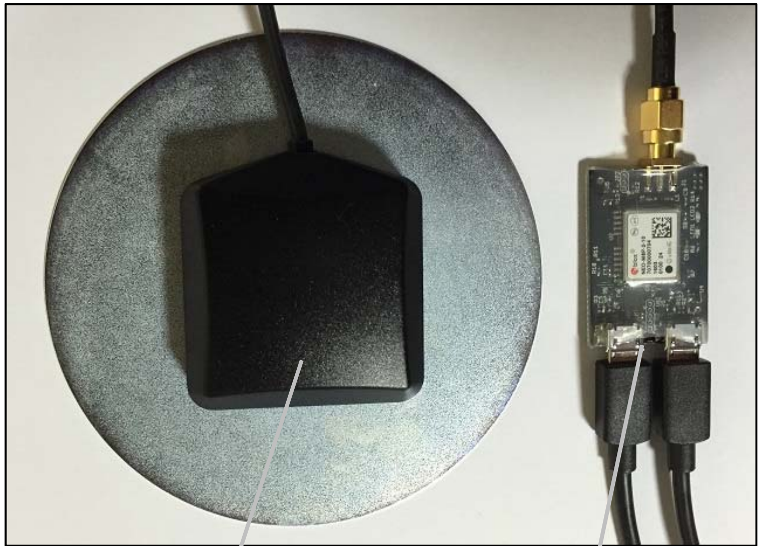
ZED-F9P offers support for a range of correction services allowing each application to optimize performance according to the application's individual need. ZED-F9P comes with built-in support for standard RTCM corrections, supporting centimeter-level navigation from local base stations or from virtual reference stations (VRS) in a Network RTK setup. The module can be upgraded to support future SSR-type correction services suitable for mass market penetration.

u-blox modules are manufactured in ISO/TS 16949 certified sites and are fully tested on a system level. Qualification tests are performed as stipulated in the ISO16750 standard: "Road vehicles – Environmental conditions and testing for electrical and electronic equipment".

	ZED-F9P
Grade	
Automotive	
Professional	•
Standard	
GNSS	
GPS / QZSS	•
GLONASS	•
Galileo	•
BeiDou	•
Number of concurrent GNSS	4
Multi-band	•
Interfaces	
UART	2
USB	1
SPI	1
DDC (I²C compliant)	1
Features	
Programmable (Flash)	•
Data logging	•
Carrier phase output	•
Additional SAW	•
RTC crystal	•
Oscillator	T
RTK rover	•
RTK base station	•
Moving base	•
Survey-in and fixed mode	•
Timepulse	1
Power supply	
2.7 V – 3.6 V	•

T = TCXO

UBX-17005151 - R05



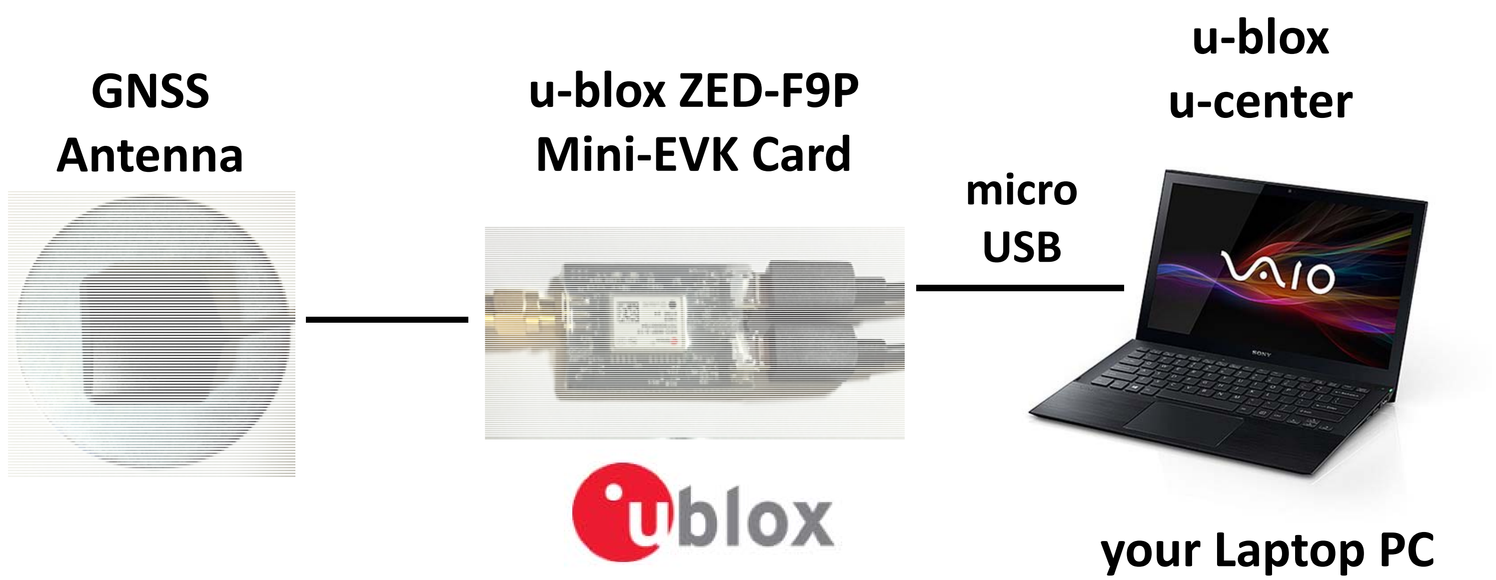
GNSS Antenna

u-blox ZED-F9P Mini-EVK Card

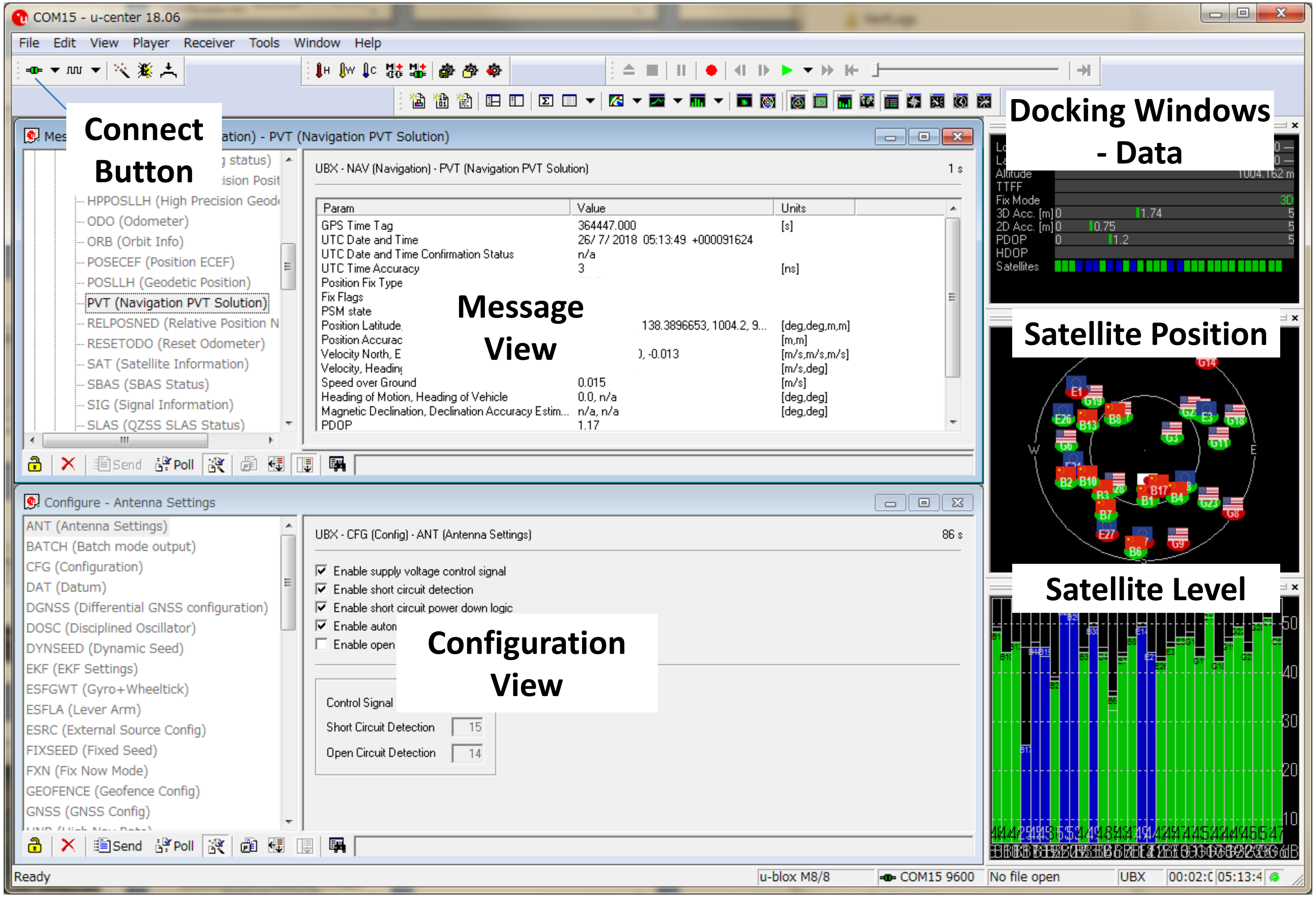
Receiver Modules are provided by u-blox .

Setup u-blox Receiver/u-center

- **Install u-center 19.04 to your laptop PC**
  - seminar_2019¥ublox¥u-centersetup_v19.04.zip



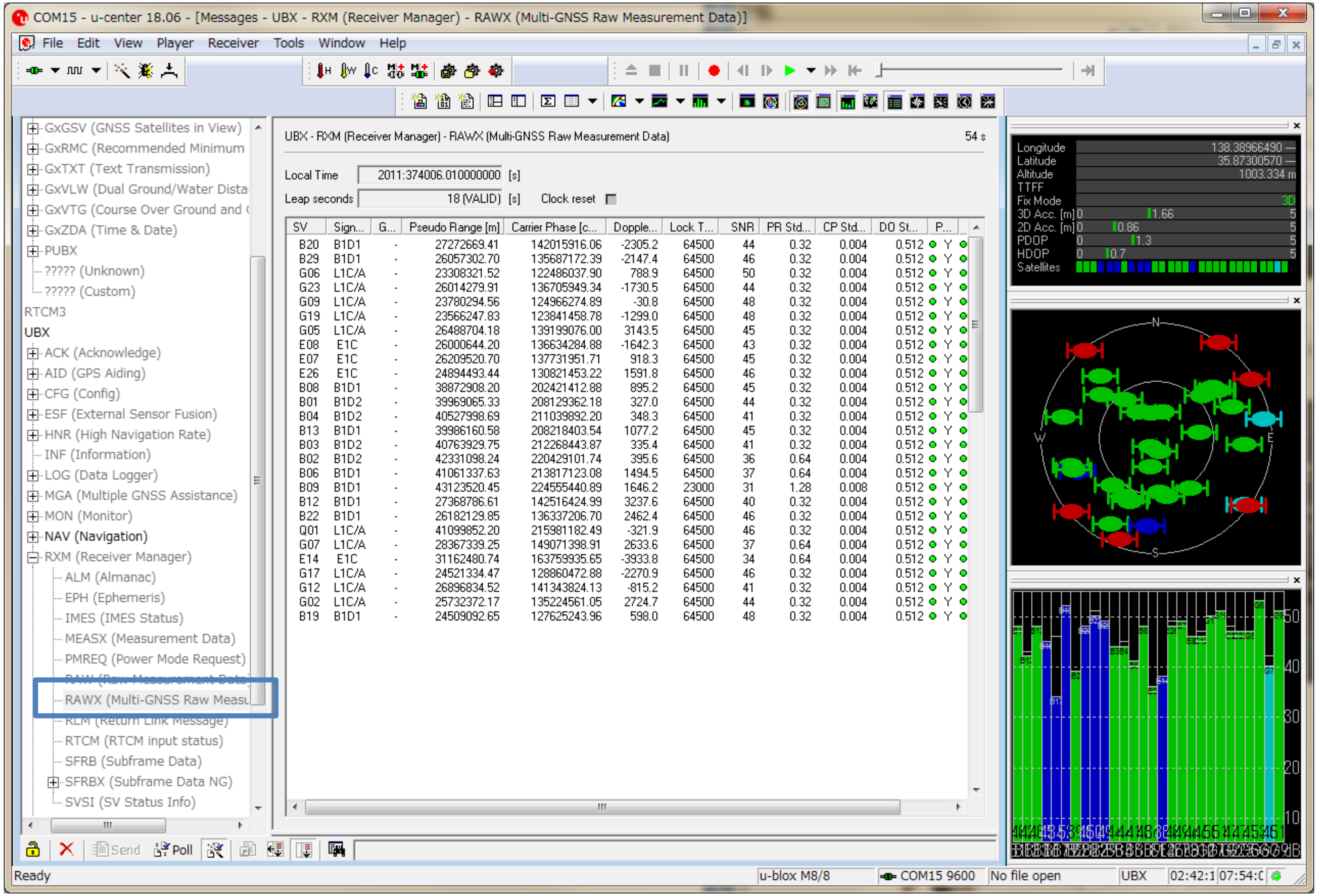
u-center 19.04



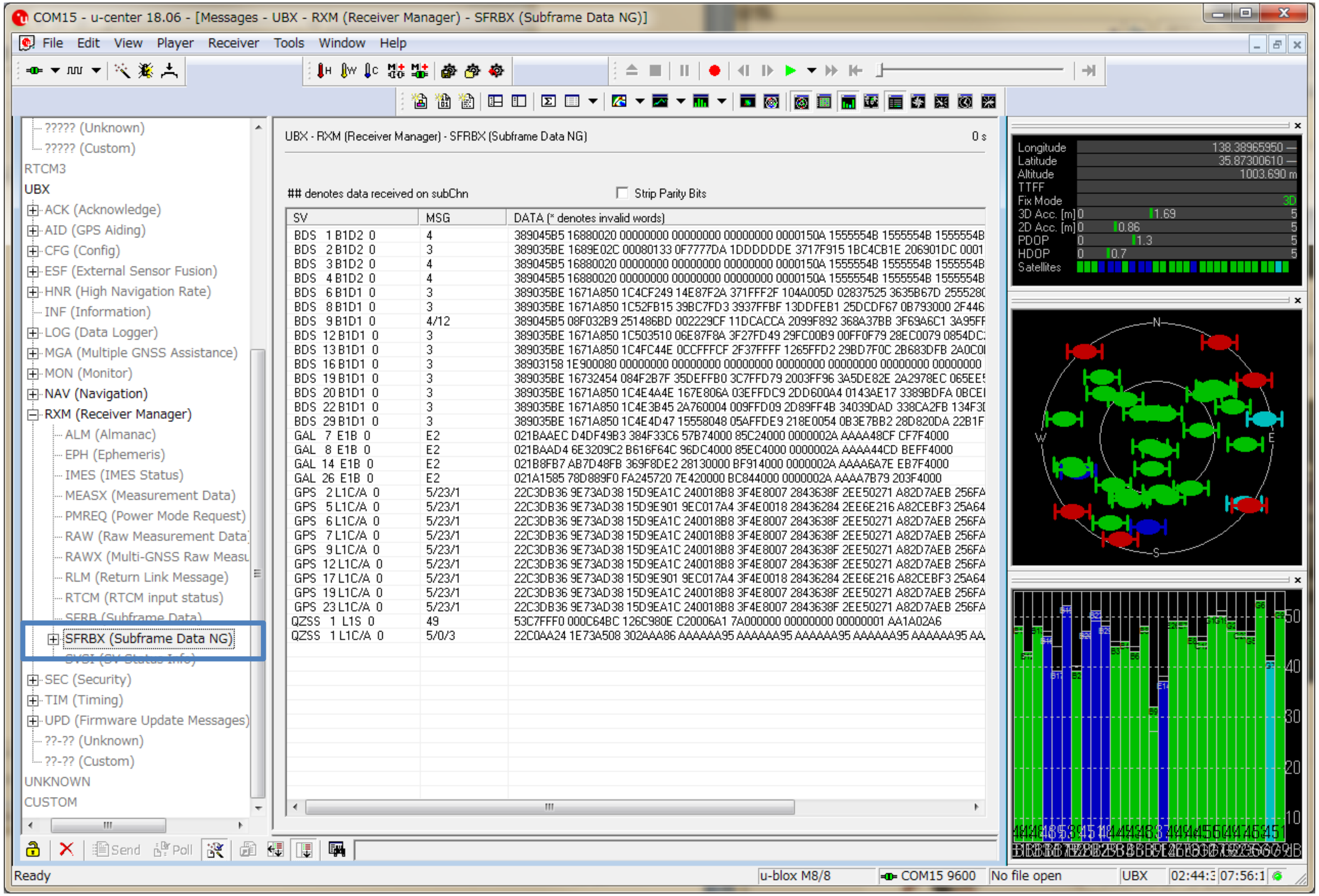
Configure u-blox Receiver

- **GNSS (GNSS Config)**
  GPS, Galileo, BeiDou, QZSS, GLONASS: Enabled
- **MSG (Messages)**
  02-15 RXM-RAWX: USB - ON (raw observation data)
  02-13 RXM-SFRBX: USB - ON (navigation data)
  01-07 NAV-PVT: USB - ON (optional)
  01-35 NAV-SAT: USB - ON (optional)
  Others: USB - OFF
- **CFG (Configuration)**
  Save current configuration

UBX-RXM-RAWX

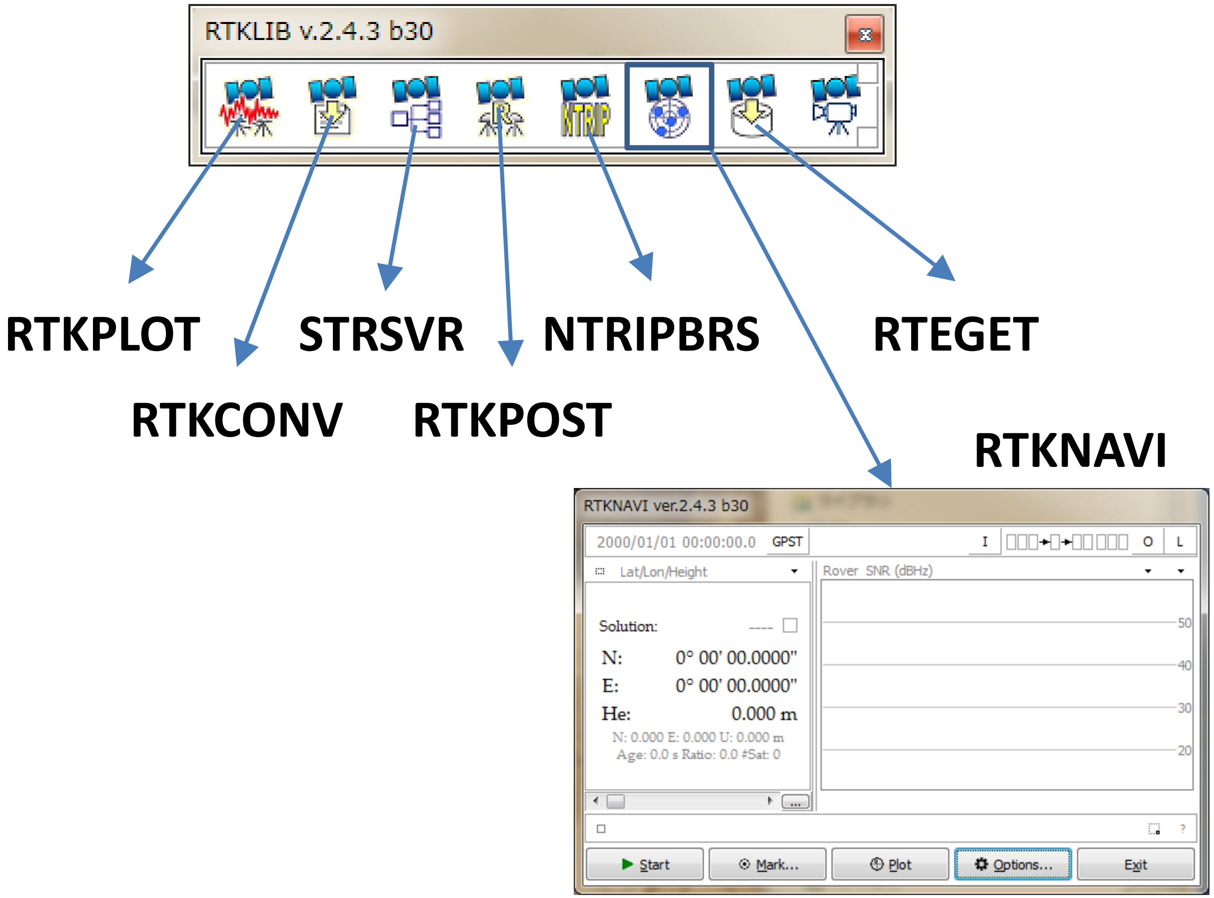

COM15 - u-center 18.06 - [Messages - UBX - RXM (Receiver Manager) - RAWX (Multi-GNSS Raw Measurement Data)]
File Edit View Player Receiver Tools Window Help
GxGSV (GNSS Satellites in View)
GxRMC (Recommended Minimum
GxTXT (Text Transmission)
GxVLW (Dual Ground/Water Dista
GxVTG (Course Over Ground and
GxZDA (Time & Date)
PUBX
????? (Unknown)
????? (Custom)
RTCM3
UBX
ACK (Acknowledge)
AID (GPS Aiding)
CFG (Config)
ESF (External Sensor Fusion)
HNR (High Navigation Rate)
INF (Information)
LOG (Data Logger)
MGA (Multiple GNSS Assistance)
MON (Monitor)
NAV (Navigation)
RXM (Receiver Manager)
ALM (Almanac)
EPH (Ephemeris)
IMES (IMES Status)
MEASX (Measurement Data)
PMREQ (Power Mode Request)
RAWX (Multi-GNSS Raw Measu
RTCM (RTCM input status)
SFRB (Subframe Data)
SFRBX (Subframe Data NG)
SVSI (SV Status Info)
UBX - RXM (Receiver Manager) - RAWX (Multi-GNSS Raw Measurement Data)
54 s
Local Time 2011:374006.010000000 [s]
Leap seconds 18 (VALID) [s]
Clock reset
SV Sign... G... Pseudo Range [m] Carrier Phase [c... Dopple... Lock T... SNR PR Std... CP Std... DO St... P...
B20 B1D1 - 27272669.41 142015916.06 -2305.2 64500 44 0.32 0.004 0.512 Y
B29 B1D1 - 26057302.70 135687172.39 -2147.4 64500 46 0.32 0.004 0.512 Y
G06 L1C/A - 23308321.52 122486037.90 788.9 64500 50 0.32 0.004 0.512 Y
G23 L1C/A - 26014279.91 136705949.34 -1730.5 64500 44 0.32 0.004 0.512 Y
G09 L1C/A - 23780294.56 124966274.89 -30.8 64500 48 0.32 0.004 0.512 Y
G19 L1C/A - 23566247.83 123841458.78 -1299.0 64500 48 0.32 0.004 0.512 Y
G05 L1C/A - 26488704.18 139199076.00 3143.5 64500 45 0.32 0.004 0.512 Y
E08 E1C - 26000644.20 136634284.88 -1642.3 64500 43 0.32 0.004 0.512 Y
E07 E1C - 26209520.70 137731951.71 918.3 64500 45 0.32 0.004 0.512 Y
E26 E1C - 24894493.44 130821453.22 1591.8 64500 46 0.32 0.004 0.512 Y
B08 B1D1 - 38872908.20 202421412.88 895.2 64500 45 0.32 0.004 0.512 Y
B01 B1D2 - 39969065.33 208129362.18 327.0 64500 44 0.32 0.004 0.512 Y
B04 B1D2 - 40527998.69 211039892.20 348.3 64500 41 0.32 0.004 0.512 Y
B13 B1D1 - 39986160.58 208218403.54 1077.2 64500 45 0.32 0.004 0.512 Y
B03 B1D2 - 40763929.75 212268443.87 335.4 64500 41 0.32 0.004 0.512 Y
B02 B1D2 - 42331098.24 220429101.74 395.6 64500 36 0.64 0.004 0.512 Y
B06 B1D1 - 41061337.63 213817123.08 1494.5 64500 37 0.64 0.004 0.512 Y
B09 B1D1 - 43123520.45 224555440.89 1646.2 23000 31 1.28 0.008 0.512 Y
B12 B1D1 - 27368786.61 142516424.99 3237.6 64500 40 0.32 0.004 0.512 Y
B22 B1D1 - 26182129.85 136337206.70 2462.4 64500 46 0.32 0.004 0.512 Y
Q01 L1C/A - 41099852.20 215981182.49 -321.9 64500 46 0.32 0.004 0.512 Y
G07 L1C/A - 28367339.25 149071398.91 2633.6 64500 37 0.64 0.004 0.512 Y
E14 E1C - 31162480.74 163759935.65 -3933.8 64500 34 0.64 0.004 0.512 Y
G17 L1C/A - 24521334.47 128860472.88 -2270.9 64500 46 0.32 0.004 0.512 Y
G12 L1C/A - 26896834.52 141343824.13 -815.2 64500 41 0.32 0.004 0.512 Y
G02 L1C/A - 25732372.17 135224561.05 2724.7 64500 44 0.32 0.004 0.512 Y
B19 B1D1 - 24509092.65 127625243.96 598.0 64500 48 0.32 0.004 0.512 Y
Longitude 138.38966490
Latitude 35.87300570
Altitude 1003.334 m
TTFF
Fix Mode 3D
3D Acc. [m] 1.66
2D Acc. [m] 0.86
PDOP 1.3
HDOP 0.7
Satellites
N
W
E
S
Send
Poll
Ready
u-blox M8/8
COM15 9600
No file open
UBX

UBX-RXM-SFRBX

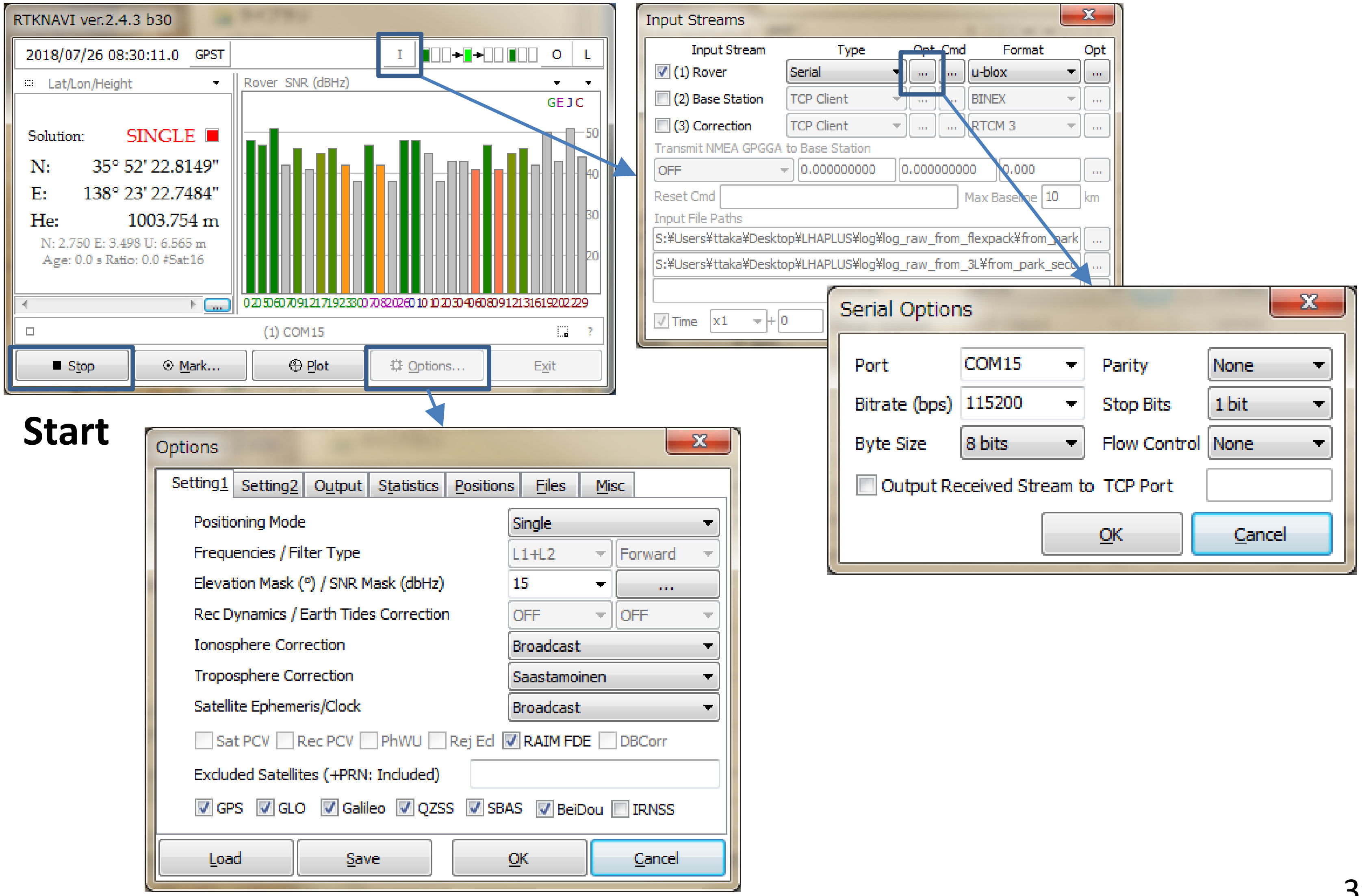


Start RTKLIB

- **RTKLAUNCH (RTKLIB AP launcher)**
  seminar_2019¥rtklib_2.4.3b32¥bin¥rtklaunch.exe

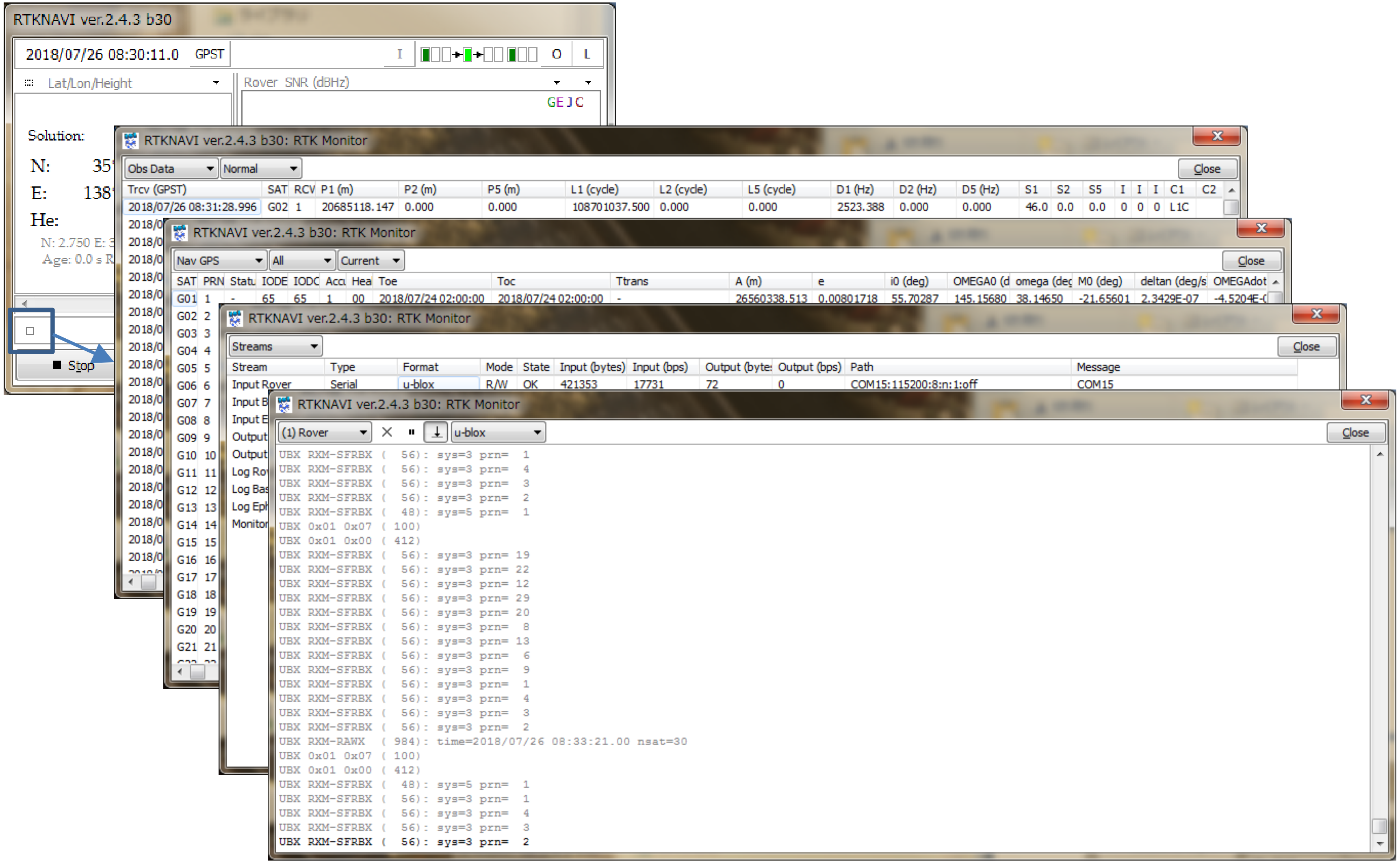


RTKNAVI

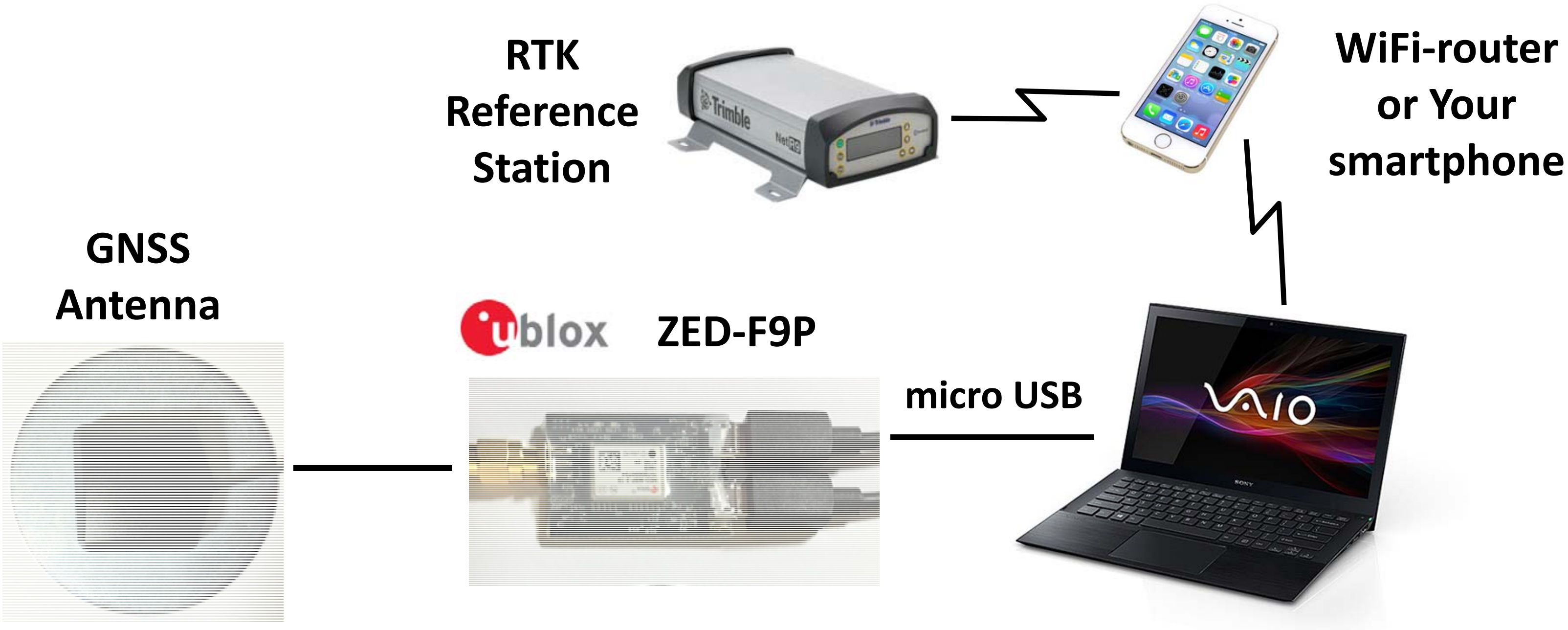


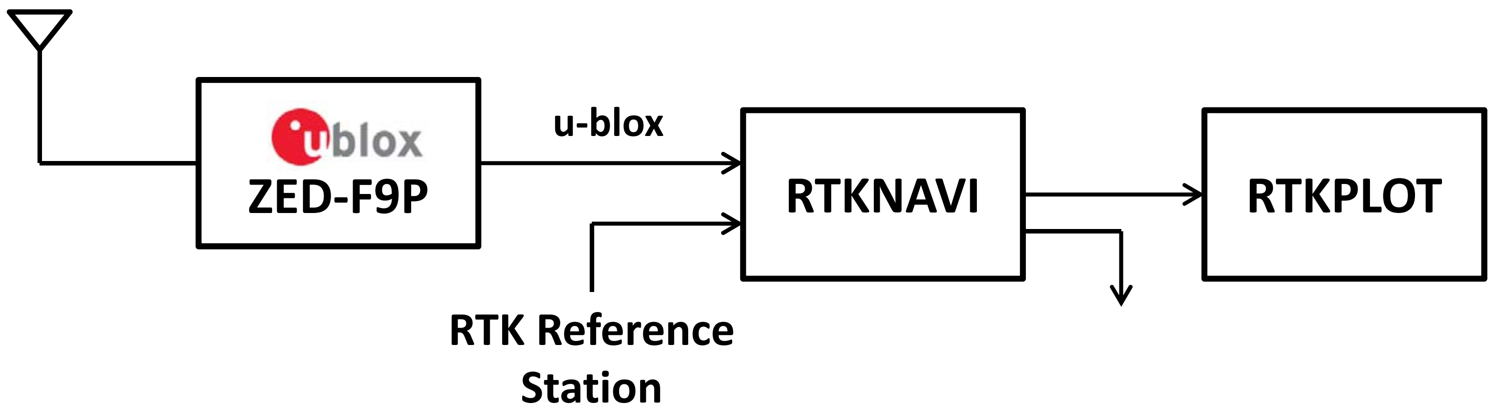
Start

RTKNAVI - RTK Monitor



Configure RTK with RTKLIB and u-blox





RTK Reference Station

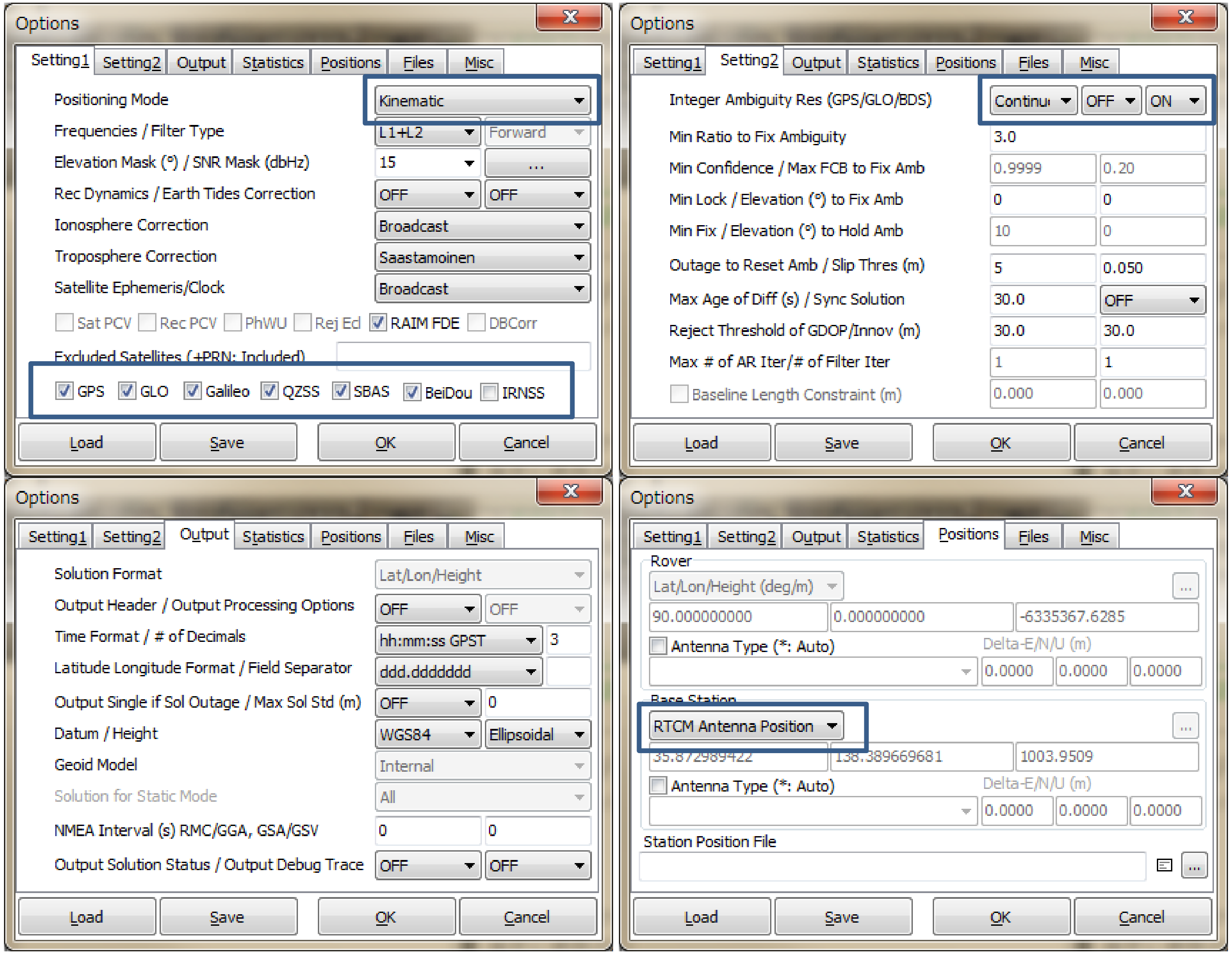
Receiver:
Trimble NetR9

IP-Addr : 153.121.xx.xx
Port : 2101 or 80
MountP : xxxxx
USER-ID : xxxxxx
PW : xxxxxx
Format : RTCM3 (GPS+GLO+GAL+QZS+BDS)

IP-Addr : 153.121.xx.xx
Port : 2101 or 80
MountP : xxxxx
USER-ID : xxxxxx
PW : xxxxxx
Format : BINEX (GPS+GLO+GAL+QZS+BDS)

Lat: 35.66633444
Lon: 139.79220107
Height: 59.746

RTKNAVI Options for RTK



4 PPP Basics

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

PPP Applications

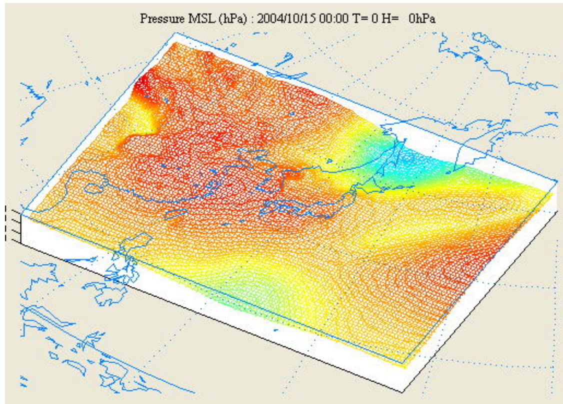
Automated Farming

Tsunami Warning

Mining Machine Control

Offshore Construction

Autonomous Driving



Weather Forecast

RTK vs. PPP

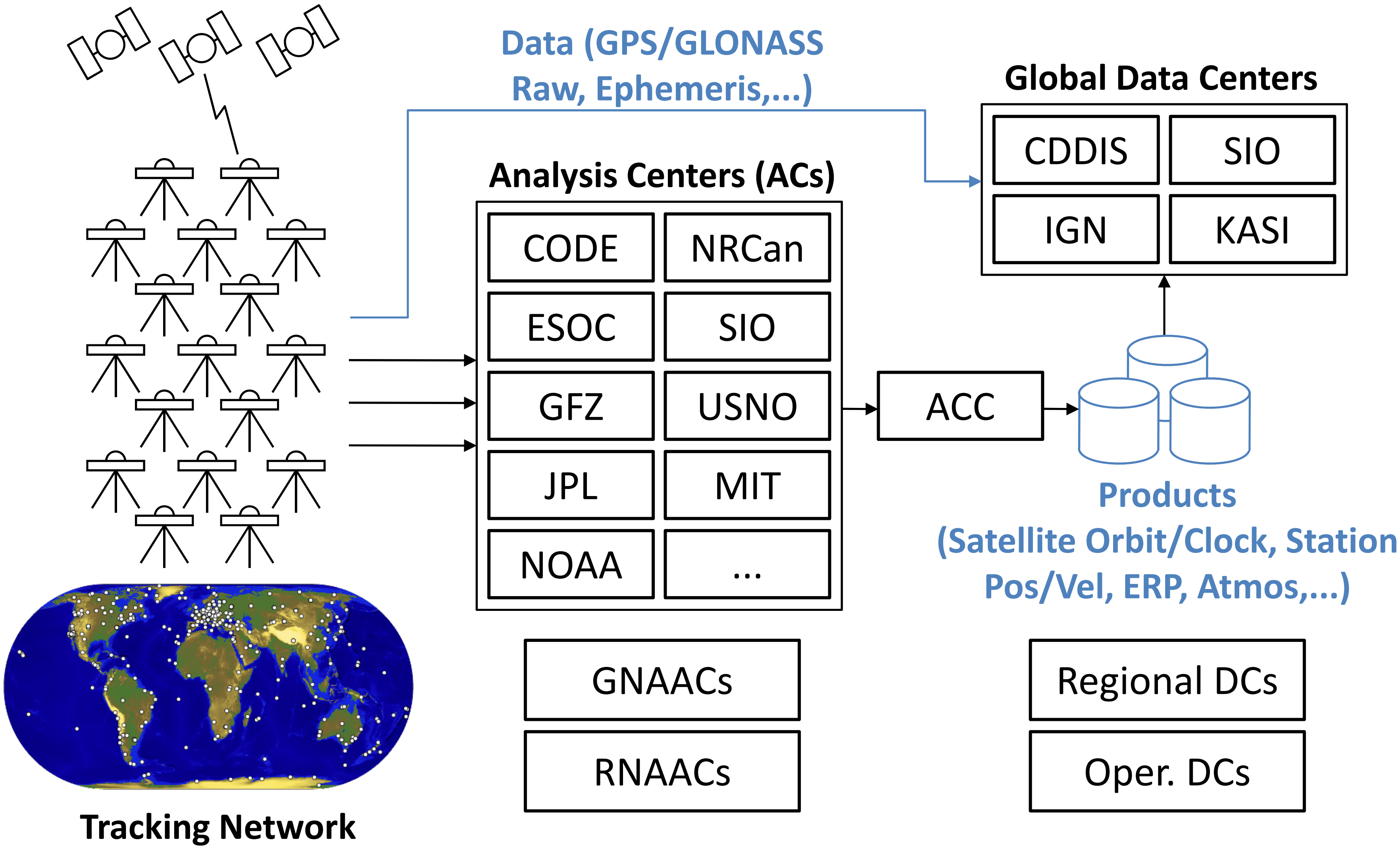
	RTK	Real-Time PPP
Coverage	Local/Regional (< 1000km)	Global
Typical Accuracy	1-3 cm HRMS	2-10 cm, much depending on orbit/clock quality
Effect of Ref Movement	Hard to separate ref and user movement	Less effect by distributed ref stations
System Complexity	Simple, at least one ref station	Complicated,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

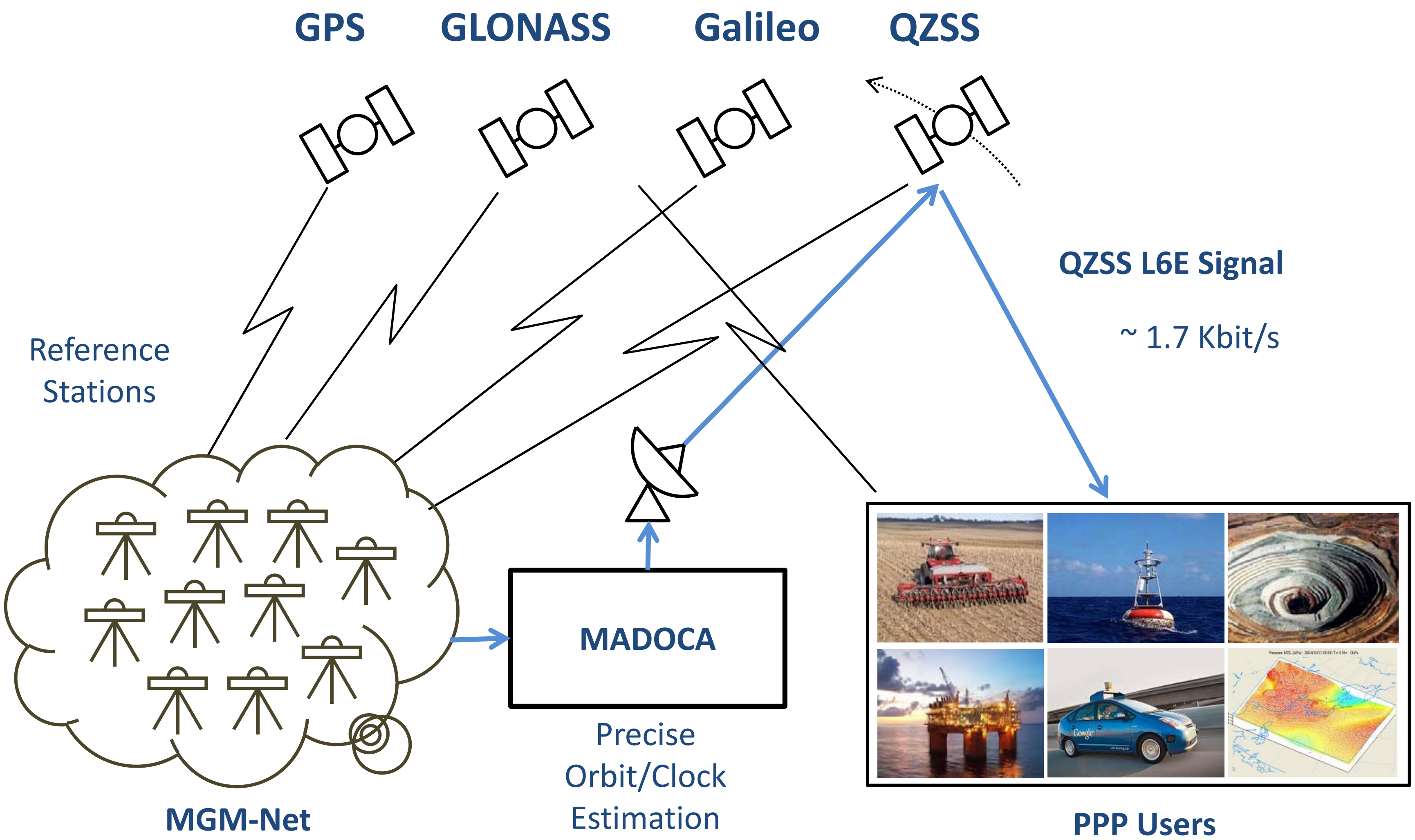


IGS Products

		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

(http://www.igs.org/)

MADOCA-PPP (1)

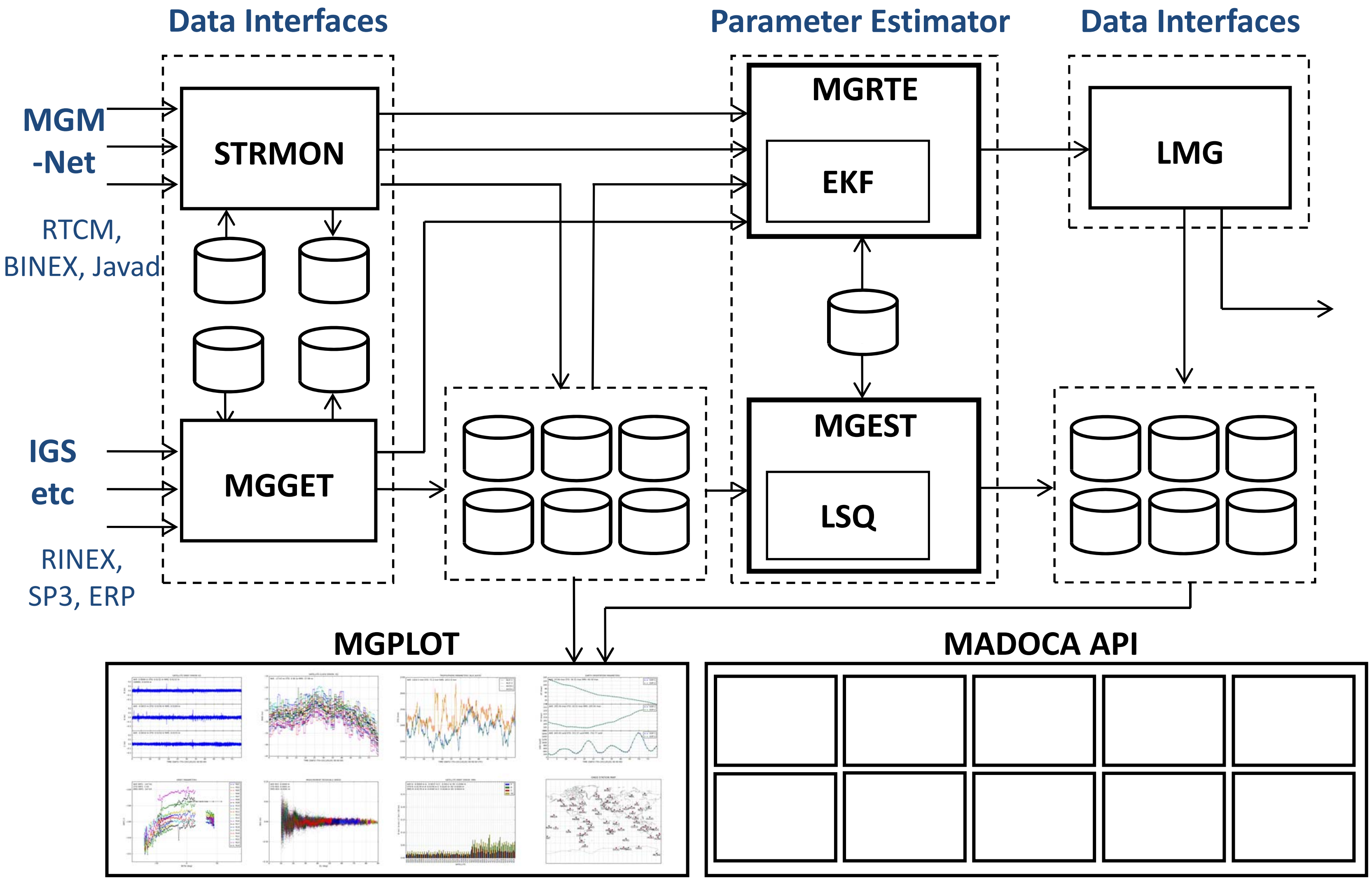

GPS
GLONASS
Galileo
QZSS
QZSS L6E Signal
~ 1.7 Kbit/s
Reference Stations
MADOCA
MGM-Net
Precise Orbit/Clock Estimation
PPP Users

MADOCA-PPP (2)

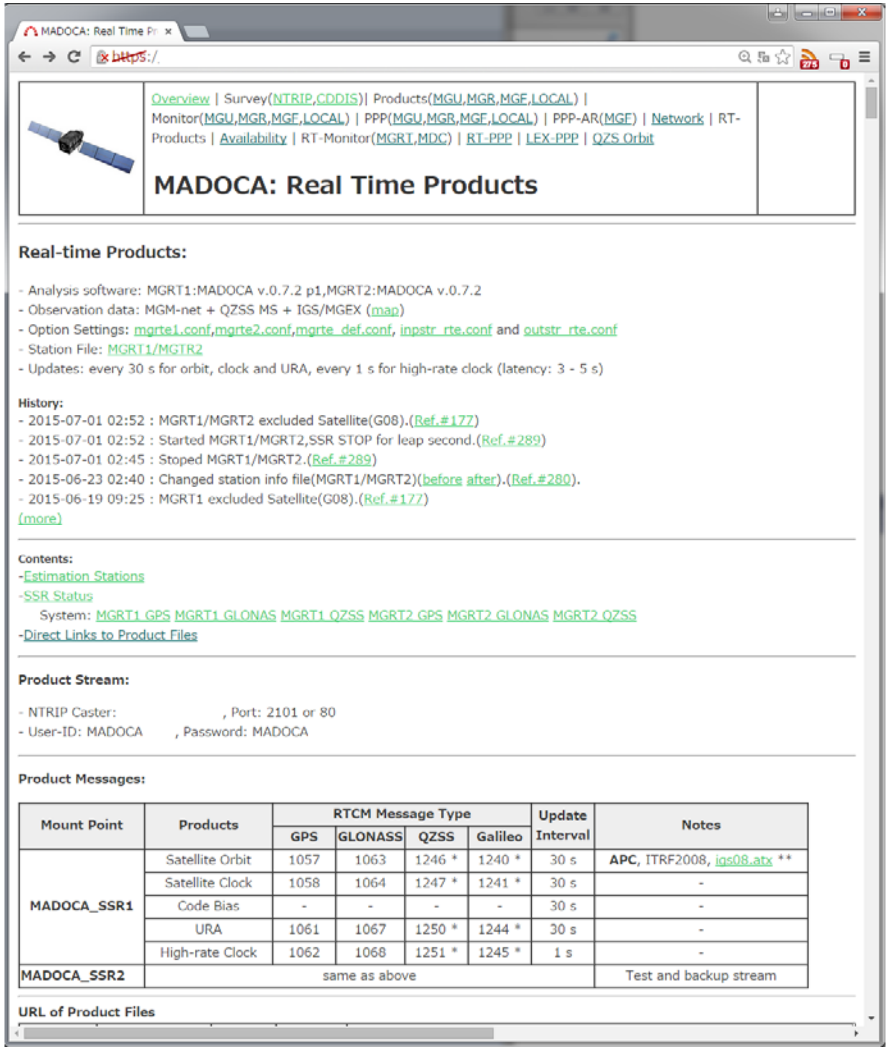
Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis

- **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-PPP (3)


Data Interfaces
Parameter Estimator
Data Interfaces
MGM
-Net
RTCM,
BINEX, Javad
IGS
etc
RINEX,
SP3, ERP
STRMON
MGGET
MGRTE
EKF
MGEST
LSQ
LMG
MGPLOT
MADOCA API

MADOCA-PPP (4)



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

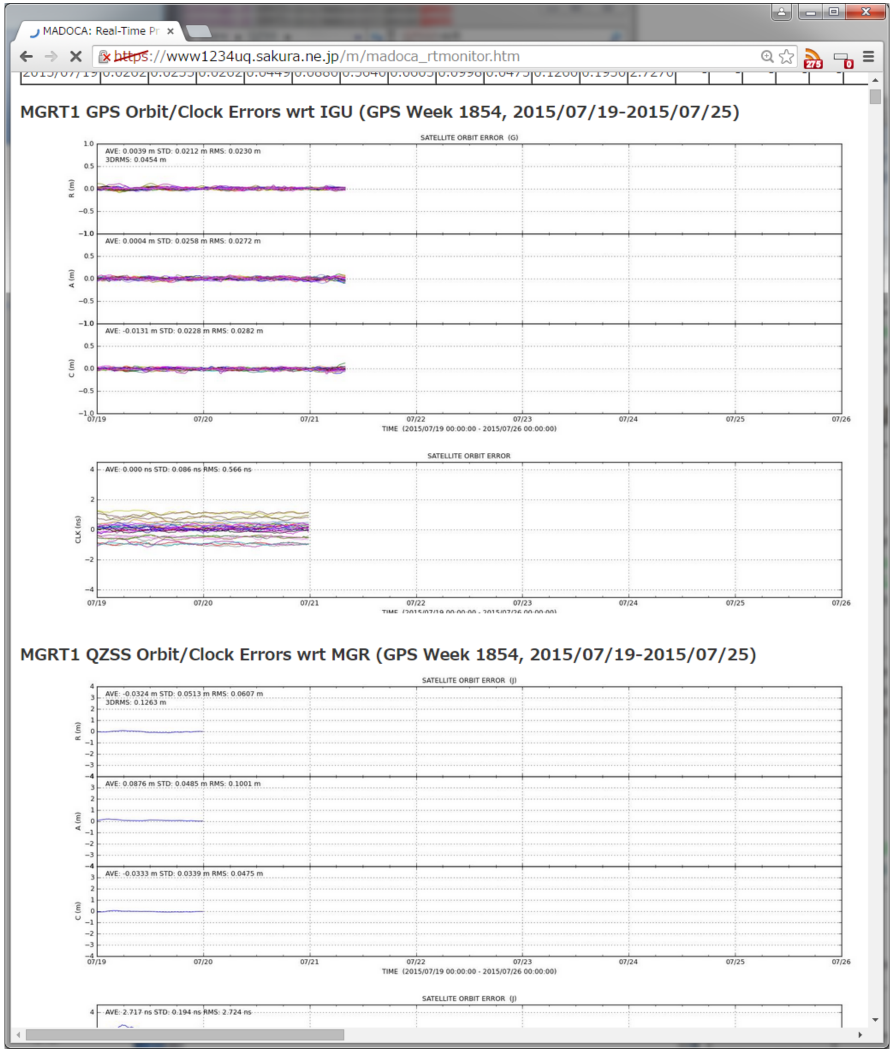
Product Stream:

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

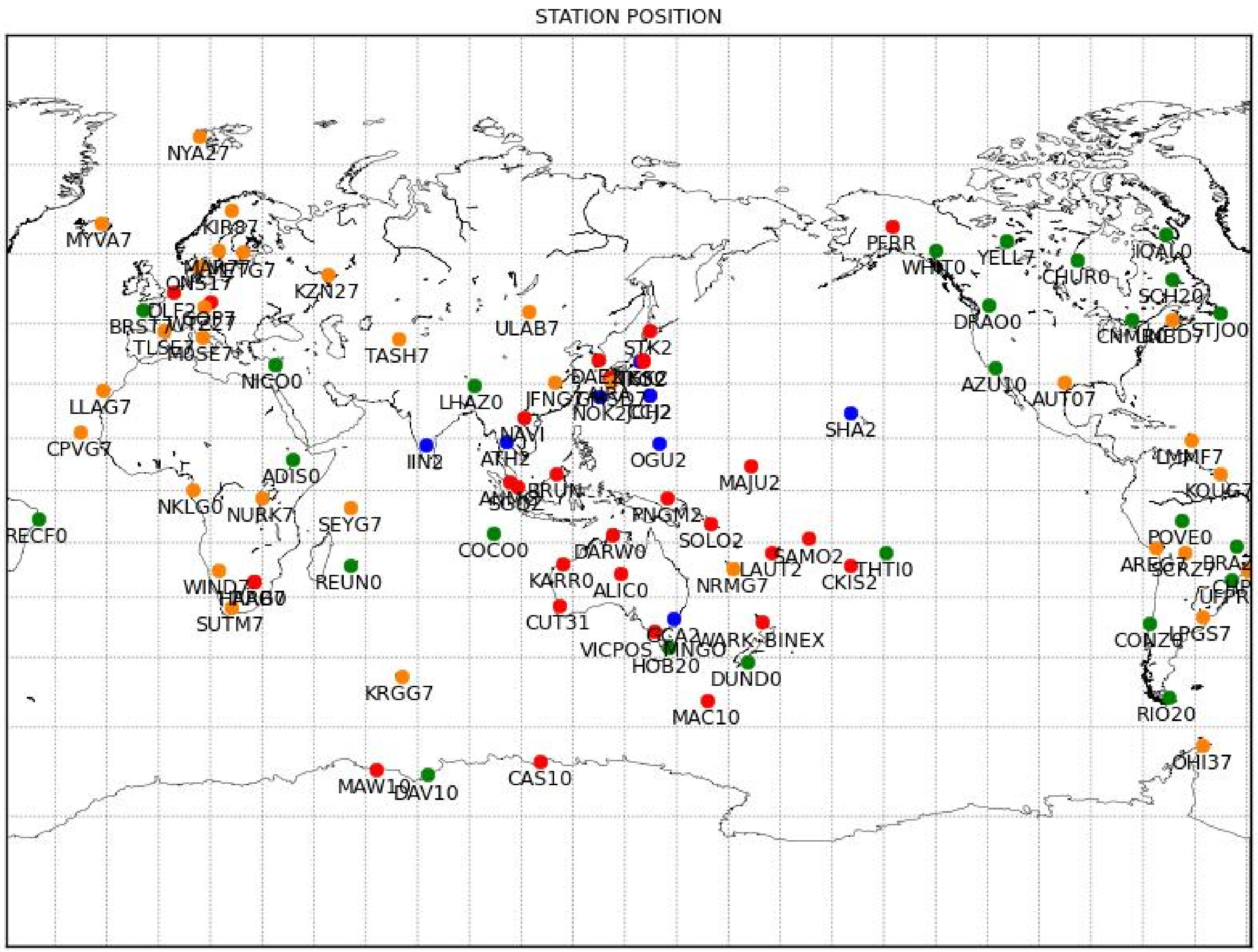
Product Messages:

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



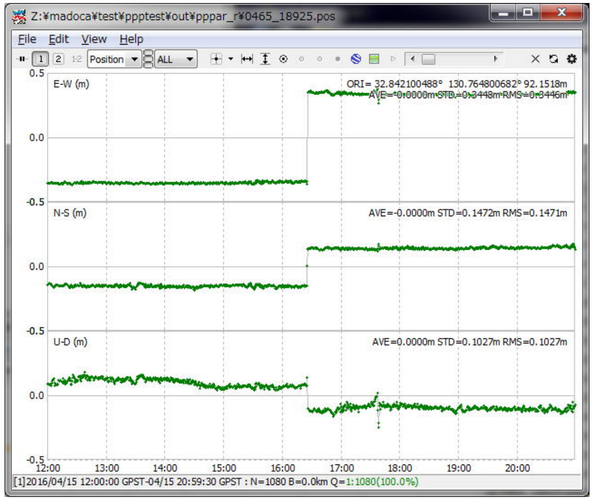
MADOCA-PPP (5)

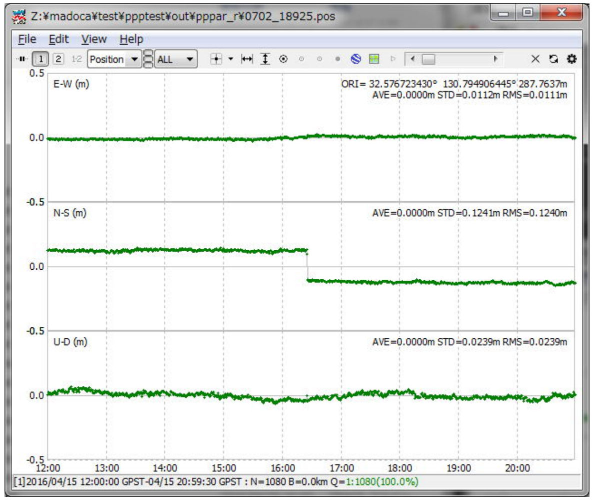


● QZSS-MS ● MGM-Net ● IGS ● MGEX

MADOCA PPP (6)

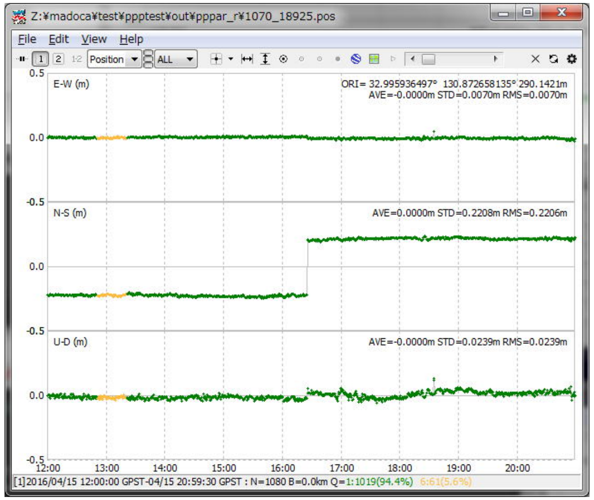
Kumamoto
(0465)

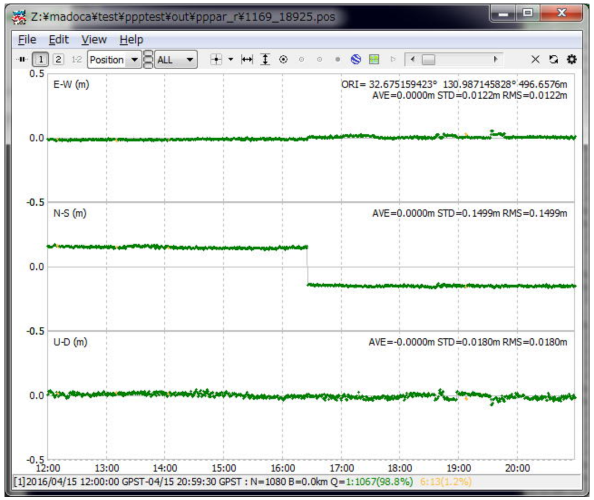




Izumi
(0702)

Kikuchi
(1070)





Yabe A
(1169)

2016/4/15 16:25 GPST PPP Analysis of Kumamoto-EQ. by MADOCA-PPP
(RTKLIB 2.4.3 b9, Kinematic-PPP-AR, MADOCA Final Products

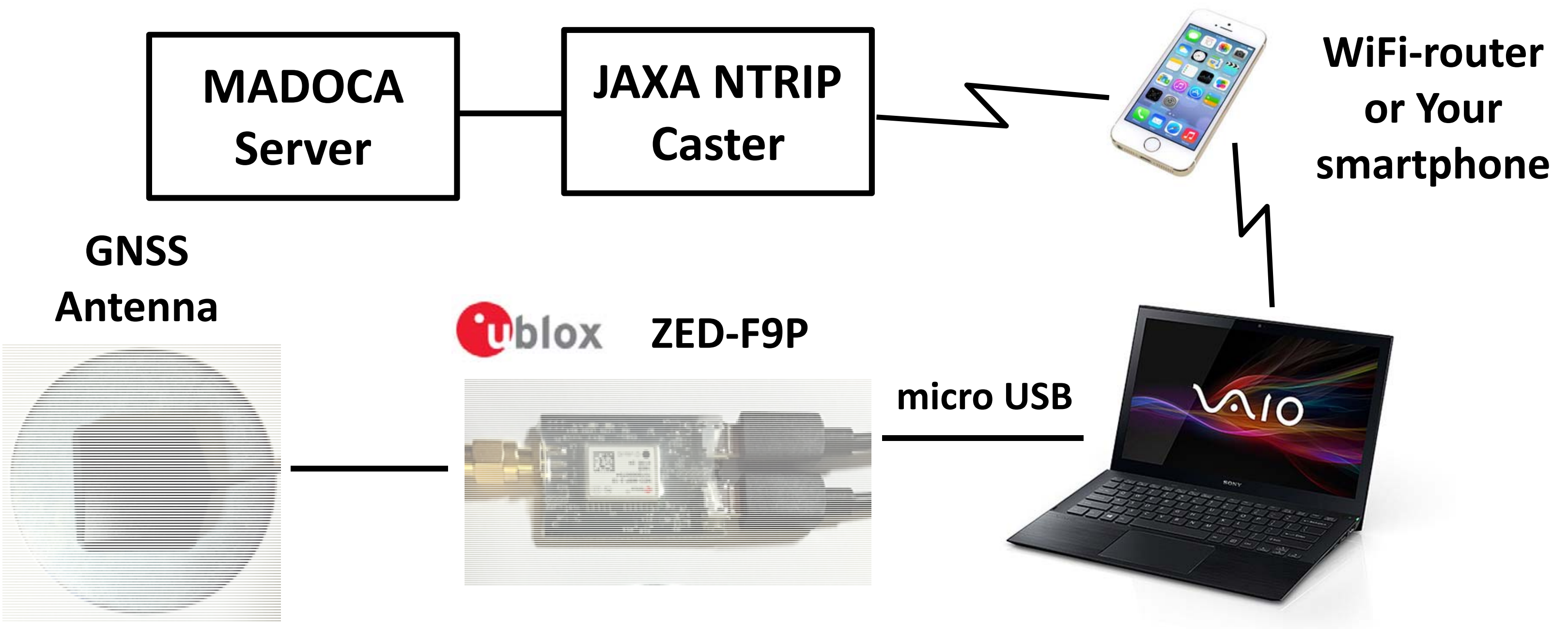
RTCM 3.3 SSR

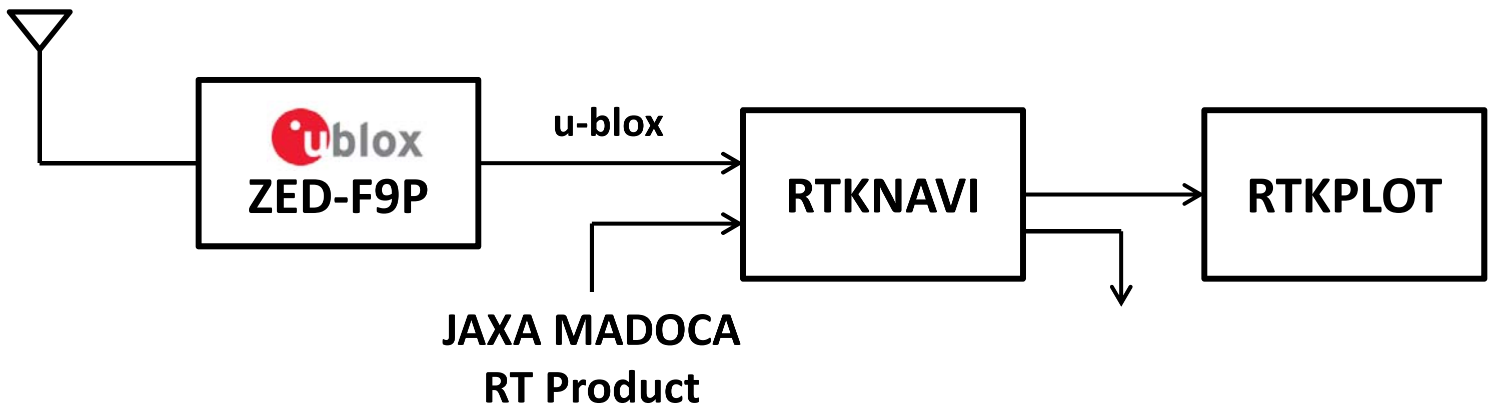
Message		GPS	GLOASS	Galileo	QZSS	BeiDou	SBAS
OBS	Compact L1	1001	1009	-	-	-	-
	Full L1	1002	1010	-	-	-	-
	Compact L1/2	1003	1011	-	-	-	-
	Full L1/2	1004	1012	-	-	-	-
Ephemeris		1019	1020	1045/6	1044	1042	-
MSM	1	1071	1081	1091	1111	1121	1101
	2	1072	1082	1092	1112	1122	1102
	3	1073	1083	1093	1113	1123	1103
	4	1074	1084	1094	1114	1124	1104
	5	1075	1085	1095	1115	1125	1105
	6	1076	1086	1096	1116	1126	1106
	7	1077	1087	1097	1117	1127	1107
SSR	Orbit Corr.	1057	1063	1240*	1246*	1258*	1252*
	Clock Corr.	1058	1064	1241*	1247*	1259*	1253*
	Code Bias	1059	1065	1242*	1248*	1260*	1254*
	Combined	1060	1066	1243*	1249*	1261*	1255*
	URA	1061	1067	1244*	1250*	1262*	1256*
	HR-Clock	1062	1068	1245*	1251*	1263*	1257*
Antenna Info		1005 1006 1007 1008 1033					

* draft

5 PPP Practice

Configure PPP with RTKLIB and u-blox



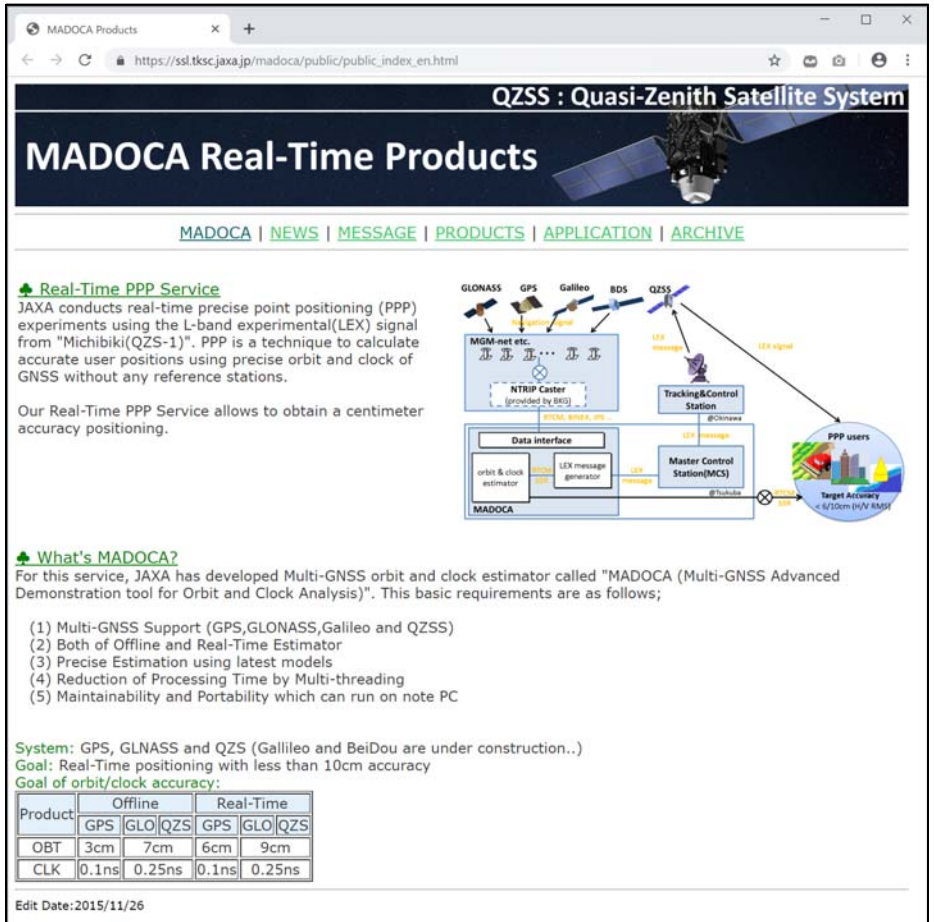


JAXA MADOCA RT Product

JAXA NTRIP Caster

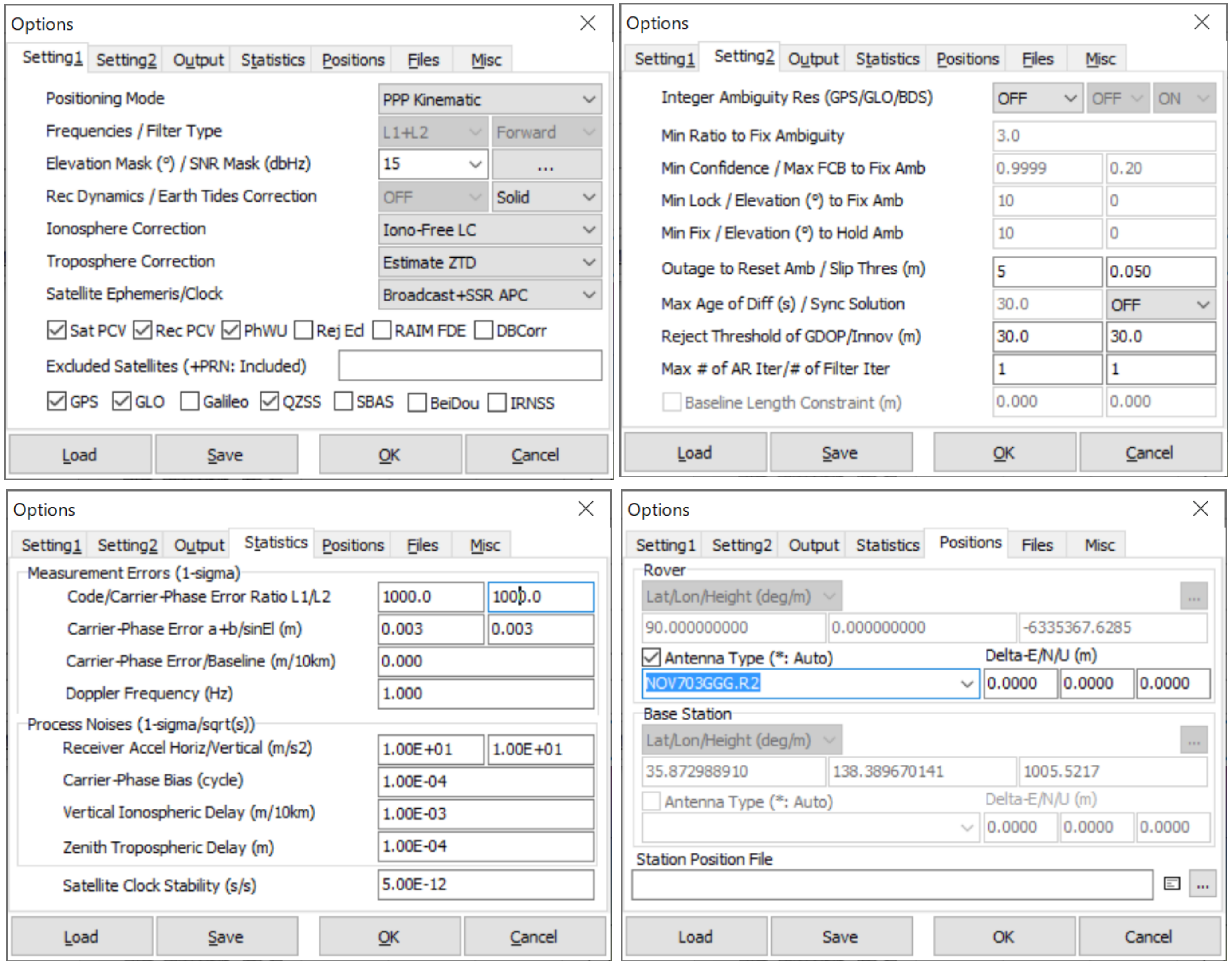
IP-Addr	: madoca.ntrip-mgm.net
Port	: 2101
MountP	: MDC0, MDC1 or MDC2
USER-ID	: xxxxxx
PW	: xxxxxx
Format	: RTCM3 SSR

USER-ID and PW are only for the seminar (temporal)



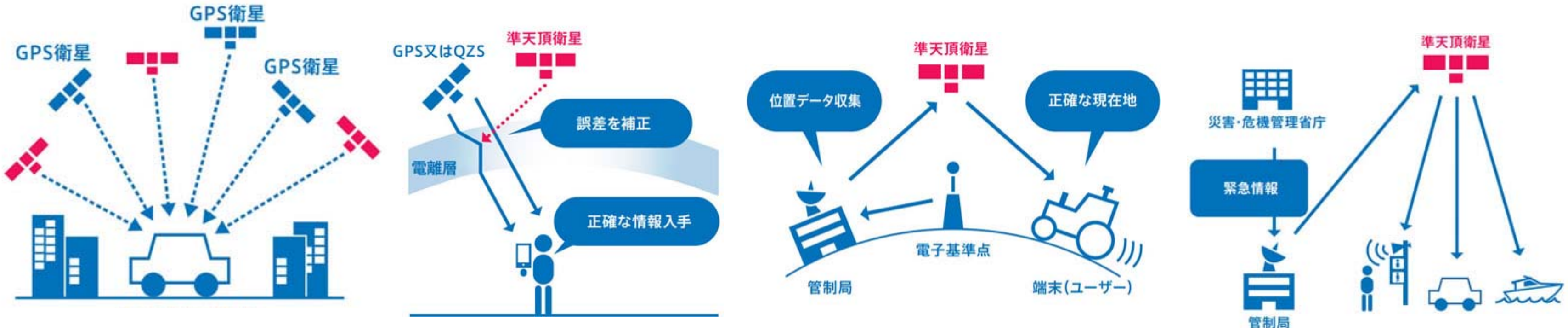
https://ssl.tksc.jaxa.jp/madoca/public/public_index_en.html

RTKNAVI Options for PPP



6 Advanced Topics of PP

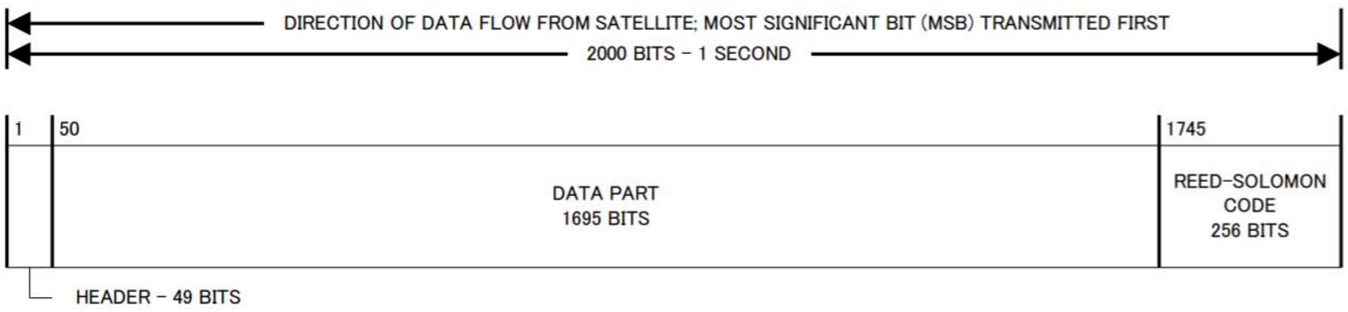
QZSS



Satellite Positioning, Navigation and Timing Service | Sub-meter Level Augmentation Service (SLAS) | Centimeter Level Augmentation Service (CLAS) | Disaster and Crisis Management (DC) Report Service

(http://qzss.go.jp)

QZSS L6




```
PRN      sig messages
-------------------------
193-199 L6D CLAS
203-209 L6E MADOCA PPP
```


```
2019-05-08 10:39:47, J01, 193, L6D: CLAS   FID=0 SF=1 AF=0
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0E3FFCD00D3FE1FF5CFF5EFE969425033FFB85D683E0C1F160FFB002880754078A03AD089BC638631CB1927F8CEFB537DAAB
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2019-05-08 09:49:39, J02, 194, L6D: CLAS   FID=0 SF=0 AF=0
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FF96052FFA003C004805FFFA003FFFFA66E7D5289DF630FF2FC00FE0000101FC00001E4F50004182000820106230C7E204004
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2019-05-08 09:49:27, J02, 204, L6E: MADOCA FID=0 SF=1 AF=1
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F6D2D7F842937F790E77F8EECFFD0D221FA4A4C7F06D997F41953FCF45A9F928DDBF2BD6138D1FA604E000022000F900000
00000000000000000000000000000000001C40A313E7B989A0F3AC88376D02513B191979A508A5FD5F6BDAC2B4A60A1558
2019-05-08 10:39:47, J03, 195, L6D: CLAS   FID=0 SF=0 AF=0
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BF02FFF4081FFEFF7DF5F88103FC07FFC040040407D9E40C07F000BF810218103F6798201F7F82FE03F820207D9EBFC07EFD
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220203F5788201F0001FBFFF830407D5E3F7E7BFDF7EFBF7DFEFBF5798606041040208 28A0A1FD3E2141FF04080010628205
F4F80103FC000FE000030207D3E1F3DFDFDF2A2B32A4EC1A9AC829F7B8D69A7E35FC283C3989642486DF949551D33986D2C4
2019-05-08 10:39:47, J03, 205, L6E: MADOCA FID=0 SF=1 AF=1
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000000000000000000000000000000000000080D87D426778E0BDFDC59C02058555274B238E3AC58DAA480F5128701DECAD5E
```
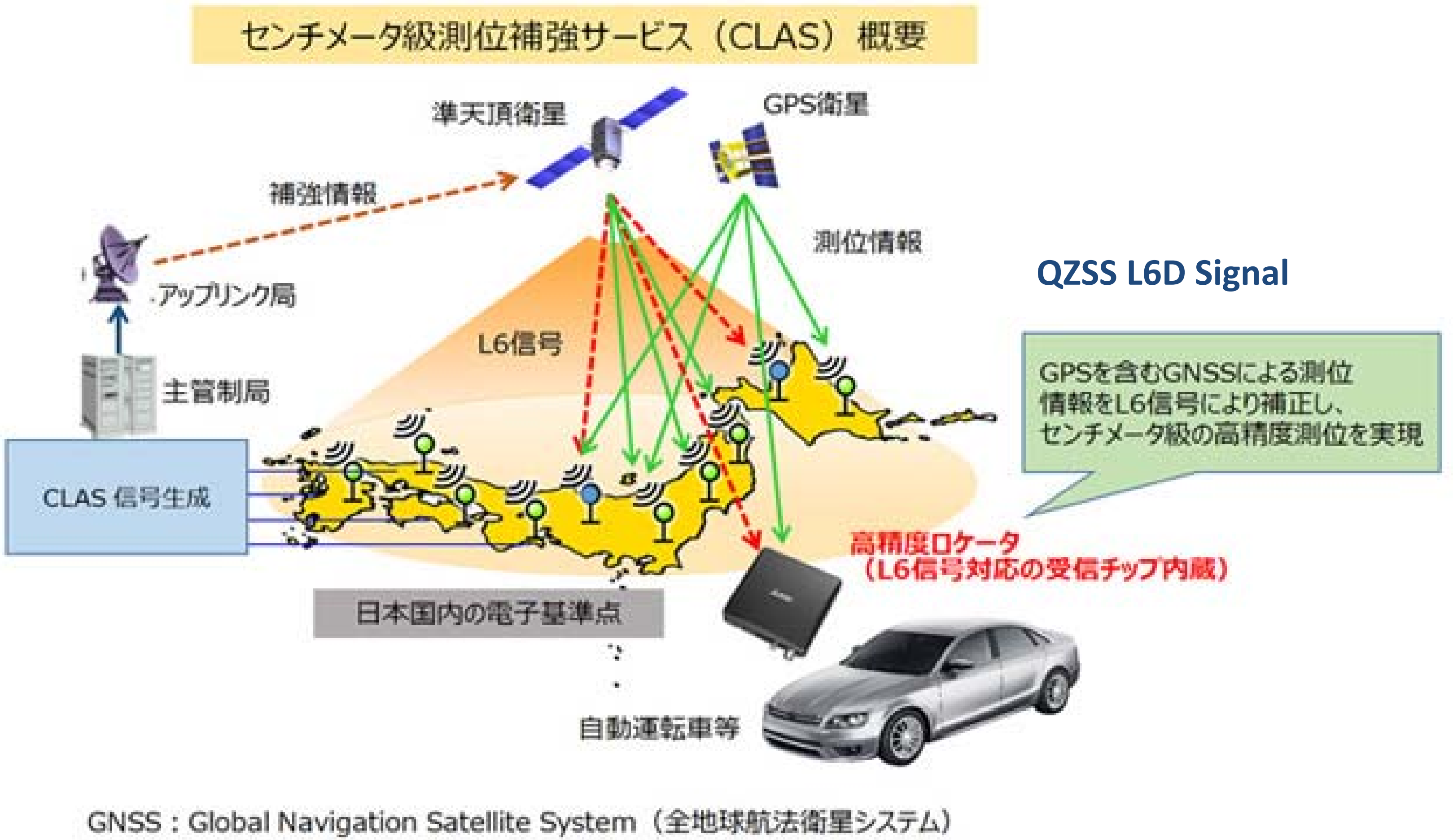


[1] IS-QZSS-L-001 Quasi-Zenith Satellite System Interface Specification Centimeter Level Augmentation Service, November 5, 2018

CLAS



QZSS L6D Signal

(http://www.mitsubishielectric.co.jp)

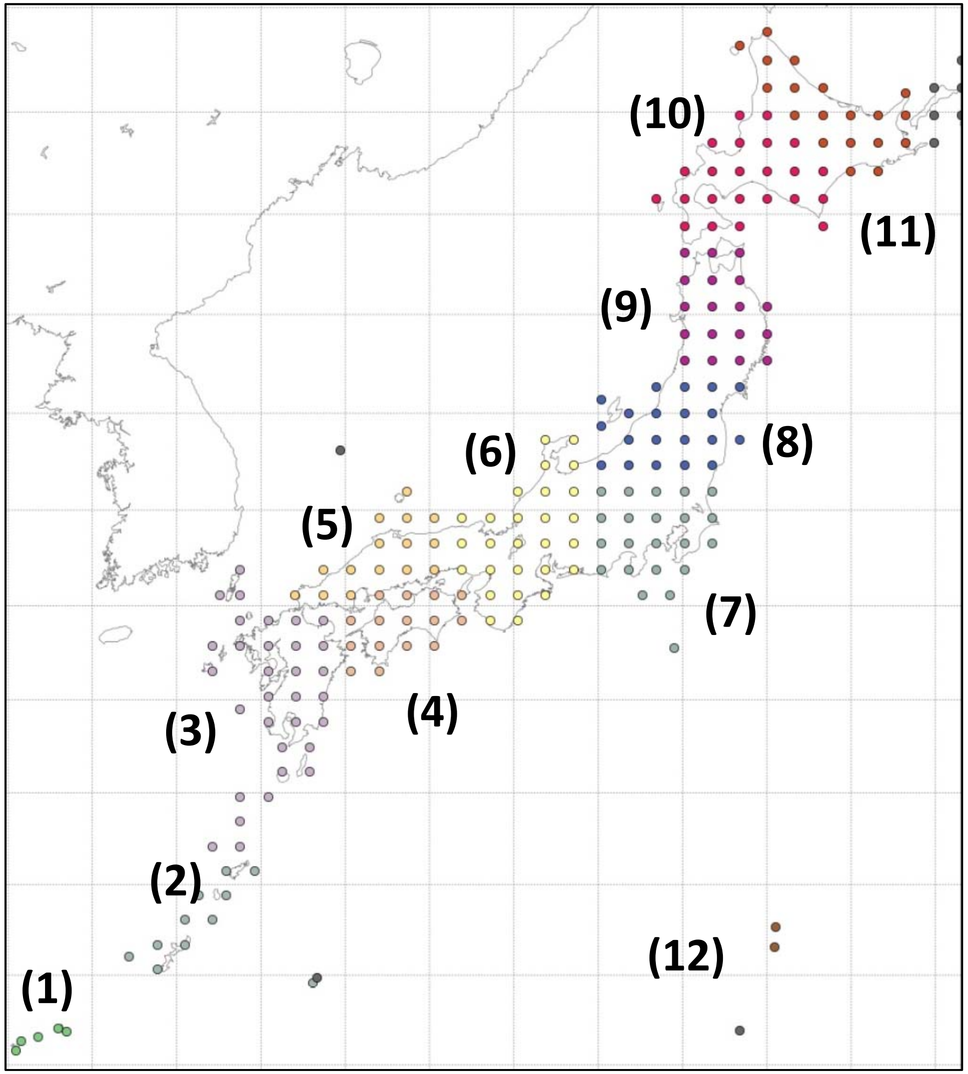
CSSR (Compact SSR)

```
+----------+--------+----------+--------------------+----------+
| preamble | 000000 | length(B) |        data        |  parity  |
+----------+--------+----------+--------------------+----------+
|<-- 8 --->|<- 6 -->|<-- 10 --->|<--- length x 8 --->|<-- 24 -->|

+---------------+-----+------------------------------------------+
|     MT(12)    |ST(4)|               message data               |
+---------------+-----+------------------------------------------+
```

NO	Message	MT	ST	Format
(1)	Compact SSR mask	4073	1	[1] 4.1.2.2.2
(2)	Compact SSR orbit corr	4073	2	[1] 4.1.2.2.3
(3)	Compact SSR clock corr	4073	3	[1] 4.1.2.2.4
(4)	Compact SSR code bias	4073	4	[1] 4.1.2.2.5
(5)	Compact SSR phase bias	4073	5	[1] 4.1.2.2.6
(6)	CSSR code and phase bias	4073	6	[1] 4.1.2.2.7
(7)	Compact SSR URA	4073	7	[1] 4.1.2.2.8
(8)	Compact SSR STEC corr	4073	8	[1] 4.1.2.2.9
(9)	Compact SSR gridded corr	4073	9	[1] 4.1.2.2.10
(10)	Compact SSR combined cor	4073	11	[1] 4.1.2.2.12

[1] IS-QZSS-L-001 Quasi-Zenith Satellite System Interface Specification Centimeter Level Augmentation Service, November 5, 2018

CLAS CSSR Grids and Networks



MADOCA PPP

(https://www.gpas.co.jp)

Today's Summary

1	Theory of PP (precise positioning)
2	RTK Basics
3	RTK Practice
	Lunch Break
4	PPP Basics
5	PPP Practice
6	Advanced Topics of PP