

# Processing GNSS Data in Real-Time

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TU Prague

Frankfurt, January 2014

## Medieval Times of GNSS (personal memories)

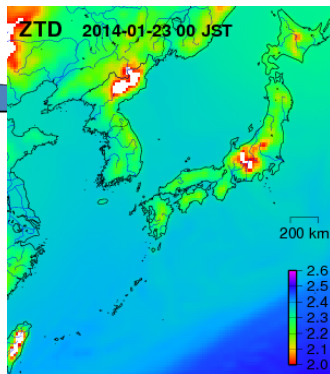
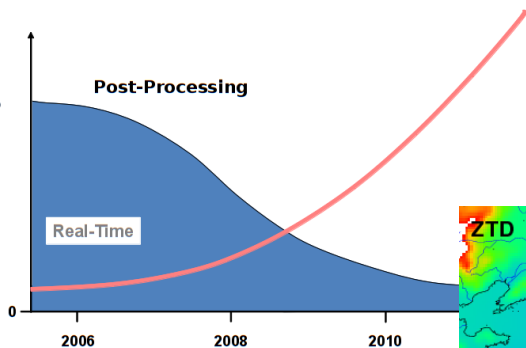
- 1991 Prof. Gerhard Beutler became the director of the Astronomical Institute, University of Berne. The so-called Bernese GPS Software started to be used for (post-processing) analyzes of GNSS data.
- 1992 LM started his PhD study at AIUB.
- 1992 Center for Orbit Determination in Europe (consortium of AIUB, Swisstopo, BKG, IGN, and IAPG/TUM) established. Roughly at that time LM met Dr. Georg Weber for the first time.
- 1993 International GPS Service formally recognized by the IAG.
- 1994 IGS began providing GPS orbits and other products routinely (January, 1).
- 1995 GPS declared fully operational.

## CODE-Related Works in 1990's

- The Bernese GPS Software was the primary tool for CODE analyzes (Fortran 77).
- IGS reference network was sparse.
- Real-time data transmission limited (Internet was still young, TCP/IP widely accepted 1989).
- CPU power of then computers was limited (VAX/VMS OS used at AIUB).

In 1990's high precision GPS analyzes were almost exclusively performed in post-processing mode. The typical precise application of GPS at that time was the processing of a network of static GPS-only receivers for the estimation of station coordinates.

# Tempora mutantur (and maybe “nos mutamur in illis”)



# O tempora! O mores!

- people want more and more ...
- everybody wants everything immediately ...
- and, of course, free of charge ...

In GNSS-world it means:

- There are many new kinds of GNSS applications - positioning is becoming just one of many purposes of GNSS usage.
- Many results of GNSS processing are required in real-time (or, at least, with very small delay).
- GPS is not the only positioning system. Other GNSS are being established (for practical but also for political reasons).
- People are used that many GNSS services are available free of charge (but the development and maintenance has to be funded).

But ...

# Nihil novi sub sole

Each GNSS-application is based on processing code and/or phase observations

$$\begin{aligned}P^i &= \varrho^i + c \delta - c \delta^i + T^i + I^i + b_P \\L^i &= \varrho^i + c \delta - c \delta^i + T^i - I^i + b^i\end{aligned}$$

where

$P^i, L^i$  are the code and phase measurements,  
 $\varrho^i$  is the travel distance between the satellite and the receiver,  
 $\delta, \delta^i$  are the receiver and satellite clock errors,  
 $I^i$  is the ionospheric delay,  
 $T^i$  is the tropospheric delay,  
 $b_P$  is the code bias, and  
 $b^i$  is the phase bias (including initial phase ambiguity).

Observation equations reveal what information can be gained from processing GNSS data:

- geometry (receiver positions, satellite orbits), and
- state of atmosphere (both dispersive and non-dispersive part)

The observation equations also show that, in principle, GNSS is an **interferometric** technique – precise results are actually always relative.

# Challenges of Real-Time GNSS Application

- Suitable algorithms for the parameter adjustment have to be used (filter techniques instead of classical least-squares).
- Reliable data links have to be established (between rover station and a reference station, between receivers and processing center, or between processing center and DGPS correction provider).
- Software tools for handling real-time data (Fortran is not the best language for that).
- Fast CPUs.

As said above – GNSS is an interferometric technique. Processing of a single station cannot give precise results. However, data of reference station(s) can be replaced by the so-called corrections (DGPS corrections, precise-point positioning etc.) These techniques are particularly suited for real-time applications because the amount of data being transferred can be considerably reduced.

# Algorithms – Kalman Filter

State vectors  $\mathbf{x}$  at two subsequent epochs are related to each other by the following linear equation:

$$\mathbf{x}(n) = \Phi \mathbf{x}(n-1) + \Gamma \mathbf{w}(n) ,$$

where  $\Phi$  and  $\Gamma$  are known matrices and *white noise*  $\mathbf{w}(n)$  is a random vector with the following statistical properties:

$$\begin{aligned} E(\mathbf{w}) &= \mathbf{0} \\ E(\mathbf{w}(n) \mathbf{w}^T(m)) &= \mathbf{0} \text{ for } m \neq n \\ E(\mathbf{w}(n) \mathbf{w}^T(n)) &= \mathbf{Q}_s(n) . \end{aligned}$$

Observations  $\mathbf{l}(n)$  and the state vector  $\mathbf{x}(n)$  are related to each other by the linearized *observation equations* of form

$$\mathbf{l}(n) = \mathbf{A} \mathbf{x}(n) + \mathbf{v}(n) ,$$

where  $\mathbf{A}$  is a known matrix (the so-called *first-design matrix*) and  $\mathbf{v}(n)$  is a vector of random errors with the following properties:

$$\begin{aligned} E(\mathbf{v}) &= \mathbf{0} \\ E(\mathbf{v}(n) \mathbf{v}^T(m)) &= \mathbf{0} \text{ for } m \neq n \\ E(\mathbf{v}(n) \mathbf{v}^T(n)) &= \mathbf{Q}_l(n) . \end{aligned}$$



## Classical KF Form

Minimum Mean Square Error (MMSE) estimate  $\hat{\mathbf{x}}(n)$  of vector  $\mathbf{x}(n)$  meets the condition  $E((\mathbf{x} - \hat{\mathbf{x}})(\mathbf{x} - \hat{\mathbf{x}})^T) = \min$  and is given by

$$\hat{\mathbf{x}}^-(n) = \Phi \hat{\mathbf{x}}(n-1) \quad (1a)$$

$$\mathbf{Q}^-(n) = \Phi \mathbf{Q}(n-1) \Phi^T + \Gamma \mathbf{Q}_s(n) \Gamma^T \quad (1b)$$

$$\hat{\mathbf{x}}(n) = \hat{\mathbf{x}}^-(n) + \mathbf{K} (\mathbf{I} - \mathbf{A} \hat{\mathbf{x}}(n-1)) \quad (2a)$$

$$\mathbf{Q}(n) = \mathbf{Q}^-(n) - \mathbf{K} \mathbf{A} \mathbf{Q}^-(n), \quad (2b)$$

where

$$\mathbf{K} = \mathbf{Q}^-(n) \mathbf{A}^T \mathbf{H}^{-1}, \quad \mathbf{H} = \mathbf{Q}_l(n) + \mathbf{A} \mathbf{Q}^-(n) \mathbf{A}^T.$$

Equations (1) are called *prediction*, equations (2) are called *update* step of Kalman filter.

# Square-Root Filter

Algorithms based on equations (1) and (2) may suffer from numerical instabilities that are primarily caused by the subtraction in (2b). This deficiency may be overcome by the so-called *square-root* formulation of the Kalman filter that is based on the so-called *QR-Decomposition*. Assuming the Cholesky decompositions

$$\mathbf{Q}(n) = \mathbf{S}^T \mathbf{S}, \quad \mathbf{Q}_l(n) = \mathbf{S}_l^T \mathbf{S}_l, \quad \mathbf{Q}^-(n) = \mathbf{S}^{-T} \mathbf{S}^- \quad (3)$$

we can create the following block matrix and its QR-Decomposition:

$$\begin{pmatrix} \mathbf{S}_l & \mathbf{0} \\ \mathbf{S}^- \mathbf{A}^T & \mathbf{S}^- \end{pmatrix} = N \begin{pmatrix} \mathbf{X} & \mathbf{Y} \\ \mathbf{0} & \mathbf{Z} \end{pmatrix}. \quad (4)$$

It can be easily verified that

$$\begin{aligned} \mathbf{H} &= \mathbf{X}^T \mathbf{X} \\ \mathbf{K}^T &= \mathbf{X}^{-1} \mathbf{Y} \\ \mathbf{S} &= \mathbf{Z} \\ \mathbf{Q}(n) &= \mathbf{Z}^T \mathbf{Z}. \end{aligned}$$

State vector  $\hat{\mathbf{x}}(n)$  is computed in a usual way using the equation (2a).

# Data Transfer – NTRIP

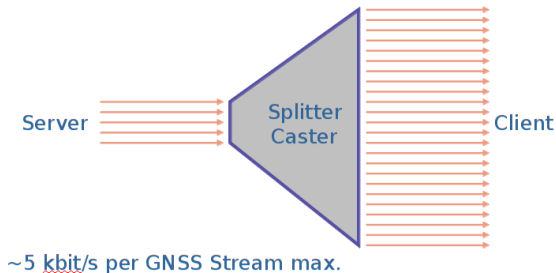
In order to be useful data have to be provided in a well-defined **format**. RTCM (Radio Technical Commission for Maritime Services) messages are widely used for GNSS data in real-time.

In addition to a format the so-called **protocol** has to be defined. Using a given protocol the data user communicates with the data provider. For GNSS data, the so-called **NTRIP** streaming protocol is used.

- NTRIP stands for Networked Transport of RTCM via Internet Protocol.
- NTRIP is in principle a layer on top of TCP/IP.
- NTRIP has been developed at BKG (together with TU Dortmund).
- NTRIP is capable of handling hundreds of data streams simultaneously delivering the data to thousands of users.
- NTRIP is world-wide accepted (great success of BKG).

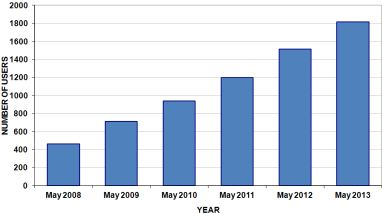
# NTRIP

Efficiency of data transfer using NTRIP is achieved thanks to the GNSS Internet Radio / IP-Streaming architecture:

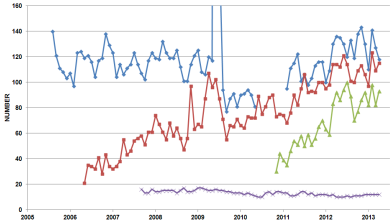


# NTRIP Users

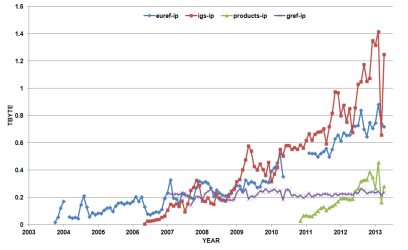
Number of registered users at broadcaster www.euref-ip.net



Ntrip Broadcaster at BKG: number of (different) active clients each month



Ntrip Broadcaster at BKG: Monthly total listener transfer in TB



# BKG Ntrip Client (BNC)

An important reason why NTRIP has been widely accepted is that BKG provided high-quality public license software tools for its usage. One of these tools is the so-called **BKG Ntrip Client**.

- BNC source consists currently of approximately 50.000 lines of code
- development started 2005 (LM and Georg Weber)
- BNC uses a few third-party pieces of software (e.g. RTCM decoders/encoders)
- BNC has a good documentation (thanks Georg Weber)

## BNC is intended to be

- user-friendly
- cross-platform
- easily modifiable (by students, GNSS beginners)
- useful (at least a little bit ...)

## BNC is not only an NTRIP client ...

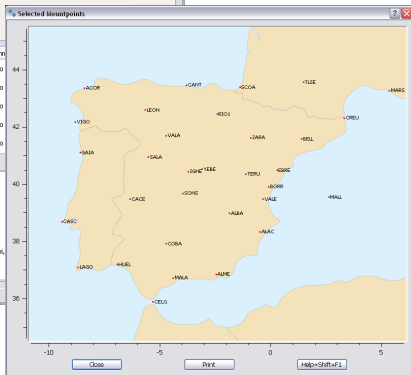
# BNC Basic Usage

Streams:

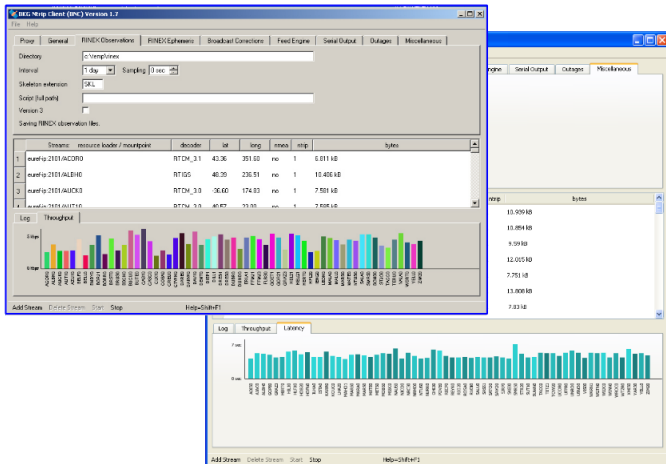
Streams	resource loader / mountpoint	decoder	lat	long	no
1	www.euref-ip.net:2101/GAIA0	RTCM_2,3	41.11	351.41	no
2	www.euref-ip.net:2101/GOPED	RTCM_2,3	49.91	14.79	no
3	www.euref-ip.net:2101/SOFI0	RTCM_3,0	42.56	23.39	no
4	www.euref-ip.net:2101/SPT00	RTCM_3,0	57.73	12.53	no
5	www.kgs-ip.net:2101/AD150	RTCM_3,0	9.03	36.74	no

Log

```
12-04-24 08:31:00 ===== Start BNC v2.6 =====
12-04-24 08:31:00 GAIA0: Get data in RTCM 2.x format
12-04-24 08:31:00 GOPED: Get data in RTCM 2.x format
12-04-24 08:31:00 SOFI0: Get data in RTCM 3.x format
12-04-24 08:31:00 SPT00: Get data in RTCM 3.x format
12-04-24 08:31:00 AD150: Get data in RTCM 3.x format
12-04-24 08:31:01 CHUR0: Get data in RTCM 3.x format
12-04-24 08:31:01 WIZR0: Get data in RTCM 3.x format
12-04-24 08:31:01 Configuration read: C:\Dokumente und Einstellungen\weber\config\BKG\BNC.in
```



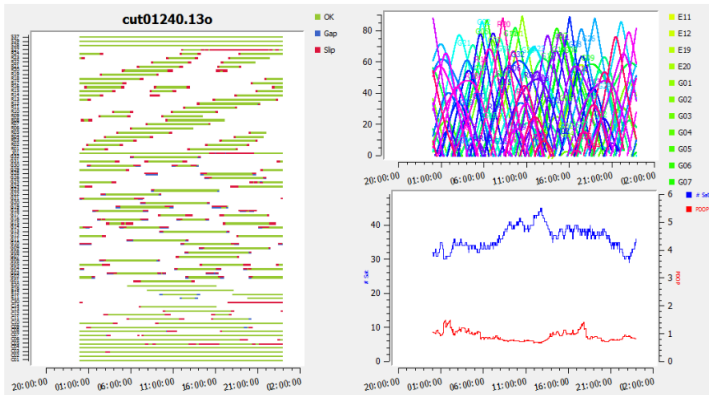
# PPP – Server-Side



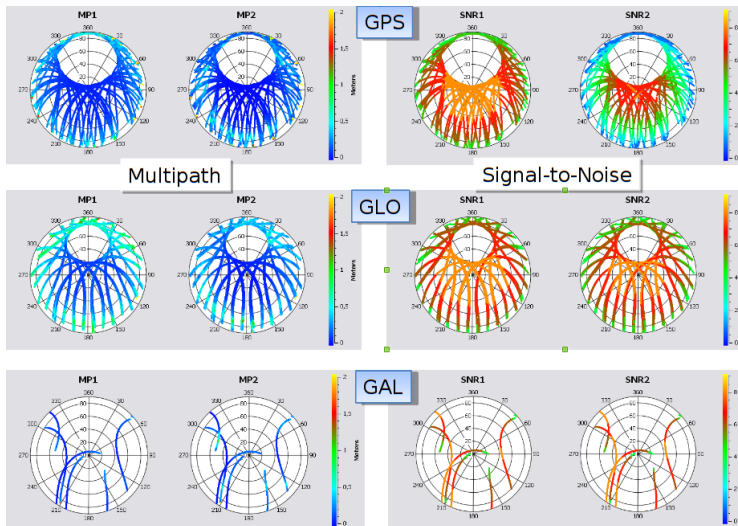


# Data QC in BNC

## GPS, GLONASS, Galileo, QZSS, BeiDou, and SBAS



# Data QC in BNC



# Precise Point Positioning with PPP

BKG Ntrip Client (BNC) Version 2.6

File Help

actions Feed Engine Serial Output Outages Miscellaneous PPP (1) **PPP (2)** Combination Upload (clk) Upload (eph)

### Precise Point Positioning (Panel 2)

Antennas  ANTEX File  LEIT Antenna Name  Apply Sat. Ant. Offsets

Sigmas  Code  Phase  Tropo Init  Tropo White Noise

Options  Use phase obs  Estimate tropo  Use GLONASS  Use Galileo

Options cont'd  Sigma XYZ Init  Sigma XYZ Noise  Quick-Start (sec)  Max Sol. Gap (sec)

Options cont'd  Sync Corr (sec)  Averaging (min)

	Streams: resource loader / mountpoint	decoder	lat	long	nmea	ntrip	bytes
1	products.igs-ip.net:2101/CLK11	RTCM_3,0	50.00	10.00	no	1	121.886 kB
2	products.igs-ip.net:2101/RTCM3EPH	RTCM_3	50.09	8.66	no	1	376.009 kB
3	www.igs-ip.net:2101/FFMJ1	RTCM_3,0	50.09	8.66	no	1	218.731 kB

Log Throughput Latency **PPP Plot**

0.10 m  
0.00 m  
-0.10 m

Start 08:25:58

08:30 08:31 08:32 08:33 08:34

Add Stream Delete Stream Start Stop Start Post-Processing Help ?=Shift+F1

# Principles of Precise Point Positioning

## Observation Equations

The PPP is based on the processing of the ionosphere-free linear combination of phase observations

$$L_3^{ij} = \varrho^{ij} - c\delta^{ij} + T^{ij} + \bar{N}_3^{ij}, \quad (5)$$

where the ambiguity term is given by

$$\bar{N}_3^{ij} = N_3^{ij} - I_3^{ij} = \frac{c f_2}{f_1^2 - f_2^2} (n_1^{ij} - n_2^{ij}) + \lambda_3 n_1^{ij} - I_3^{ij} \quad (6)$$

and (optionally) the ionosphere-free linear combination of code observations

$$P_3^{ij} = \varrho^{ij} - c\delta^{ij} + T^{ij} + p_3^{ij}, \quad (7)$$

where the code bias  $p_3^{ij}$  is the linear combination of biases  $p_1^{ij}, p_2^{ij}$

# Principles of PPP Service

The server has to provide the orbit corrections and the satellite clock corrections  $c\delta^{ij}$ . That is sufficient for a client processing phase observations only.

Using the code observations on the client-side is not mandatory. After an initial convergence period (tens of minutes) there is almost no difference between a phase-only client and the client that uses also the code observations. However, correct utilization of accurate code observations improves the positioning results during the convergence period.

Client which processes code observations either

- 1 has to know the value  $p_3^{ij}$  (the value must be provided by the server – the most correct approach), or
- 2 has to estimate terms  $p_3^{ij}$ , or
- 3 neglect the bias (de-weight the code observations – not fully correct).

Options (2) and (3) mean that the benefit of using the code observations on the client-side (in addition to phase observations) is minor only.

# PPP Options in BNC

- single station, SPP or PPP
- real-time or post-processing
- processing of code and phase ionosphere-free combinations, GPS, Glonass, and Galileo

**Precise Point Positioning (Panel 1)**

Obs Mountpoint   X  Y  Z

Corr Mountpoint  dN  dE  dU

Output NMEA File  NMEA Port  PPP Plot

Post-Processing Obs  Nav  Corr

Output

**Precise Point Positioning (Panel 2)**

Antennas  ANTEX File  LEIT  Antenna Name  Apply Sat. Ant. Offsets

Sigmas  Code  Phase  Tropo Init  Tropo White Noise

Options  Use phase obs  Estimate tropo  Use GLONASS  Use Galileo

Options cont'd  Sigma XYZ Init  Sigma XYZ Noise  Quick-Start (sec)  Max Sol. Gap (sec)

Options cont'd  Sync Corr (sec)  Averaging (min)

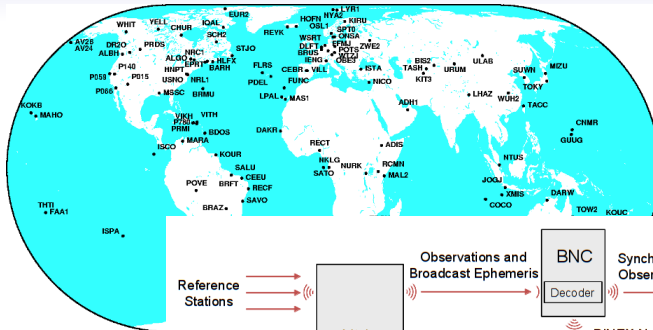
# PPP of Moving Receiver by BNC

The image displays three overlapping windows from the BNC (Boris N. C. N. Client) software, version 2.9, used for Precise Point Positioning (PPP).

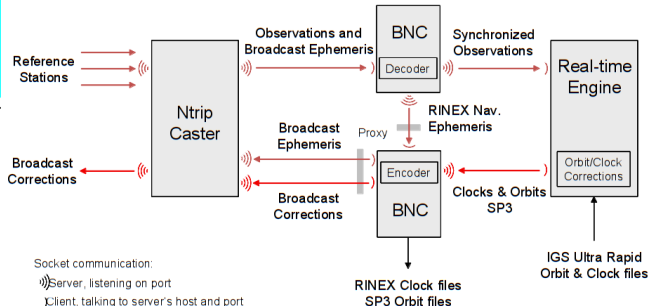
- Top Window (PPP (1)):** Shows the "Precise Point Positioning, Panel 1." configuration. The "Mode & mountpoints" is set to "Post-Processing". Fields for "Marker coordinates" (X, Y, Z), "Antenna eccentricity" (dN, dE, dU), and "NMEA & plot output" (NMEA File, NMEA Port) are visible. The "Post-processing" section includes "Input/Arm01690.130", "Obs" (set to "testtop/BRDC1690.13P"), "Nav", "Log (full path)", and "Corr".
- Middle Window (PPP (2)):** Shows "Precise Point Positioning, Panel 3." with the "PPP Plot" checkbox checked and "Non-East-Up Time Series" selected. The "Track Plot" is set to "Open Map".
- Bottom Window (Map View):** Displays a satellite map of a highway interchange. A red circle highlights a specific location on the road, and several red dots are plotted along the road's path, representing the receiver's trajectory. The map includes a compass, a scale bar, and the text "Karte | Satellit". The Google Maps logo and copyright information are visible at the bottom of the map area.

At the bottom of the map window, the coordinates are displayed: Latitude: 50 3 39.3075 Longitude: 8 38 53.1142.

# PPP – Server-Side



GNSS 2012 Jun 6 13:33:53







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RTNET

Realttime Demo

PPPAR

RTRef Network RTK

GNSS Meteorology

GNSS Converter

References

Application

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## CFW: GPS-Enhanced Operational Forecast System Version. 3

CFW OPS v3

CFW operational forecast package version 3



### CFW OP3: Impact Study (Precipitation 2013/10/14)

Forecast w/o GPS PWV

Forecast with GPS PWV

NOAA Radar Image (Observation)



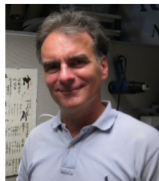
# Server-Side – RTNet ([www.gps-solutions.com](http://www.gps-solutions.com))



Prof. L. Mervart  
Algorithm / software development



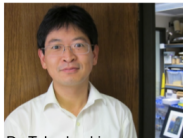
Mr. J. Johnson  
Co Founder, head of engineering



Dr. C. Rocken  
Co Founder, science lead,



Dr. Z. Lukes  
Algorithm / software development



Dr. T. Iwabuchi  
Software applications,  
development and  
testing



Mr. J. Barron,  
Programmer / Software testing



Dr. T.  
Springer  
Orbit  
Determination  
(PosiTim)



Mr. S. Cumminss, Programmer  
Nov. 2011, Leuven, Belgium



# Server-Side – RTNet (www.gps-solutions.com)

RTNet Input Editor

File Edit View Language Help

ations | Input Devices 1 | Input Devices 2 | Output Devices | Processing Options | Processed Stations | Estimated Parameters 1 | x |

Estimated Parameters 1

A Priori Sigmas

initial prediction

Ambiguities: resolve  1e2  cyc

Constrain ZD  Min. fixed DD 2

Reset Interval  (Testing)

Rec. Clk  1e3

Sat. Clk 1 ref.  1e-6

Sat. Clk. Drift

Precise Orbit Determination

Orbit corrections: Radial    
 Along track    
 Cross track

Inter-System Biases

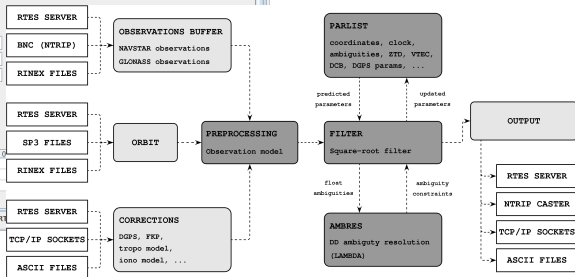
Receiver delays

LC	sig 0	sig P	C	LC	sig 0
GpM	100.0	Inf		GpM	3.0
GpIF	100.0	Inf		GpIF	3.0

Satellite delays

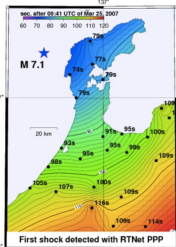
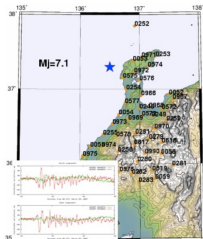
LC	sig 0	LC	sig 0

Local file: /home/mervart/gpss\_src/veripos/GPSDATA/VERIPOS\_SERVER/INP/RT

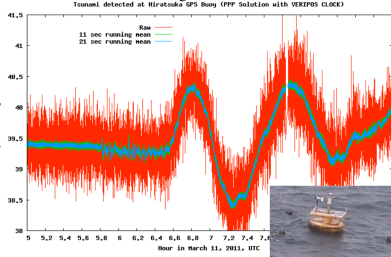


# Server-Side – RTNet (www.gps-solutions.com)

GPS monitoring of 2007 EQ, M 7.1, Japan



GPS Monitoring of Tsunami Arrival



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- Contact Veripos

## INVESTOR INFORMATION

Quote

Index	Last	Change	%	Bid	Ask	High	Low	Volume	Timestamp	Time
SP500	14.00	-0.06	-0.4%	13.98	14.00	14.00	13.98	1,000	03/11/11	08:30

Information averages

- All-in Index
- Intraday
- Volume
- Volatility

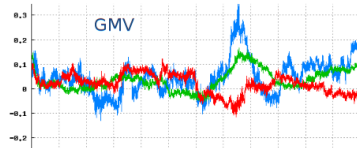
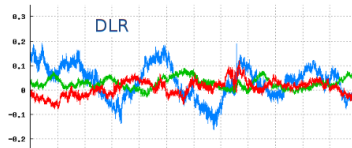
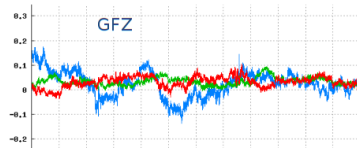
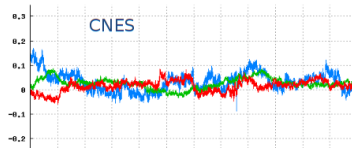
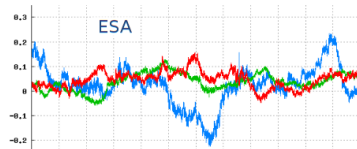
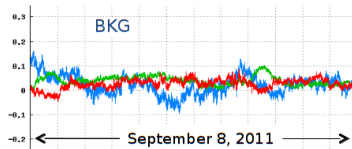
Compare to

Technical analysis

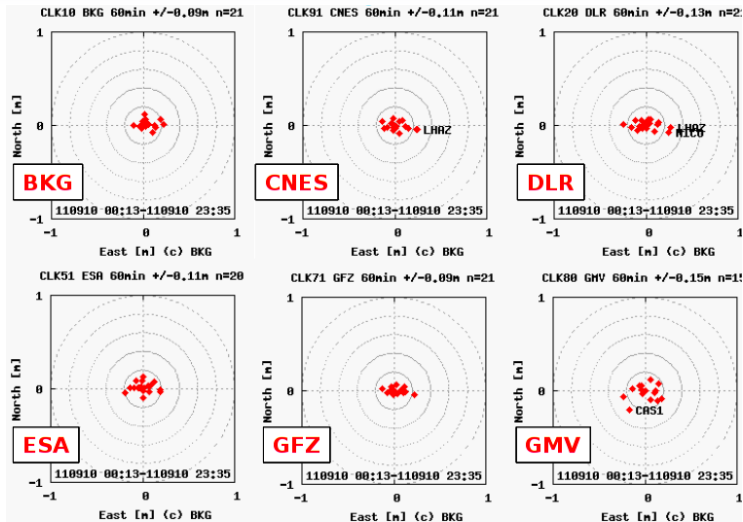
Share performance

Period	4%	5%	10%	20%	50%	100%
Price	14.00	13.98	13.98	13.98	13.98	13.98
Volume	100	100	100	100	100	100
Volatility	100	100	100	100	100	100
Yield	100	100	100	100	100	100

# PPP – Server-Side



# PPP – Server-Side



# Combination using Kalman filtering

The combination is performed in two steps

1. The satellite clock corrections that refer to different broadcast messages (different IODs) are modified in such a way that they all refer to common broadcast clock value (common IOD is that of the selected “master” analysis center).
2. The corrections are used as pseudo-observations for Kalman filter using the following model (observation equation):

$$c_a^s = c^s + o_a + o_a^s$$

where

$c_a^s$  is the clock correction for satellite  $s$  estimated by the analysis center  $a$ ,

$c^s$  is the resulting (combined) clock correction for satellite  $s$ ,

$o_a$  is the AC-specific offset (common for all satellites), and

$o_a^s$  is the satellite and AC-specific offset.

The three types of unknown parameters  $c^s$ ,  $o_a$ ,  $o_a^s$  differ in their stochastic properties: the parameters  $c^s$  and  $o_a$  are considered to be epoch-specific while the satellite and AC-specific offset  $o_a^s$  is assumed to be a static parameter.

# PPP – Combination of Corrections

**BKG Ntrip Client (BNC) Version 2.6**

File Help

Mount Corrections Feed Engine Serial Output Outages Miscellaneous PPP (1) PPP (2) Combination Upload (A) |>

Mountpoint	AC Name	Weight
1 CLK30	BKG	1.0
2 CLK20	DLR	1.0
3 CLK51	ESA	1.0
4 CLK71	GFZ	1.0
5 CLK80	GRV	1.0
6 CLK91	CHES	1.0

Add Row Delete

Combine Broadcast/Ephemeric corrections streams.

Streams	resource loader / mountpoint	decoder	lat	long	rmses	ntrip	bytes
1	products.igs-ip.net:2101/CLK30	RTCM_3_0	50.00	10.00	no	1	100 byte(s)
2	products.igs-ip.net:2101/CLK20	RTCM_3_0	50.00	10.00	no	1	781 byte(s)
3	products.igs-ip.net:2101/CLK51	RTCM_3_0	50.00	10.00	no	1	100 byte(s)
4	products.igs-ip.net:2101/CLK71	RTCM_3_0	50.00	10.00	no	1	1.1 kB
5	products.igs-ip.net:2101/CLK80	RTCM_3_0	50.00	10.00	no	1	861 byte(s)

Log Throughput Latency PPP Plot

```
11:06:29 13:35:49 ----- Start BNC v2.6 -----
11:06:29 13:35:49 Current find IOS ANTEX file
11:06:29 13:35:49 CLK30: Get data in RTCM 3.x format
11:06:29 13:35:49 CLK20: Get data in RTCM 3.x format
11:06:29 13:35:49 CLK51: Get data in RTCM 3.x format
11:06:29 13:35:49 CLK71: Get data in RTCM 3.x format
11:06:29 13:35:49 CLK80: Get data in RTCM 3.x format
11:06:29 13:35:50 CLK91: Get data in RTCM 3.x format
11:06:29 13:35:50 RTCM3PH: Get data in RTCM 3.x format
11:06:29 13:35:50 PPM1: Get data in RTCM 3.x format
11:06:29 13:35:50 Configuration read C:\Users\waber\Desktop\BNC_conf.0 stream(s)
Add Stream Delete Stream Start Stop Help T-QRHF #1
```

Real-time Clock Combination in BKG Ntrip Client (BNC v2.6)

**BKG Ntrip Client (BNC) Version 2.6**

File Help

5: Feed Engine Serial Output Outages Miscellaneous PPP (1) PPP (2) Combination Upload (A) |> Upload (up) |>

Host	Port	Mount	Password	System	CaM	SP3 File	EPX File	bytes
1 products.igs-ip.net	2101	CLK30	*****	IGD05				0 byte(s)
2 products.igs-ip.net	2101	CLK32	*****	GD044		/home/waber/bnc~/	/home/waber/bnc~/	0 byte(s)

Upload RTNet or Combination Results Add Row Del Row Interval 1 day Sampling 0 sec

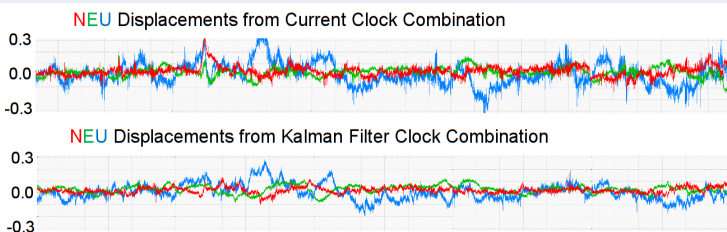
Streams	resource loader / mountpoint	decoder	lat	long	rmses	ntrip	bytes
1	products.igs-ip.net:2101/CLK30	RTCM_3_0	50.00	10.00	no	1	100 byte(s)
2	products.igs-ip.net:2101/CLK20	RTCM_3_0	50.00	10.00	no	1	100 byte(s)
3	products.igs-ip.net:2101/CLK51	RTCM_3_0	50.00	10.00	no	1	1.872 kB
4	products.igs-ip.net:2101/CLK71	RTCM_3_0	50.00	10.00	no	1	100 byte(s)

Log Throughput Latency PPP Plot

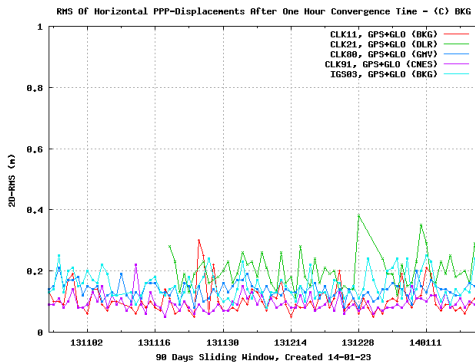
```
11:06:29 13:42:22 CLK30: Get data in RTCM 3.x format
11:06:29 13:42:23 CLK20: Get data in RTCM 3.x format
11:06:29 13:42:23 CLK51: Get data in RTCM 3.x format
11:06:29 13:42:23 CLK71: Get data in RTCM 3.x format
11:06:29 13:42:23 CLK80: Get data in RTCM 3.x format
11:06:29 13:42:23 CLK91: Get data in RTCM 3.x format
11:06:29 13:42:24 RTCM3PH: Get data in RTCM 3.x format
11:06:29 13:42:24 PPM1: Get data in RTCM 3.x format
11:06:29 13:42:24 Configuration read C:\Users\waber\Desktop\BNC_conf.0 stream(s)
Add Stream Delete Stream Start Stop Help T-QRHF #1
```



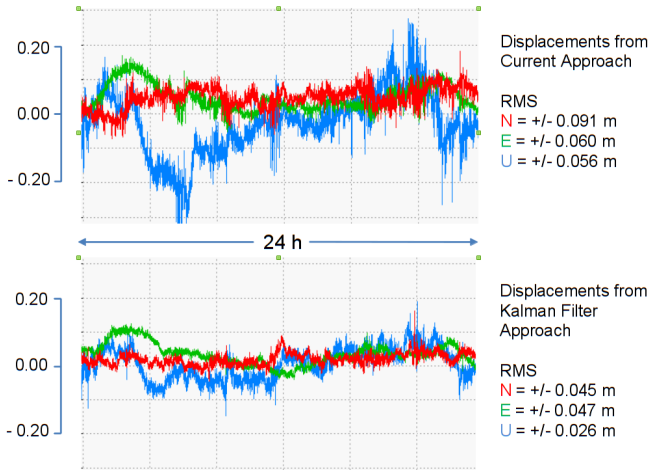
# PPP – Combination of Corrections



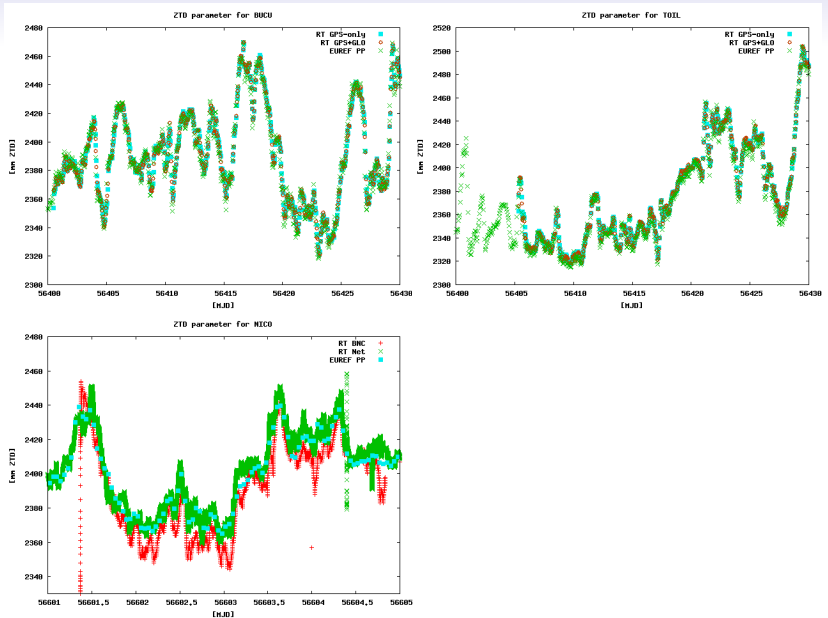
Frankfurt, 24-28 June 2011



# PPP – Combination of Corrections



# PPP – Estimated Troposphere



# PPP with Ambiguity Resolution (PPPAR or PPP-RTK)

For a dual-band GPS receiver, the observation equations may read as

$$\begin{aligned}P^i &= \varrho^i + c \delta - c \delta^i + T^i + b_P \\L^i &= \varrho^i + c \delta - c \delta^i + T^i + b^i\end{aligned}$$

where

$P^i, L^i$  are the ionosphere-free code and phase measurements,  
 $\varrho^i$  is the travel distance between the satellite and the receiver,  
 $\delta, \delta^i$  are the receiver and satellite clock errors,  
 $T^i$  is the tropospheric delay,  
 $b_P$  is the code bias, and  
 $b^i$  is the phase bias (including initial phase ambiguity).

The single-difference bias  $b^{ij} = b^i - b^j$  is given by

$$b^{ij} = \frac{\lambda_5 - \lambda_3}{2} (n_5^{ij} + b_5^{ij}) + \lambda_3 (n_1^{ij} + b_1^{ij})$$

where

$n_1^{ij}, n_5^{ij}$  are the narrow-lane and wide-lane integer ambiguities  
 $b_1^{ij}$  is the narrow-lane (receiver-independent) SD bias  
 $b_5^{ij}$  is the wide-lane (receiver-independent) SD bias

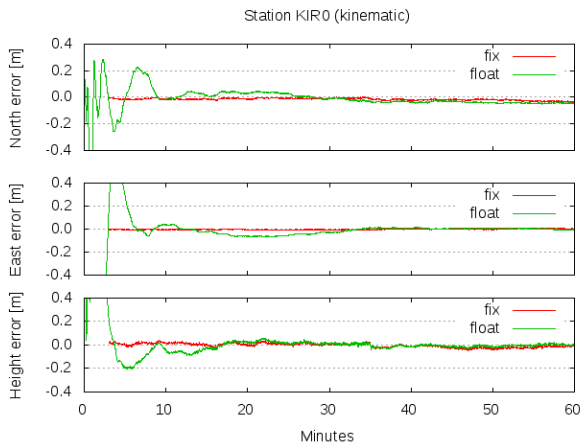
## PPPAR Algorithm (cont.)

Receiver-independent single-difference biases  $b_1^{ij}$  and  $b_5^{ij}$  have to be estimated on the server-side.

- Narrow-lane bias  $b_1^{ij}$  may be combined with satellite clock corrections  $\implies$  **modified satellite clock corrections**.
- Wide-lane bias have to be transmitted from the server to the client (this bias is stable in time and can thus be transmitted in lower rate).

On the client-side the biases  $b_1^{ij}$  and  $b_5^{ij}$  are used as known quantities. It allows fixing the integer ambiguities  $n_5^{ij}$  and  $n_1^{ij}$ . The technique is called Precise Point Positioning with Ambiguity Resolution (PPP AR) or PPP RTK, or zero-difference ambiguity fixing (the latter term not fully correct because the ambiguities are actually being fixed on single-difference level).

# Performance



## Standard deviations (N,E,U)

	10-60 min			30-60 min		
float	0.034	0.026	0.026	0.010	0.009	0.011
fix	0.007	0.003	0.016	0.007	0.003	0.012

# Challenges

There are still both principal and technical problems and challenges:

- Principal problems:
  - Convergence time: PPP RTK in the form outlined above provides accuracy similar (or even slightly better) to RTK but the convergence time is longer.
  - There is a degradation in accuracy with the age of corrections.
  - Glonass ambiguity resolution: is it possible to resolve Glonass ambiguities? (yes, it is possible but it implicates introducing new parameters - does it really improve the results?)
  - ...
- Technical problems:
  - Availability of data in real time (reference network, high-precision satellite orbits).
  - Very high CPU requirements on the server-side.
  - Solution robustness on the server-side (problems with reliable DD ambiguity resolution).
  - ...

# Challenges (cont.)

## Longer convergence time

In case of a standard RTK the very short convergence time is being achieved thanks to the combined DD ambiguity resolution on both  $L_1$  and  $L_2$  when the differential ionospheric bias can either be neglected (short baselines) or its influence is mitigated (stochastic ionosphere estimation with constraints).

On the contrary, the outlined PPP RTK algorithm is in principle based on processing single (ionosphere-free) linear combination and resolving only one set of (narrow-lane) initial phase ambiguities.

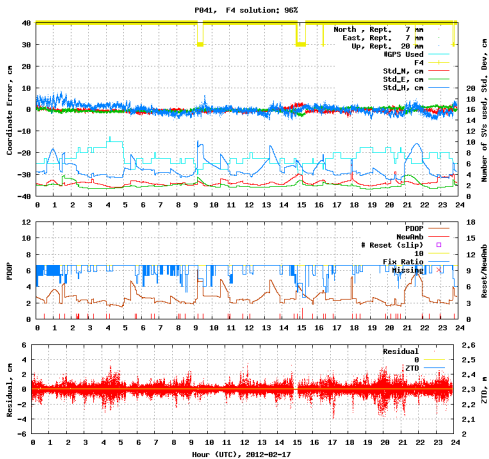
## Possible solutions

- third carrier
- multiple GNSS (Glonass ambiguity resolution?)
- processing original carriers (instead of ionosphere-free linear combination) and modeling the ionosphere?
- ?



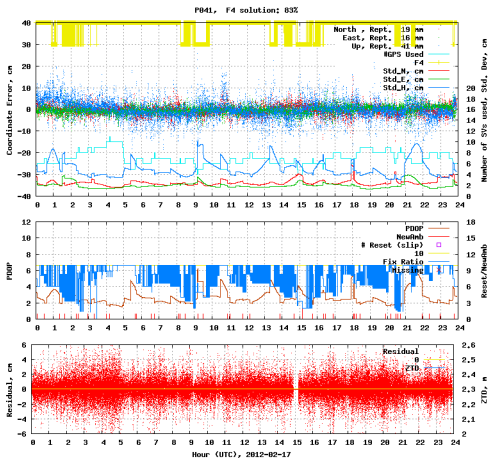
# Challenges (cont.)

## Age of corrections 0 s



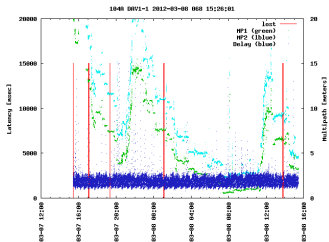
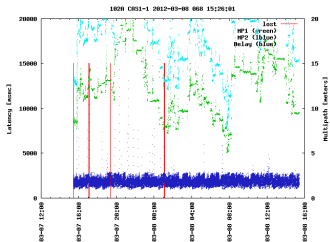
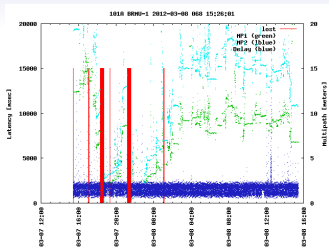
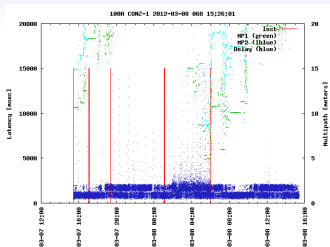
# Challenges (cont.)

Age of corrections up to 35 s





# Real-Time Data Availability (cont.)



Gaps in reference network data may degrade the PPP RTK server performance considerably!

# Technical issues

## CPU-requirements on the server-side

Processing a global reference network is a very CPU-intensive task. Numerically stable forms of the Kalman filter (square-root, UDU factorization etc.) require very fast hardware.

Possible solutions:

- Processing optimization (estimating various kinds of parameters in different rates)
- Parallel processing
- Advanced hardware (GPS Solutions uses GPU-accelerated library)

## Reliable DD ambiguity resolution on the server-side

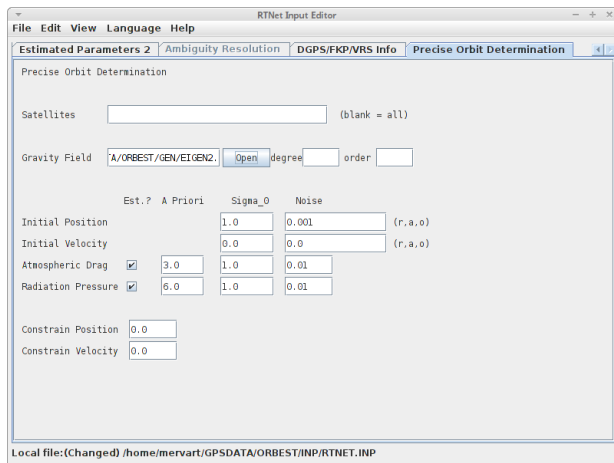
Reliable double-difference ambiguity resolution on the server-side remains the crucial issue of the PPP RTK technique.

## Dissemination of PPP RTK corrections

- data links
- formats (standardization?)
- optimization of correction rates (bandwidth)

# Satellite orbits

Predicted part of the IGS ultra-rapid orbits (available in real-time) is sometimes not sufficient for the processing of a global reference network (with narrow-lane ambiguity resolution). We have been forced to implement the real-time orbit determination capability in our main processing tool RTNet (Real-Time Network software).



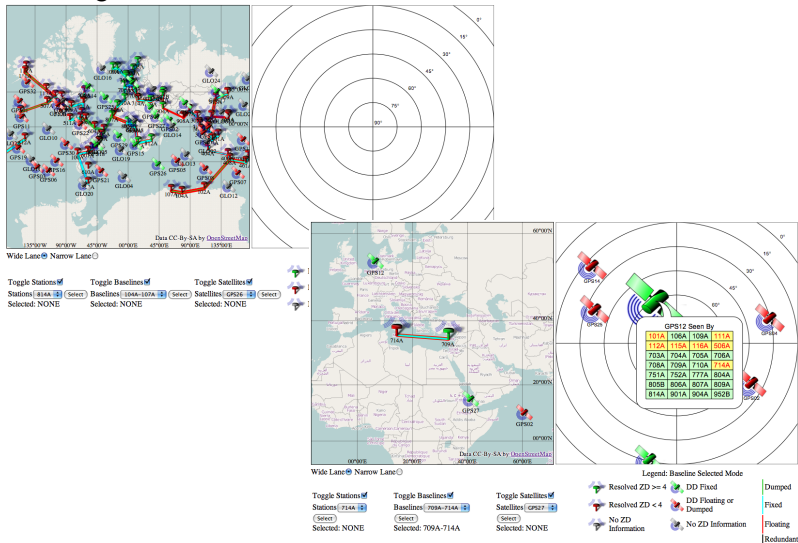
# Regional versus global PPP RTK services

Currently we are routinely running both regional and global PPP RTK service demonstrators in real-time (some of the results will be shown below).

- in principal there is no difference between a global and regional service as far as the data processing, algorithms etc. is concerned
- global PPP RTK service has at least the following two advantages
  1. a single correction stream can serve all users
  2. all satellites are tracked permanently (helps ambiguity resolution)
- global PPP RTK service is much more challenging (data availability, CPU-requirements on the server-side, DD ambiguity resolution on long baselines, the highest requirements for the accuracy of the satellite orbits)

# Services monitoring

Reliable, production-quality PPP RTK service requires sophisticated monitoring tools.

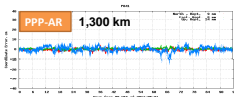
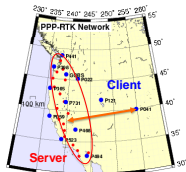




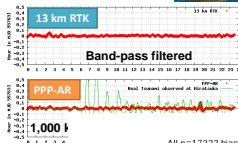
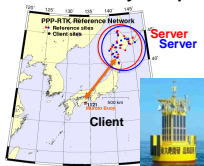
# Results

## Real-time Monitoring of coordinate with PPP-AR

### UNAVCO PBO Network

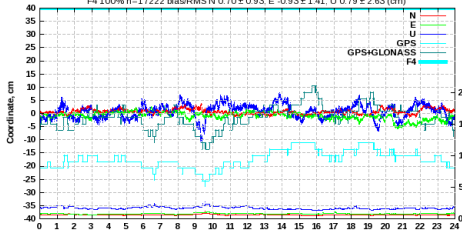


### GPS tsunami buoy in Japan



### Station: 301C\_RAR

All n=17222 bias/RMS N 0.70 ± 0.93 E -0.93 ± 1.41 U 0.79 ± 2.63 (cm)  
 F4 100% n=17222 bias/RMS N 0.70 ± 0.93 E -0.93 ± 1.41 U 0.79 ± 2.63 (cm)





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## Realtime GPS Enhancement to Tsunami Warning System (Prototype)

### Time Series Plots

**Update Period**  
10 seconds

**Time Remaining**  
1 second

[Figure Information](#)

**Change Plot Parameters:**

**Select Source:**  
RTNET\_PPP

**Scale (mm):**  
min : -200  
max : 200

Time Series	Positions	Station Map	Background Info
	North	East	Up

