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Poster-
EGU2015-984

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Tropospheric delays derived from Kalman-filtered VLBI observations

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Introduction

One of the most important error sources in the products of space geodetic techniques is the troposphere. Currently, it is not possible to model the rapid variations in the path delay caused by water vapor with sufficient accuracy; thus it is necessary to estimate these delays in the data analysis. Very long baseline interferometry (VLBI) is well suited to determine non-hydrostatic (wet) delays with high accuracy and precision. VLBI data are usually analyzed by estimating geodetic parameters in a least squares adjustment (LSM). However, once the VLBI Global Observing System (VGOS) is operational, algorithms providing real-time capability, for instance a Kalman filter (KF, e.g. Herring et al., 1990), should be preferred. Even today, certain advantages of such a filter, for example, allowing stochastic modeling of geodetic parameters, warrant its application. The estimation of tropospheric wet delays, in particular, greatly benefits from the stochastic approach of the filter, compared to the deterministic nature of piece-wise linear functions used in LSM.

Kalman filter

In our implementation of a Kalman filter in the VLBI software VieVS@GFZ, the zenith wet delays (ZWD) are modeled as random walk processes. Other parameters estimated in the KF include station and source coordinates, Earth orientation parameters, clock offsets, and tropospheric gradients. The filter is run forwards and backwards, followed by a smoothing operation.

Data

The VLBI datasets considered are the IVS (Schuh & Behrend, 2012) CONT campaigns, which demonstrate state-of-the-art capabilities of the VLBI system. They are unique in following a continuous observation schedule over 15 days and in having data recorded at a higher rate than usual. The large amount of observations leads to a very high quality of geodetic products. CONT campaigns are held every three years; we have analyzed all five CONT campaigns between 2002 and 2014 for this study.

Noise characterization

From ZWD time series of all CONT campaigns and all stations, Allan standard deviations (ASD) have been calculated (for an example, see ***Fig. 1***). The ASD indicate that the ZWD can be modeled as a random walk process (k_{RW} = -0.5 ≈ -0.49 = k_{ZWD}). Then, the power spectral densities (PSD) of the white noise driving the random walks were estimated from the ASD. The PSD values of the individual stations, averaged over all CONT campaigns, are shown in ***Fig. 2***. PSD changes over time for stations that participated in more than 2 CONT campaigns are displayed in ***Fig. 3***.

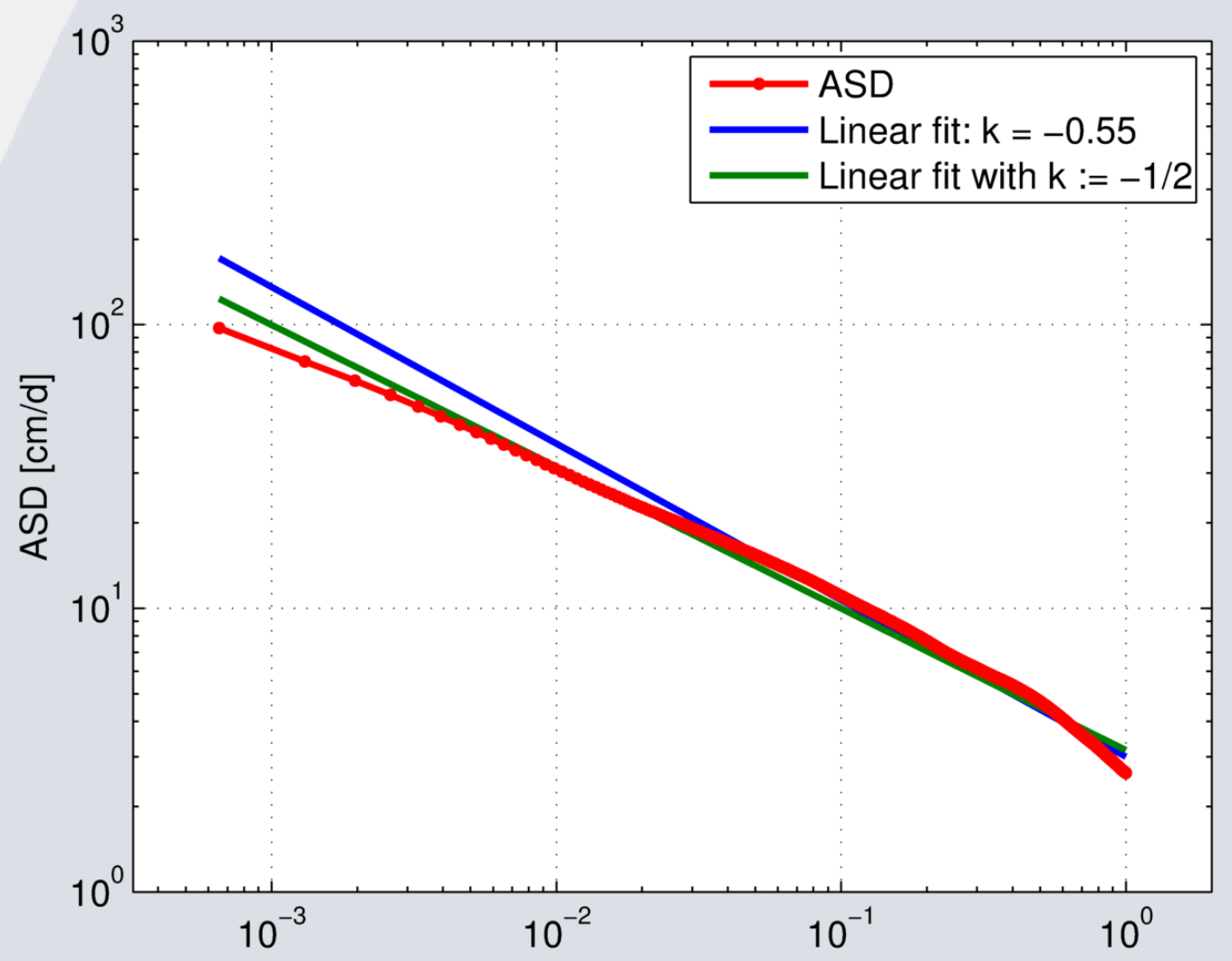

Fig. 1: ZWD ASD for Wettzell during CONT14

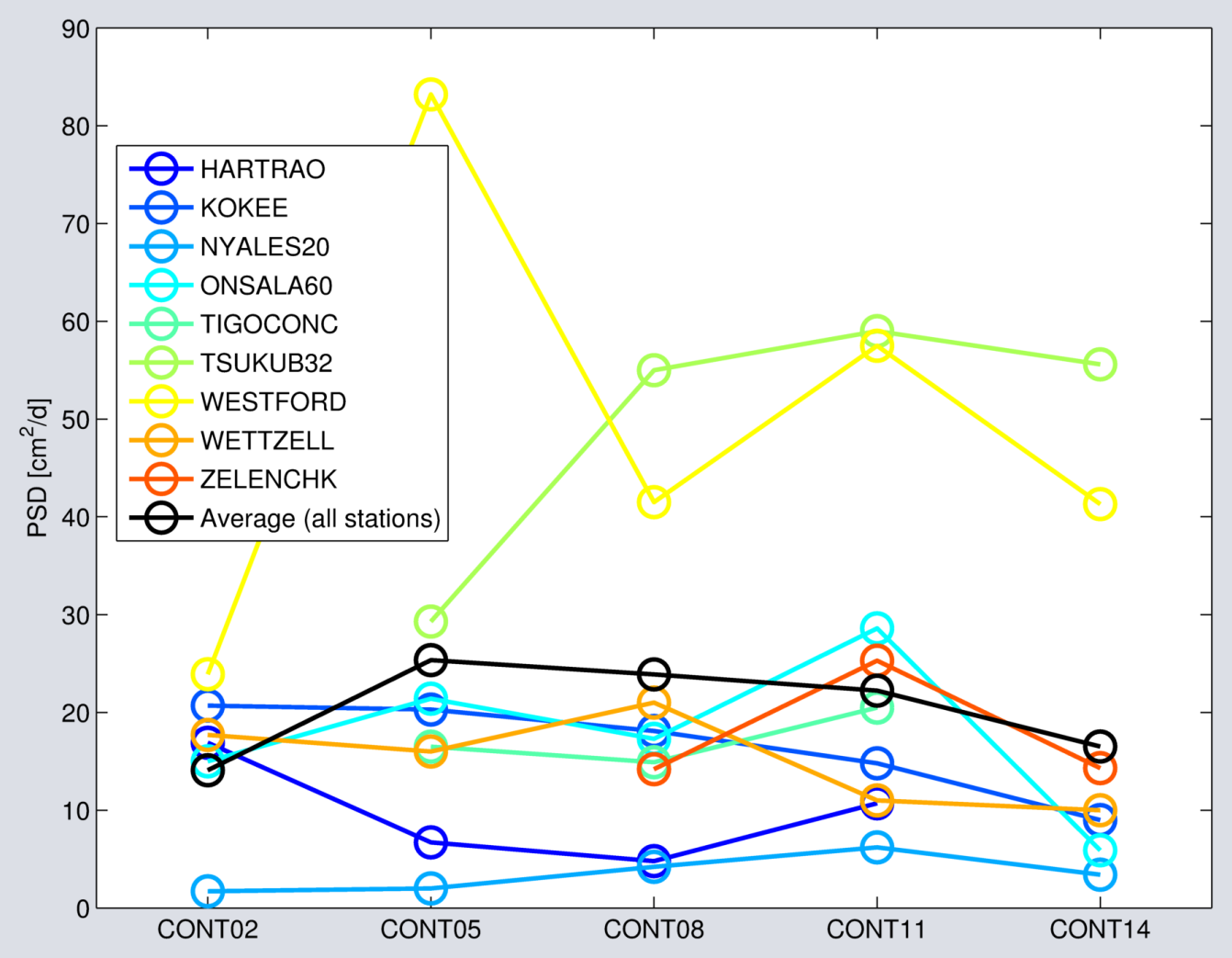

Fig. 3: ZWD PSD time series

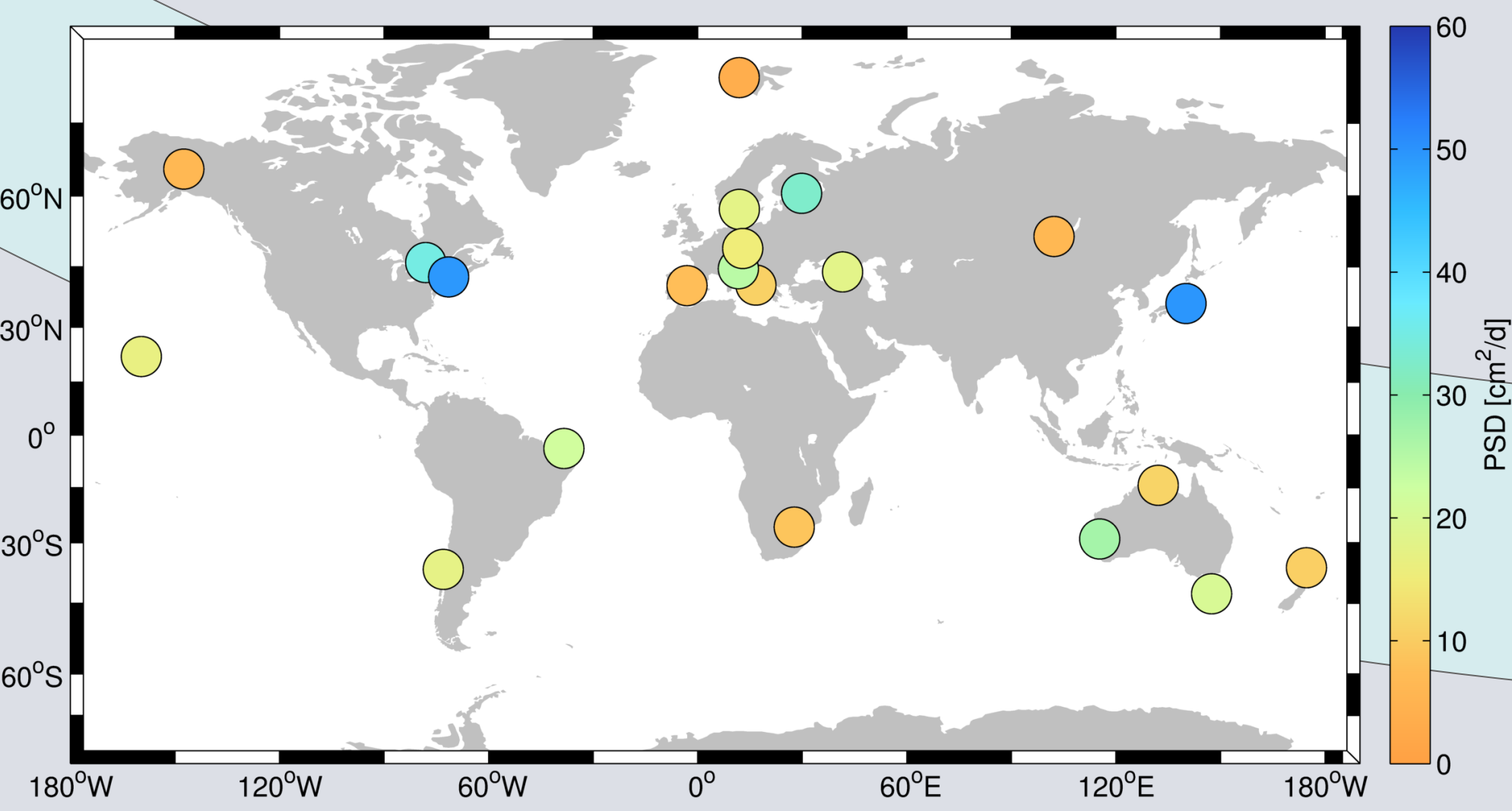

Fig. 2: ZWD PSD map averaged over all CONT campaigns

Effects on station coordinates

Baseline length and station coordinate repeatabilities have been computed for a KF solution applying the station based ZWD noise model (***Fig. 2***), a KF solution with constant ZWD noise parameters, and an LSM solution. ***Fig. 4*** and ***Fig. 5*** illustrate the baseline length and 3D position repeatabilities for CONT14. ***Fig. 6*** shows the difference in station coordinate repeatabilities for the two KF solutions. The best performance is achieved by using the KF solution with station dependend PSD (2-3% improvement over the solution with constant PSD, 3-7% over LSM).

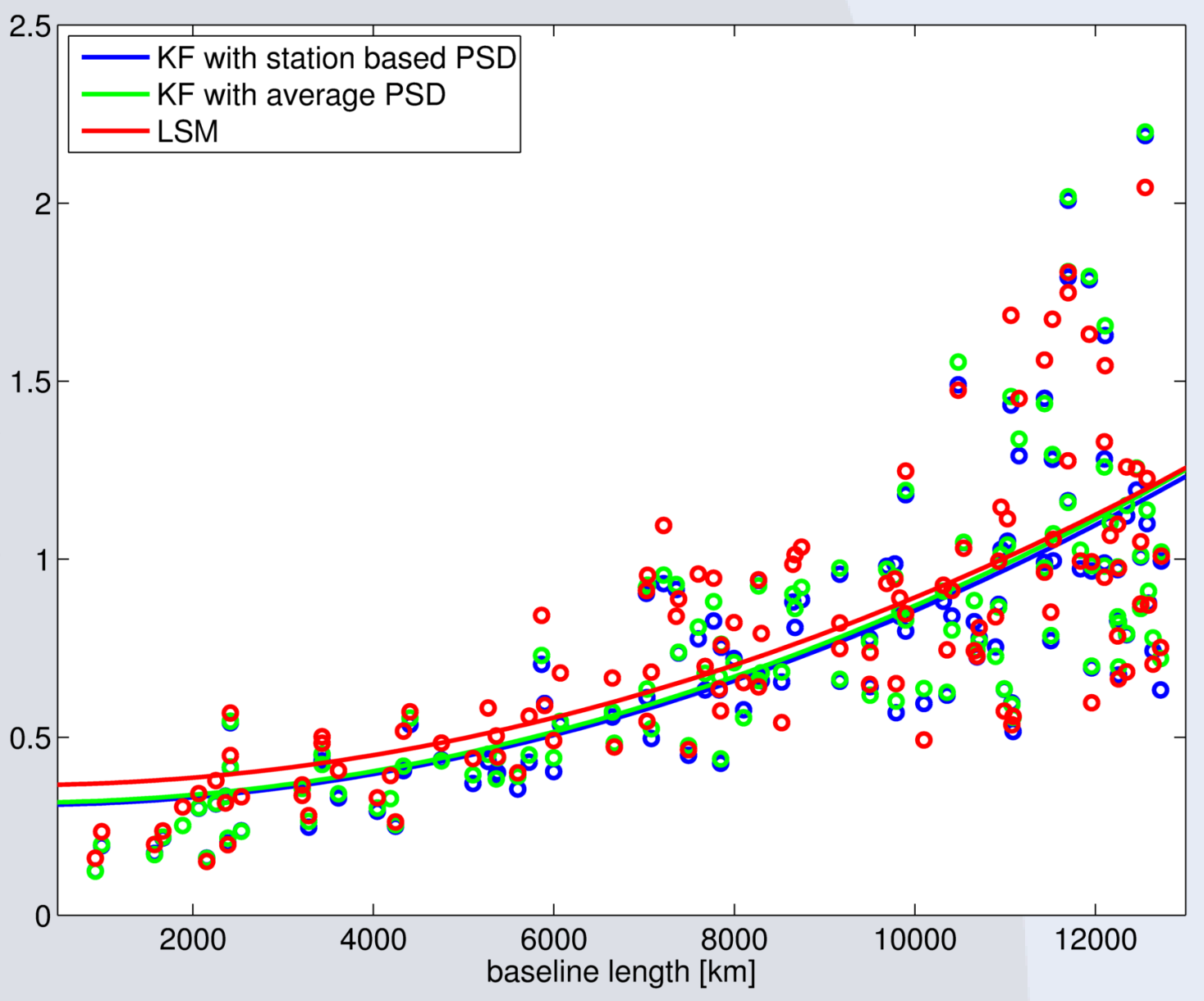

Fig. 4: Baseline length repeatabilities for CONT14

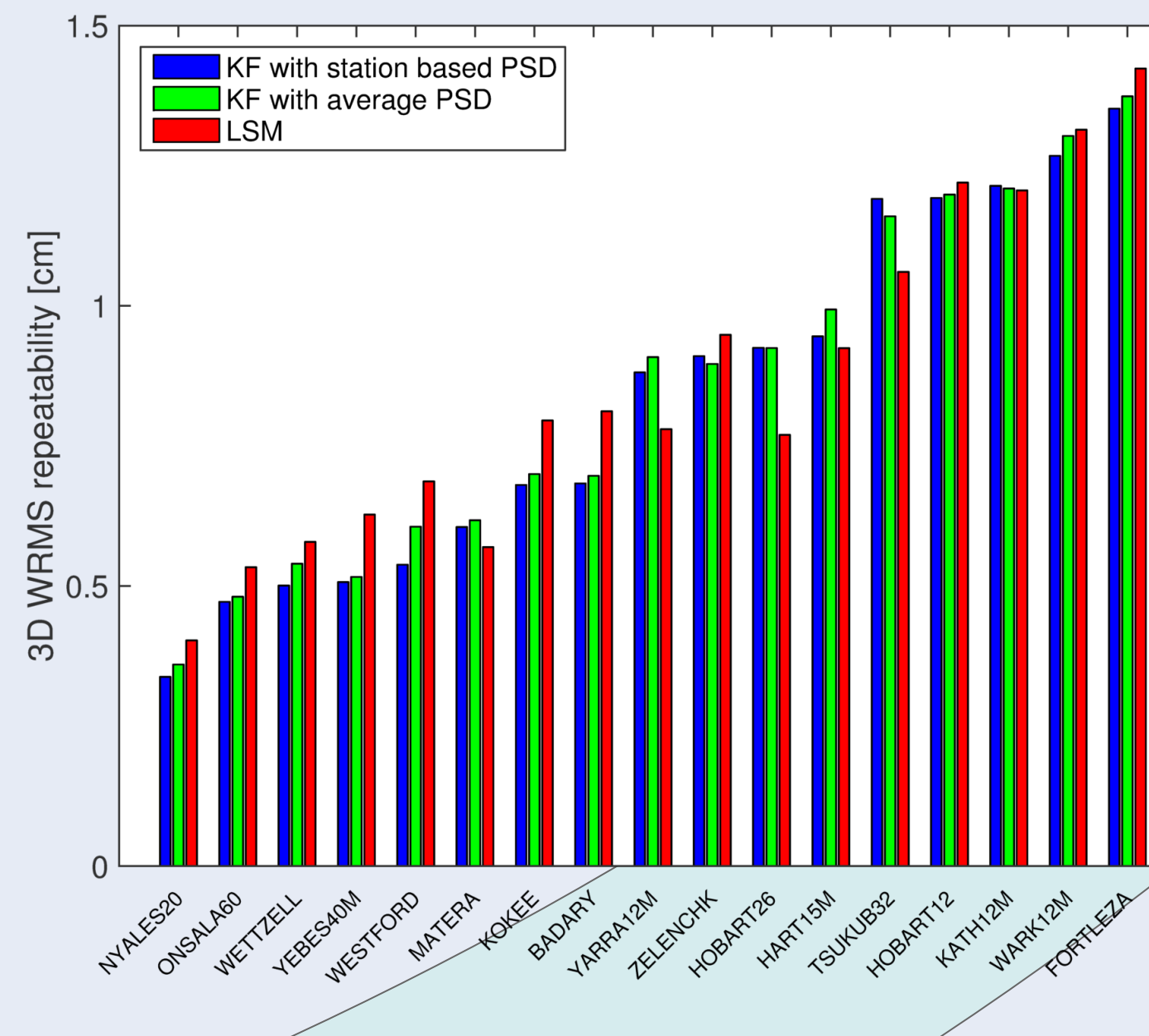

Fig. 5: 3D position repeatabilities for CONT14

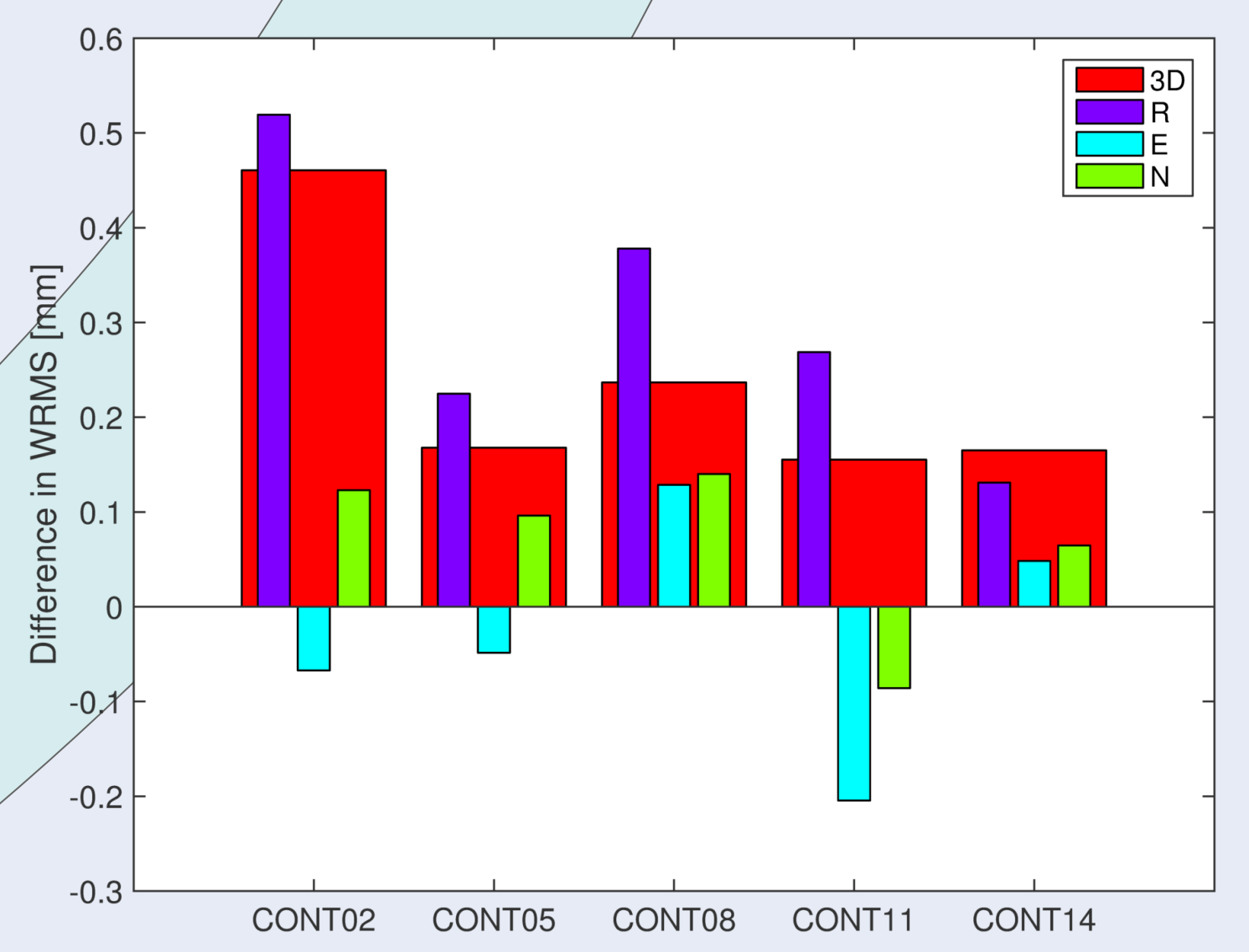

Fig. 6: Difference of repeatabilities for KF solution seen in Figs. 4 & 5. Positive values: KF with station based PSD performs better.

Comparison of ZWD

For stations Onsala, Sweden (CONT11 - ***Fig. 7*** & CONT14 - ***Fig. 8***) and Tsukuba, Japan (CONT11 - ***Fig. 9***), the ZWD from VLBI (KF & LSM) have been compared to those from water vapor radiometers (WVR), GPS, and ray tracing through the numerical weather models GFS (provided by NCEP) and IFS (ECMWF). When calculating ZWD differences w.r.t. the WVR data, the KF has a lower standard deviation compared to LSM by 6-12%.

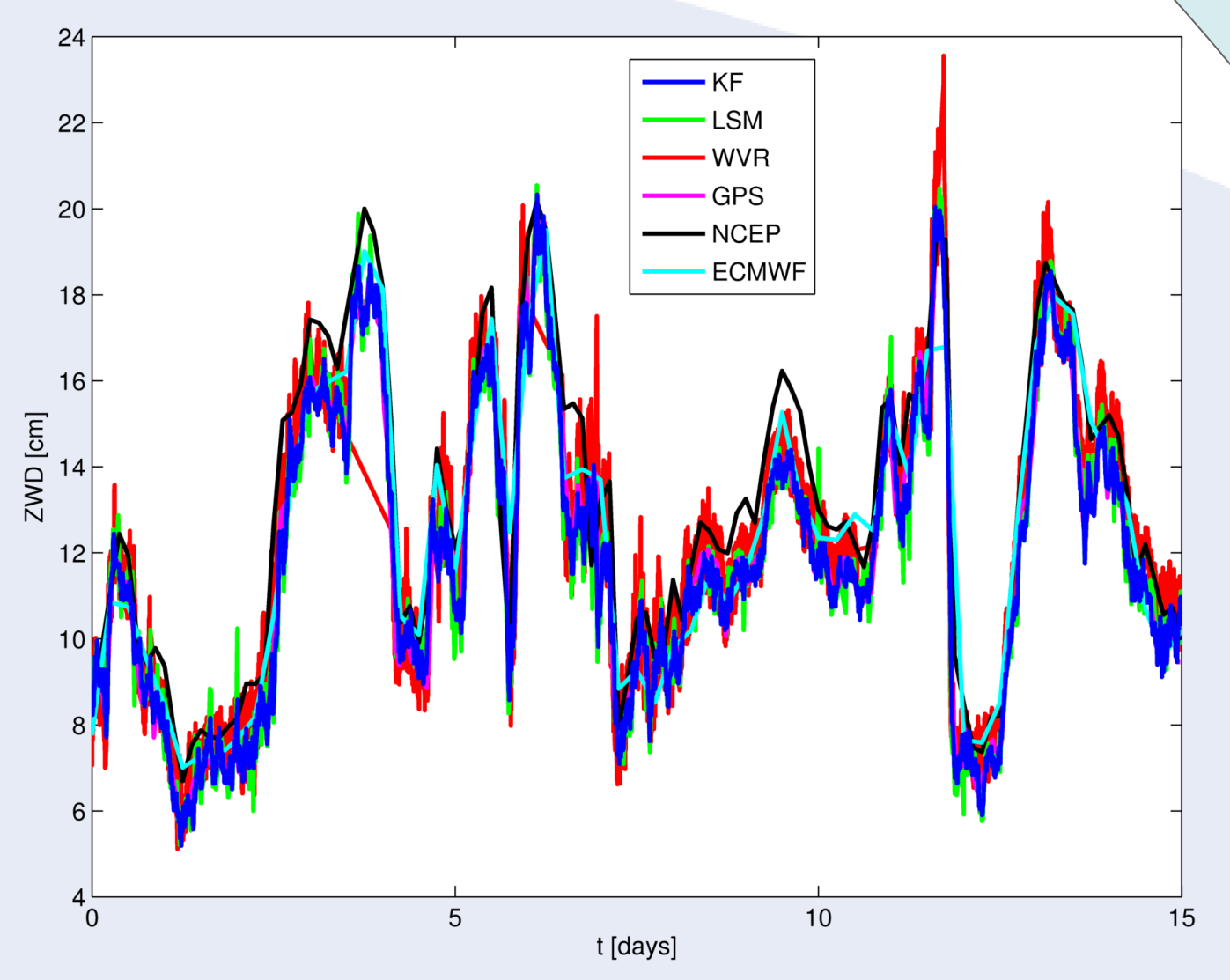

Fig. 7: ZWD from different techniques for Onsala during CONT11

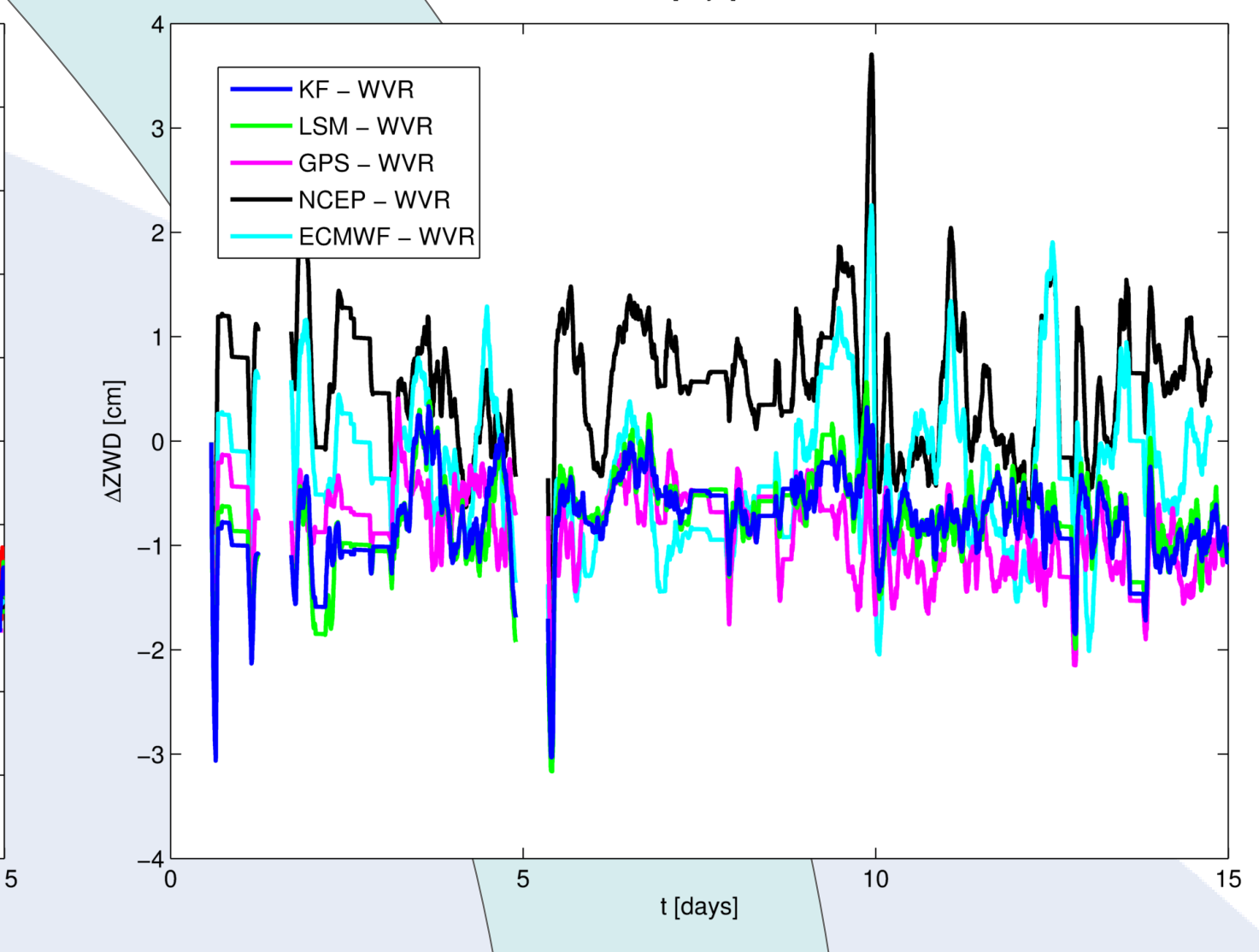

Fig. 8: Differences in ZWD from different techniques for Onsala during CONT14

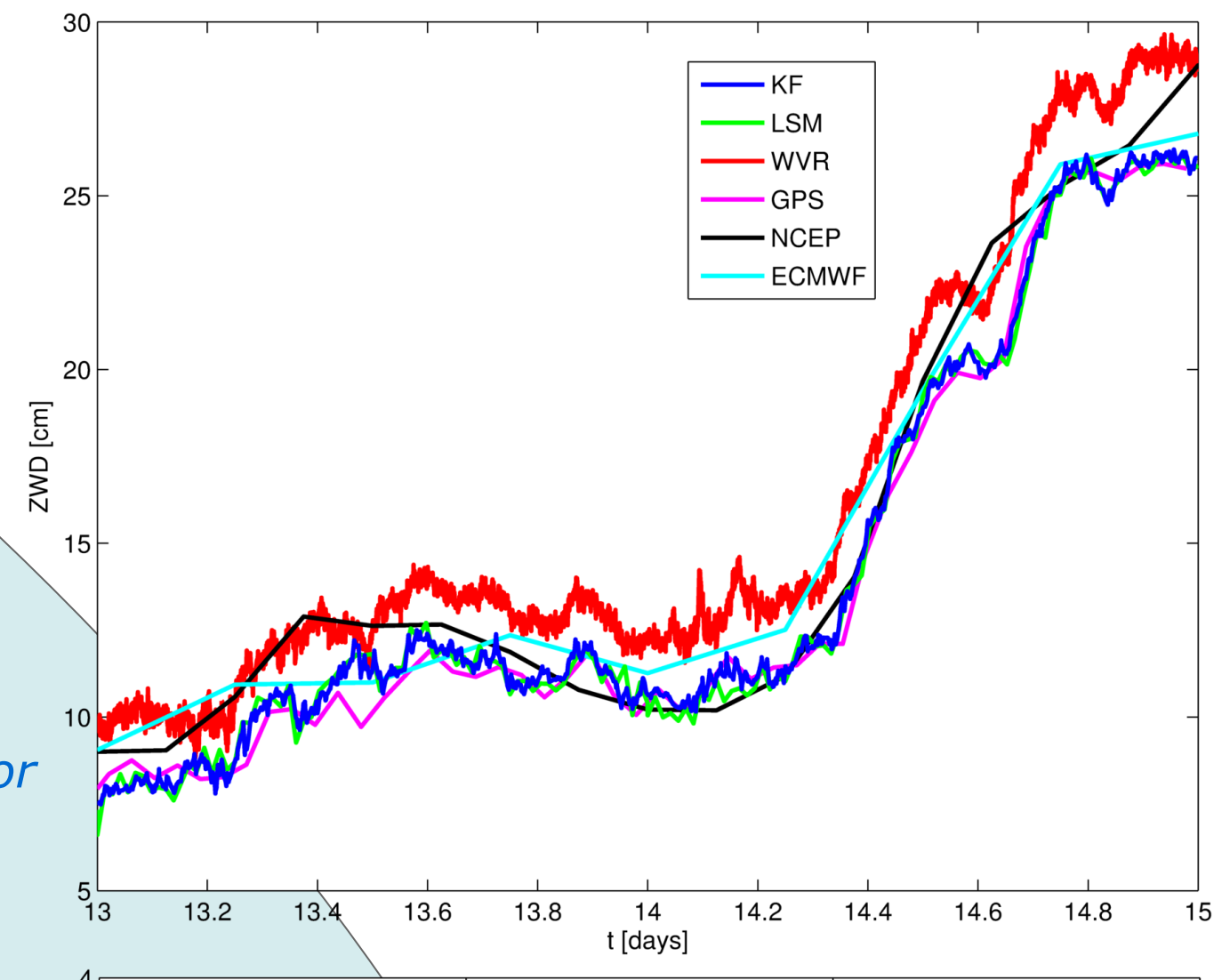

Fig. 9: ZWD from different techniques for Tsukuba during the last two days of CONT11

Conclusions

- The average **ZWD noise has decreased** during the last CONT campaigns.
- The **KF performs better than LSM** in terms of baseline length and station position repeatabilities (3-7%), as well as when compared to ZWD from external datasets (6-12%).
- The **improvement** gained by using a **station dependent ZWD noise** model is 2-3% for baseline length and station position repeatabilities. The most significant improvement is in the height component, as expected.

References:
Herring, T.A., Davis, J.L., Shapiro, I.I.: Geodesy by radio interferometry: The application of Kalman Filtering to the analysis of very long baseline interferometry data. Journal of Geophysical Research: Solid Earth 95(B8), 12561–12581 (1990). doi:10.1029/JB095iB08p12561
Schuh, H., Behrend, D.: VLBI: A fascinating technique for geodesy and astrometry. J. Geodyn. 61, 68–80, (2012). doi:10.1016/j.jog.2012.07.007

Acknowledgements:
The authors would like to thank the IVS for observing, correlating and providing the VLBI data used in this work. The work of Dr. Galina Dick, Dr. Zhiguo Deng (providing GPS data), and Dr. Florian Zus (providing the ray tracing data) is highly appreciated.

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