Multi-GNSS Benefits to Real-Time and Long-Term Monitoring Applications

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Advances, Opportunities and Challenges
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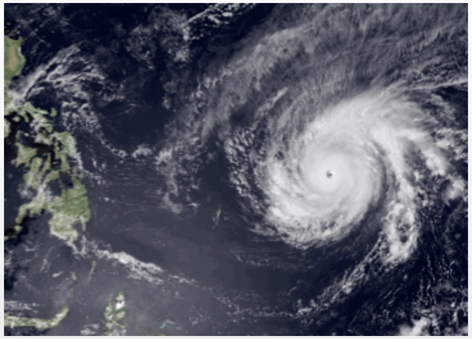
Overview



- Two applications
  - Real-time (RT) zenith total delay (ZTD) estimation using Precise Point Positioning (PPP) with observations from GPS, GLONASS and Galileo
  - Long-term geodetic monitoring of geophysical signals and time series analysis with observations from GPS and GLONASS
- Conclusions

China steps up flood rescue in Wuhan

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The local football team's stadium has been completely flooded

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Features

Previous RT ZTD Comparison Results

- Evaluated several RT software packages (BNC, PPP-Wizard, G-nut/Tefnut)
- see **Ahmed et al. (2016) GPS Sol**
- Contributions to the COST Action GNSS4SWEC RT Campaign
- Similar work was reported by Yuan et al. (2014) and Li et al. (2015)

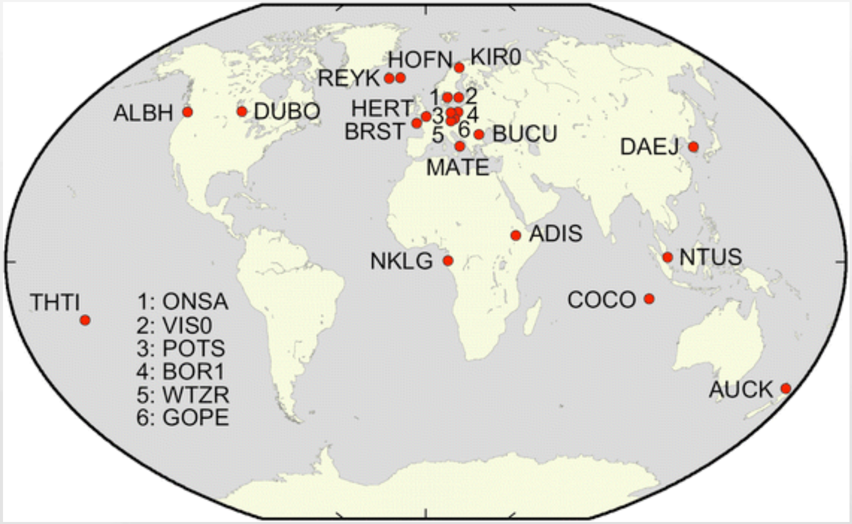


Table 7 Biases in RT-PPP ZTD solutions to IGFT

Solution	Mean [cm]	STD [cm]	RMS [cm]
BN01	3.17	4.61	6.04
BN02	0.46	2.72	2.92
PWFL	6.81	2.42	14.96
GN01	1.16	0.82	1.43
GN02	1.11	0.80	1.38

Largely due to
no PCO corrections
In PPP-Wizard

PPP-Wizard Modifications

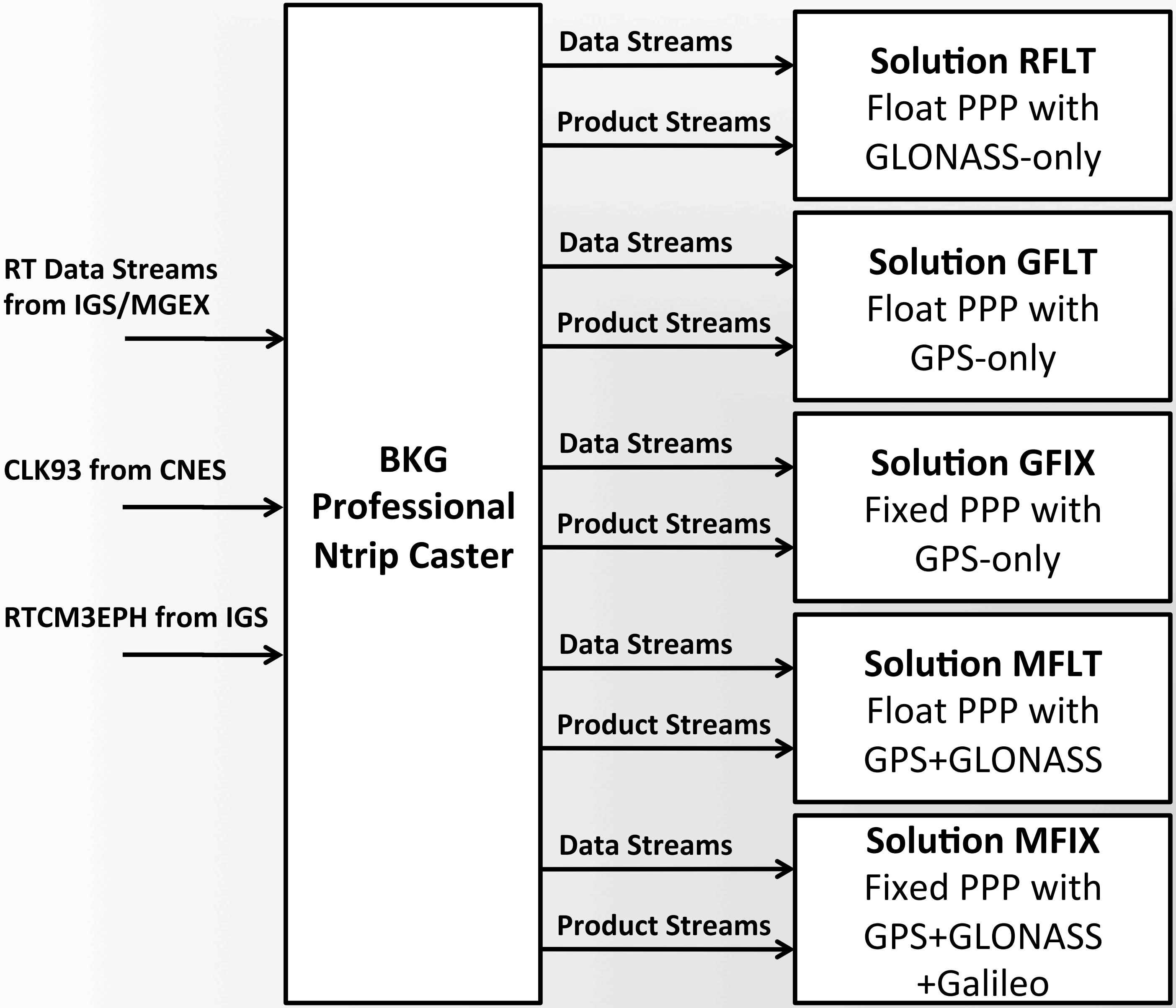
PPP-Wizard developed by CNES

- GPS/GLONASS/Galileo observations
- Real-time products from CNES CLK93, including satellite orbit, clock and code/phase biases
- PPP ambiguity resolution (GPS only) [zero-difference ambiguity resolution]

Modifications

- Apply Antenna Reference Point (ARP) correction from igs08.atx
- Apply receiver PCO + PCV correction from igs08.atx
- Solid earth tide + ocean tide loading correction (FES2004)
- ZTD (GPT and Saastamoinen) + ZWD (modeled as random walk process)
- Troposphere Mapping Function (GMF)
- Elevation dependent weighting strategy (Q = 1/cos(zen)**2)

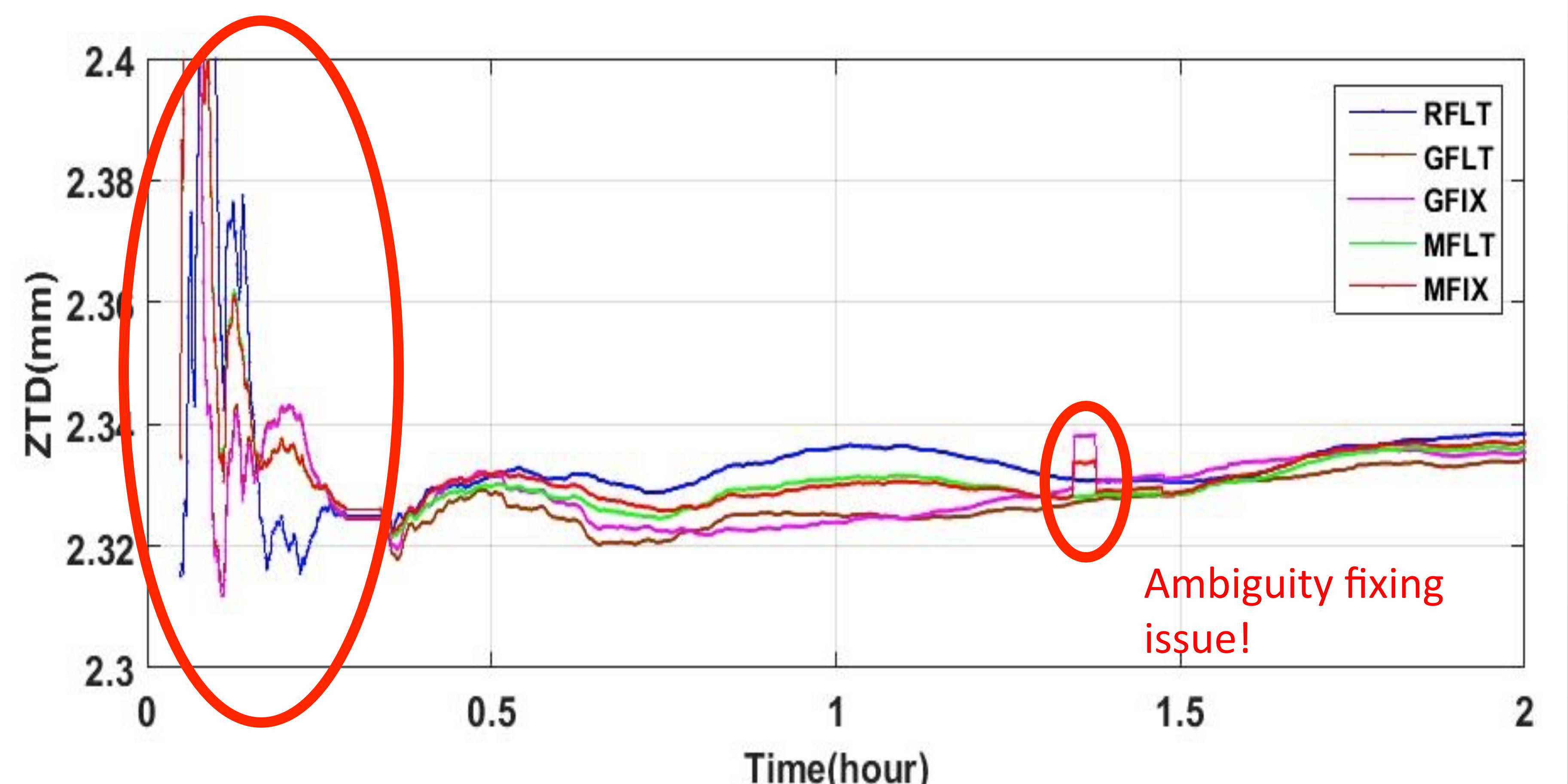
True RT ZTD Systems Test: Feb-Mar 2016



Other settings:

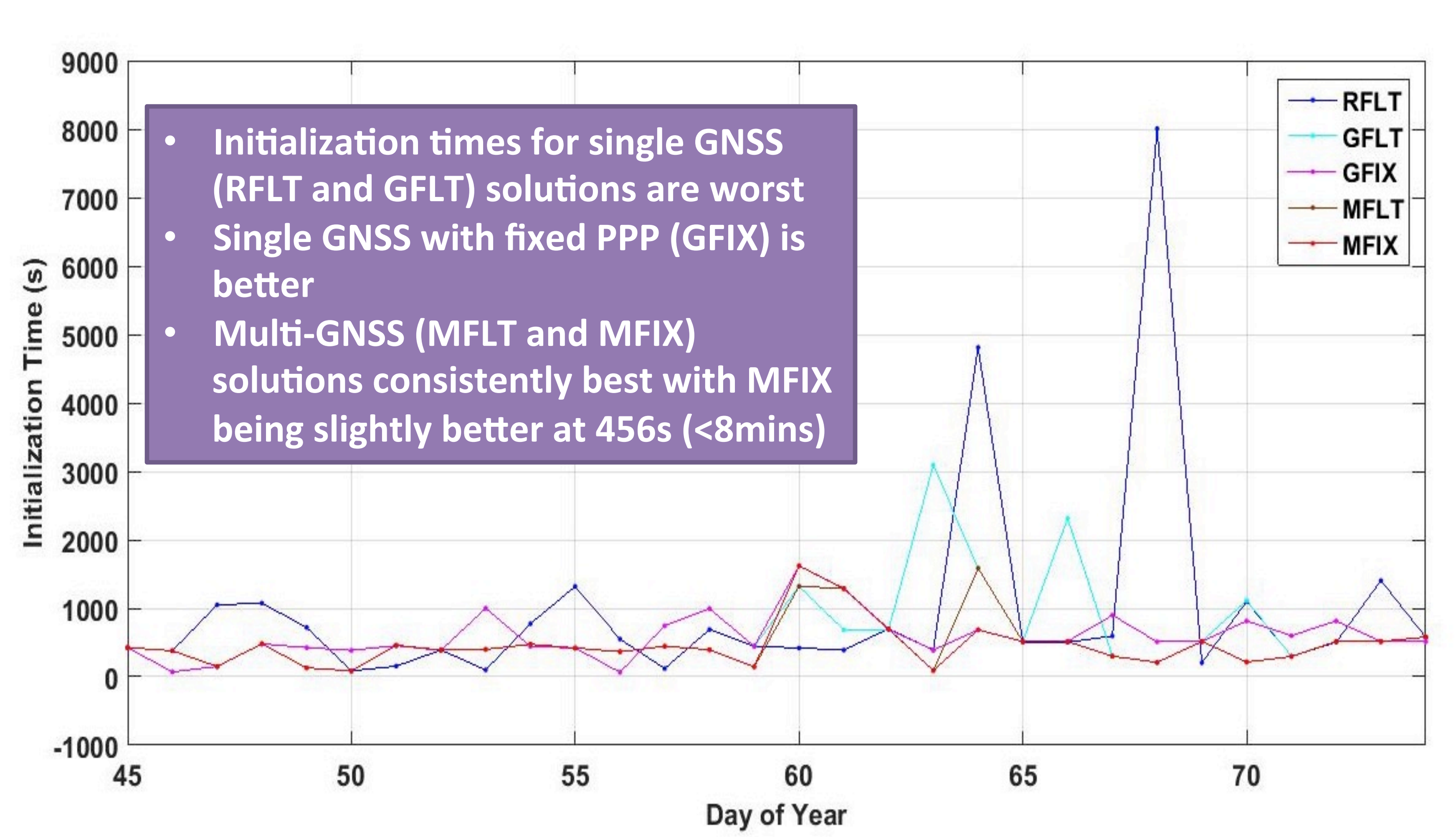
- 14/2-14/3 2016
- 7° elevation cut-off
- Internal evaluation using CODE and USNO final troposphere products
- External evaluation using integrated ZTD from radiosonde observations

Example RT ZTD for station BRST (DoY 45, first two hours after reset)



We considered the initialization completed once the error in the troposphere results becomes and remains smaller than the threshold of 20 mm within a 1.5-hour window.

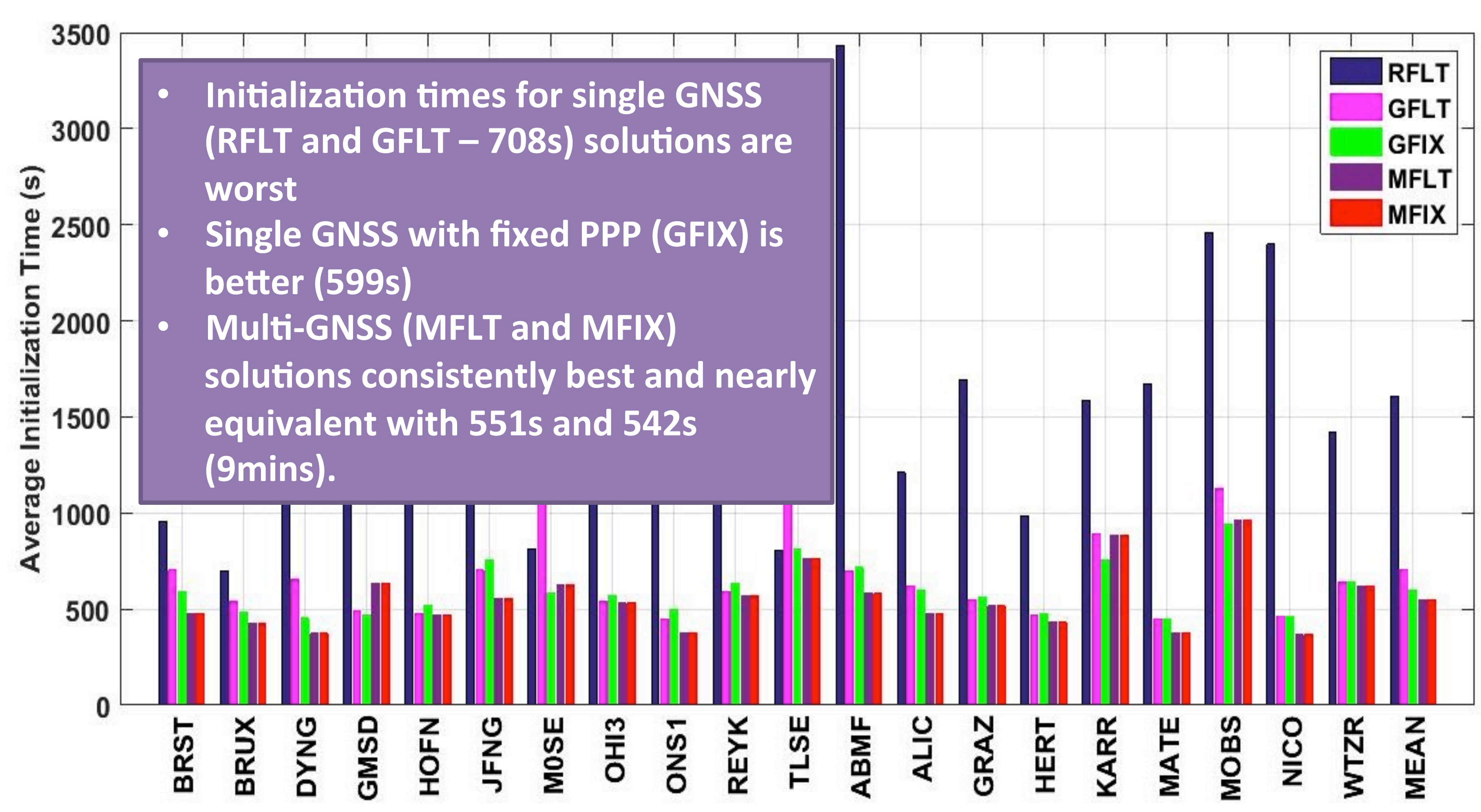
Example Initialization Time for BRST (DoYs 45-75)



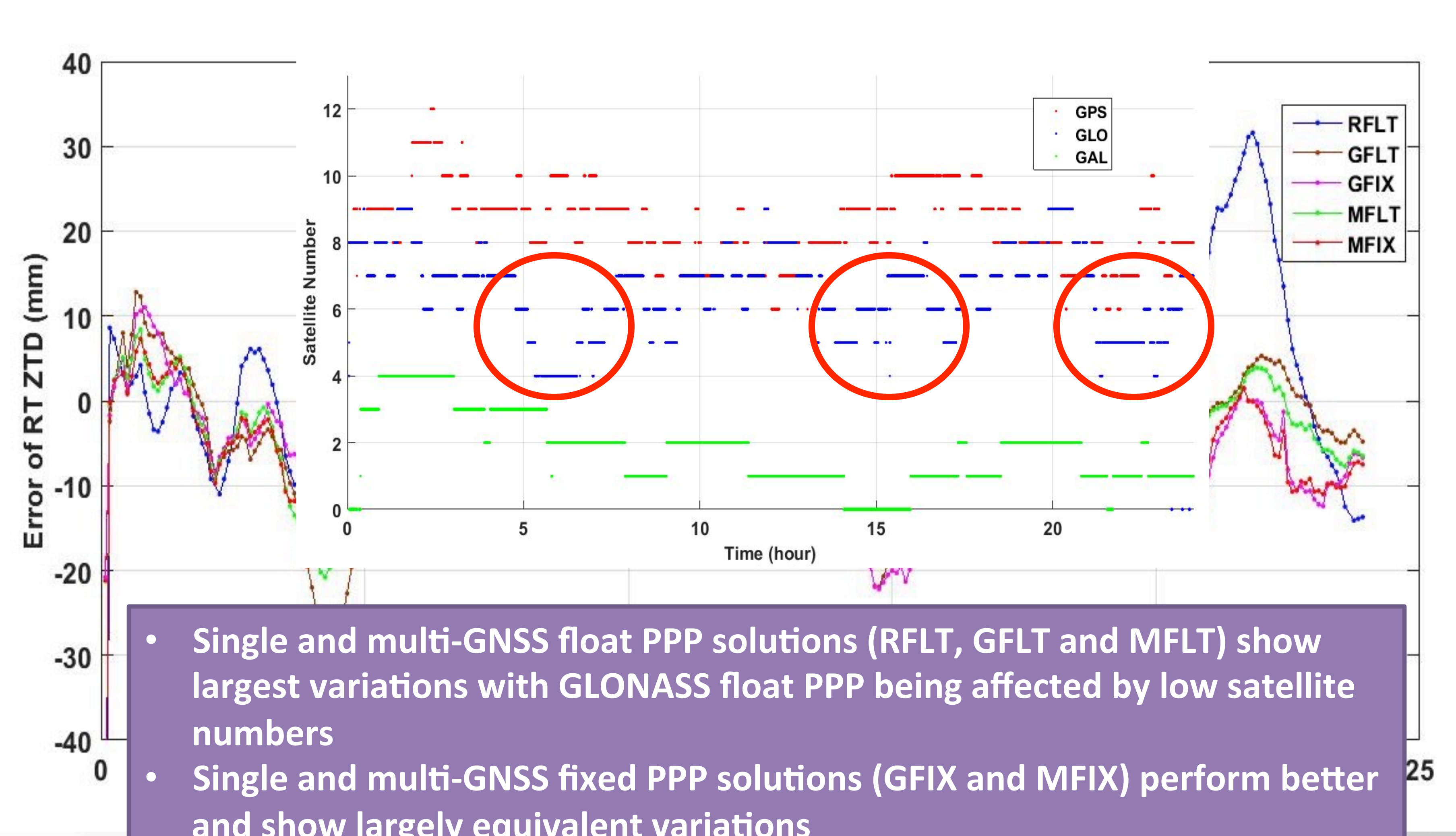
- Initialization times for single GNSS (RFLT and GFLT) solutions are worst
- Single GNSS with fixed PPP (GFIX) is better
- Multi-GNSS (MFLT and MFIX) solutions consistently best with MFIX being slightly better at 456s (<8mins)

Initialization Times for All Stations

- Initialization times for single GNSS (RFLT and GFLT – 708s) solutions are worst
- Single GNSS with fixed PPP (GFIX) is better (599s)
- Multi-GNSS (MFLT and MFIX) solutions consistently best and nearly equivalent with 551s and 542s (9mins).



Example RT ZTD Error for BRST
(DoY 45, difference to USNO final tropo product)



- Single and multi-GNSS float PPP solutions (RFLT, GFLT and MFLT) show largest variations with GLONASS float PPP being affected by low satellite numbers
- Single and multi-GNSS fixed PPP solutions (GFIX and MFIX) perform better and show largely equivalent variations

RT ZTD Error Summary (Internal Evaluation using CODE and USNO)

	CODE			USNO		
	Mean(mm)	STD(mm)	RMS(mm)	Mean(mm)	STD(mm)	RMS(mm)
RFLT	1.22	13.54	13.99	0.81	13.73	14.0
GFLT	-0.62	7.81	8.69	0.11	8.46	9.22
GFIX	-2.34	6.93	7.75	-1.65	7.57	8.26
MFLT	-0.27	7.84	8.41	0.06	8.38	8.84
MFIX	-1.63	7.25	7.78	-1.26	7.78	8.20

- GLONASS-only float solution is worst; GPS-only float solution is better
- Biases (mean differences) are at +/-2 mm level
- GPS-only (fixed PPP) and multi-GNSS solutions (float and fixed PPP) are fairly equivalent but both fixed PPP solutions (GFIX and MFIX) are slightly better
- All solutions meet threshold user requirements and all but GLONASS-only solution approach the target user requirements

Meteorology User Requirements

6 mm – target accuracy

30 mm – threshold accuracy

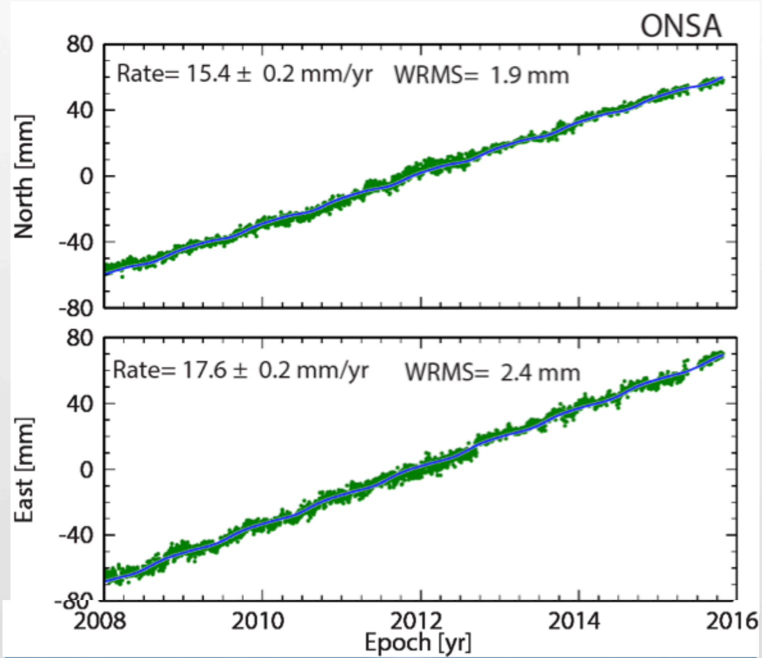
Long-term Geodetic Monitoring using GNSS

GNSS Coordinate Time Series

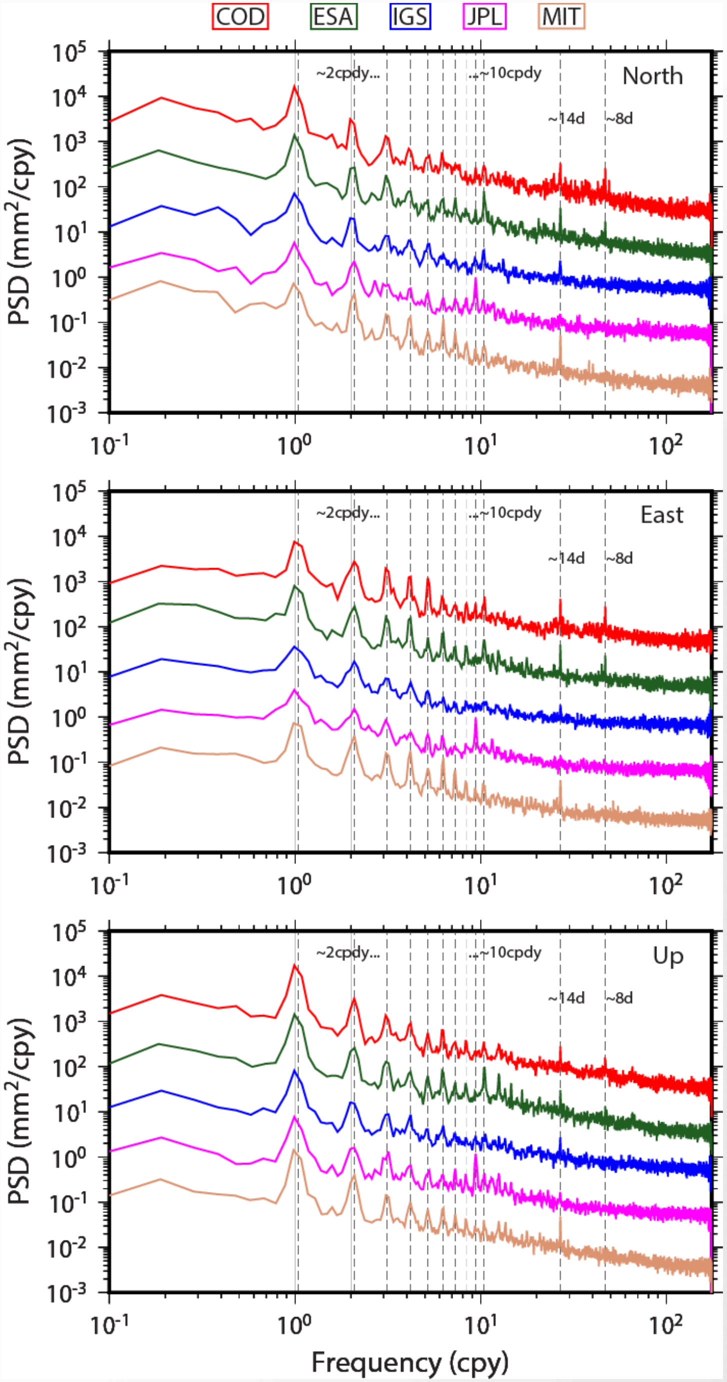
- Fundamental to many geodetic and geophysical applications
  - sea level studies
  - constraints on geophysical models
- Non-linear/periodic motions
  - Real geophysical signals
  - Technical errors, un-modelled effects
- Subtle geophysical signals?

Known periodic signals

- Annual and semi-annual signals
- Draconitic signals and harmonics
  - GPS -> 351.2 days and its fractions 351.22/n, n=2,..
  - GLONASS -> 353.2 days and its fractions 353.2/n, n=2,..
  - Fortnightly (direct-13.63/aliased-14.7)
  - 8-day Period -> GLONASS-specific



Stacked Spectra of PPP Coordinate Time Series

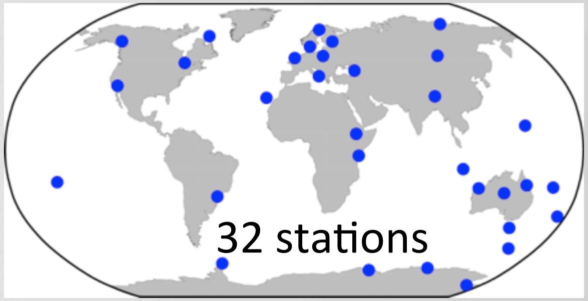


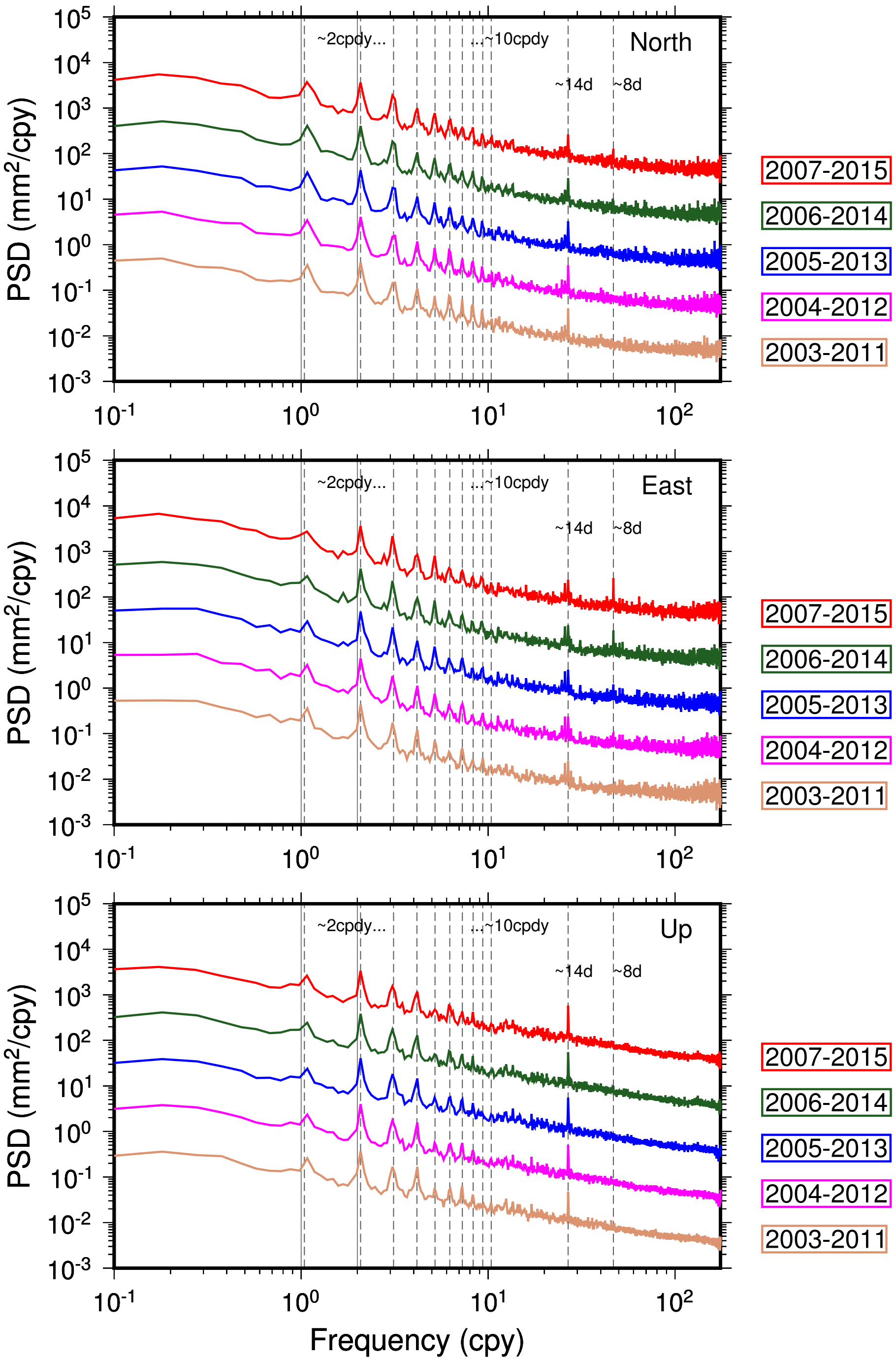
Approach

- PPP solutions based on GPS-only data and products from CODE, ESA, IGS, JPL and MIT
- All solutions computed using the same settings and models except for the products
- Spectra of coordinates for all stations, stacked and smoothed

Main features

- Overall, similar to previous solutions (periods, noise character), but …
- No-fortnightly period in JPL-based PPP
- 8-day period in CODE- and ESA-based PPP
- Are the GPS orbits containing GLONASS-specific frequencies?





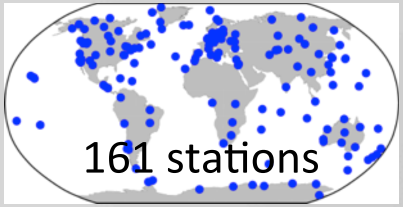
Is the 8-day period in the GPS-only solution GLONASS-specific?

Approach:

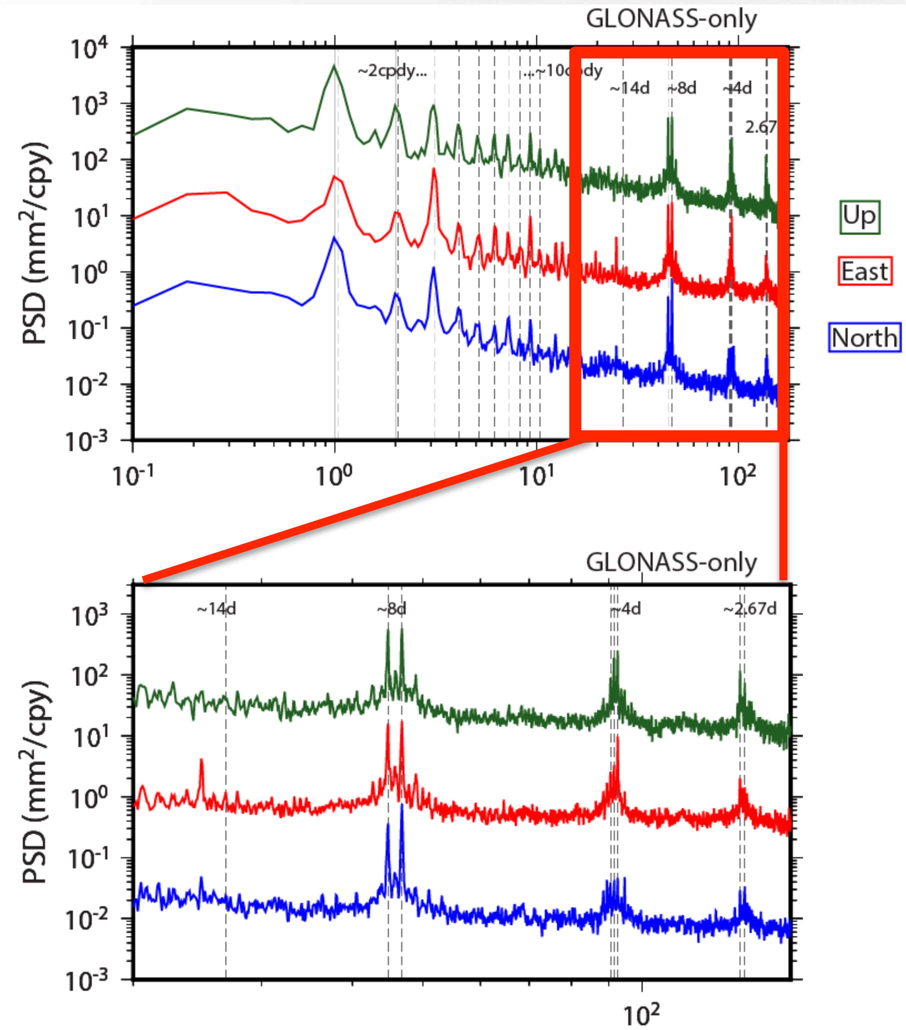
- 161 selected stations from global DD network solution including 700+ stations
- CODE (repro2+operational) products, used GPS-only observations
- Spectra of coordinates for all stations, stacked and smoothed for 9-year windows

Main features:

- All draconitics and fortnightly signals are consistent in the defined windows
- 8-day period is
  - faint in all components for early windows
  - Shows up in later windows (horizontal components)
  - Strong in East (ambiguity issues?)
  - Faint in Up



Stacked Spectra of Coordinate Time Series, GLONASS-only



Approach

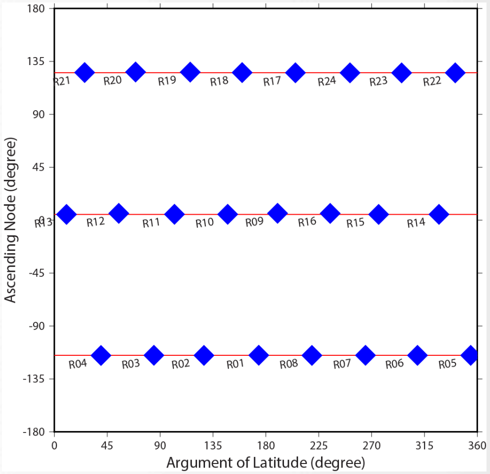
- PPP solution based on GLONASS-only products from ESA
- Spectra of coordinates for all stations, stacked and smoothed

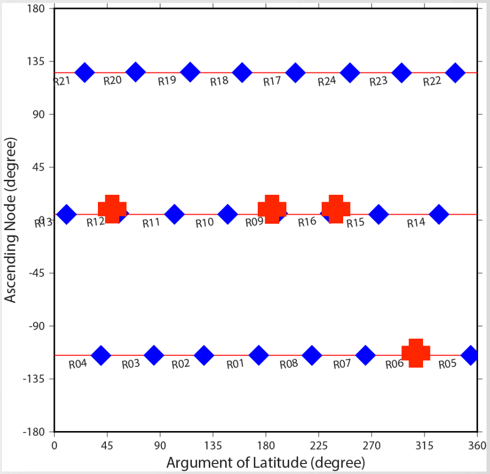
Main features

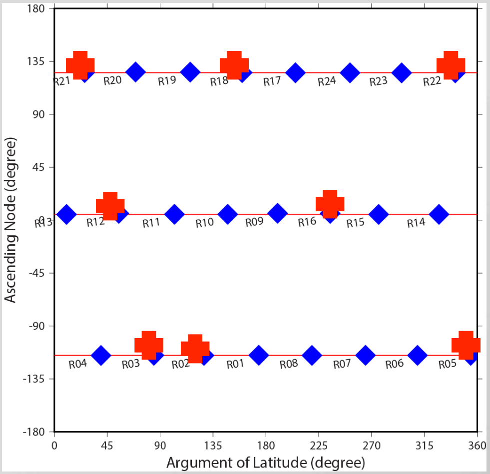
- Draconitic and its harmonics
- Elevated 3rd draconitic (~120-day period)
- 8-day period and its harmonics (very clear)
- Fortnightly signal doesn't exist
  - Due to Shallow resonance of GLONASS?
  - Absorption effect?
- Why is there a series of spikes in the 8-day period and its harmonics?

Does the GLONASS Constellation Gap Contribute to the Powers?

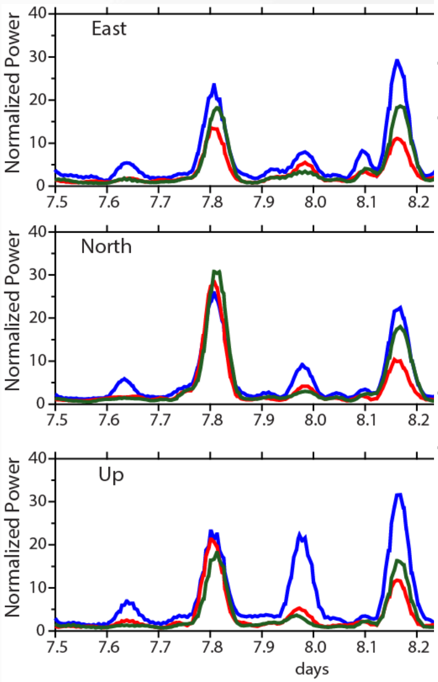
- GLONASS-Constellation was incomplete before October 2011: 16 satellite 2008-2010; 20 satellites 2010-2011.
- The gap contributing to the powers on some of the frequencies?
- Compare power spectra before and after the constellation is complete
- Unfair comparison due to equipment changes, data gaps and orbit accuracy differences
- **Three GLONASS-only PPP Solutions for 2012-2015 with 24, 20 and 16 satellites using ESA products**
- All solutions with the same settings and models except for the number of satellites

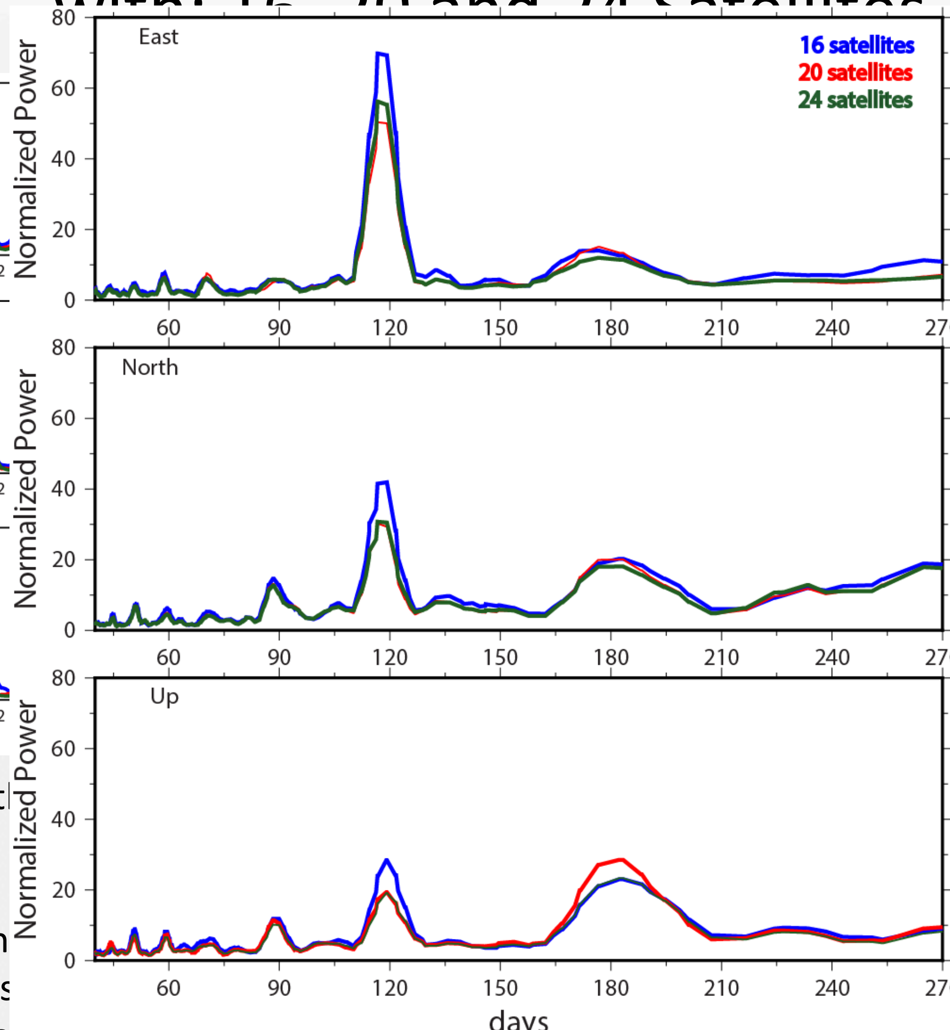


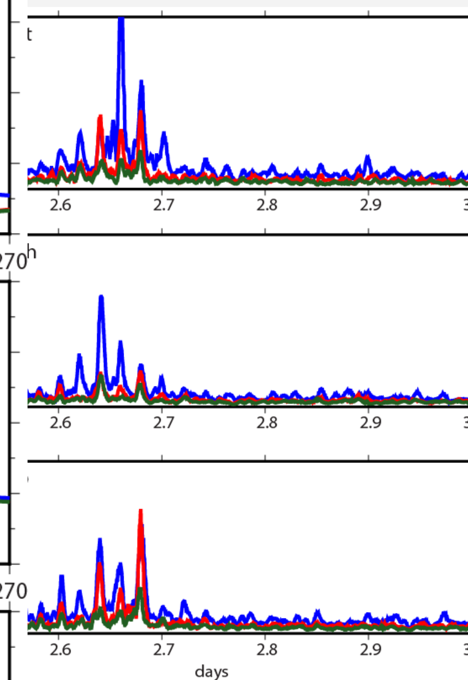




Stacked spectra of Coordinate Time Series for Solutions with: 16, 20 and 24 Satellites





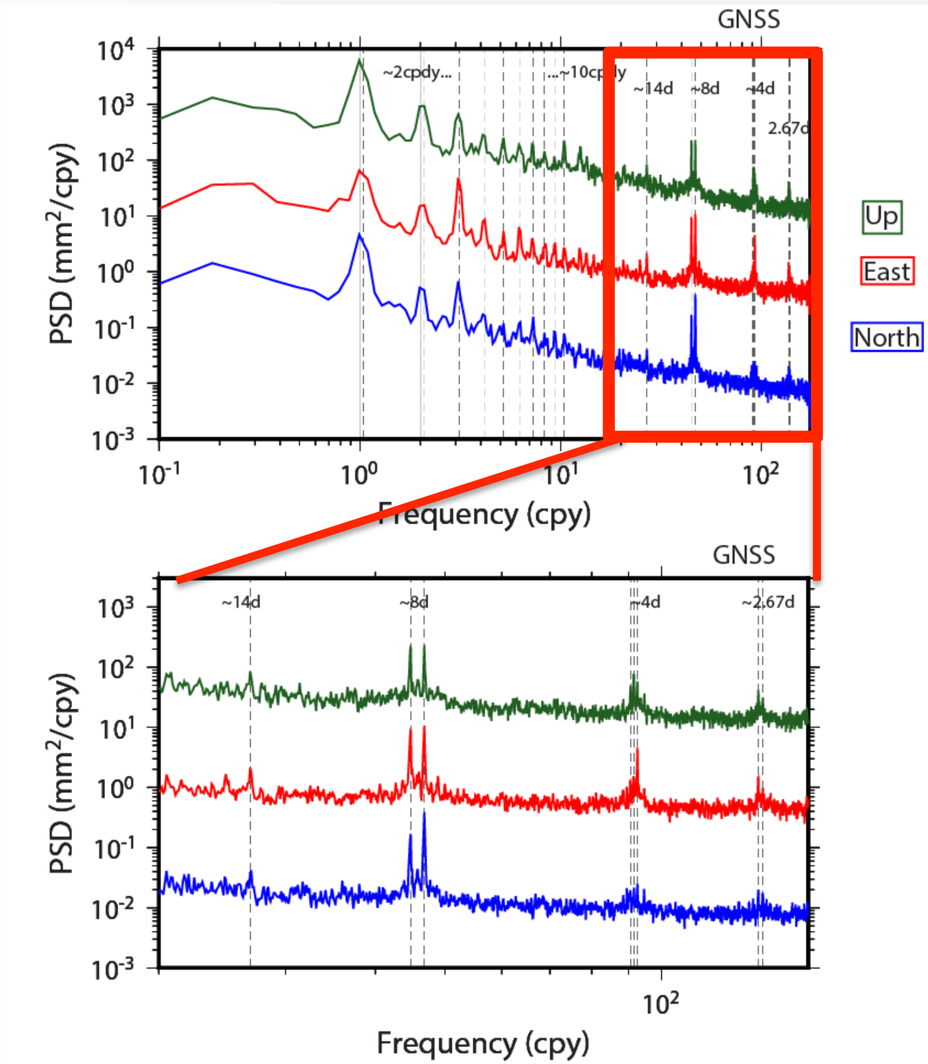


Smoot… …igh freq.)

Main Results

- The 8-day period an…
- The 7.8-day period s…
- The constellation ga… …4 day and 2.67 day periods
- The ~120-day period also affected (23% reduction using 24 satellites compared to 16)
- The signals are not fully gone with the full constellation but highly reduced

Combined GPS + GLONASS Solution



Approach

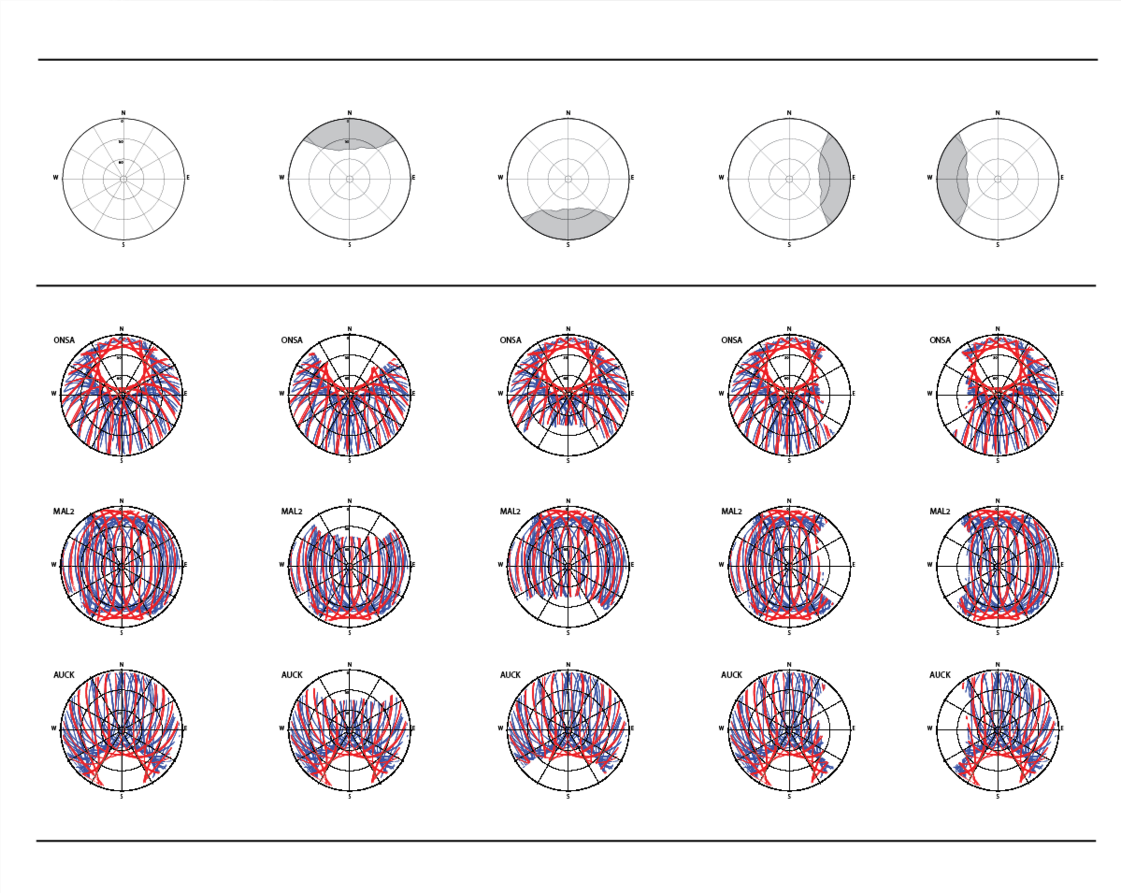
- PPP solutions based on GPS+GLONASS products from ESA
- Spectra of coordinates for all stations, stacked and smoothed

Main features

- Power reduction, nearly all frequencies
- GLONASS is more benefited
- The reason for reduced power of fortnightly for CODE, ESA in repro2

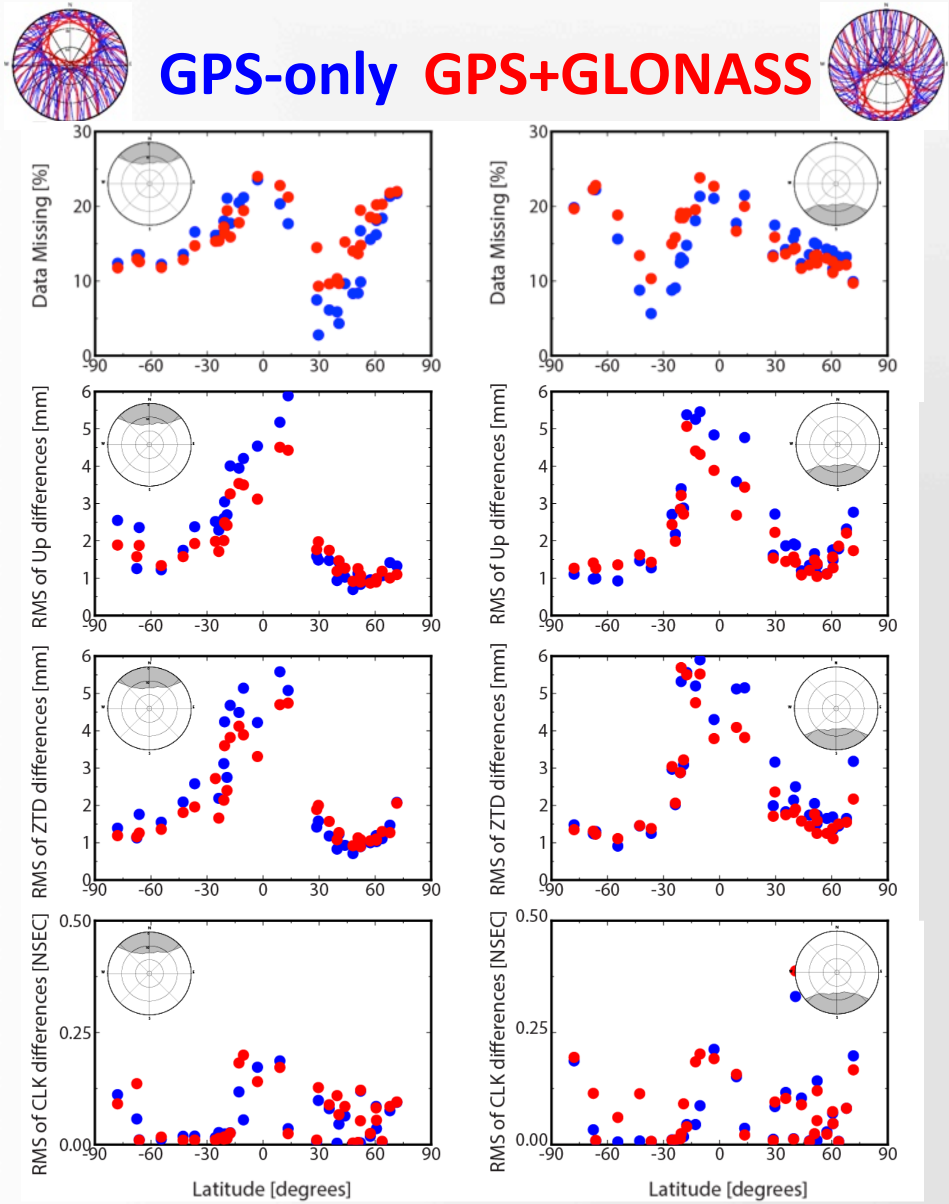
Power Reduction (%)						
	GPS			GLONASS		
period	North	East	Up	North	East	Up
1 cpdy	-29.0	37.9	1.2	20.8	0.7	7.0
2 cpdy	23.8	60.5	21.1	15.8	16.1	35.4
3 cpdy	-51.5	-128.8	-8.8	63.3	48.5	59.3
4 cpdy	12.4	58.8	6.6	39.1	15.9	58.0
5 cpdy	12.7	29.8	7.3	29.2	30.0	49.1
6 cpdy	13.9	42.0	44.0	22.6	52.7	63.2
7 cpdy	-11.3	31.5	3.98	31.7	63.8	63.0
8 cpdy	11.2	29.8	27.4	8.5	46.3	2.73
13.63 days	52.0	52.2	36.7			

Multi-GNSS at Stations with Signal Obstructions?



- Signal Obstructions simulated in North – South – East – West directions
- PPP solutions computed with and without obstructions
- Differences in the parameter estimates computed
  - Station coordinates
  - Troposphere parameters
  - Receiver clock corrections
- The differences reveal the effects of the obstructions
- The simulated obstructions cause 10-25 % of missing data (moderate to severe effects)

Effects of Signal Obstructions



Data Missing

- Latitude-dependency effects from North and South obstructions scenarios
- 10-25% of missing data

Up component

- Latitude-dependency effects from North and South obstructions scenarios
- Benefits from the combined solution with lower RMS

ZTD

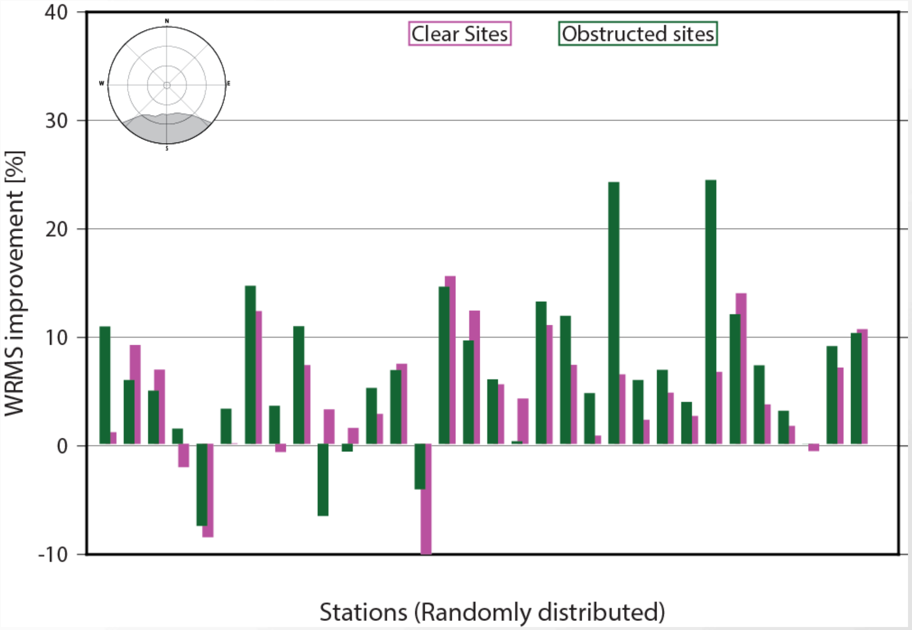
- Similar feature as Up component
- Correlation with the Up component
- Benefits from the combined solution with lower RMS

Receiver CLK

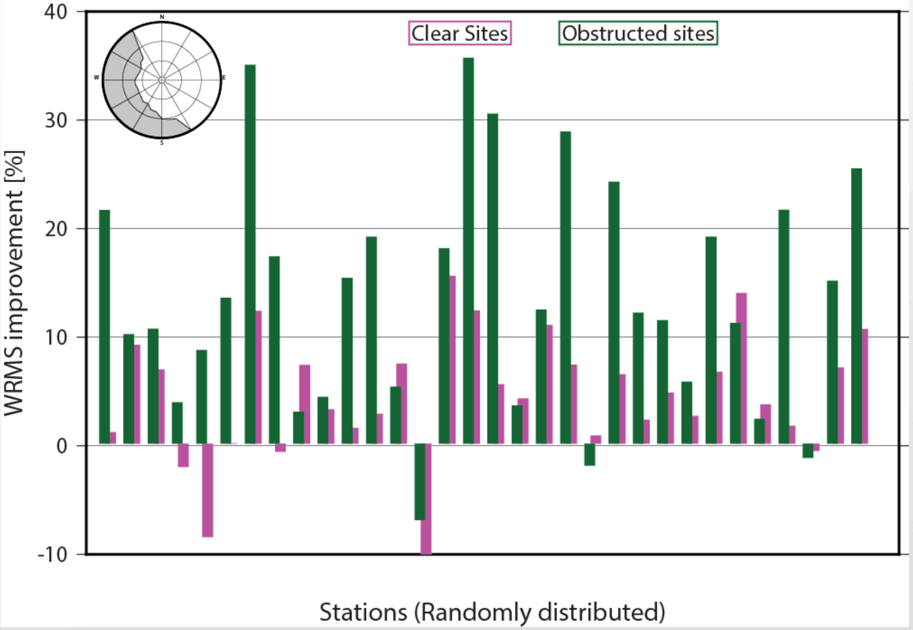
- Less dependent on latitude
- Less affected

WRMS Improvements for GPS+GLONASS Solutions

10-25 % missing data



27-42 % missing data

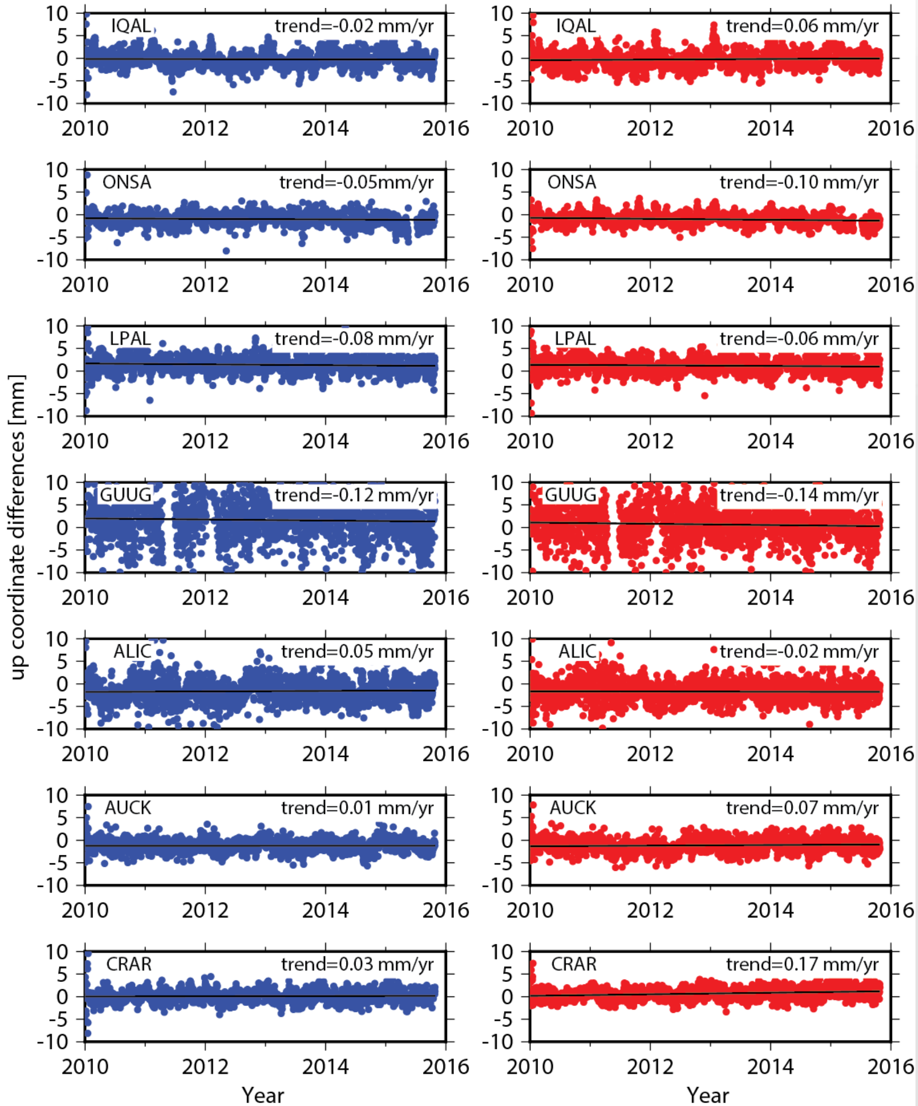


- Benefits of GPS+GLONASS solution for stations with both clear and obstructed scenarios
  - Obstructed stations show larger improvements
  - Improvements increase for more severe obstructions

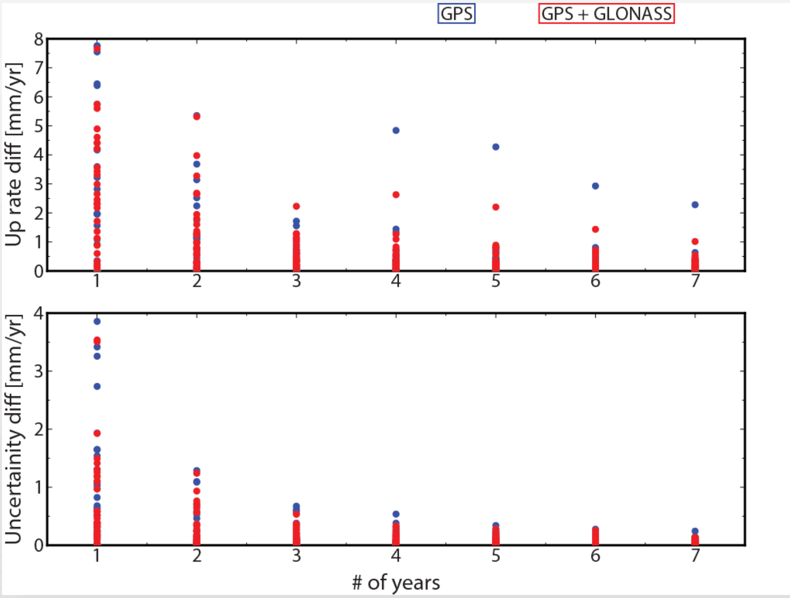
Long-term Time Series & Rate Effects

Up coordinate differences

GPS-only **GPS+GLONASS**



Up rate differences



Up coordinate differences

- Less scatter for the combined solution

Up rate differences

- Range between 0.02 to 0.6 mm/yr are evident for series of 7 years
- Reach 1-2 mm/yr for more severe obstructions (not shown)
- Are large over short periods and combined solution is more beneficial

Conclusions

- In general GNSS solutions benefit from the larger number of observations and improved geometry of multi-GNSS
- For real-time PPP, resolving the integer ambiguities and the use of multi-GNSS reduce the initialization/ re-initialization times, should improve accuracy and add robustness to the solutions
- For long-term monitoring, multi-GNSS reduces GNSS-specific technical signals, helps our understanding of various biases and their sources, while they also provide some remedy for stations with strong-geometry effects (multipath and obstructions)

Thank you for your attention!

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