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

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Review of PPP Technology

Precise Point Positioning (PPP)

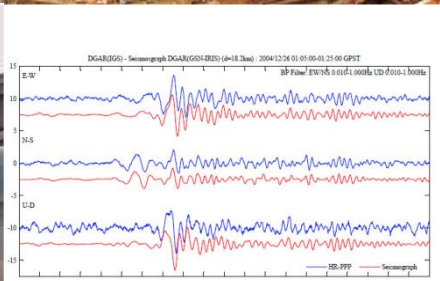
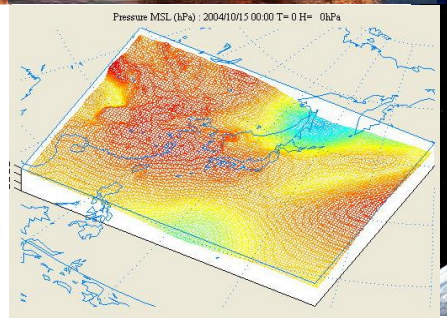
- **Introduced by JPL (GIPSY/OASIS) in 1990s**
  - J.F. Zumberge et al., **Precise Point Positioning** for the Efficient and Robust Analysis of GPS Data from Large Networks, *JGR,* 1997
- **Many previous works by IGS**
  - High-quality and accurate orbit and clock products since 1994
  - Development 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)

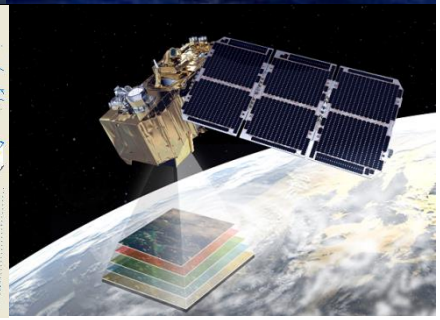
PPP Applications

- 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





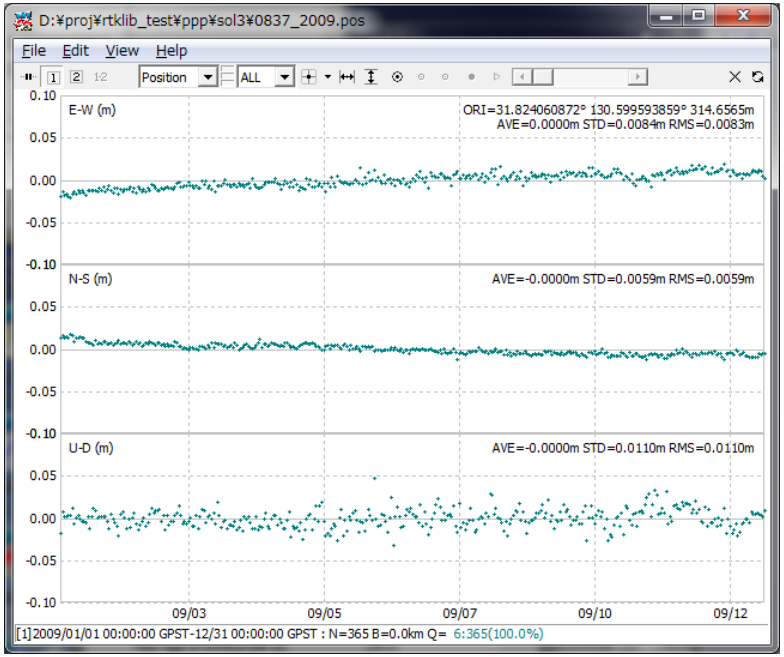


Typical PPP Models

- **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)

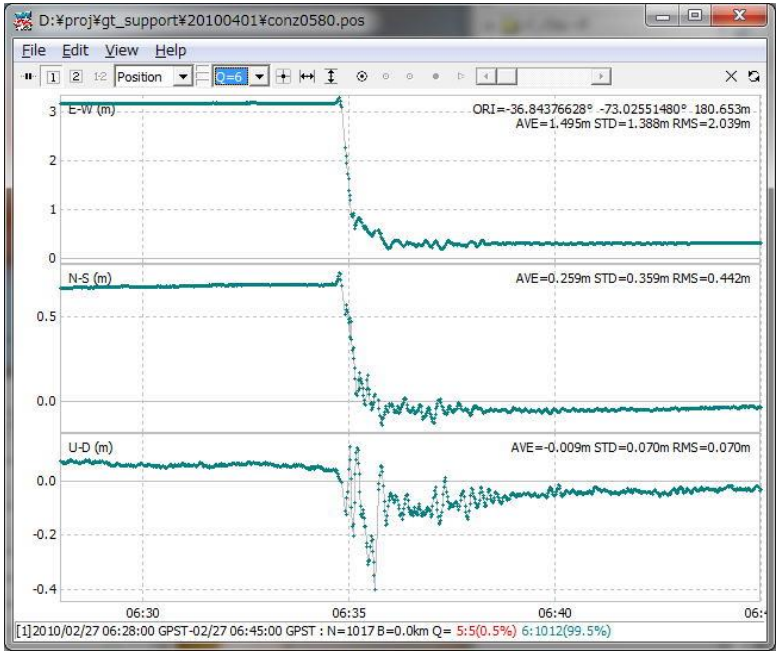


GEONET 0837, 2009/1/1-12/31

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

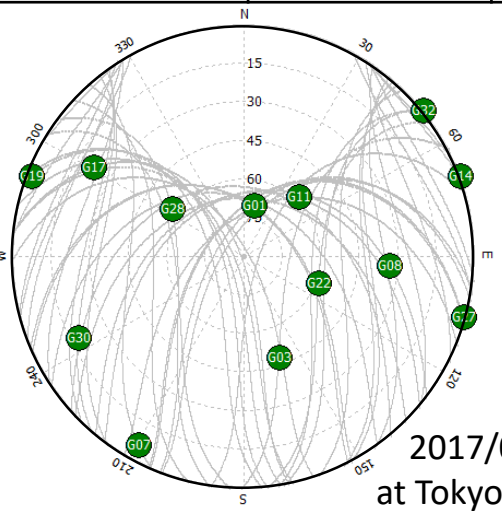
- **IGS-RTS (real-time service)**
  - RTWG and RTPP since 2001
  - IGS-RTS formally launched in 2013 (only GPS)
  - NTRIP via Internet with standard RTCM 3.2 SSR format
  - Free of charge according to IGS "open data policy"
- **Commercial PPP services**
  - Navcom StarFire, Trimble RTX, Fugro Seastar 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)

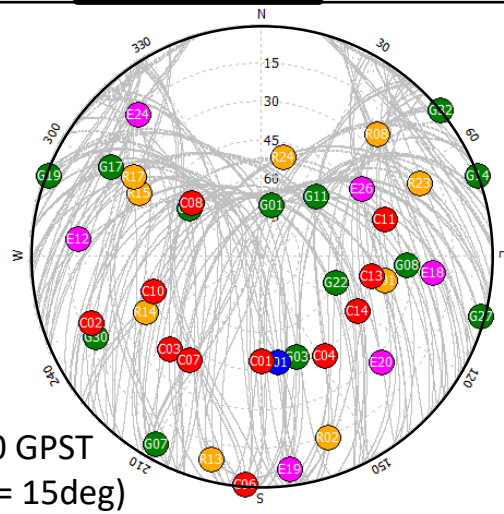
Multi-constellation GNSS

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





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

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

MADOCA

MADOCA

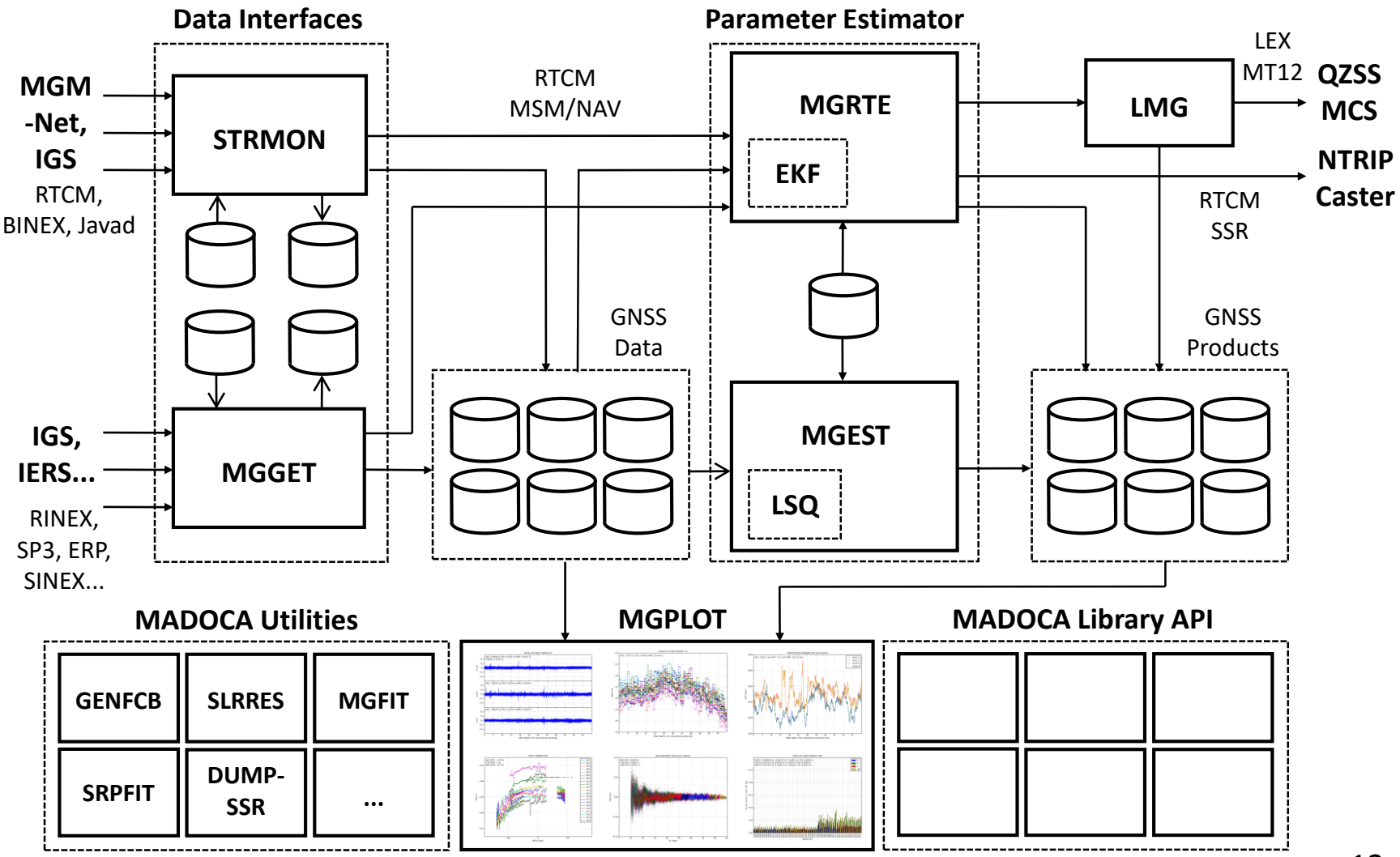
Multi-GNSS Advanced Demonstration tool for Orbit and Clock Analysis

- **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

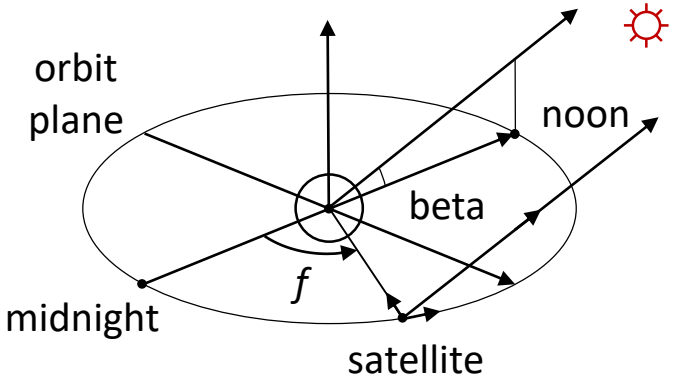
MADOCA Architecture

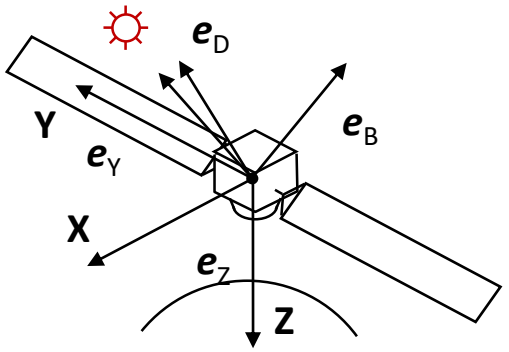


MADOCA Models

- **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~)



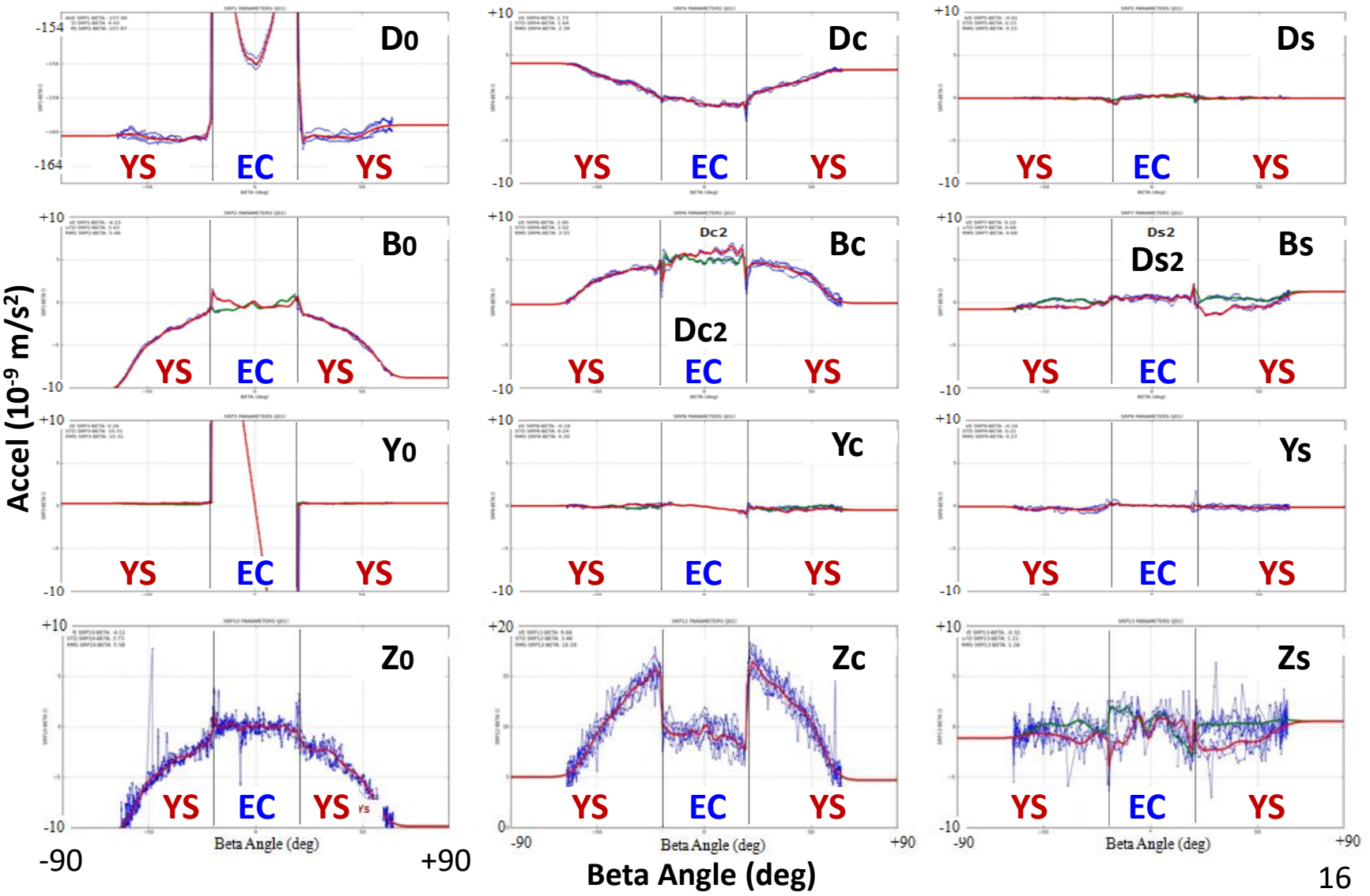


YS: $a_{srp} = S((D_0 + D_C \cos f + D_S \sin f)\, e_D +$
$(B_0 + B_C \cos f + B_S \sin f)\, e_B +$
$(Y_0 + Y_C \cos f + Y_S \sin f)\, e_Y +$
$(Z_0 + Z_C \cos f + Z_S \sin f)\, e_z) * 10^{-9}$ (m/s²)

EC: $a_{srp} = S((D_0 + D_C \cos f + D_S \sin f +$
$D_{2C} \cos 2f + D_{2S} \sin 2f)\, e_D + B_0\, e_B +$
$(Y_0 + Y_C \cos f + Y_S \sin f)\, e_Y +$
$(Z_0 + Z_C \cos f + Z_S \sin f)\, e_z) * 10^{-9}$ (m/s²)

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

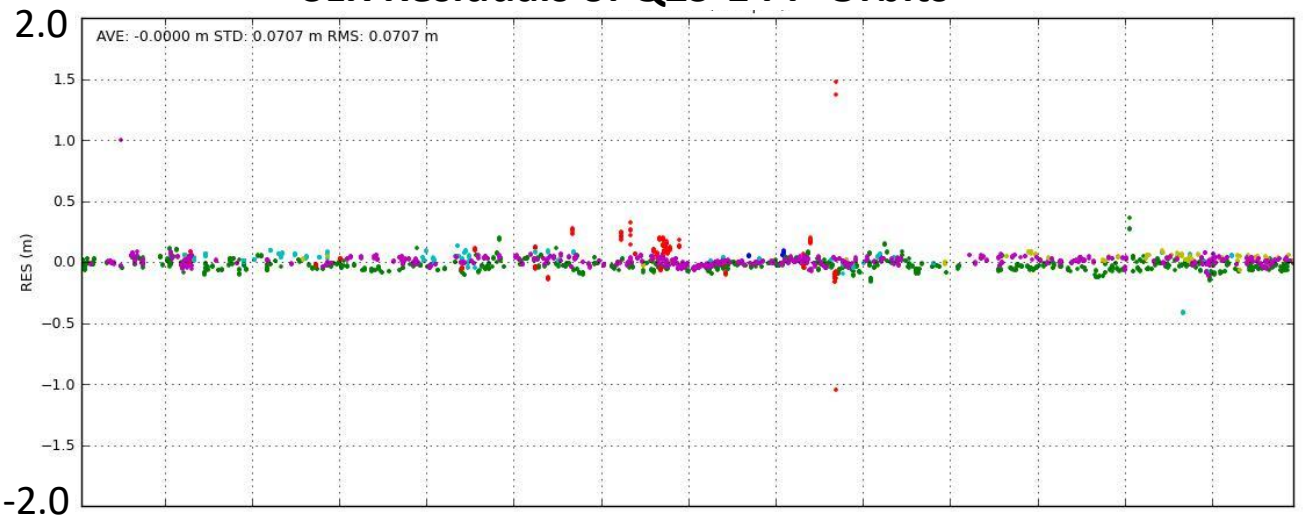
EDBY Coefficients for QZS-1



Model Improvement for QZS-1

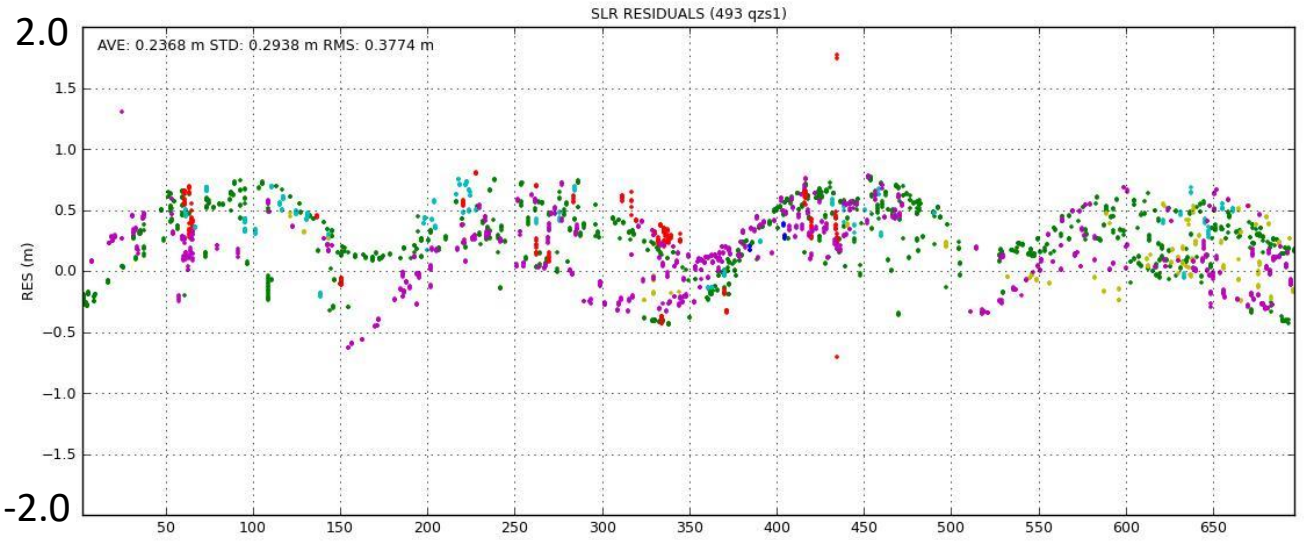
SLR Residuals of QZS-1 PP-Orbits

Ver. 0.7.0 EDBY



RMS 7.07 cm

Ver. 0.6.7 MDBY



RMS 37.74 cm

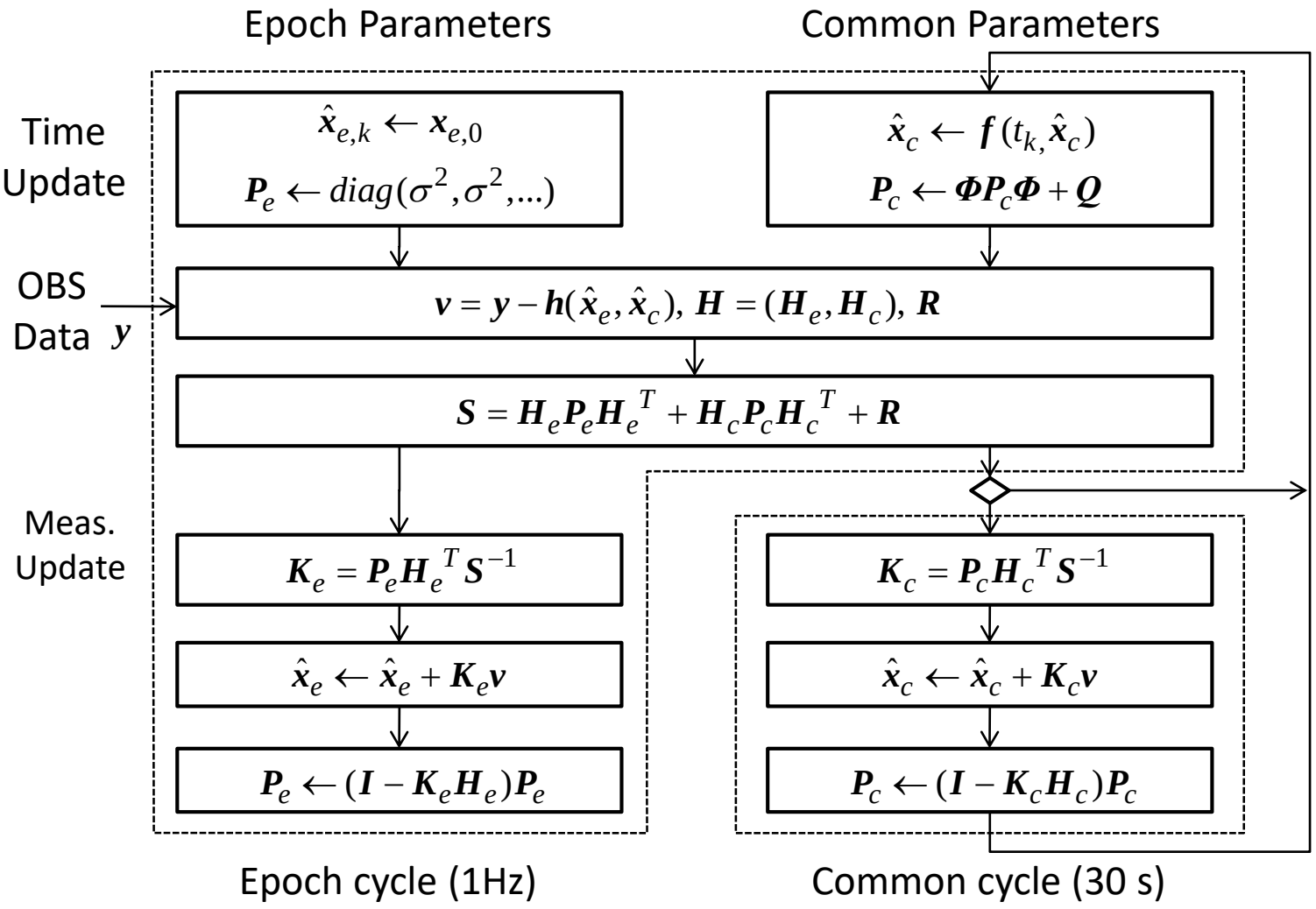
(m)

Days (2013/01/01-2014/11/30)

Parameter Adjustment

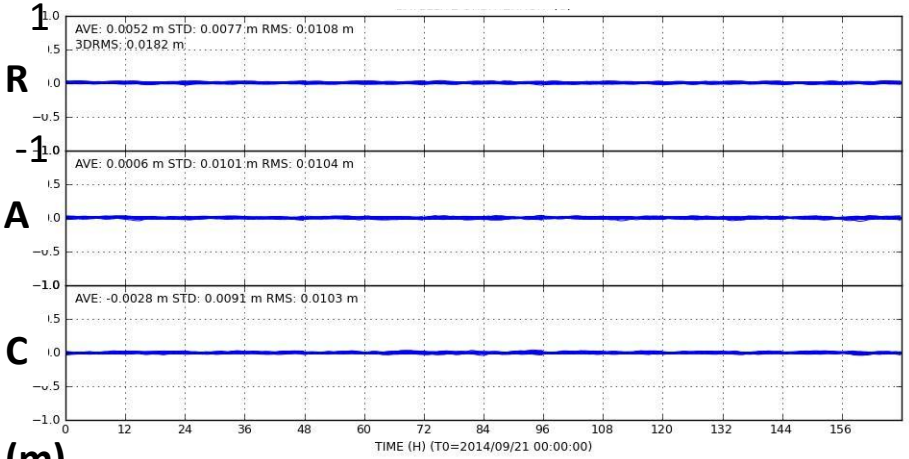
	MGEST (Post-Processing)	MGRTE (Real-Time)
Algorithm	Iterated Weighted LSQ	Dual-Cycle-EKF
Estimated Parameters	Orbit, SRP, Drag, Emp-Acc, Thru-Acc, Sat/Rcv Clock, Position, ZTD/Grad, Amb, EOP, Geocenter, Rcv Bias	
Measurements	ZD Iono-free Carrier-Phase and Peudorange	
Numerical Solver	NEQ by Cholesky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

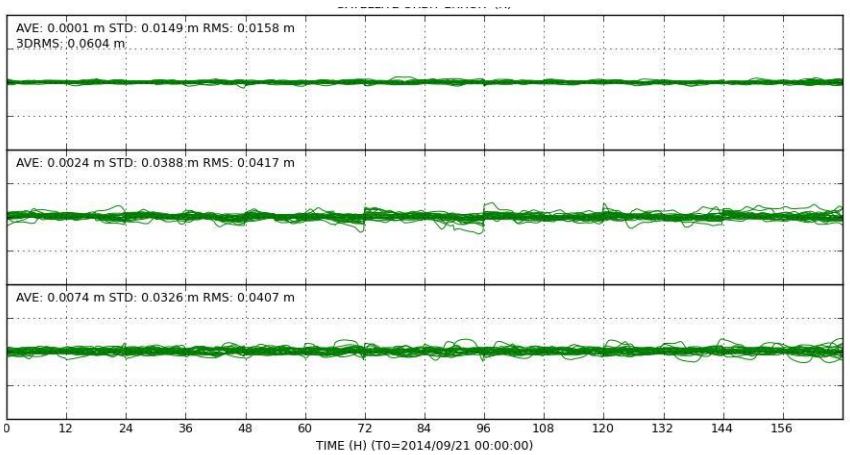


Quality of PP-Products

MGF wrt IGR (GPS)



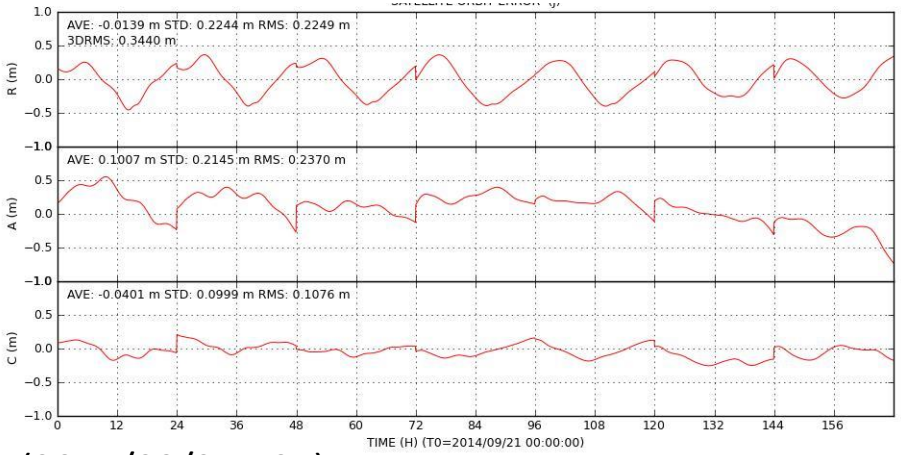
MGF wrt IGV (GLONASS)



Orbit Error

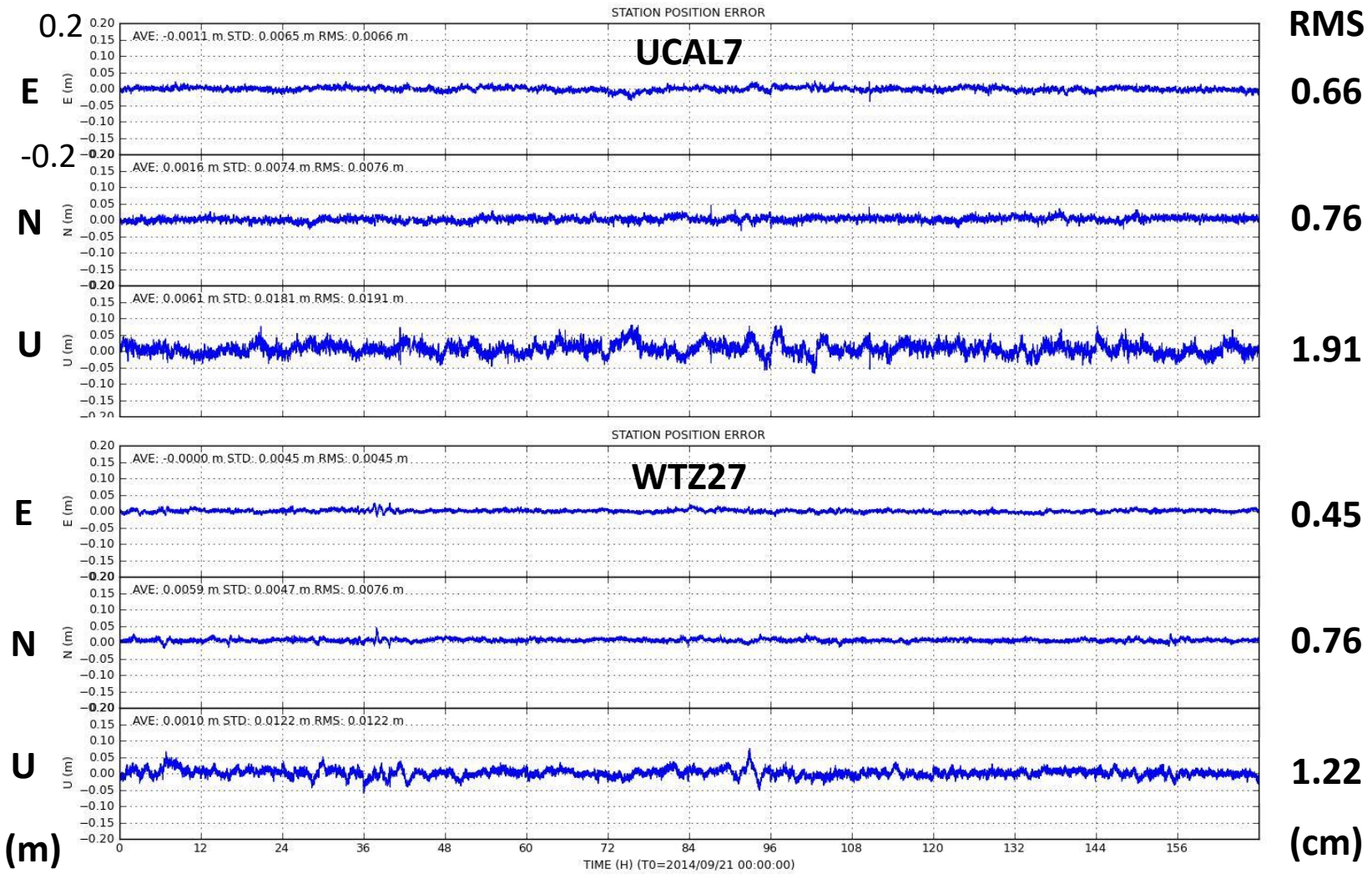
	RMS (cm)			
	R	A	C	3D
GPS	1.08	1.04	1.03	1.82
GLO	1.58	4.17	4.07	6.04
QZSS	22.49	23.70	10.76	34.40

MGF wrt QZF (QZSS)



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

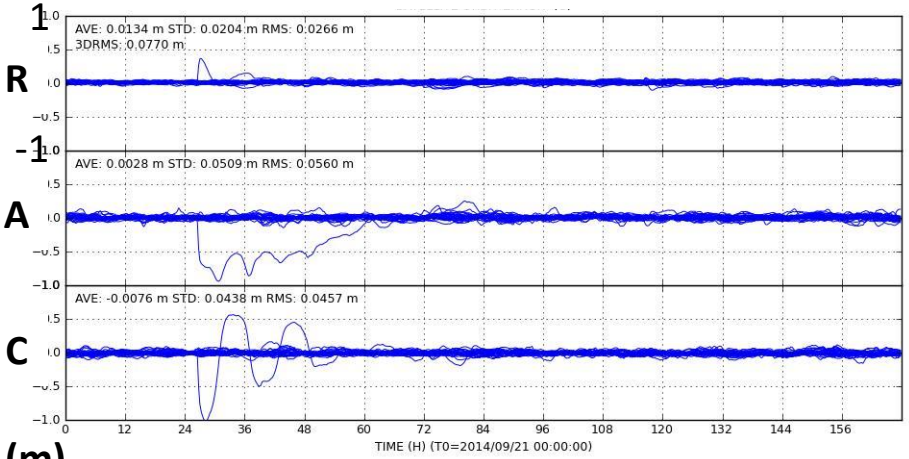
PPP with PP-Products



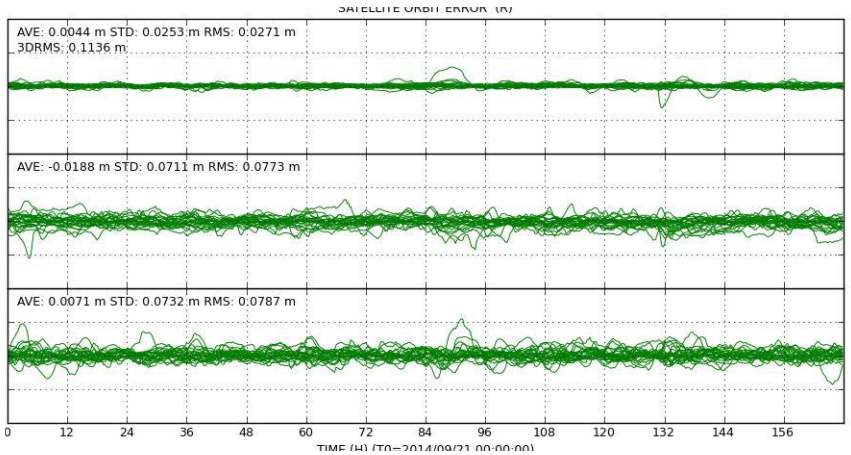
Kinematic PPP with MGF (GPS+GLO), GPS Week 1811 (2014/09/21 - 27)

Quality of RT-Products

MGRT1 wrt IGR (GPS)



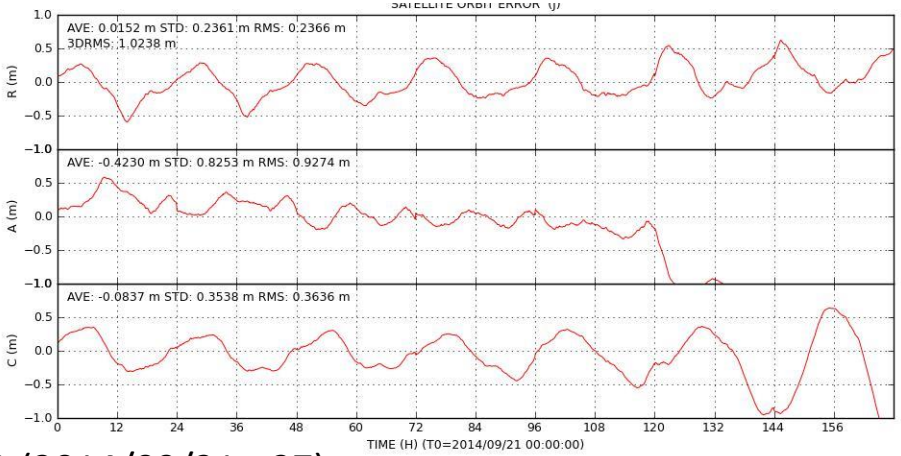
MGRT1 wrt IGV (GLONASS)



Orbit Error

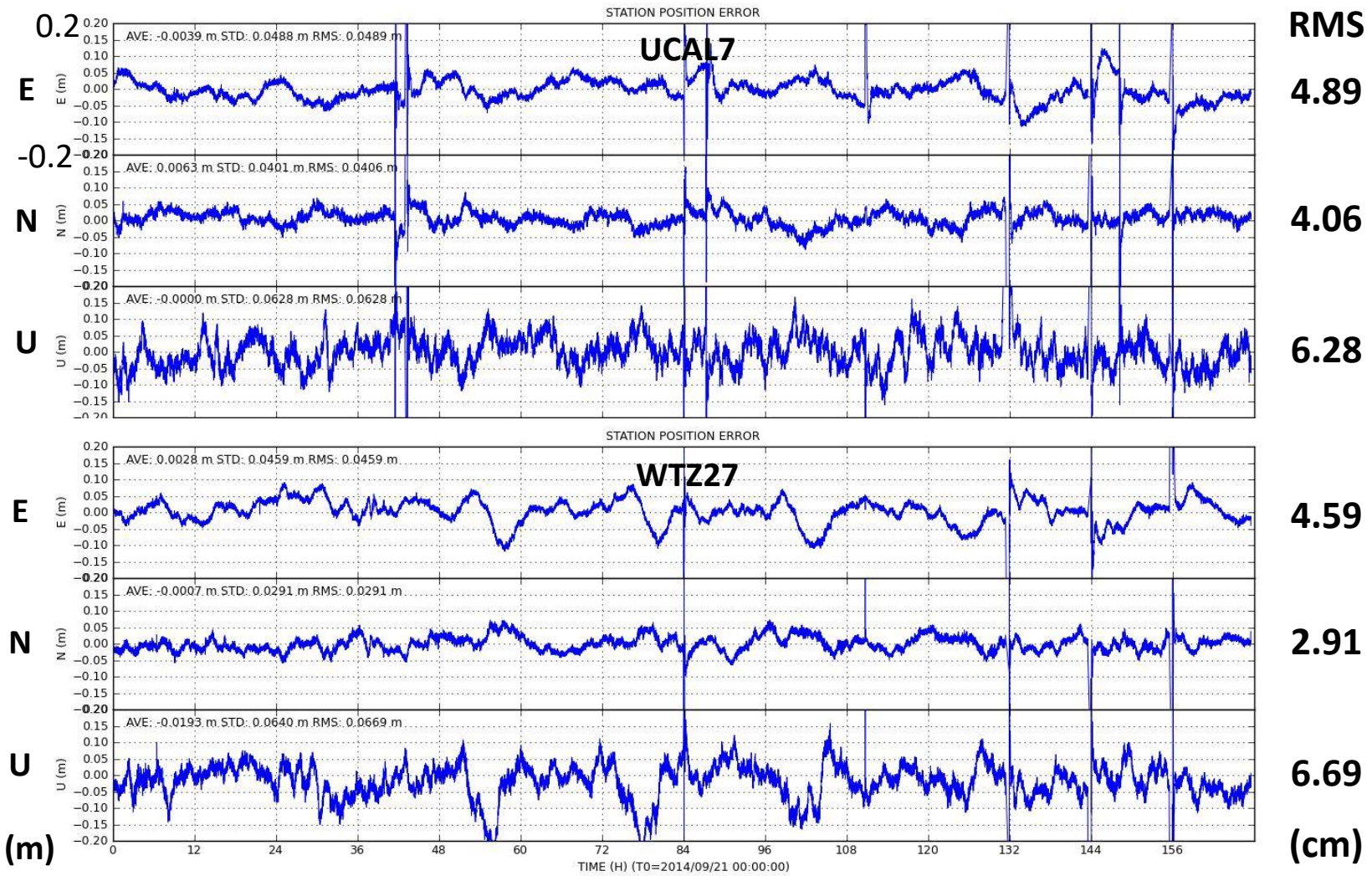
	RMS (cm)			
	R	A	C	3D
GPS	2.66	5.60	4.57	7.70
GLO	2.71	7.73	7.87	11.36
QZSS	23.66	92.74	36.36	102.4

MGRT1 wrt QZF (QZSS)



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

PPP with RT-Products



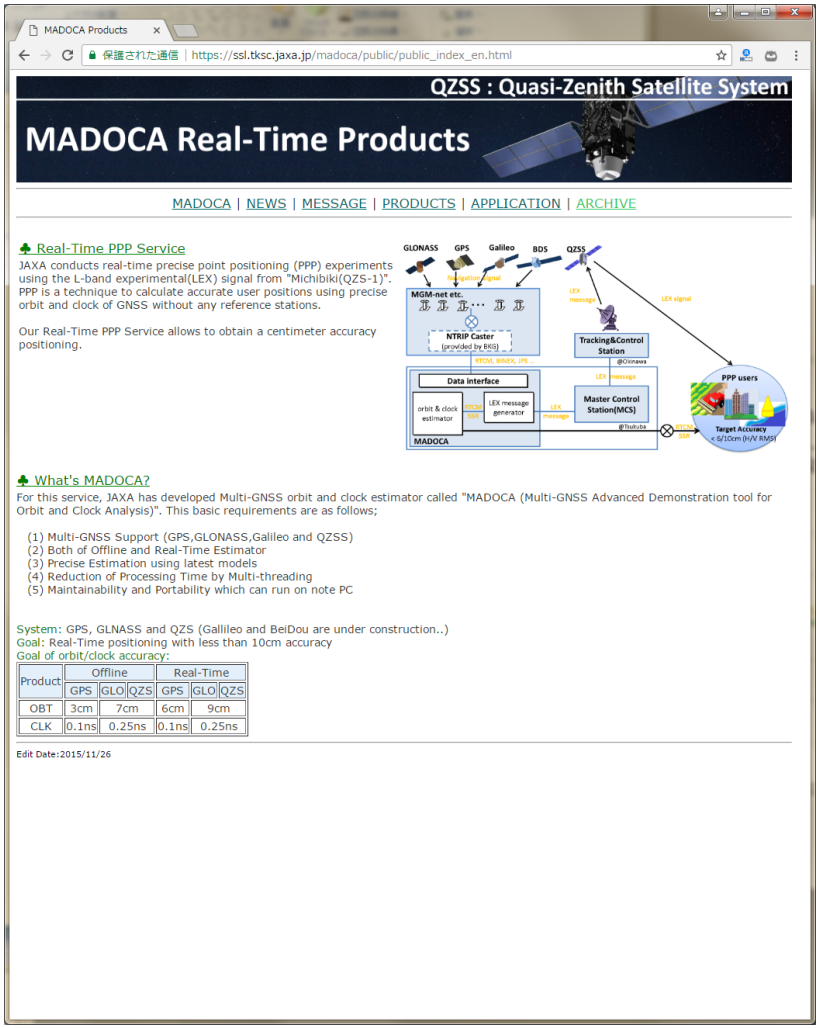
0.2 / -0.2 (m)

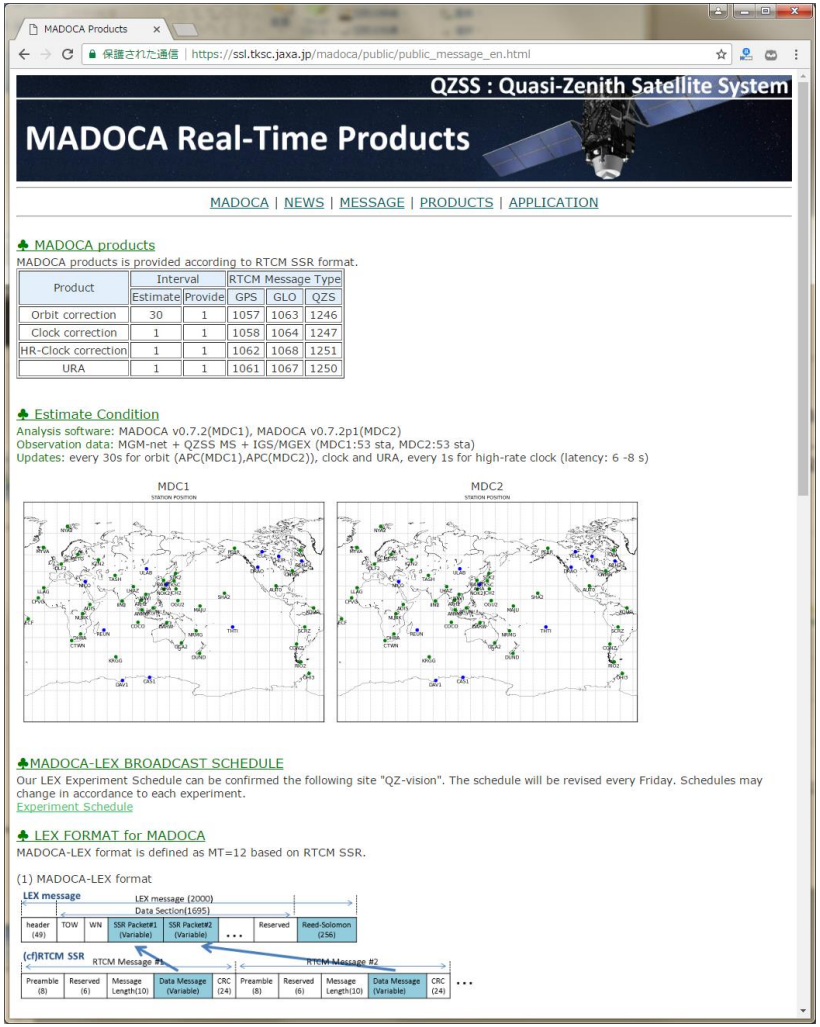
RMS (cm)

	UCAL7	WTZ27
E	4.89	4.59
N	4.06	2.91
U	6.28	6.69

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

JAXA MADOCA Products



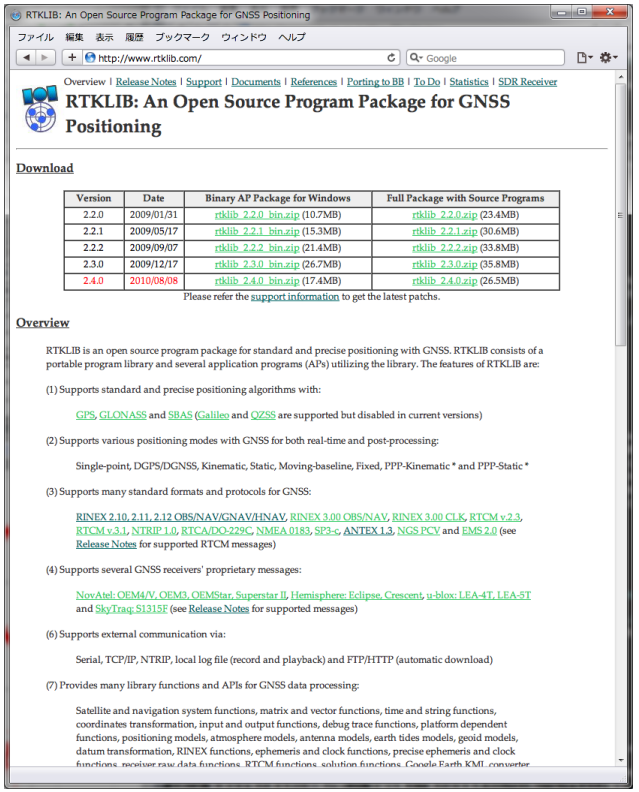


https://ssl.tksc.jaxa.jp/madoca/public/public_index_en.html

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



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	**Support PPP** 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

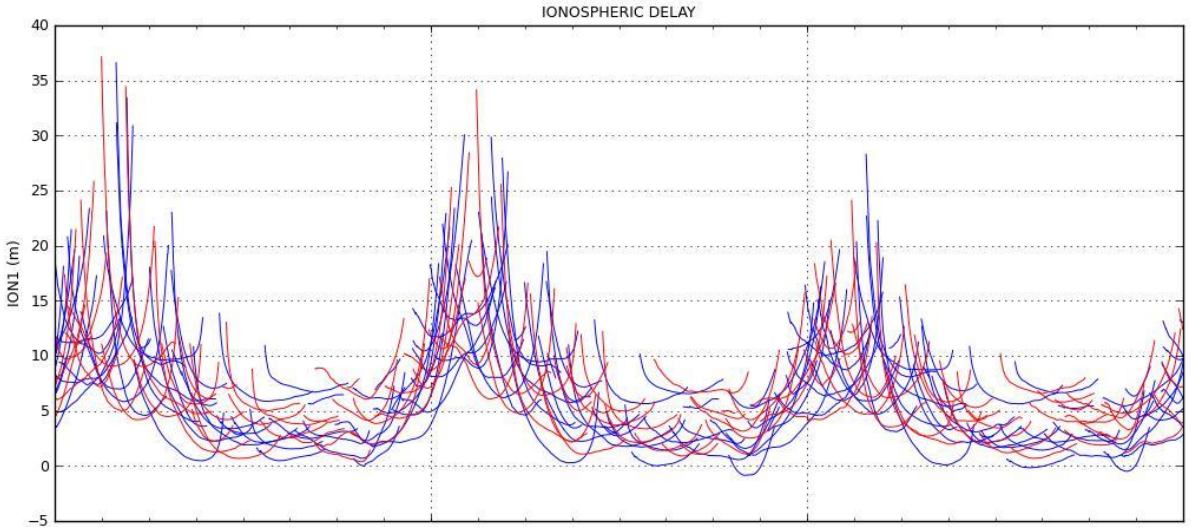
OK

retry

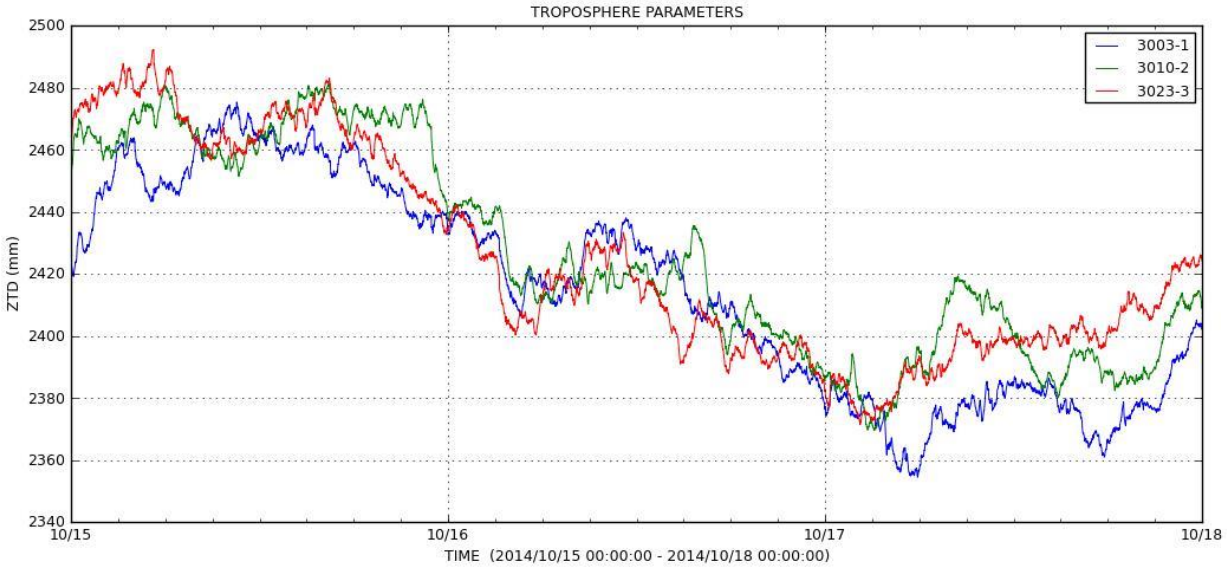
```
      SOLUTION ERROR          RATIO   # OF FIXED AMBIGUITIES (N1,N2,...)
   E(m)     N(m)     U(m)
--------------------------------------------------------------------------------
 0.0024   0.0074   0.0141     1.577  12 (57 72 53 10 39 -78 40 607 -1496 -165 -576 812)
 0.0026   0.0084   0.0132     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

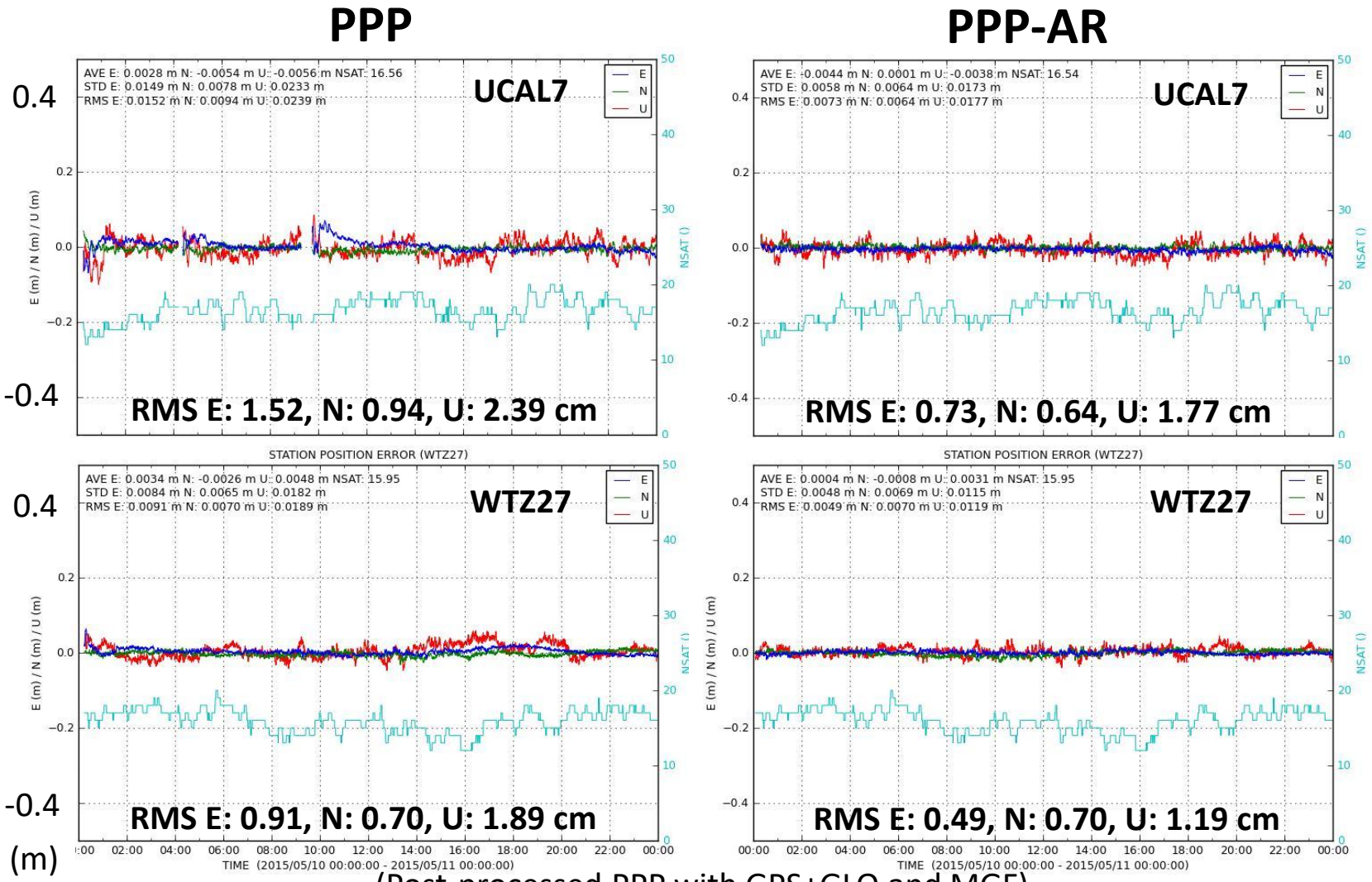
TEC (VTEC)



ZTD

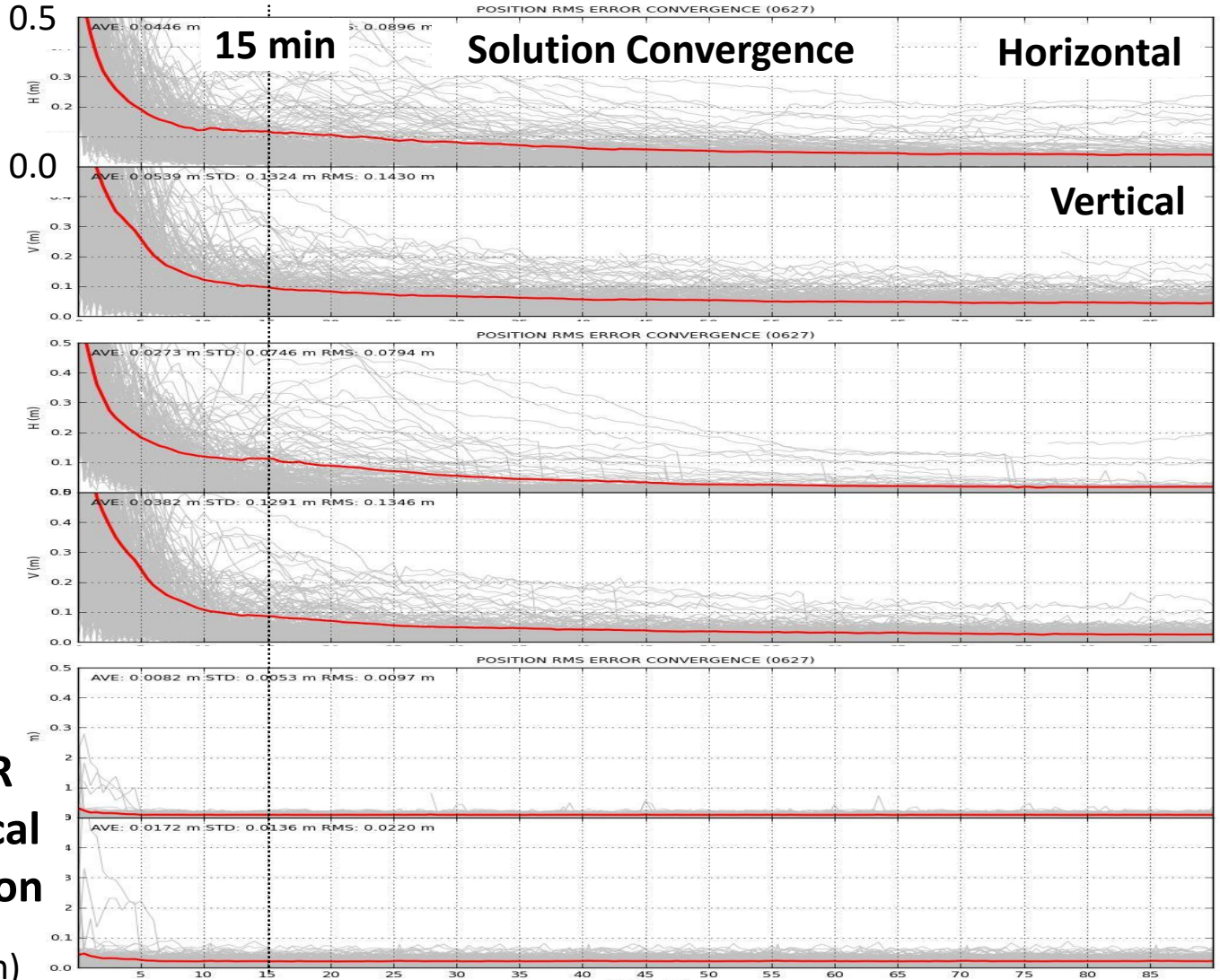


PPP-AR Accuracy



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

Convergence with Local Correction



(GEONET: 0627, Post-processed PPP with MGF)

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