Processing GNSS Data in Real-Time

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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).

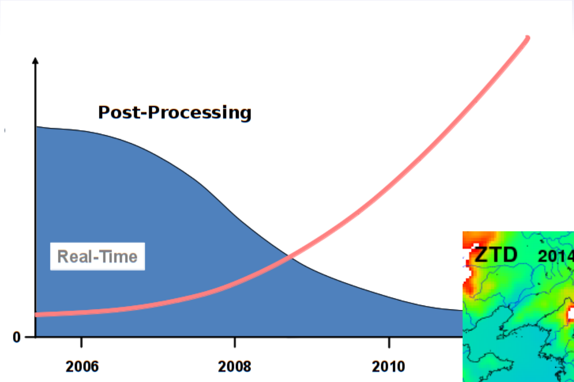
1995 GPS declared fully operational.

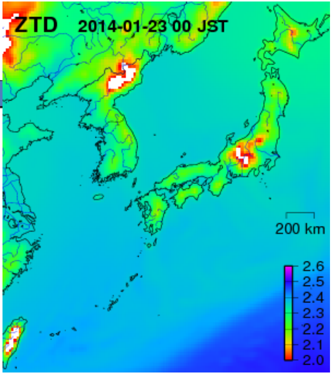
CODE-Related Works in 1990's

- 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,
ϱ^i	is the travel distance between the satellite and the receiver,
δ, δ^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 been 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:

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

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

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

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:

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

Classical KF Form

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

$$\begin{aligned} \widehat{\mathbf{x}}^-(n) &= \mathbf{\Phi}\widehat{\mathbf{x}}(n-1) && \text{(1a)} \\ \mathbf{Q}^-(n) &= \mathbf{\Phi}\mathbf{Q}(n-1)\mathbf{\Phi}^T + \mathbf{\Gamma}\mathbf{Q}_s(n)\mathbf{\Gamma}^T && \text{(1b)} \end{aligned}$$

$$\begin{aligned} \widehat{\mathbf{x}}(n) &= \widehat{\mathbf{x}}^-(n) + \mathbf{K}\left(\mathbf{I} - \mathbf{A}\widehat{\mathbf{x}}(n-1)\right) && \text{(2a)} \\ \mathbf{Q}(n) &= \mathbf{Q}^-(n) - \mathbf{K}\mathbf{A}\mathbf{Q}^-(n)\ , && \text{(2b)} \end{aligned}$$

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

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

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

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

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

Data Transfer – NTRIP

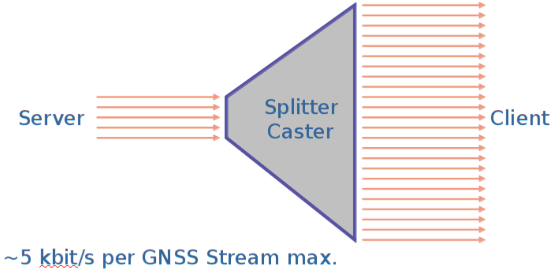
In order to be useful data have to be provided in a well-defined format. RTCM (Radio Technical Commission for Maritime Services) messages are widely used for GNSS data in real-time.

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.

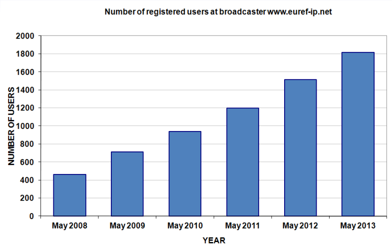
- NTRIP stands for Networked Transport of RTCM via Internet Protocol.
- NTRIP is in principle a layer on top of TCP/IP.
- NTRIP has been developed at BKG (together with TU Dortmund).
- NTRIP is capable of handling hundreds of data streams simultaneously delivering the data to thousands of users.
- NTRIP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

NTRIP

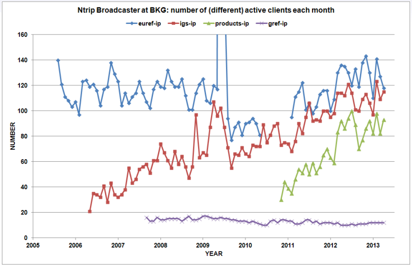
Efficiency of data transfer using NTRIP is achieved thanks to the GNSS Internet Radio / IP-Streaming architecture:



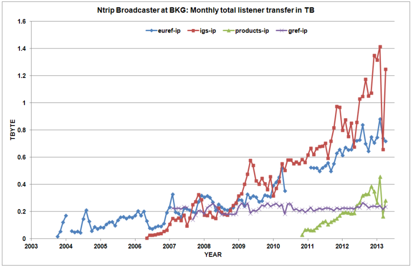
NTRIP Users



Number of registered users at broadcaster www.euref-ip.net
NUMBER OF USERS
2000
1800
1600
1400
1200
1000
800
600
400
200
0
May 2008
May 2009
May 2010
May 2011
May 2012
May 2013
YEAR



Ntrip Broadcaster at BKG: number of (different) active clients each month
euref-ip
igs-ip
products-ip
gref-ip
NUMBER
160
140
120
100
80
60
40
20
0
2005
2006
2007
2008
2009
2010
2011
2012
2013
YEAR



Ntrip Broadcaster at BKG: Monthly total listener transfer in TB
euref-ip
igs-ip
products-ip
gref-ip
TBYTE
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
YEAR

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.

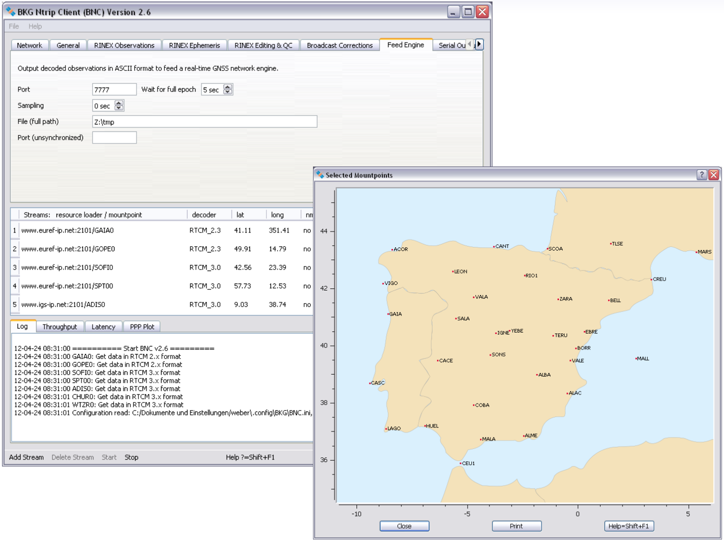
- BNC source consists currently of approximately 50.000 lines of code
- development started 2005 (LM and Georg Weber)
- BNC uses a few third-party pieces of software (e.g. RTCM decoders/encoders)
- BNC has a good documentation (thanks Georg Weber)

BNC is intended to be

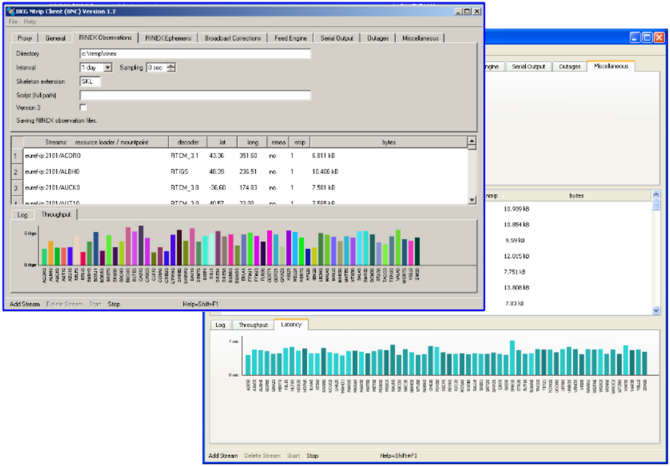
- user-friendly
- cross-platform
- easily modifiable (by students, GNSS beginners)
- useful (at least a little bit ...)

BNC is not only an NTRIP client . . .

BNC Basic Usage

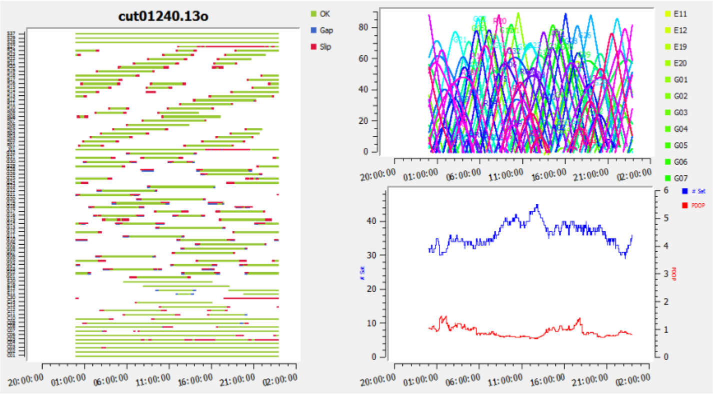


PPP – Server-Side

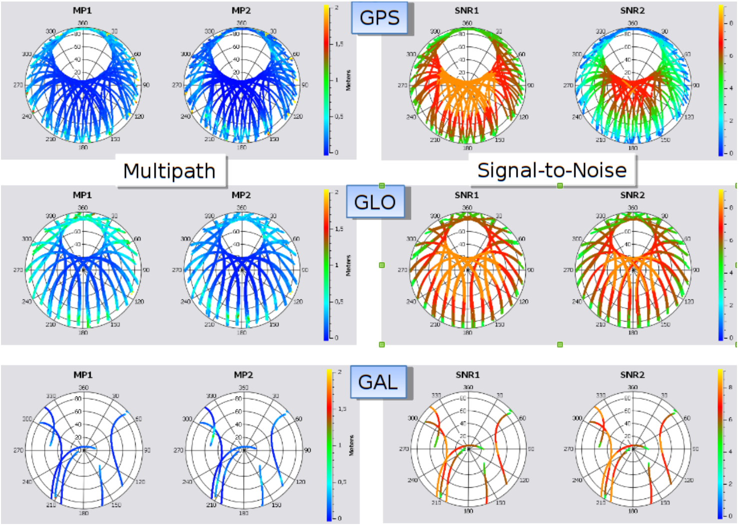


Data QC in BNC

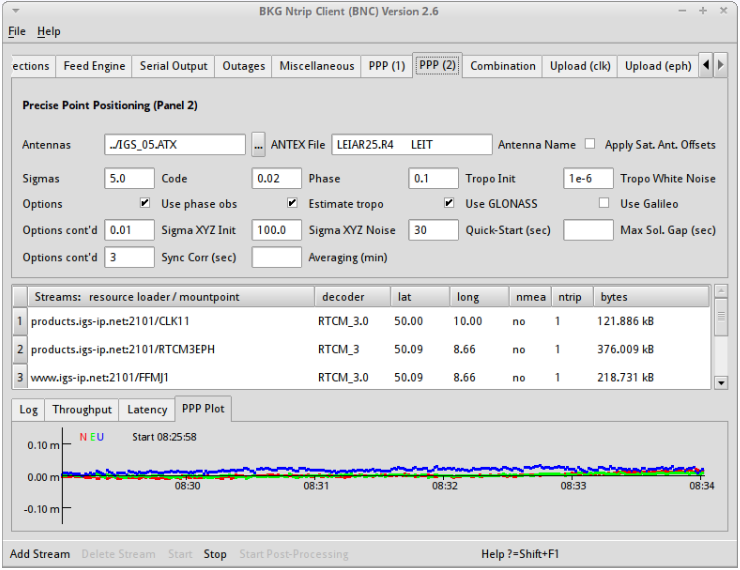
GPS, GLONASS, Galileo, QZSS, BeiDou, and SBAS



Data QC in BNC



Precise Point Positioning with PPP



Principles of Precise Point Positioning

Observation Equations

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

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

where the ambiguity term is given by

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

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

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

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.

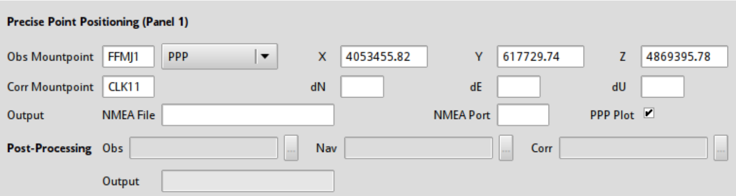
Client which processes code observations either

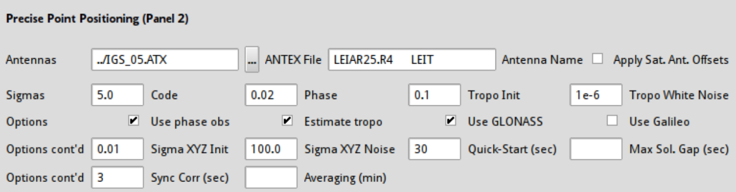
1. has to know the value p_3^{ij} (the value must be provided by the server – the most correct approach), or
2. has to estimate terms p_3^{ij}, or
3. neglect the bias (de-weight the code observations – not fully correct).

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.

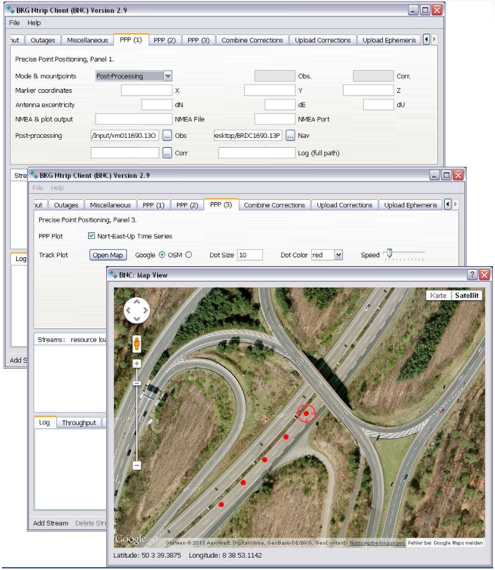
PPP Options in BNC

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

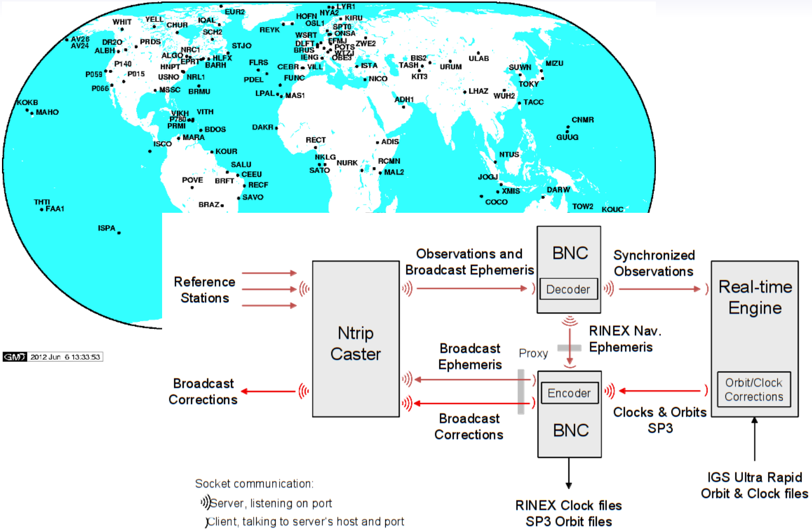




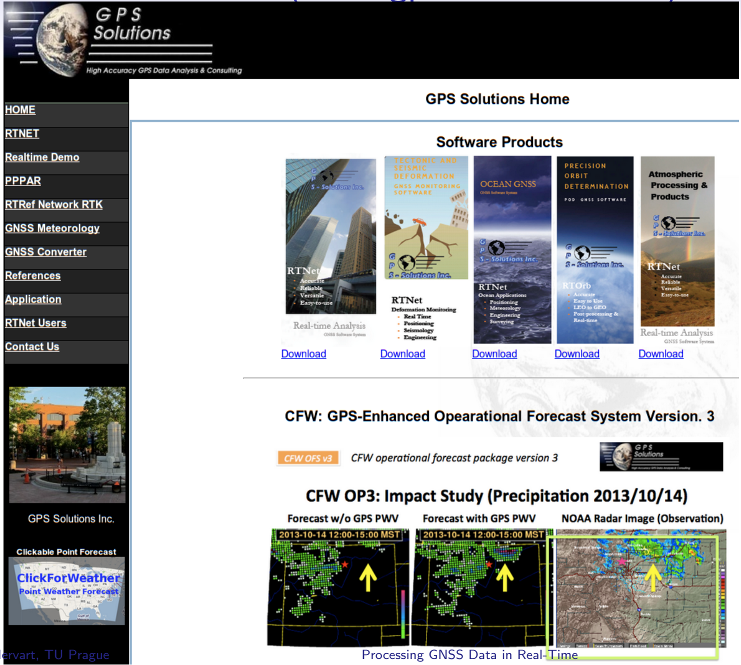
PPP of Moving Receiver by BNC



PPP – Server-Side



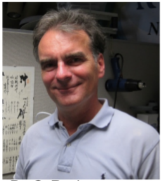
Server-Side – RTNet (www.gps-solutions.com)



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

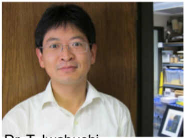
Prof. L.Mervart
Algorithm / software development

Mr. J. Johnson
Co Founder, head of engineering



Dr. C. Rocken
Co Founder, science lead,
business development

Dr. Z. Lukes
Algorithm / software development



Dr. T. Iwabuchi
Software applications, development and testing

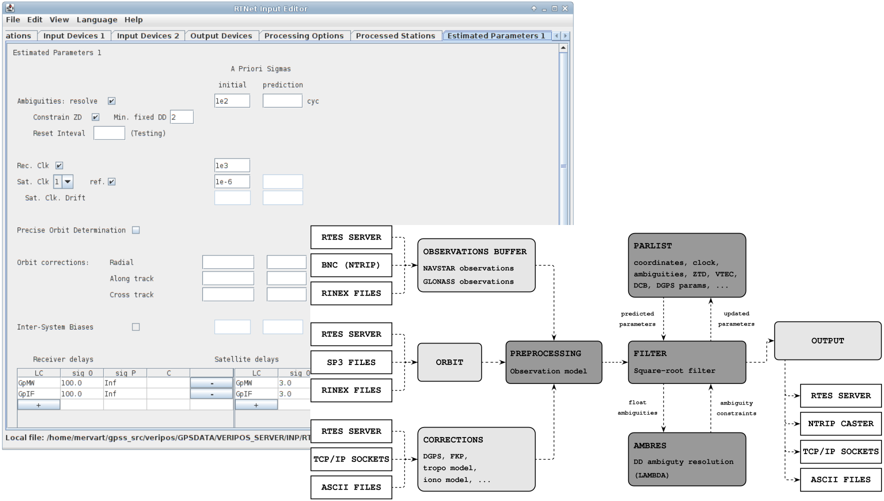
Mr. J. Barron,
Programmer / Software testing

Dr. T. Springer
Orbit Determination (PosiTim)

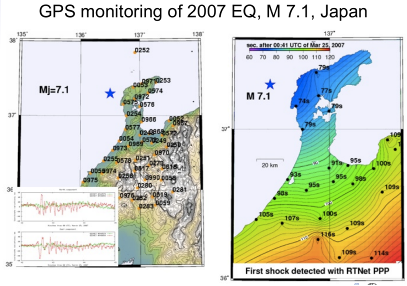
Mr. S. Cumminss, Programmer

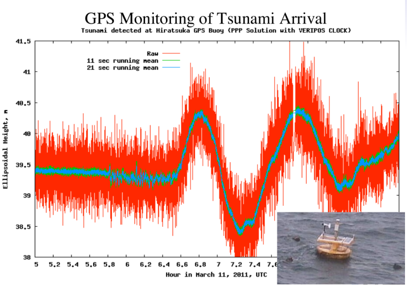
Nov. 2011, Leuven, Belgium

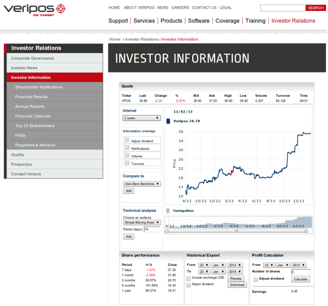
Server-Side – RTNet (www.gps-solutions.com)



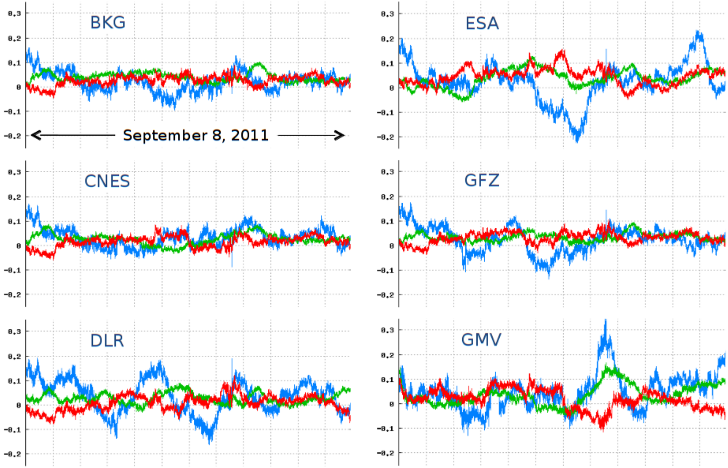
Server-Side – RTNet (www.gps-solutions.com)



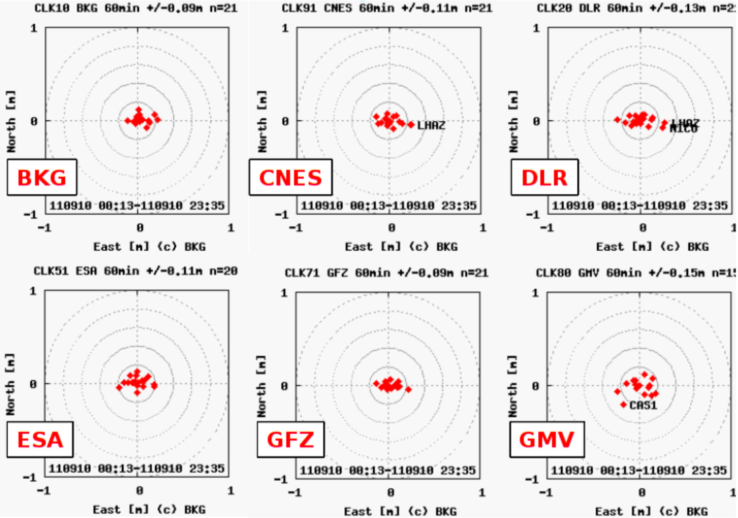




PPP – Server-Side



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):

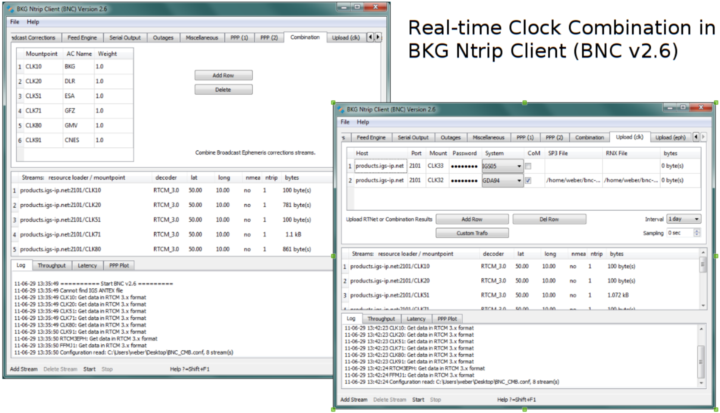
$$c_a^s = c^s + o_a + o_a^s$$

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.

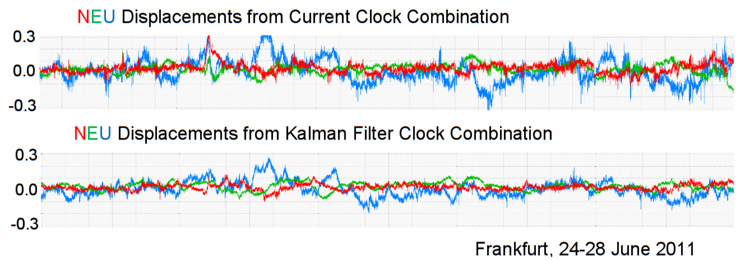
The three types of unknown parameters c^s, o_a, o_a^s differ in their stochastic properties: the parameters c^s and o_a are considered to be epoch-specific while the satellite and AC-specific offset o_a^s is assumed to be a static parameter.

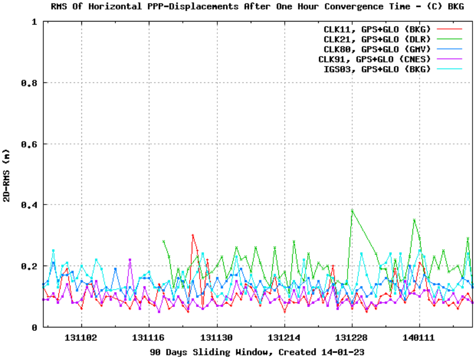
PPP – Combination of Corrections



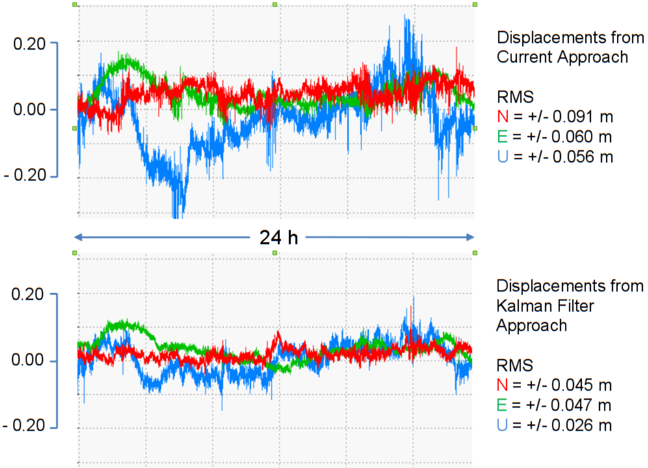
Real-time Clock Combination in BKG Ntrip Client (BNC v2.6)

PPP – Combination of Corrections

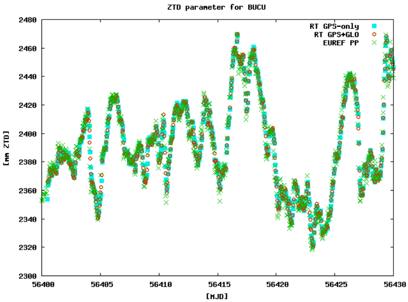


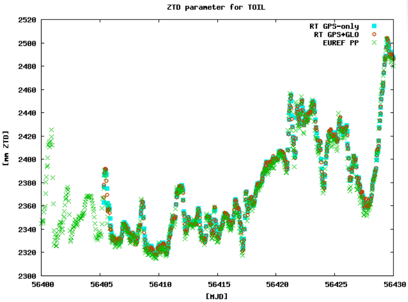


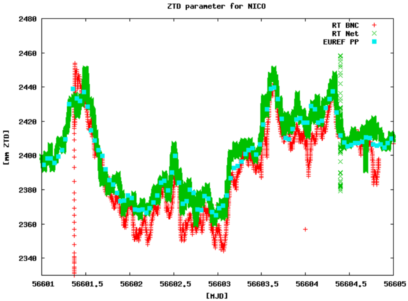
PPP – Combination of Corrections



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,
ϱ^i	is the travel distance between the satellite and the receiver,
δ, δ^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

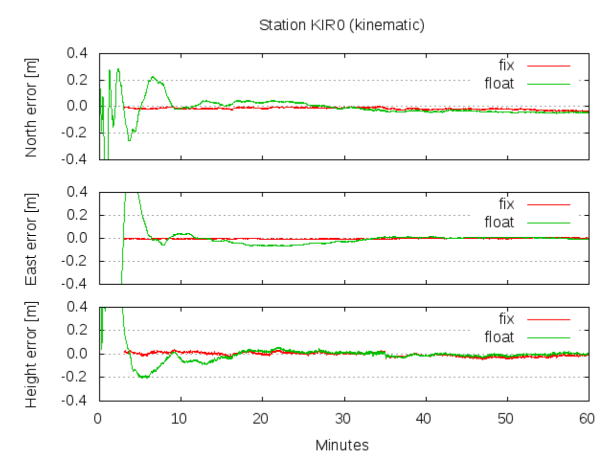
PPPAR Algorithm (cont.)

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 $\Longrightarrow$ **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

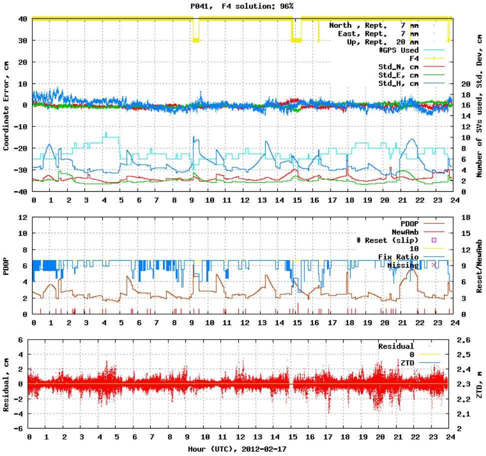
In case of a standard RTK the very short convergence time is being achieved thanks to the combined DD ambiguity resolution on both L_1 and L_2 when the differential ionospheric bias can either be neglected (short baselines) or its influence is mitigated (stochastic ionosphere estimation with constraints).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

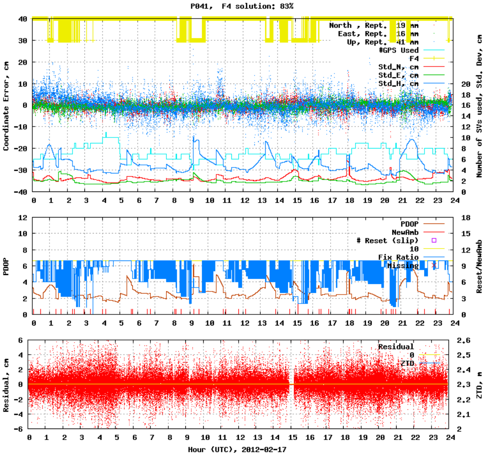
Challenges (cont.)

Age of corrections 0 s



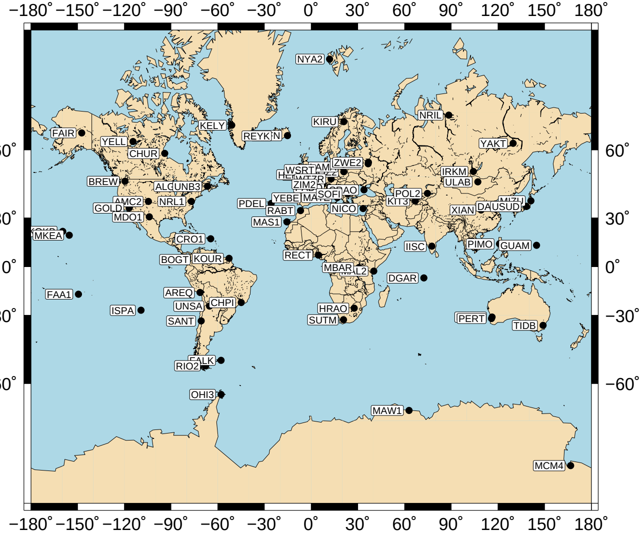
Challenges (cont.)

Age of corrections up to 35 s

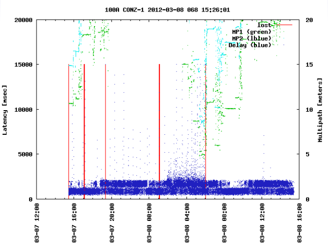


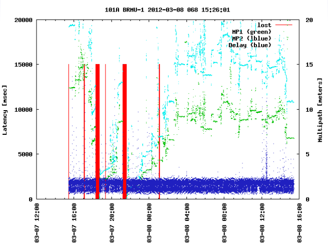
Real-Time Data Availability

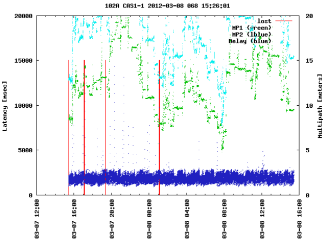
IGS network: very good global coverage:

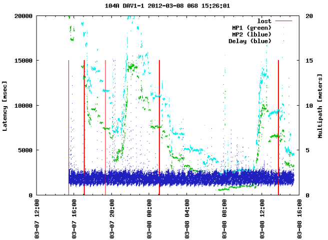


Real-Time Data Availability (cont.)









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

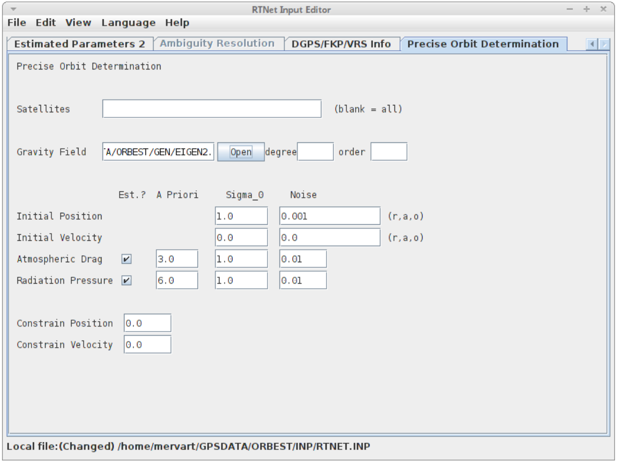
Reliable double-difference ambiguity resolution on the server-side remains the crucial issue of the PPP RTK technique.

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).



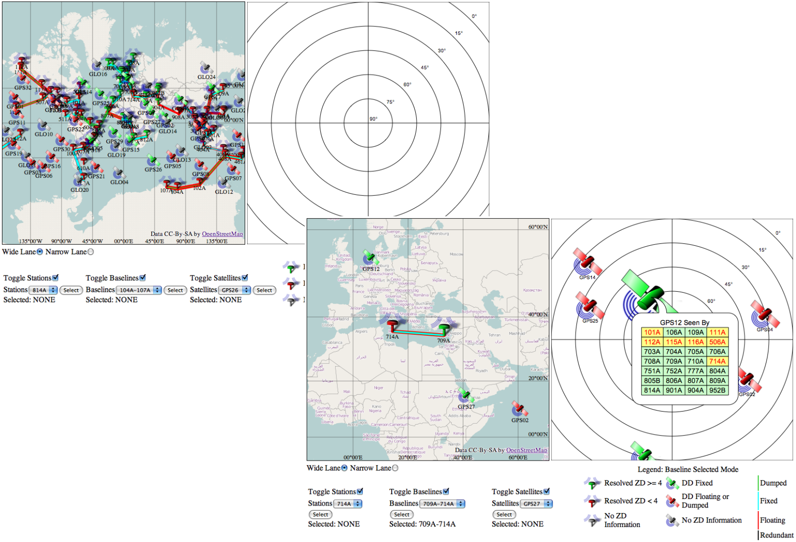
Regional versus global PPP RTK services

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

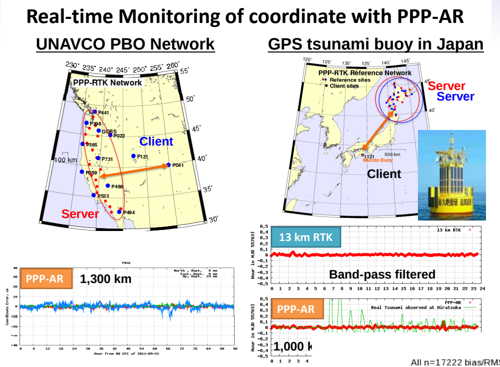
- in principal there is no difference between a global and regional service as far as the data processing, algorithms etc. is concerned
- global PPP RTK service has at least the following two advantages
  1. a single correction stream can serve all users
  2. all satellites are tracked permanently (helps 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

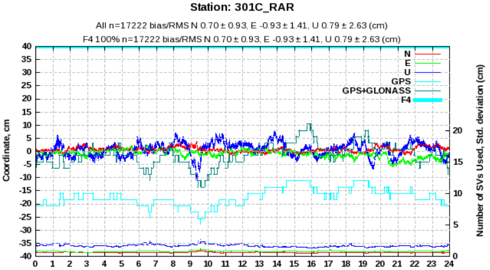
Reliable, production-quality PPP RTK service requires sophisticated monitoring tools.



Results

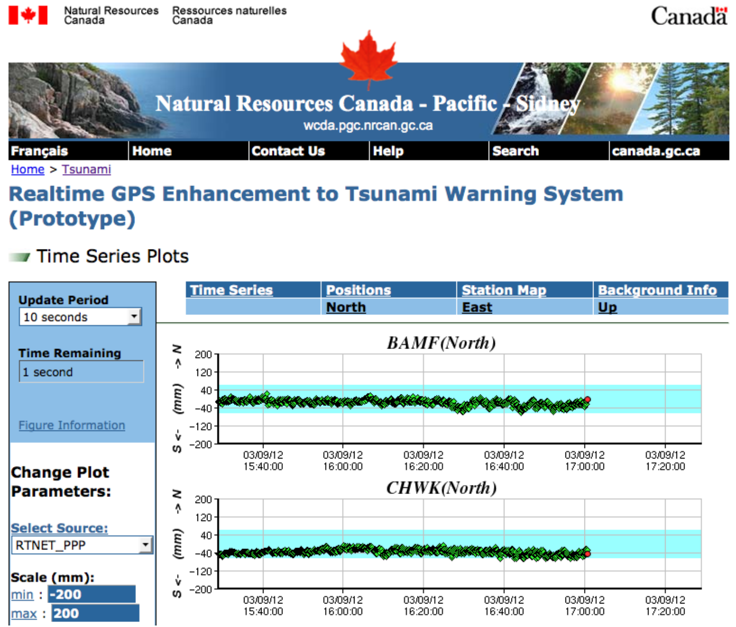


Real-time Monitoring of coordinate with PPP-AR
UNAVCO PBO Network
GPS tsunami buoy in Japan
PPP-RTK Network
Client
Server
100 km
PPP-AR
1,300 km
PPP-RTK Reference Network
Reference sites
Client sites
Server
Server
Client
500 km
Muroto Buoy
13 km RTK
Band-pass filtered
PPP-AR
Real Tsunami observed at Hiratsuka
1,000 k



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)
N
E
U
GPS
GPS+GLONASS
F4
Coordinate, cm
Number of SVs Used, Std. deviation (cm)

Results (cont.)



New Project - GNSS Center