第57回宇宙科学技術連合講演会

2O-13
複数GNSS対応高精度軌道時刻推定ツールMADOCAの開発

東京海洋大学 ○高須知二、安田明生
宇宙航空研究開発機構 小暮聡、中村信一、三吉基之、河手香織
日本電気株式会社 平原康孝、澤村寿一

2013-10-9 ~ 11 @米子コンベンションセンター「ビッグシップ」

Contents

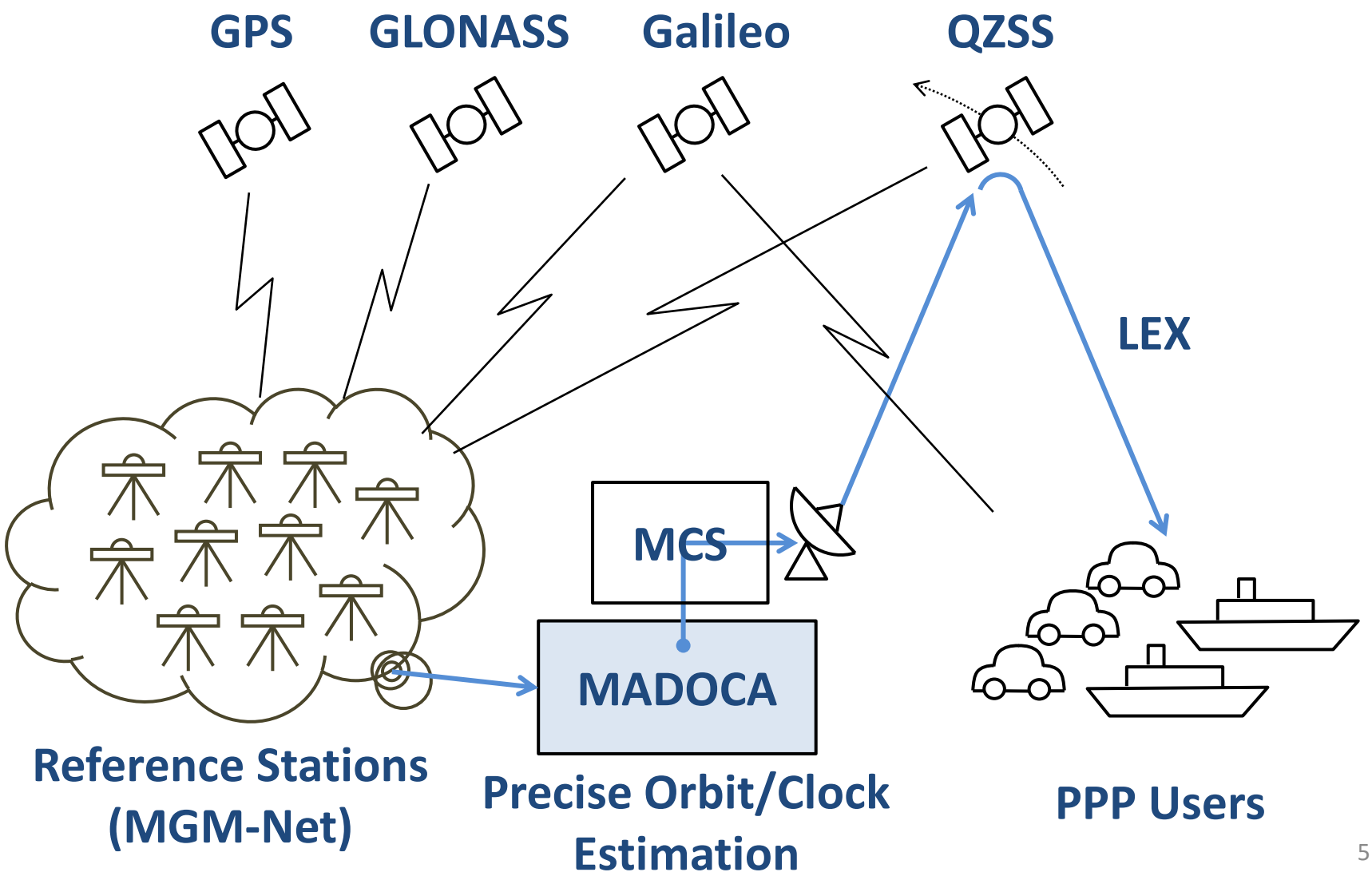
Overview

MADOCA

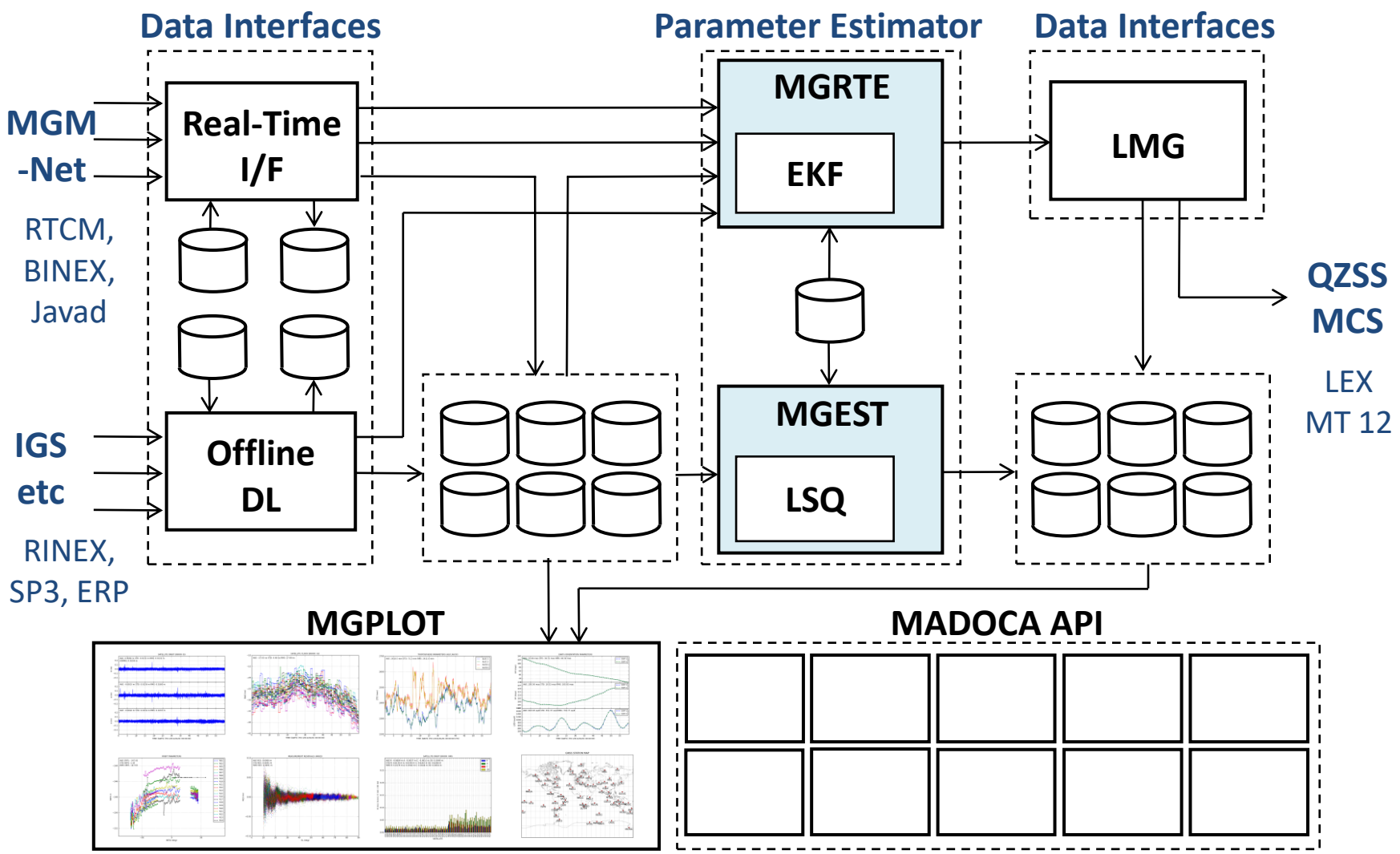
Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis

- **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

Real-Time PPP via QZSS



MADOCA Architecture

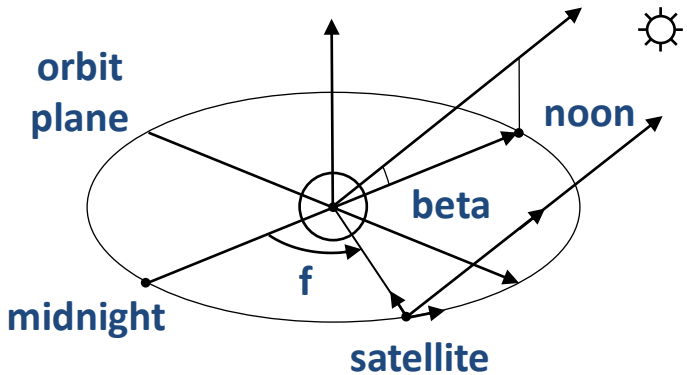


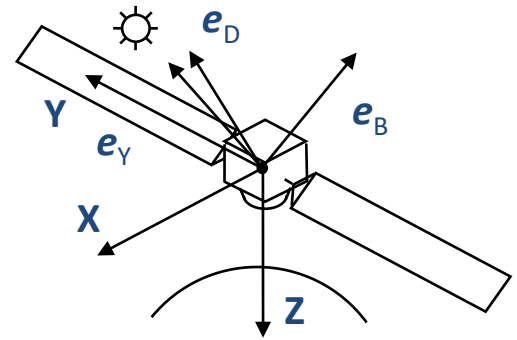
Models and Algorithms

Models

- **Satellite Orbit Models**
  - EGM 2008+solid earth tide+FES2004
  - Sun, Moon, Venus and Jupiter with JPL DE421
  - Empirical SRP model, ...
- **Measurement Models**
  - ZD Iono-free phase+ pseudorange, 2nd-order-iono
  - ZTD+gradient estimation with GPT+GMF/VMF1
  - IERS DEHANTIDEINEL+FES2004+pole tide+CMC
- **ECI-ECEF Coordinates Transformation**
  - IAU 2000A/2006 by IAU SOFA

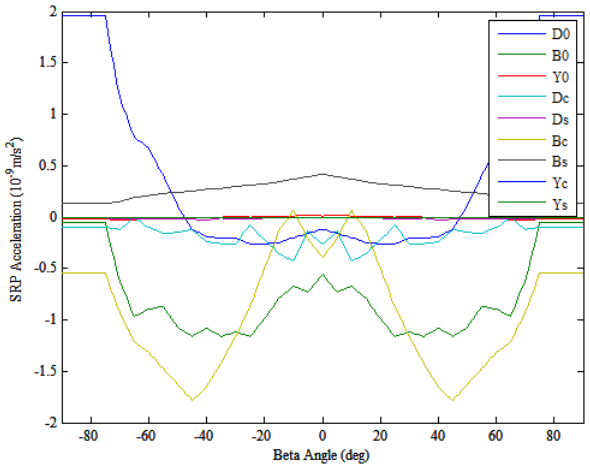
Empirical SRP Model



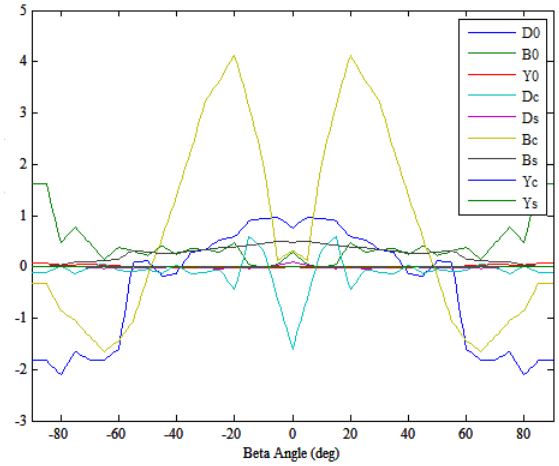


$$\boldsymbol{a}_{srp} = S\left((D_0 + D_C \cos f + D_S \sin f)\,\boldsymbol{e}_D + (B_0 + B_C \cos f + B_S \sin f)\,\boldsymbol{e}_B + (Y_0 + Y_C \cos f + Y_S \sin f)\,\boldsymbol{e}_Y\right) \times 10^{-9}\ (m/s^2)$$

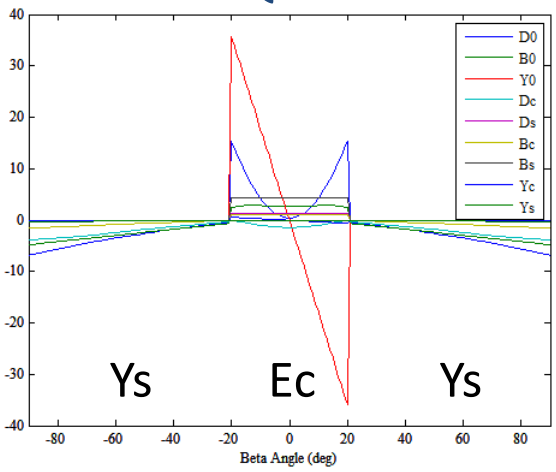
GPS Block IIR



GLONASS



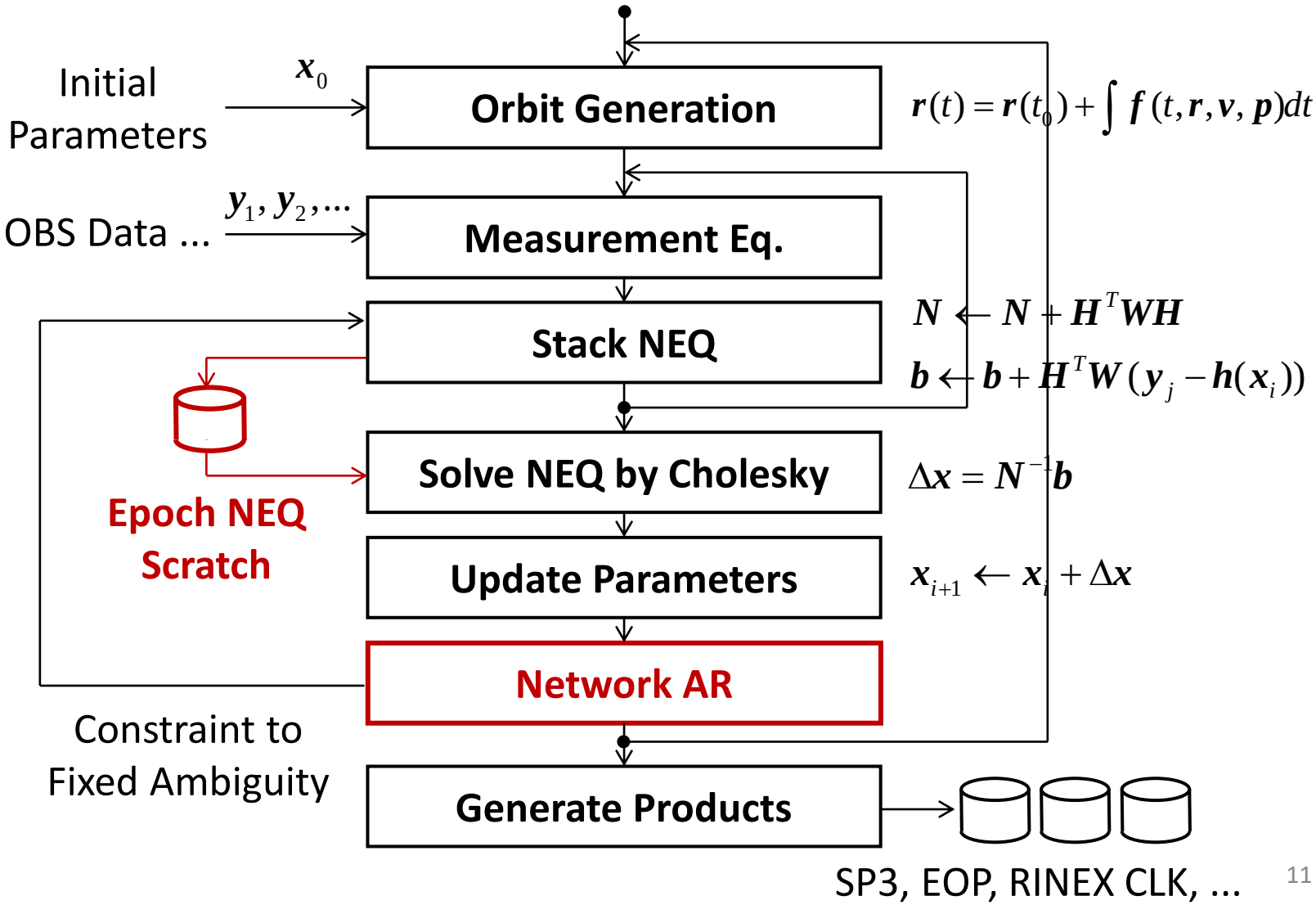
QZSS



Parameter Adjustment

	Offline	Real-Time
Algorithm	**Iterated Weighted LSQ**	**Dual-Cycle-EKF**
Estimated Parameters	Orbit, SRP/Emp-Acc, Clock, Position, ZTD/Grad, Ambiguity, Bias, EOP	
Measurements	ZD Carrier-Phase and Peudo-range	
Numerical Solver	NEQ by Cholesky Factorization	**Numerical Stable EKF**
Clock Estimation	**Parameter Elimination in NEQ**	State as White-Noise or Random-Walk
Integer Ambiguity Resolution	**Network AR** (Ge., 2005)	Real-Time Network AR

Iterated Weighted LSQ



Parameter Elimination in NEQ

$$\left(\begin{array}{c|ccc} \boldsymbol{N}_c & \boldsymbol{N}_{ce,1} & \cdots & \boldsymbol{N}_{ce,m} \\ \hline \boldsymbol{N}_{ce,1}{}^T & \boldsymbol{N}_{e,1} & & \\ \vdots & & \ddots & \\ \boldsymbol{N}_{ce,m}{}^T & & & \boldsymbol{N}_{e,m} \end{array}\right) \left(\begin{array}{c} \hat{\boldsymbol{x}}_c \\ \hline \hat{\boldsymbol{x}}_{e,1} \\ \vdots \\ \hat{\boldsymbol{x}}_{e,m} \end{array}\right) = \left(\begin{array}{c} \boldsymbol{b}_c \\ \hline \boldsymbol{b}_{e,1} \\ \vdots \\ \boldsymbol{b}_{e,m} \end{array}\right)$$

neq_stack()

$$\boldsymbol{N} \leftarrow \boldsymbol{N} + \boldsymbol{H}_i{}^T \boldsymbol{W}_i \boldsymbol{H}_i$$

$$\boldsymbol{b} \leftarrow \boldsymbol{b} + \boldsymbol{H}_i{}^T \boldsymbol{W}_i \boldsymbol{y}_i$$

neq_elim_ep()

$$\boldsymbol{N}_c \leftarrow \boldsymbol{N}_c - \boldsymbol{N}_{ce,i} \boldsymbol{N}_{e,i}{}^{-1} \boldsymbol{N}_{ce,i}{}^T$$

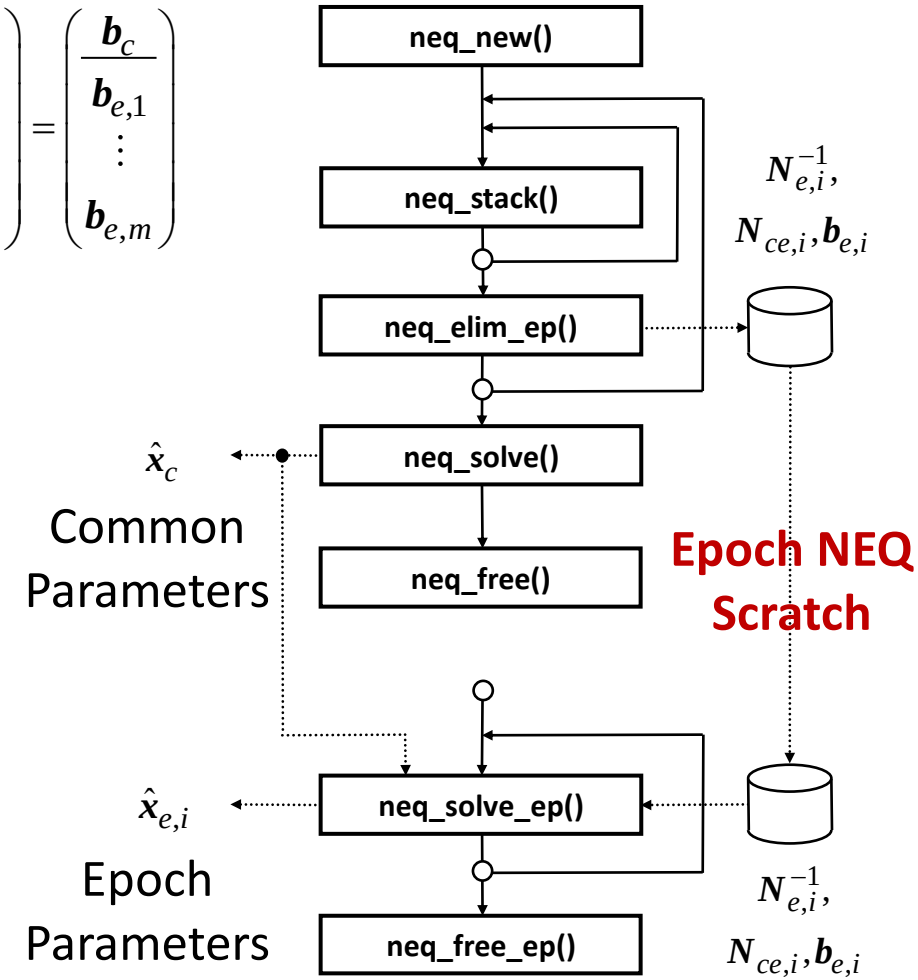
$$\boldsymbol{b}_c \leftarrow \boldsymbol{b}_c - \boldsymbol{N}_{ce,i} \boldsymbol{N}_{e,i}{}^{-1} \boldsymbol{b}_{e,i}$$

neq_solve()

$$\hat{\boldsymbol{x}}_c \leftarrow \boldsymbol{N}_c{}^{-1} \boldsymbol{b}_c$$

neq_solve_ep()

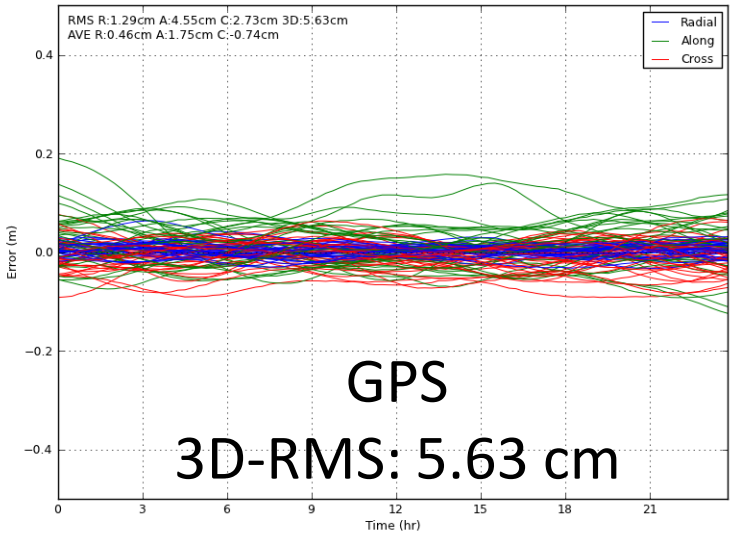
$$\hat{\boldsymbol{x}}_{e,i} \leftarrow \boldsymbol{N}_{e,i}{}^{-1} (\boldsymbol{b}_{e,i} - \boldsymbol{N}_{ce,i} \hat{\boldsymbol{x}}_c)$$



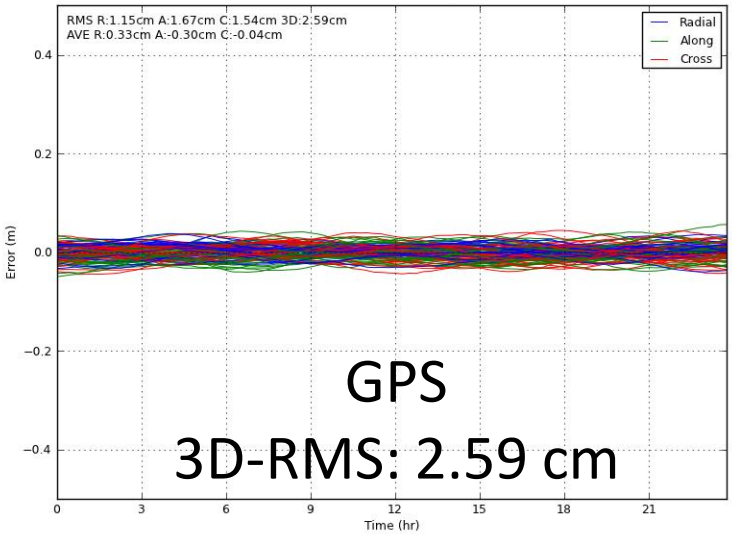
Network AR

- Dynamic baseline selection to convert ZD to DD
- WL and NL DD ambiguities by rounding
- Validation by confidence function and FCB
- For GPS, QZSS and Galileo (no GLONASS)

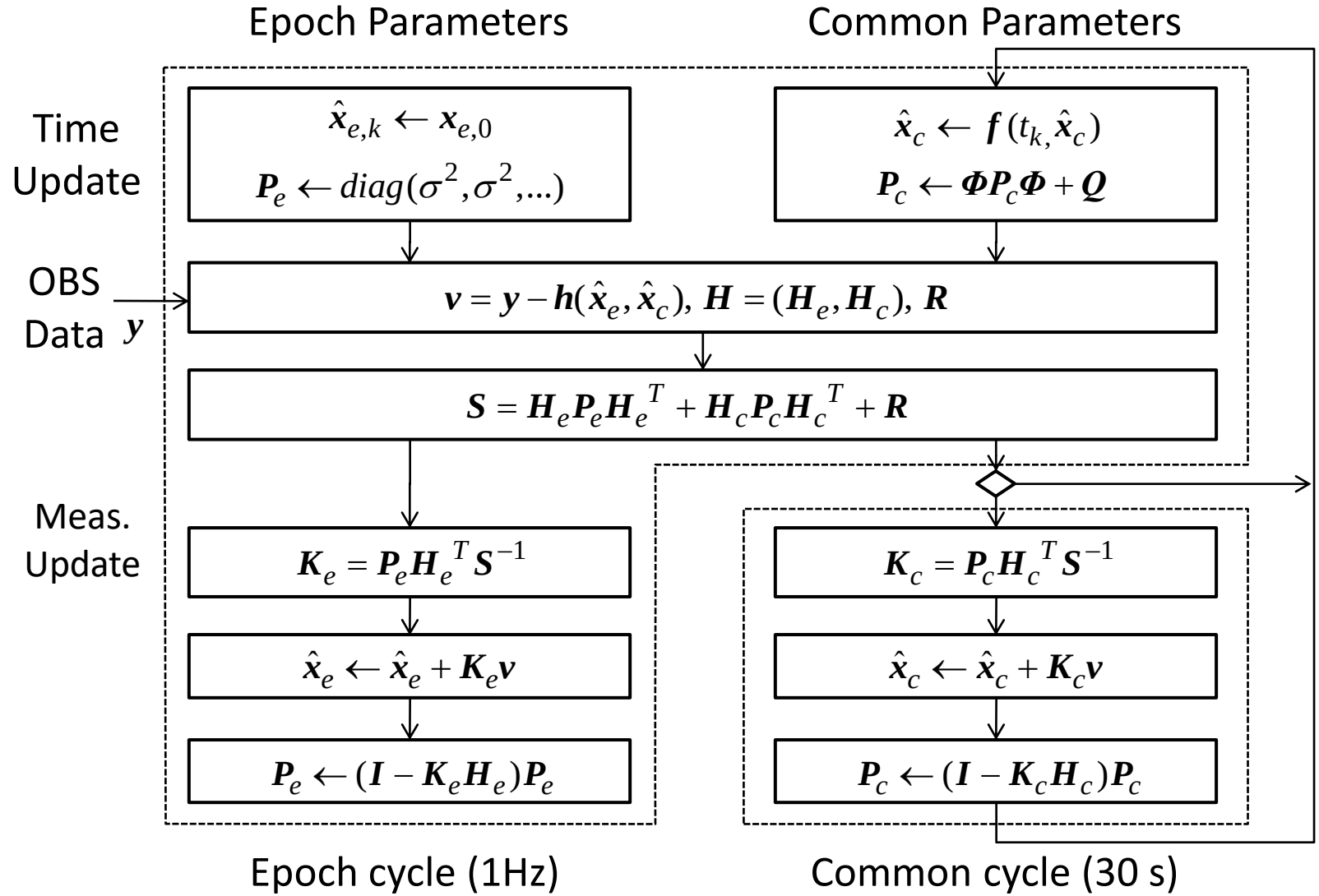
AR-OFF



AR-ON



Dual-Cycle-EKF



Numerically Stable EKF

Measurement Update of EKF

$$\boldsymbol{K} = \boldsymbol{P}^{-}\boldsymbol{H}^{T}(\boldsymbol{H}\boldsymbol{P}^{-}\boldsymbol{H}^{T} + \boldsymbol{R})^{-1}$$

$$\boldsymbol{x}^{+} = \boldsymbol{x}^{-} + \boldsymbol{K}(\boldsymbol{y} - \boldsymbol{h}(\boldsymbol{x}^{-}))$$

$$\boldsymbol{P}^{+} = (\boldsymbol{I} - \boldsymbol{K}\boldsymbol{H})\boldsymbol{P}^{-}$$

Standard EKF

(1) $\mathbf{v} = \mathbf{y} - \mathbf{h}(\mathbf{x})$, $\mathbf{H}$, $\mathbf{R}$	
(2) $\mathbf{D} = \mathbf{P}\,\mathbf{H}^{T}$	(sparse)
(3) $\mathbf{S} = \mathbf{H}\,\mathbf{D} + \mathbf{R}$	(sparse)
(4) $\mathbf{U} = \mathrm{chol}(\mathbf{S})$	DPOTRF
(5) $\mathbf{K} = (\mathbf{D}\,\mathbf{U}^{-1})\,\mathbf{U}^{-T}$	DTRSM
(6) $\mathbf{x} = \mathbf{x} + \mathbf{K}\,\mathbf{v}$	DGEMV
(7) $\mathbf{P} = \mathbf{P} - \mathbf{K}\,\mathbf{D}^{T}$	DGEMM

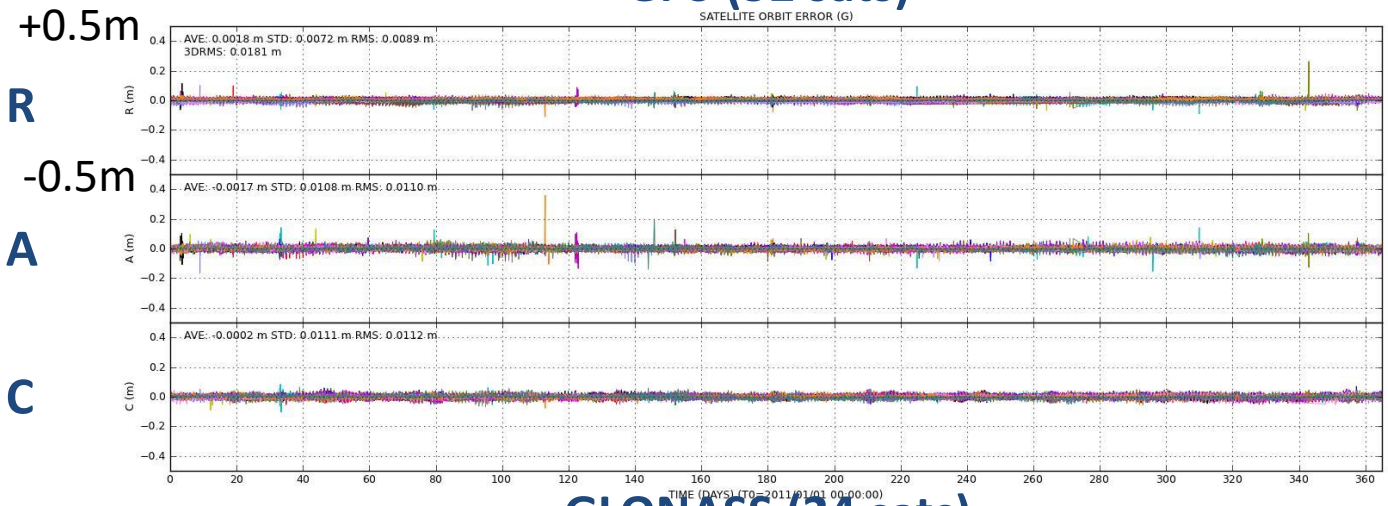
Numerically Stable EKF

(1) $\mathbf{v} = \mathbf{y} - \mathbf{h}(\mathbf{x})$, $\mathbf{H}$, $\mathbf{R}$	
(2) $\mathbf{D} = \mathbf{P}\,\mathbf{H}^{T}$	(sparse)
(3) $\mathbf{S} = \mathbf{H}\,\mathbf{D} + \mathbf{R}$	(sparse)
(4) $\mathbf{U} = \mathrm{chol}(\mathbf{S})$	DPOTRF
(5) $\mathbf{E} = \mathbf{D}\,\mathbf{U}^{-1}$	DTRSM
(6) $\mathbf{K} = \mathbf{E}\,\mathbf{U}^{-T}$	DTRSM
(7) $\mathbf{x} = \mathbf{x} + \mathbf{K}\,\mathbf{v}$	DGEMV
(8) $\mathbf{P} = \mathbf{P} - \mathbf{E}\,\mathbf{E}^{T}$	DSYRK

Evaluation

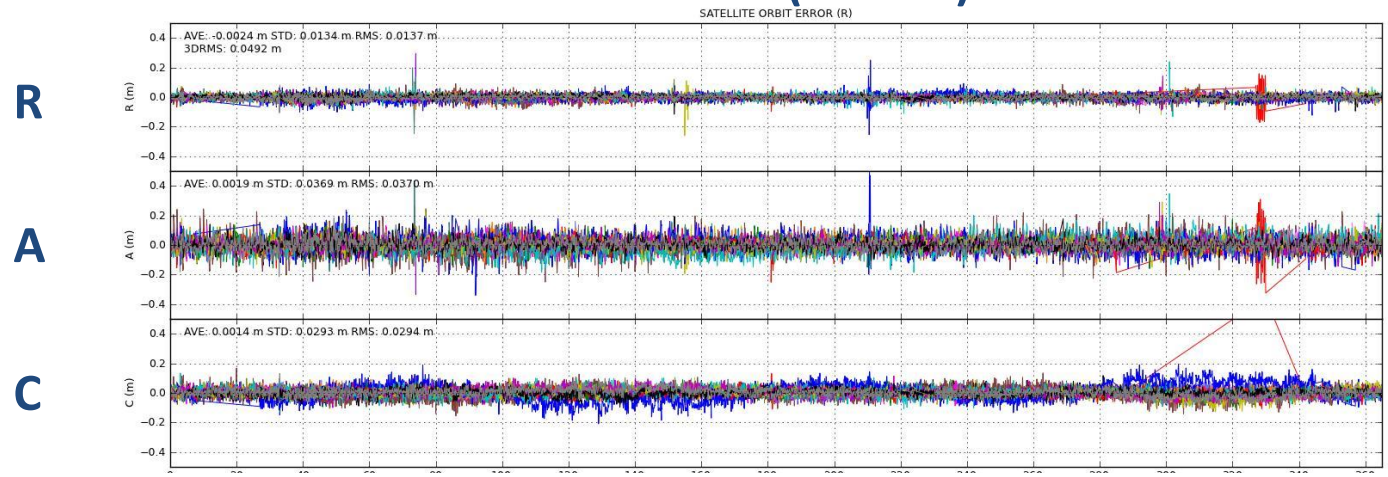
Offline GPS/GLO Orbit

GPS (32 sats)



RMS
R: 0.89 cm
A: 1.10 cm
C: 1.12 cm
3D: 1.81 cm

GLONASS (24 sats)



RMS
R: 1.37 cm
A: 3.70 cm
C: 2.94 cm
3D: 4.92 cm

2011/01/01 - 2011/12/31 (365 days), wrt IGS Final

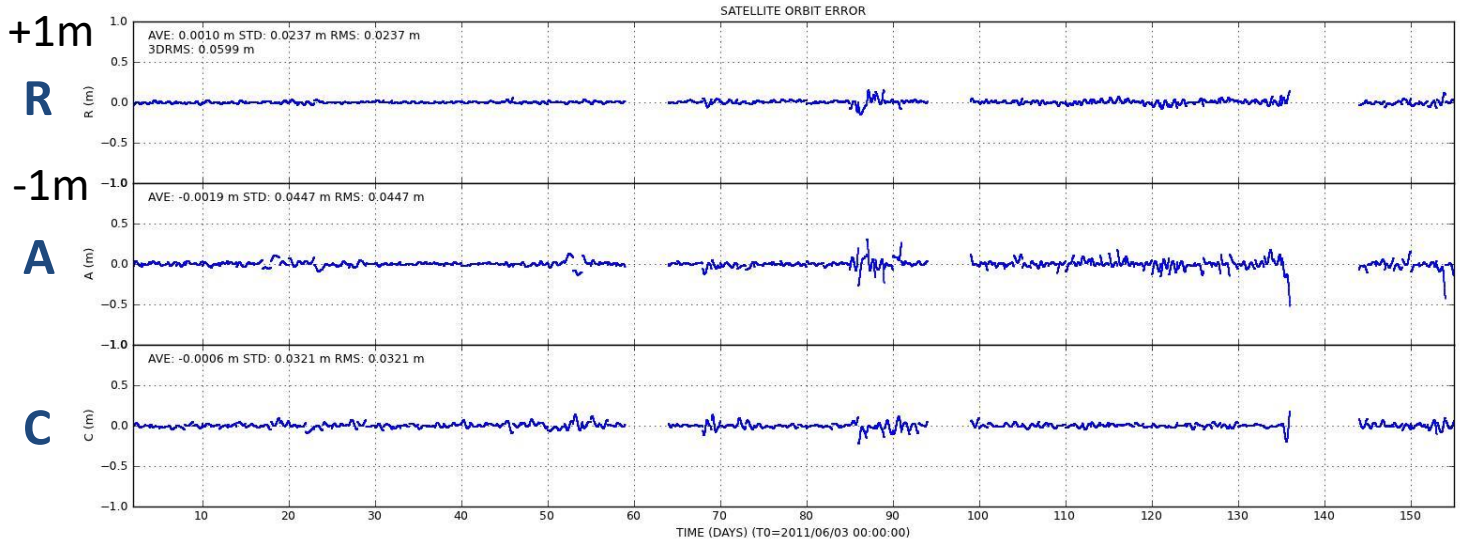
GPS Orbit vs. IGS AC

IGS AC	Analysis Software	# of Stas	GPS Orbit RMS (cm)				Clock (ns)	
			R	A	C	3D	STD	RMS
	MADOCA 0.3.0	**77**	**0.89**	**1.10**	**1.12**	**1.81**	**0.109**	**0.131**
ESA	NAPEOS 3.5	110	0.97	1.33	1.09	1.98	0.116	0.183
CODE	Bernese 5.1	231	1.01	1.36	1.14	2.04	0.075	0.089
NGS	arc, orb, pages, gpscom	199	0.95	1.46	1.41	2.24	-	-
GFZ	EPOS.P.V2	191	1.15	1.64	1.59	2.56	0.146	0.169
MIT	GAMIT 10.33, GLOBK 5.16	263	1.37	2.12	1.39	2.88	0.277	0.316
NRCan	GIPSY/OASIS-II 5.0	91	2.58	1.72	1.77	3.57	0.128	0.148
JPL	GIPSY/OASIS-II 5.0	142	2.62	1.67	1.98	3.68	0.168	0.226
SIO	GAMIT 10.20, GLOBK 5.08	258	2.42	2.26	1.77	3.75	-	-
GRG	GINS, DYNAMO	134	2.47	2.80	1.74	4.12	0.172	0.212

2011/01/01 -2011/12/31 (365 days), wrt IGS Final

Offline QZSS Orbit

QZSS-1 Michibiki J01



RMS
R: 2.37 cm
A: 4.47 cm
C: 3.21 cm
3D: 5.99 cm

2011/06/04 - 2011/11/03 (153 days), 24 H-overlap

Offline Galileo Orbit

Galileo E11

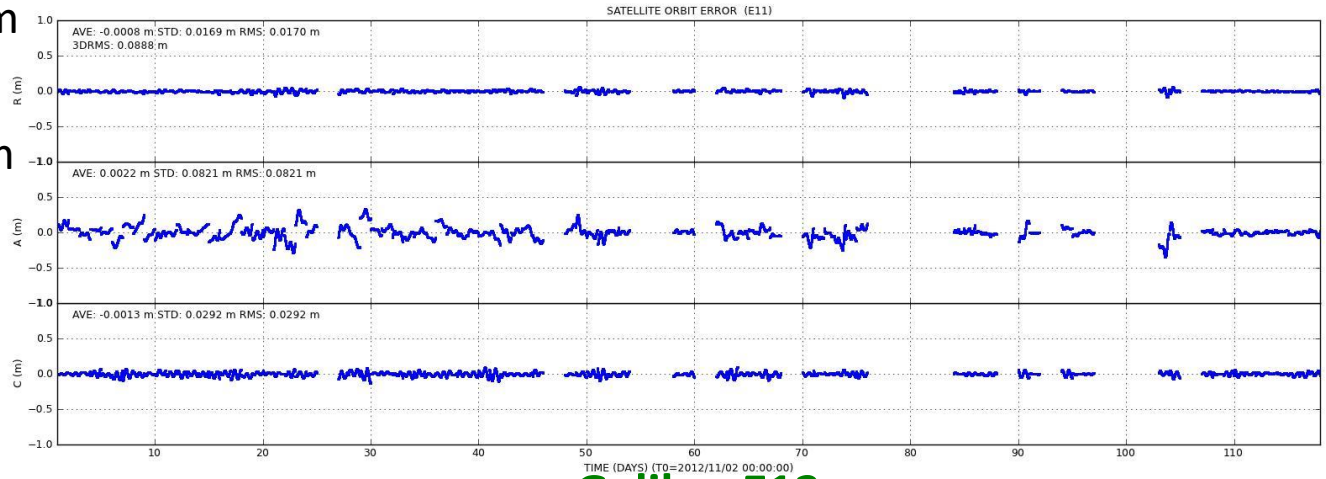
+1m

R

-1m

A

C



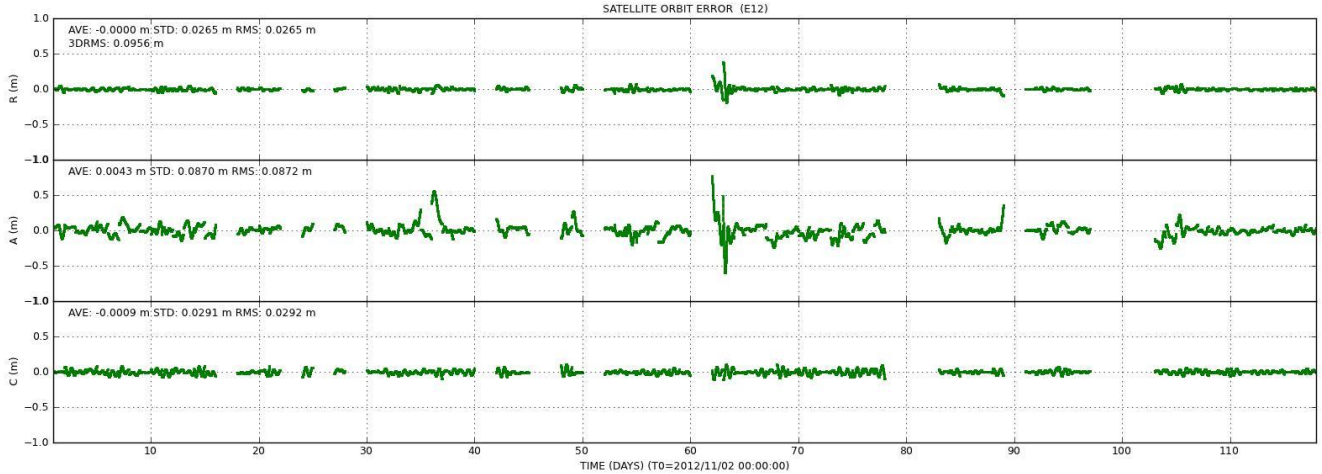
RMS
R: 1.70 cm
A: 8.21 cm
C: 2.92 cm
3D: 8.88 cm

Galileo E12

R

A

C



RMS
R: 2.65 cm
A: 8.72 cm
C: 2.92 cm
3D: 9.56 cm

2012/11/2 - 2013/02/27 (117 days), 24H-overlap

Galileo Orbit vs. TUM/GRM

Galileo E11, E12: MADOCA - TUM

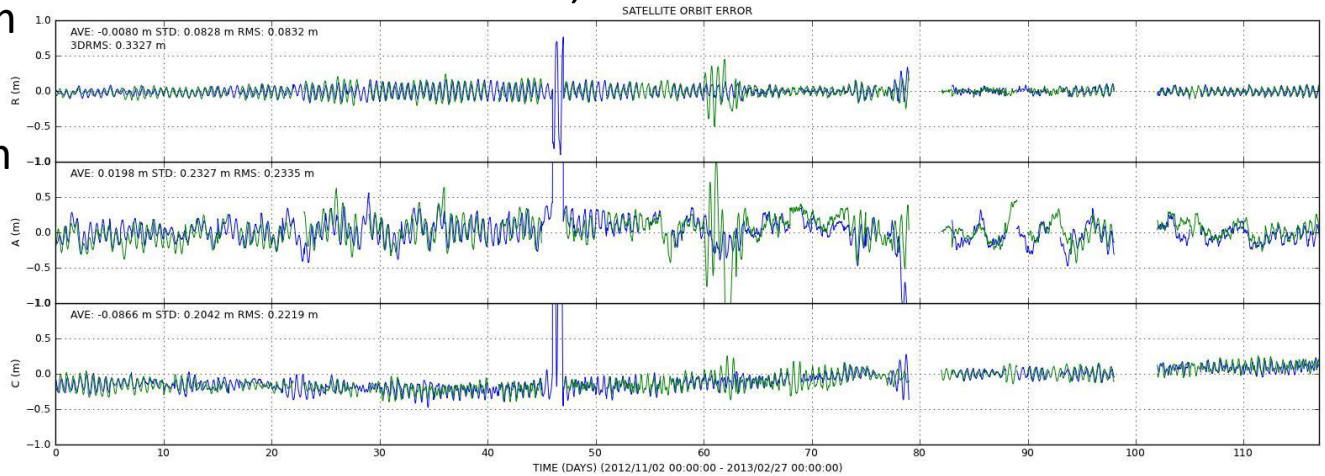
+1m

R

-1m

A

C



RMS

R: 8.32 cm

A: 23.35 cm

C: 22.19 cm

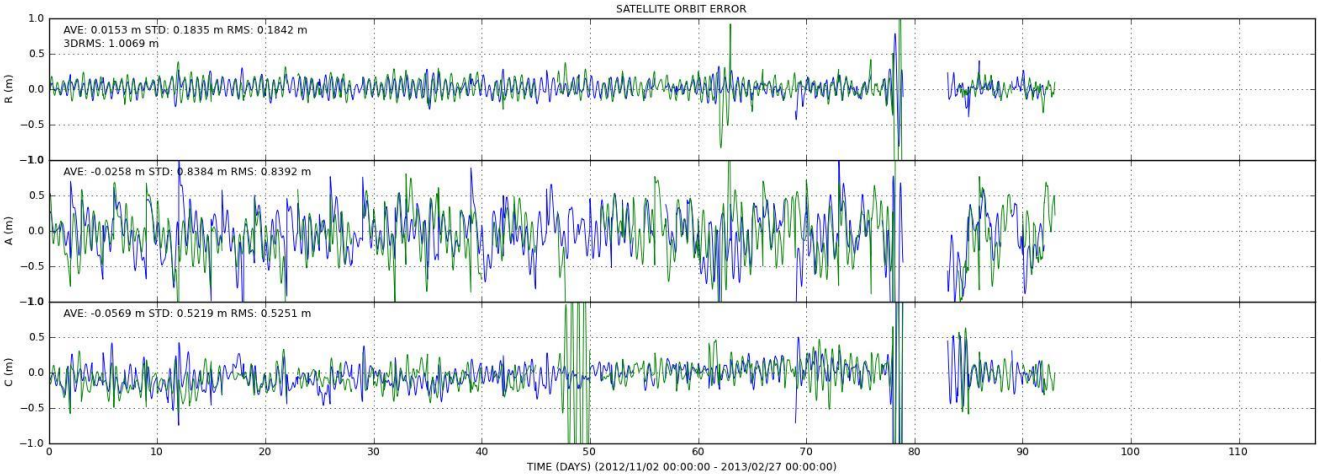
3D: 33.27 cm

Galileo E11, E12: MADOCA - GRM

R

A

C



RMS

R: 18.42 cm

A: 83.92 cm

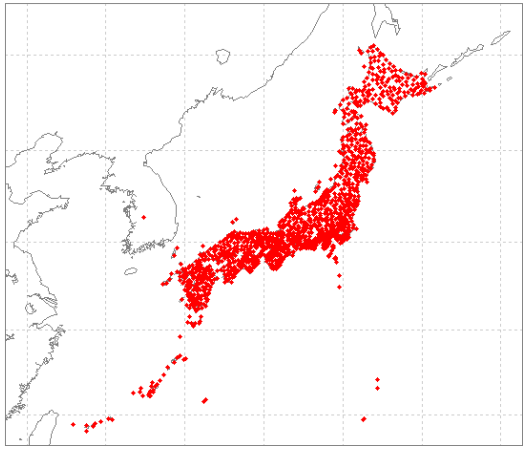
C: 52.51 cm

3D: 100.69 cm

2012/11/02 - 2013/02/27 (117 days)

Large Network Solution

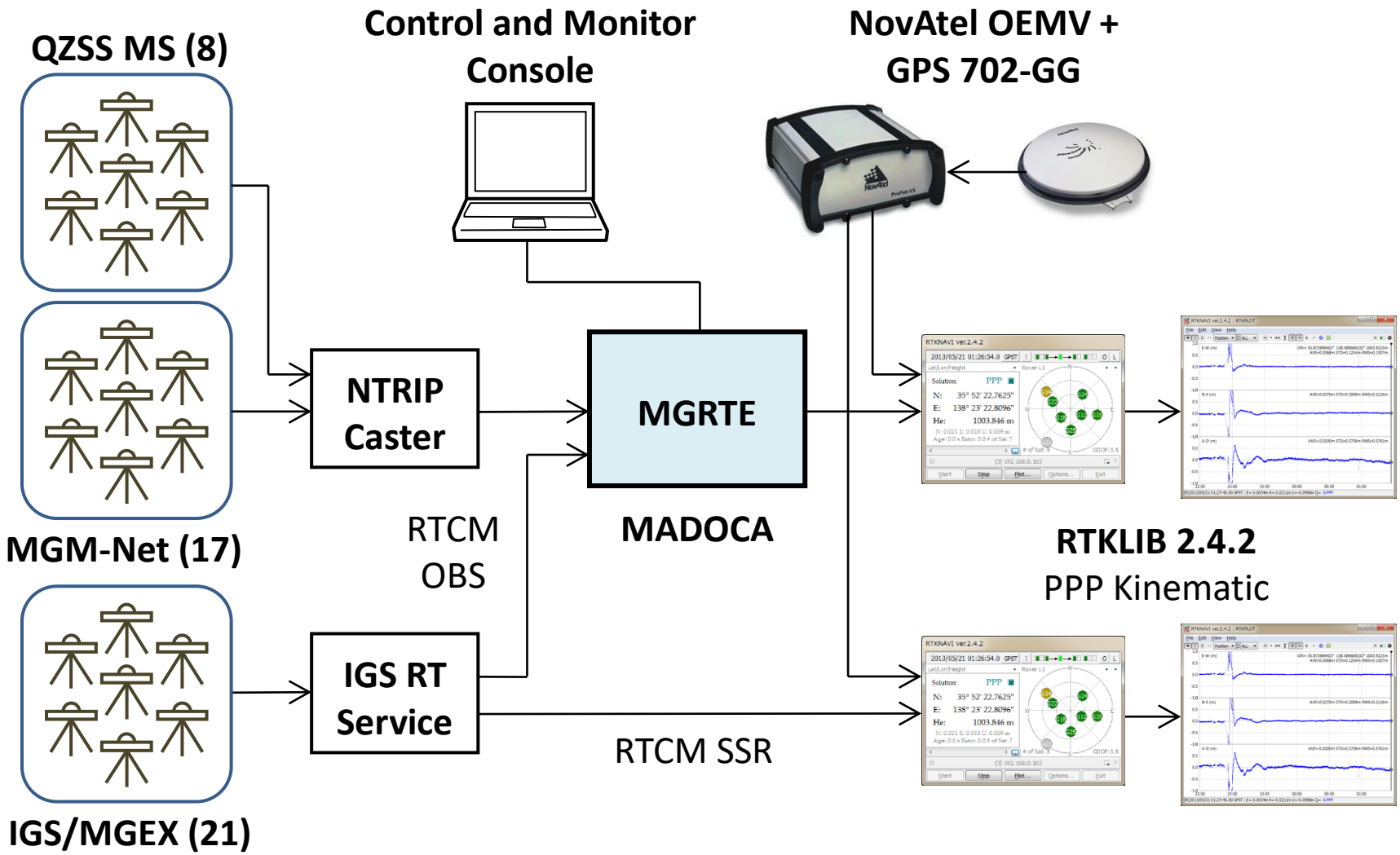
- **Single NEQ + Network AR**
  - GEONET (1244) + IGS (7)
  - Position (24h static), Clock, ZTD/Grad and Ambiguity



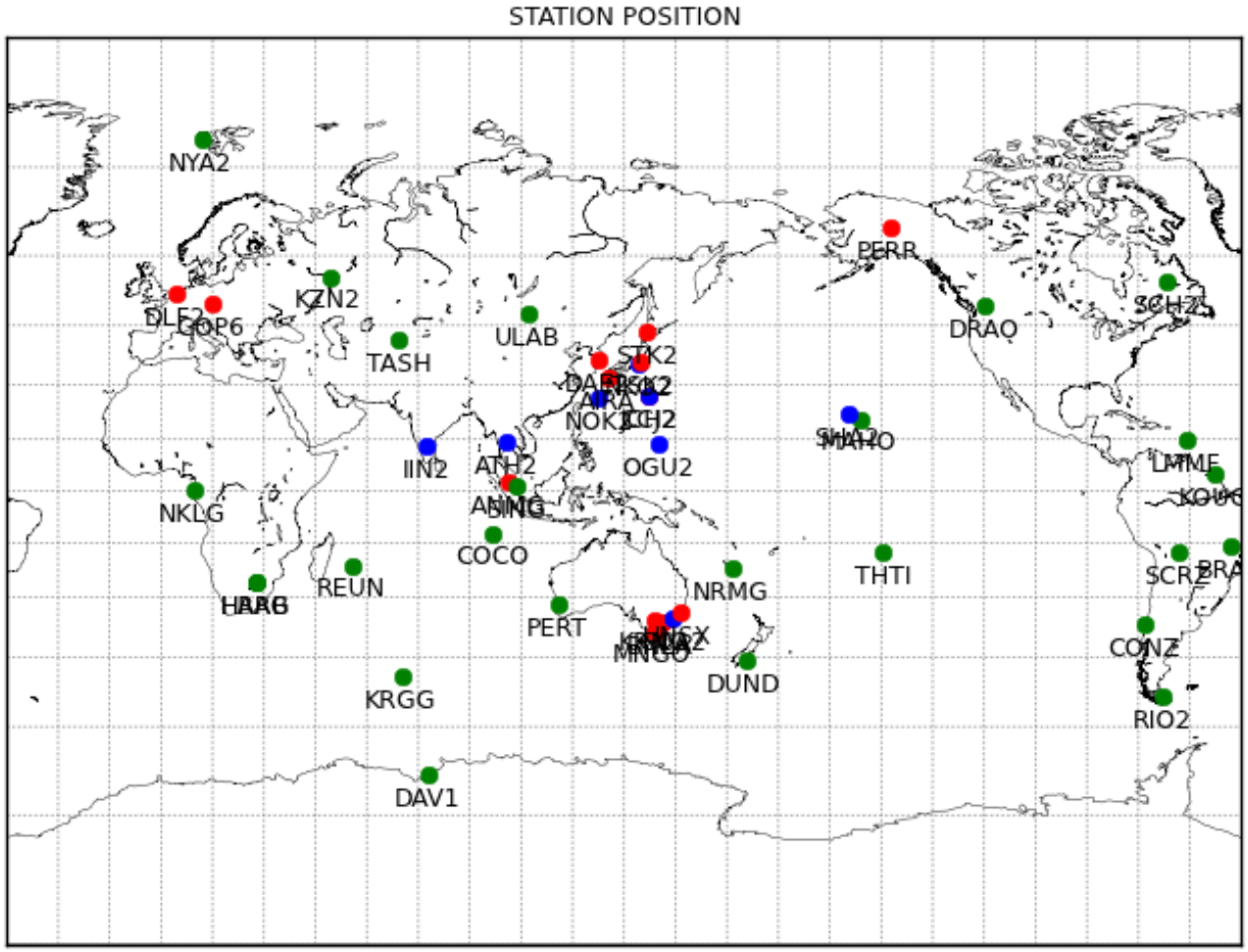
# Estimations			# Parameters		CPU Resource		
Sat	**Sta**	**EP**	**CMN**	**EP**	**RAM**	**File**	**Time**
31	307	288	28,770	97,632	9.1 GB	21.2 GB	15m
31	604	288	57,099	183,168	29.2 GB	78.8 GB	1h 40m
31	904	288	86,659	269,568	62.8 GB	173.9 GB	5h 27m
31	**1,251**	**288**	**119,090**	**369,216**	**113.3 GB**	**380.4 GB**	**14h 05m**

Xeon E5-2687W x 2 (16 core), RAM 128 GB, HDD 8TB, SSD 480GB

Real-Time PPP Test



Reference Station Network



● QZSS-MS (8) ● MGM-Net (17) ● IGS/MGEX (21)

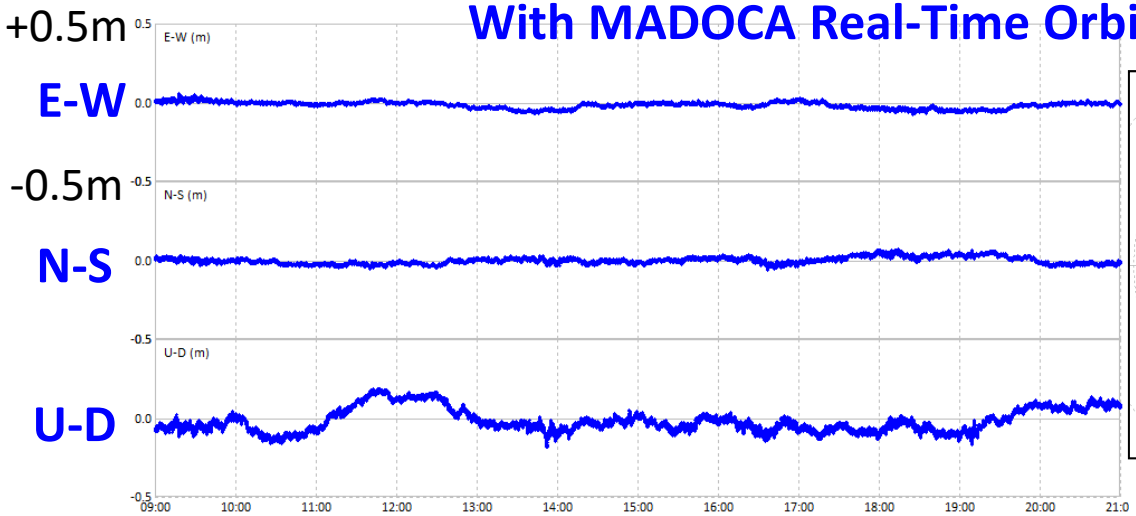
Test Snapshots

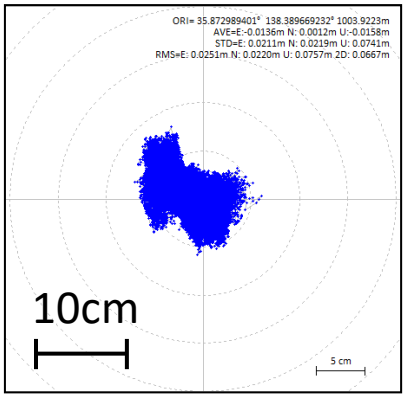
Control and Monitor Console of MADOCA MGRTE

Real-time PPP by RTKLIB 2.4.2

Real-Time PPP Test Results

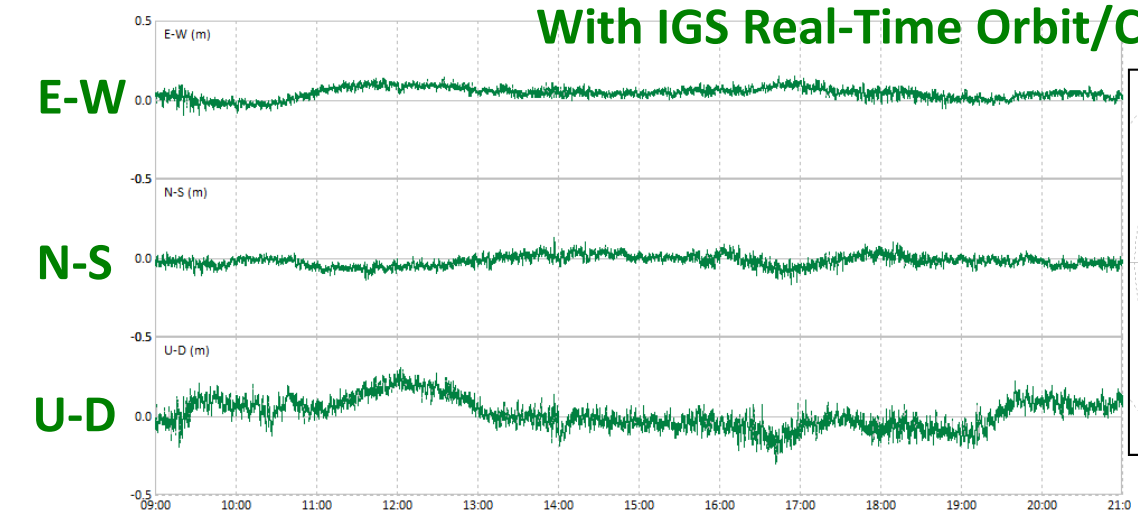
With MADOCA Real-Time Orbit/Clock

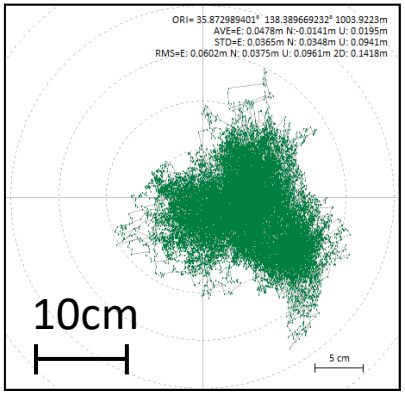




RMS
E: 2.51 cm
N: 2.20 cm
U: 7.57 cm

With IGS Real-Time Orbit/Clock

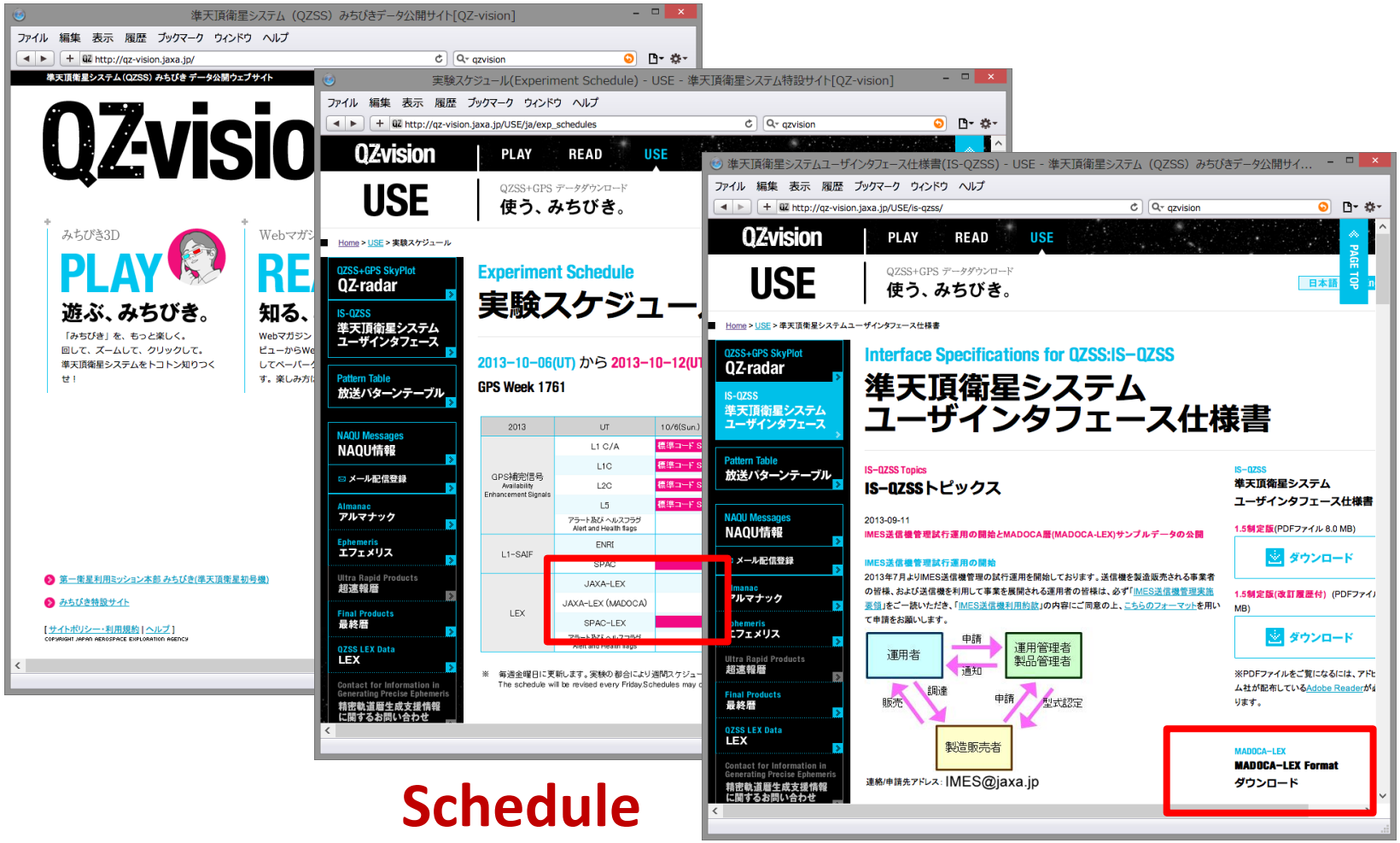




RMS
E: 6.02 cm
N: 3.75 cm
U: 9.61 cm

2013/05/20 09:00 - 21:00 (12 h), 1 Hz, only with GPS

Real-Time Experiment



Schedule

LEX Data Format

LEX Data Format (MT12)

■メッセージタイプ　　：JAXA実験用信号としてメッセージタイプ 12 で放送予定

■メッセージフォーマット　：PPPユーザ向けのRTCM(*1) SSR(State Space Representation)フォーマットに基づき、MADOCAにより生成したプロダクトを格納する。
LEXメッセージのデータ部には、RTCMメッセージの“Variable Length Data Message” のみを先頭から詰めて格納する。
LEXメッセージとRTCMメッセージの関係は、下記のとおり。
(*1)RTCM (Radio Technical Commission for Maritime services)

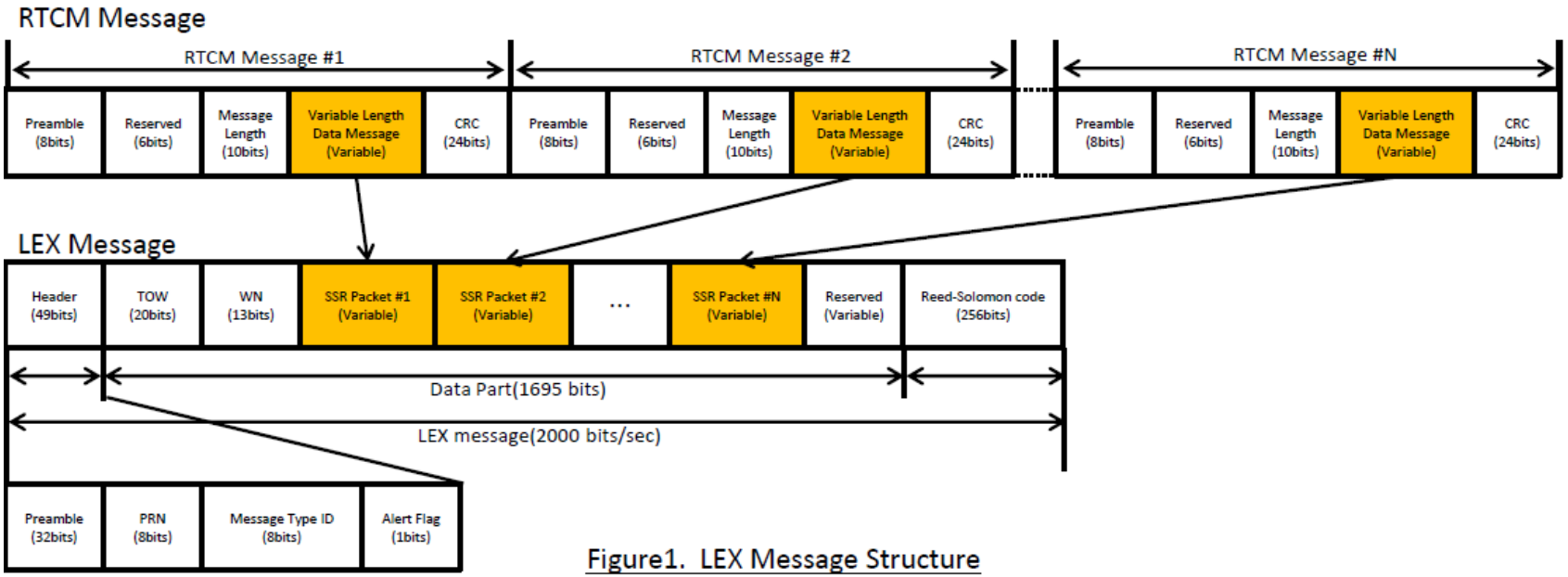


Figure1. LEX Message Structure

Conclusion

- **MADOCA**
  - Precise orbit/clock for multi-GNSS constellation
  - Offline and real-time estimation engine
  - Optimized for both of performance and accuracy
  - RT-PPP accuracy: < 5 cm HRMS, < 10 cm VRMS
  - QZSS LEX Experiment for RT-PPP (2013/4 ~)
  - Evaluation of long-term stability of RT-orbit/clock
- **Future Plan**
  - Evaluate and add RT-GLONASS orbit/clock
  - Enhancement for PPP-AR and BeiDou