

JpGU-AGU Joint Meeting 2017

[MTT38] [EE] 統合地球観測システムとしてのGPS/GNSSの新展開

The development and application of PPP technology with multi-constellation GNSS

Tomoji TAKASU



Tokyo University of Marine Science and Technology

May 20-25, 2017 Makuhari-Messe, Chiba, Japan

Contents

- **Review of PPP Technology**
- **MADOCA**
- **RTKLIB and PPP-Extension**
- **Summary**

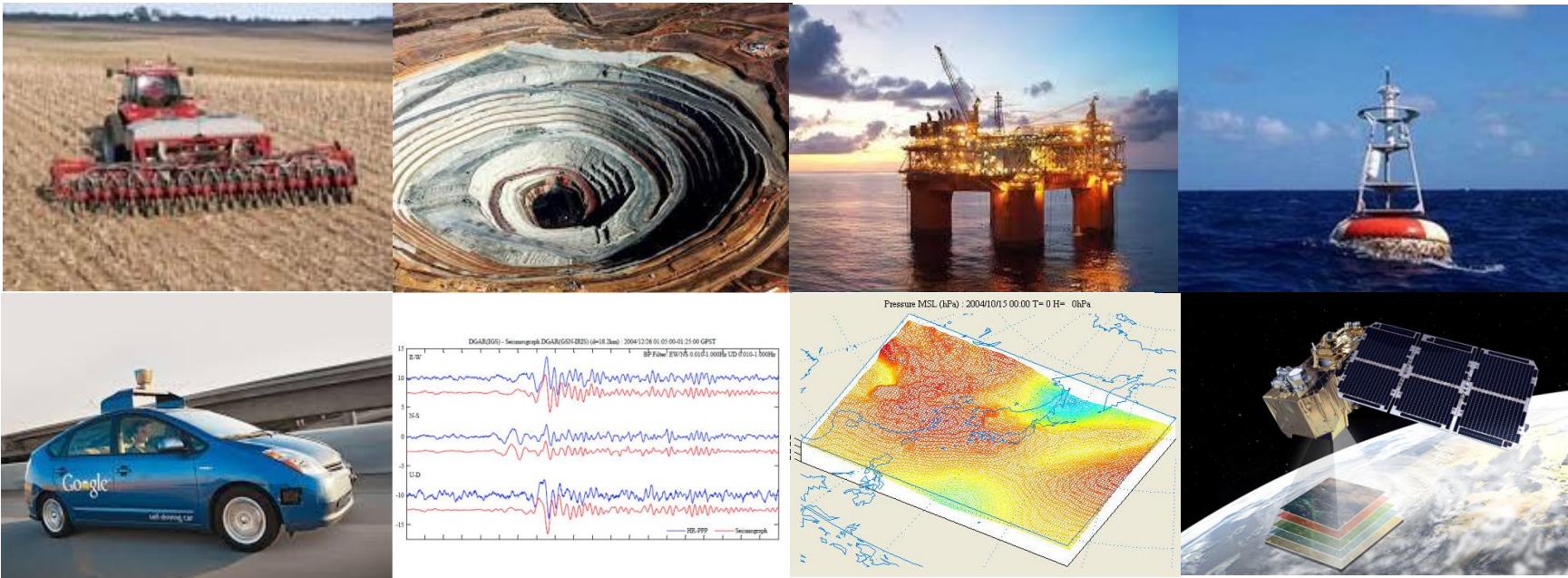
Review of PPP Technology

Precise Point Positioning (PPP)

- **Introduced by JPL (GIPSY/OASIS) in 1990s**
 - J.F. Zumberge et al., Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks, *JGR*, 1997
- **Many previous works by IGS**
 - High-quality and accurate orbit and clock products since 1994
 - Development of precise models for PPP
 - Standardization of GNSS data and products
- **Technical Features of PPP**
 - Global coverage (anywhere on the earth surface)
 - With single receiver, w/o reference station
 - Efficient analysis for many stations/receivers (huge N/W analysis)
 - Absolute position in global frame (ITRF)

PPP Applications

- Precision Agriculture
- Mining
- Offshore Construction
- Tsunami Warning
- Auto Driving
- Crustal Deformation Monitor
- GPS/GNSS Seismometer
- GPS/GNSS Meteorology
- POD of LEO Satellite
- Precise Time Transfer

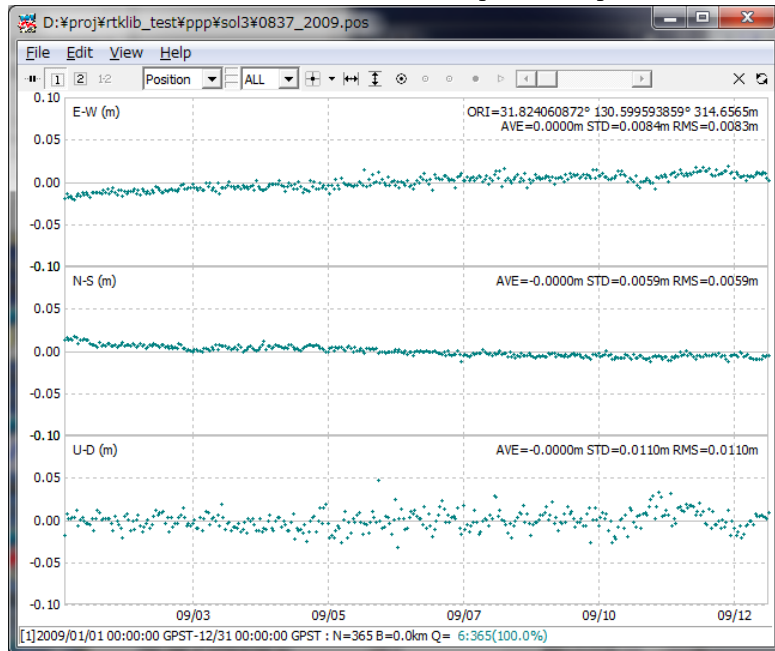


Typical PPP Models

- **ZD carrier-phase and pseudorange**
- **External precise orbit and clock**
- **Ionosphere: eliminated by iono-free LC (L1/L2 or L1/L5)**
- **Troposphere: estimated as ZTD with MF**
- **IERS models for site displacement by earth-tides**
- **Antenna PCV models derived from field-calibration**
- **Phase rotation corrections for LHCP signal**
- **Carrier-phase ambiguity:**
 - estimated as float value in conventional PPP
 - resolved as integer-cycle with external FCB in PPP-AR

Typical PPP Accuracy

Static PPP (24H)

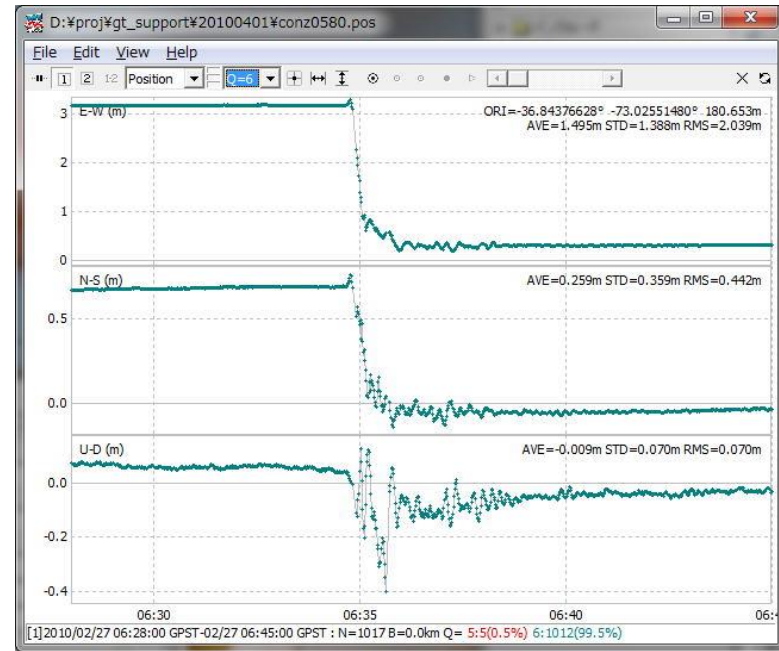


GEONET 0837, 2009/1/1-12/31

H-RMS: 3 mm

V-RMS: 8 mm

Kinematic PPP (1Hz)



IGS CONZ, 2010/2/27 6:28-6:45

H-RMS: 1 cm

V-RMS: 2 cm

(post-processing with GPS and IGS final)

Real-time PPP

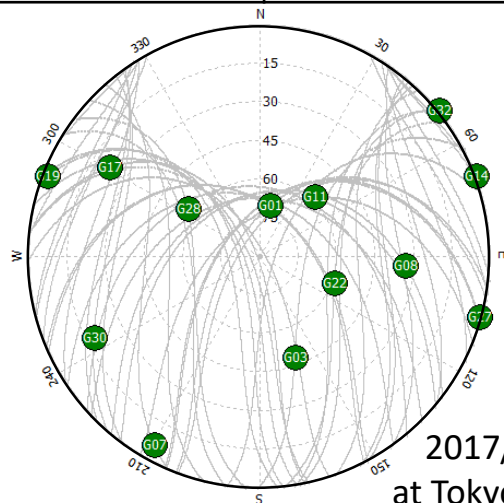
- **IGS-RTS (real-time service)**
 - RTWG and RTPP since 2001
 - IGS-RTS formally launched in 2013 (only GPS)
 - NTRIP via Internet with standard RTCM 3.2 SSR format
 - Free of charge according to IGS "open data policy"
- **Commercial PPP services**
 - Navcom StarFire, Trimble RTX, Fugro Seastar and VERIPOS/TerraStar
 - via L-band link by GEO satellite
 - Specific receiver F/W and vendor proprietary correction format
- **PPP services via GNSS satellite link**
 - Galileo L6 CS (planned)
 - QZSS L6/D2 MADOCA-PPP (planned as technical verification)

Multi-constellation GNSS

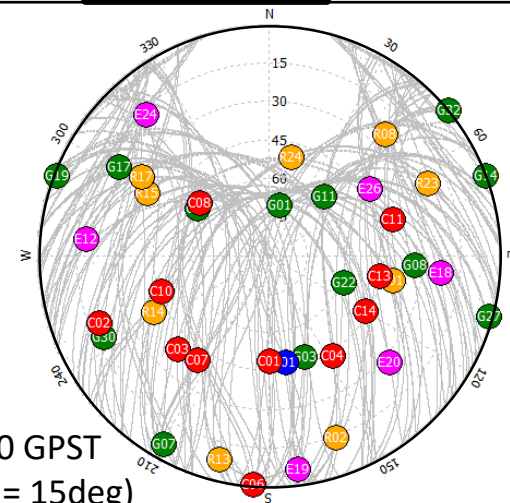
Number of GNSS Satellites

System	2010	2014	2018	2022
GPS	31	31	31	32
GLONASS	23 (+2)	24 (+3)	24 (+3)	24 (+3)
Galileo	0	4	22	27 (+3)
BeiDou	6	16	23	35
QZSS	1	1	4	7
IRNSS (NAVIC)	0	3	7	7
SBAS	7	8	11	11
Total	68	87	122	143

GPS only :
of SAT = 8
GDOP = 2.7



2017/05/23 0:00 GPST
at Tokyo (EL mask = 15deg)



GPS+GLO+GAL
+BD+QZS :
of SAT = 32
GDOP = 1.2

MADOCA

MADOCA

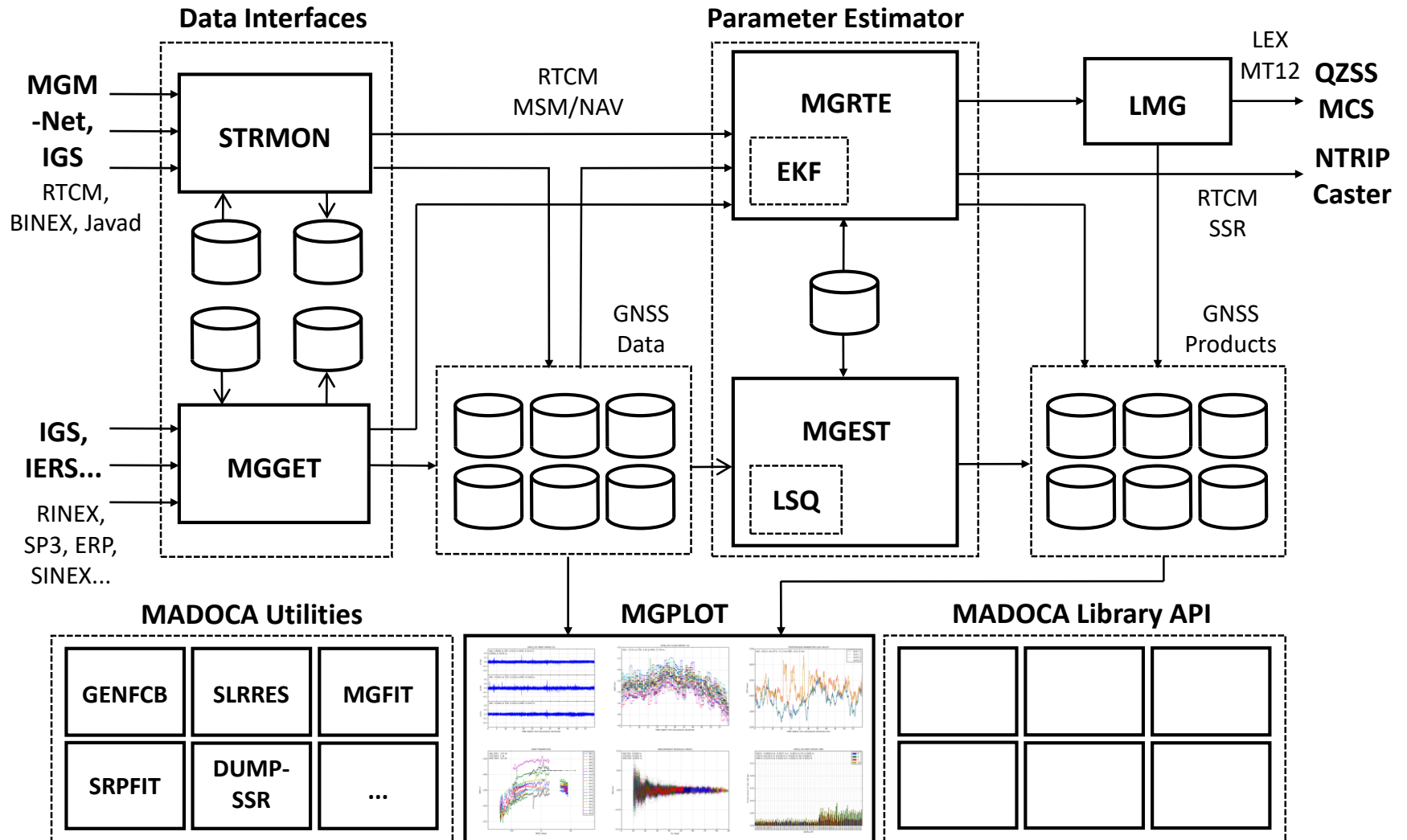
Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis

- **Developed and sponsored by JAXA since 2011**
- **For precise orbit and clock for PPP service**
 - Many PPP applications over global area
 - Expecting sub-dm to cm-class accuracy
 - Both for post-processing and real-time
 - Experimental verification via QZS-1 LEX channel (done)
- **Support multi-constellation GNSS satellites**
 - Over 100 satellites in 2018
 - GPS, GLONASS, QZSS and Galileo (in 1st phase)
 - + BeiDou (in 2nd phase)
 - Careful handling of time/coordinate difference and ISB

MADOCA R&D Activities

- **1st Phase (2011/6 - 2013/3)**
 - Design and implementation of S/W completely from scratch
 - Post-processing analysis (FY2011)
 - Real-time analysis and product generation (FY2012)
 - Support GPS, GLONASS, QZSS and Galileo
- **2nd Phase (2014/2 - 2015/12)**
 - Add BeiDou
 - Improvement of orbit dynamics (SRP model)
 - Support FCB product for PPP-AR
 - Experimental local-iono/tropos corrections for PPP-RTK
 - INS/odometer integration for severe environment
- **3rd Phase (2016/4 - 2018/3)**
 - Improvement of product quality and stability
 - Transition from experimental to operational service

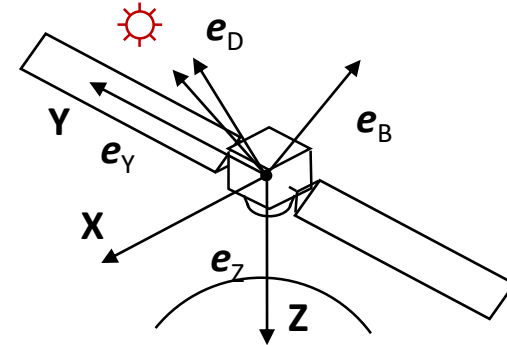
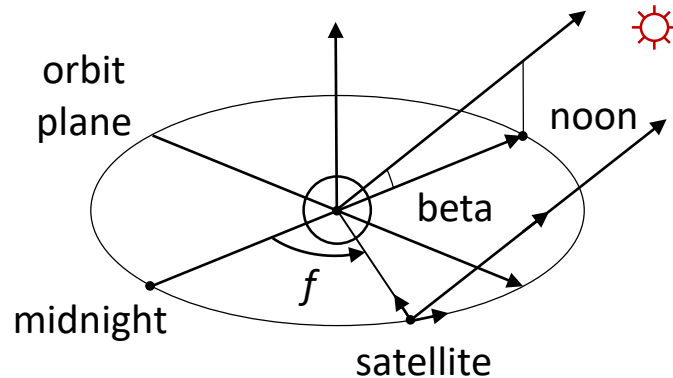
MADOCA Architecture



MADOCA Models

- **Satellite orbit dynamics**
 - Geopotential: EGM 2008 + solid earth tide + FES2004
 - 3rd body: Sun, Moon, Venus and Jupiter with JPL DE421
 - Empirical SRP model (MDBY/EDBY)
 - Accel by thruster-events + atmospheric drag (for LEO satellites)
- **GNSS measurement models**
 - ZD Iono-free carrier-phase + pseudorange
 - 2nd-order-iono with IONEX
 - ZTD/gradient estimation with GPT/GPT2 + NMF/GMF/VMF1
 - Site Displacement: DEHANTIDEINEL + FES2004 + pole tide + CMC
- **ECI-ECEF coordinates transformation**
 - IAU 2000A/2006 by IAU SOFA
 - EOP (XP, YP, UT1, XPR, YPR, LOD) and geocenter

EDBY SRP Model (ver.0.7.0~)



YS:

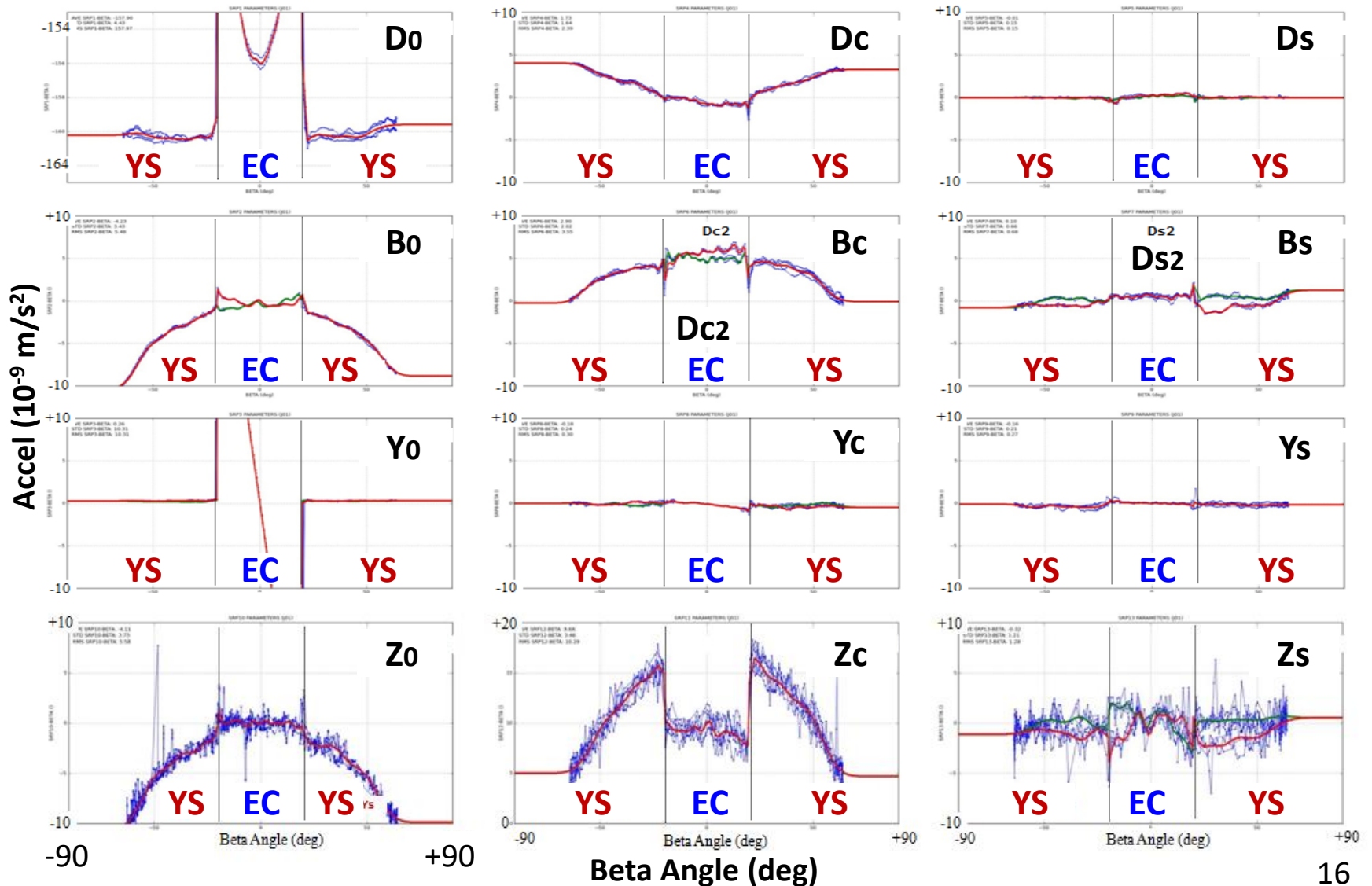
$$\mathbf{a}_{srp} = S \left((D_0 + D_C \cos f + D_S \sin f) \mathbf{e}_D + (B_0 + B_C \cos f + B_S \sin f) \mathbf{e}_B + (Y_0 + Y_C \cos f + Y_S \sin f) \mathbf{e}_Y + (Z_0 + Z_C \cos f + Z_S \sin f) \mathbf{e}_Z \right) * 10^{-9} \text{ (m/s}^2\text{)}$$

EC:

$$\mathbf{a}_{srp} = S \left((D_0 + D_C \cos f + D_S \sin f + D_{2C} \cos 2f + D_{2S} \sin 2f) \mathbf{e}_D + B_0 \mathbf{e}_B + (Y_0 + Y_C \cos f + Y_S \sin f) \mathbf{e}_Y + (Z_0 + Z_C \cos f + Z_S \sin f) \mathbf{e}_Z \right) * 10^{-9} \text{ (m/s}^2\text{)}$$

$$(S = F_{Shadow} * AU^2 / |r - r_{sun}|^2)$$

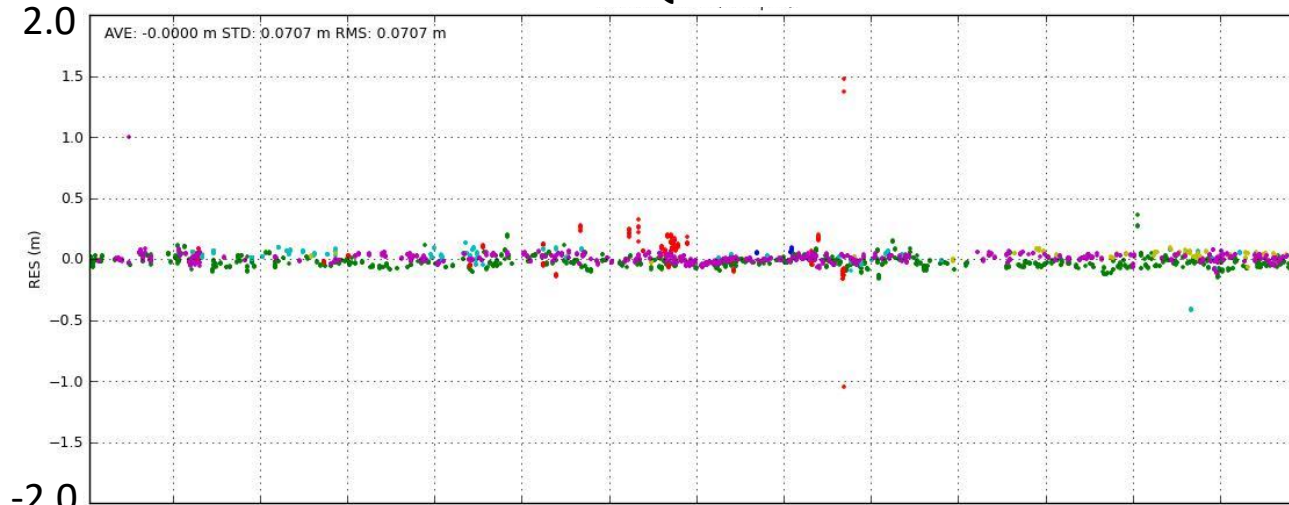
EDBY Coefficients for QZS-1



Model Improvement for QZS-1

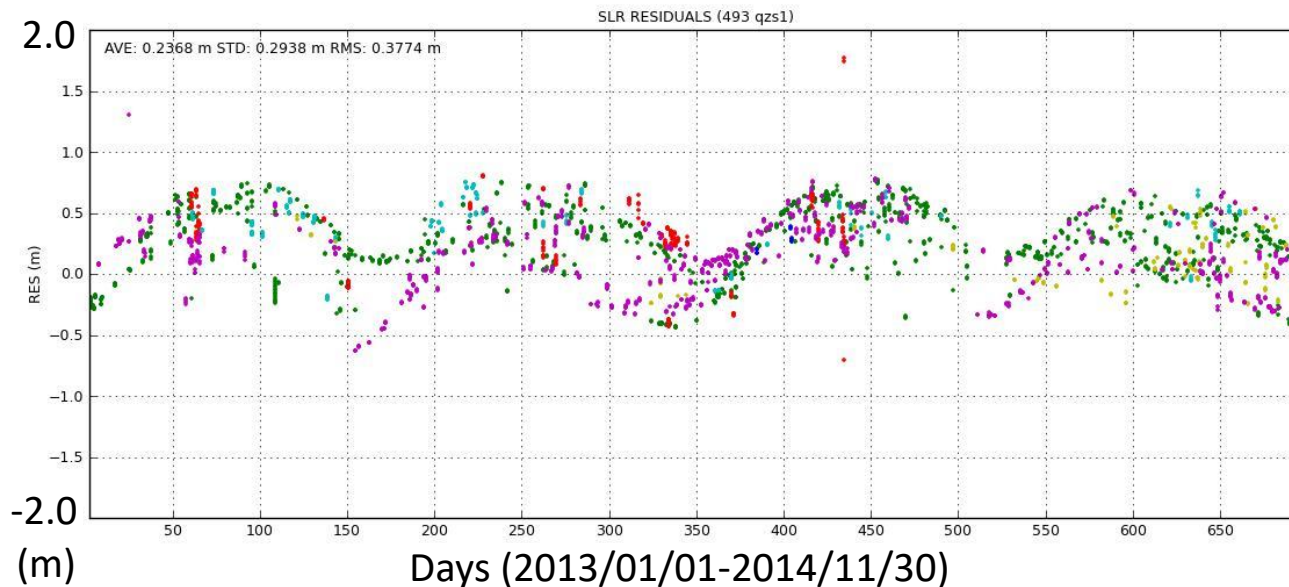
SLR Residuals of QZS-1 PP-Orbits

Ver.
0.7.0
EDBY



RMS
7.07
cm

Ver.
0.6.7
MDBY

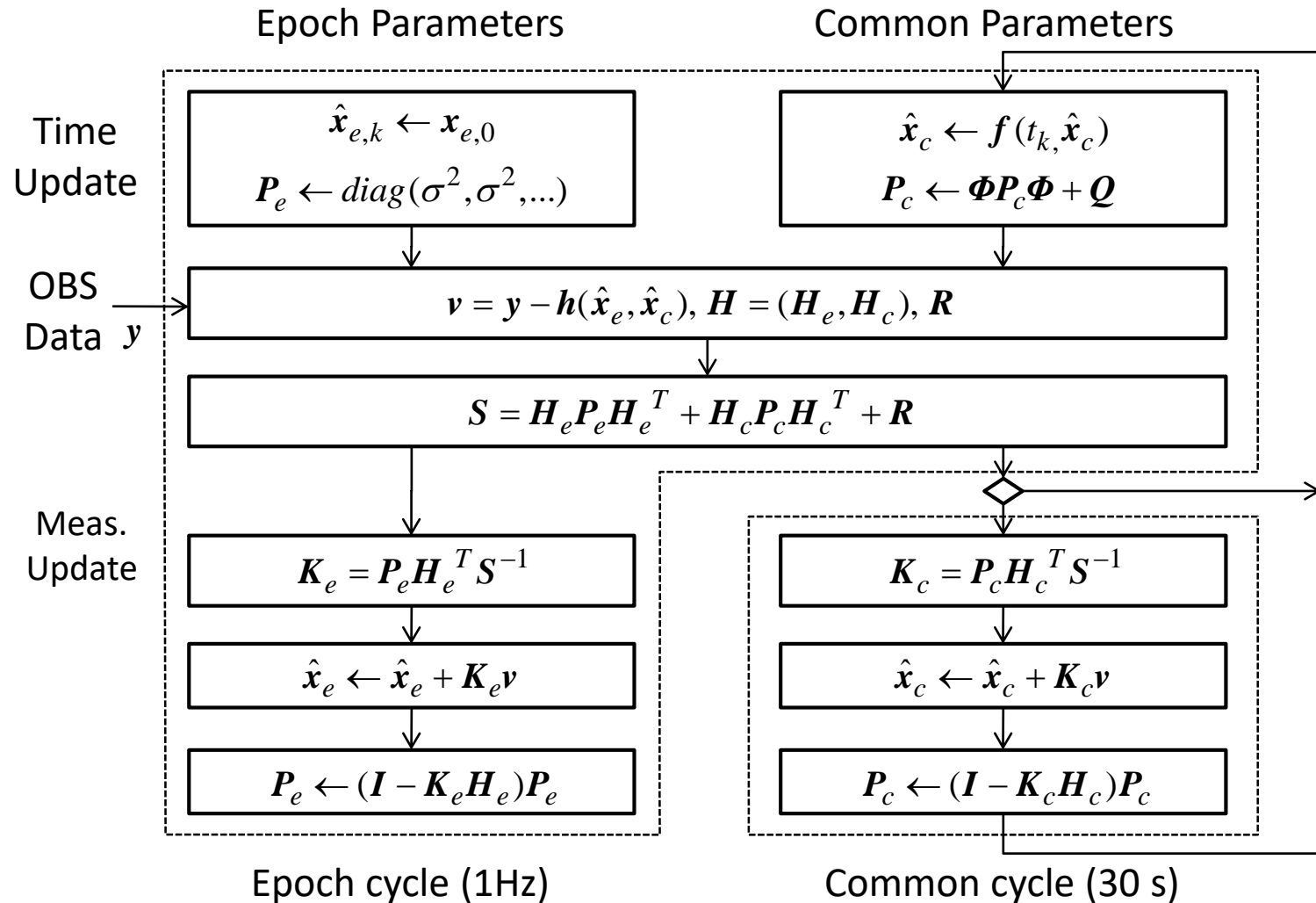


RMS
37.74
cm

Parameter Adjustment

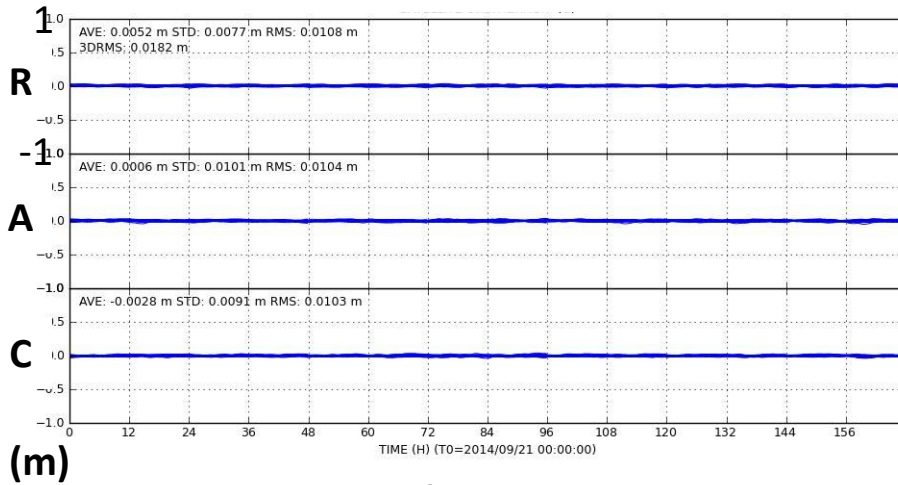
	MGEST (Post-Processing)	MGRTE (Real-Time)
Algorithm	Iterated Weighted LSQ	Dual-Cycle-EKF
Estimated Parameters	Orbit, SRP, Drag, Emp-Acc, Thru-Acc, Sat/Rcv Clock, Position, ZTD/Grad, Amb, EOP, Geocenter, Rcv Bias	
Measurements	ZD Iono-free Carrier-Phase and Pseudorange	
Numerical Solver	NEQ by Cholesky 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

Dual-Cycle-EKF



Quality of PP-Products

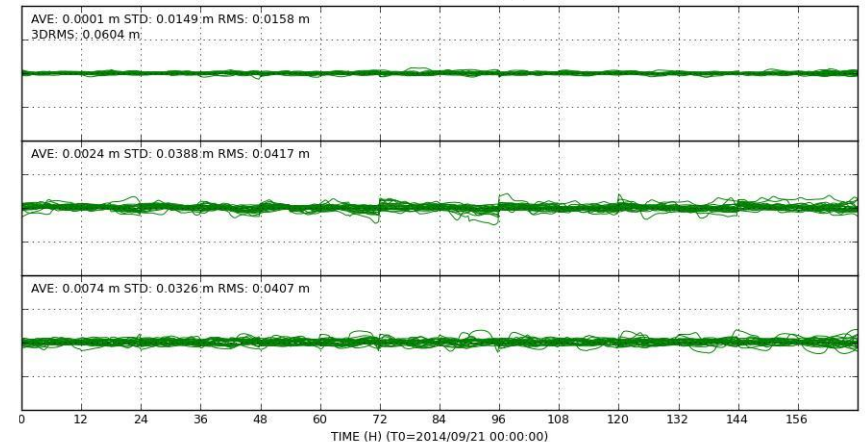
MGF wrt IGR (GPS)



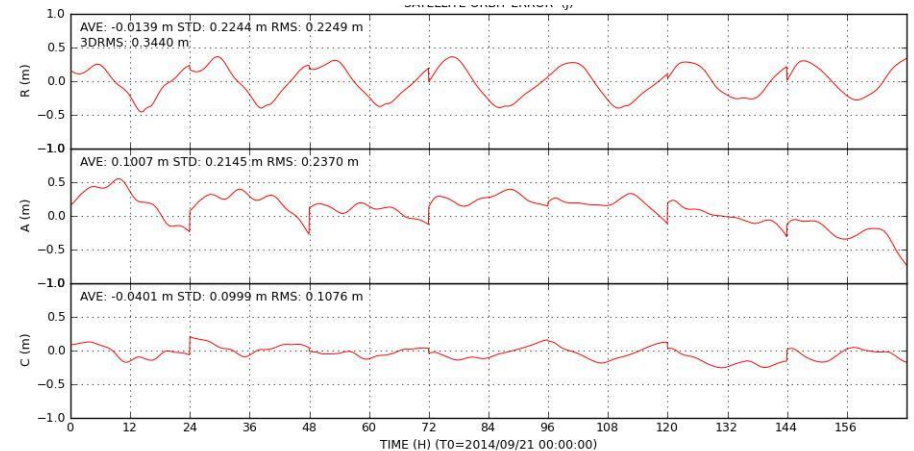
Orbit Error

	RMS (cm)			
	R	A	C	3D
GPS	1.08	1.04	1.03	1.82
GLO	1.58	4.17	4.07	6.04
QZSS	22.49	23.70	10.76	34.40

MGF wrt IGV (GLONASS)

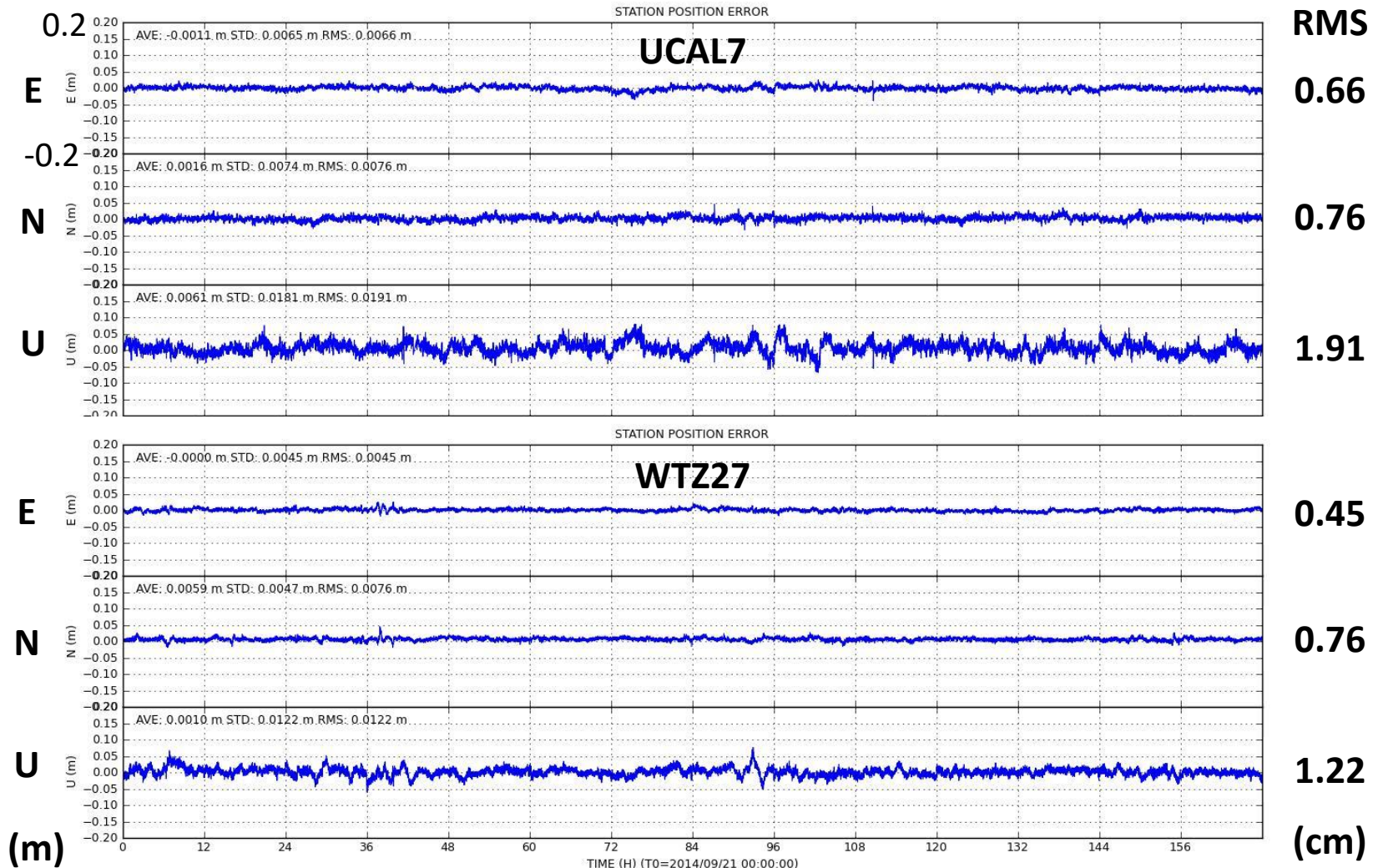


MGF wrt QZF (QZSS)



GPS Week 1811 (2014/09/21 - 27)

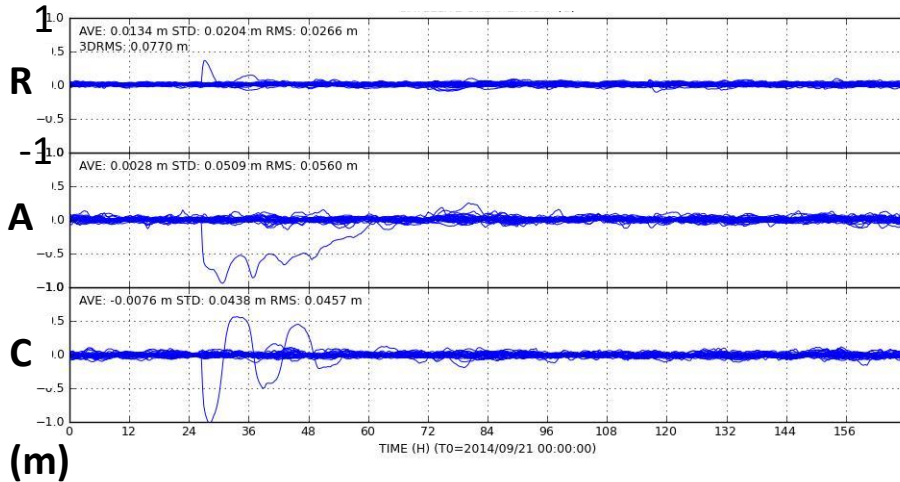
PPP with PP-Products



Kinematic PPP with MGF (GPS+GLO), GPS Week 1811 (2014/09/21 - 27)

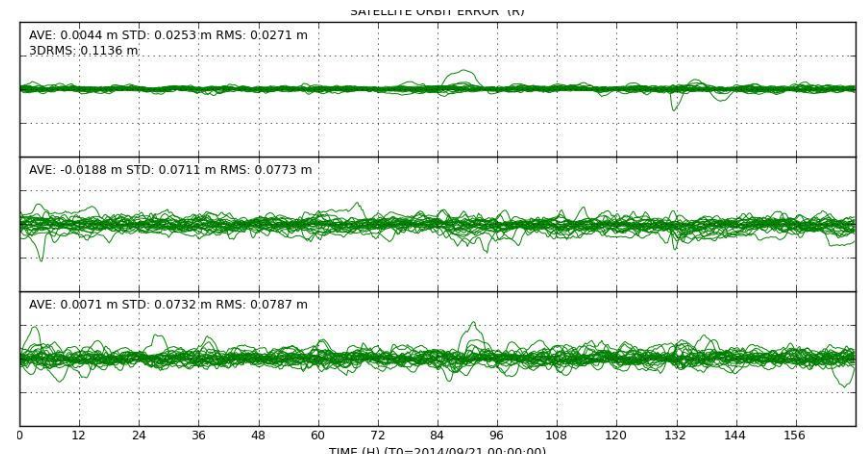
Quality of RT-Products

MGRT1 wrt IGR (GPS)

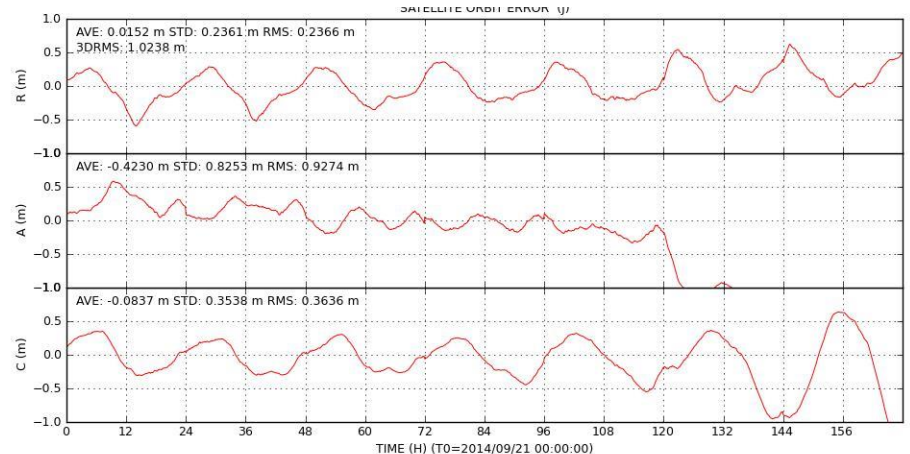


Orbit Error

MGRT1 wrt IGV (GLONASS)



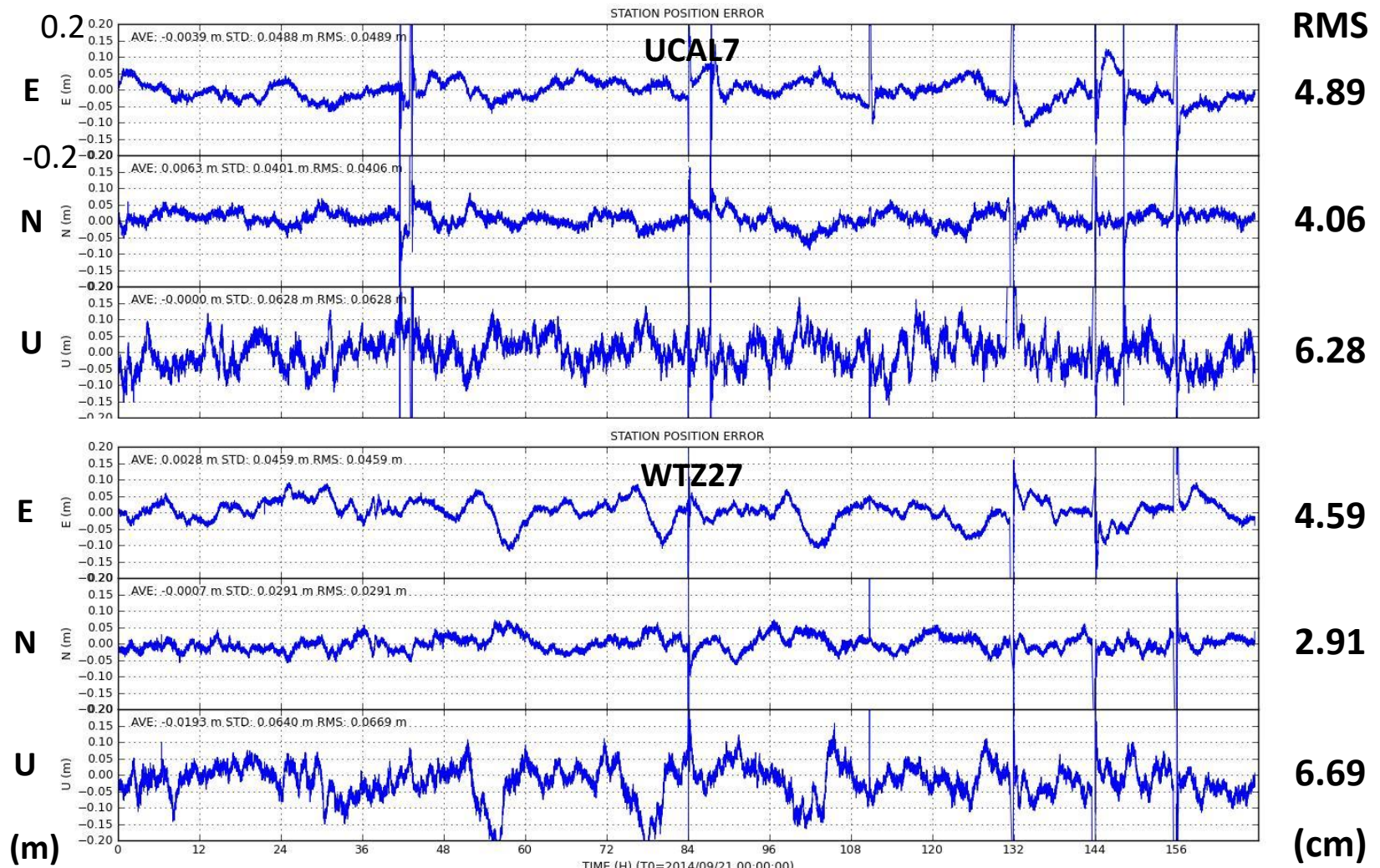
MGRT1 wrt QZF (QZSS)



	RMS (cm)			
	R	A	C	3D
GPS	2.66	5.60	4.57	7.70
GLO	2.71	7.73	7.87	11.36
QZSS	23.66	92.74	36.36	102.4

GPS Week 1811 (2014/09/21 - 27)

PPP with RT-Products



Kinematic PPP with MGRT1 (GPS+GLO), GPS Week 1811 (2014/09/21 - 27)

JAXA MADOCA Products

MADOCA Products

QZSS : Quasi-Zenith Satellite System

MADOCA Real-Time Products

MADOCA | NEWS | MESSAGE | PRODUCTS | APPLICATION | ARCHIVE

Real-Time PPP Service

JAXA conducts real-time precise point positioning (PPP) experiments using the L-band experimental(LEX) signal from "Michibiki(QZS-1)". PPP is a technique to calculate accurate user positions using precise orbit and clock of GNSS without any reference stations.

Our Real-Time PPP Service allows to obtain a centimeter accuracy positioning.

What's MADOCA?

For this service, JAXA has developed Multi-GNSS orbit and clock estimator called "MADOCA (Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis)". This basic requirements are as follows;

- (1) Multi-GNSS Support (GPS, GLONASS, Galileo and QZSS)
- (2) Both of Offline and Real-Time Estimator
- (3) Precise Estimation using latest models
- (4) Reduction of Processing Time by Multi-threading
- (5) Maintainability and Portability which can run on note PC

System: GPS, GLNASS and QZS (Galileo and BeiDou are under construction..)
 Goal: Real-Time positioning with less than 10cm accuracy
 Goal of orbit/clock accuracy:

Product	Offline			Real-Time		
	GPS	GLO	QZS	GPS	GLO	QZS
OBT	3cm	7cm	6cm	6cm	9cm	9cm
CLK	0.1ns	0.25ns	0.1ns	0.1ns	0.25ns	0.25ns

Edit Date:2015/11/26

MADOCA Products

QZSS : Quasi-Zenith Satellite System

MADOCA Real-Time Products

MADOCA | NEWS | MESSAGE | PRODUCTS | APPLICATION

MADOCA products

MADOCA products is provided according to RTCM SSR format.

Product	Interval		RTCM Message Type		
	Estimate	Provide	GPS	GLO	QZS
Orbit correction	30	1	1057	1063	1246
Clock correction	1	1	1058	1064	1247
HR-Clock correction	1	1	1062	1068	1251
URA	1	1	1061	1067	1250

Estimate Condition

Analysis software: MADOCA v0.7.2(MDC1), MADOCA v0.7.2p1(MDC2)
 Observation data: MGM-net + QZSS M5 + IGS/MGEX (MDC1:S3 sta, MDC2:S3 sta)
 Updates: every 30s for orbit (APC(MDC1),APC(MDC2)), clock and URA, every 1s for high-rate clock (latency: 6 ~8 s)

MDC1
STATION POSITION

MDC2
STATION POSITION

MADOCA-LEX BROADCAST SCHEDULE

Our LEX Experiment Schedule can be confirmed the following site "QZ-vision". The schedule will be revised every Friday. Schedules may change in accordance to each experiment.
[Experiment Schedule](#)

LEX FORMAT for MADOCA

MADOCA-LEX format is defined as MT=12 based on RTCM SSR.

(1) MADOCA-LEX format

LEX message (2000)

header (4B)	TOW	WN	SSR Packet#1 (Variable)	SSR Packet#2 (Variable)	...	Reserved	Reed-Solomon (24B)
Data Section(1695)							

(c)RTCM SSR

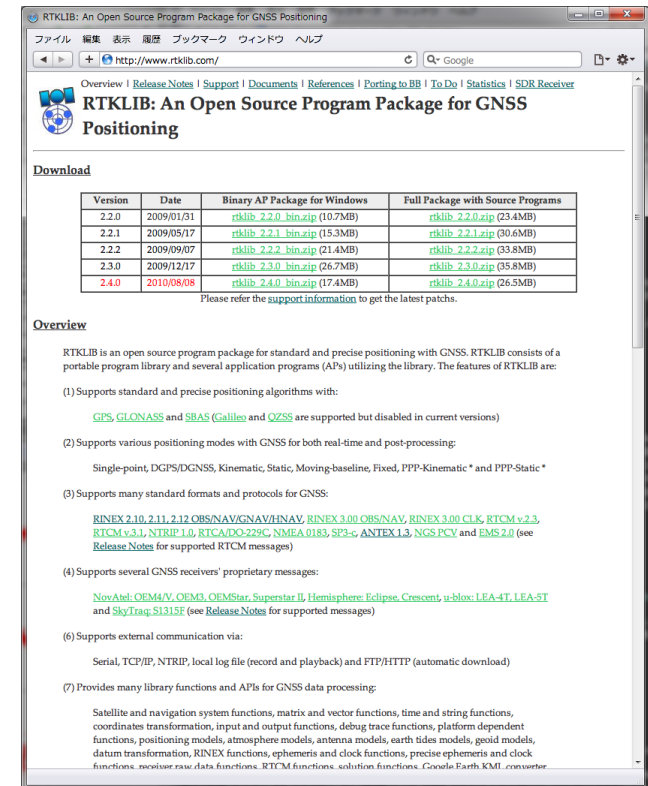
Preamble (8)	Reserved (6)	Message Length(10)	Data Message (Variable)	CRC (24)	Preamble (8)	Reserved (6)	Message Length(10)	Data Message (Variable)	CRC (24)	...
RTCM Message #1										
RTCM Message #2										

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

RTKLIB and PPP-Extension

RTKLIB

- **An Open Source Software Package for GNSS Positioning**
 - Has been developed since 2006
 - The latest ver. 2.4.2 p12 distributed under BSD license
 - Newer features are implemented in Beta branch
- **Portable APIs and Useful APs**
 - "All-in-one" GUI AP package for Windows
 - CLI APs for any environments



The screenshot shows the RTKLIB website in a browser window. The page title is "RTKLIB: An Open Source Program Package for GNSS Positioning". Below the title, there is a "Download" section with a table listing versions, dates, and download links for binary and full packages. The table is as follows:

Version	Date	Binary AP Package for Windows	Full Package with Source Programs
2.2.0	2009/01/31	rtklib_2.2.0_bin.zip (10.7MB)	rtklib_2.2.0.zip (23.4MB)
2.2.1	2009/05/17	rtklib_2.2.1_bin.zip (15.3MB)	rtklib_2.2.1.zip (30.6MB)
2.2.2	2009/09/07	rtklib_2.2.2_bin.zip (21.4MB)	rtklib_2.2.2.zip (33.8MB)
2.3.0	2009/12/17	rtklib_2.3.0_bin.zip (26.7MB)	rtklib_2.3.0.zip (35.8MB)
2.4.0	2010/08/08	rtklib_2.4.0_bin.zip (17.4MB)	rtklib_2.4.0.zip (26.5MB)

Below the table, there is an "Overview" section. The text states: "RTKLIB is an open source program package for standard and precise positioning with GNSS. RTKLIB consists of a portable program library and several application programs (APs) utilizing the library. The features of RTKLIB are:"

- (1) Supports standard and precise positioning algorithms with:
 - [GPS](#), [GLONASS](#) and [SBAS \(Galileo\)](#) and [QZSS](#) are supported but disabled in current versions
- (2) Supports various positioning modes with GNSS for both real-time and post-processing:
 - Single-point, DGPS/DGNSS, Kinematic, Static, Moving-baseline, Fixed, PPP-Kinematic * and PPP-Static *
- (3) Supports many standard formats and protocols for GNSS:
 - [RINEX 2.10](#), [2.11](#), [2.12 OBS/NAV/GNAV/HNAV](#), [RINEX 3.00 OBS/NAV](#), [RINEX 3.00 CLK](#), [RTCM v2.3](#), [RTCM v3.1](#), [NTRIP 1.0](#), [RTCA/DO-229C](#), [NMEA 0183](#), [SP3-C](#), [ANTEX L3](#), [NGS PCV](#) and [EMS 2.0](#) (see [Release Notes](#) for supported RTCM messages)
- (4) Supports several GNSS receivers' proprietary messages:
 - [NovAtel](#): [OEM4/V](#), [OEM3](#), [OEMStar](#), [Superstar II](#), [Hemisphere](#), [Eclipse](#), [Crescent](#); [u-blox](#): [LEA-4T](#), [LEA-5T](#) and [SkyTrac](#); [51315F](#) (see [Release Notes](#) for supported messages)
- (6) Supports external communication via:
 - Serial, TCP/IP, NTRIP, local log file (record and playback) and FTP/HTTP (automatic download)
- (7) Provides many library functions and APIs for GNSS data processing:
 - Satellite and navigation system functions, matrix and vector functions, time and string functions, coordinates transformation, input and output functions, debug trace functions, platform dependent functions, positioning models, atmosphere models, antenna models, earth tides models, geoid models, datum transformation, RINEX functions, ephemeris and clock functions, precise ephemeris and clock functions, [postproc raw data](#) functions, RTCM functions, solution functions, [Google Earth KM](#), [converter](#)

<http://www.rtklib.com>

RTKLIB History

Date	Version	Release Notes
• 2006/04	0.0.0	First version for RTK+C program lecture
• 2007/01	1.0.0	Simple post processing AP
• 2008/07	2.1.0	Add APs, support medium-range
• 2009/01	2.2.0	Start to distribute as Open Source S/W
• 2009/05	2.2.1	Support RTCM, NRTK, many receivers
• 2009/12	2.3.0	Support GLONASS, several receivers
• 2010/08	2.4.0	<u>Support PPP</u> and Long-baseline RTK (<1000 km)
• 2011/06	2.4.1	Support QZSS, JAVAD receiver, ...
• 2013/04	2.4.2	Support Galileo, Enable BeiDou, ... Hosting at GitHub, BSD License
• 2017/01	2.4.2 p12	The newest release and patch
• 2017/05	2.4.3 b28	Working on beta branch for 2.5.0
• 2017/12	2.5.0	New version release (planned)

RTKLIB Features

- **Standard and precise positioning algorithms with:**
 - GPS, GLONASS, Galileo, QZSS, BeiDou and SBAS
- **Positioning mode for real-time and post-processing:**
 - Single, SBAS, DGPS, RTK, Static, Moving-base and PPP
- **Supports many GNSS formats/protocols and receivers:**
 - RINEX 2.x/3.0, RTCM v.2/v.3, NTRIP 1.0, NMEA0183, SP3, RINEX CLK, ANTEX, NGS PCV, IONEX, RTCA-DO-229, EMS, ...
 - NovAtel, JAVAD, Hemisphere, u-blox, SkyTraq, Furuno, ...
- **Supports real-time communication via:**
 - Serial, TCP/IP, NTRIP and file (record and playback)

PPP Models in RTKLIB

	ver. 2.4.1	ver. 2.4.2
Satellites	GPS, GLO and QZS	GPS, GLO, QZS, GAL and BDS
Troposphere	Standard-Atmosphere NMF + Gradient	Standard-Atmosphere NMF or GMF (opt) + Gradient
Ionosphere	Iono-Free LC (L1-L2)	Iono-Free LC (L1/L2, L1/L5) or STEC estimation
Site Displacement	Solid Earth Tide: IERS Step 1 + Step 2 K1 radial only	Solid Earth Tide: DEHANTTIDEINEL.F (opt) Ocean Tide Loading: IERS 2010 with BLQ Pole Tide: IERS 2010 with IGS ERP
Ambiguity Resolution	No (FLOAT)	Experimental (CNES WL FCB + phase-clock)

PPP-Extension for MADOCA

- **PPP-extension based on ver. 2.4.2 p11**
 - PPP codes are completely re-written for JAXA
 - Not published in RTKLIB trunk codes as OSS
- **PPP-AR Features**
 - with FCB products generated by MADOCA
 - Explicit STEC estimation and ILR (integer least square)
 - Partial fixing with auto-shrink of search space
- **PPP with local corrections**
 - PPP-RTK with local corrections to reduce convergence time
 - STEC and ZTD estimation for local correction generation
- **PP (RNX2RTKP) and RT (RTKRCV) APs**

Partial Fixing for PPP-AR

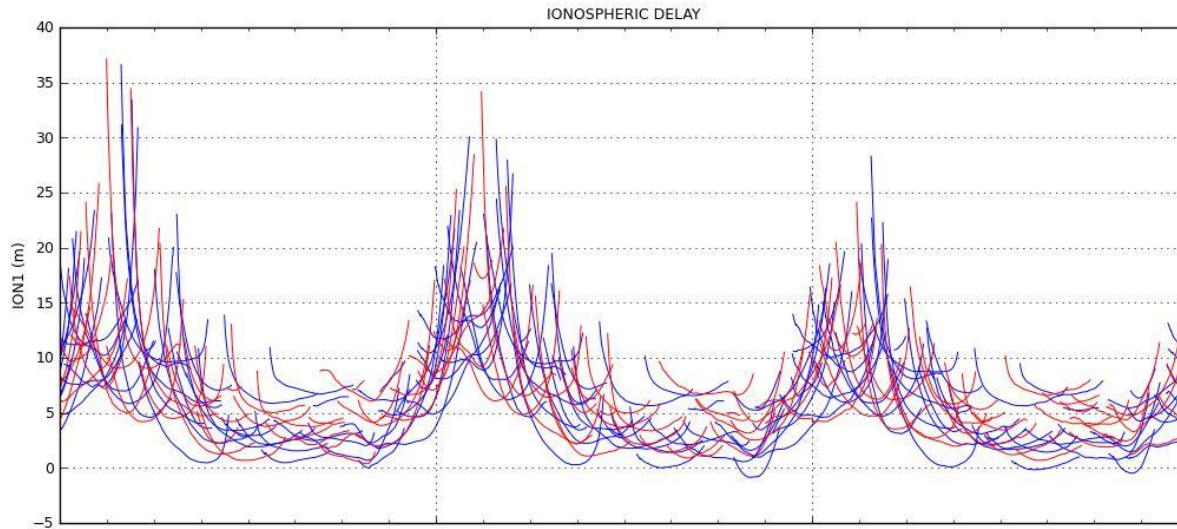
- **Procedure**

- Generate DD-ambiguities
 - LAMBDA decorrelation
 - MLAMBDA search
 - Validation by ratio-test
 - Shrink integer search space
- OK ↓
- ← retry
-

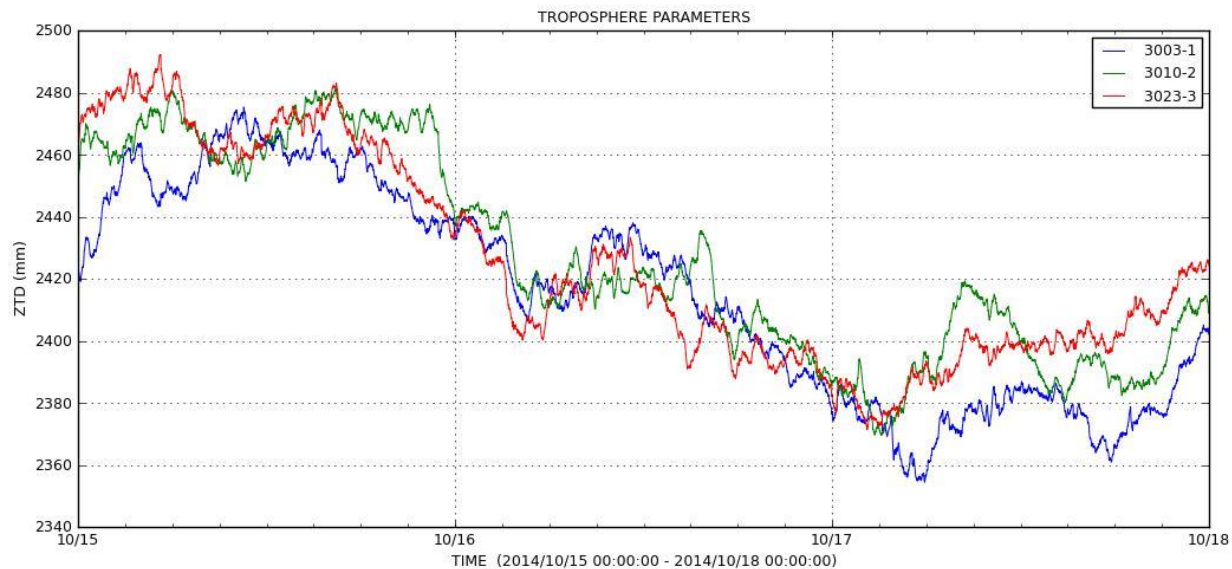
SOLUTION ERROR			RATIO	# OF FIXED AMBIGUITIES (N1,N2,...)
E(m)	N(m)	U(m)		
0.0024	0.0074	0.0141	1.577	12 (57 72 53 10 39 -78 40 607 -1496 -165 -576 812)
0.0026	0.0084	0.0132	1.484	11 (57 72 53 10 39 -78 40 607 -1496 -165 -576)
-0.0144	0.0301	-0.0198	1.537	10 (57 72 53 10 39 -78 40 607 -1496 -165)
0.0404	0.0129	-0.0962	5.401	9 (57 72 53 10 39 -78 40 607 -1496)
0.0295	0.0151	-0.1035	4.105	8 (57 72 53 10 39 -78 40 607)
-0.2267	0.0351	-0.1898	13.118	7 (57 72 53 10 39 -78 40)
-0.2288	0.0359	-0.1848	13.131	6 (57 72 53 10 39 -78)
-0.2492	0.0396	-0.1930	49.235	5 (57 72 53 10 39)
-0.2505	0.0391	-0.1943	102.132	4 (57 72 53 10)

Local Correction Generation

**TEC
(VTEC)**

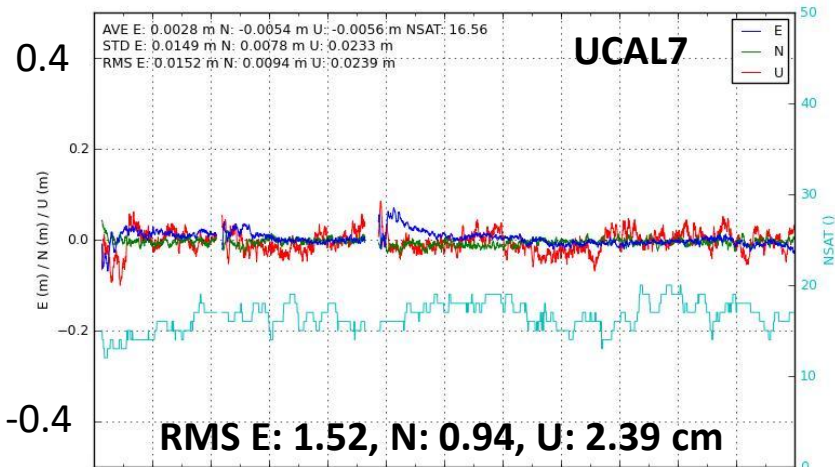


ZTD

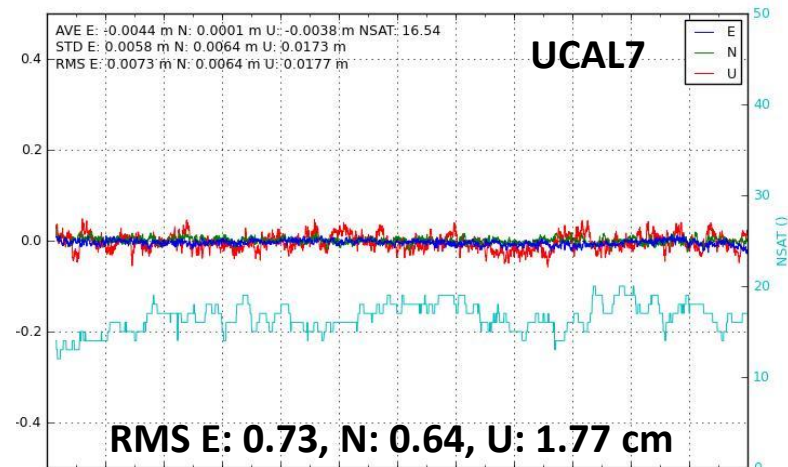


PPP-AR Accuracy

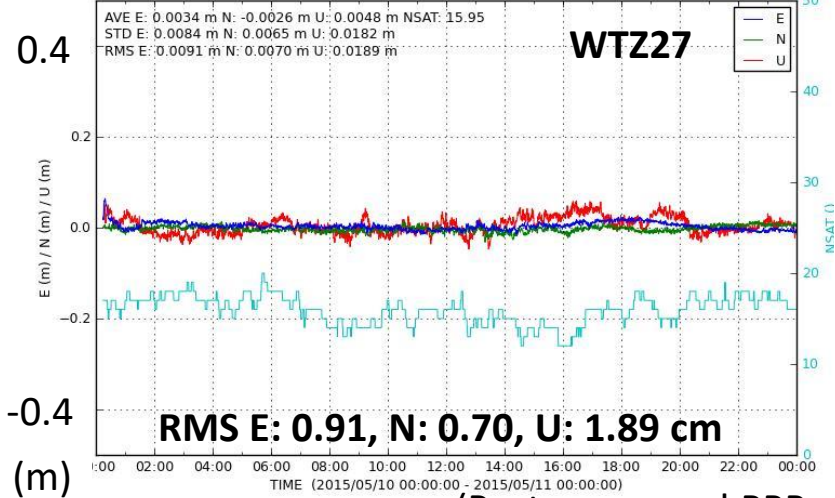
PPP



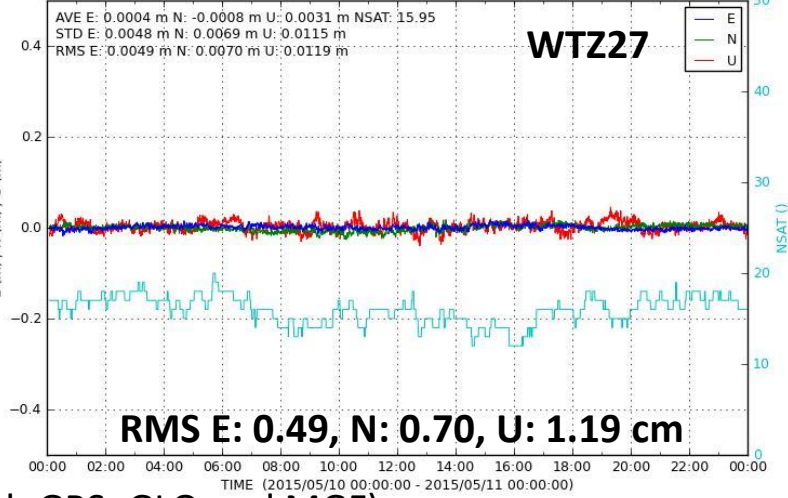
PPP-AR



STATION POSITION ERROR (WTZ27)

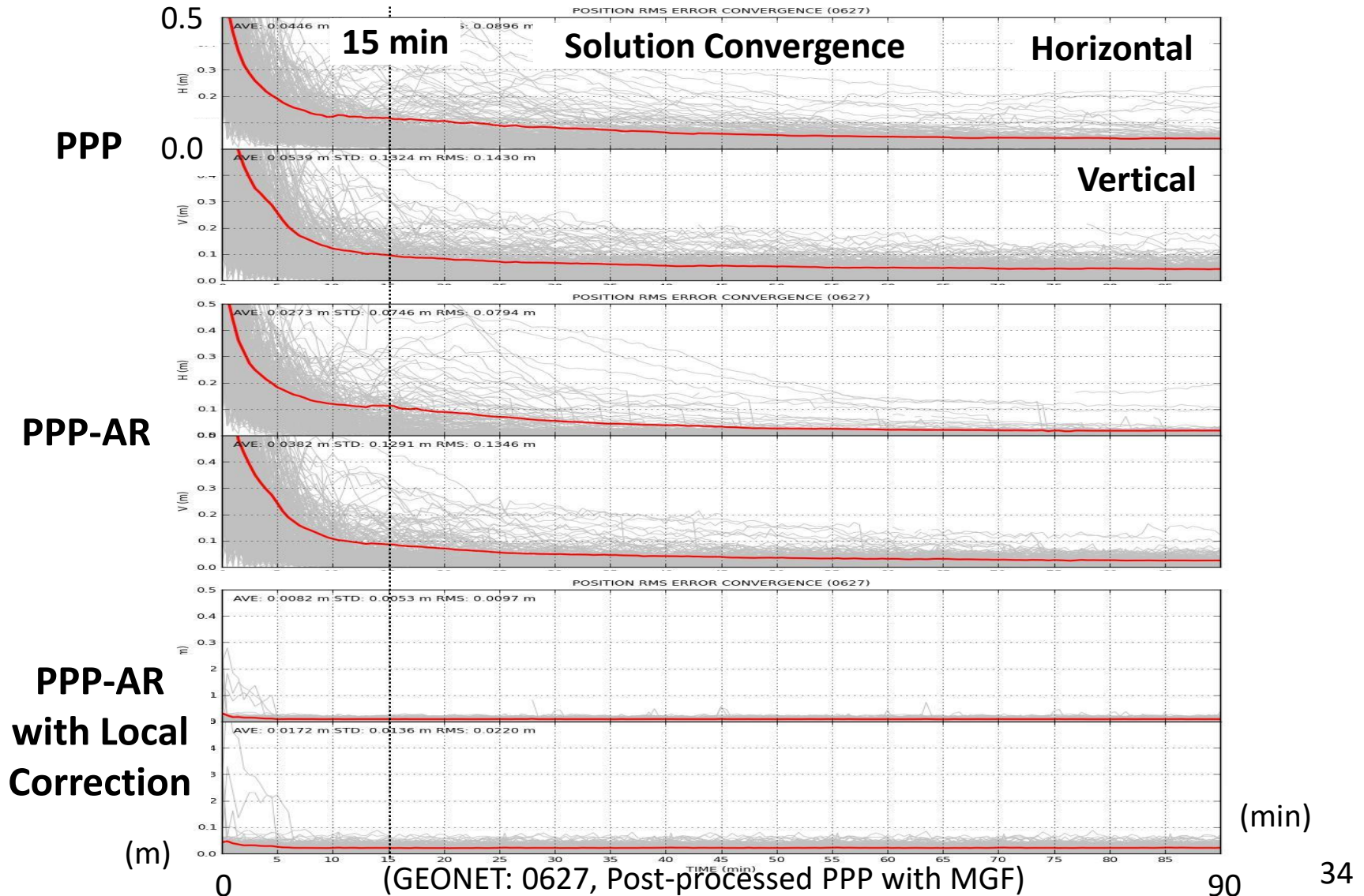


STATION POSITION ERROR (WTZ27)



(Post-processed PPP with GPS+GLO and MGF)

Convergence with Local Correction



Summary

- **Review of PPP technology**
 - History, applications and models
- **MADOCA**
 - Development and current status
 - Models and algorithms
 - Products and their quality
- **RTKLIB and PPP-Extension**
 - History and Features
 - Extension for PPP-AR and local corrections for PPP