Applying Kalman filtering to investigate tropospheric effects in VLBI

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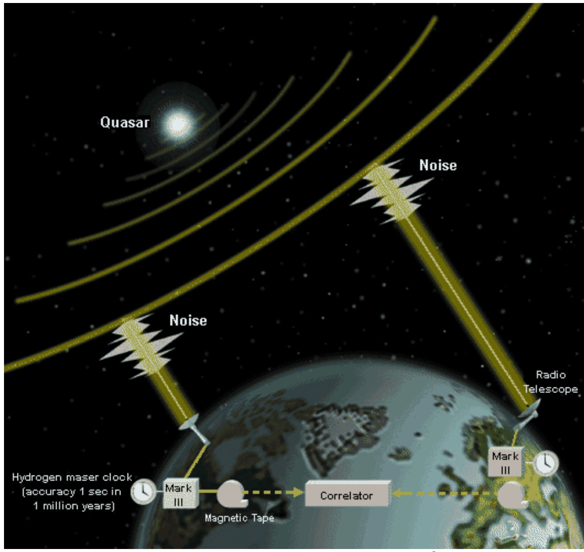
Overview: VLBI & troposphere

- VLBI important for EOP, TRF scale, CRF

- Precise determination of tropospheric delays



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$$\tau_{tropo} = {\tau_h}^z \cdot mf_h\,(e) + \,{\tau_w}^z \cdot mf_w\,(e)$$

- Zenith hydrostatic delays: from pressure at sites
- Zenith wet delays: normally parameterized as piecewise linear functions and estimated by least squares method (LSM)
- Horizontal gradients for azimuthal variations

Motivation for Kalman filtering

- Capable of real-time analysis of continuous observations
  - VLBI Global Observing System (VGOS): e-VLBI, observations 24/7
- Efficient handling of large number of observations
  - VGOS: increase in number of observations by 1-2 orders of magnitude
- Ease of including different data sets in the estimation
  - GGOS: combination of space-geodetic techniques
- Stochastic modeling (focus of this presentation)

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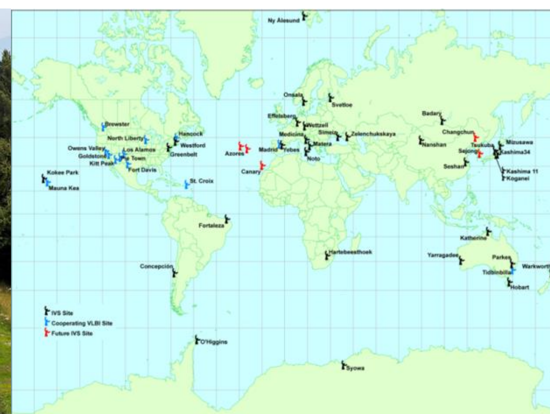

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Kalman filter overview

- Extended Kalman filter

Prediction

$$\tilde{x}_k = F_k x_{k-1} + w_k$$

$$\tilde{P}_k = F_k P_{k-1} {F_k}^T + Q_k$$

Correction

$$x_k = \tilde{x}_k + K_k(z_k - H_k \tilde{x}_k)$$

$$P_k = (I - K_k H_k)\tilde{P}_k$$

$$K_k = \tilde{P}_k {H_k}^T (H_k \tilde{P}_k {H_k}^T + R_k)^{-1}$$

- Forward + backward + smoothing
- Extension of the GFZ version of VieVS (Böhm et al., 2012)
- FWF project VLBI Analysis in Real-Time

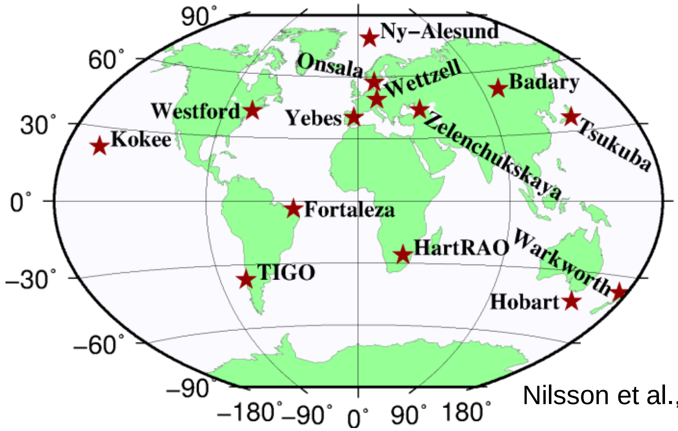
Kalman filter solution

- Estimating
  - Station coordinates (NNT+NNR constraints)
  - ERP: x pole, y pole, UT1
  - Clock + clock rate
  - ZWD + gradients
- IERS Conventions 2010
- Precession/nutation and radio source positions fixed (so far)
  - ERP results presented by M. Karbon (session G2.2, poster)
- Stochastic modeling for all parameters: random walk
- ZWD process noise
  - Herring, 1990: PSD = 58 cm^2/d
  - Schüler, 2001: PSD = 6 cm^2/d

VLBI data: CONT11

- CONT sessions: 15 days of continuous observations
- Large network of 10+ stations
  - R1/R4: 6-10 stations
- High data rate (512 Mbps)
  - R1/R4: 256 Mbps
- Highest quality of geodetic results
- Coordinated by the IVS

- CONT11 from Sept 15-29, 2011
- 14 stations
- ~1100 scans per day
- ~9000 observations per day

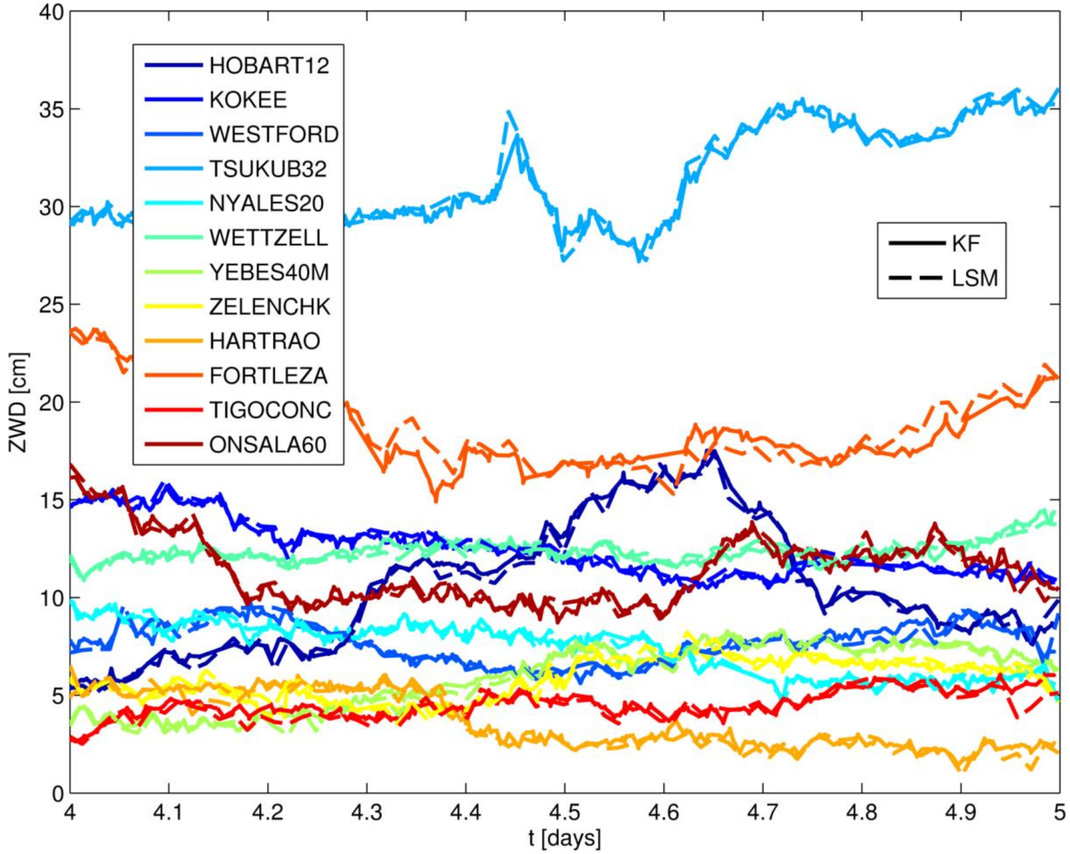


Nilsson et al., 2014

ZWD from KF and LSM

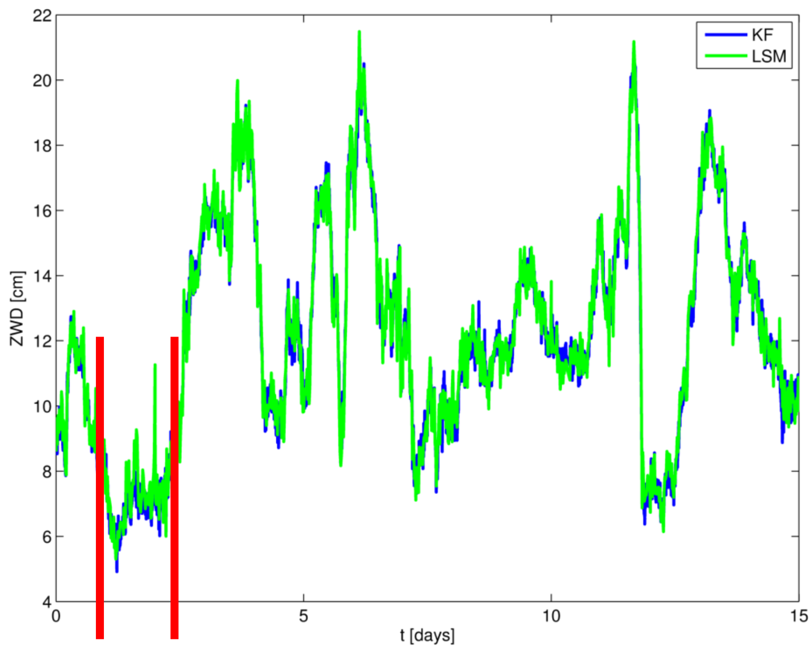
- Day 5 of CONT11
- KF: PSD_{ZWD} = 58 cm^2/d
- LSM: 20 min intervals

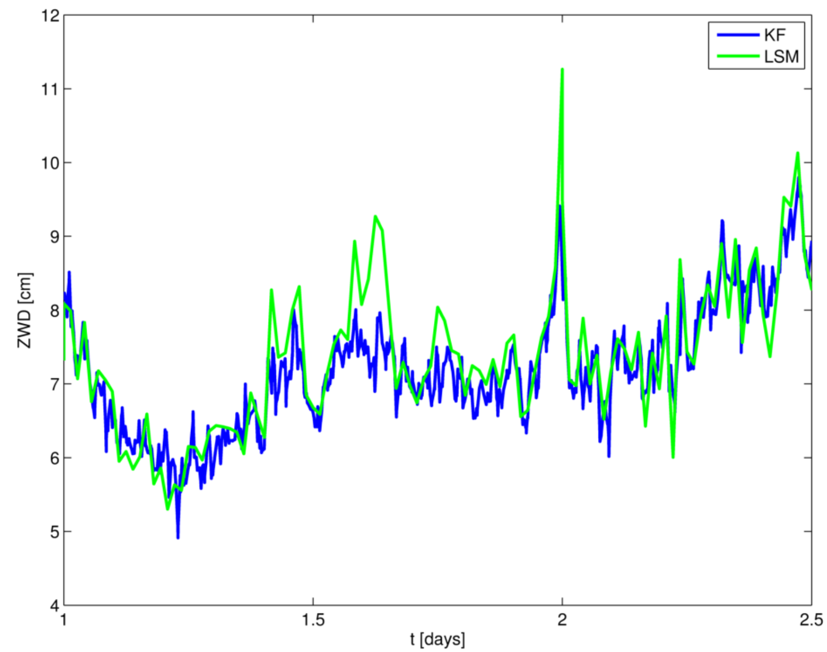
- RMS
  - LSM interpolated to KF epochs
  - Maximum: 7.4 mm (Fortaleza)
  - Average: 3.7 mm
- Difference of mean ZWDs
  - Maximum: 1.7 mm (Zelenchukskaya)
  - Average: 1.0 mm



ZWD from KF and LSM

- ZWDs for Onsala during complete CONT11 (left), excerpt (right)





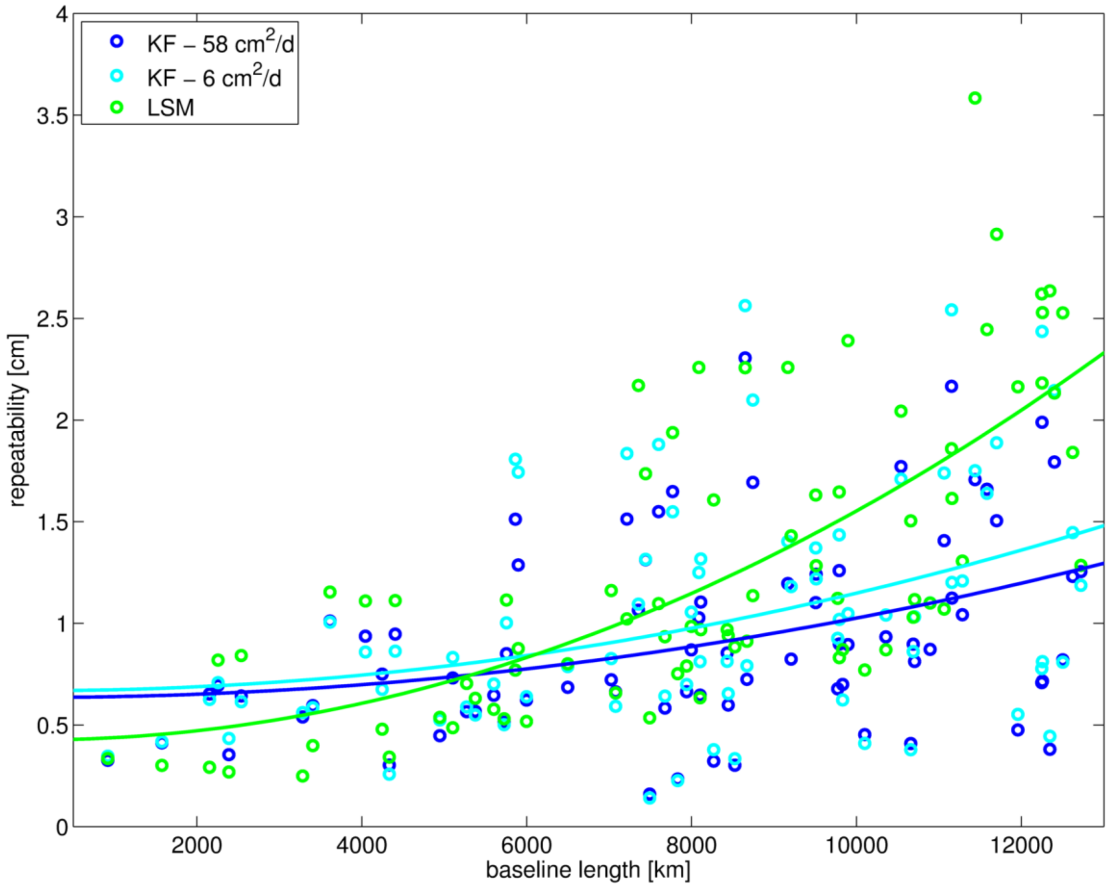
ZWD a posteriori standard deviations

- From KF and LSM covariance matrices
- Averaged over CONT11
- Smallest σ_{ZWD} for Kalman filter using PSD_{ZWD} = 6 cm^2/d

σ_{ZWD} [mm]	Onsala	Tsukuba
LSM	3.0	2.4
KF (58 cm^2/d)	3.8	3.3
KF (6 cm^2/d)	2.0	1.7

Baseline length repeatabilities

- LSM: station coordinates estimates once per day
- KF: random walk with PSD = 1 cm^2/d
  - for comparison with LSM: averaged over 1 day



External data during CONT11

- Water Vapor Radiometers at stations Onsala and Tsukuba
  - Onsala: ~7 s resolution
  - Tsukuba: ~50 s resolution, gaps
  - Data not used when liquid water > 0.7 mm

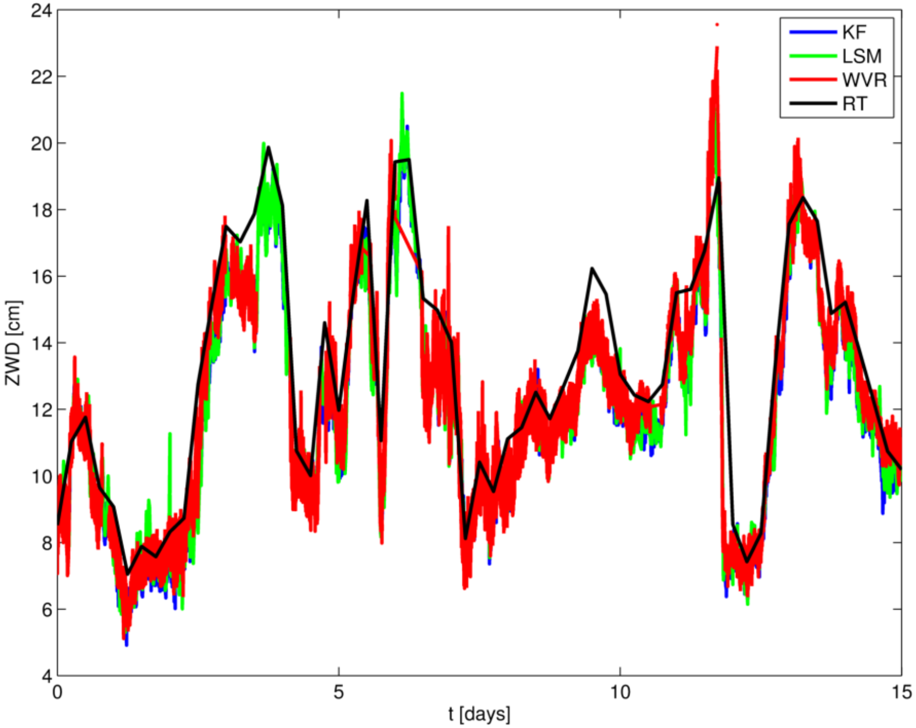
IVS 1999 Annual Report

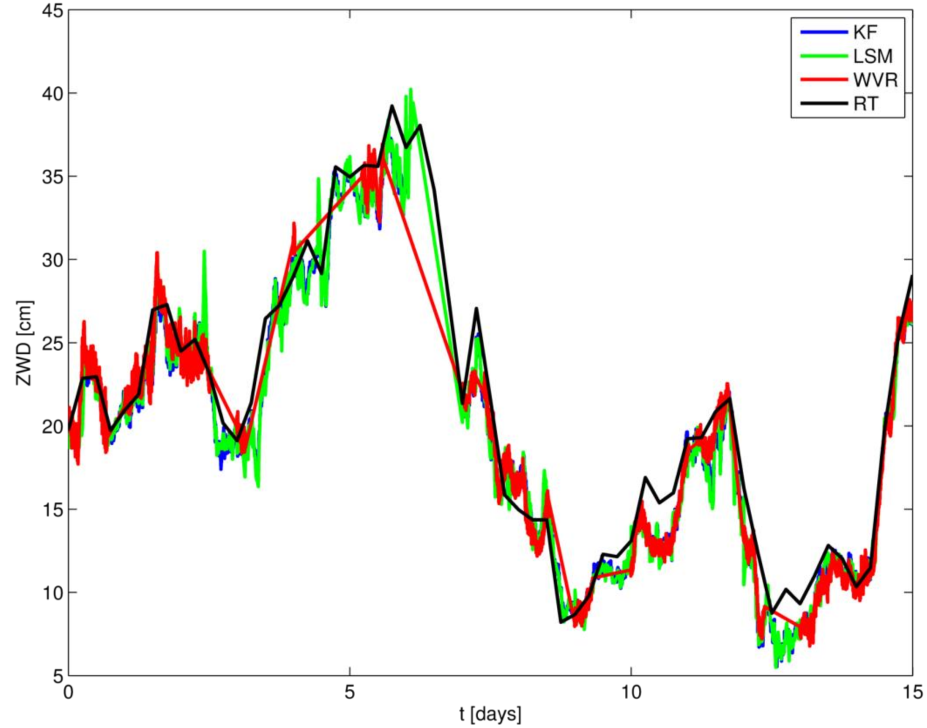
IVS 2005 Annual Report

- Ray-traced delays using the NCEP numerical weather models
  - 6 h resolution
  - Zus et al., 2014

Comparison to external data

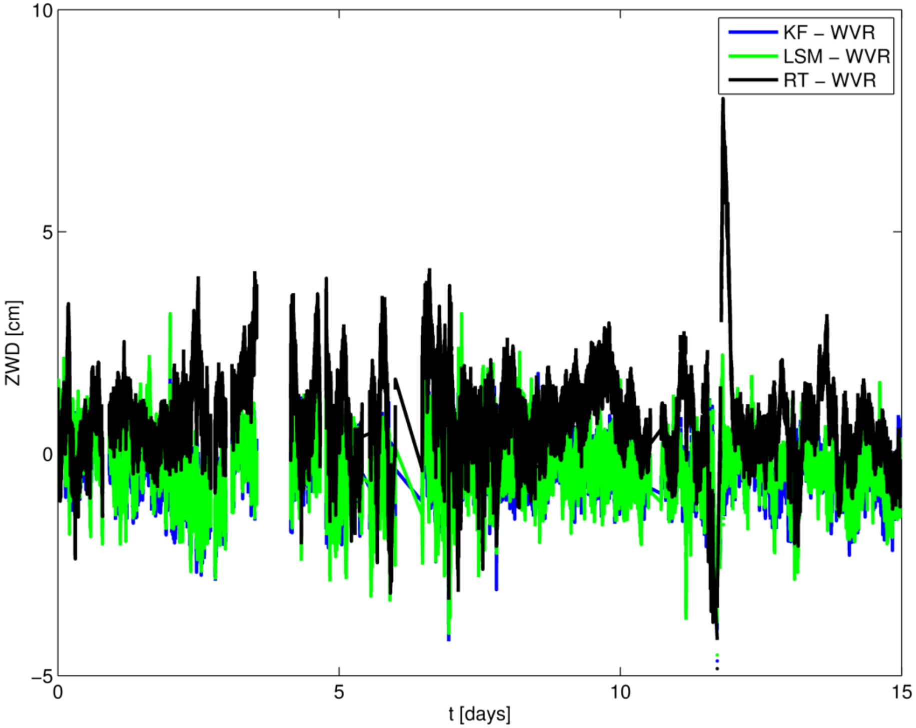
- ZWD comparisons for Onsala (left) and Tsukuba (right)

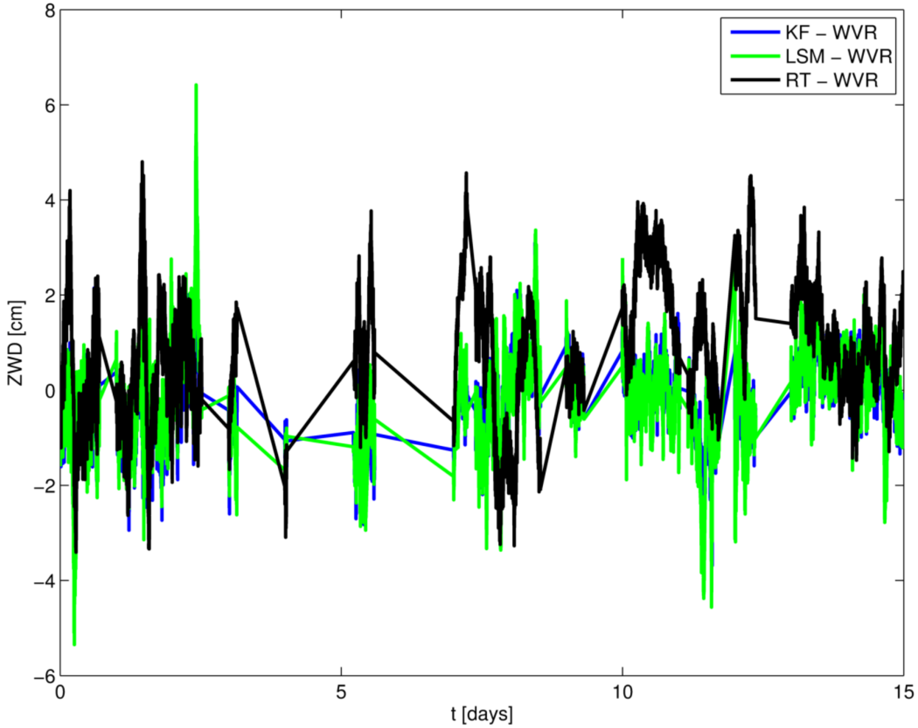




Differences w.r.t. WVR

- ZWDs interpolated to epochs of WVR data





RMS w.r.t. WVR

- Root-mean-square of differences w.r.t WVR
- Onsala: smallest RMS for KF using PSD_{ZWD} = 6 cm^2/d
  - 12% improvement w.r.t. LSM
- Tsukuba: smallest RMS for KF using PSD_{ZWD} = 58 cm^2/d
  - 15% improvement w.r.t. LSM

RMS [cm]	Onsala	Tsukuba
RT	1.33	1.61
LSM	0.74	1.04
KF (58 cm^2/d)	0.67	0.88
KF (6 cm^2/d)	0.65	0.95

Summary

- Successful implementation of Kalman filter for VLBI analysis
- ZWDs from KF and LSM show good agreement for CONT11
- KF with better baseline length repeatabilities
- Comparison with WVR ZWDs: KF up to 15% better than LSM

Outlook

- Station-dependent, dynamic process noise for ZWDs
- Comparisons to GNSS ZWDs
- Tropospheric gradients comparisons (WVR, RT, GNSS)
- Simulations using turbulence theory
- Integration of external data in the estimation

Thanks for your attention!

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