CENTRE NATIONAL D'ÉTUDES SPATIALES

Phase Biases Estimation for Undifferenced Ambiguity Resolution

D. Laurichesse
Centre National d'Etudes Spatiales
Toulouse, France

Ambiguity resolution background

- Double differences

- Satellite-satellite single differences
  - Gabor (2002)
  - Ge & Al (2007)
  - Trimble RTX™ (ION GNSS 2011)

- Zero-difference methods
  - CNES method, “Integer phase clocks”, (ION GNSS 2007, ENC-GNSS 2008, ION ITM 2009, Navigation 2009)
  - Collins, NrCan, “Decoupled clock model”, ION ITM 2008
  - Geng method (University of Nottingham,), “Undifferenced Hardware Delays”, (ION GNSS 2008)
  - Similar concepts: Mervart, Rocken, GPS Solutions, (ION GNSS 2008)
  - Blewitt (NBMG & JPL), “Carrier Range”, (AGU 2009)

CNES method overview

- **Wide-Lane (ionosphere-free, geometry-free combination, ~0.1 cycle noise)**

$$f(L_2 - L_1, P_1, P_2) = -N_w + \Delta h_w$$

phase

pseudo-range

integer widelane

receiver - emitter 'Integer' widelane clocks

- **Narrow-Lane, ionosphere-free combinations**

$$\frac{\gamma\lambda_1 L_1 - \lambda_2 (L_2 + N_w)}{\gamma - 1}$$

$$P_c = D_c + \Delta h_p$$

$$Q_c = \underbrace{D_c + \lambda_c W}_{} + \Delta h - \lambda_c N_1$$

receiver - emitter pseudo-range clocks

integer ambiguity

10.7 cm

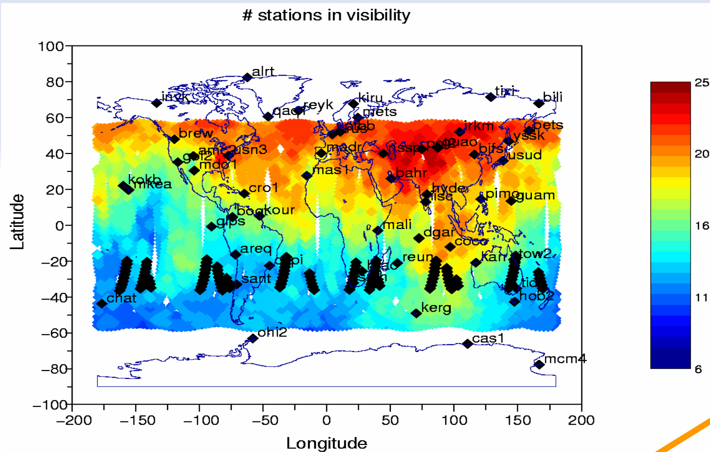
propagation model

receiver - emitter 'Integer' phase clocks

Single-frequency ionosphere-free system with a wavelength of 10.7 cm

Resulting phase clocks have "integer nature"
zero-difference ambiguity resolution at receiver level becomes possible
=> ambiguity fixed PPP for isolated receivers

Application to real-time integer-PPP



Network raw data flow

widelane fixing (sliding window)

Raw measurements (Nw fixed)

Kalman filter
(mixed float/integer for N_1 fixing)
clock/orbit corrections computation

PPP-like compact representation

h_w clock

GPS orbits

h_p, h clocks

Receiver

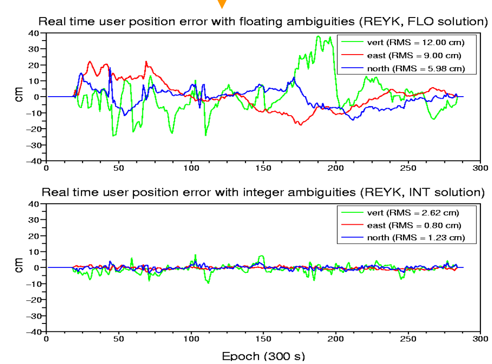
Raw measurements

widelane fixing (sliding window)

Raw measurements (Nw fixed)

Kalman filter
N_1 fixing and position estimation

Precise trajectory



- ambiguity fixing strategy based on network connectivity
- 1200 parameters for a network of 60 stations and 32 satellites
- 1000 measurements per epoch

Network side (orbit and clock estimation)

User side (PPP trajectory)

RTIGS Pilot Project participation

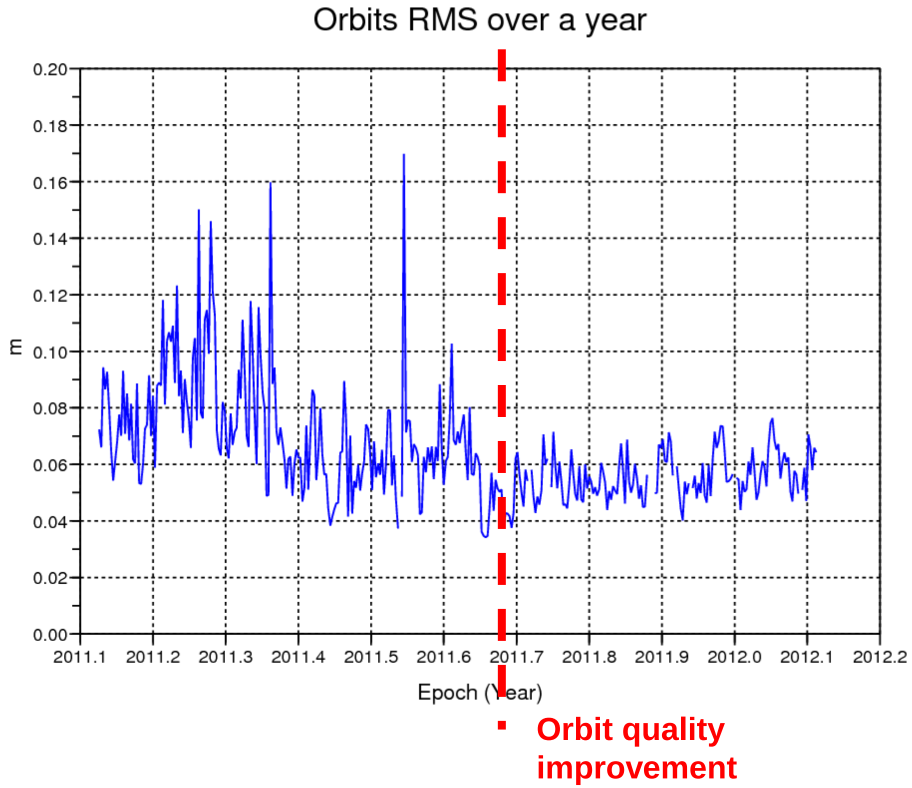
- CNES has developed a demonstrator based on integer PPP
  - PPP-WIZARD: Acronym for "*Precise Point Positioning With Integer And Zero-difference Ambiguity Resolution Demonstrator*"

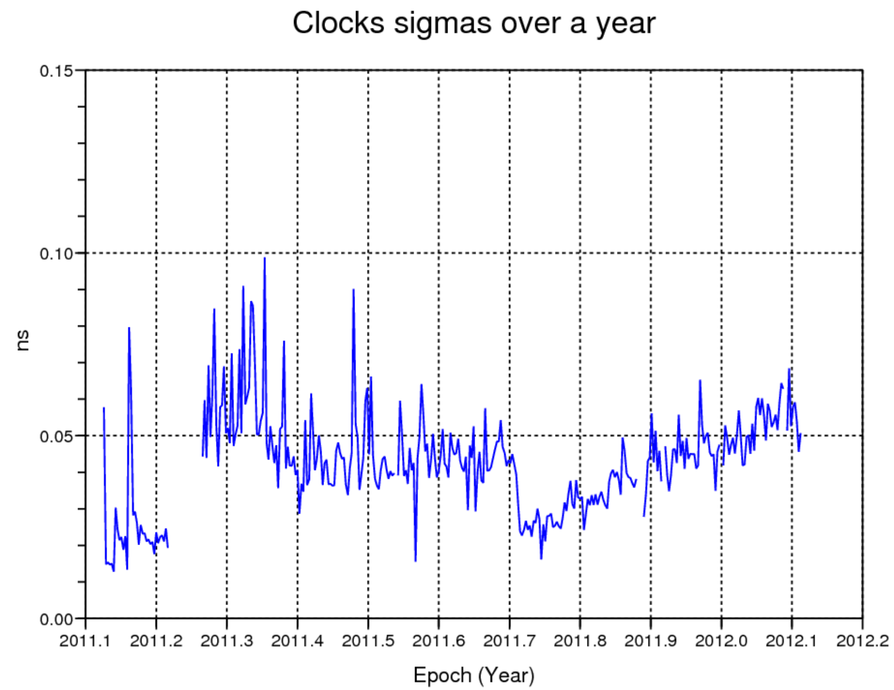
- In the framework of the RTIGS Pilot Project, the demonstrator has two objectives:
  - To contribute as an analysis center to the improvement of the combined product
  - To provide the full state space representation to users, including additional quantities for integer ambiguity resolution (using our own caster)

- CNES real-time analysis center since January 2011
  - GPS products since January 2011
  - GPS+Glonass products since December 2011

- CNES solution part of the combination since February 2011

Products statistics (one year)





Orbit quality around 5 cm

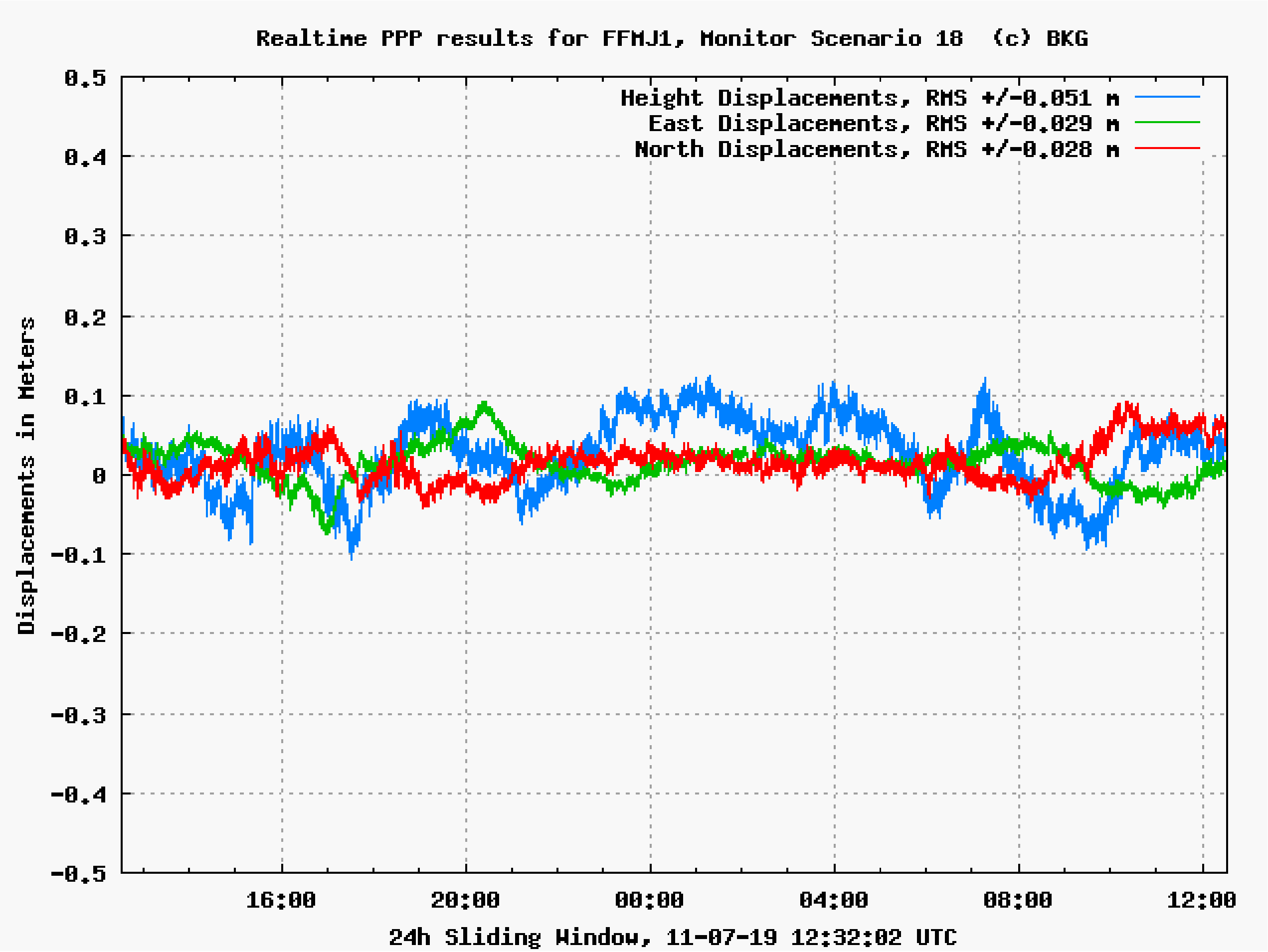
Clocks standard dev. around 0.05 ns (initial project target ~ 0.3 ns)

Contents of the demonstrator dynamic web server www.ppp-wizard.net

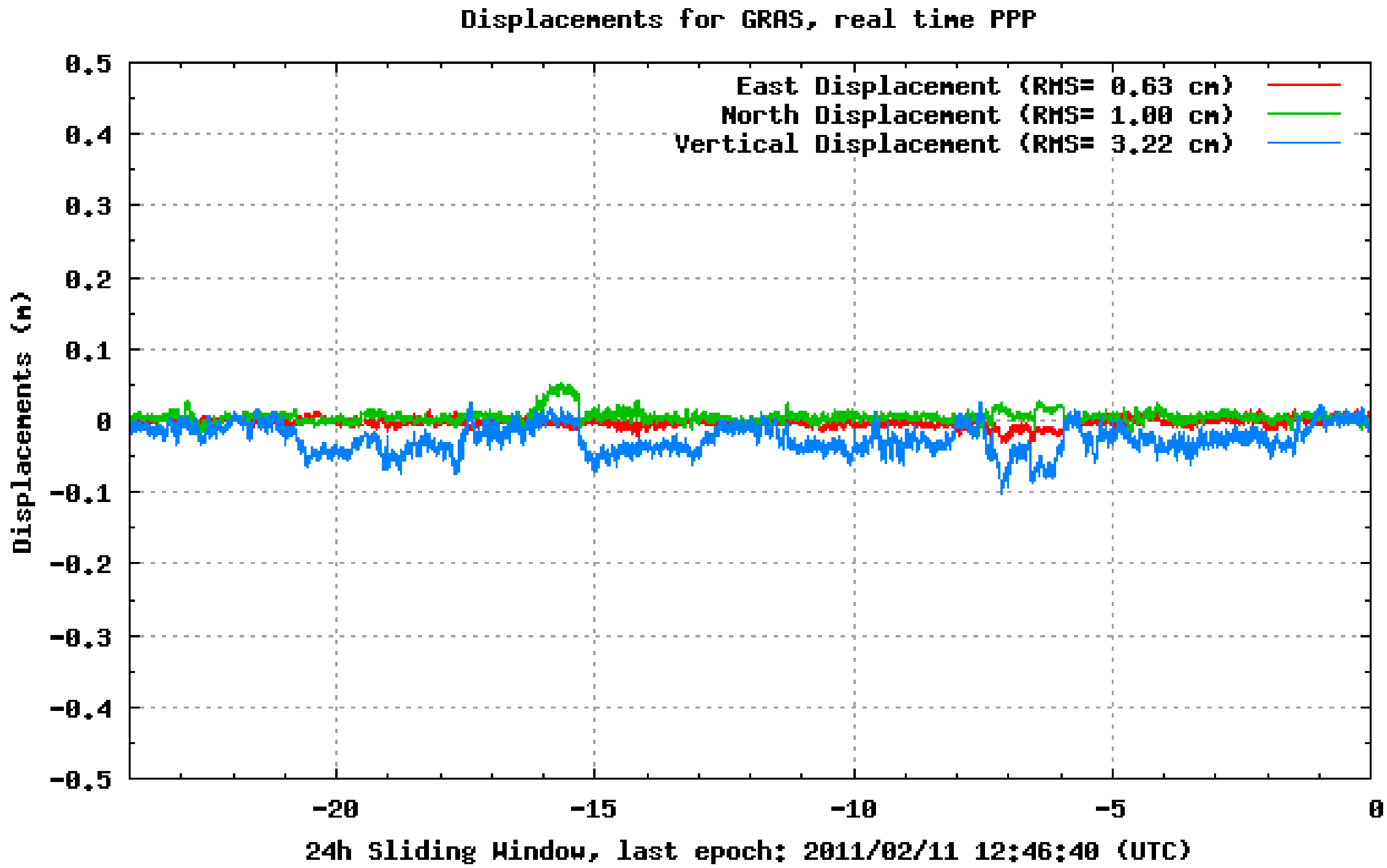
- ODTS network monitoring & current status updated in real-time.
- A PPP software modified for real time ambiguity resolution. Freeware, source code available, as well as a precompiled version for windows.
- Free access to real-time products
  - An anonymous access to the orbits/clocks stream dedicated to ambiguity resolution, from the CNES caster (CLK93 mountpoint).
  - A link to the current widelane biases compatible with this orbits/clocks stream.
  - A quick guide (ICD) on how to perform ambiguity resolution using CNES products.
- A set of PPP monitoring stations scenarios
  - Uses the PPP freeware with integer ambiguity resolution.
  - Uses the anonymous real-time stream dedicated to ambiguity resolution.
  - Displays errors in real-time.
- Daily consolidated products, to perform ambiguity resolution off-line (sp3 and clk files).

Real time PPP monitoring (floating mode, BKG)

http://igs.bkg.bund.de/ntrip/ppp



Real time PPP monitoring with integer ambiguity resolution (CNES)



Advantages and drawbacks of the method

	PPP 2-frequencies	RTK 2-frequencies	CNES Integer PPP 2-frequencies
Geometry	Global	Local (< 50 km)	Global
Convergence time (TTFF)	Convergence : < 30 cm Kick start: 1 min static: 15 min dynamic: 30 min	Convergence : ~ 1 cm Instantaneous	Convergence : ~ 1 cm Kick start: 1 min static: 30 min dynamic: 90 min
Horizontal accuracy	10-50 cm	~ 1 cm	~ 1 cm

- **The method is operationally equivalent to PPP but with the accuracy of RTK on the horizontal component (1 cm vs. 10 cm)**

Current biases representation and related problems

- **Current representation: biases on 2 combinations of observables**

$$\mathrm{MW}: L_1 - L_2 + \alpha_1 P_1 + \alpha_2 P_2 + \underline{H_w} \approx N_W$$

$$\text{Phase iono-free}: \frac{\gamma\lambda_1 L_1 - \lambda_2 \left(L_2 + N_W\right)}{\gamma - 1} + \underline{\left(H_P - H_L\right)} \approx D + \lambda_C N_1 + H_P + \ldots$$

igs clock

- **Related problems**
  - Representation too dependent on the resolution method
  - No clear distinction between phase and code biases -> difficult to standardize
  - Combinations are unique for the 2-frequency problem, but not for the 3-frequency problem

Switch to a new bias representation

- **We assume that code biases are already defined and known**
  - **They are already standardized in RTCM (message type 1059)**
  - **They are added to the raw measurements to obtain corrected measurements**

- **We extend the definition of code biases to the phase**
  - **Example with L_1, L_2:**

Integer values

$$P_1' = P_1 + b_{P_1} \approx D + h + \dots$$

$$P_2' = P_2 + b_{P_2} \approx D + h + \dots$$

$$L_1' = L_1 + b_{L_1} \approx N_1 + \frac{D+h}{\lambda_1} + \dots$$

$$L_2' = L_2 + b_{L_2} \approx N_2 + \frac{D+h}{\lambda_2} + \dots$$

Already standardized (b_{P1}, b_{P2})

New quantities (b_{L1}, b_{L2})

- **Phase biases are expressed in cycles and follow the same adding convention as code biases.**
- **The integer nature of phase ambiguities is explicit in phase biases equations**
  - **The biases can be used to retrieve the integer nature of phase ambiguities**
- **This representation needs to be completed**
  - **phase bias continuity indicator**
  - **Variance-covariance matrix**

Computation of new phase biases

- For the 2-frequency case, the new phase biases can be easily computed from the old convention, using a simple inversion:

$$\begin{pmatrix} b_{L_1} \\ b_{L_2} \end{pmatrix} = \frac{1}{\gamma\lambda_1 - \lambda_2} \begin{pmatrix} -\lambda_2 & 1 \\ -\gamma\lambda_1 & 1 \end{pmatrix} \begin{pmatrix} H_w - \alpha_1 b_{P_1} - \alpha_2 b_{P_2} \\ (\gamma - 1)(H_P - H_L) \end{pmatrix}$$

- At the user level, we:
  - Add the code and phase biases to the raw measurements
  - Perform the MW and iono-free phase combinations to retrieve the integer values of ambiguities

- This new bias representation is already implemented in our demonstrator:
  - We use a modified message type 1059 with new field numbers
    - 21 and 22 for L1 and L2 biases respectively
  - Caster: www.ppp-wizard.net:2101
  - Mountpoints: CLK9A (CoM), CLK9B (APC)
  - Access available on demand

Benefits of the new bias representation

- It uses the same convention as the existing RTCM standard for code biases
- It is closer to the physical behavior of the navigation payload than complex combinations
- It is independent of the method used on the network side to compute the biases
- It allows the user to implement the ambiguity resolution method of his choice
- The integer nature of phase ambiguities is conserved
  - But this representation can also take in account non-integer phase biases
    - For example it can represent the difference of clocks L1L2 and L1L5 observed by O. Montenbruck and others (ION GNSS 2011)
- It can easily be extended to multi-frequency biases, without any assumptions on ambiguity resolution methods at the network or user level

Extension to 3 frequencies

- **One day of biases have been generated off-line**
  - **Using CONGO network measurements (about 20 stations, courtesy O. Montenbruck)**
  - **Rinex-like file available on demand**
- **Integer ambiguity nature is conserved for all iono-free combinations**
- **For combinations that involve geometry, a reference orbits/clocks solution is chosen (in this case the JPL solution)**

- **3-frequency biases could already be computed in real-time thanks to the BNC 2.5 freeware and the appropriate real-time network**

PRN	Year	Month	Day	Hour	Min	Sec	C1	C2	C5	P1	P2	L1	L2	L5
G01	11	10	19	0	0	0.000	-4.952	-8.372	-0.052	-4.890	-8.053	24.694	31.637	0.860
G02	11	10	19	0	0	0.000	2.769	0.000	0.000	2.776	4.572	-14.252	-18.120	0.000
G03	11	10	19	0	0	0.000	-1.280	0.000	0.000	-1.089	-1.794	8.456	10.689	0.000
G04	11	10	19	0	0	0.000	-0.193	0.000	0.000	-0.519	-0.856	3.608	4.594	0.000
G25	11	10	19	0	0	0.000	-4.198	-7.138	0.052	-4.023	-6.625	23.507	30.254	-0.860
G26	11	10	19	0	0	0.000	-0.556	0.000	0.000	-0.751	-1.237	4.004	5.168	0.000

Already broadcast

Already standardized

New quantities

Client side: Undifferenced three-carrier ambiguity resolution

1. **Solve for extra widelane ambiguity (L2-L5)**

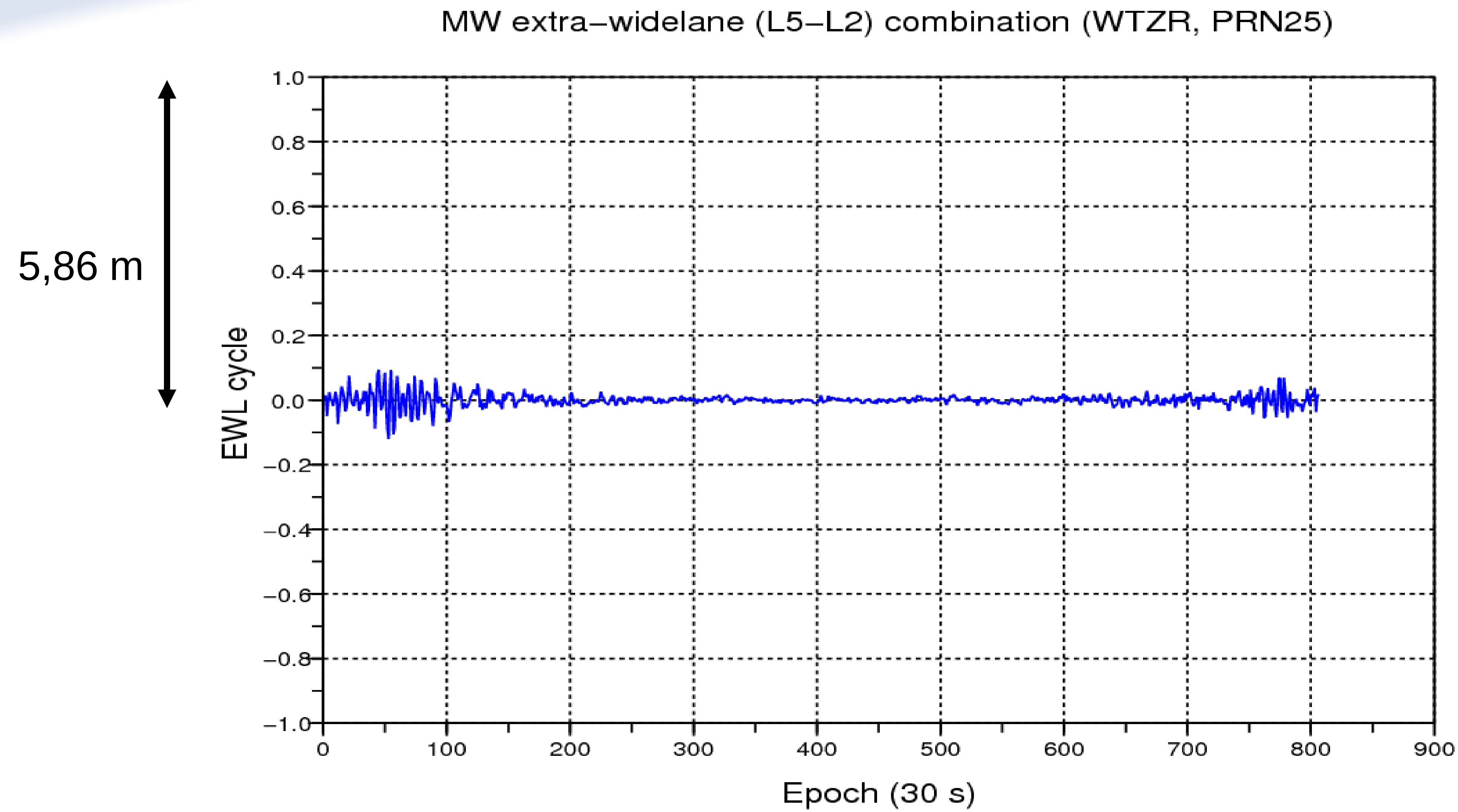
2. **Using extra widelane integer ambiguity value, solve for (L1-L2) wide-lane ambiguity**

    - **An intermediate observable where only widelane ambiguities are solved is of particular interest (unambiguous observable with low noise)**

3. **Solve for last ambiguity N1**

- **The entire ambiguity resolution process is reduced to a few minutes.**

Extra-widelane (L_5-L_2) resolution



Widelane (L_1-L_2) resolution

- One key combination : iono-free combination of widelanes in meters

$$f\left[(L_5 - L_2),(L_2 - L_1)\right] \approx D + \lambda_w (N_2 - N_1) + \dots$$

- We assume that the extra-widelane ambiguity (N_5-N_2) is already solved

$$\Rightarrow \lambda_w = 3.4m$$

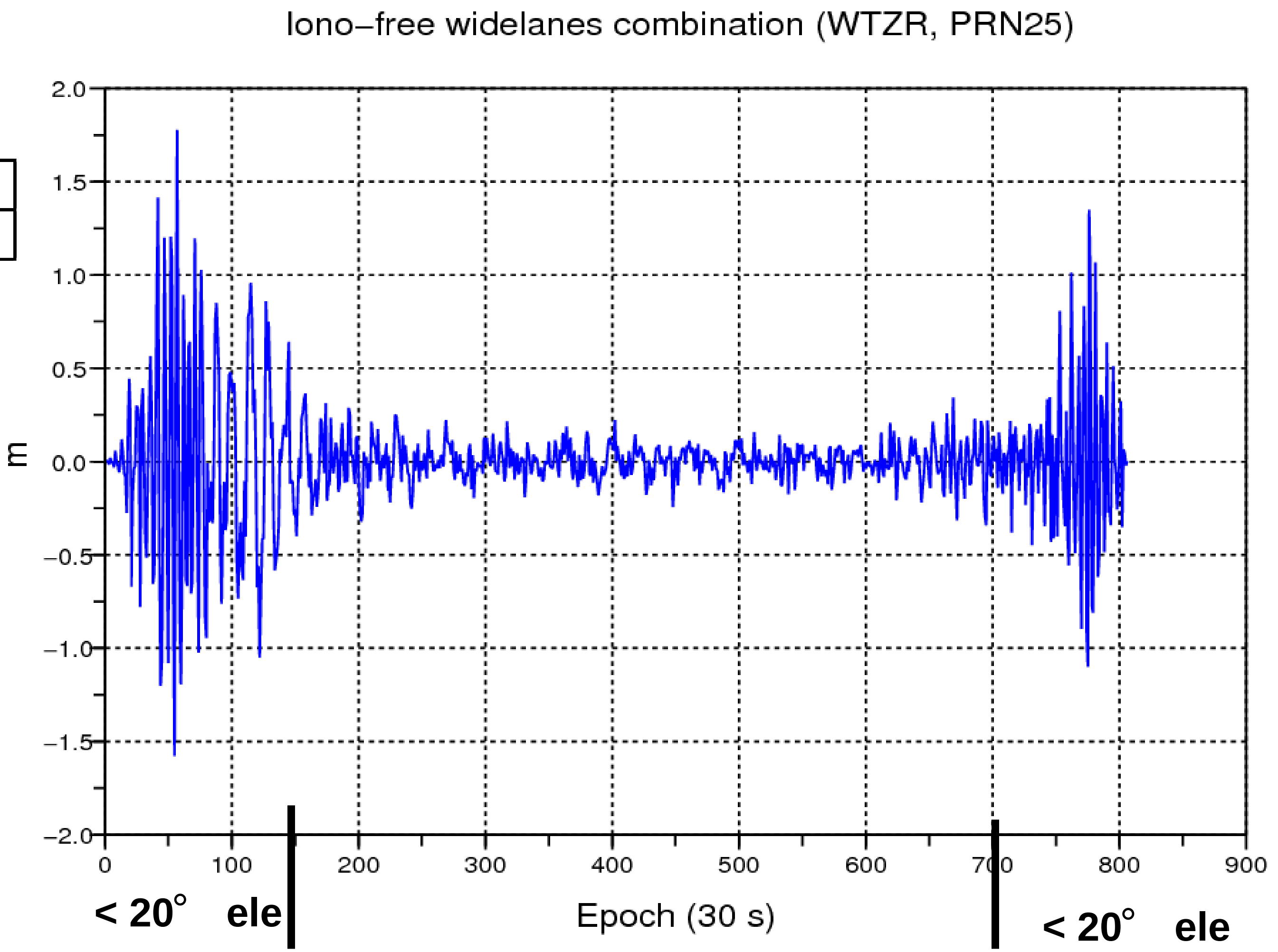
- This widelane ambiguity is easy to solve with the help of the geometry

Noise of the widelanes combination

- Phase amplification factors

L1	L2	L5
3.4	-20.7	17.3

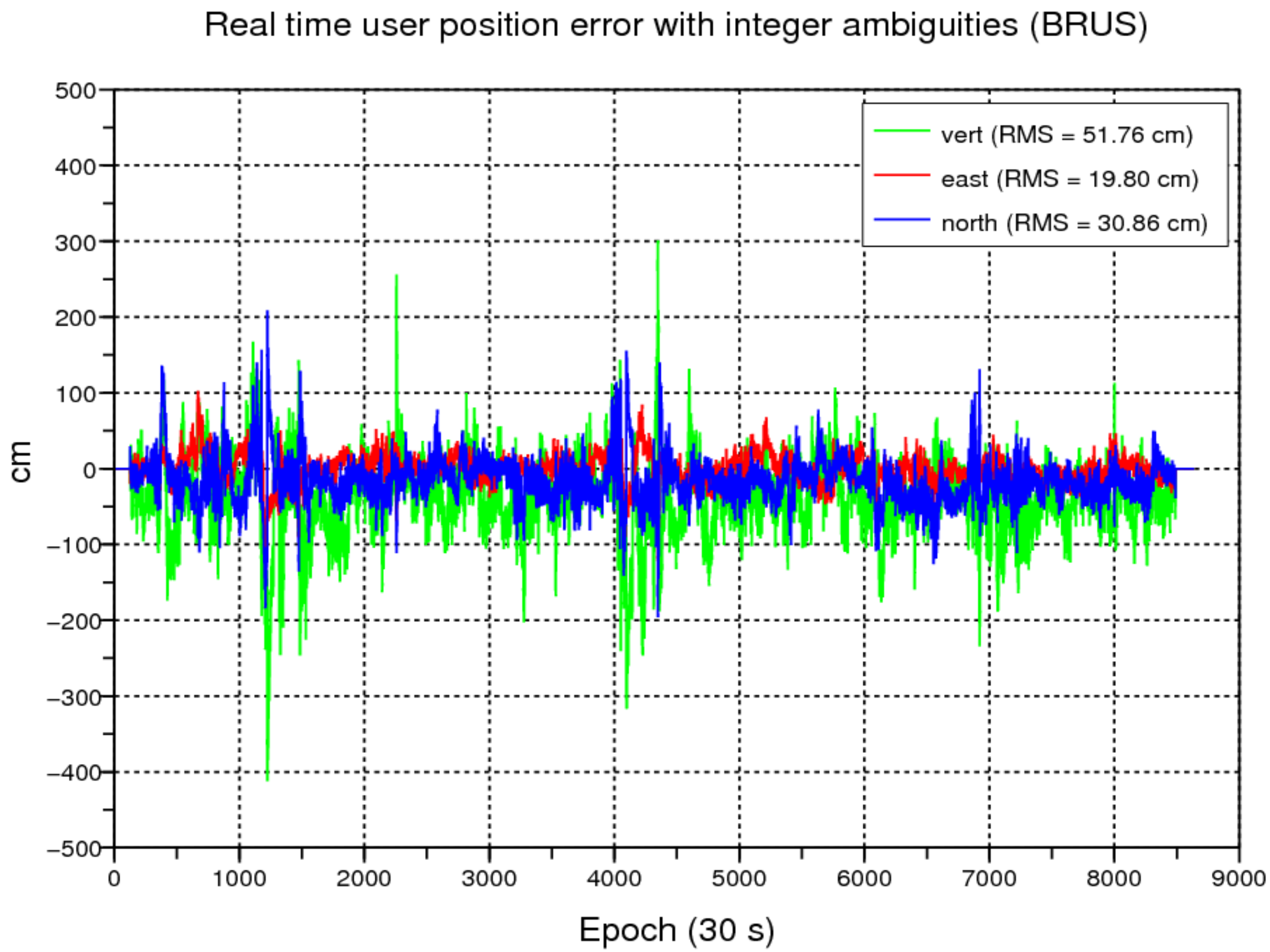
- Mainly phase multipath errors
- Strong dependency with elevation



PPP using the widelanes combination

- Based on real measurements (BRUS)
- Noise profile based on elevation and real 3-freq. meas.
- Weighting of measurements with a function of elevation

- 10 cm class accuracy
- No convergence time (instantaneous)
- No pseudo-ranges involved (phase only solution)



Remaining ambiguity (N1), geometry-free approach

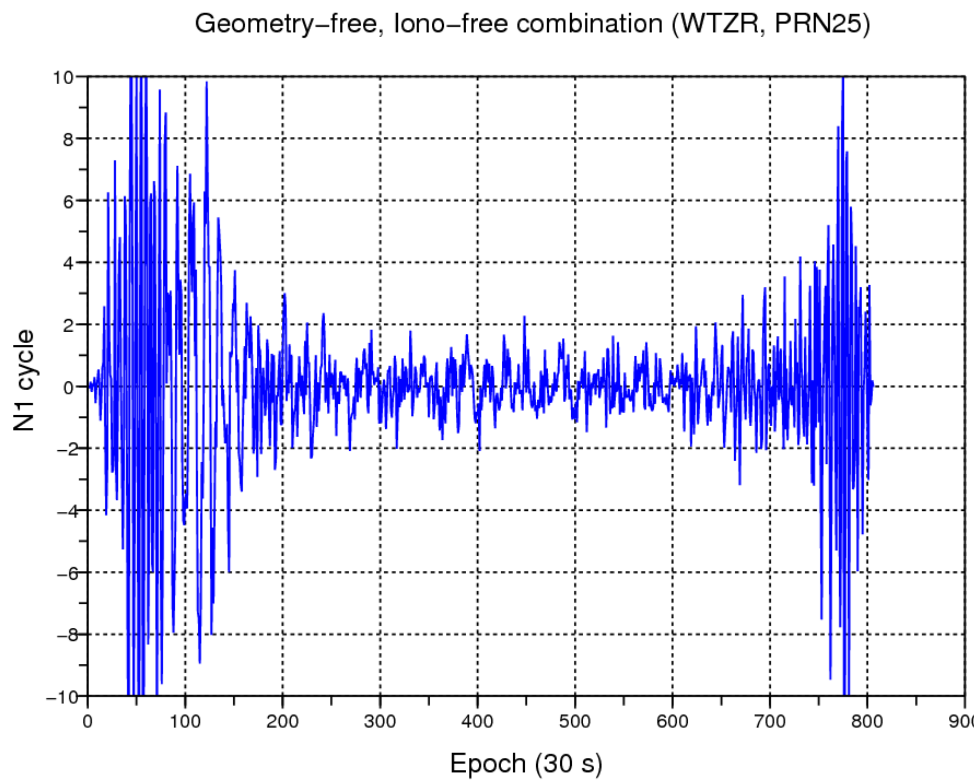
- We assume that the widelanes ambiguities are already solved
- Combination : geometry-free and iono-free combination in N1 cycles

$$f(L_1, L_2, L_5) \approx N_1 + \ldots$$

- Phase amplification factors

L1	L2	L5
27.3	189.9	-161.6

- Very important phase multipath amplification
- Strong time correlation
- N1 estimation longer than expected ~ 5 minutes
- Geometry approach -> same issue



Advantages and drawbacks of the method (ext. 3-freqs)

	PPP 2,3 frequencies	RTK 2,3 frequencies	Integer PPP 2-frequencies	Integer PPP 3-frequencies Widelanes ambiguities only	Integer PPP 3-frequencies All ambiguities
Geometry	Global	Local (< 50 km)	Global	Global	Global
Convergence time (TTFF)	Convergence : < 30 cm Kick start: 1 min static: 15 min dynamic: 30 min	Convergence : ~ 1 cm Instantaneous	Convergence : ~ 1 cm Kick start: 1 min static: 30 min dynamic: 90 min	Convergence : < 30 cm Instantaneous	Convergence : < 1 cm ~5 min
Horizontal accuracy	10-50 cm	~ 1 cm	~ 1 cm	10-50 cm	~ 1 cm

Conclusion

- Integer ambiguity orbits and clocks solutions have been computed in real-time using the current RTIGS network and NTRIP tools.

- A full scale demonstrator using this method was developed in the RTIGS framework and has been running operationally since January 2011.

- State space phase biases haven been switched to a new representation
  - One phase bias per frequency
  - Already broadcast for the 2-frequency case
  - Off-line computation of 3-frequency biases in this representation

- User PPP 3-frequency algorithms are under study and show:
  - Instantaneous resolution at 10 cm level.
  - Full accuracy in minutes.