平成24年度　測位航法学会全国大会

複数GNSS対応高精度軌道時刻推定ツール (MADOCA) の開発状況

Development Status of MADOCA

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、三吉基之、河手香織
日本電気株式会社　曽我広志、平原康孝

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Overview

- Background
- PPP (Precise Point Positioning)
- Design
- Models
- Implementation
- Accuracy Evaluation
- Enhancement Plan

Background

- **QZSS-1 "Michibiki" launched in Sep. 2010**
  - LEX experimental signal channel
  - 2 Kbps message band-width
  - LEX experiments by JAXA, SPAC, GSI ...
  - First phase LEX-PPP accuracy < 30 cm (H-RMS)

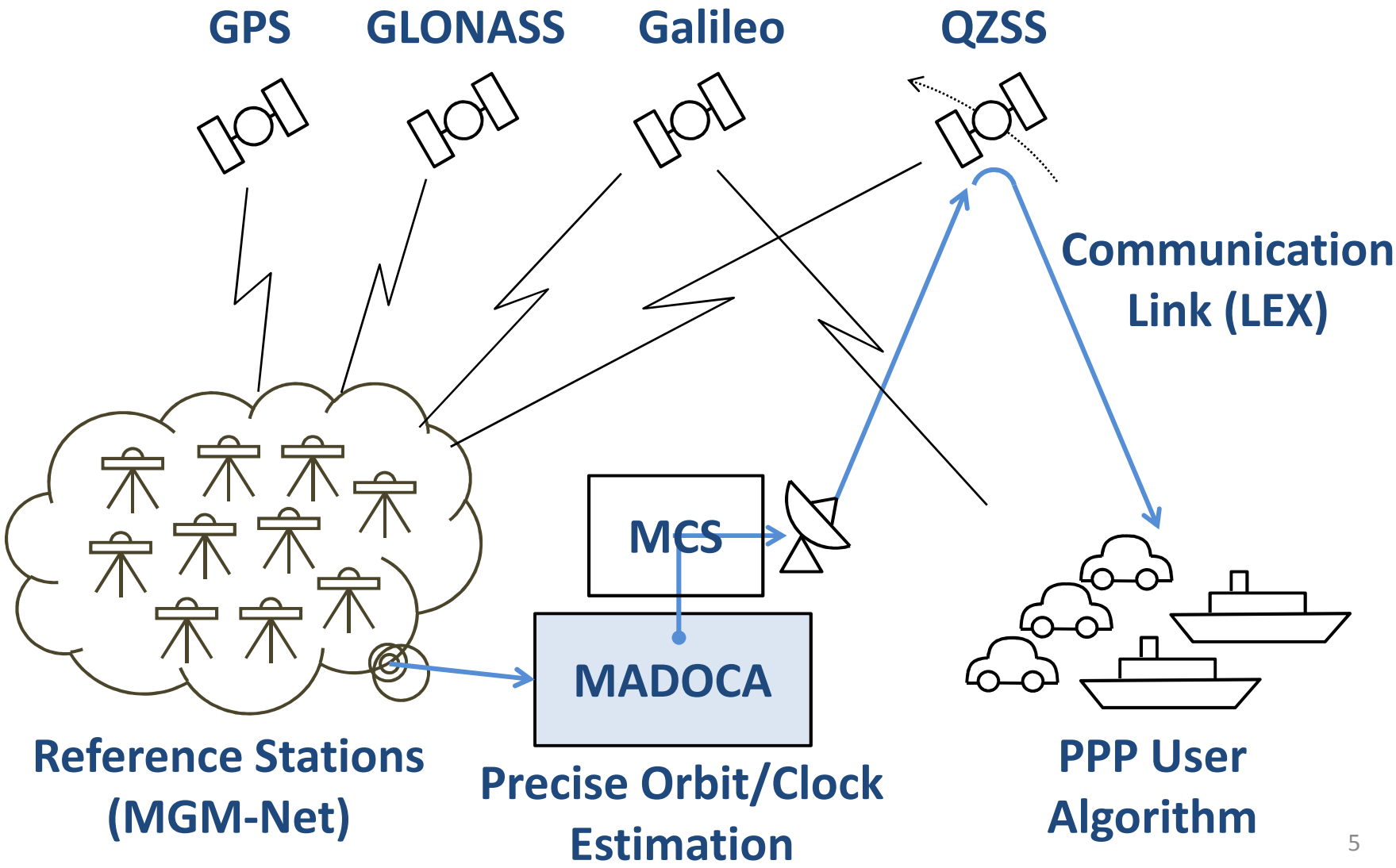
- **Multi-GNSS Demonstration Campaign**
  - MGA (Multi-GNSS Asia) activities started in 2010
  - Establishment of MGM (Multi-GNSS Monitoring) network
  - Demonstrations in various application areas
  - Regional workshops (Bangkok, Melbourne, Jeju, ...)

PPP (Precise Point Positioning)

- **Carrier-phase-based Single Positioning**
  - No need of reference stations nearby
  - Global coverage world-wide
  - Accuracy: sub-dm ~ cm-level
  - Need precise satellite orbit/clock
- **Applications (Expected)**
  - Precision agriculture, machine control
  - Crustal deformation monitoring
  - Sea surface (Tsunami) monitoring
  - GNSS meteorology, LEO satellite POD

http://www.tsunamigps.com

Architecture for Real-Time PPP

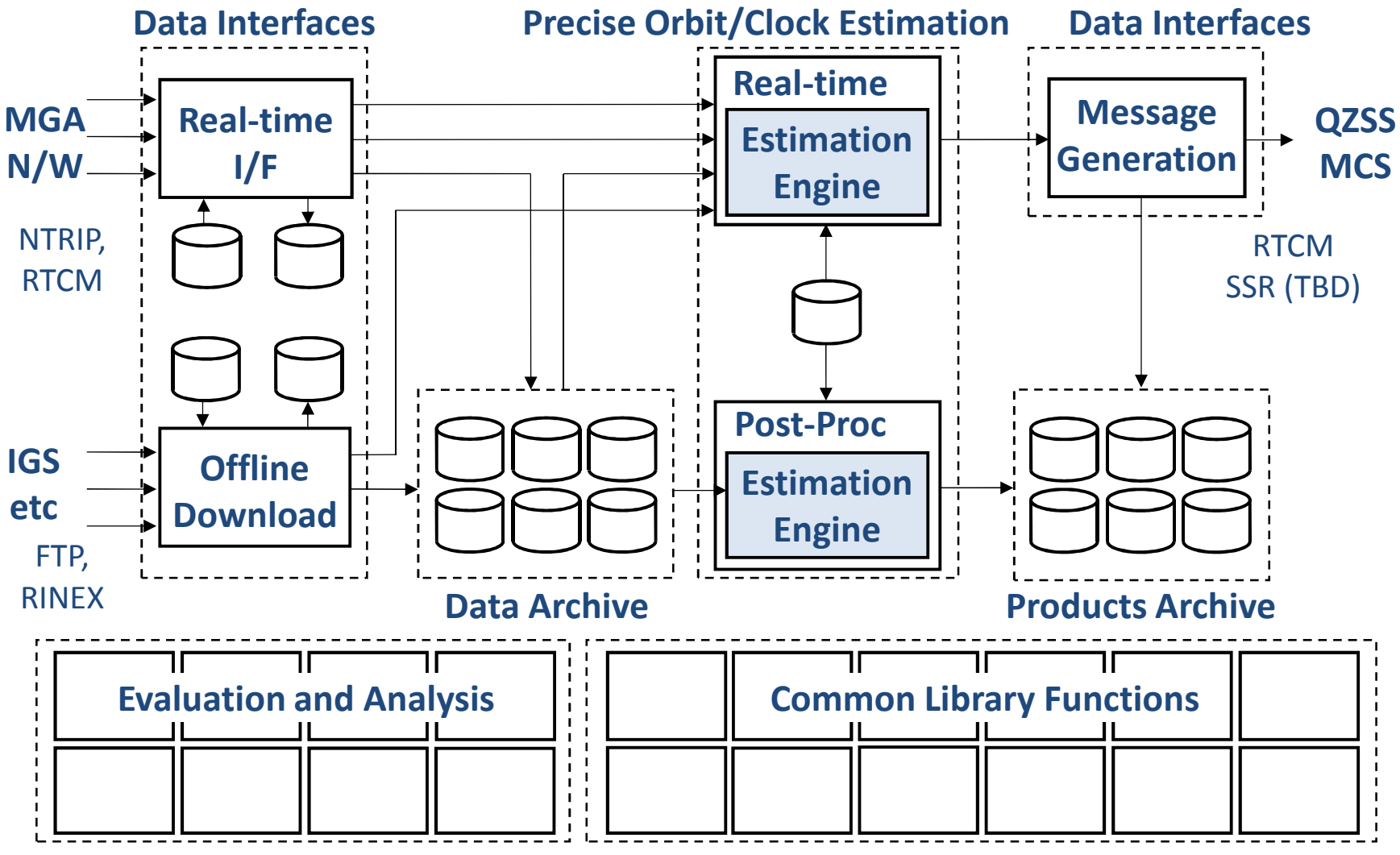


MADOCA

Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis

- **Precise Orbit/Clock Estimation for Multiple GNSS**
  - Key-technology for precise positioning with GNSS
- **Requirements**
  - Satellites: GPS, GLONASS, QZSS and Galileo
  - Offline (FY23) and real-time (FY24) functions
- **Goal of Orbit/Clock Accuracy**
  - Offline : 3 cm/0.1 ns (GPS), 7 cm/0.25 ns (GLO/QZS)
  - Real-time: 4 cm/0.1 ns (GPS), 9 cm/0.25 ns (GLO/QZS)

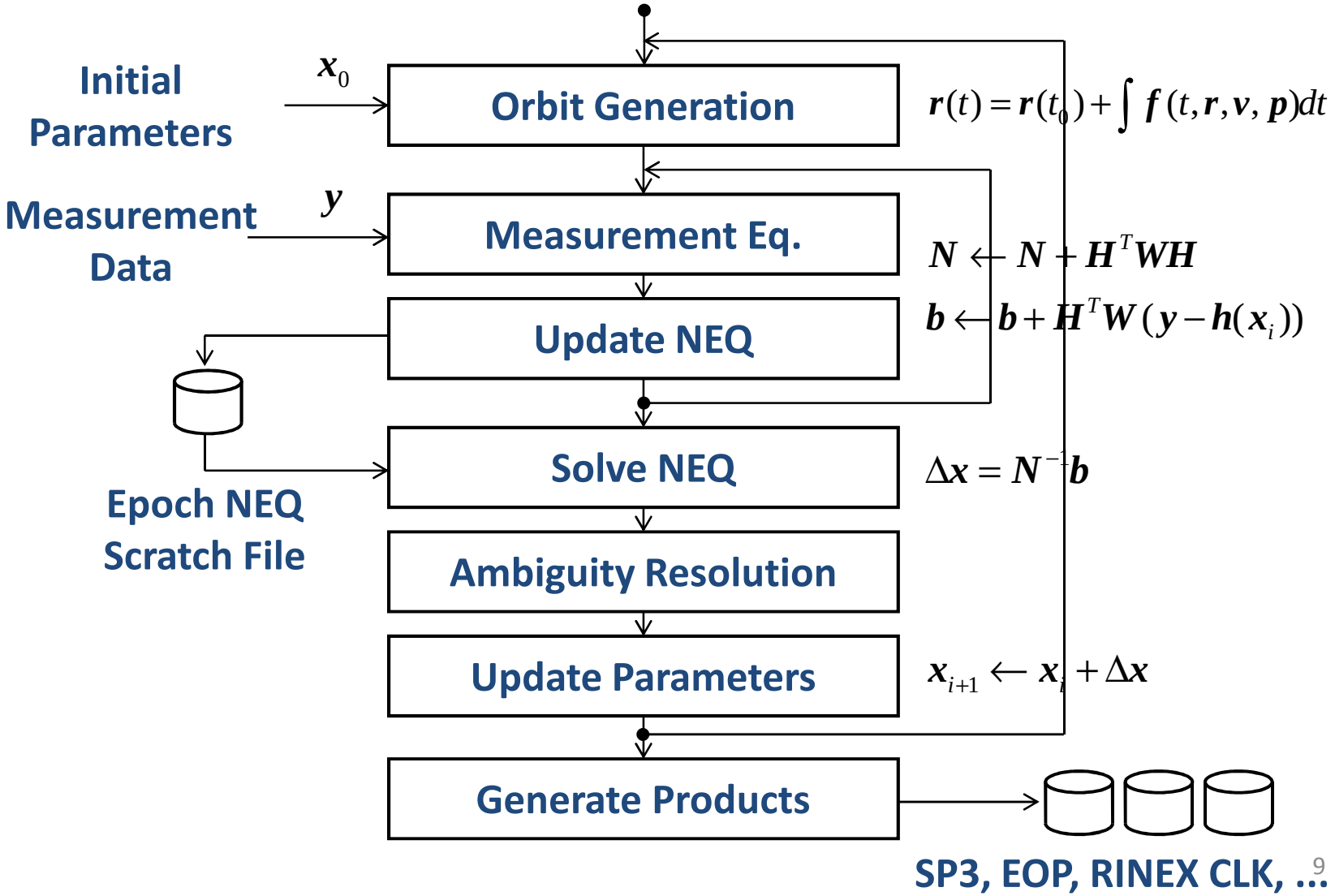
MADOCA Block Diagram



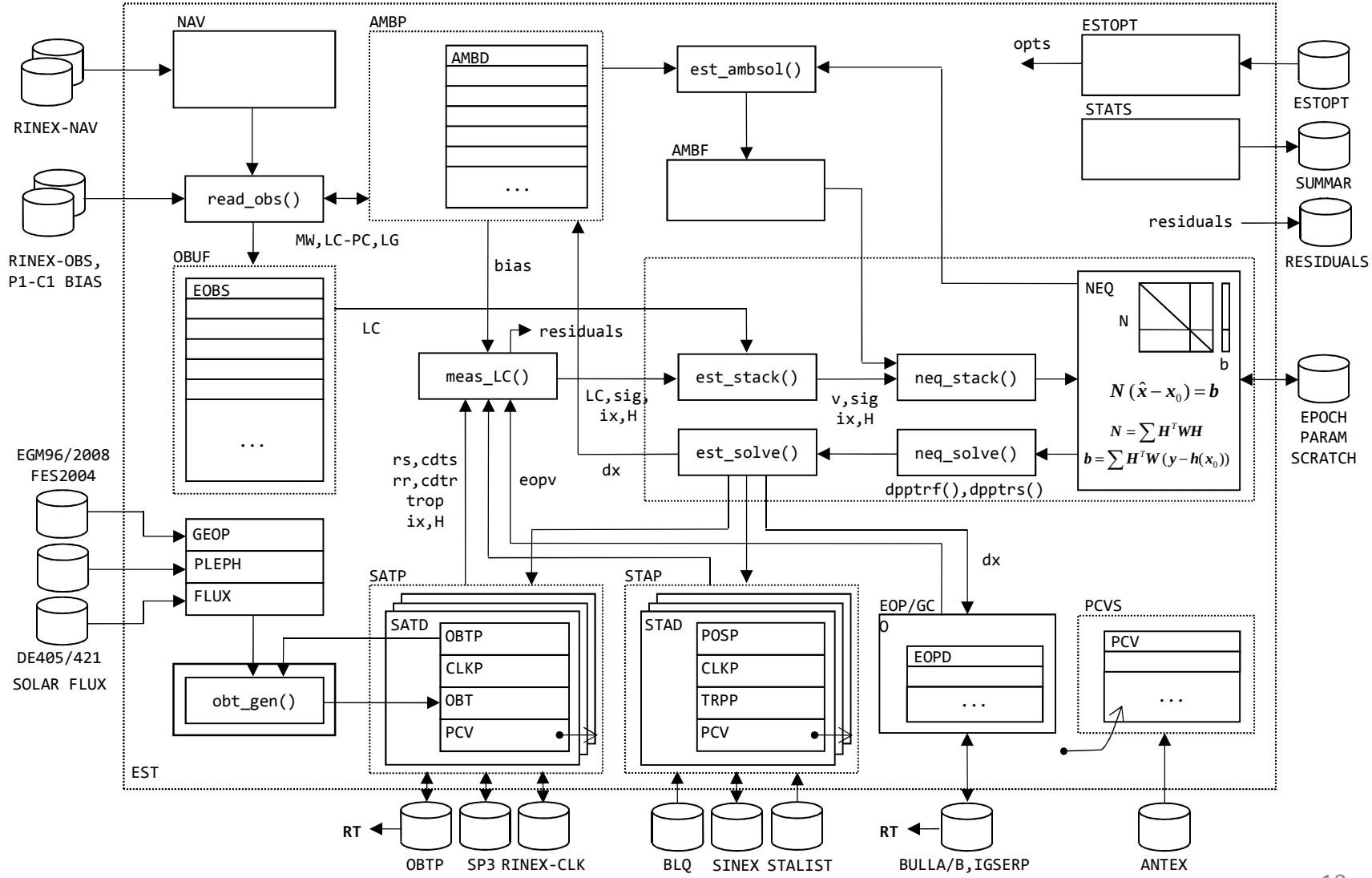
Estimation Engine Design

- **Both of Batch and Real-Time Estimators**
  - Mostly shared models and libraries
  - User-configurable with options file
- **Batch Estimator**
  - Iterated least square estimation
  - Normal equation (NEQ) by Cholesky factorization
  - Network mode ambiguity resolution (Ge et al., 2005)
- **Real-Time Estimator**
  - Extended Kalman filter (EKF)
  - Details are under design

Batch Estimator Flow



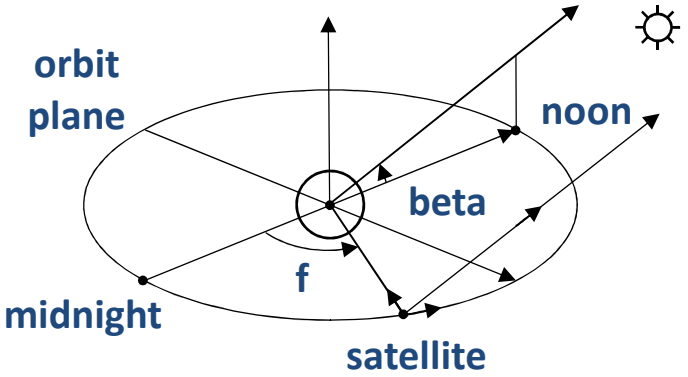
Batch Estimator Block Diagram

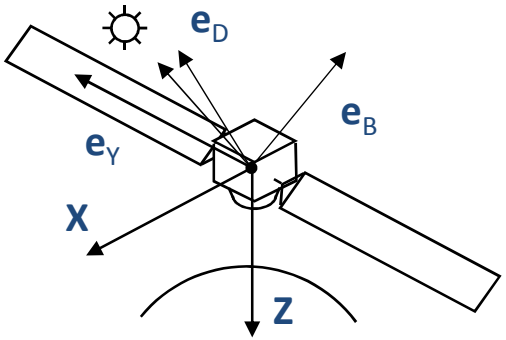


Models

- **Satellite Force Models**
  - Geopotential (EGM2008), Sun/Moon (DE421)
  - SRP and eclipse, empirical-acceleration, relativity, ...
- **Geodetic Models**
  - IAU2000A/2006 nutation/precession (SOFA)
  - Earth tides based on IERS conventions 2010
- **Measurement Models**
  - undifferenced (ZD) carrier-phase and pseudorange
  - Troposphere , antenna phase center, phase wind-up,
  - Yaw-attitude for GPS, GLO, QZSS

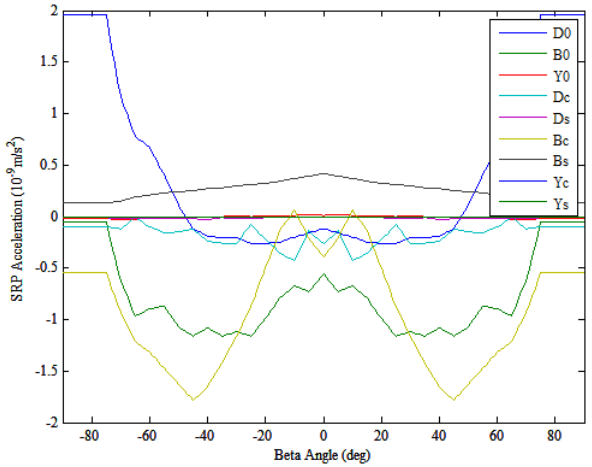
Optimized SRP Models



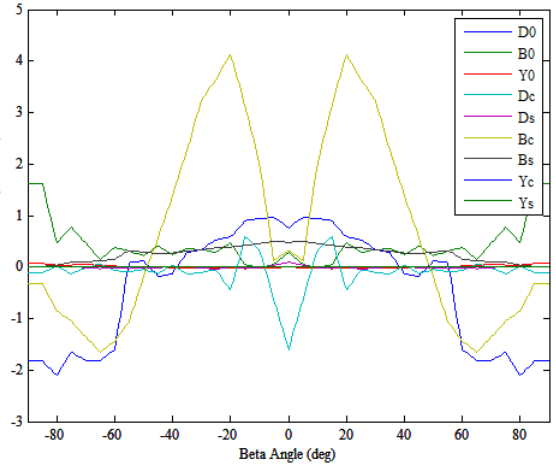


$$\mathbf{a}_{srp} = S\,((D_0 + D_C \cos f + D_S \sin f)\,\mathbf{e}_D + (B_0 + B_C \cos f + B_S \sin f)\,\mathbf{e}_B + (Y_0 + Y_C \cos f + Y_S \sin f)\,\mathbf{e}_Y) \times 10^{-9}\ (m/s^2)$$

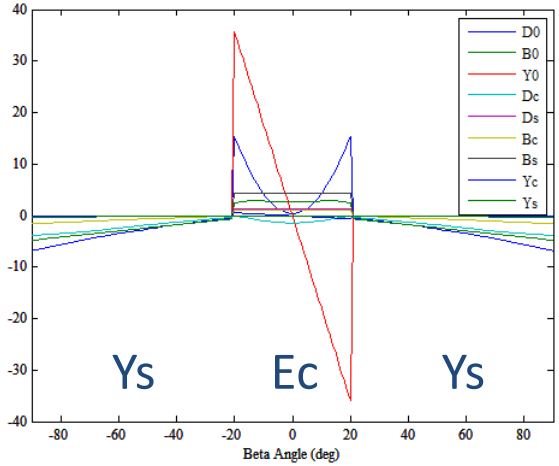
GPS Block IIR



GLONASS

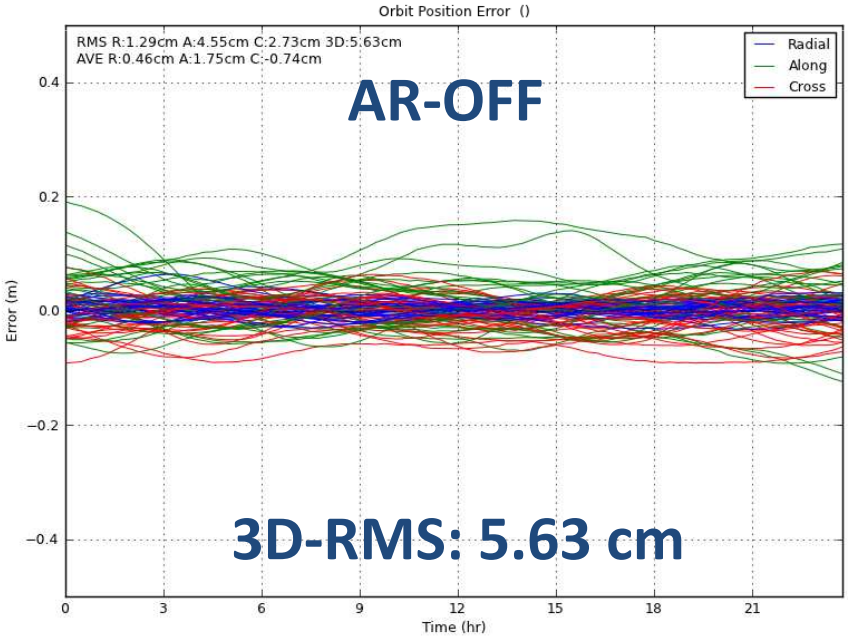


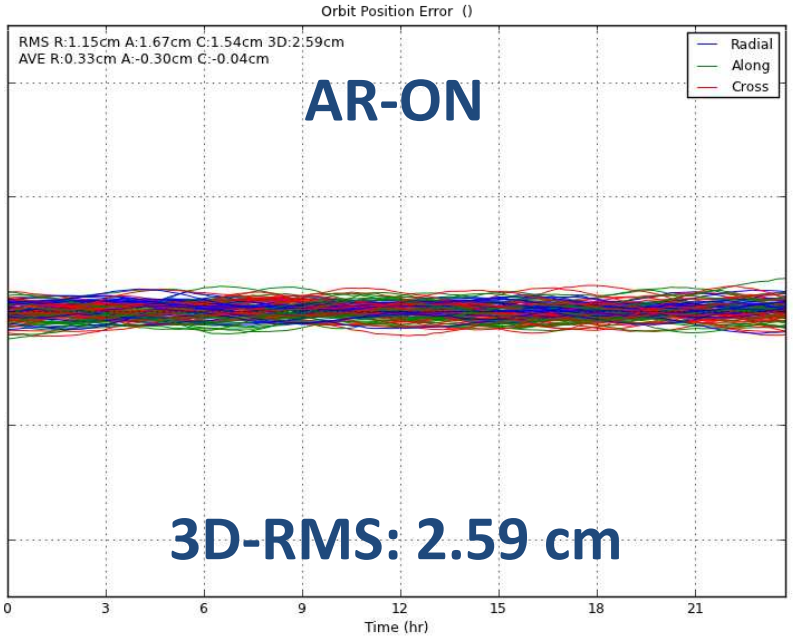
QZSS



Network Ambiguity Resolution

- Based on Ge et al., (2005)
- Modified to reduce CPU usage
- All baselines < 6,000 km, GPS and QZSS (no GLO)





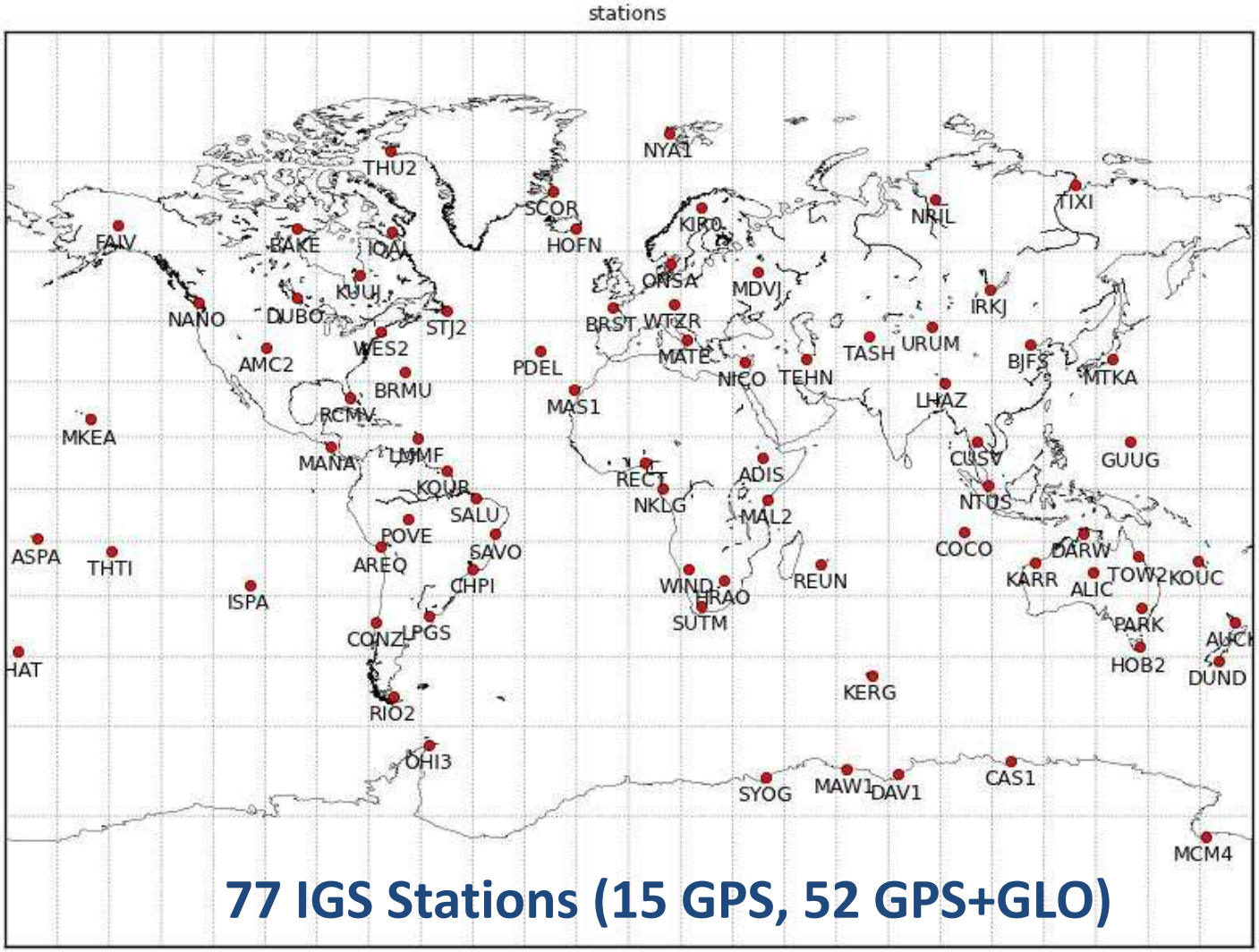
Implementation

- **Implemented from Scratch**
  - Language: ANSI C + python
  - Common Libraries + APs (application programs)
  - Code size: ~ 15 K lines (without comments)
- **Environment/Libraries**
  - Linux (64 bit) + gcc, gfortran
  - RTKLIB, SOFA, IERS, Intel MKL (AVX supported)
  - Multi-threading by OpenMP for multi-core CPU
- **To Reduce CPU Time**
  - Benchmark, profiling and optimized matrix handling

Evaluation for GPS/GLO

- **77 IGS Station (15 GPS, 52 GPS+GLO)**
- **Step 1: Orbit/Clock**
  - Estimated: OBT, S/RCLK, STAPOS, TROPOS, AMB, EOP
  - Tight constrained: STAPOS (Fiducial), EOP(UT1)
  - Arc: 3H + 24 H + 3H, Interval: 300 s, 3 Iteration
- **Step 2: 30 s Clock**
  - Estimated: S/RCLK, AMB
  - Fixed: OBT, STAPOS, TROPOS, EOP by Step 1
  - Arc: 24 H, Interval: 30 s, 2 Iteration

Reference Stations for GPS/GLO

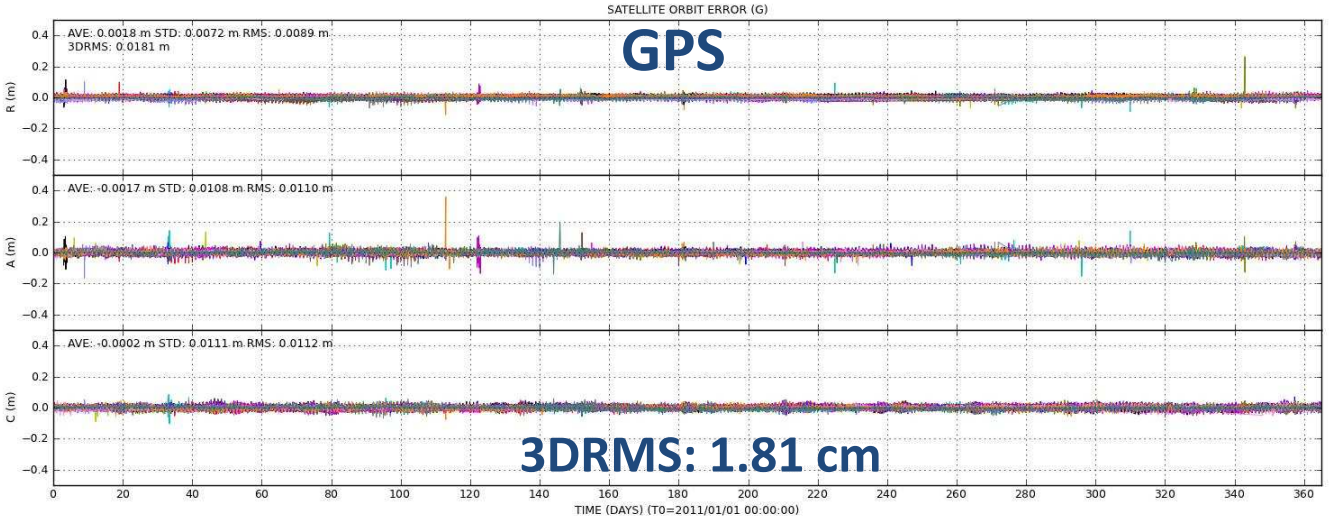


77 IGS Stations (15 GPS, 52 GPS+GLO)

Option Settings

Option	Model/Setting	Option	Model/Setting
OBS Type	ZD-Phase + Code	Tidal Correction	IERS2010+FES2004
Data Span	3H+24H+3H/24H	3rd-Body	S+M+V+J (DE421)
Data Interval	300 s/30 s	Attitude Model	Precise Yaw
Elevation Mask	10 deg	SRP Model	Modified-DBY (7-par)
Sat-System	GPS+GLO	Empirical Accel	R/A/C, every 12H
Excluded Sats	Unhealthy	Station Position	Fiducial: ITRF (2mm)
Meas. Noise	3 + 3 mm/sin(EL)	Site Disp.	IERS2010+FES2004
Nutation	IAU2000A	Troposphere	GPT+GMF
Initial EOP	IGS ERP	Tropos. Param.	ZTD+Grad, every 2H
Geopotential	EGM2008 (Nmax=12)	Ambiguity	Fixed (<6000km, GPS)

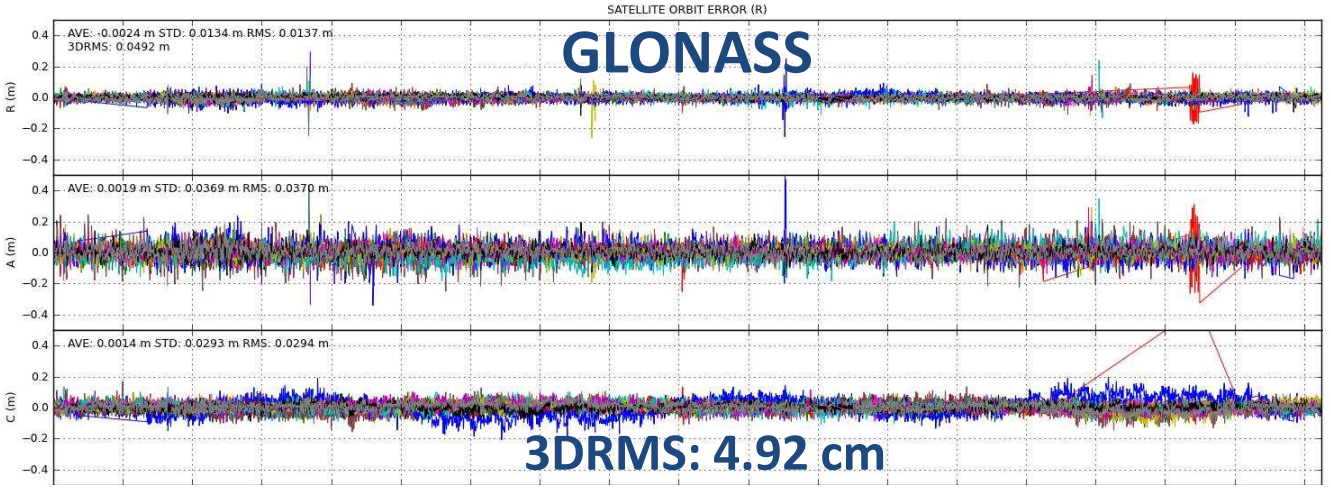
Orbit Accuracy of GPS/GLO



Radial — 0.89 cm

Along-Track — 1.10 cm

Cross-Track — 1.12 cm



Radial — 1.37 cm

Along-Track — 3.70 cm

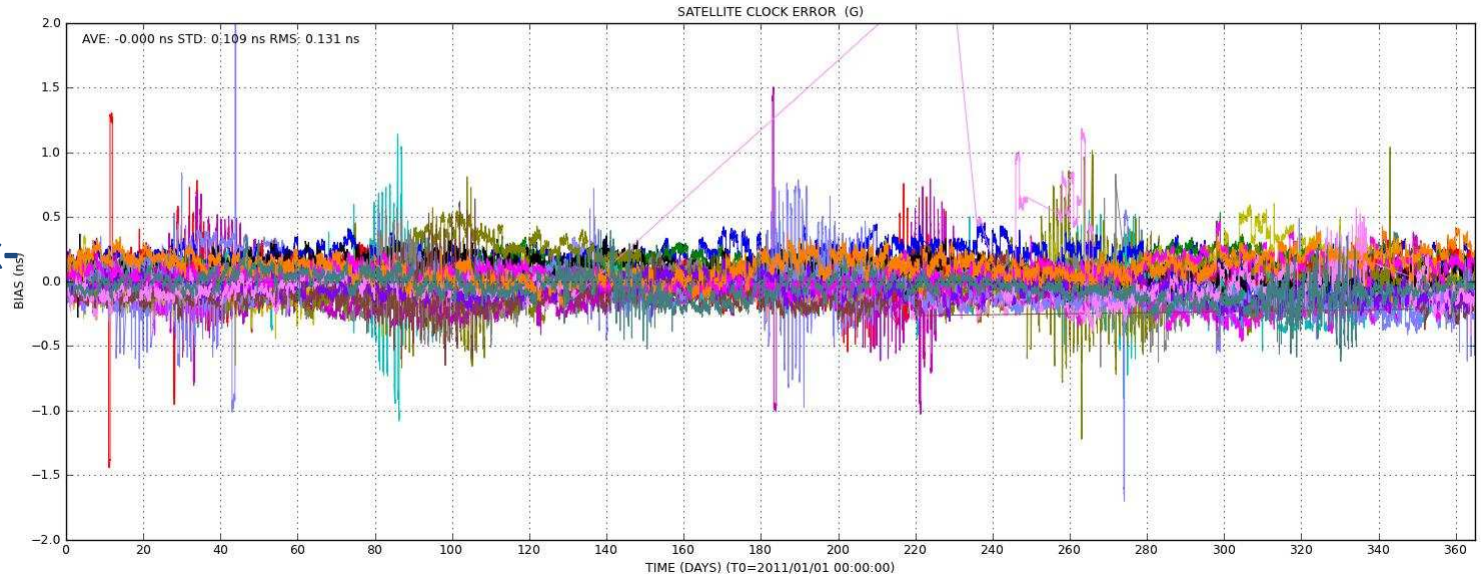
Cross-Track — 2.94 cm

2011/1/1 - 12/31 (365 days), Interval 900 s, wrt IGS Final

Clock Accuracy of GPS

GPS

Clock-Bias



STD: 0.109 ns, RMS: 0.131 ns

2011/1/1 - 12/31 (365 days), interval 300 s, wrt IGS Final

GPS Orbit/Clock Comparison

IGS AC	Analysis Software	# of Stas	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

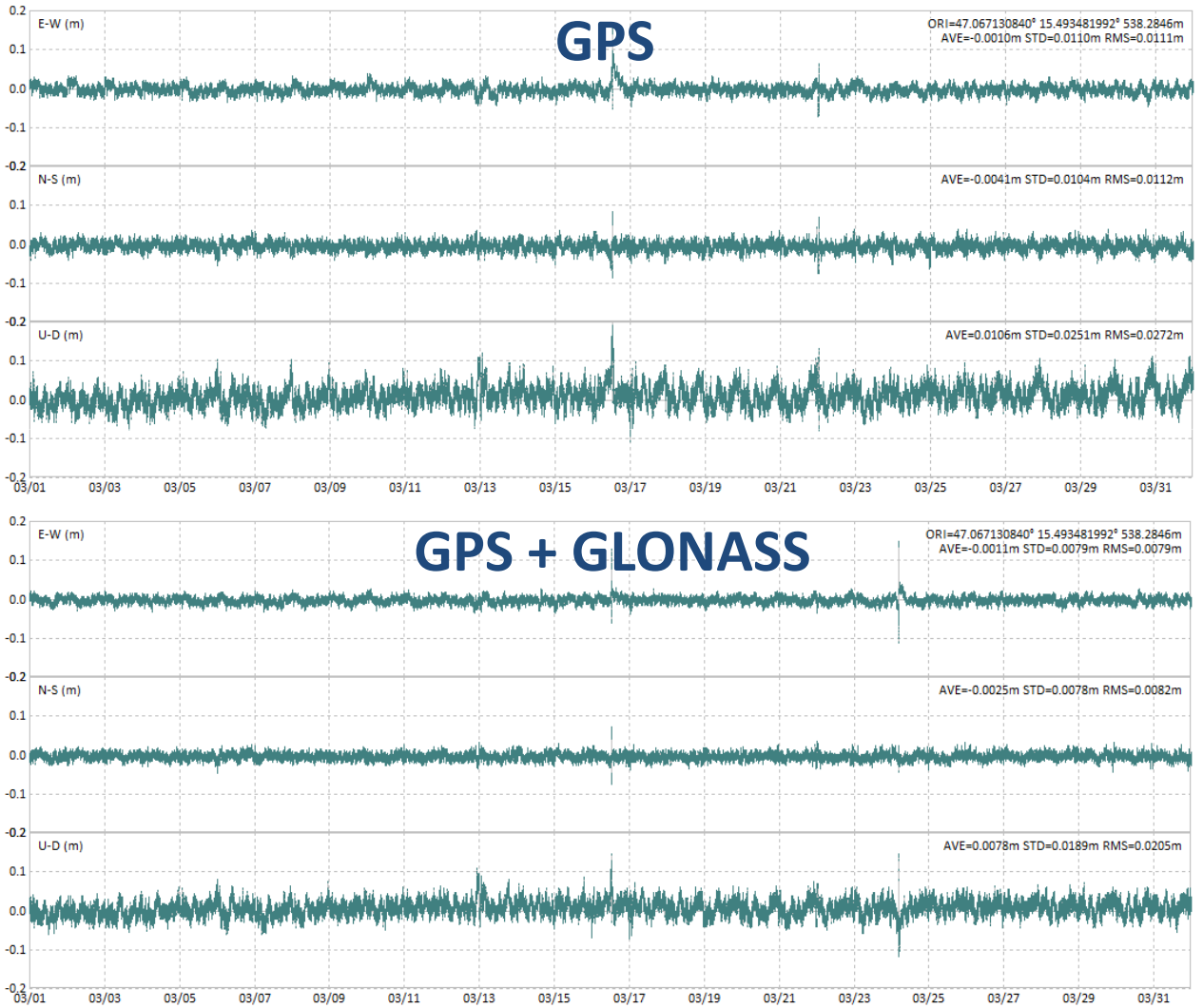
2011/1/1 - 12/31 (365 days), interval 900/300 s, wrt IGS Final

GLONASS Orbit Comparison

IGS AC	Analysis Software	# of Stas	Orbit RMS (cm)				Clock (ns)	
			R	A	C	3D	STD	RMS
ESA	NAPEOS 3.5	110	1.40	3.09	2.20	4.04	-	-
	MADOCA 0.3.0	**77**	**1.37**	**3.70**	**2.94**	**4.92**	**-**	**-**
CODE	Bernese 5.1	231	1.68	4.17	3.87	5.94	-	-
IAC	STARK, POLAR	?	2.52	7.40	4.96	9.26	-	-
BKG	Bernese 5.1	139	3.10	8.00	4.19	9.55	-	-
GFZ	EPOS P.V2	191	2.81	13.03	2.62	13.59	-	-
MCC	STARK, POLAR	?	4.94	21.67	21.78	31.08	-	-
GRG	GINS, DYNAMO	134	6.35	48.45	5.21	49.14	-	-

2011/1/1 - 12/31 (365 days), Interval 900 s, wrt IGS Final

Kinematic PPP Accuracy



	RMS
E-W	1.11 cm
N-S	1.12 cm
U-D	2.72 cm
E-W	0.79 cm
N-S	0.82 cm
U-D	2.05 cm

IGS GRAZ, 2011/3/1 - 3/31 (31 days), interval 30s, RTKPOST 2.4.2b

Kinematic PPP Comparison

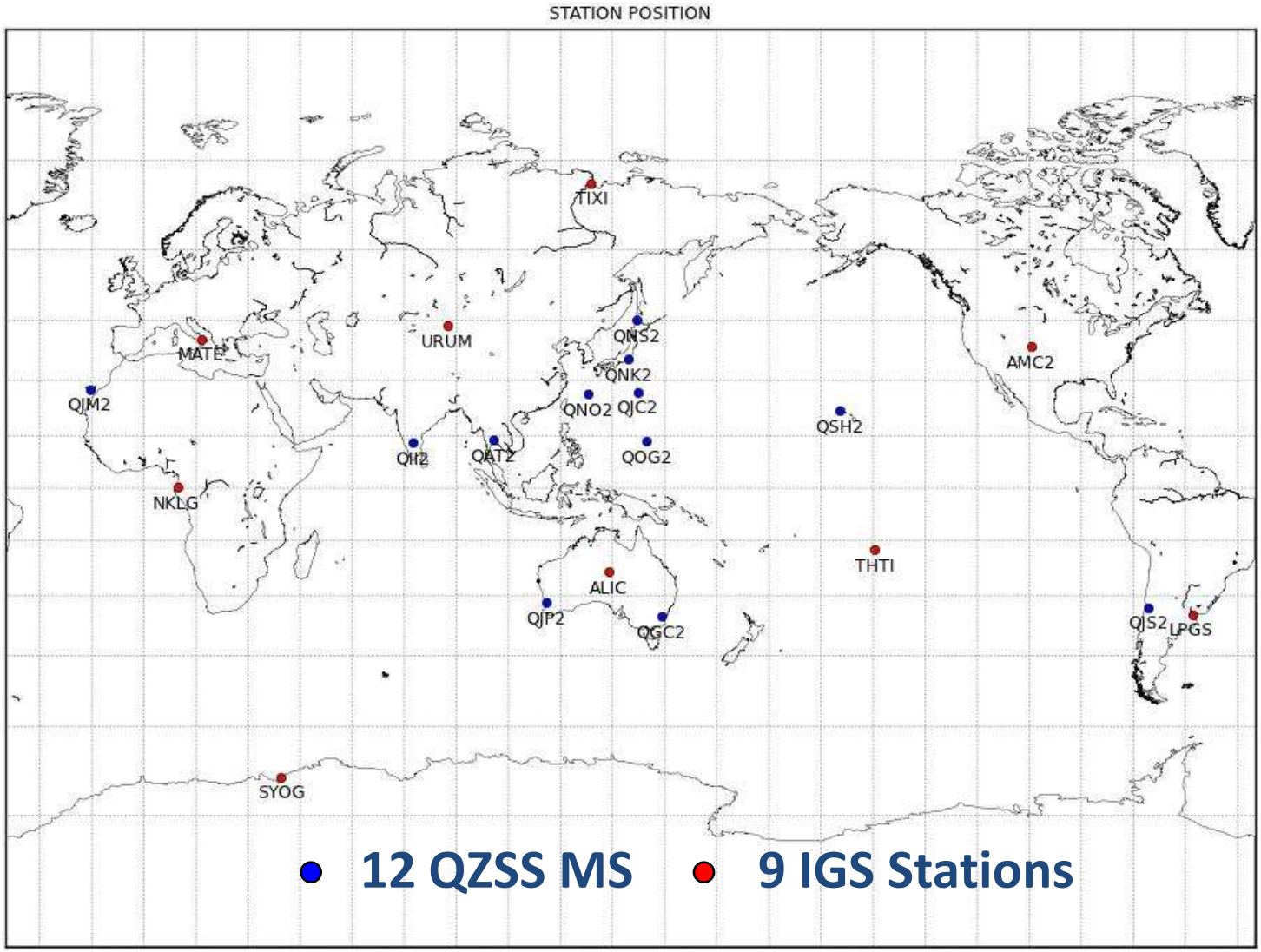
Orbit/Clock	Analysis Software	Satellites	RMS Error (cm)		
			E-W	N-S	U-D
IGS Final	-	GPS	1.10	1.11	2.64
MADOCA	**MADOCA 0.3.0**	**GPS**	**1.11**	**1.12**	**2.72**
ESA	NAPEOS 3.5	GPS	1.15	1.23	2.82
CODE	Bernese 5.1	GPS	1.15	1.29	2.84
MIT	GAMIT 10.33, GLOBK 5.16	GPS	1.18	1.25	3.07
NRCan	GIPSY/OASIS-II 5.0	GPS	1.29	1.56	3.05
MADOCA	**MADOCA 0.3.0**	**GPS + GLO**	**0.79**	**0.82**	**2.05**
ESA	NAPEOS 3.5	GPS + GLO	0.83	0.99	2.18

IGS GRAZ, 2011/3/1 - 3/31 (31 days), interval: 30s, RTKPOST 2.4.2b

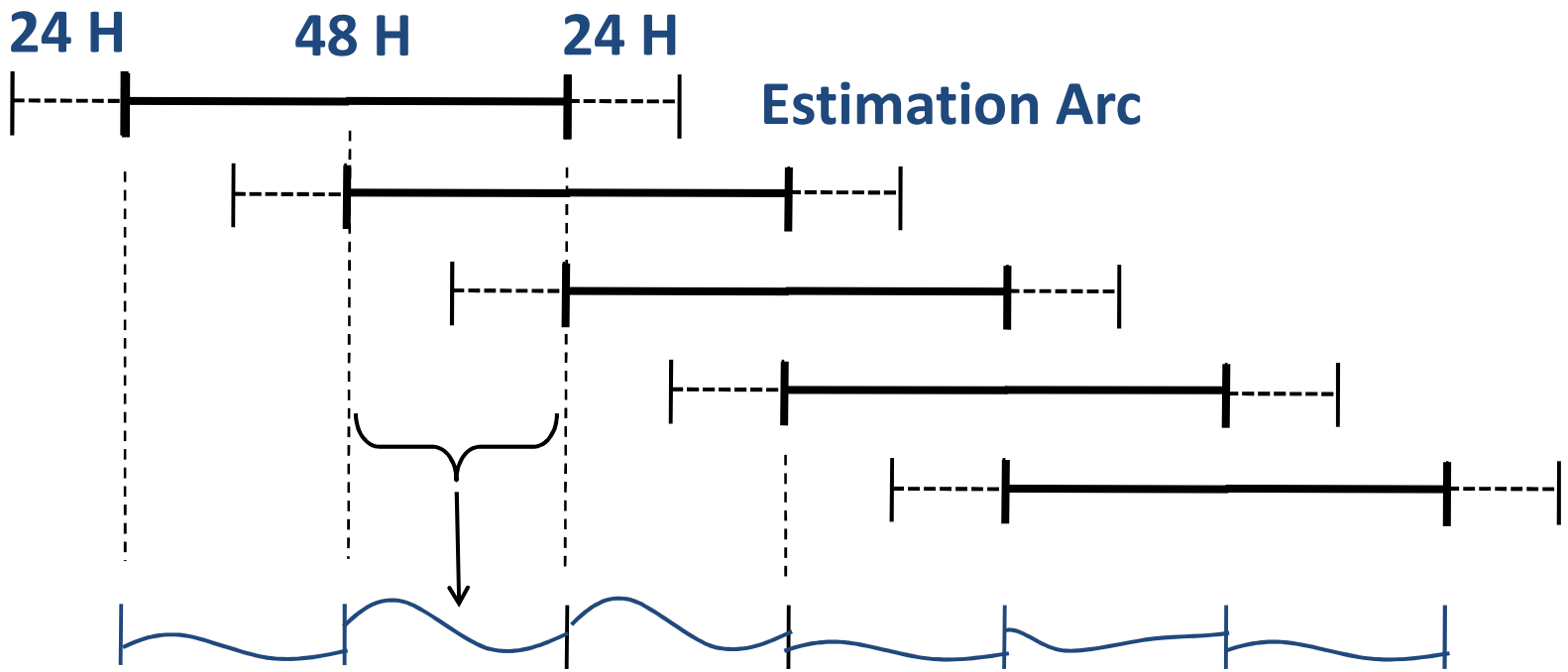
Evaluation for QZSS

- **12 QZSS MS (GPSR, QZSR) + 9 IGS Station**
- **Step 1: MS Coordinates**
  - Estimated: STAPOS (MS), TROPOS, AMB
  - Tight-Constraint: STAPOS (IGS)
  - Fixed: GPS OBT/CLK (IGS), EOP (IGS)
- **Step 2: QZSS Orbit/Clock**
  - Estimated: QZS OBT/CLK, RCLK, TROPOS, AMB
  - Fixed: GPS OBT/CLK (IGS), EOP (IGS)
  - Tight-Constraint: STAPOS (MS) by Step 1 + Local Tie
  - Arc: 24H + 48H + 24H, Interval: 300 s, 3 Iteration

Reference Stations for QZSS



Orbit Overlap Error

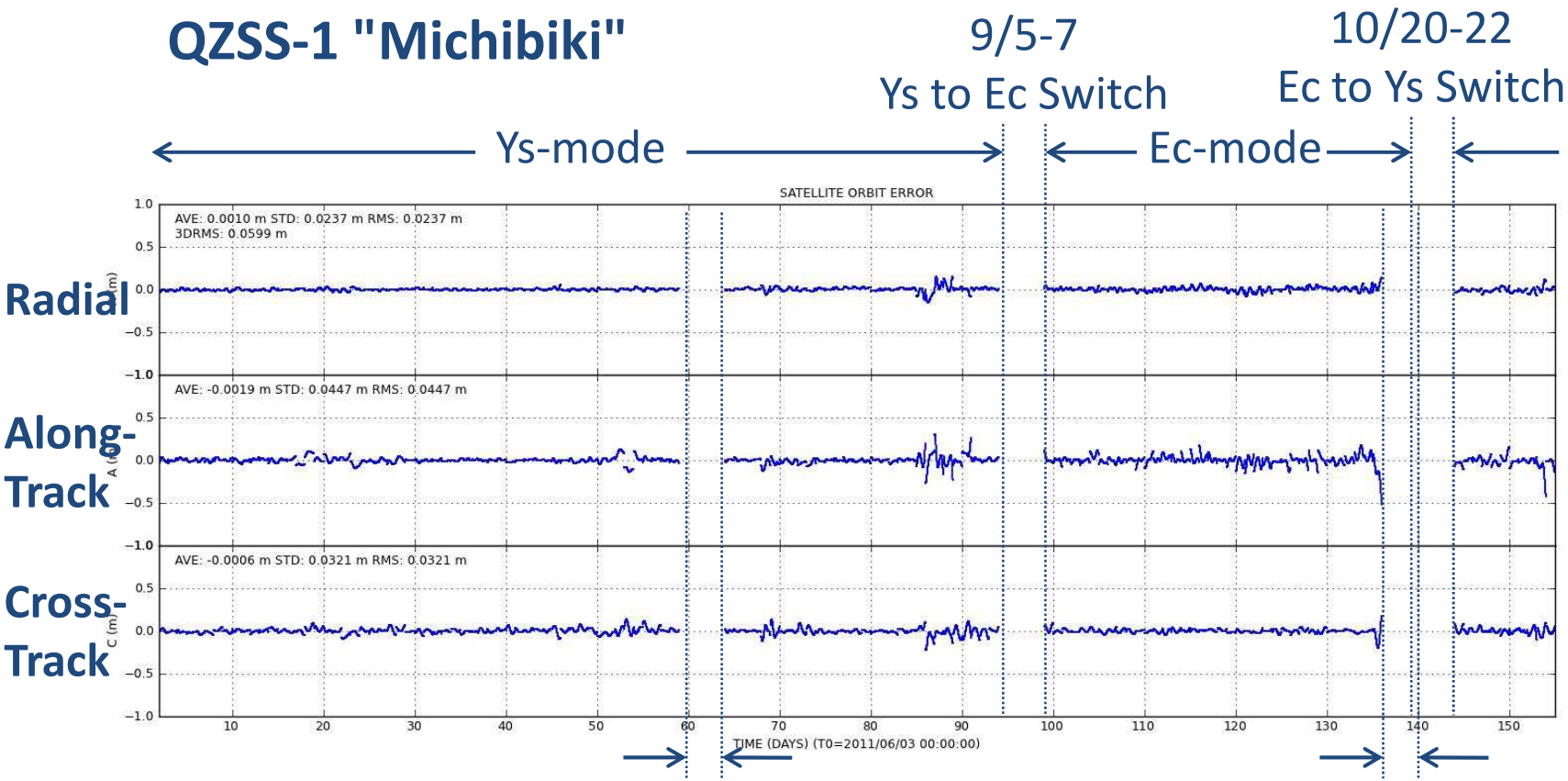


24 H Overlap Error

(Radial, Along-track, Cross-track)

Orbit Accuracy of QZSS

QZSS-1 "Michibiki"



R: 2.37 cm, A: 4.47 cm, C: 3.21 cm, 3DRMS: 5.99 cm

2011/6/4 - 11/3 (153 days), 24 H-overlap

Enhancement Plan (FY24)

- **Galileo Support**
  - L1-L5 Iono-free LC, Galileo SRP Model
- **Real-Time Enhancement**
  - EKF based real-time clock estimation
  - Combination to near-real-time orbit estimation
  - Various formats support for real-time Multi-GNSS data
  - Reduce end-to-end latency of correction messages
- **LEX Message Generation**
  - RTCM SSR based corrections generation
  - Dynamic satellite selection by visibility analysis

Real-Time Message Band-Width

Type	GNSS	MT	# of Sats	Size (bits)	Interval (s)	Rate (bps)
Orbit/ Clock	GPS	1060	20	5728	15	381.9
	GLONASS	1066	16	4573	15	304.9
	QZSS	X+3	3	894	15	59.6
	Galileo	X+9	16	4592	15	306.1
High Rate Clock	GPS	1062	20	608	5	121.6
	GLO	1067	16	477	5	95.4
	QZSS	X+5	3	126	5	25.2
	Galileo	X+11	16	496	5	99.2
URA	GPS	1061	20	248	30	8.3
	GLO	1066	16	189	30	6.3
	QZSS	X+4	3	72	30	2.4
	Galileo	X+10	16	208	30	6.9
Code Bias	GPS	1059	20	1408	30	46.9
	GLO	1065	16	813	30	27.1
	QZSS	X+2	3	246	30	8.2
	Galileo	X+8	16	1136	30	37.9
Code-Phase Bias	GPS, GLO, ...	X+12,...	55	1946	30	64.9
Time Offset	GPS-GLO...	X+16,...	1	216	30	7.2
Total						**1609.9**

PPP-AR

- **Ambiguity Resolution (AR) in PPP**
  - Improve convergence time
  - Improve accuracy of positions (cm-class)
  - Orbit quality is a key issue for successful PPP-AR
  - Feasibility study is just started for GPS and QZSS
  - No standard, message format should be investigated
- **Proto-type Implementation Plan**
  - Offline-mode PPP-AR as first step
  - Real-time PPP-AR as next step
  - Need evaluation of long-time stability

Summary

- **MADOCA**
  - Multi-GNSS precise orbit/clock estimation
  - For JAXA PPP experiment via QZSS LEX channel
  - Key-technology for precise positioning with GNSS
- **Development Status**
  - Offline functions are completed in FY23
  - Orbit: GPS < 2 cm, GLO < 5 cm, QZS ~ 6 cm (3D-RMS)
  - PPP with GPS/GLO: ~ 1 cm (H-RMS), ~3 cm (V-RMS)
  - Enhancement for real-time and Galileo in FY24
  - PPP-AR features will be investigated