Subdaily station motions from Kalman filtering VLBI data

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Kalman filtering of VLBI data

- Main motivation: real-time analysis of continuous observations
  - VLBI Global Observing System (VGOS): e-VLBI, 24/7 operations
  - FWF project VLBI Analysis in Real-Time (VLBI-ART)
- Main advantage today (post-processing): state based approach
  - Stochastic processes instead of deterministic functions
- Implementation in VieVS@GFZ
  - Kalman filter & smoother
  - Estimation of same geodetic parameters as Vie_LSM
  - Same models and conventions as Vie_LSM
  - Random walk (RW) for most parameters, optional to use integrated RW or first order Gauss-Markov processes
- KF & troposphere: Soja et al. (P3-03)
- KF & EOP: Karbon et al. (P3-11)

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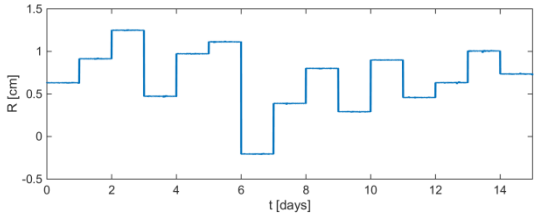
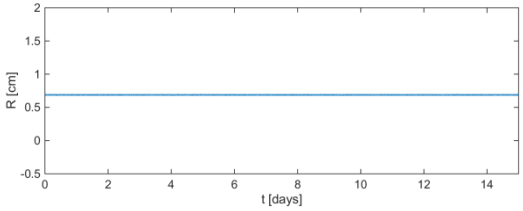
Estimation of station coordinates by KF

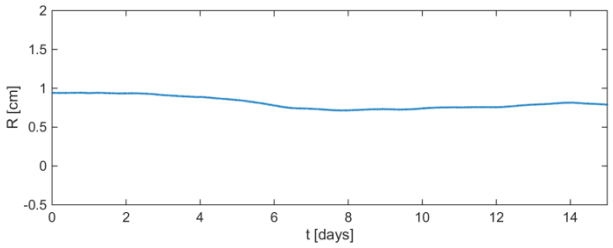


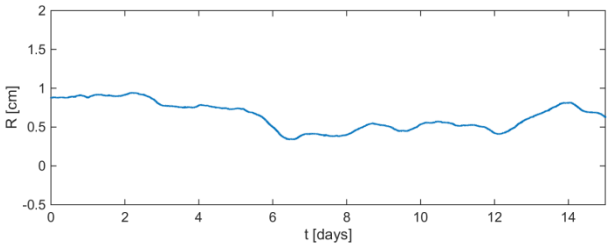
- Option to estimate daily values
  - Random walk with process noise set to zero
- Option to force continuity at session borders
  - Prediction from previous session

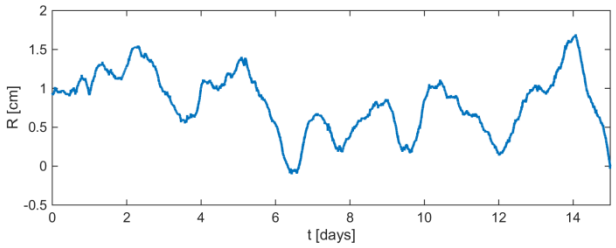


- Option to allow subdaily motion
  - Process noise ≠ zero
  - Example noise levels (power spectral densities PSD of the driving white noise):
    1. 0.01 cm^2/d
    2. 0.1 cm^2/d
    3. 1 cm^2/d

Onsala, CONT14



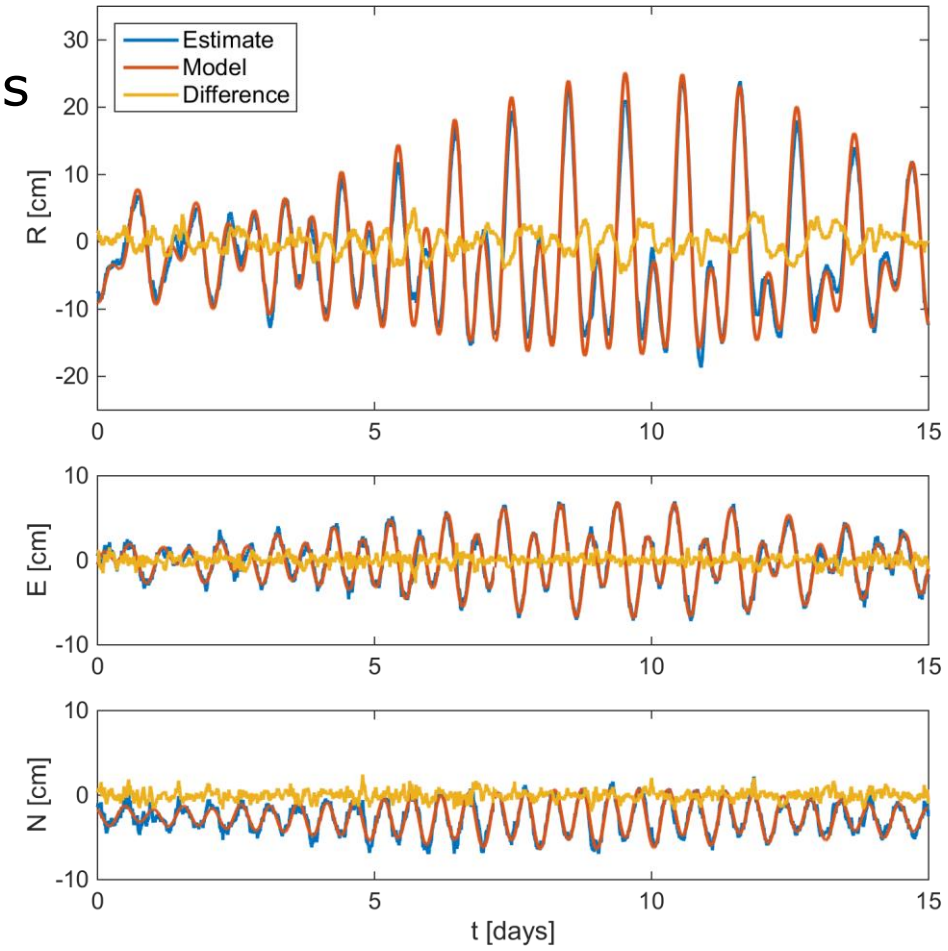




Test case: recovery of neglected geophysical displacements (I)

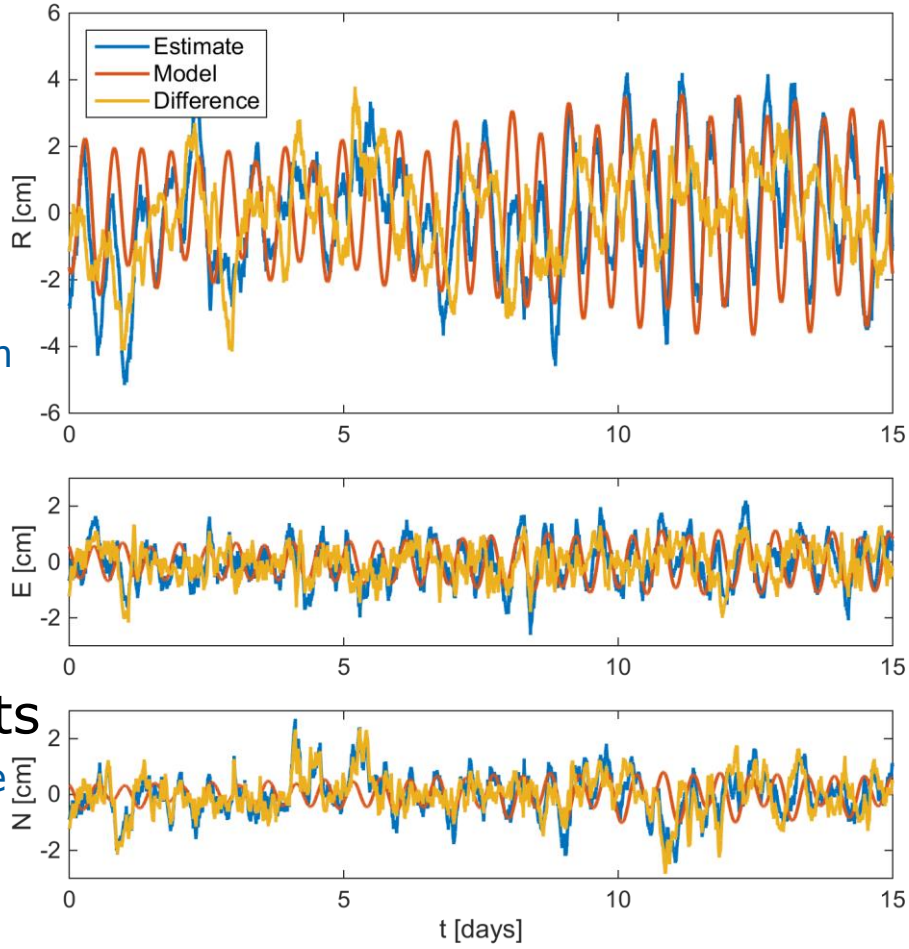
- Switch off displacement models for selected stations
- Exclude them from the datum
- Increase PSD significantly
- KF should recover signals

- Solid Earth tide displacements
  - Example of YEBES40M during CONT14
  - Model itself: RMS of 10.8 cm, peaks of ± 20 cm
  - PSD in the KF set to 100 cm^2/d
  - WRMS KF minus IERS model: 1.8 cm
  - 83% successfully recovered
  - Similar performance for other stations



Test case: recovery of neglected geophysical displacements (II)

- Ocean tide displacements
  - Example of WARK12M during CONT14
  - Model itself: RMS of 1.9 cm, peaks of ± 4 cm
  - PSD in the KF set to 30 cm^2/d
  - WRMS KF minus FES2004 model: 1.6 cm
  - 16% recovered, but phase agrees well
- Tidal & non-tidal atmosphere loading displacements
  - Effects too small to recover
- Hydrology loading displacements
  - Only monthly models publically available



Subdaily motions in VLBI analysis

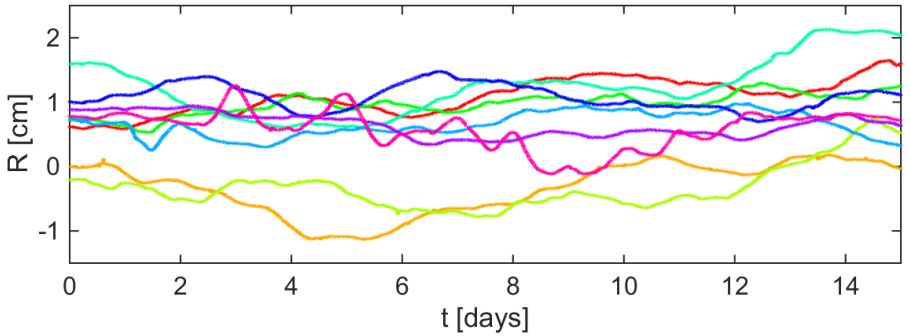
Assumptions:

- Applying all loading models except for hydrology and non-tidal ocean loading
- Hydrology and non-tidal ocean loading not relevant on timescales of a few days
- Solid Earth tide correction and Love/Shida numbers accurate enough

→ Variations in estimated coordinates mainly due to:

1. Deficiencies in tidal ocean and atmosphere loading models
2. Correlations with troposphere and clock parameters

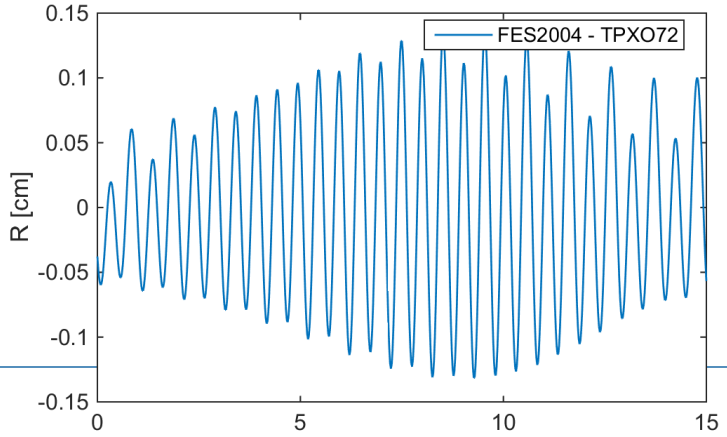
Different stations, CONT14

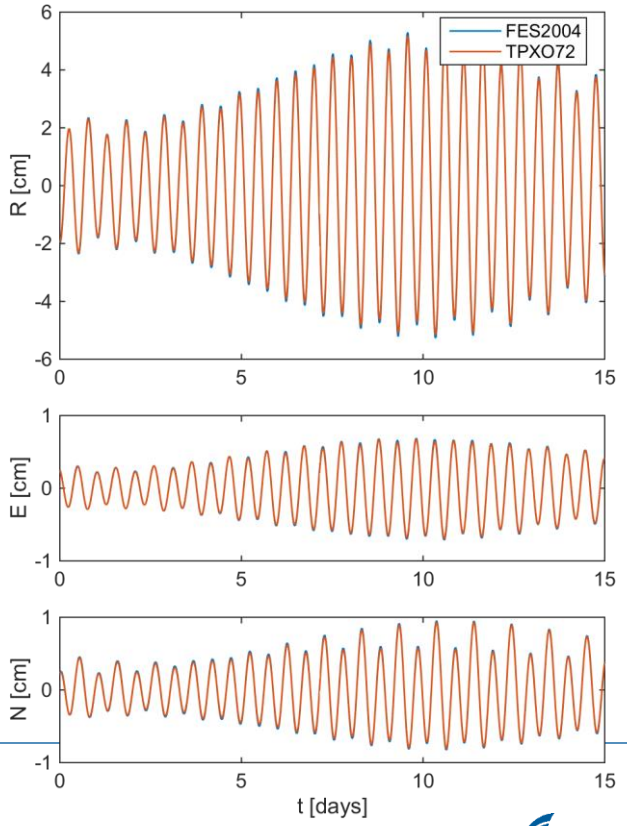


Deficiencies in loading models (I)

- Accuracy and reliability of models difficult to assess
- Approach: investigate differences between loading models provided by different institutions

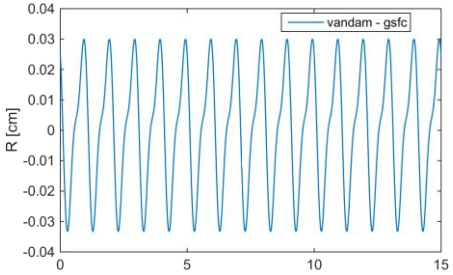
- Ocean tide loading
  - FES2004
  - TPXO 7.2
  - Tested many others, similar results



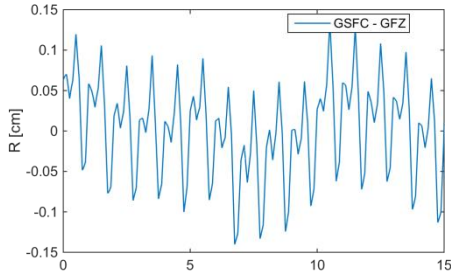


Deficiencies in loading models (II)

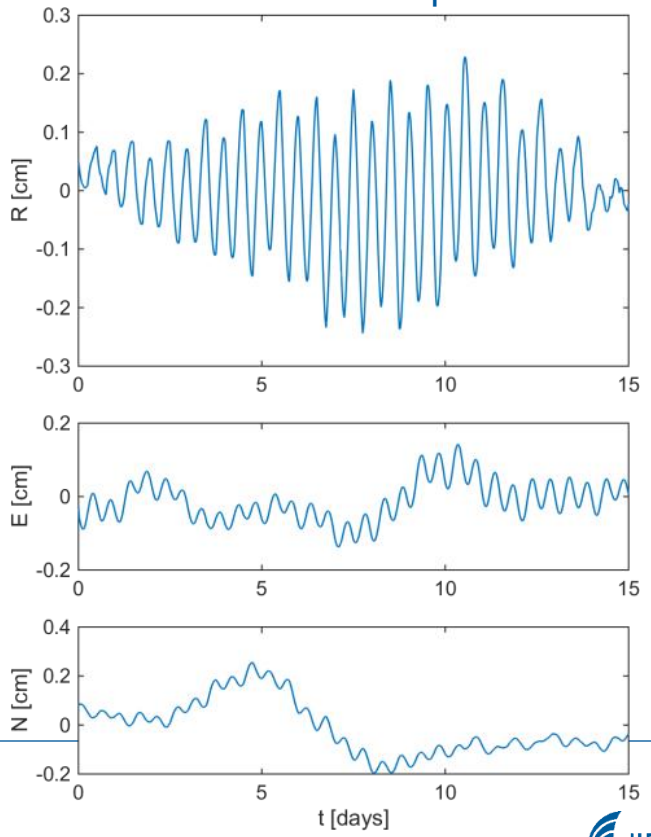
- Tidal atmosphere loading
  - University of Luxembourg
  - GSFC



- Non-tidal atmosphere loading
  - GSFC
  - GFZ



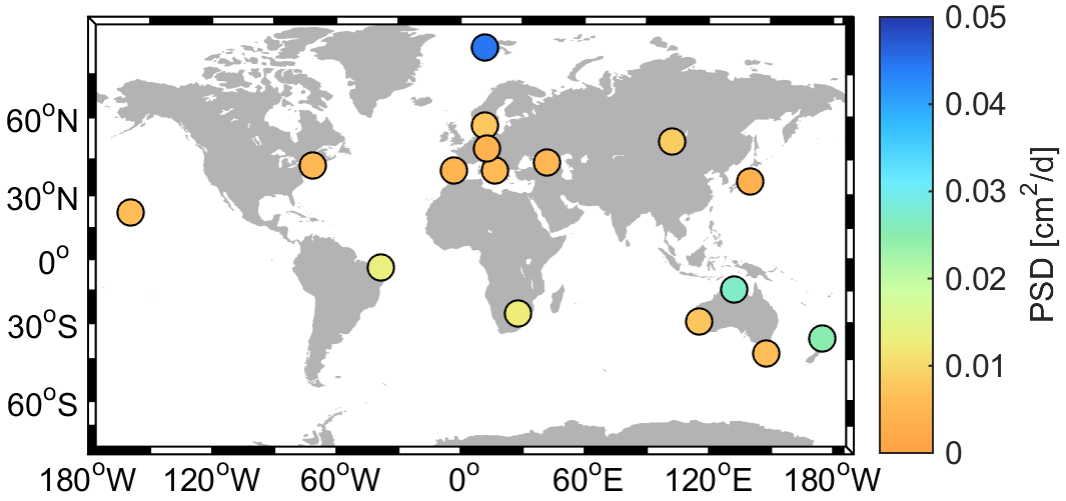
- Summation of all differences
  - ocean & atmosphere



Deficiencies in loading models (III)

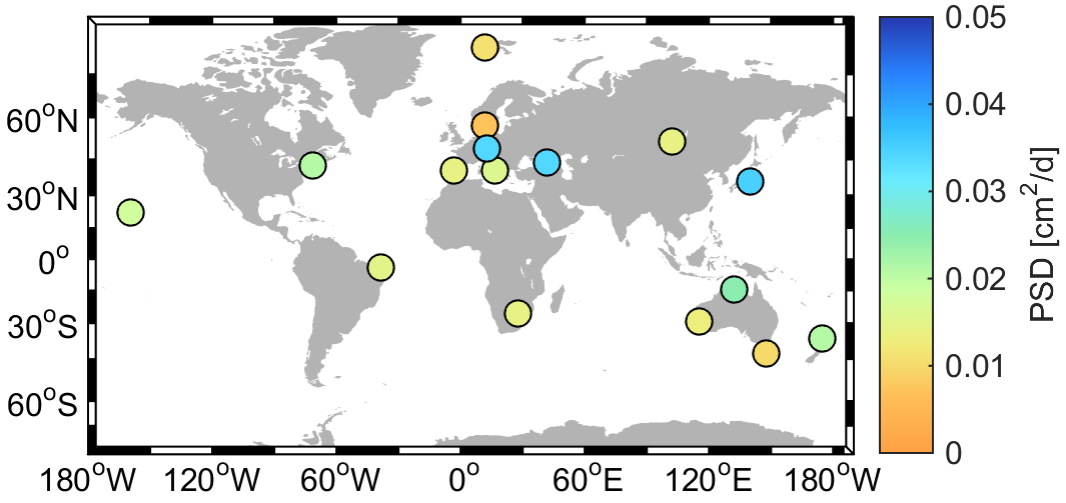
- Time series of loading model differences computed
  - for every station of CONT14
- PSD estimated via Allan standard deviation
  - Assuming random walk process
- Map: PSD averaged over radial, east, and north components

- Station average: 0.011 cm²/d
- Maximum at Ny-Ålesund
  - Ocean loading models with large differences
- Average 0.009 cm²/d without Ny-Ålesund



Process noise of station coordinates

- PSD of station coordinates computed from KF solution
  - KF setup with random walk, PSD of 0.1 cm^2/d
- PSD estimated via Allan standard deviation
  - Assuming random walk process
- Map: PSD averaged over radial, east, and north components
- Station average: 0.019 cm^2/d
- Compared to PSD from model deficiencies:
  - 2x as large
  - No significant correlations



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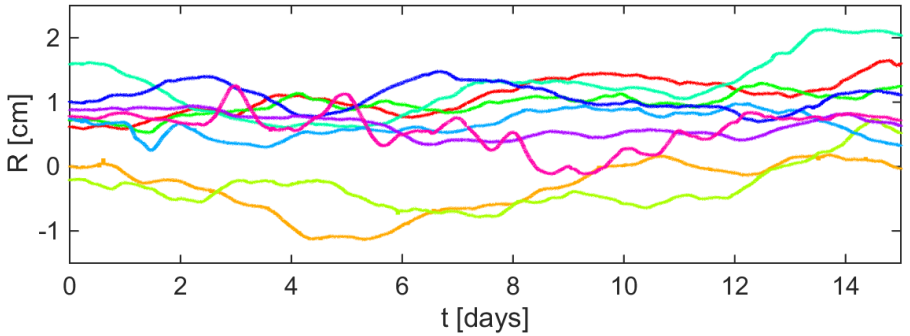
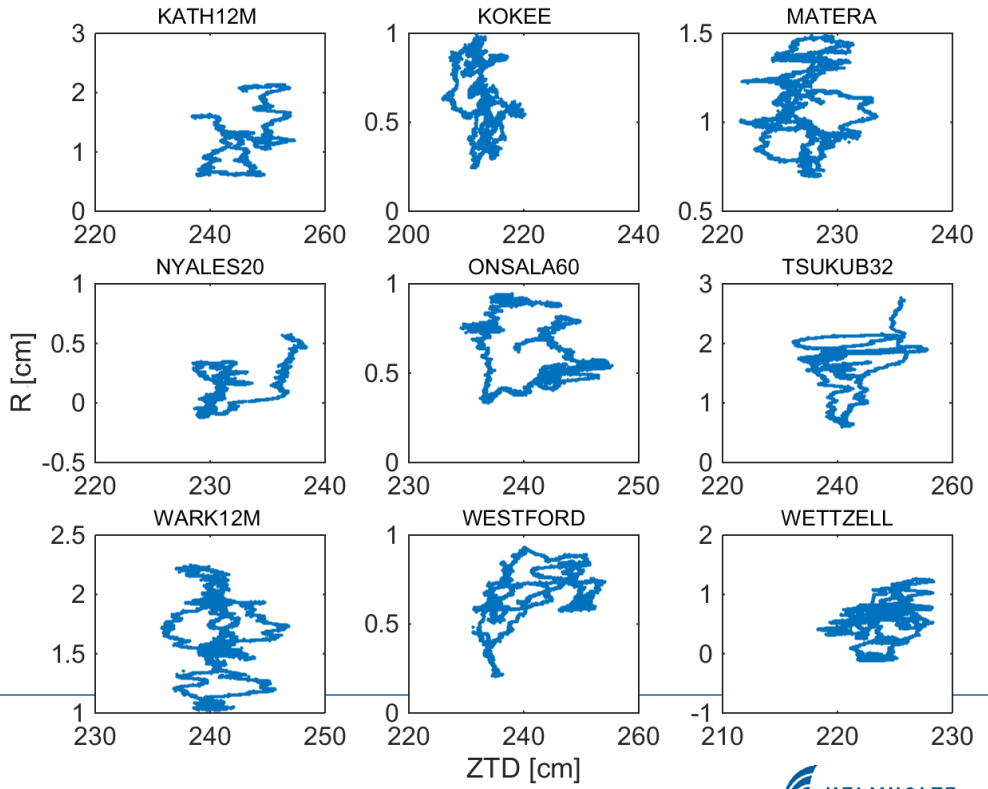


Correlations with other parameters

- Correlations between station height, tropospheric delays, clocks
- Separation by aiming for good sky coverage
  - CONT14 with better geometry compared to standard IVS sessions

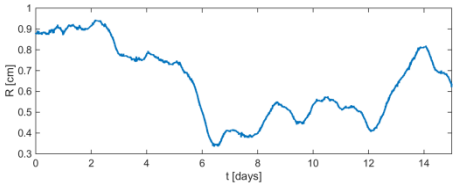
- KF solution
  - Station coordinate PSD of 0.1 cm^2/d
  - ZWD PSD of 17 cm^2/d
- Correlations between ZTD and radial component (R):
  - From -0.51 to 0.60, average 0.09
  - Statistically significant ($p < 0.05$)



Correlations with troposphere (I)

- Possibility in our KF implementation to fix ZWD to that from other solutions or external data
- Four different solutions, example: Wettzell, CONT14
  - Station coordinate PSD always 0.1 cm^2/d

1. ZWD estimated (standard)
2. ZWD fixed to KF solution with constant station coordinates
3. ZWD fixed to KF solution with daily station coordinates
4. ZWD fixed to GPS solution
   - 5 min temporal resolution
   - Lu et al. 2015



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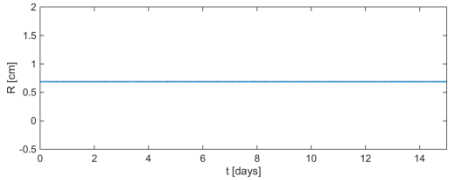

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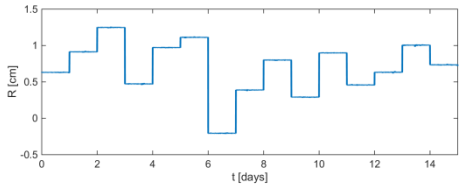

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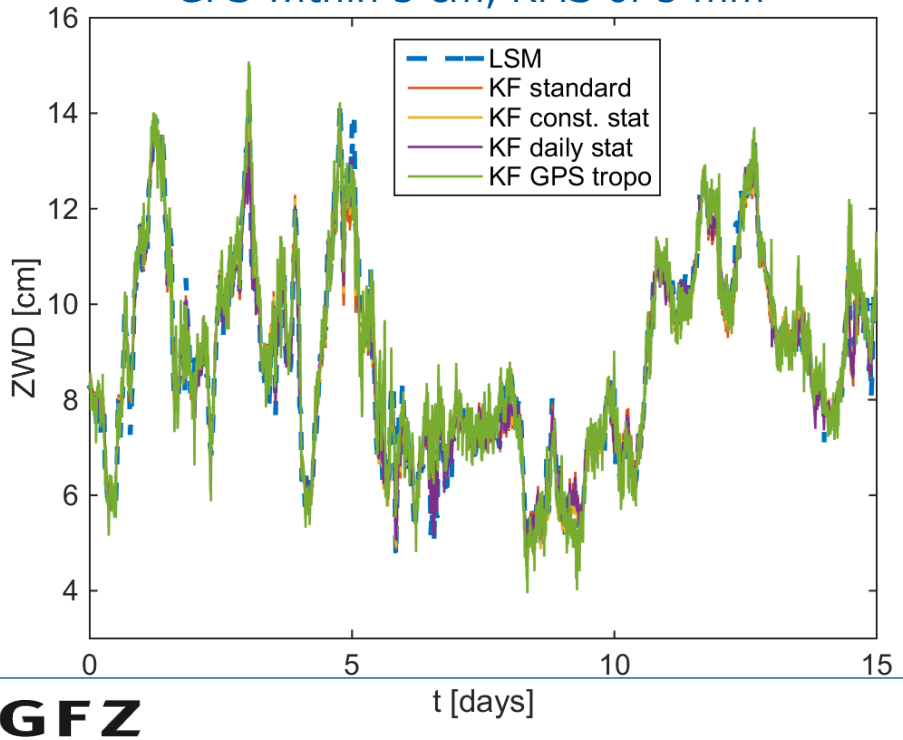
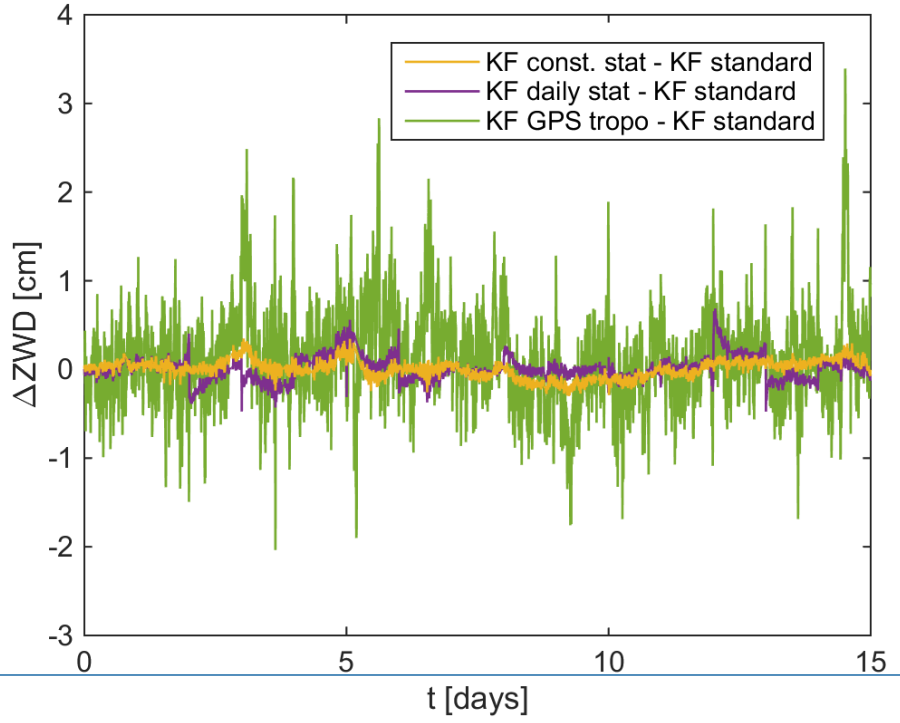
4.

Correlations with troposphere (II)

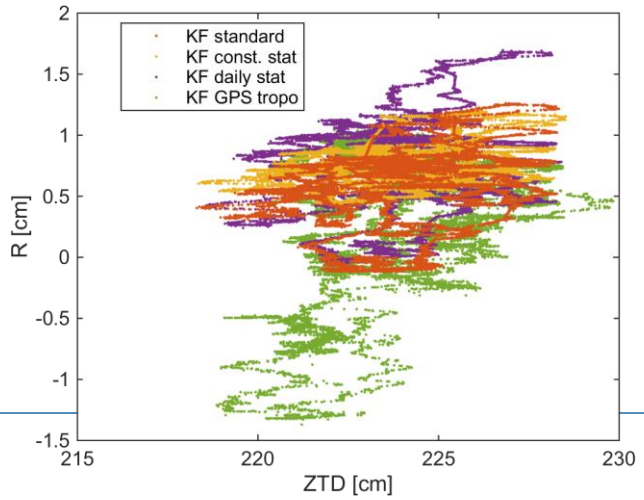
- Comparison of ZWD from the different solutions
- Differences w.r.t. KF standard solution
  - VLBI solutions within 5 mm, RMS of 1 mm
  - GPS within 3 cm, RMS of 5 mm

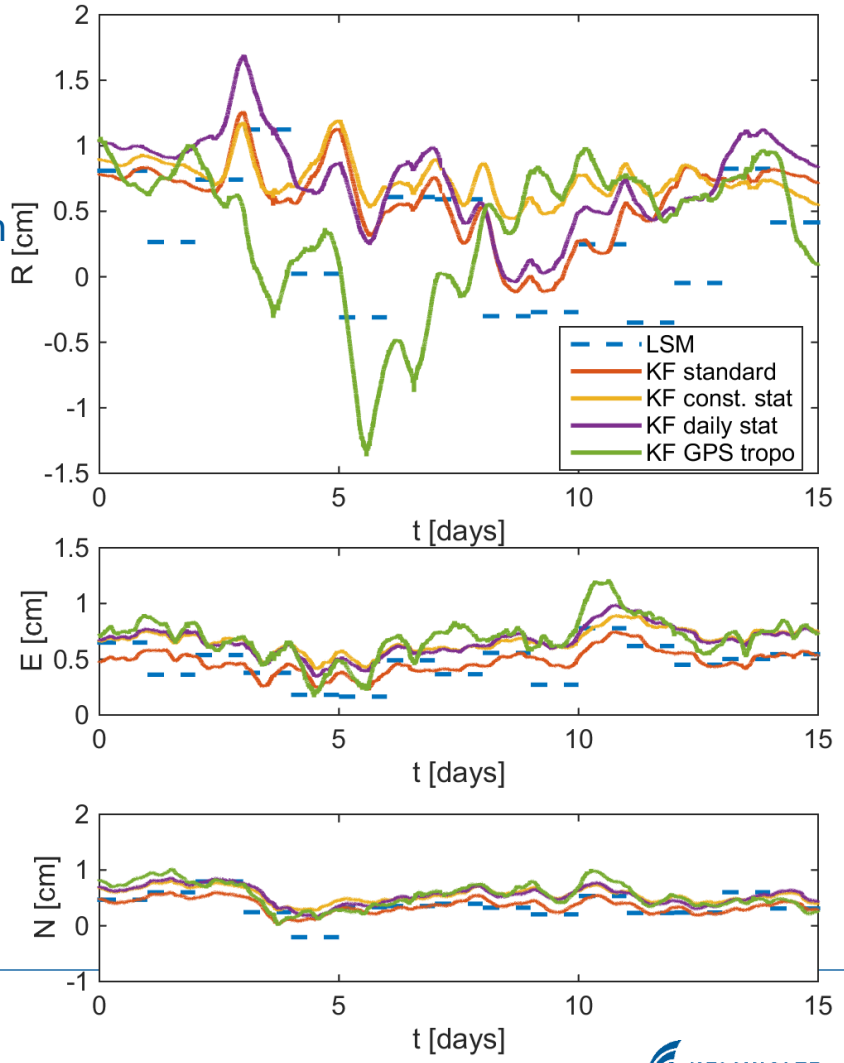




Correlations with troposphere (III)

- Effect on station coordinates
- Differences in radial components
  - VLBI solutions within 6 mm, RMS of 2.5 mm
  - GPS within 9 mm, RMS of 6 mm
- Correlations between ZTD & R
  - KF ZWD solutions: 0.1-0.3
  - GPS ZWD solution: 0.4
  - Statistically significant



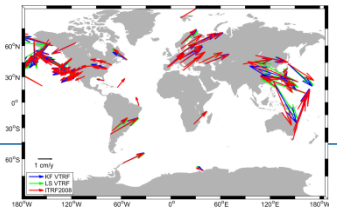


Summary

- **Kalman filtering allows to study station displacements** on various timescales by adapting the stochastic model
- **Residual differences of loading models** may explain about 50% of the estimated variations in station coordinates
  - in terms of noise level; assumptions could be too optimistic
- **Correlations with tropospheric delays** found to be significant, impact of up to 1 cm in height
  - when applying different ZWD solutions from VLBI and GPS

Outlook

- Compare to external data: GNSS coordinates, gravimetry
- Estimate empirical subdaily model from residual VLBI time series
- *Advertisment*: Kalman filter for VTRF creation
  - Talk at IUGG 2015 in Prague by Soja et al.



Thanks for your attention!

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GPS data: Cuixian Lu
Loading models: several institutions (see talk)
Project funding: FWF (VLBI-ART – P 24187-N21)