Application of Kalman filtering for the determination of a VLBI terrestrial reference frame

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HELMHOLTZ ASSOCIATION

Kalman filter for TRF determination

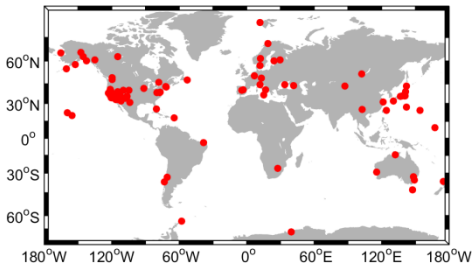
- Time series representation → capture short-term variations
- Short-term stability by restrictive stochastic model
- Predictions by extrapolating the functional model
- TRF easy to update & real-time capable

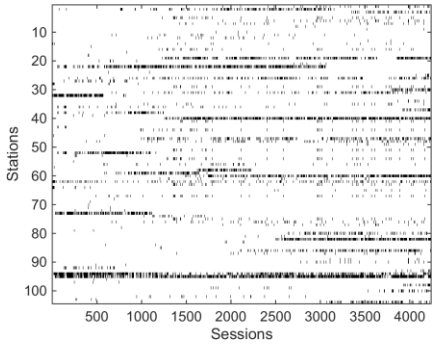
- Kalman filter software for multi-technique TRFs (KALREF) developed at NASA JPL
  - Wu et al., 2015
  - JTRF2014
- Software at GFZ: VLBI only – focus on different modeling approaches
  - Soja et al. (JoG, submitted)

raege.net

Input VLBI data

- 4239 IVS VLBI sessions between 1980 and 2013
  - 4 or more telescopes participating
  - Spanning a polyhedron with a volume of more than 10^{15} m^3
- 104 stations out of 143 stations considered
  - Regular observations over more than 1 year
- Session-wise station coordinates XYZ
  - NNT+NNR w.r.t. ITRF2008 for all stations with ITRF2008 coordinates





Kalman filter setup

- Kalman filter & smoother
- States updated for every VLBI session (usually every 1-4 d)
- Breaks in position and/or velocity
  - Earthquakes, equipment changes
- Output:
  - Filtered and smoothed XYZ time series
  - Average: XYZ at reference epoch, velocities, amplitude + phase of annual signals
- Datum by 12 parameter transformation (scale not changed)
  - Average coordinates & velocities w.r.t. ITRF2008 for selected datum stations

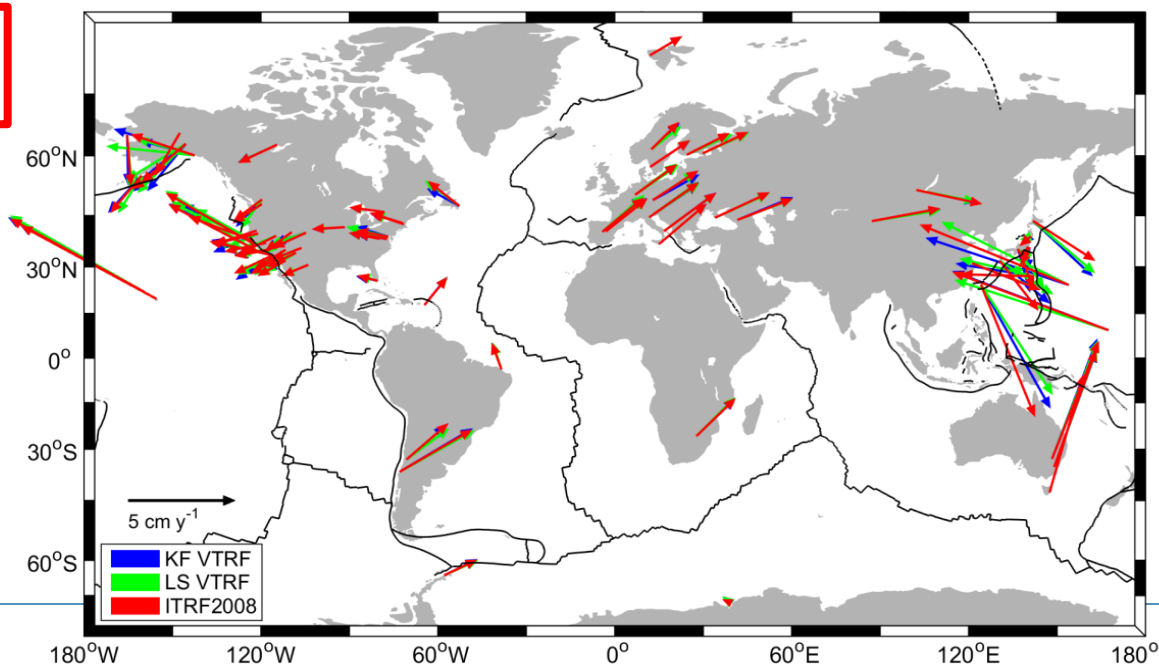
$$\tilde{x}_k = F_k x_{k-1}$$

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

$$F_k = \begin{bmatrix} 1 & dt & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 2\cos\left(2\pi\frac{dt}{T}\right) & -1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Comparison of linear TRFs

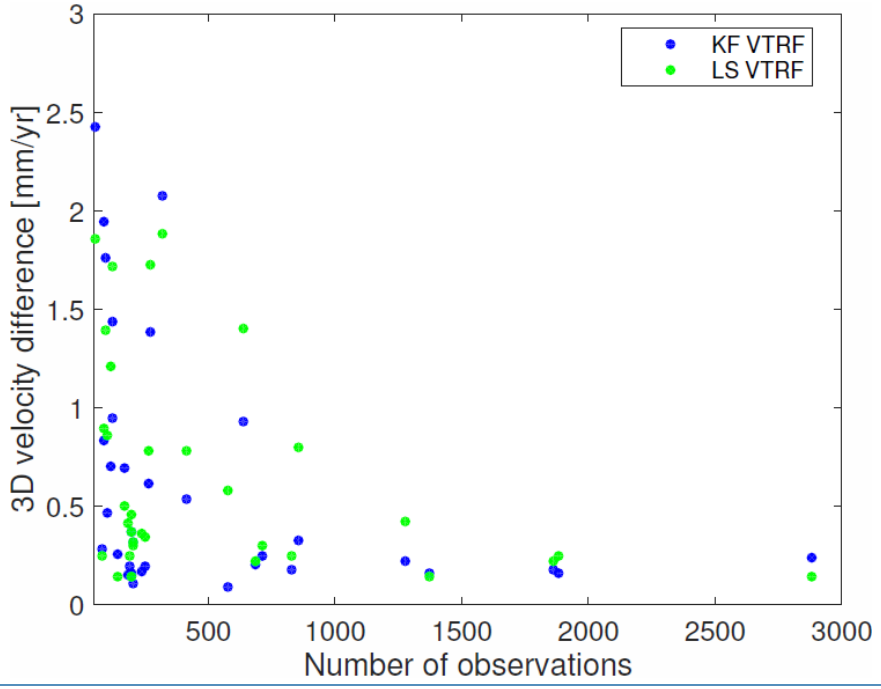
- Kalman filter in „linear mode“ (zero noise)
  - Transformation to ITRF2008 based on 10 stable core stations
- Consistent global solution (with VIE_GLOB)
  - Stacking of normal equations
  - NNT+NNR w.r.t. ITRF2008 for same 10 core stations
- ITRF2008
  - Altamimi et al., 2011



Velocity differences w.r.t. ITRF2008

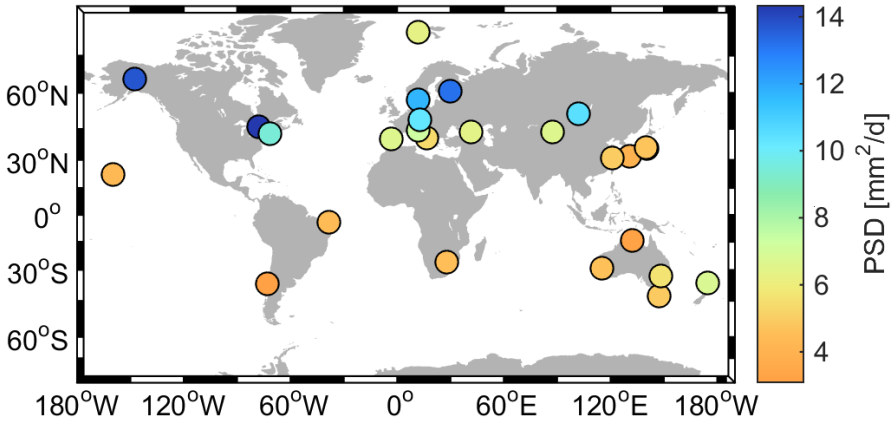
- RMS values of the velocity differences of linear Kalman filter and least-squares VLBI TRF solutions
- 64 stations
  - present in all 3 solutions
  - with observation history > 3 years
  - without breaks
- 21 stations
  - out of the 64 stations
  - participated in more than 200 sessions

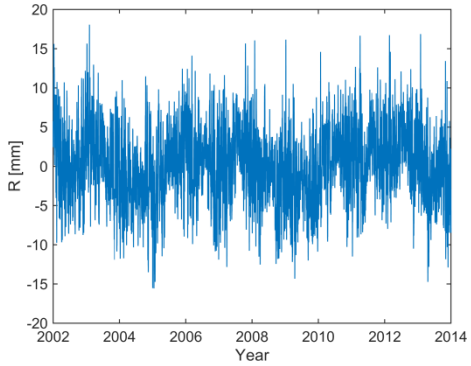
RMS [mm/yr]	64 stations R	E	N	3D	21 stations (> 200 obs.) R	E	N	3D
KF VTRF	3.91	1.43	1.53	4.44	1.42	0.67	0.32	1.60
LS VTRF	6.59	2.23	2.35	7.34	1.87	0.70	0.44	2.05



Process noise of station coordinates

- Assumption: irregular station coordinate variations due to unmodeled NTAL, NTOL & CWSL displacements
- Time series of NTAL, NTOL & CWSL
  - Downloaded from `massloading.net` (Petrov, 2015), resolution 6 h
  - Sum calculated, trend & annual signal removed
- Assuming random walk (RW) processes → computation of power spectral densities (PSDs) of driving white noise

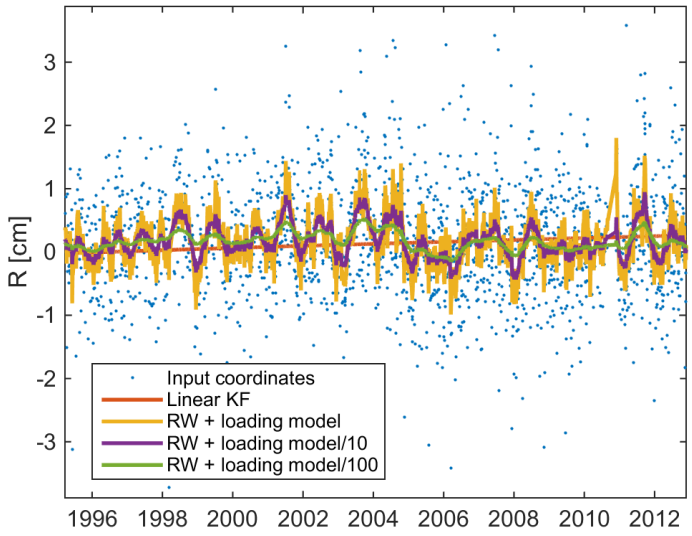




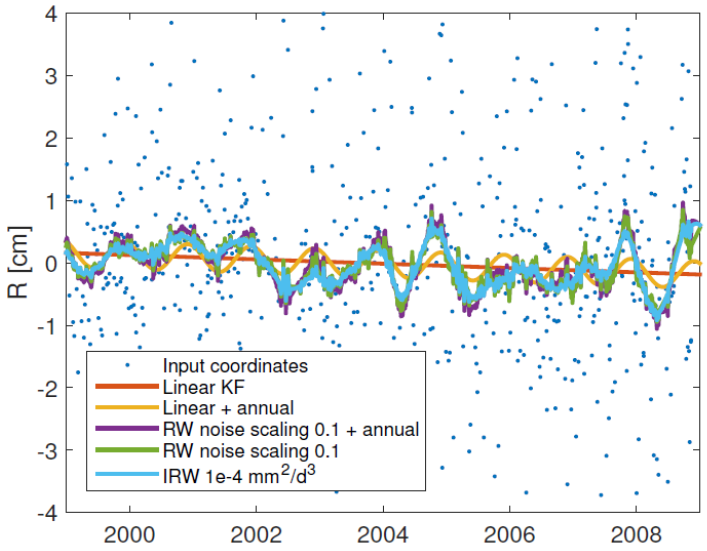
ALGOPARK

Station coordinate time series

- Solutions with different functional and stochastic models
  - Linear, linear+annual, RW, RW+annual, integrated RW
- RW solutions: applying noise model from loading displacements
  - Scaled by factor 1, 1/10, 1/100



WETTZELL

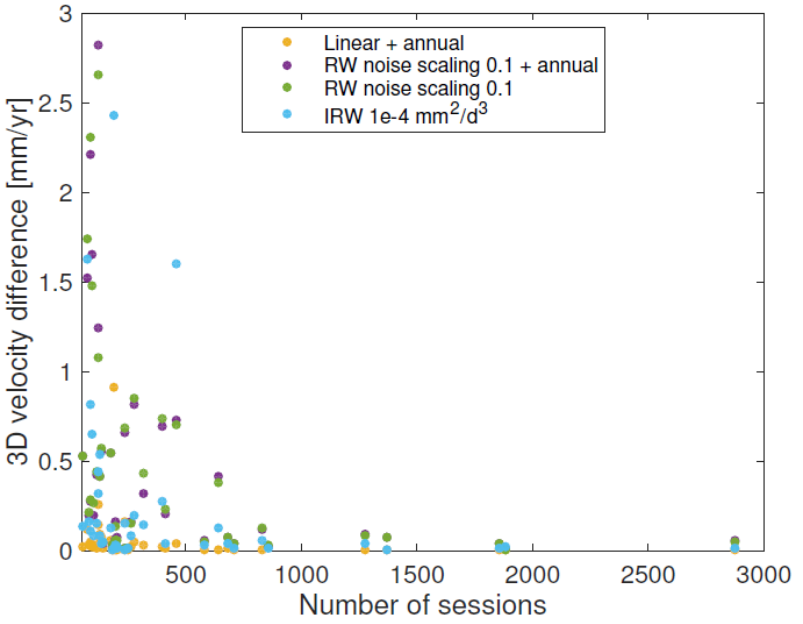


FORTLEZA

Velocity comparison of TRF solutions

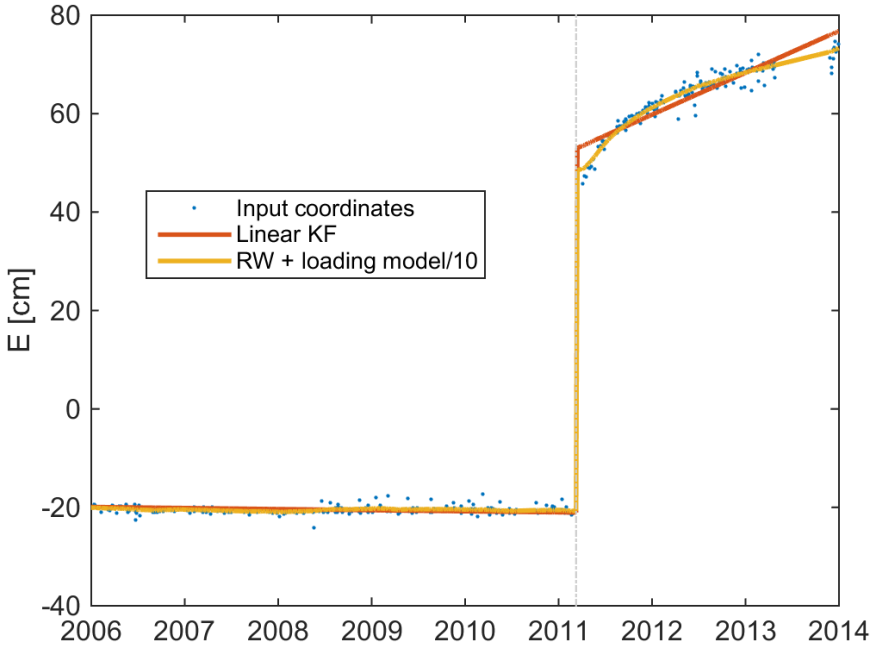
- RMS values of the velocity differences of Kalman filter TRF solutions w.r.t. the linear Kalman filter TRF solution
- 74 stations
  - with observation history > 3 years
  - without breaks
- 22 stations
  - out of the 74 stations
  - participated in more than 200 sessions

RMS [mm/yr]	74 stations R	E	N	3D	22 stations (> 200 obs.) R	E	N	3D
Linear + annual	1.65	0.64	0.52	1.85	0.03	0.01	0.01	0.04
RW noise scaling 0.1 + annual	3.52	0.88	2.61	4.47	0.30	0.12	0.09	0.34
RW noise scaling 0.1	1.26	0.56	1.48	2.02	0.31	0.13	0.10	0.35
IRW 10^{-4} mm^2/day^3	1.26	0.39	0.61	1.45	0.28	0.09	0.19	0.35

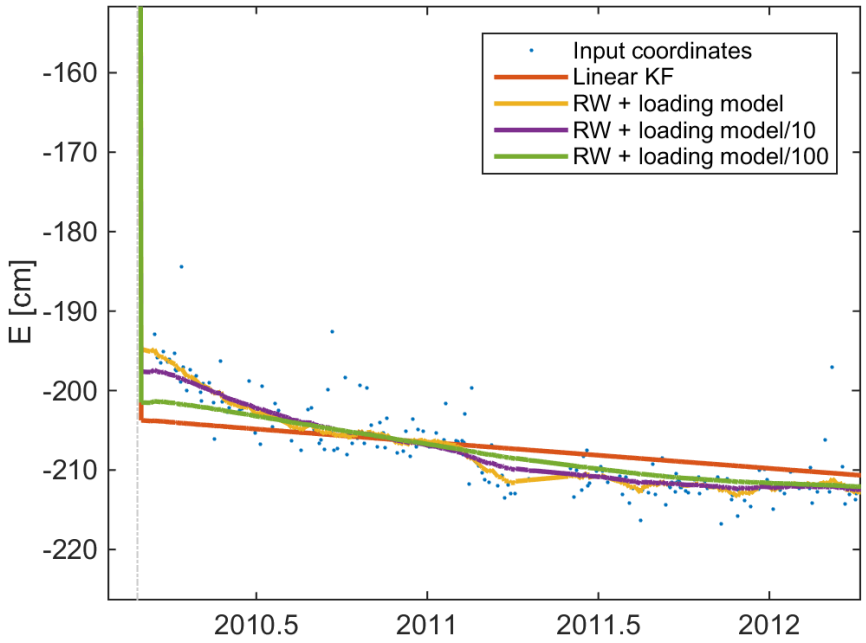


Earthquake handling

- Post-seismic motion captured by KF setups with process noise
  - Unscaled noise from loading model best right after Earthquake
  - At other times maybe too noisy → dynamic scaling of noise desirable



TSUKUB32



TIGOCONC

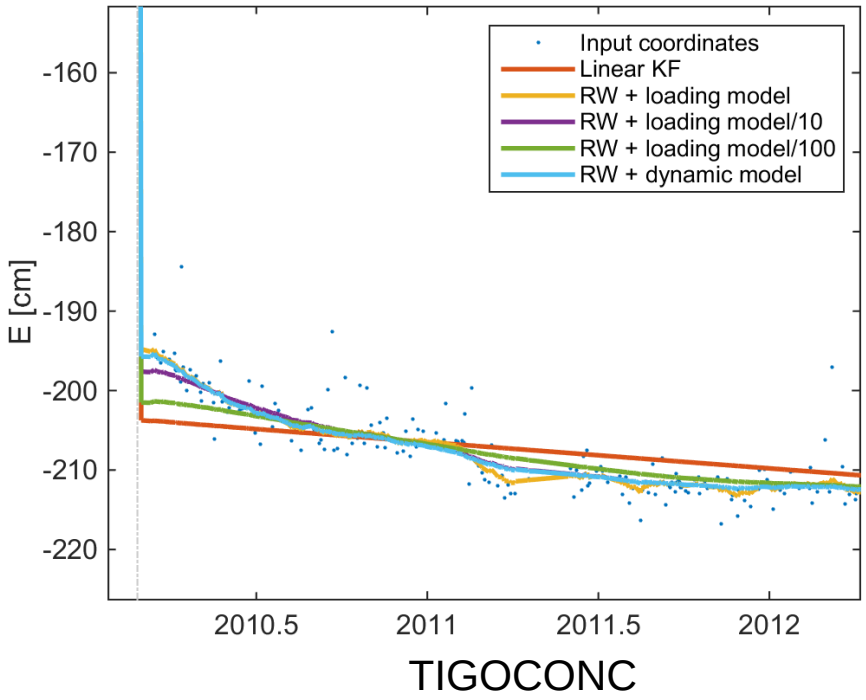
Time-dependent noise after earthquakes

- Exponential scaling of noise q_{rw} after earthquakes
  - Applied during period T after earthquakes
  - Δt from 0 to T, α from α_0 to 1

$$\alpha(t) = \alpha_0^{-\frac{\Delta t}{T}+1}$$

α scaling factor for q_{rw}
Δt time since earthquake
α_0 scaling factor for $\Delta t = 0$
T relaxation time

KF solution with
$\alpha_0 = 10$, $T = 1$ yr
q_{rw} from loading model/10

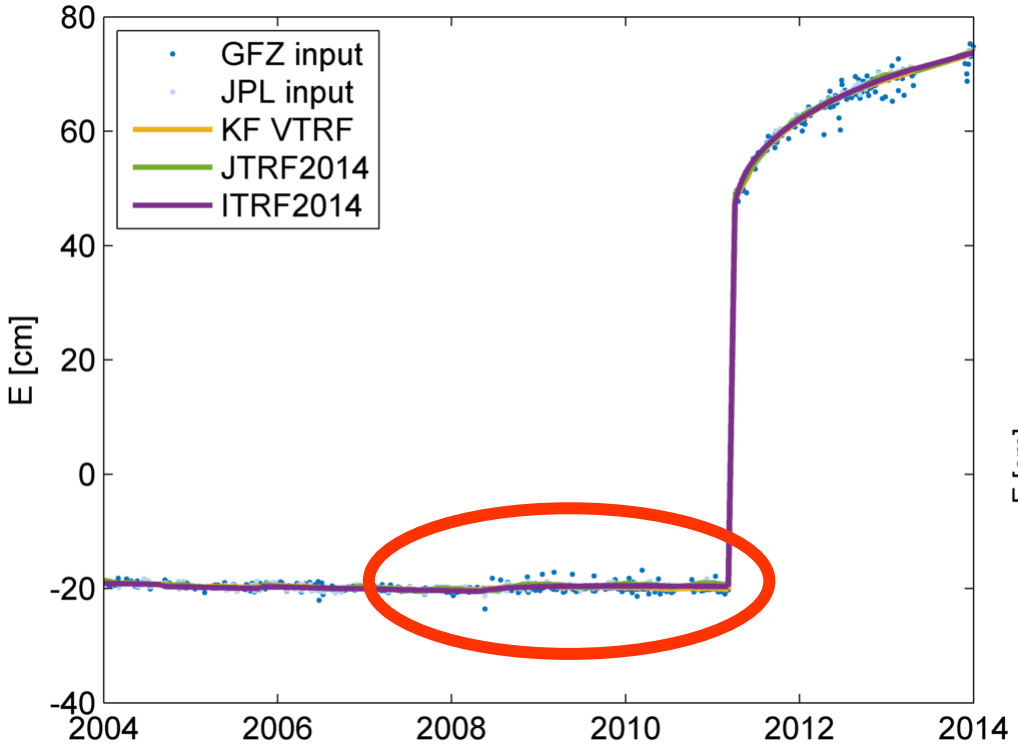


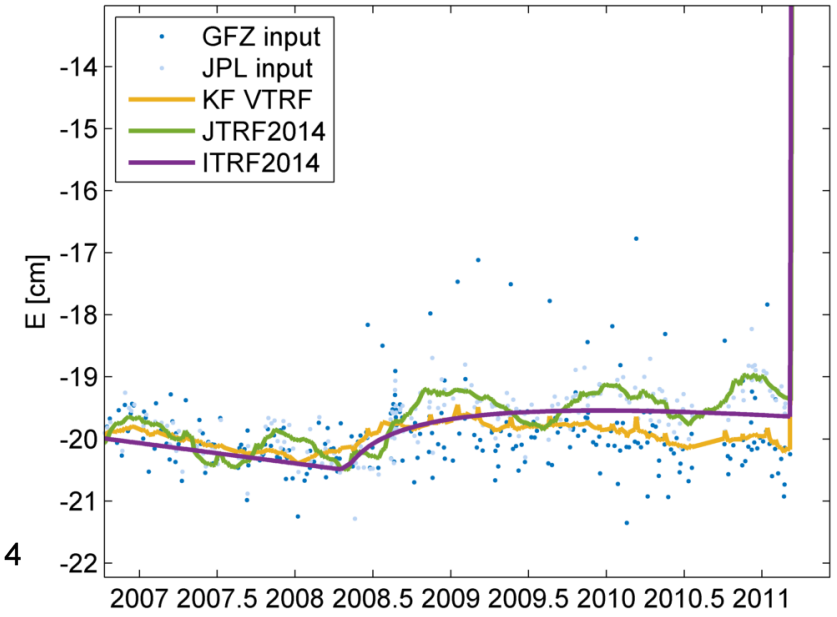
ITRF2014 & JTRF2014

- Based on GNSS, VLBI, SLR & DORIS SINEX files
- Combination at the parameter level
  - VLBI normal equations inverted before combination
- Datum: SLR origin, ITRF2008 orientation, VLBI+SLR scale
- ITRF2014: least squares estimation
  - Linear + post-seismic (+ annual + semi-annual)
- JTRF2014: Kalman filter & smoother
  - Linear + annual + semi-annual
  - Process noise for non-linear & non-harmonic signals
  - Weekly time steps

Comparison VTRF vs. JTRF/ITRF

- TSUKUB32





Comparison VTRF vs. JTRF/ITRF

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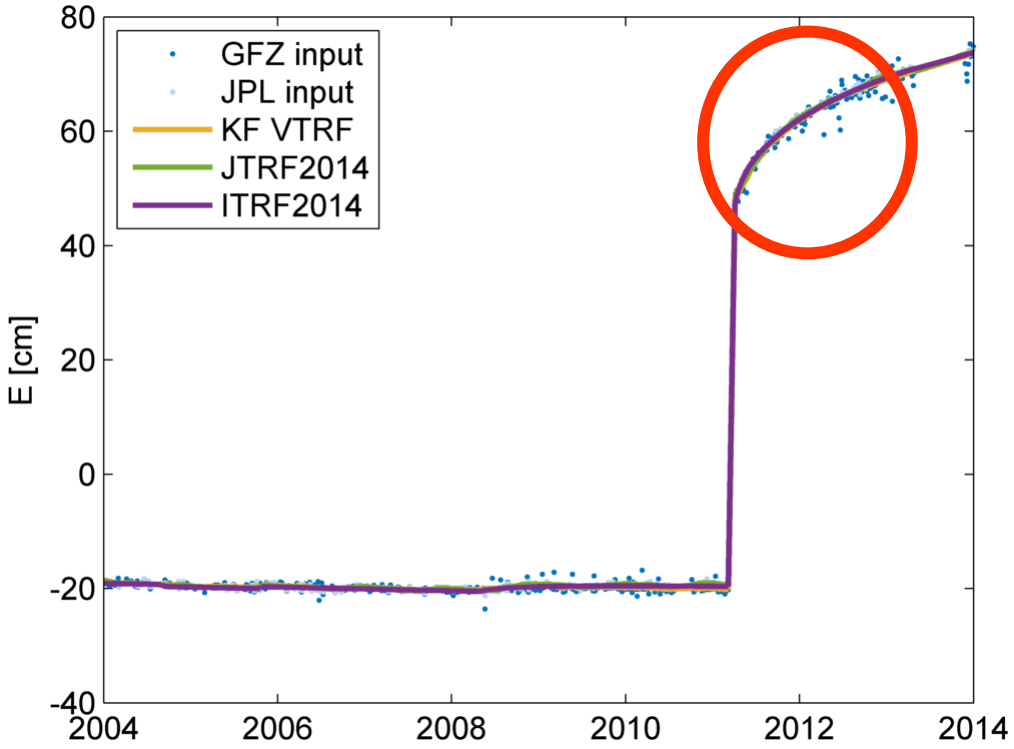

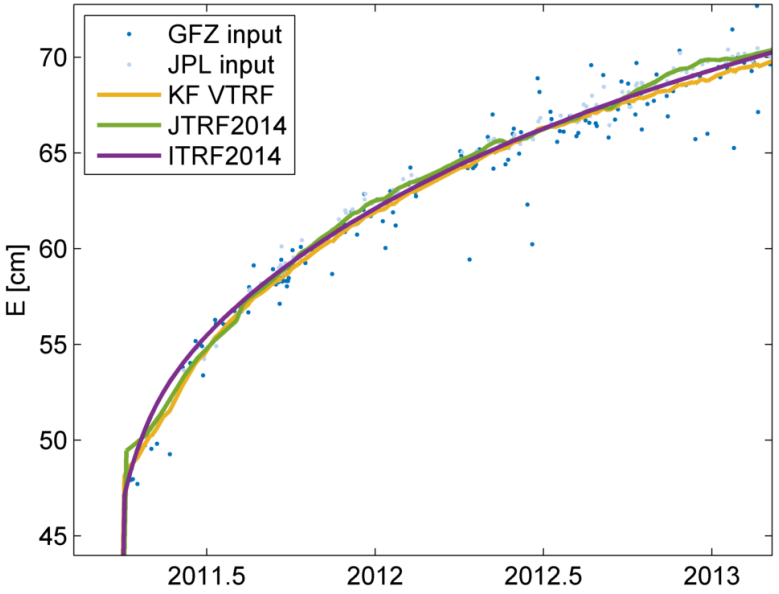

Recapitulation

- Kalman filtering successfully used to create VLBI TRFs
  - Linear KF TRF comparable to standard TRFs (velocities & transformation parameters)
  - Time series representation – recovery of non-linear signals
- Stochastic model station-dependent and time-variable
  - Noise from unmodeled elastic displacements
  - Scaling of noise for post-seismic activity
- Comparison to ITRF2014 and JTRF2014
  - Promising agreement during post-seismic periods
  - Investigations to be extended…

References

- Altamimi et al., 2011: ITRF2008: an improved solution of the international terrestrial reference frame. J Geod. 85(8), 457-473. doi:10.1007/s00190-011-0444-4
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- Soja et al., 2016: Determination of a Terrestrial Reference Frame via Kalman Filtering of Very Long Baseline Interferometry Data. Journal of Geodesy, submitted.
- Wu et al., 2015: KALREF—A Kalman filter and time series approach to the International Terrestrial Reference Frame realization. J. Geophys. Res. Solid Earth, 120, 3775–3802. doi:10.1002/2014JB011622.

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Loading data: IMLS
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