Integer Ambiguity Resolution in Precise Point Positioning: Method Comparison and Real-Time Application

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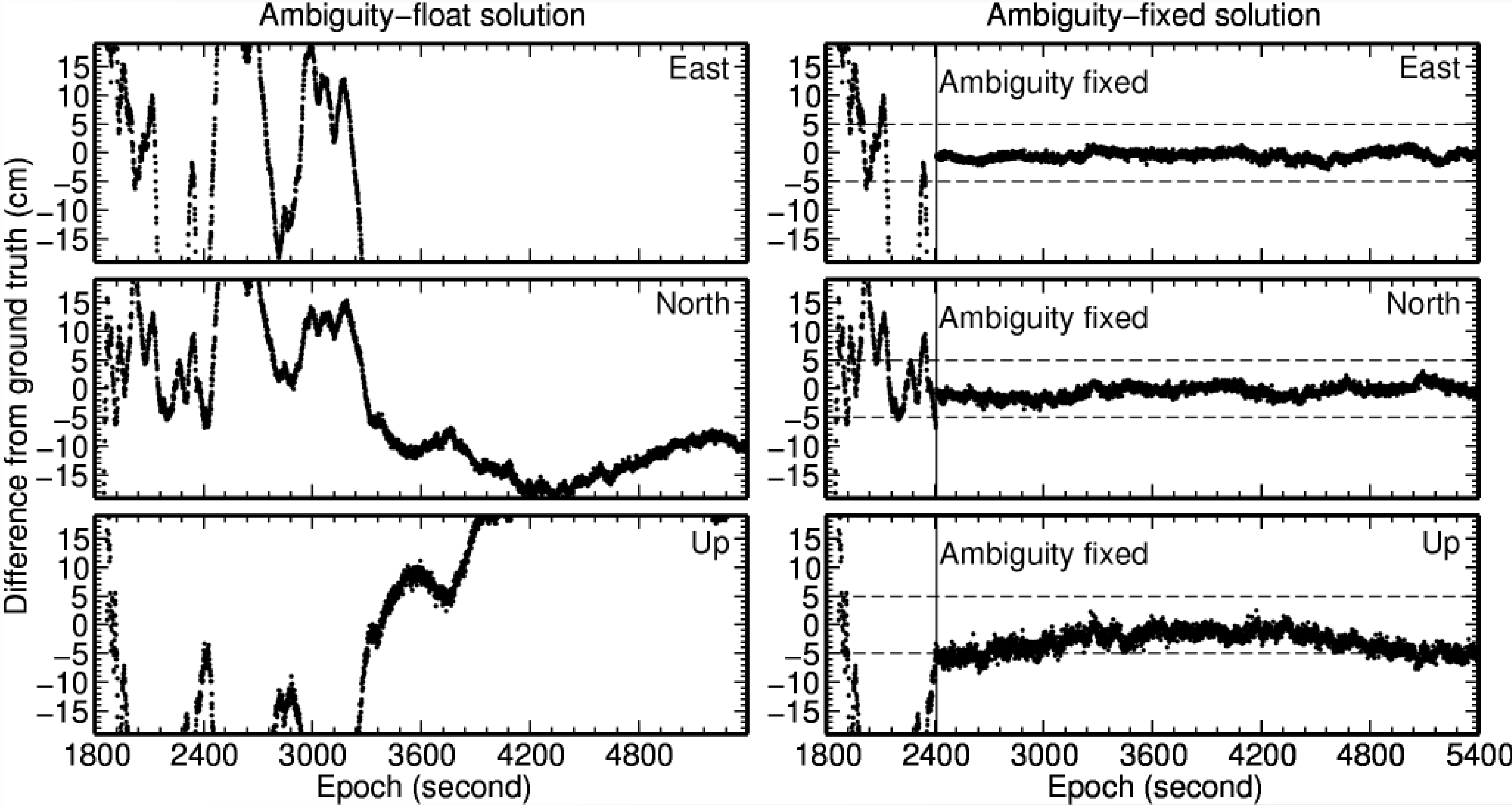
Contents

- Introduction to integer ambiguity resolution in un-differenced observables
- Fractional cycle bias (FCB) and Integer-recovery clock (IRC) method comparison
- CNES Real-Time integer-PPP Demonstrator
- Conclusions

Impact of Ambiguity Resolution in PPP



Geng (2011), Rapid Integer Ambiguity Resolution in PPP, PhD Thesis, University of Nottingham

Ambiguities in Un-Differenced Observables

- Until ~2007 considered as difficult, if not impossible, due to non-integer character of ambiguities in un-differenced observables
- For example, the one-way carrier phase observation equation from receiver k to satellite i with frequency m and wavelength λ_m can be written as (e.g. Goad, 1985; Blewitt, 1989; Gabor & Nerem, 1999; Ge et al., 2008):

$$L_{mk}^{i} = \rho_k^i - \frac{\kappa}{f_m^2} + \lambda_m b_{mk}^{i}$$

where the carrier-phase ambiguity $b_{mk}^{i} = n_{mk}^{i} + \phi_{mk} - \phi_m^{i}$

with n_{mk}^{i} being the integer ambiguity, and ϕ_{mk} and ϕ_m^i being the fractional-cycle biases (FCB) in receiver and transmitter

- First attempt to overcome these FCB was by Gabor & Nerem (1999)

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Methods for resolving integer ambiguities in un-differenced observables

- Estimate the fractional cycle biases (FCB) that are common for all involved PPP ambiguity estimates (e.g. Gabor and Nerem 1999; Ge et al. 2008; Geng et al., 2008; 2009; Mervart et al., 2008)
- Estimate integer-recovery clocks (IRC) which absorb the FCBs (e.g. Laurichesse & Mercier, 2007; Delporte et al., 2007; Laurichesse et al. 2008; 2009) – mixing of satellite clocks and FCBs
- Provide ambiguity estimates derived from a global network solution based on PPP (for GIPSY OASIS 6.0; Bertiger et al. 2010). In essence, double-difference ambiguities are fixed to integers
- Estimate a “decoupled clock model” (Collins, 2008, Collins et al. 2008, 2010)

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Wide-lane and narrow-lane FCBs

- It can be shown that the carrier-phase bias term of the ionosphere-free combination can be written as (e.g. Ge et al., 2008):

$$b_{ck}^{i} = \frac{f_1}{f_1 + f_2} b_{nk}^{i} + \frac{f_1 f_2}{f_1^2 - f_2^2} b_{wk}^{i}$$

- where b_{nk}^{i} is the narrow-lane (NL) and b_{wk}^{i} the wide-lane (WL) carrier phase bias.
- In order to remove receiver specific FCBs one can form between satellite single differences (SD).
- The SD carrier phase bias term can be shown to be:

$$b_{ck}^{i,j} = \frac{f_1}{f_1 + f_2}\left(n_{nk}^{i,j} - \phi_{n}^{i,j}\right) + \frac{f_1 f_2}{f_1^2 - f_2^2}\left(n_{wk}^{i,j} - \phi_{w}^{i,j}\right)$$

- where $\phi_{n}^{i,j}$ and $\phi_{w}^{i,j}$ denote the SD NL and WL FCB, and $n_{nk}^{i,j}$ and $n_{wk}^{i,j}$ the SD NL and WL integer phase ambiguities, respectively.

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Determination of the FCBs

- Using the Melbourne-Wübbena combination observable the WL FCB can be determined from

$$\phi_w^{i,j} = \left\langle \left[b_{wk}^{i,j} \right] - b_{wk}^{i,j} \right\rangle$$

- where ?·? denotes averaging over all stations and [·] denotes the rounding operation.
- Once $\phi_w^{i,j}$ is determined, $n_{wk}^{i,j}$ can be fixed to an integer.
- The NL FCB can then be estimated from

$$\phi_n^{i,j} = \left\langle \left[b_{nk}^{i,j} \right] - b_{nk}^{i,j} \right\rangle$$

- with $b_{nk}^{i,j} = \dfrac{f_1 + f_2}{f_1} b_{ck}^{i,j} - \dfrac{f_2}{f_1 - f_2} n_{wk}^{i,j}$

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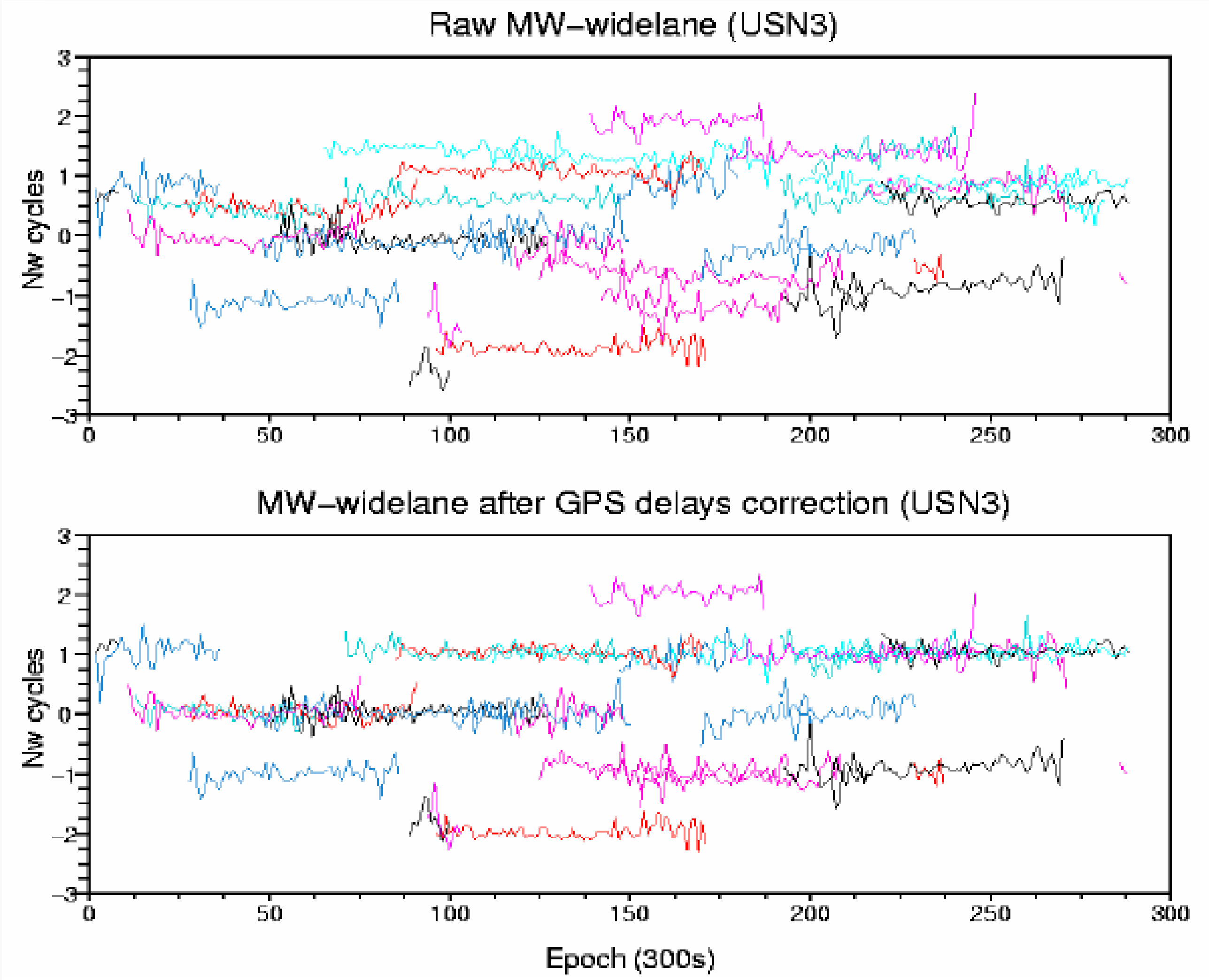
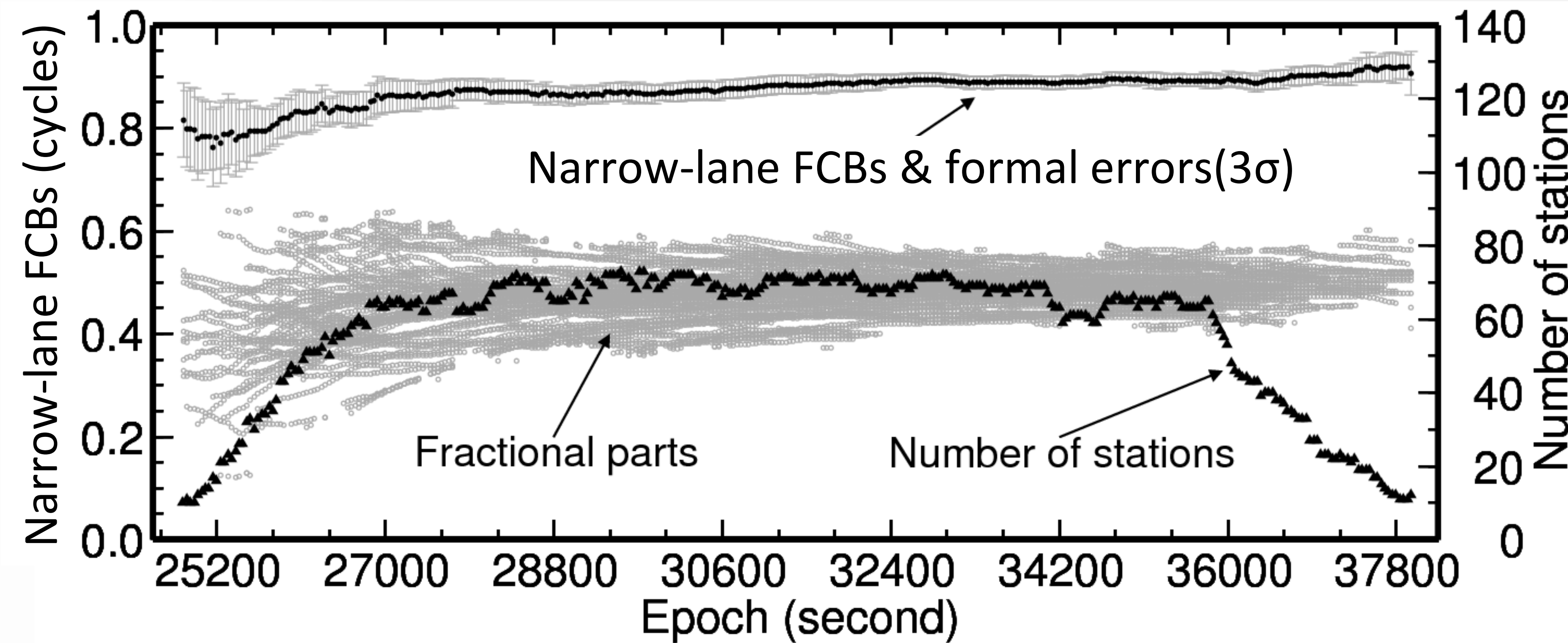
Impact of WL FCBs on MW WL (USN3)



Laurichesse & Mercier (2007)

Narrow-lane FCB (PRN02 and PRN04)



Geng et al. (2011)

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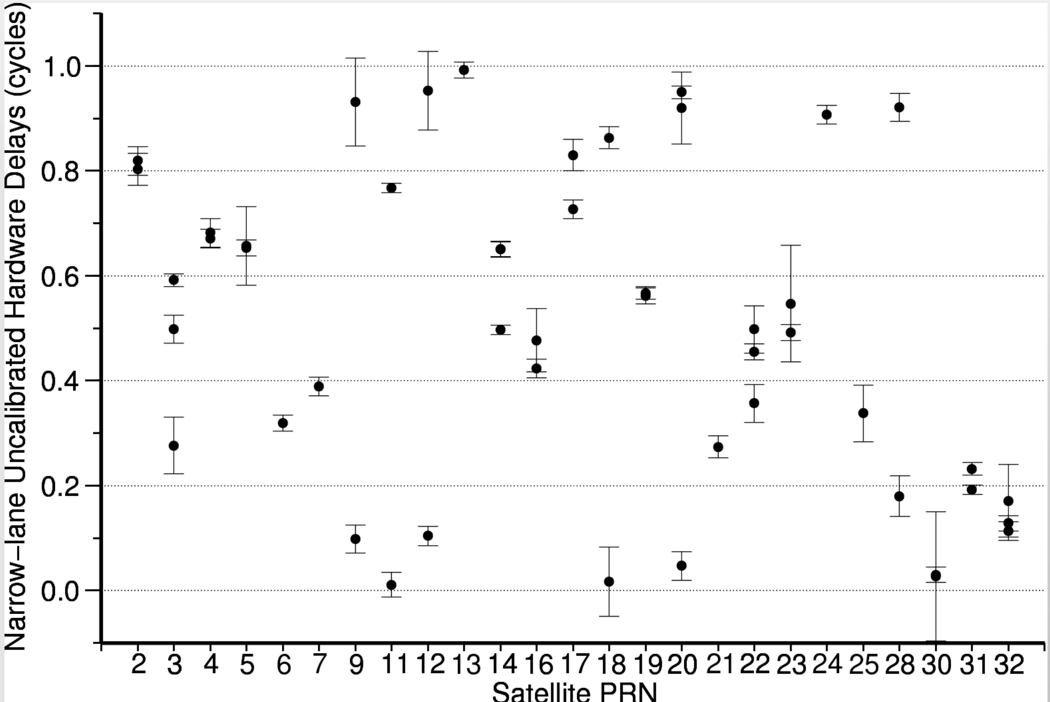
Determination of the FCBs (cont.)

- Daily mean WL FCB can be considered as stable over days to months (e.g. Gabor & Nerem, 1999; Ge et al., 2008; Geng et al., 2009; Laurichesse & Mercier, 2007)
- However, the NL FCBs need to be estimated more frequently:
  - Ge et al. (2008) – every 15 minutes
  - Geng et al. (2008; 2009) – once per continuous tracking period of a satellite pair over a region
- The latter is more convenient in practice while retaining high precision

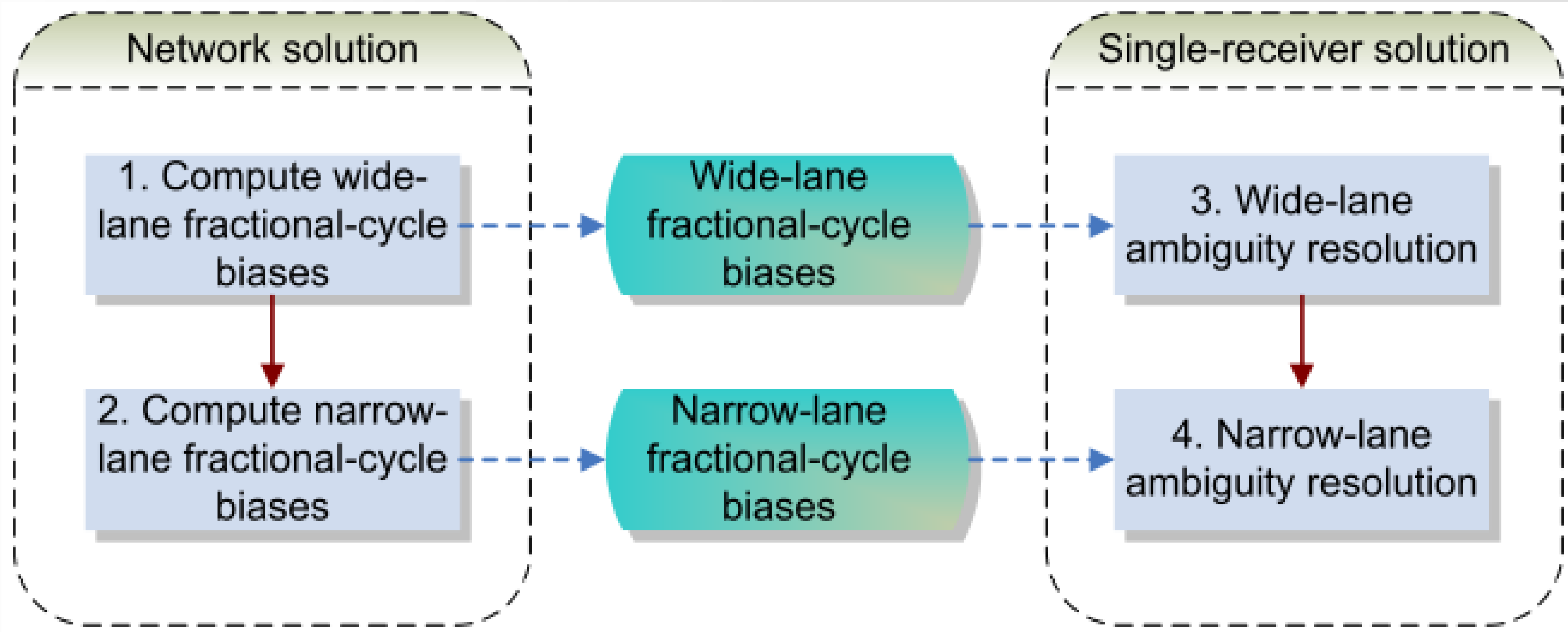


NL FCB estimates for all satellites with respect to PRN01 on Day 247 in 2007.

FCB-based method for PPP ambiguity resolution

- Service providers: estimate satellite-dependent FCBs with un-differenced ambiguity estimates from a GNSS network solution, and deliver FCBs to users

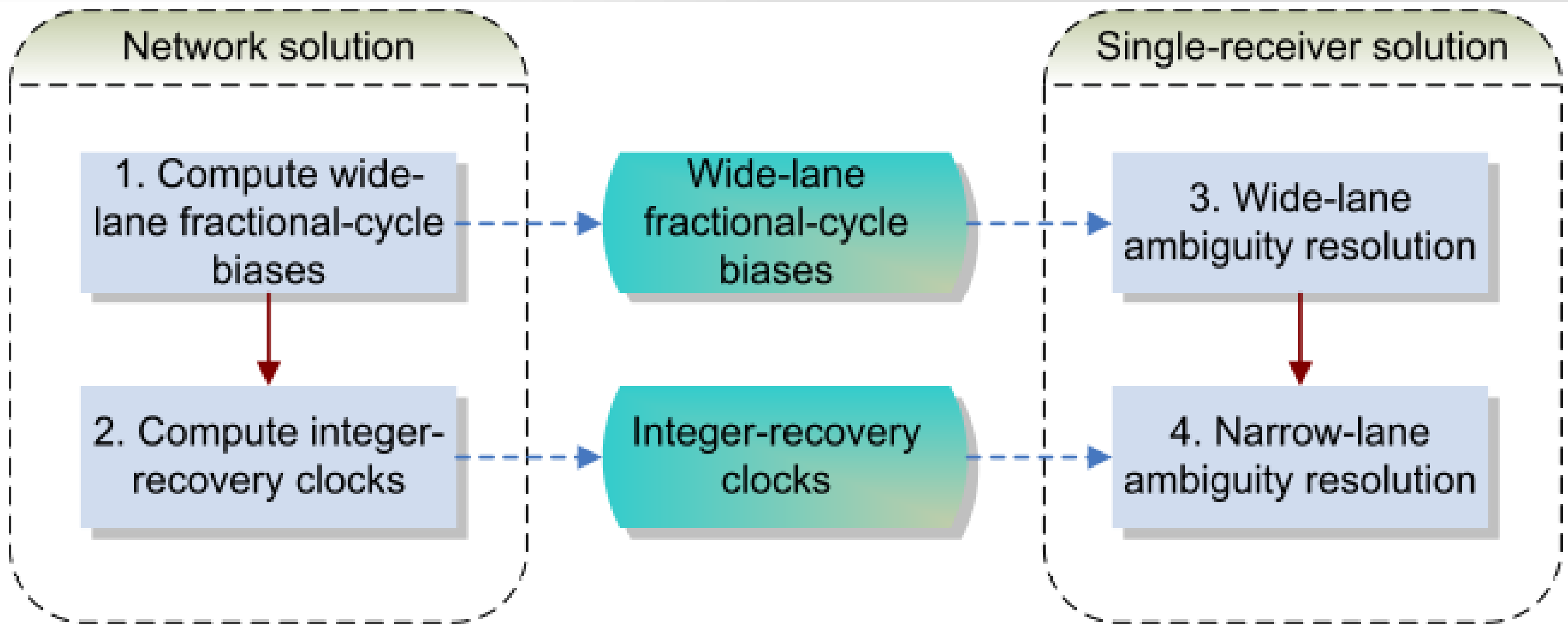
- PPP users: correct un-differenced ambiguity estimates with FCBs, and attempt integer resolution on un-differenced ambiguities



IRC-based method for PPP ambiguity resolution

- Service providers: estimate satellite IRCs by fixing un-differenced ambiguities to integers in advance in a GNSS network solution, and deliver these IRCs to users

- PPP users: apply IRCs, instead of the official clock products by IGS, in PPP data processing, and attempt integer resolution on un-differenced ambiguities



How do these two methods agree and differ?

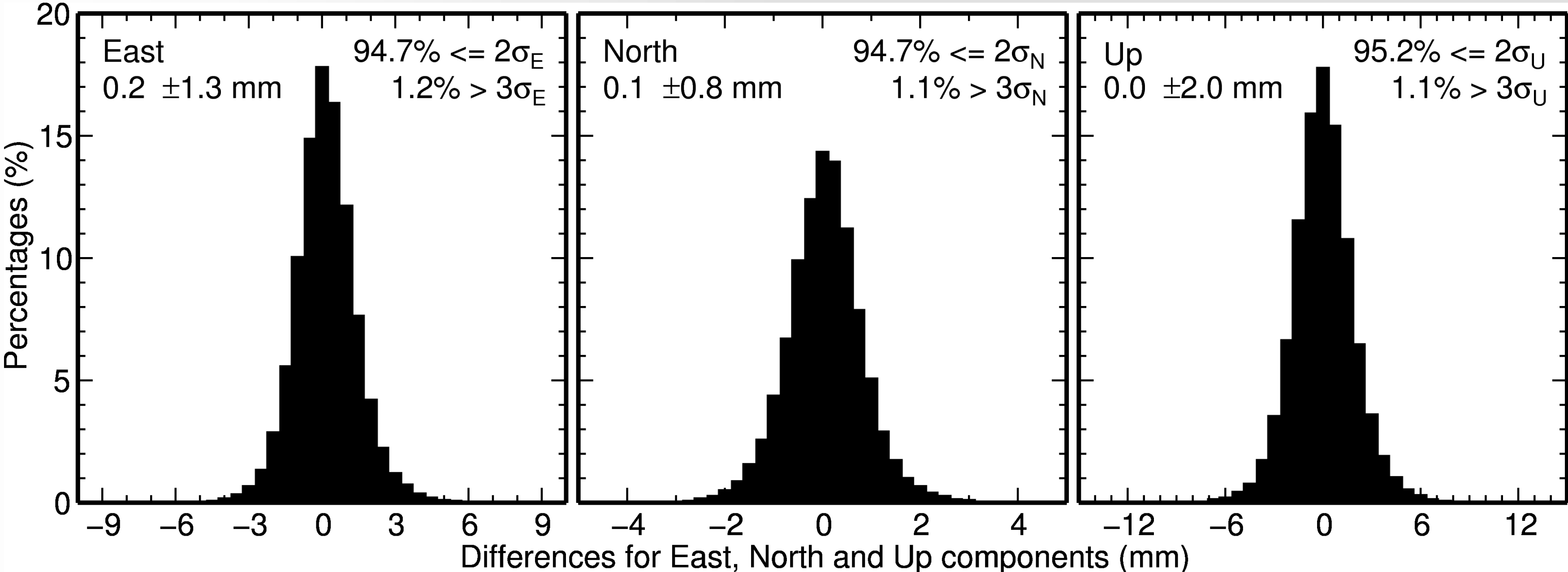
- In theory, the ambiguity-fixed estimates of these two methods are identical (Geng et al. 2010)

- The key difference between the two methods is the separation of the FCBs from the integer ambiguities
  - FCB-based method: average the fractional parts of all involved ambiguity estimates every 15 minutes to estimate FCBs
  - IRC-based method: assimilate the fractional parts of all involved ambiguity estimates to epoch-wise clocks to estimate IRCs

- What is the impact of this difference on the positioning quality?
- To investigate ambiguity-fixed positions, we use
  - One year (2008) of GPS data from 350 globally-distributed stations
  - CODE satellite orbits
  - Estimate daily positions, hourly zenith troposphere delays and 12-hourly horizontal troposphere gradients

Position differences between the FCB and IRC methods

>100,000 differences	East (mm)	North (mm)	Up (mm)
Bias	0.2	0.1	0.0
Standard deviation	1.3	0.8	2.0
RMS	1.3	0.8	2.0



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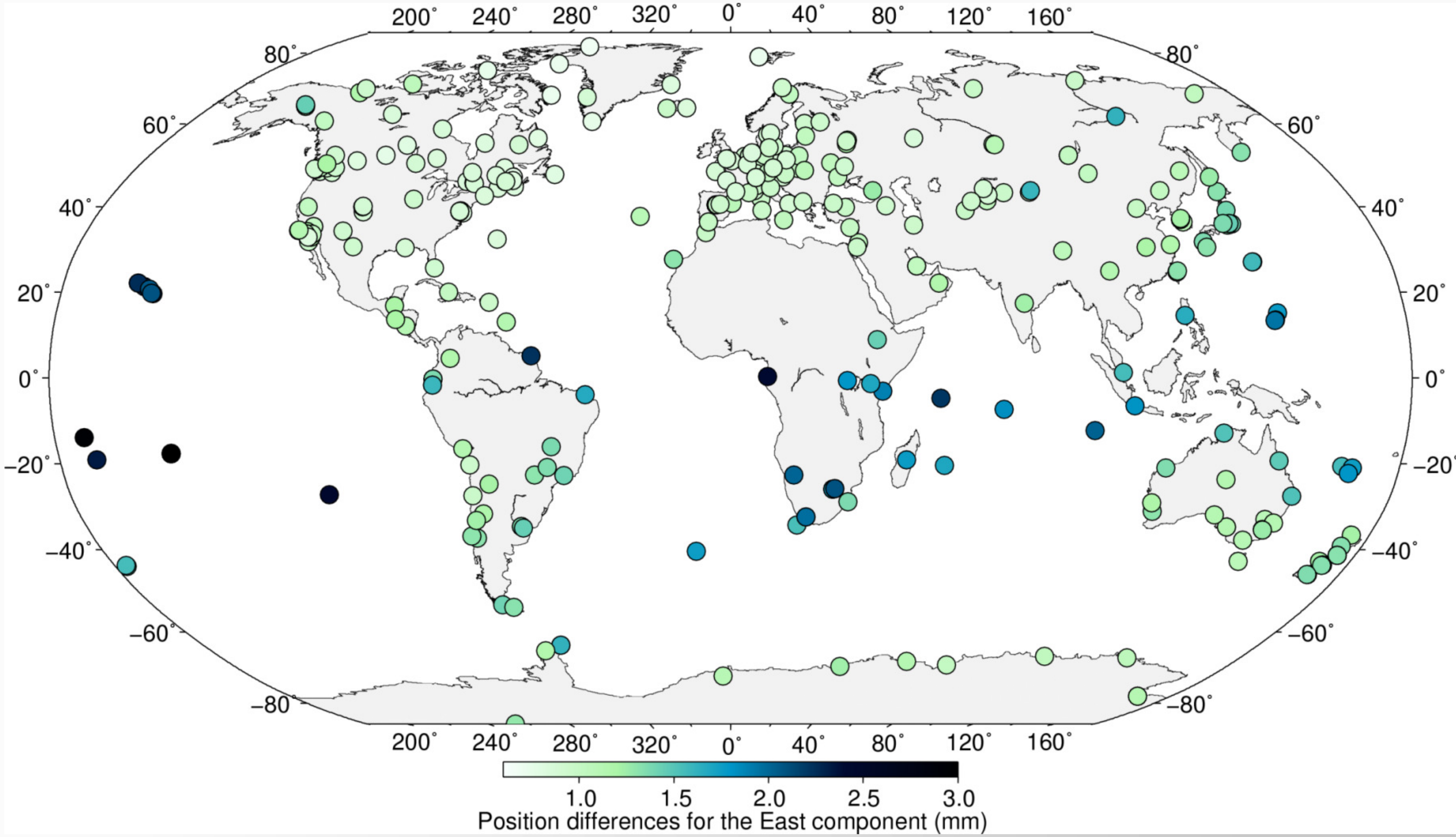
Position differences for the East component for each station



- Small differences are present mainly in Europe and North America (<2mm)
- Large differences are present for sparse networks, e.g. oceanic islands, Africa (>1.5mm)
- Also visible for the North and Up components

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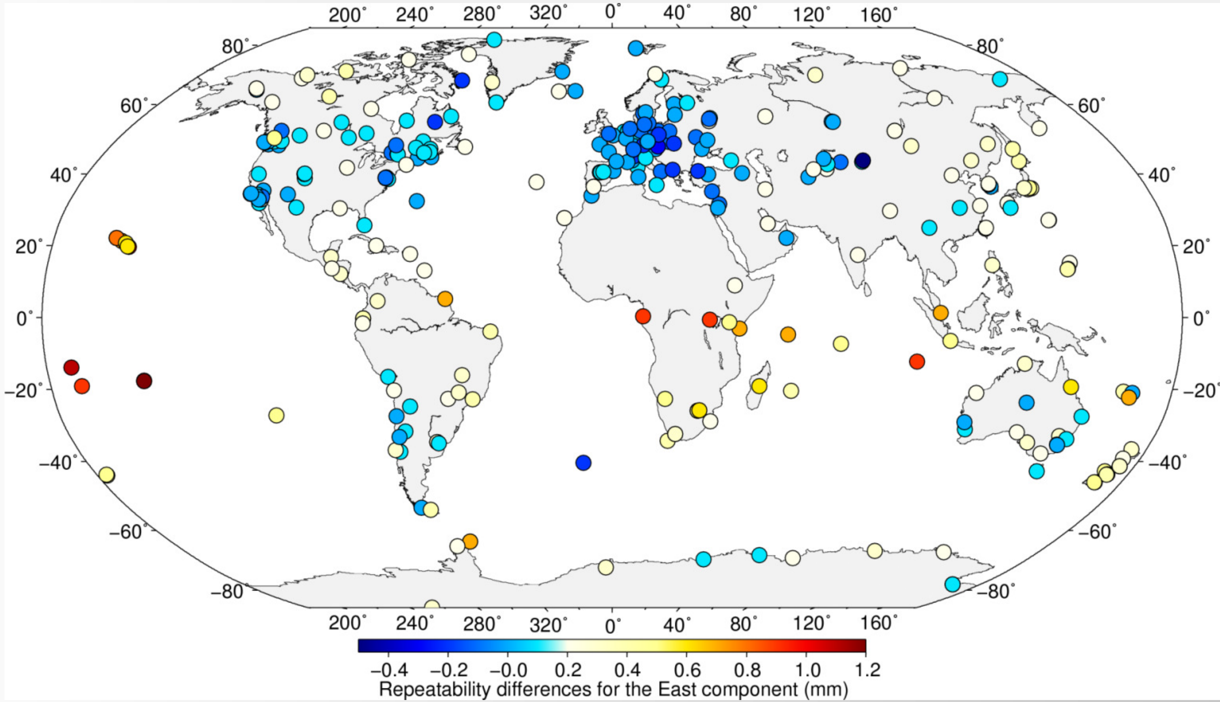
Position repeatability differences between FCB and IRC methods for East component

Methods	East (mm)	North (mm)	Up (mm)
FCB-based	2.4	2.2	7.7
IRC-based	2.2	2.3	7.6

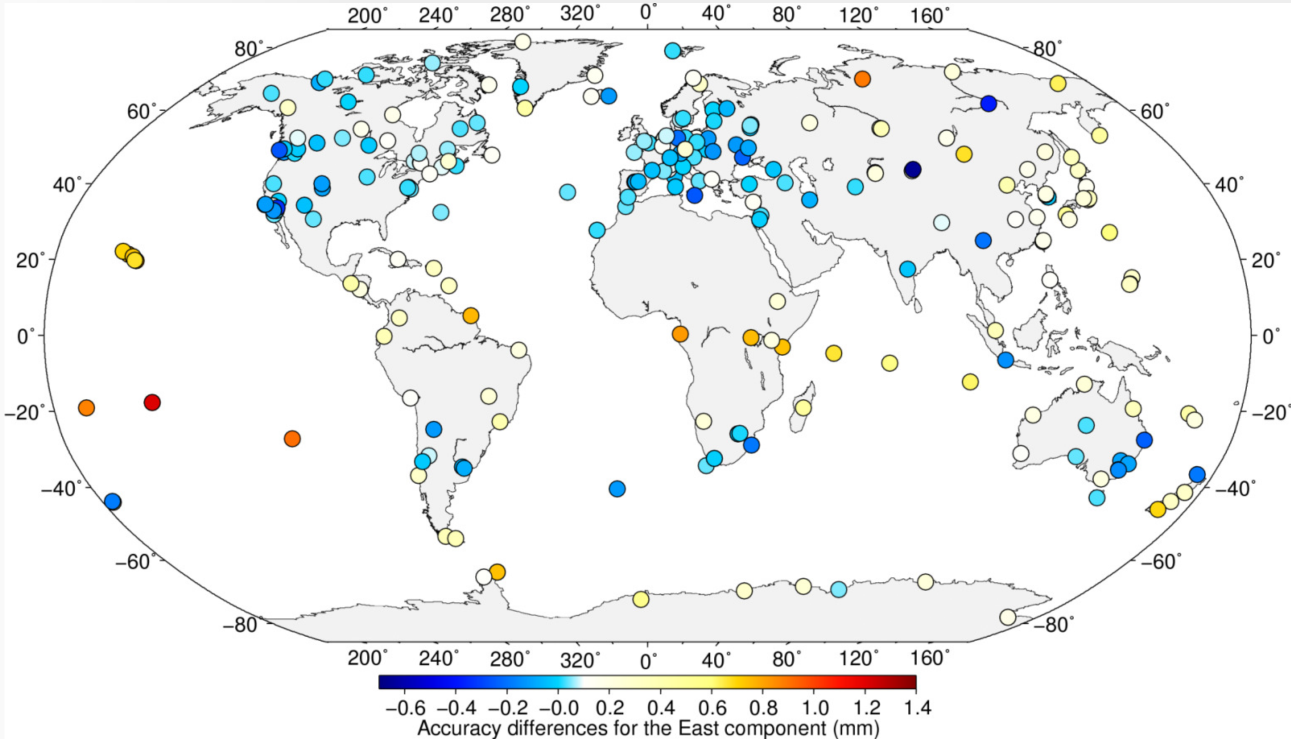
within 0.2mm!



- FCB-based method outperforms IRC-based method over dense networks (<0.5mm)
- IRC-based method even more outperforms FCB-based method over sparse networks (>0.5mm)
- Not visible for the North and Up components

Comparison with IGS weekly solutions: differences in East

	Ambiguity-float solutions (mm)			Ambiguity-fixed solutions (mm)		
	East	North	Up	East	North	Up
FCB-based	3.4	2.2	6.2	2.0	2.1	5.9
IRC-based	3.5	2.3	6.3	1.9	2.1	5.8



- FCB-based method outperforms IRC-based method over dense networks (<0.7mm)
- IRC-based method outperforms even more over sparse networks (up to 1.4mm)
- Not visible for North and Up components

Discussion

- Slightly inferior performance of the FCB-based method may be due to the averaging operation over 15 minutes, rather than every epoch

- Epoch-wise FCBs + IGS clocks = IRCs?
  - In this case, it would not be necessary to separate FCB and clock products in the FCB-based method. They can be combined.
- FCB-based method is compatible with current official clock-generation methods within IGS
  - Users can apply the current IGS clock products + the FCB product

- IRC-based method is not compatible
  - Users apply the IRC clock products
- But IRC-based method can lead to slightly better positioning quality (at the sub-millimetre to millimetre level), especially in areas with sparse networks

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A real-time integer-PPP implementation: The CNES demonstrator (ppp-wizard)

- CNES has developed a demonstrator based on real-time PPP with ambiguity resolution
  - PPP-WIZARD: Acronym for "*Precise Point Positioning With Integer And Zero-difference Ambiguity Resolution Demonstrator*"
  - Goal: centimeter accuracy in real-time

- 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

- CNES is a real-time IGS analysis center since January 2011
  - GPS products since January 2011 (in official combination since February 2011)
  - GPS+Glonass products since December 2011

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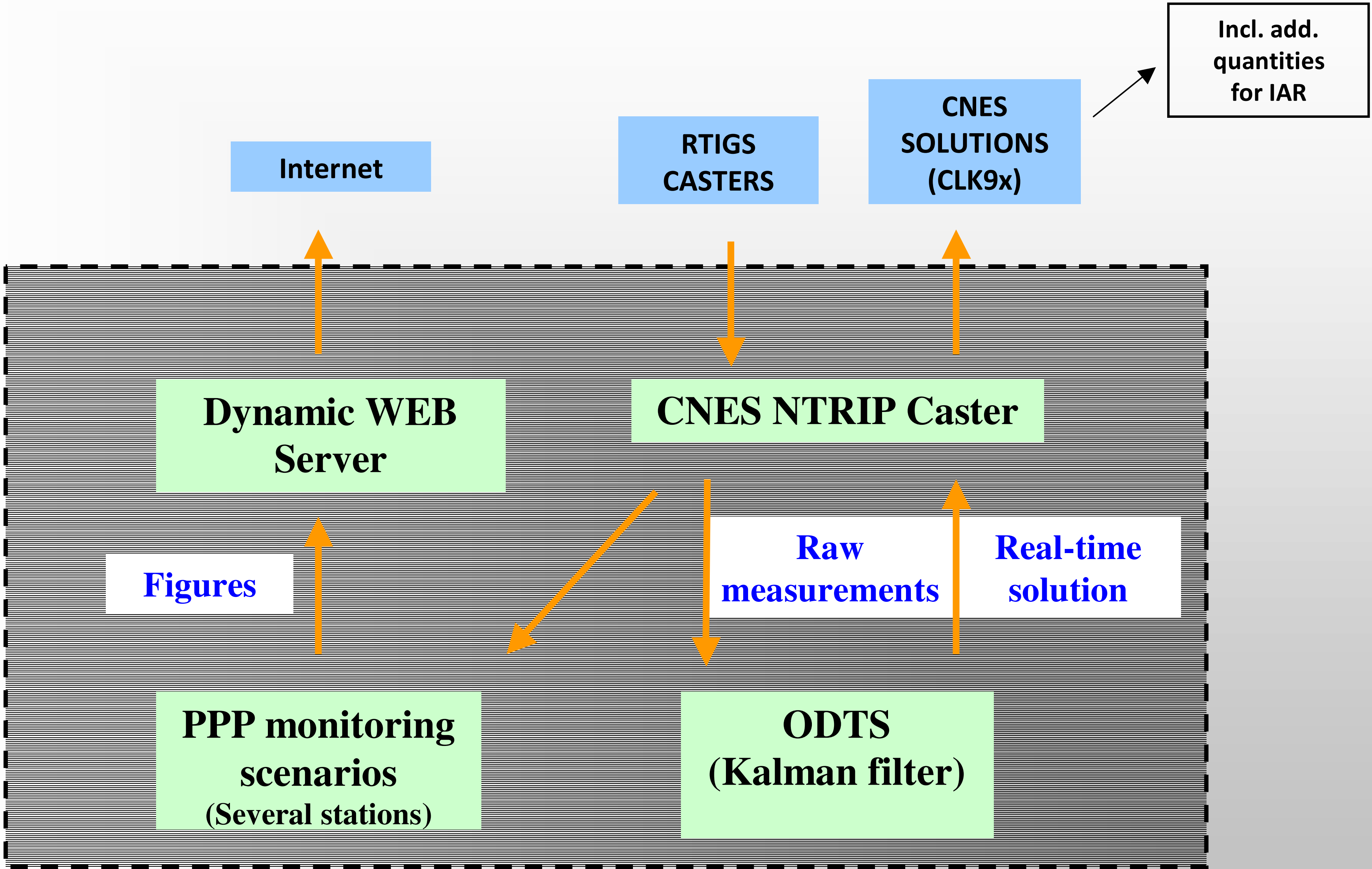
Demonstrator architecture



1 machine running under Linux

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

- ODTS network monitoring & current status updated in real-time.

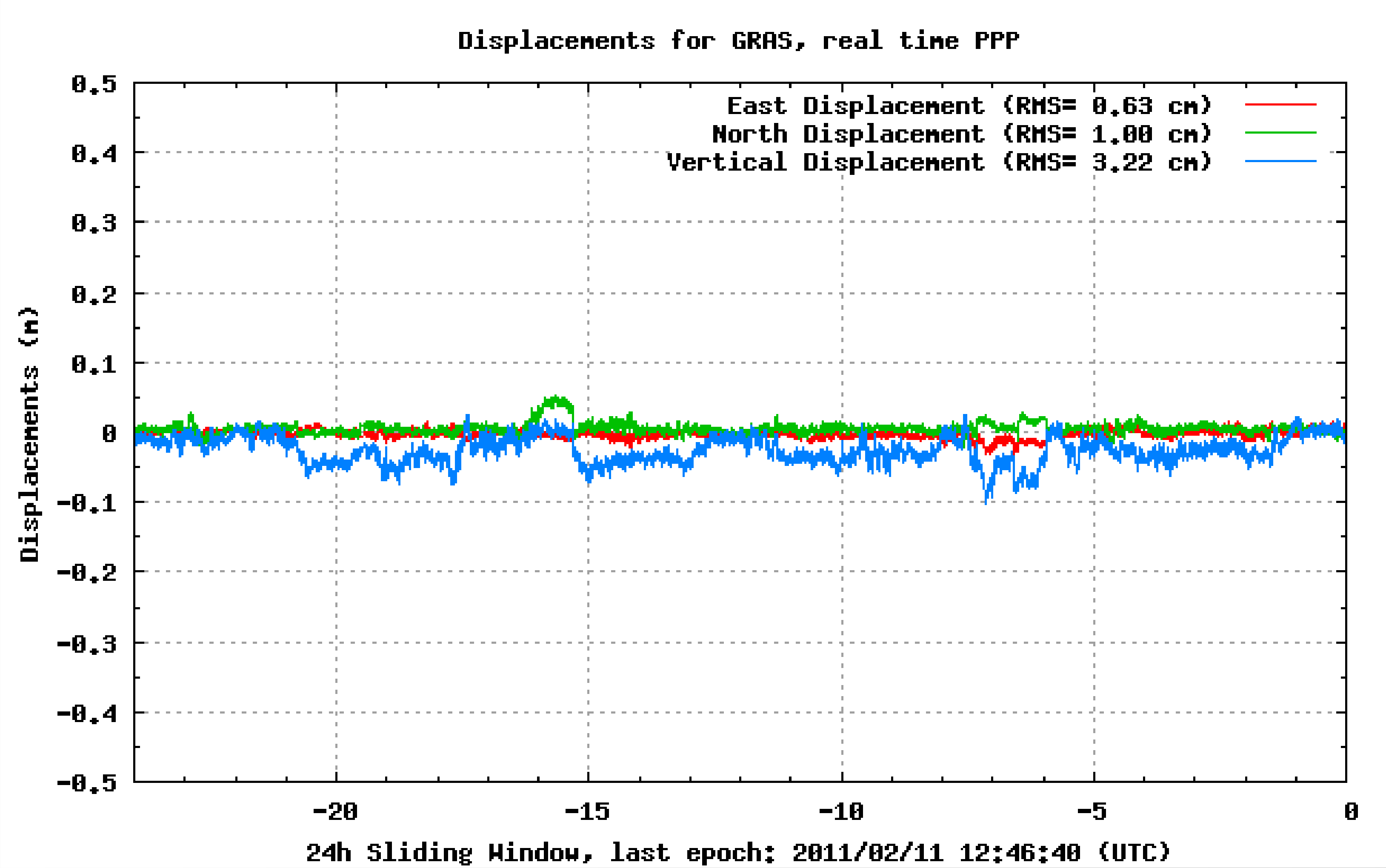
- PPP software modified for real time ambiguity resolution. Freeware, source code available as well as a precompiled version for windows.

- 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.

- 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).

Example of station monitoring using the demonstrator streams



Conclusions

- Introduced methods for integer ambiguity resolution of un-differenced observables
- For integer-PPP, the FCB-based and IRC-based methods agree to within 2 mm for daily position estimates
- FCB-based method outperforms the IRC-based method over dense networks of stations by less than 0.5 mm
- IRC-based method can outperform the FCB-based method over sparse networks by over 1 mm
- Both methods can be implemented in real-time
- Introduced the real-time integer-PPP Demonstrator (1-2cm EN, <10cm U)

Thank you!

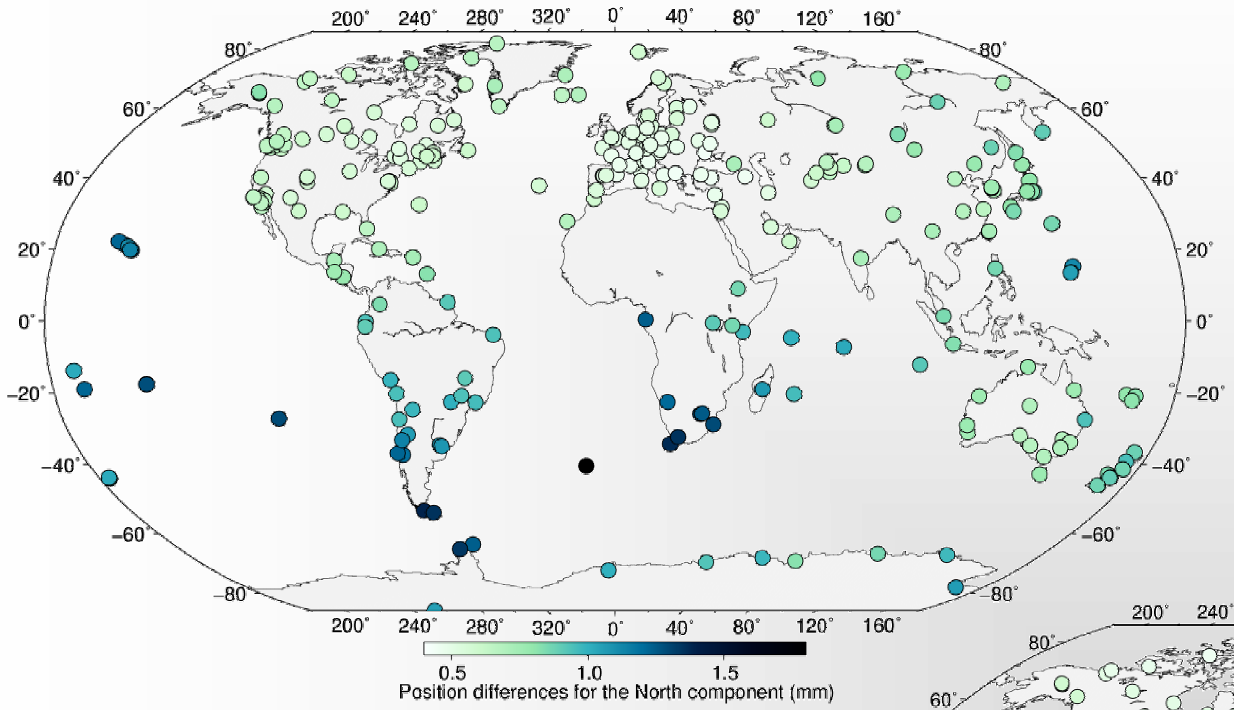
The main publications:

•Geng, J., X. Meng, A. H. Dodson, and F. N. Teferle (2010), *Integer ambiguity resolution in precise point positioning: method comparison*, Journal of Geodesy, 84(9), 569-581.

•Geng, J., F. N. Teferle, X. Meng, and A. H. Dodson (2011)*, Towards PPP-RTK: Ambiguity Resolution in Real-Time Precise Point Positioning*, Advances in Space Research, 47(10), 1664-1673.

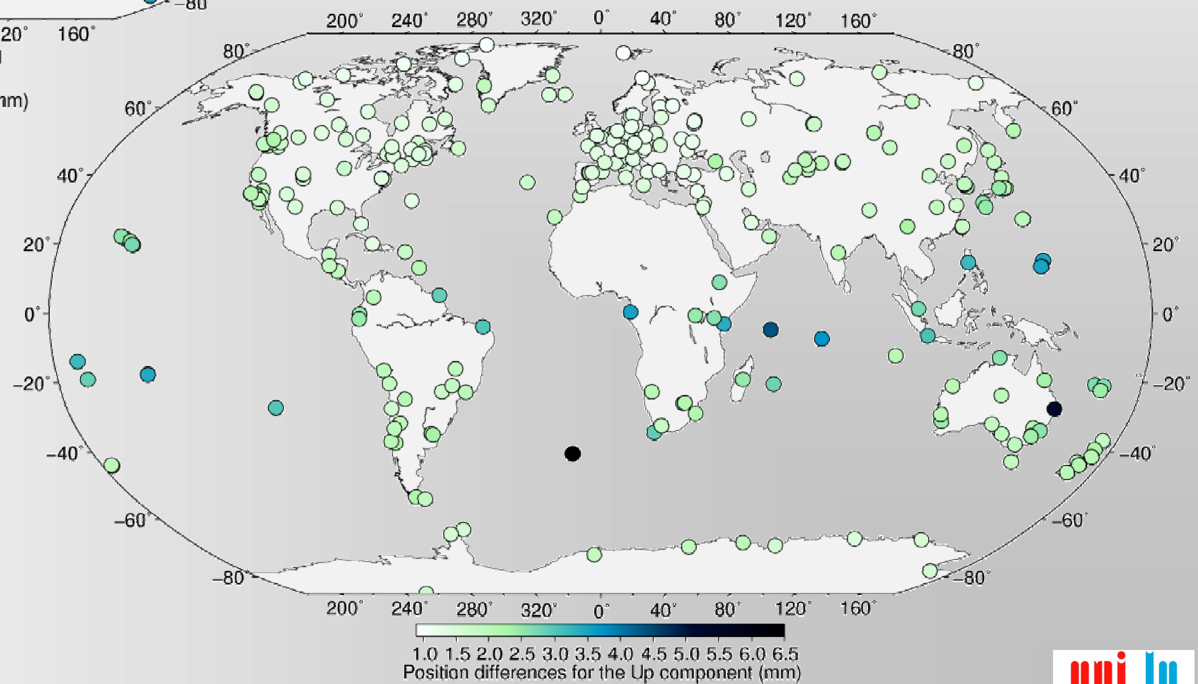
•Laurichesse, D. (2011), The CNES real-time PPP with un-differenced integer ambiguity resolution demonstrator, Proc. 24th Int. Tech. Meet. Sat. Div. ION, ION GNSS 2011, 19-23 September, Portland, USA

Position differences for the North & Up components



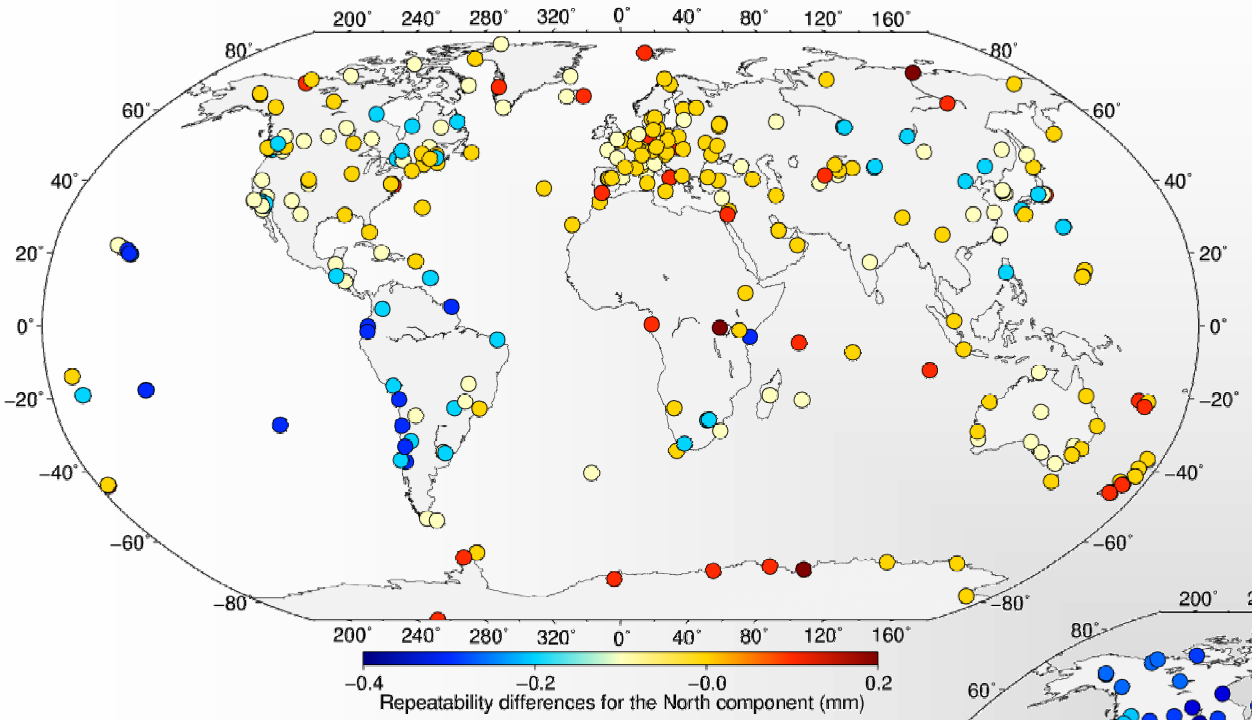
North

Up



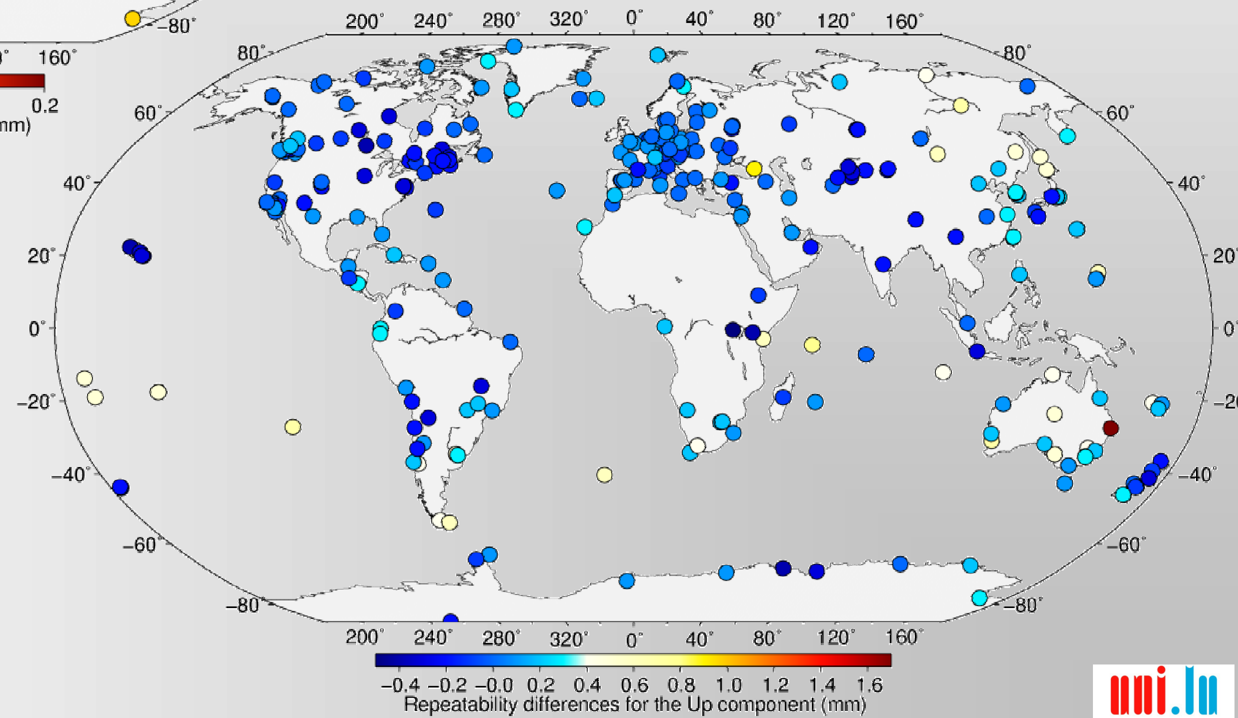
Note the different colour scales!

Position repeatability differences for North and Up components



North

Up



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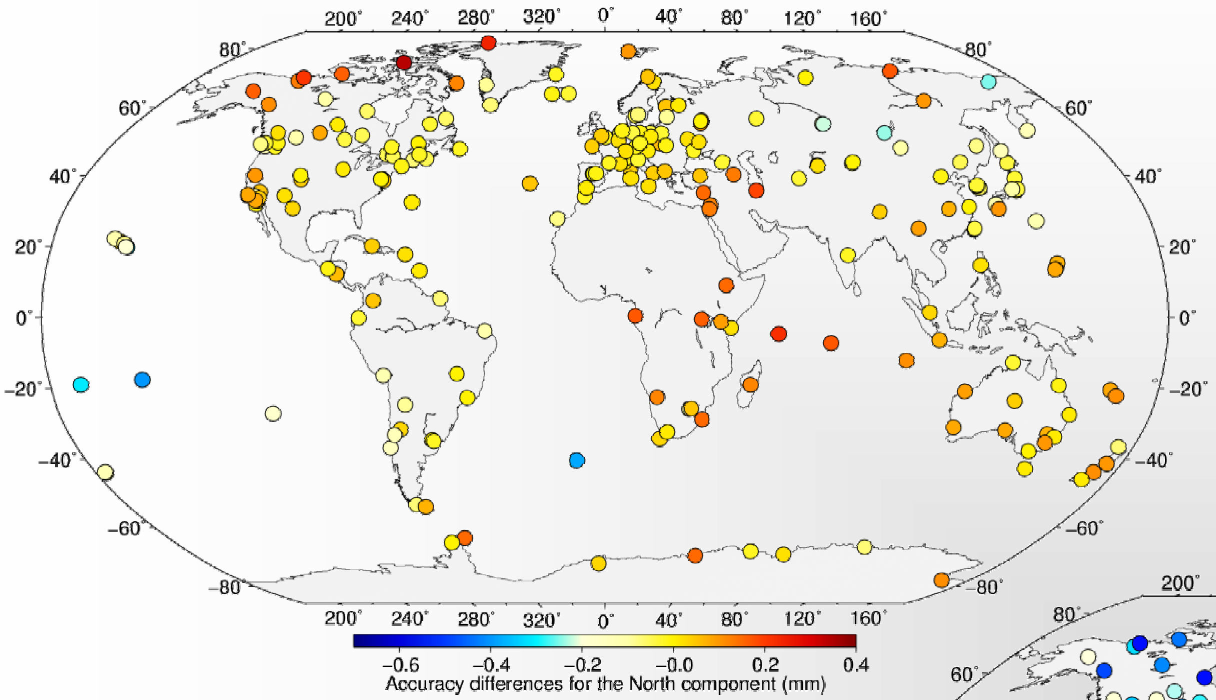
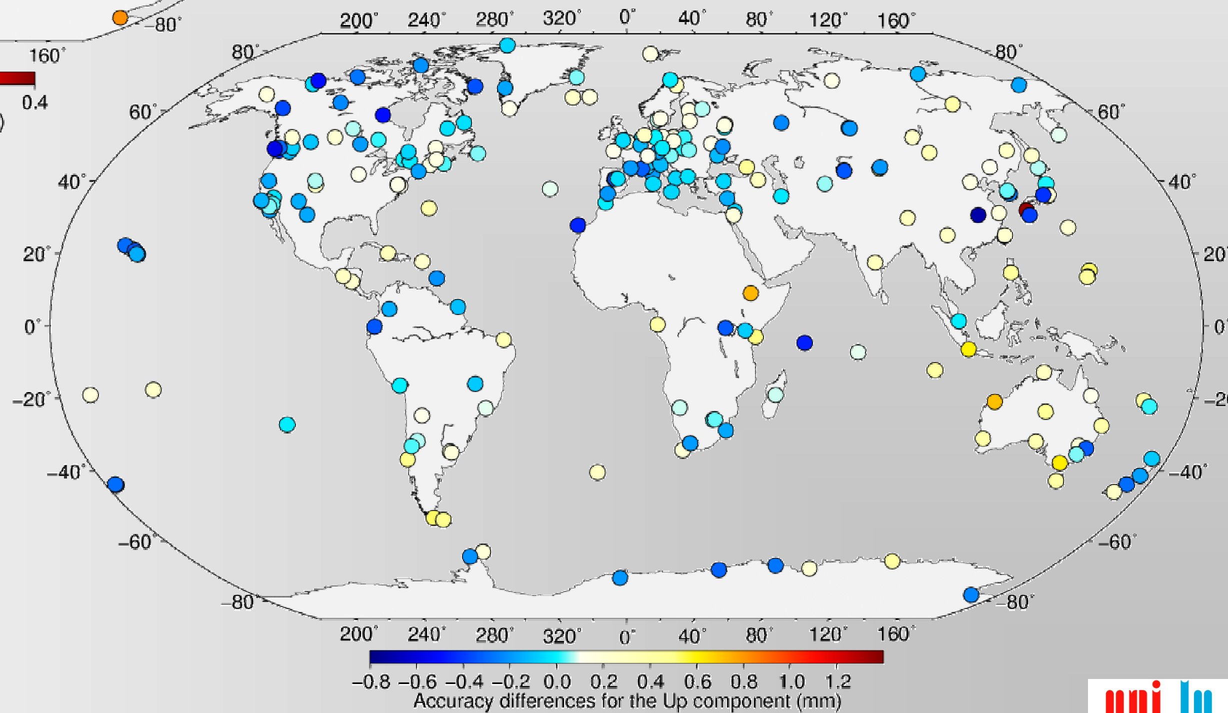
Comparison with IGS weekly solutions: differences in North & Up



North

Up



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