GNSS and VLBI integrated processing at the observation level

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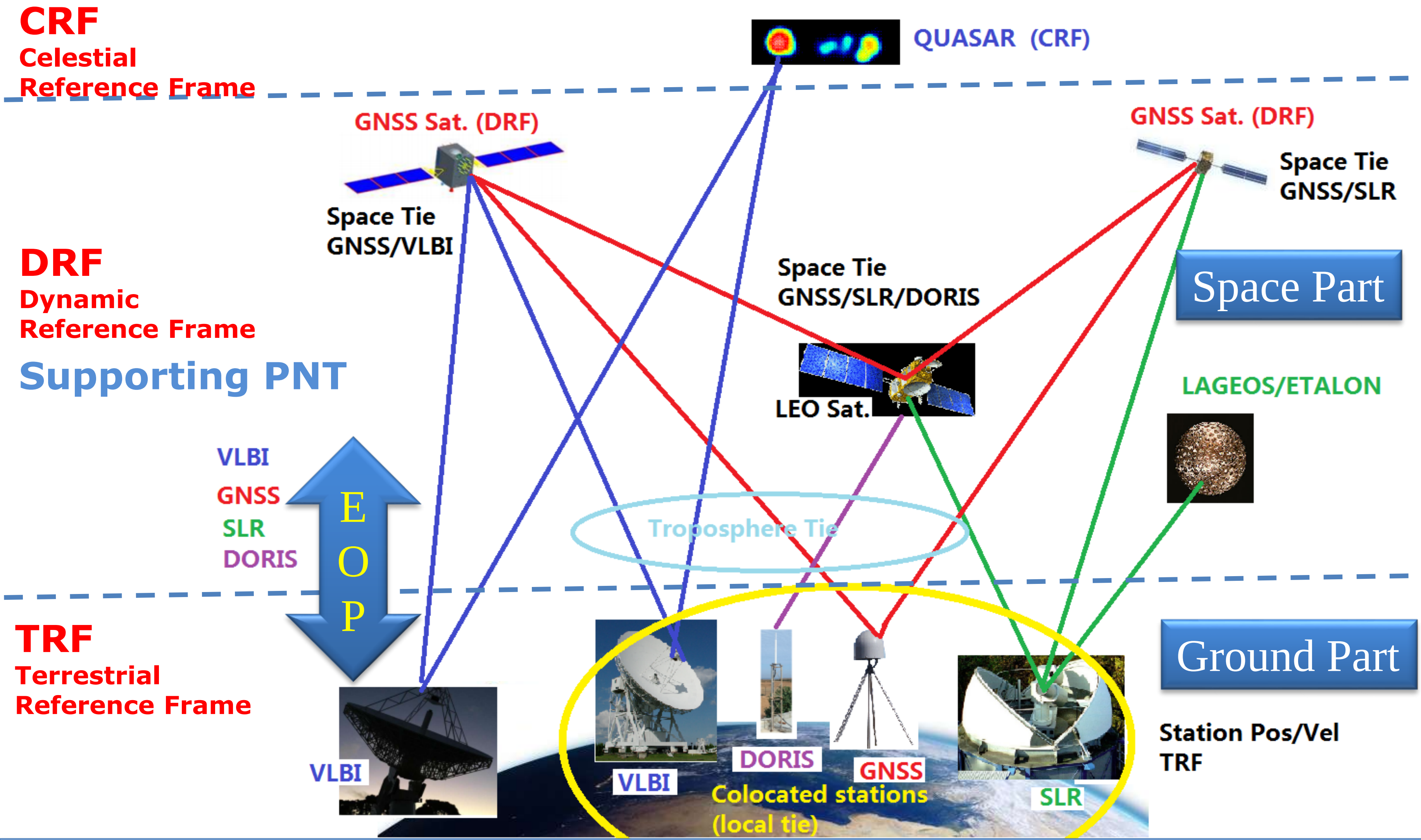
Outline

- Background and motivation
- Current status of the VLBI implementation
- Troposphere parameter bias between GNSS and VLBI
- Integration of VLBI INT sessions and GNSS PPP
  - Improving the UT1 estimates in VLBI Intensive (INT) sessions with the integration of GNSS Precise Point Positioning (PPP)
- Integration of VLBI CONT sessions and GNSS PPP
  - Improving coordinate estimates and EOP accuracy in Continuous (CONT) campaigns by ZTD tie, gradient tie, and local tie
- Conclusions and future work

Motivation: Space Geodetic Techniques



VLBI, GNSS, SLR, and DORIS are the four space geodetic techniques that determine the TRF, CRF, DRF, and EOP, which are supporting daily Positioning, Navigation and Timing.

EOP: Earth Orientation Parameter; VLBI: Very Long Baseline Interferometry; GNSS: Global Navigation Satellite System; SLR: Satellite Laser Ranging; DORIS: Doppler Orbitography and Radio-positioning Integrated by Satellite

Motivation: Consistent Reference Frame

		GNSS	VLBI	SLR	
Quasar	Coordinate		X		
Satellite	Orbit	X	**(X)**	X	Space Tie
EOP	Polar Motion	X	**X**	X	
	Nutation		**X**		EOP Tie
	dUT1		**X**		
	LOD	X	**X**	X	
Atmosphere	Troposphere	X	X		Trop. Tie
	Ionosphere	X	X		
Receiver	Coordinate	X	X	X	**Local Tie**
	Clock	X	X		Clock Tie
Datum			Scale	Scale+Origin	

Full EOP set

Only VLBI can determine the full EOP set and CRF; while GNSS has good geometry, global coverage with continuous observation.
Different techniques are connected by common parameters (EOP, satellite orbit, troposphere delay) or external measurement (local tie).

Motivation: Multi-Technique Combination

Combination level

Easiest — Parameter

Common way — Normal Equation

Best Consistency — **Observation**

Drawbacks

Missing: parameter correlation, datum

A priori models
Parameterization
Processing methods

A software package capable of processing all techniques on a very high quality level

Integrated processing of different techniques at the observation level provides the most rigorous consistent solution with all the possible ties available.
However, this integration can only be achieved within one software, which should be able to process all the techniques with state-of-the-art models.

Motivation: Our Goals

- One software to process all the four techniques
- Capable of generating FULL EOPs
- Enable to combine all space-geodetic techniques at the observation level (also NEQ level)
- Exploit features of different techniques
  - GNSS: dense network with continuous observation, good geometry
  - VLBI: full EOP set, space exploration
  - SLR: absolute accuracy, gravity field
- Investigate the possibility/**problems** in integrated processing

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Current Status of VLBI Implementation

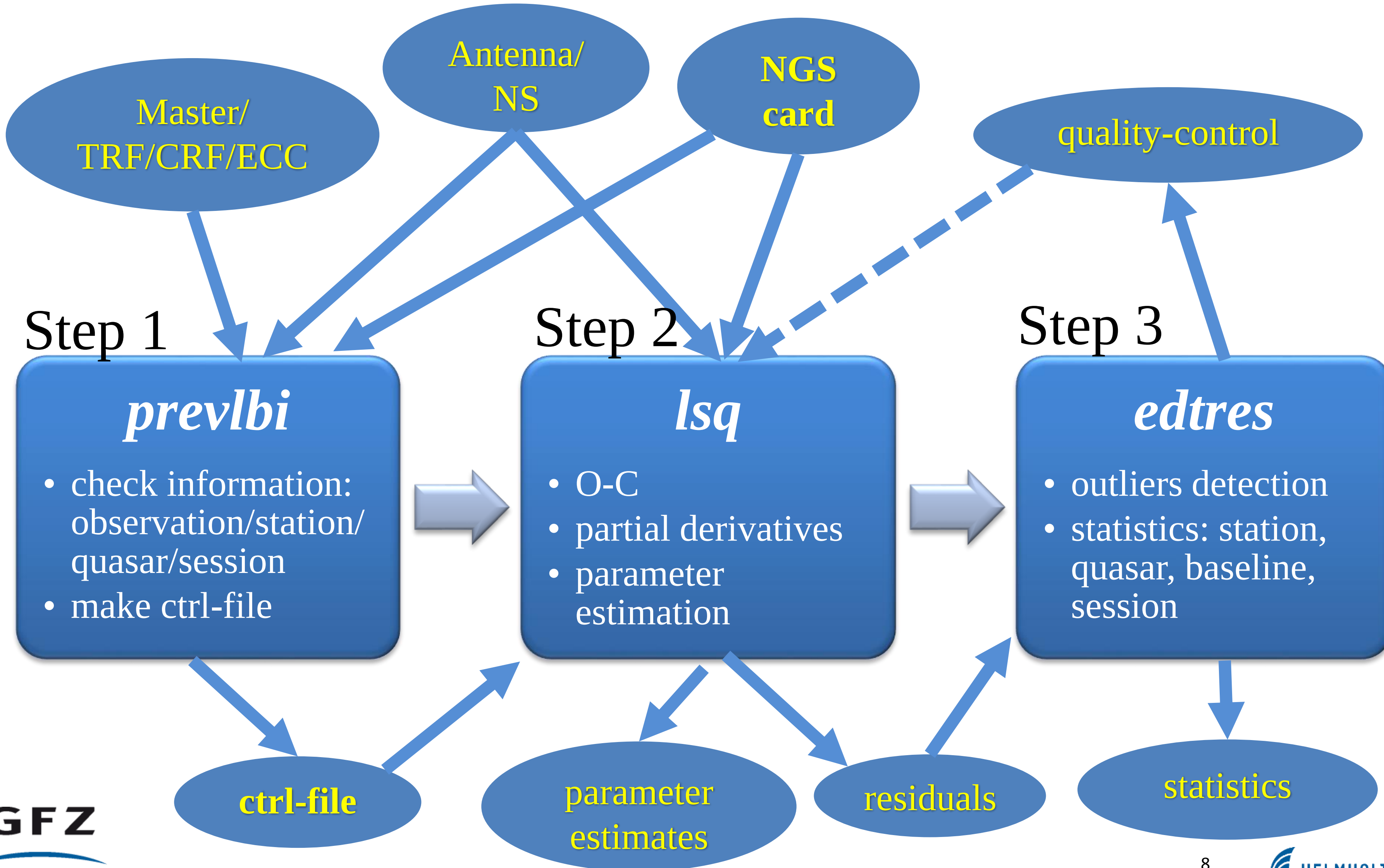
- Based on the PANDA platform
  - Positioning And Navigation Data Analyst (PANDA)
  - Real-time, post-processing
  - Orbit, Clock, ERP
  - Multi-GNSS, POD, PPP, LEO
- **VLBI module**
  - **based on NGS card files**
  - **IERS consensus model**
  - **Integrated in LSQ estimator**
  - **Outlier elimination**

Library	• Data structure • Constants • File reading/writing • Math, etc
Modules	• Pre-processing • Residual editing • trs2crs • Orbit/clock • Ambiguity fixing
Estimator least-squares	• Read GNSS/VLBI/SLR observation, local tie • Compute O-C, partial derivatives • Parameter estimation

Software structure

Current Status of VLBI Implementation

- VLBI data processing flowchat



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Current Status of VLBI Implementation

- VLBI modeling
  - Single-session processing achieved
  - Long-term (global solution) in progress

Parameter	VLBI	GNSS
Polar Motion	offset+drift	
UT1-UTC	offset+drift	drift
Nutation	offset(+drift)	
Source Coordinate	NNR/fix	
Station Coordinate	NNR/NNT/NNS/fix/free	
Clock (satellite/receiver)	polynominal (+RWK)	white noise/polynominal/RWK
Troposphere	PWC/RWK	
Satellite orbit		dynamic parameters
Baseline clock	constant	

PWC: piece wise constant; RWK: random walk process
NNR: no-net rotation; NNT: no-net translation; NNS: no-net scale

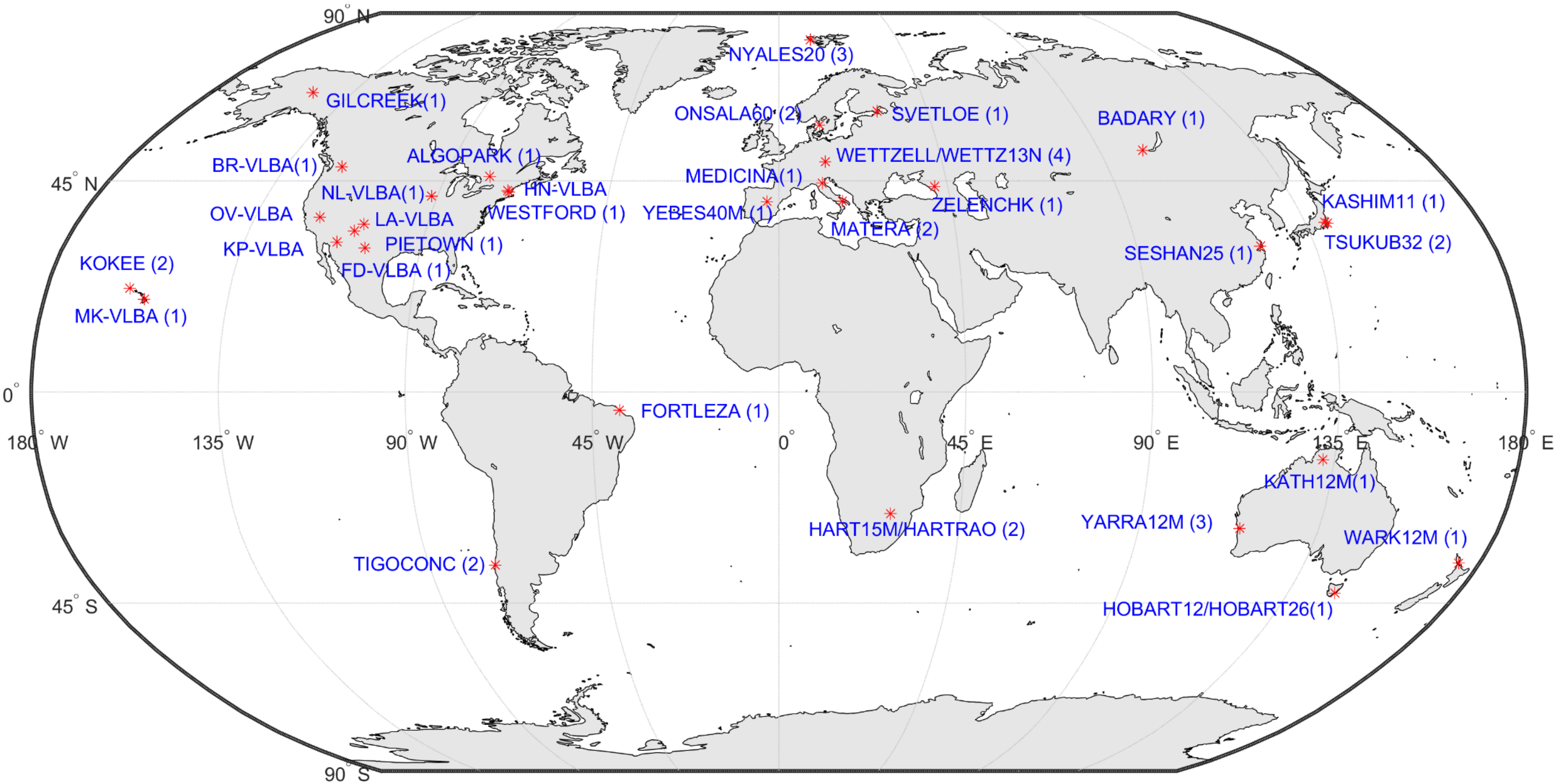
Troposphere Parameter: CONT Campaigns

- Processing the CONT05-CONT17 campaigns and PPP at co-located GNSS stations
  - To investigate the agreement of the troposphere parameters at these co-located stations
- The VLBI CONT campaigns
  - to acquire state-of-the-art VLBI data over a time period of about two weeks to demonstrate the highest accuracy

Session Name	ID	Time	Comment
CONT02		DOY 289-304, 2002	Not used
CONT05	C05	DOY 256-269, 2005	C05B is used, TIGOCONC removed
CONT08	C08	DOY 225-239, 2008	
CONT11	C11	DOY 258-272, 2011	
CONT14	C14	DOY 126-140, 2014	
CONT17 Legacy-1	V17	DOY 332-346, 2017	VLBA network
CONT17 Legacy-2	C17	DOY 332-346, 2017	IVS network

Troposphere Parameter: CONT Campaigns

- VLBI CONT05-CONT17 campaigns



Distribution of all the VLBI stations for CONT05-CONT17
For those with co-located GNSS stations, the number of co-locations is presented after the VLBI name

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Troposphere Parameter: Data Processing

- Data processing at CONT sessions

	GNSS	VLBI
Mode	GPS-only **PPP**, daily solution	Single-session solution
Interval	300-sec LC+PC	All available X-band
Space Part	Orbit & clock fixed to GF2/GFZ product	Fixed to ICRF3xs
Receiver Part	Antenna PCO/PCV: IGS08/14 CODE DCB product	Antenna axis offset Antenna thermal deformation
Weight	Range: 1 m, phase: 0.02 cycle Elevation dependent	1 cm + observation noise Elevation dependent
Clock	White noise	Linear + **RWK** ($0.3mm/\sqrt{s}$)
Coordinate	Freely estimated	NNR+NNT to ITRF2014
EOP		Full EOP estimation
Ionosphere	Eliminated by ionosphere-free combination	Corrected by S-band observation
Displacement	Solid earth tides, ocean tides (FES2004), pole tides, atmosphere loading	

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Troposphere Delay in GNSS and VLBI

- Troposphere delay modeling
  - A priori ZHD_0 and ZWD_0 from ECMWF (VMF3), thus the ZTD difference between GNSS and VLBI at co-located stations caused by the height difference are modeled in advance
  - Mapping function: VMF3
  - ZWD residual estimated as PWC every 1 hour
  - North and east gradients estimated as PWC every 3 hours

$$Trop = mf_h \times ZHD_0 + mf_w \times (ZWD_0 + dZWD) + mf_g \times (G_N \cos\alpha + G_E \sin\alpha)$$

Trop: troposphere delay at signal transmitting path
ZHD_0: a priori zenith hydrostatic delay
ZWD_0: a priori zenith wet delay
***dZWD*: residual zenith wet delay**
G_N,G_E: north and east gradients
mf_h, mf_w: hydrostatic and wet mapping functions
mf_g: gradient mapping function

dZWD is **NOT** correlated to the station height if the ZHD_0 and ZWD_0 are modeled properly, e.g., from ECMWF.
It can be constrained for co-located GNSS-VLBI stations.

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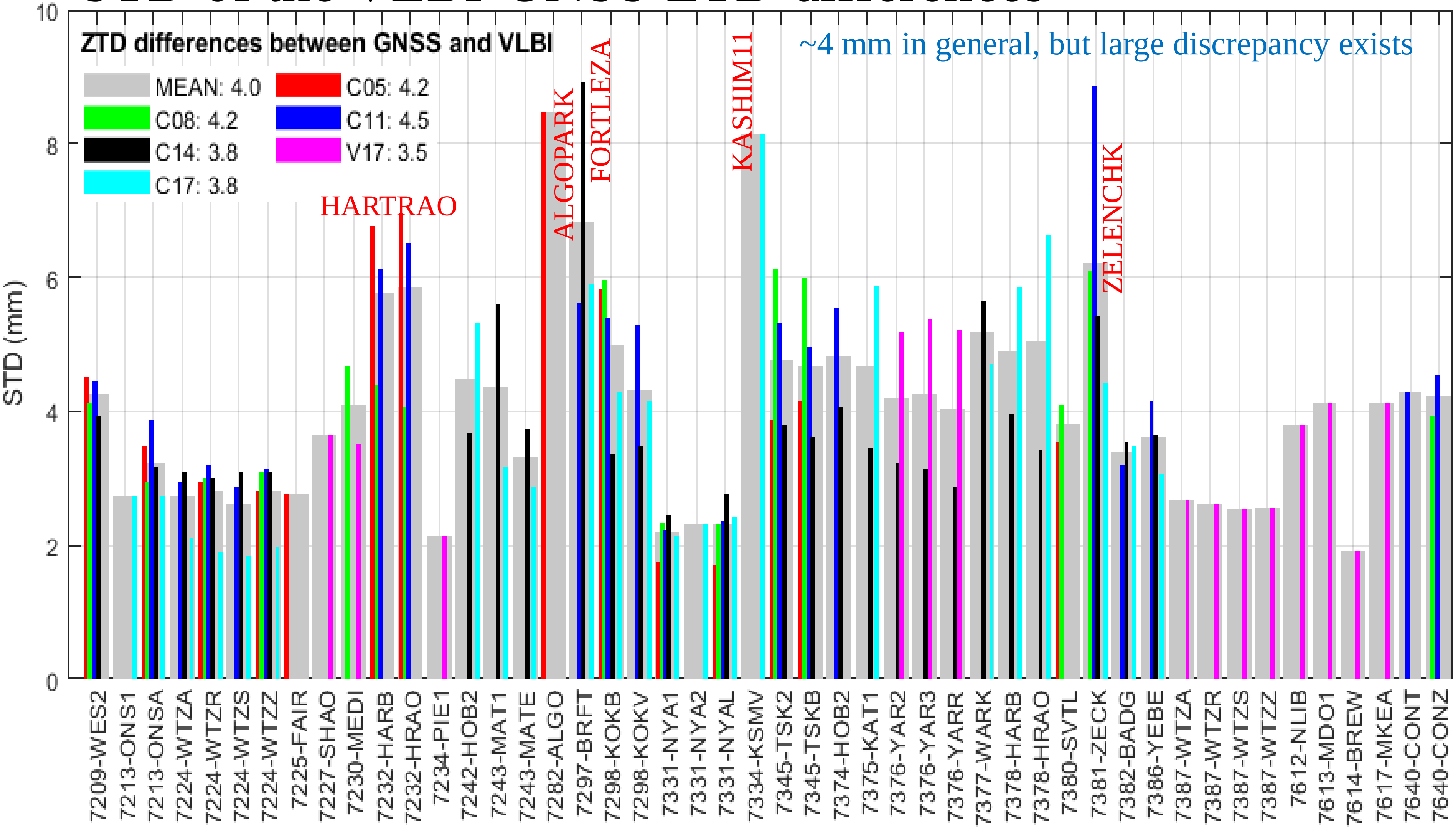
Troposphere Parameter Bias: ZTD

- STD of the VLBI-GNSS ZTD differences



X-axis: VLBI-GNSS co-located stations

Y-axis: Standard Deviation of the ZTD differences between GNSS and VLBI

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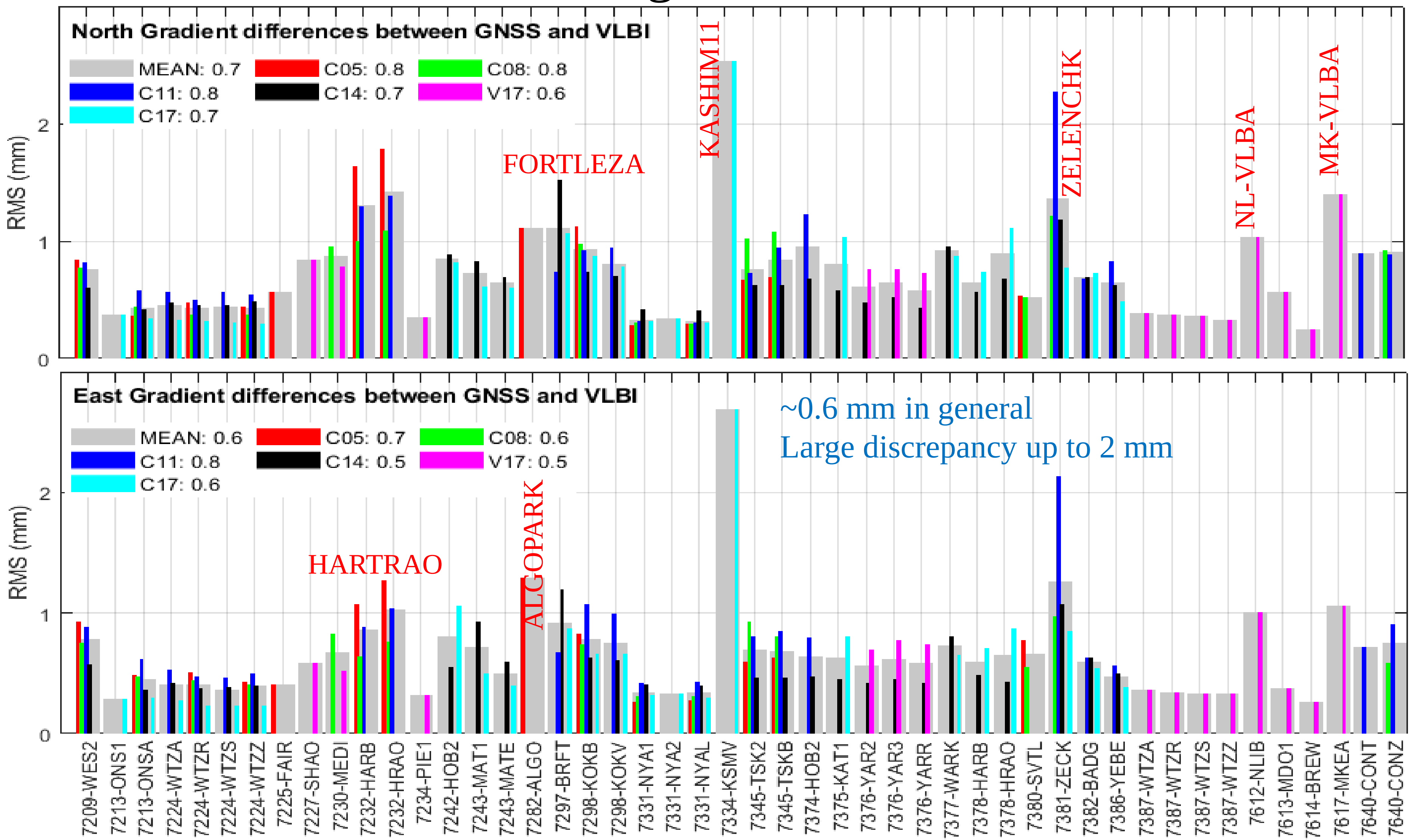
Troposphere Parameter Bias: Gradients

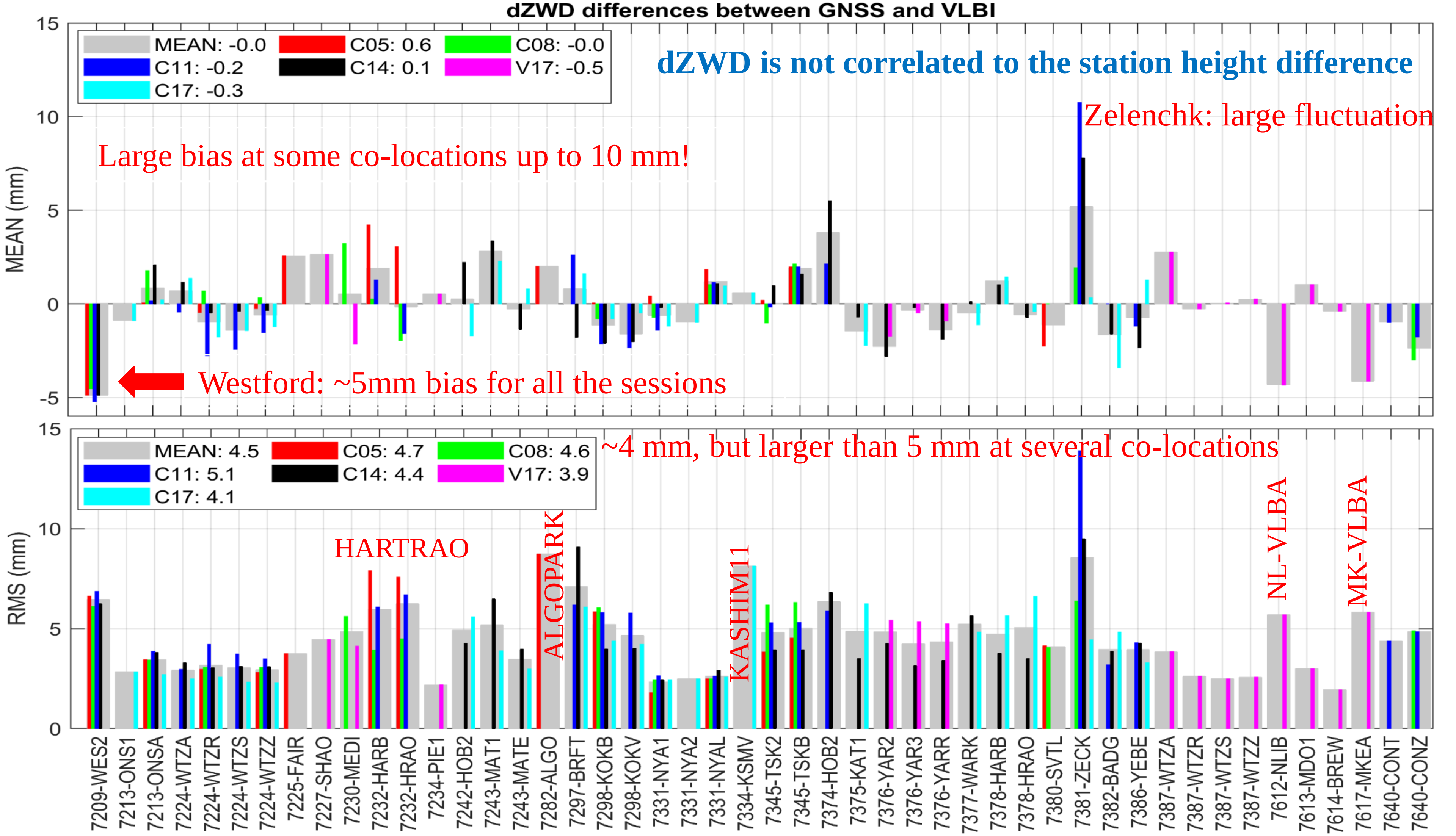
- RMS of the VLBI-GNSS gradient differences



X-axis: VLBI-GNSS co-located stations; Y-axis: RMS of the gradient differences

Troposphere Parameter Bias: dZWD

- MEAN and RMS of the VLBI-GNSS dZWD differences

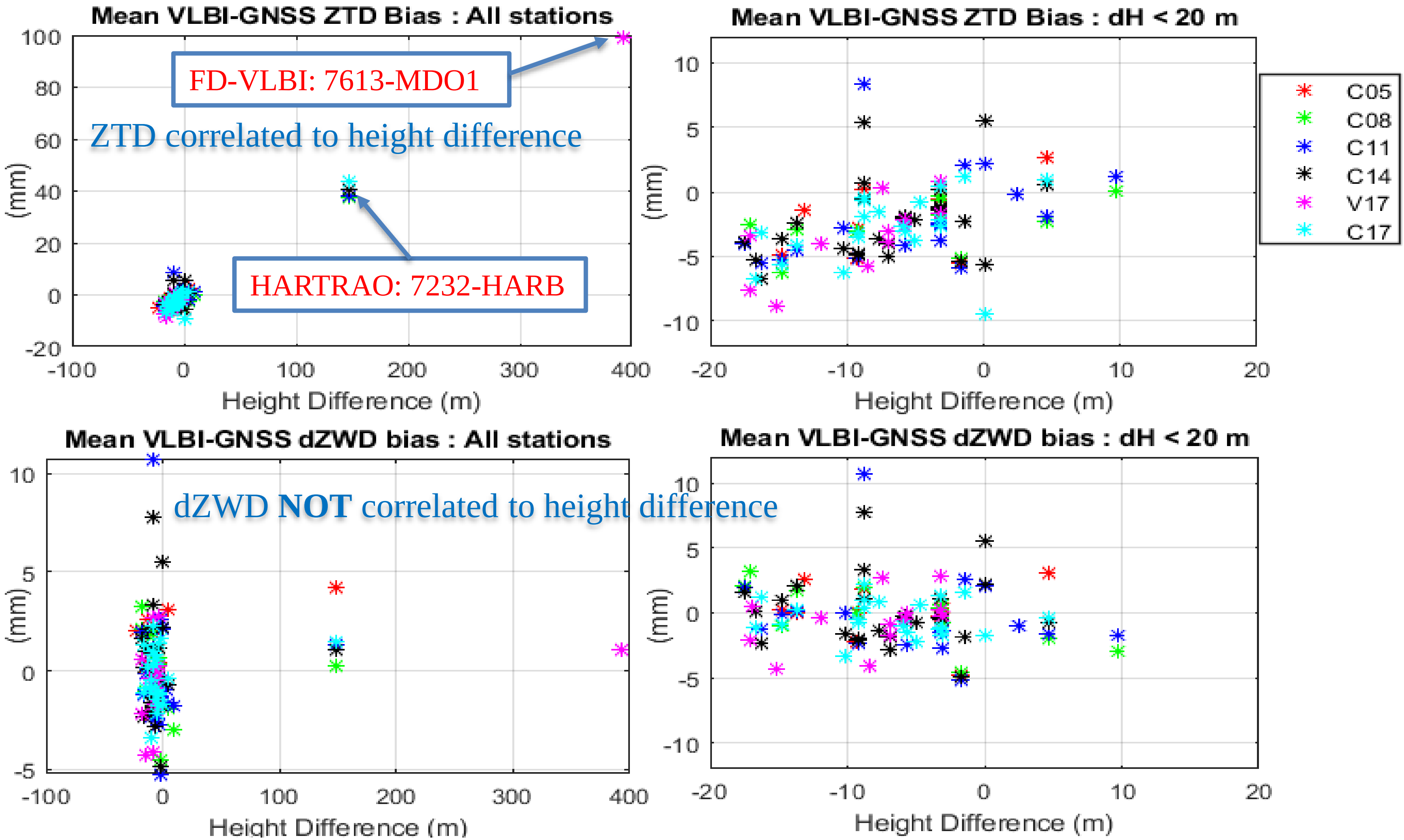


X-axis: VLBI-GNSS co-located stations

Y-axis: MEAN (up) and RMS (bottom) of the dZWD differences

Troposphere Parameter Bias: dZWD

- MEAN of the VLBI-GNSS ZTD and dZWD differences



X-axis: height difference of the GNSS-VLBI co-locations
Y-axis: average value of the VLBI-GNSS ZTD/dZWD differences

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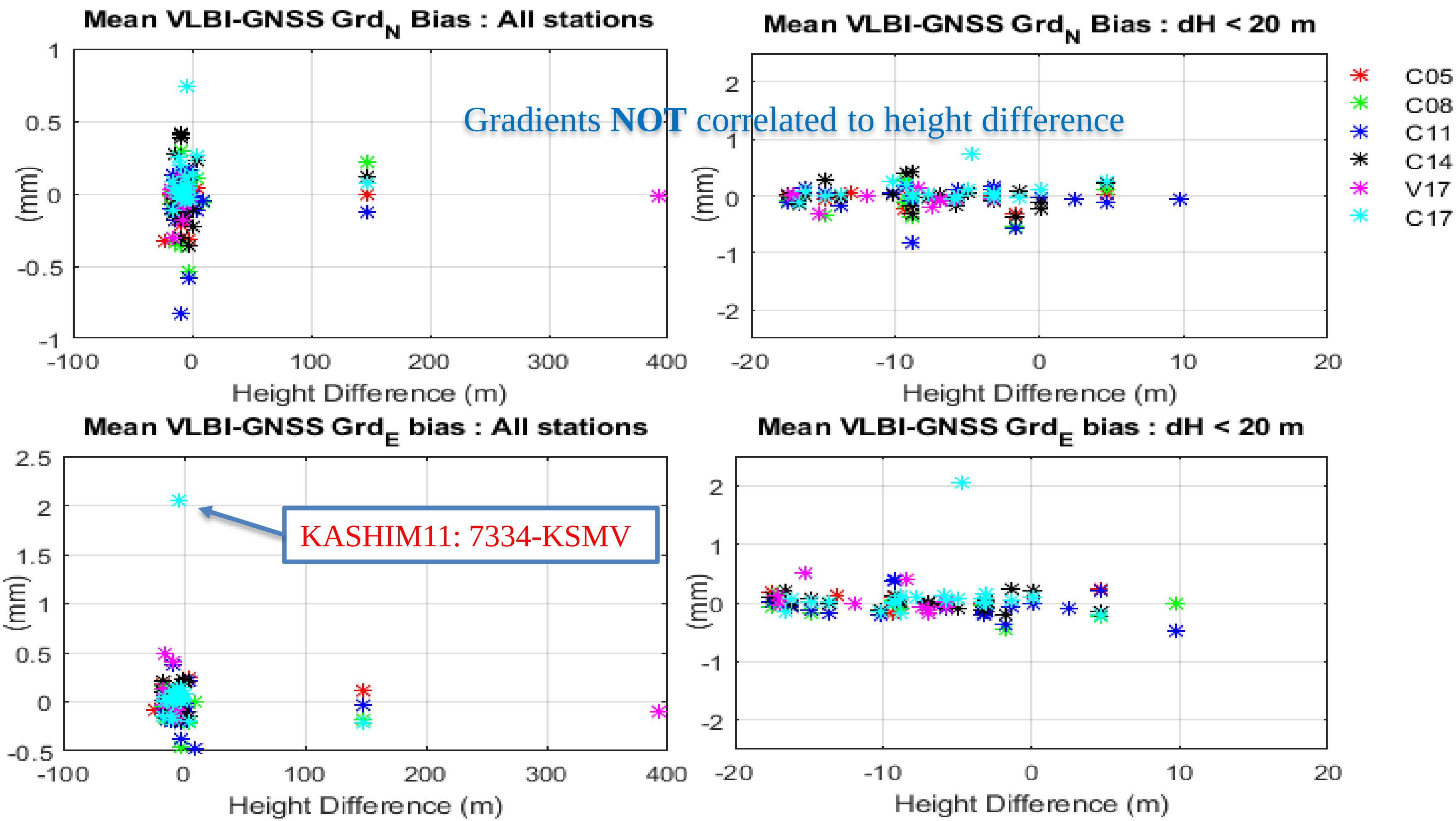
Troposphere Parameter Bias: Gradient

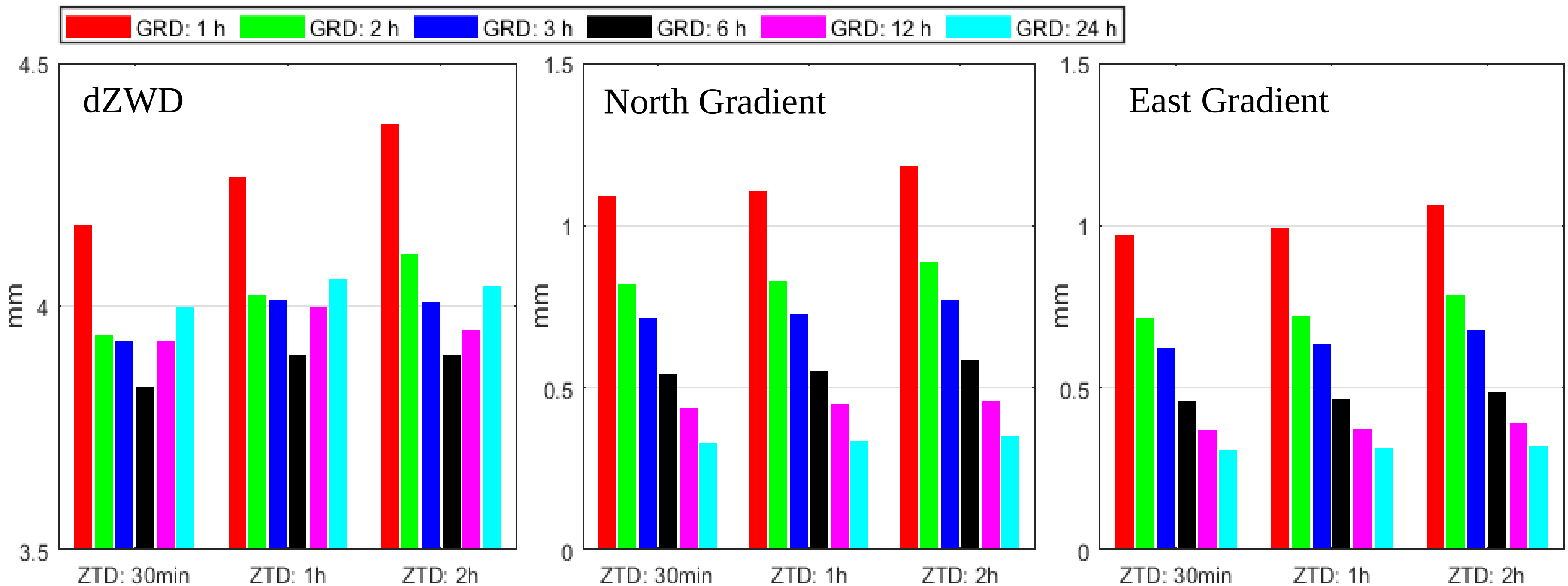
- MEAN of the VLBI-GNSS gradients differences



X-axis: height difference of the GNSS-VLBI co-locations
Y-axis: average value of the VLBI-GNSS gradient differences

Troposphere Parameter Bias

- Impact of the ZTD/gradient temporal resolution
  - ZTD/Gradients agreement not very sensitive to ZTD resolution
  - Gradients agreement improves as the gradient resolution increases
  - dZTD agreement achieves the best with 6-h gradient resolution

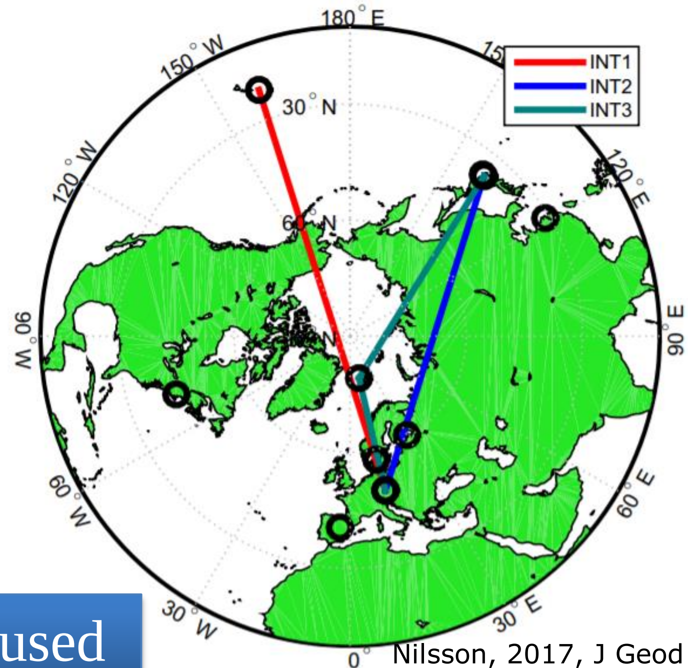


X-axis: ZTD temporal resolution
Y-axis: RMS value of the troposphere parameter differences between GNSS and VLBI
Different colors represent different gradient temporal resolutions

Integration of VLBI INT and GNSS PPP

- VLBI Intensive sessions
  - 2/3 VLBI stations only; 1-hour session, 20-40 observations
  - Rapid UT1 estimation and prediction
  - Parameter: 1 clock + 2 ZWD + 1 UT1
  - No gradients: biased UT1 estimates
- Improve VLBI using GNSS troposphere information

Session	Time	VLBI	GNSS
INT1	Weekday 18:30-19:30	Wettzell Kokee	WTZR KOKB
INT2	Weekend 07:30-08:30	Wettzell Tsukuba	WTZR TSKB
INT3	Monday 07:00-08:00	Wettzell Kokee Ny-Ålesund	



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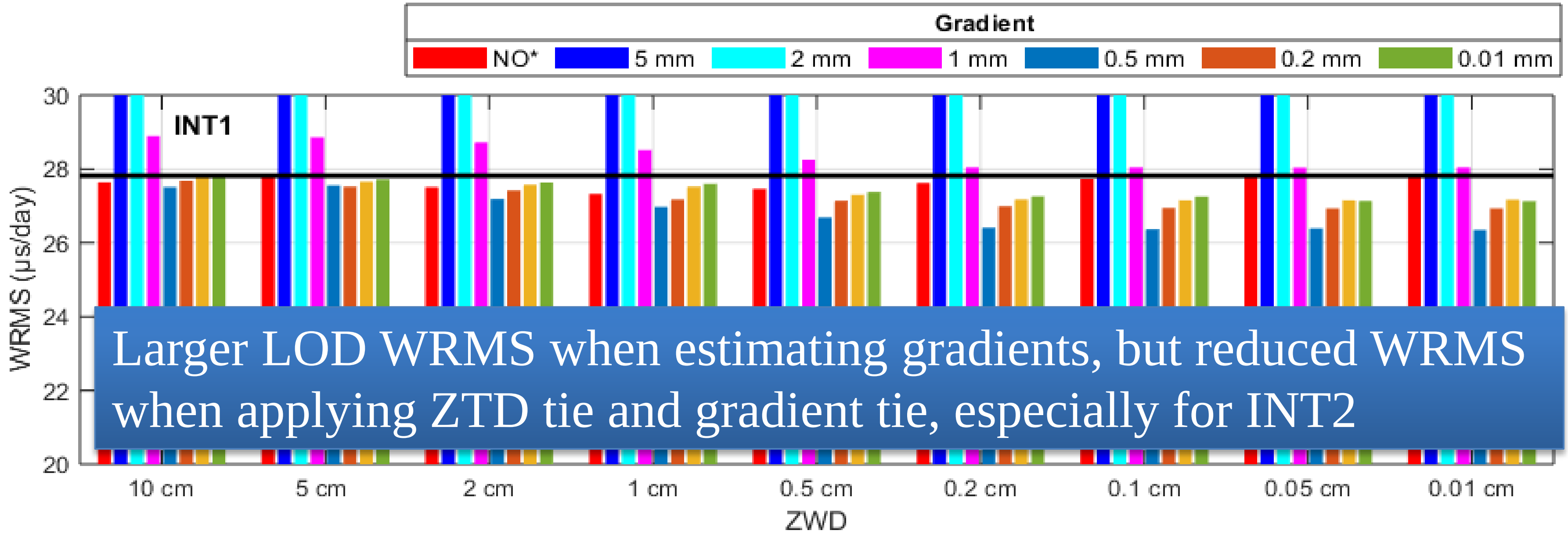
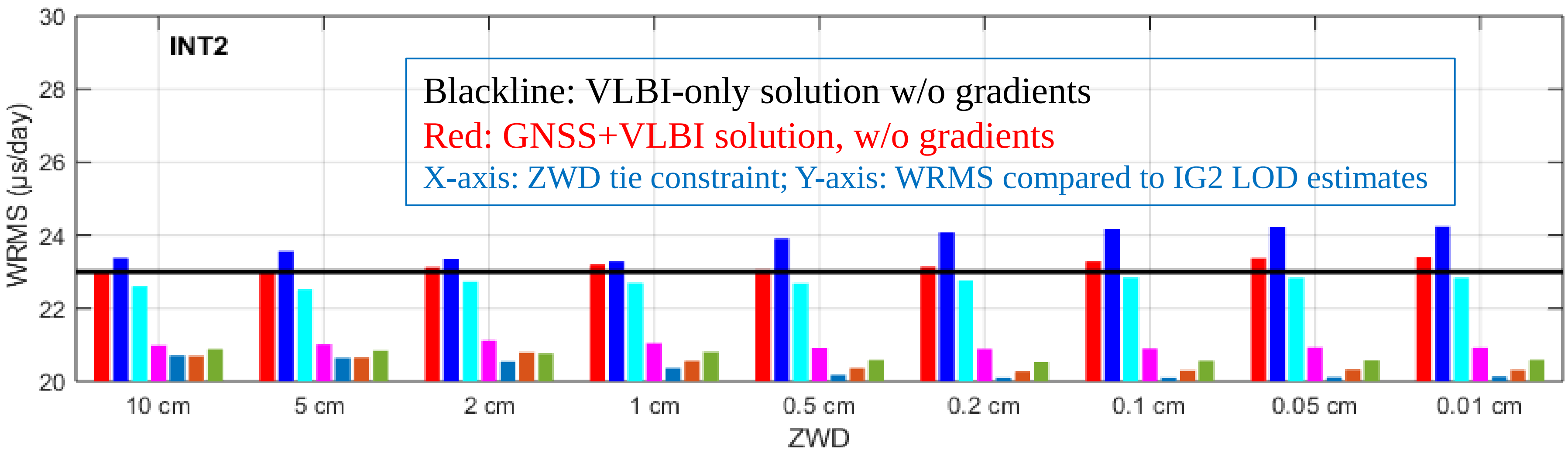
The INT1 & INT2 from 2001 to 2014 are used

Integration of VLBI INT and GNSS PPP

- Different constraint applied to ZTD tie and Gradient tie



Larger LOD WRMS when estimating gradients, but reduced WRMS when applying ZTD tie and gradient tie, especially for INT2



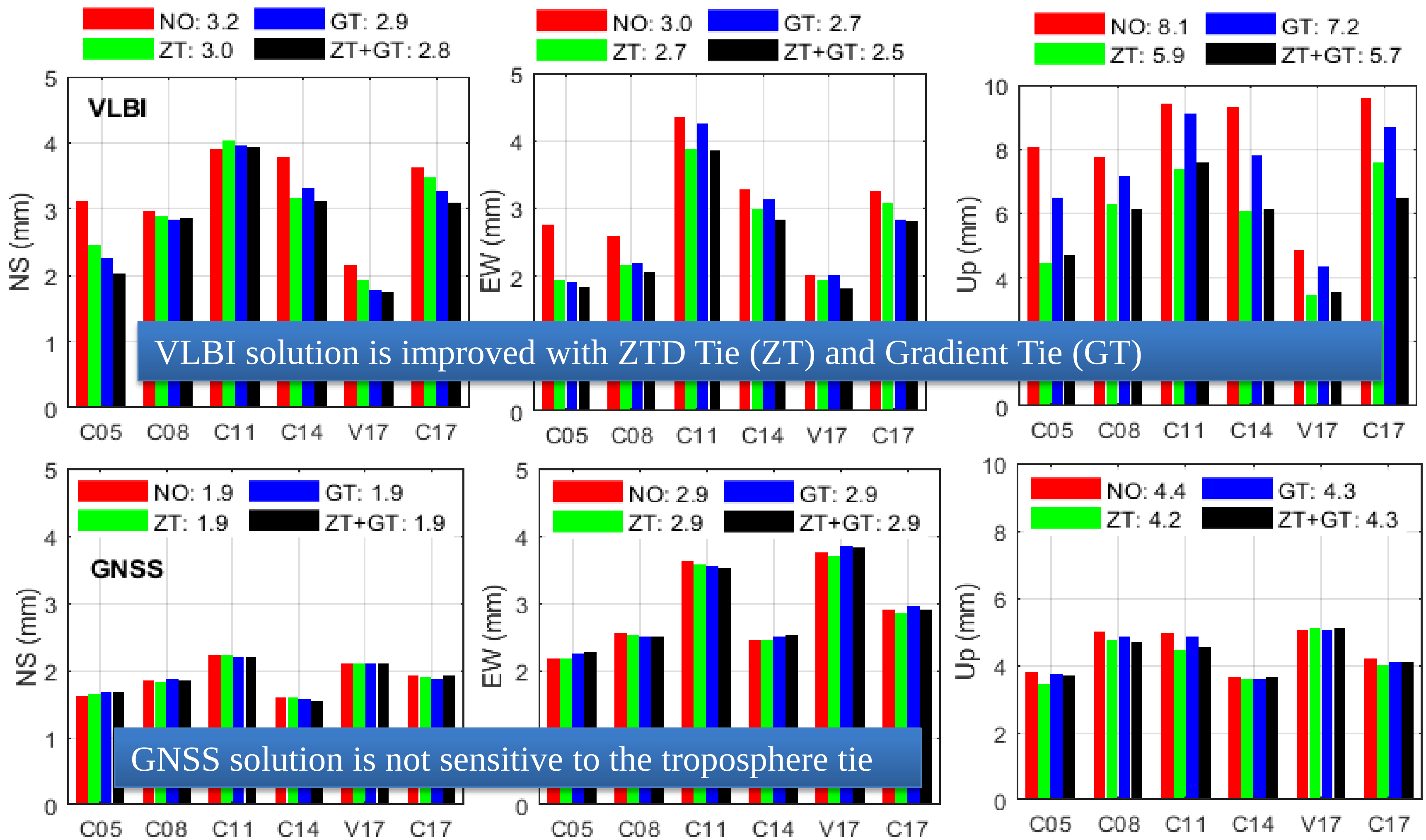
Blackline: VLBI-only solution w/o gradients
Red: GNSS+VLBI solution, w/o gradients
X-axis: ZWD tie constraint; Y-axis: WRMS compared to IG2 LOD estimates

Integration of VLBI CONT and GNSS PPP

- Data processing strategy:
  - VLBI single-session, GPS daily static PPP solution
  - Full EOP estimates in VLBI
  - A priori ZHD&ZWD from ECMWF(VMF3) for GNSS and VLBI
  - Residual ZWD estimated as PWC, and tied between GNSS and VLBI with a constraint of 0.1 mm
  - Gradients estimated as PWC, and tied between GNSS and VLBI with a constraint of 0.01 mm
  - Local tie applied using the constraint from sinex file
  - Use more than one co-located GNSS stations whenever possible
- Expected to see:
  - Better coordinate repeatability
  - Improved EOP accuracy

Integration of VLBI CONT and GNSS PPP

- Coordinate repeatability: troposphere tie



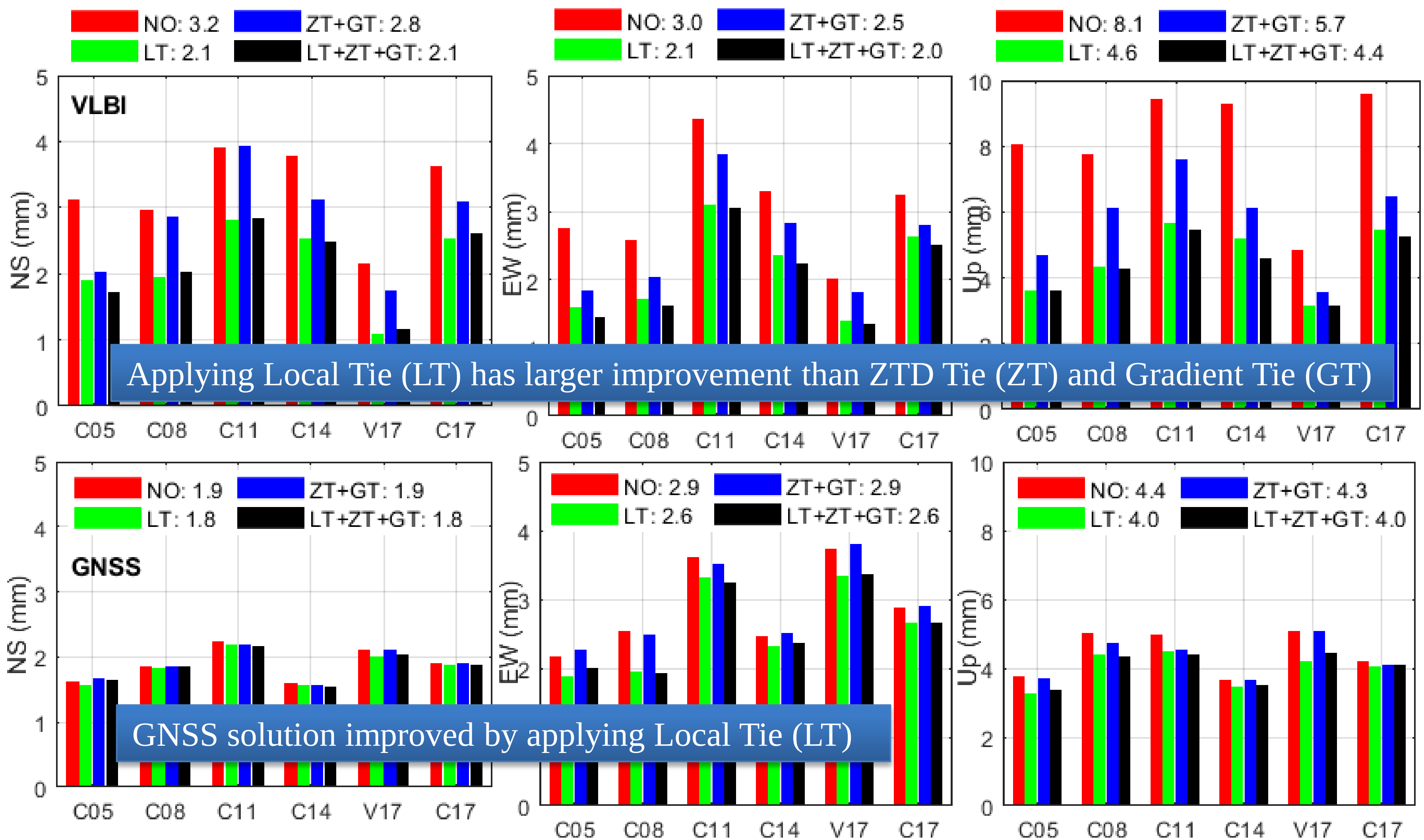
VLBI solution is improved with ZTD Tie (ZT) and Gradient Tie (GT)

GNSS solution is not sensitive to the troposphere tie

X-axis: VLBI sessions; Y-axis: coordinate repeatability
VLBI: up subplots; GNSS: bottom subplots

Integration of VLBI CONT and GNSS PPP

- Coordinate repeatability: local tie



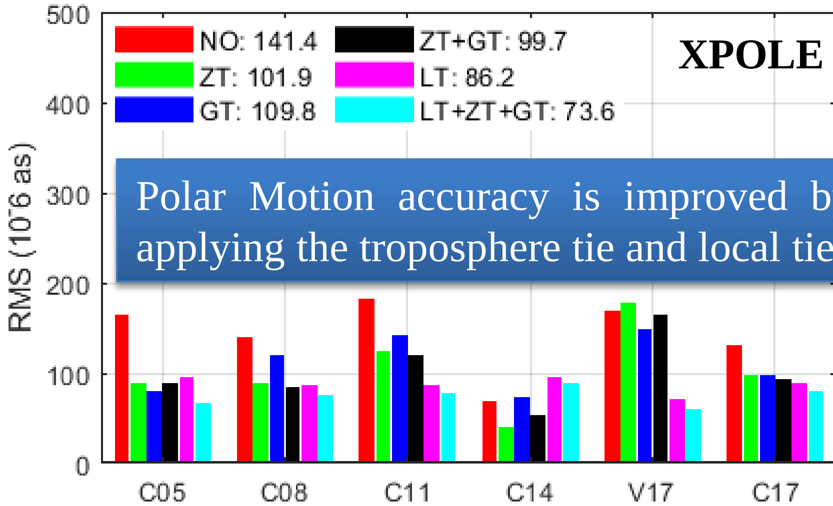
Applying Local Tie (LT) has larger improvement than ZTD Tie (ZT) and Gradient Tie (GT)

GNSS solution improved by applying Local Tie (LT)

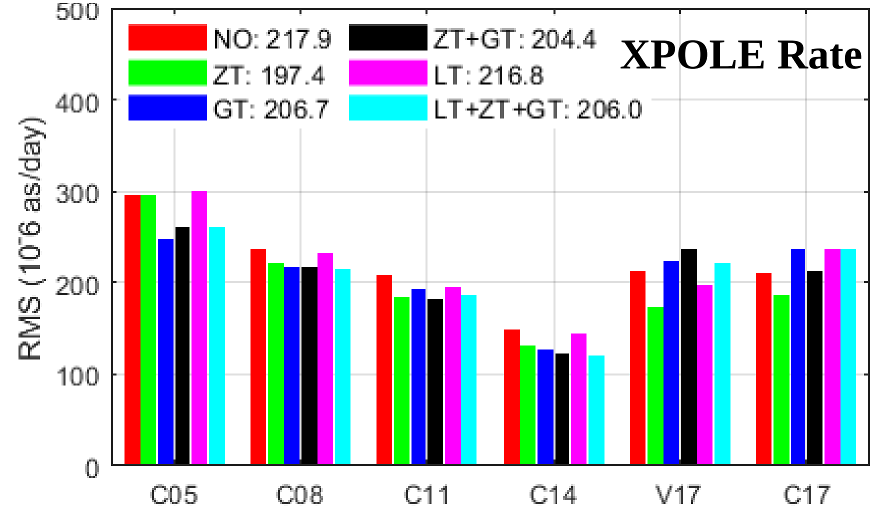
X-axis: VLBI sessions; Y-axis: coordinate repeatability
VLBI: up subplots; GNSS: bottom subplots

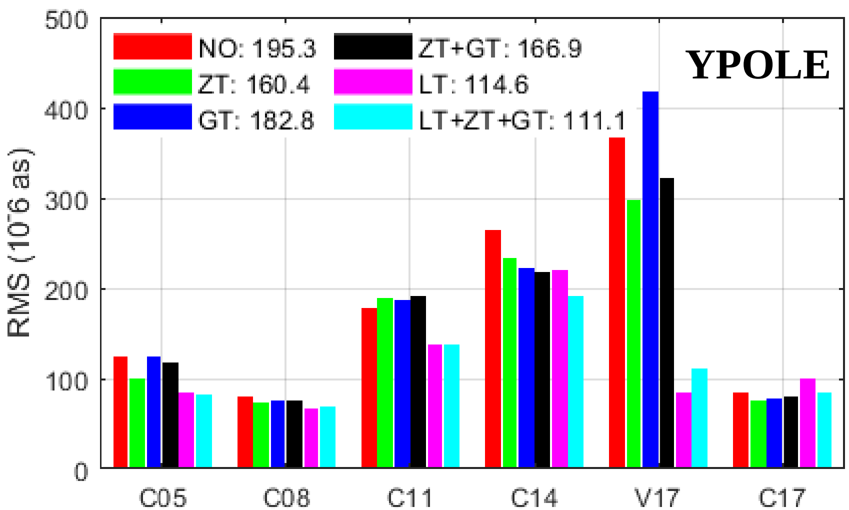
Integration of VLBI CONT and GNSS PPP

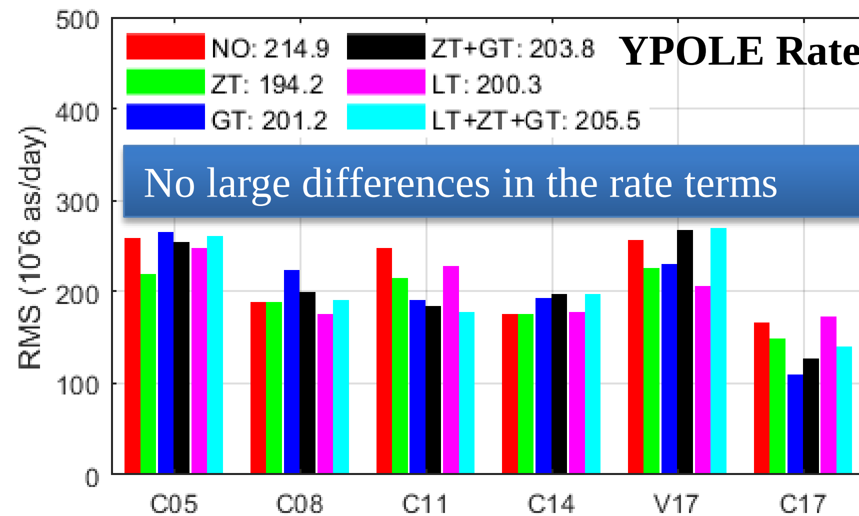
- EOP accuracy of all CONT sessions: Polar Motion



Polar Motion accuracy is improved by applying the troposphere tie and local tie





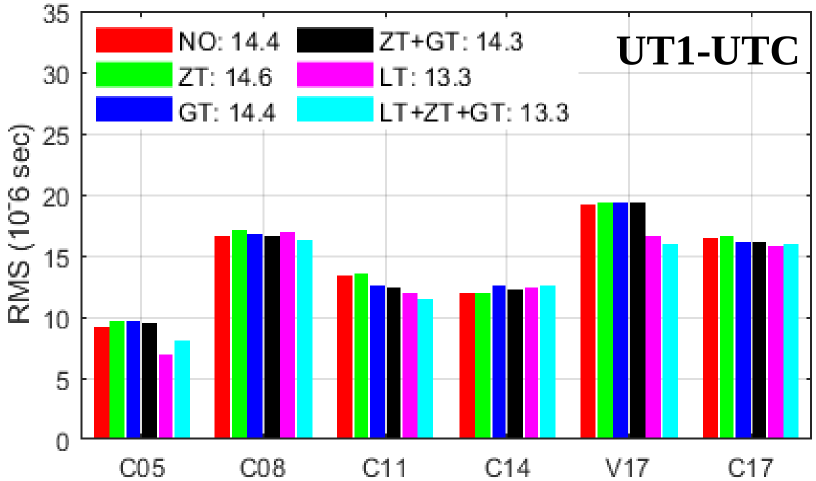


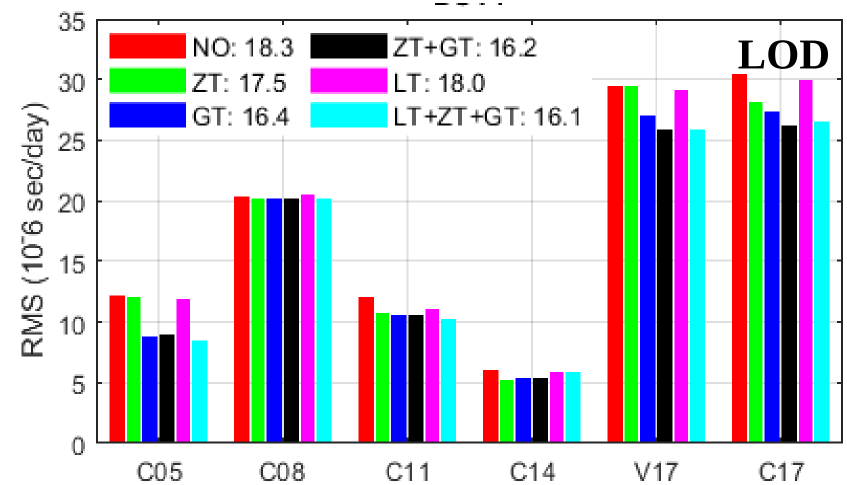
No large differences in the rate terms

X-axis: VLBI sessions; Y-axis: RMS value compared to IERS C04 EOP

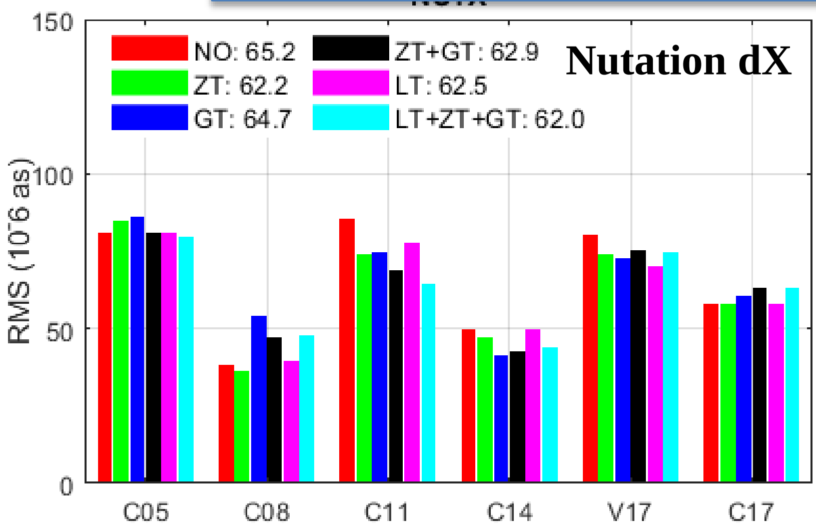
Integration of VLBI CONT and GNSS PPP

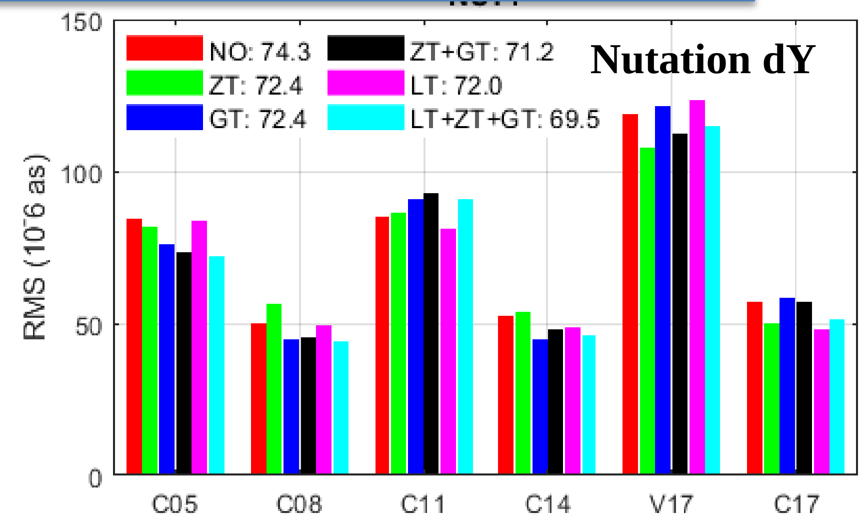
- EOP accuracy of all CONT sessions: UT1 and Nutation





No large differences can be observed in terms of UT1-UTC and nutation offsets





X-axis: VLBI sessions; Y-axis: RMS value compared to IERS C04 EOP

Conclusions and future work

- The VLBI module is fully implemented in the PANDA software and the integration with GNSS is ready
- The troposphere parameters show good agreement at co-located GNSS and VLBI stations
- By integration of VLBI INT sessions and GNSS PPP, the UT1 estimate is improved in terms of LOD
- Both coordinate repeatability and EOP accuracy are improved in CONT sessions by applying GNSS PPP, due to the troposphere tie and local tie
- Next step
  - Integration of VLBI CONT sessions with GNSS POD
  - Implementation of the SLR module

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