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Determination of celestial reference frames via Kalman filtering

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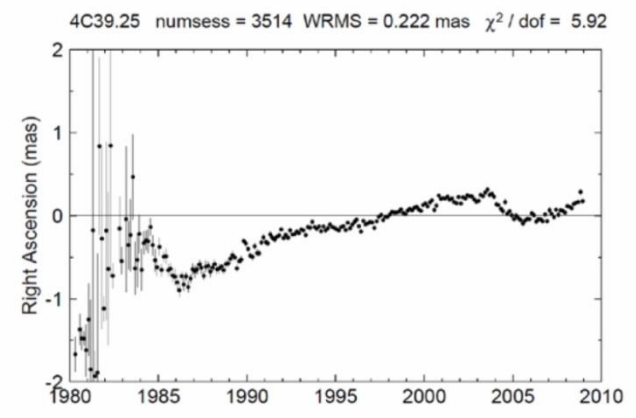
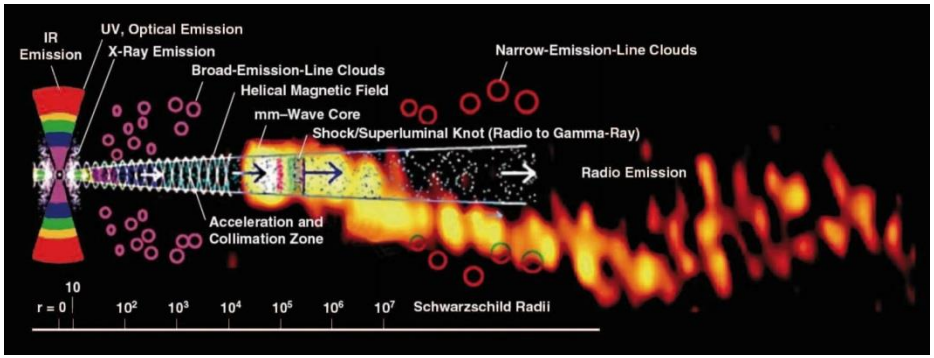
Background

- Extragalactic radio sources exhibit time variability, for example due to (changes in) **source structure**
  - Not considered in this talk: variations with hour angle and observing frequency
- Source structure effects are commonly not accounted for
  → leads to a degradation of the quality of the frame
  - Problem: no correction models exist
  - Example: ICRF2 with a constant coordinate model



[Ma et al., 2009]



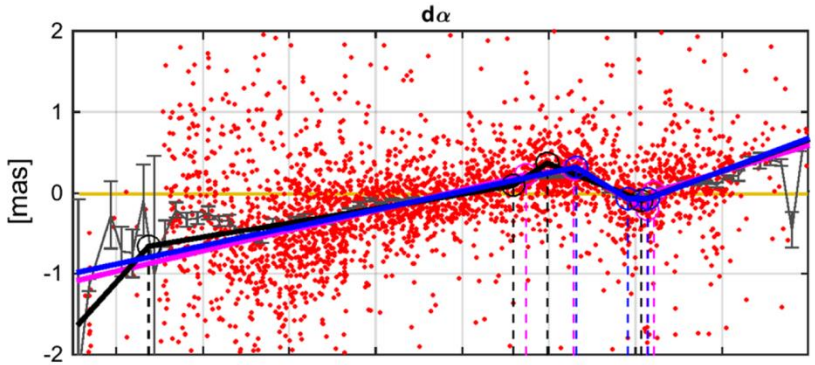
[Marscher, 2006 / Kirchbaum et al., 1999 / Wehrle et al., 2010]

Approaches for considering time variability

- Extension of the coordinate model (Karbon et al., 2016)
  - Source coordinates modeled by linear splines (MARS algorithm)

  → allows for more sources to stabilize the datum

  → improved estimates of nutation by 10%



[Karbon et al., 2016]

- Time series representation (this talk – using Kalman filtering)
  - Temporal resolution as high as input data
  - Stochastic approach to reflect physical nature
  - Higher computational demands

Additional motivation

- JPL is an IERS ITRS combination center (JTRF2014)
- Future goal: joint TRF/EOP/CRF determination
  → eliminate current inconsistencies to improve quality
  - Framework: NASA Postdoctoral Program fellowship
- JPL uses Kalman filtering for their TRF and EOP products
  → CRF also needs to be determined this way

Two-level approach for CRFs

ICRF2

- Least-squares adjustment
- Input: normal equations
- Constant frame

[Fey et al., 2015]

Kalman filter CRF

- Kalman filter + smoother
- Input: source coordinates + covariances
- Time series frame

[Soja et al., 2017]

New concept

- Least-squares adjustment
- Input: normal equations
- Constant frame
- Optional Kalman filter time series based on residuals of constant frame

Advantages

- Most radio sources have been observed less than five times
  - Constant model computationally very efficient
- Some radio sources with excellent observational history but irregular behavior (e.g., source structure)
  - Time series able to capture these non-linear effects

New concept

- Least-squares adjustment
- Input: normal equations
- Constant frame
- Optional Kalman filter time series based on residuals of constant frame

- Constant + time series approach allows for a complete CRF, taking into account non-linearity of selected sources

Realizing the new concept

1. Single-session analysis to create normal equations
2. Computation of secular frames (global solution)
   - NNT/NNR w.r.t. DTRF2014 and NNR w.r.t. ICRF2
   - Two TRF solutions: linear & linear + annual + semi-annual
3. Apply secular frames in single-session analysis to estimate station and source coordinates
   - Residuals w.r.t. secular frames
4. Feed residuals into Kalman filter and smoother to create time series consistent with secular frame
   - 6-parameter transformation to DTRF2014
   - 3-parameter rotation to ICRF2

VieVS
Vienna VLBI and Satellite Software

Single-session analysis

- Analysis with least-squares module of VieVS
- Correction models according to IERS Conventions 2010
- Estimated parameters
  - Radio sources (NNR constraints w.r.t. ICRF2)
  - 5 EOPs
  - Station coordinates (NNT+NNR constraints w.r.t. ITRF2014)
  - Auxiliary parameters (clocks & troposphere)

Radio source coordinates and their covariances serve as input to the Kalman filter CRF

Kalman filter setup

- Kalman filter & smoother
- State updated for every VLBI session (usually every 1-4 d)
- Source coordinates assumed to behave like random walk
- Output: filtered and smoothed α & δ time series

Prediction	Correction
$\tilde{x}_k = F_k x_{k-1} + w_k$	$x_k = \tilde{x}_k + K_k(z_k - H_k \tilde{x}_k)$
$\tilde{P}_k = F_k P_{k-1} {F_k}^T + Q_k$	$P_k = (I - K_k H_k)\tilde{P}_k$

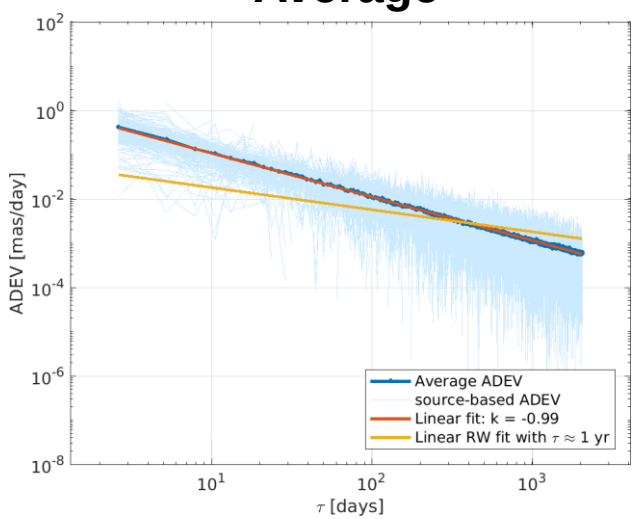
$$K_k = \tilde{P}_k {H_k}^T (H_k \tilde{P}_k {H_k}^T + R_k)^{-1}$$

Process noise of radio source coordinates

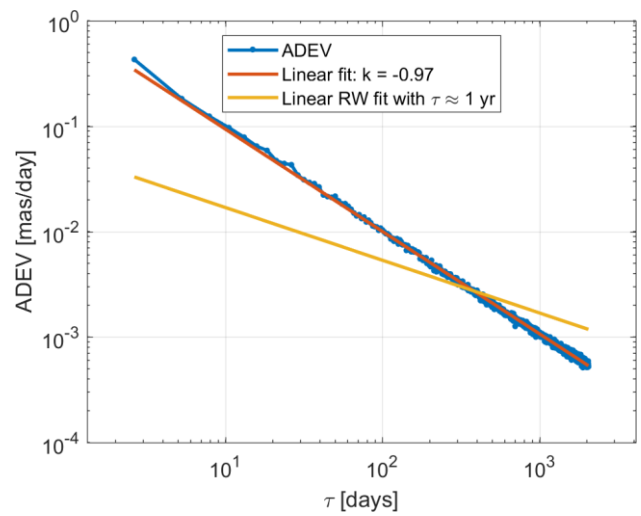
- Lack of external data to derive noise model
- Allan standard deviation (ADEV) computed from single-session coordinate time series of the 334 radio sources
- ADEV indicates almost perfect *white noise*
  - Observational errors
  - Network / datum effects

$d\alpha \cos \delta$

Average



4C 39.25

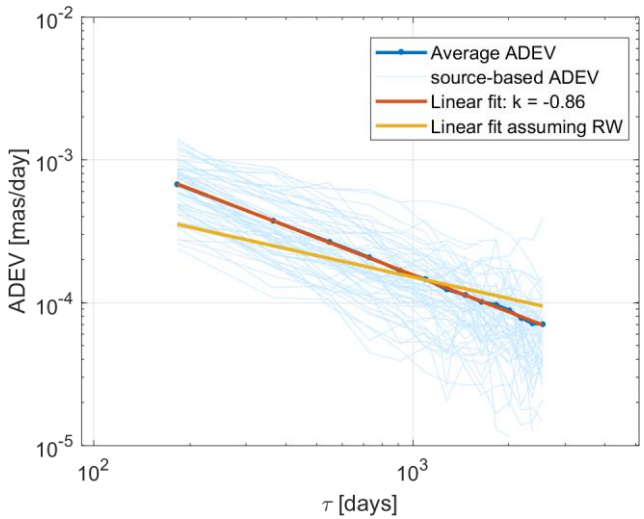


Process noise of radio source coordinates

- Half-yearly averages instead of single-session coordinates to remove most of the datum / observation noise
  - At least 20 data points in each interval → only 66 sources
- ADEV of certain sources best described by *random walk*
- Source-based noise parameters (PSDs) estimated assuming *random walk*

$d\alpha \cos \delta$

Average



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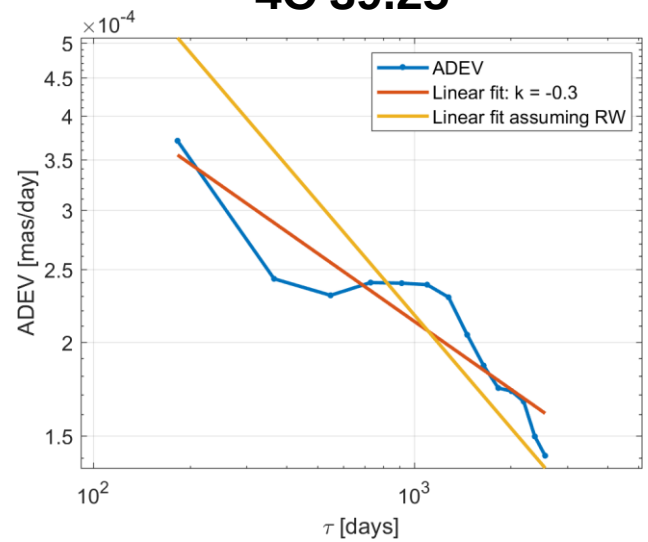
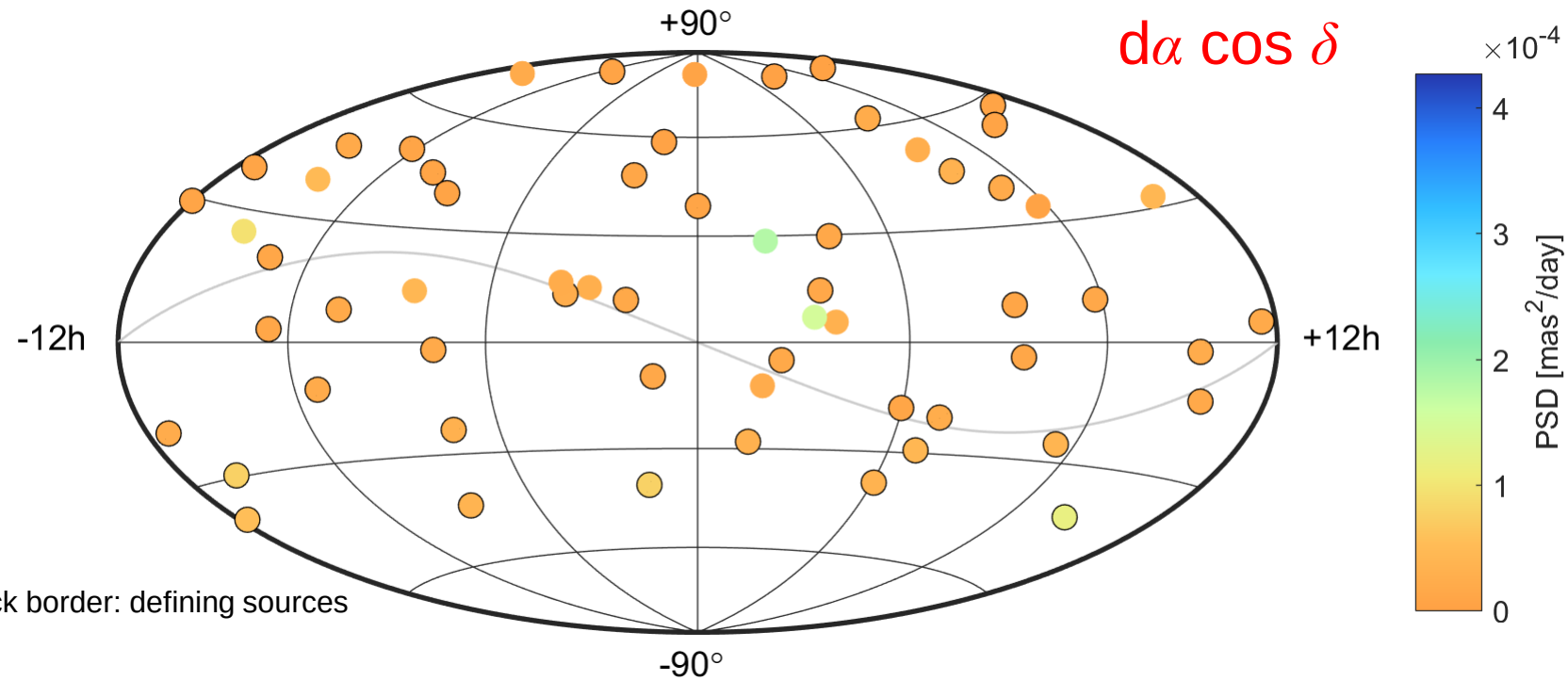


Source-based process noise sky map

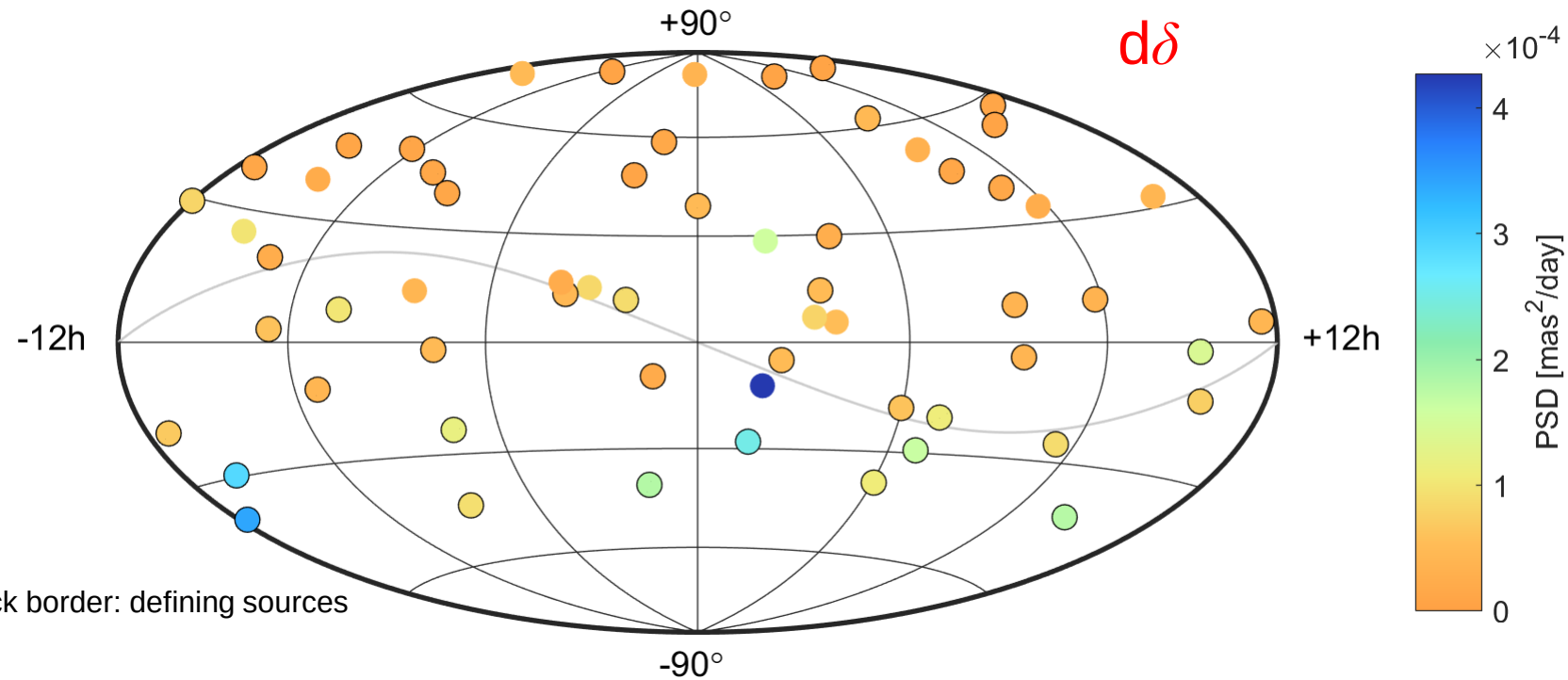
- Average PSD: 28 µas²/day
- Defining sources: 21 µas²/day
- Special handling: 50 µas²/day



black border: defining sources

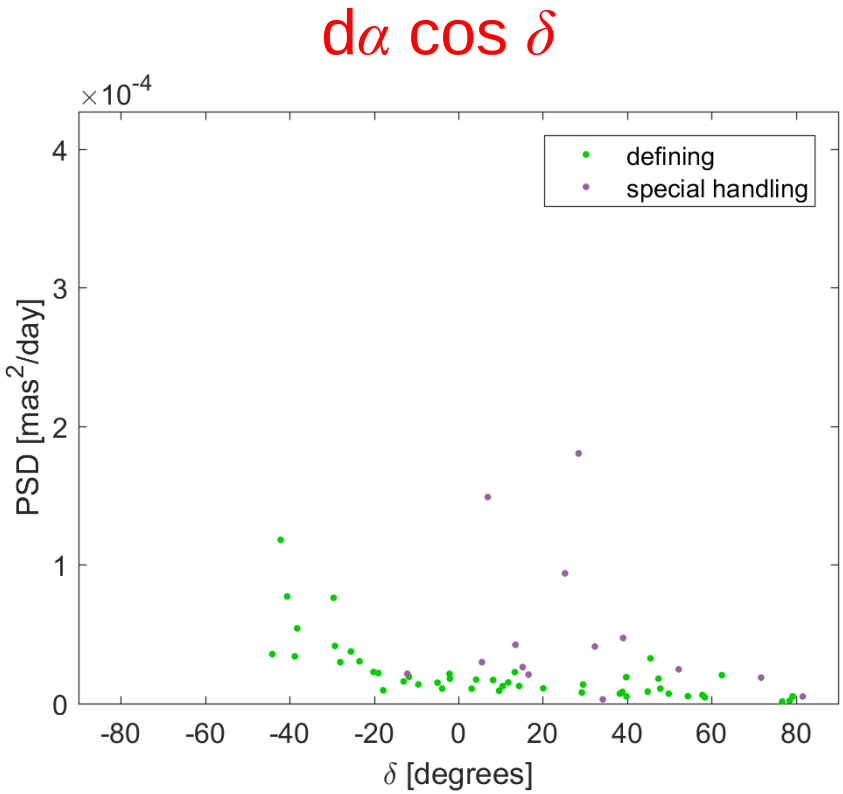
Source-based process noise sky map

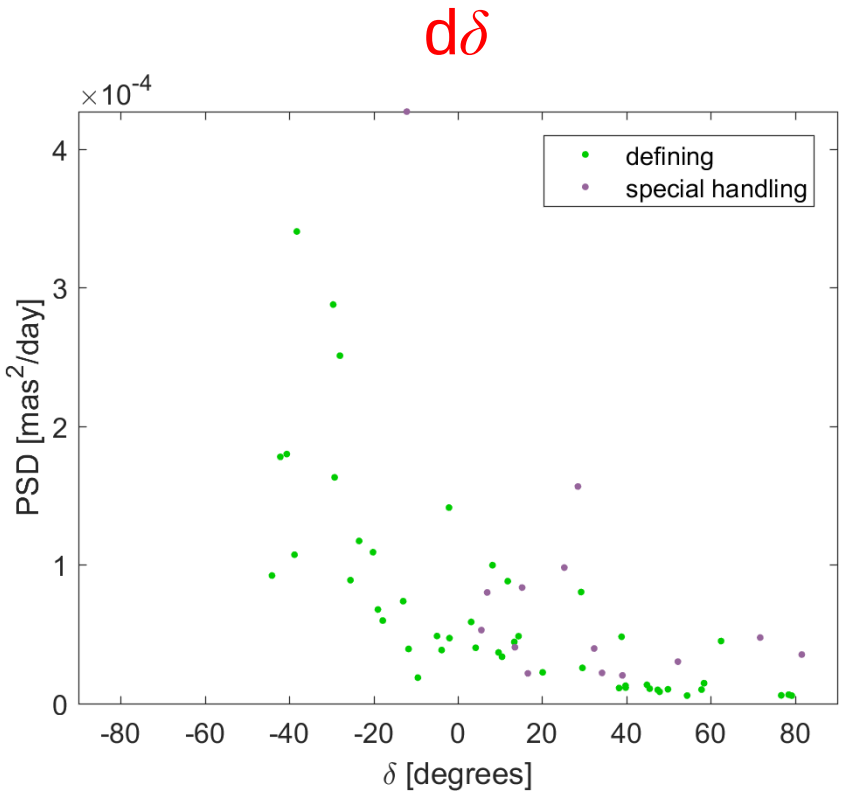
- Average PSD: 72 µas²/day
- Defining sources: 69 µas²/day
- Special handling: 83 µas²/day



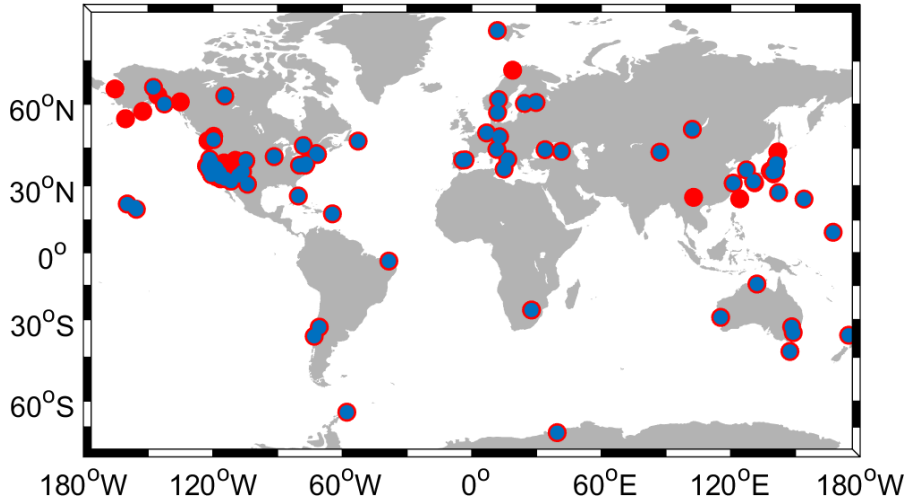
black border: defining sources

Source-based process noise vs. declination





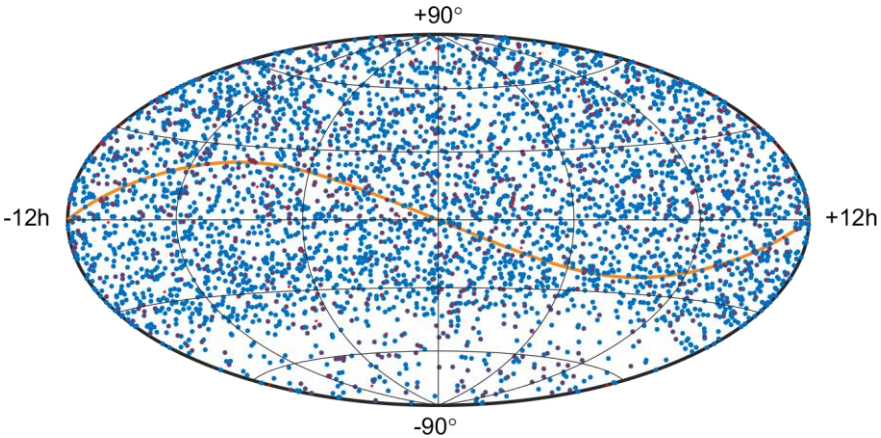
VLBI data



- 1980 – 2016.5
- 5446 IVS-VLBI sessions

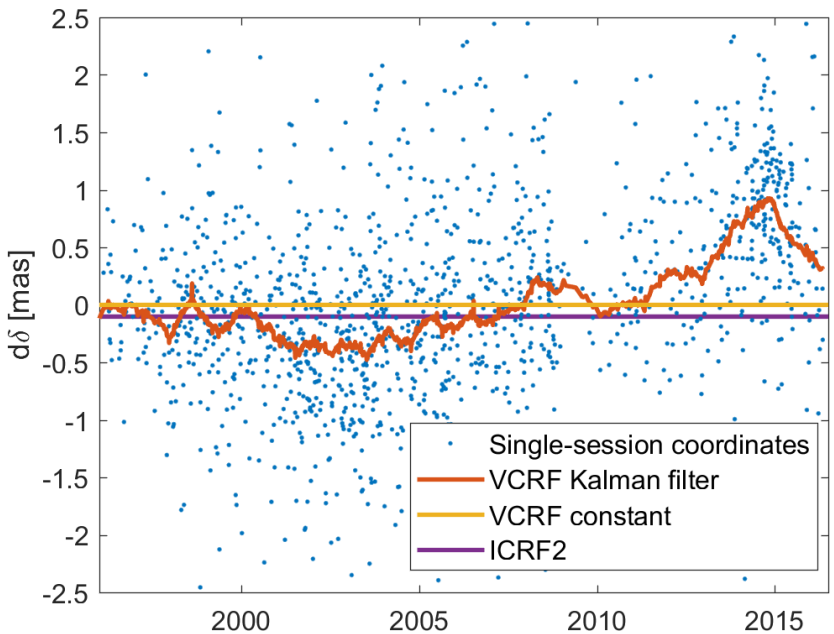
- Secular frame
  - 102 VLBI stations (22 used for datum definition)
  - 4097 radio sources (295 used for datum definition)

- Time series frame
  - 119 VLBI stations
  - 822 radio sources



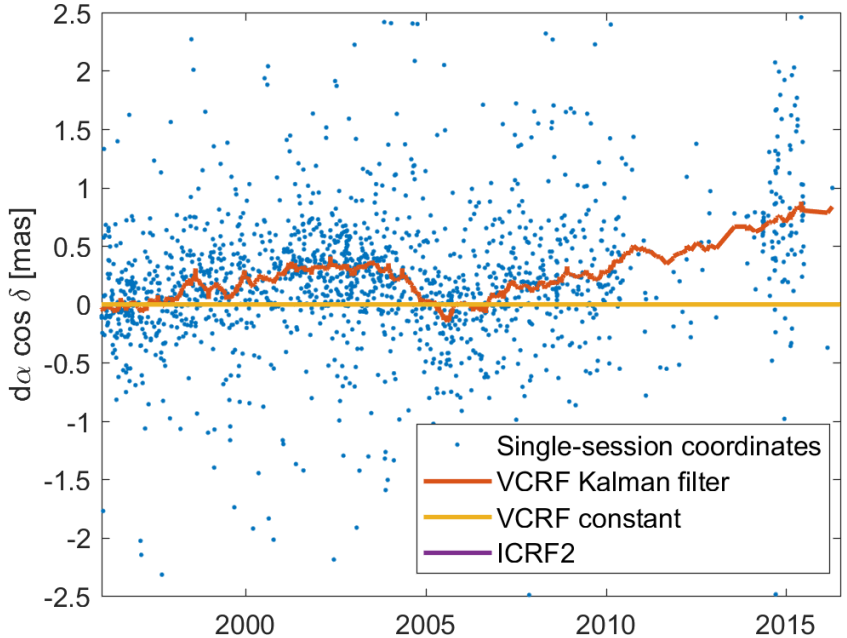
Kalman filter CRF solution examples

0119+115, declination



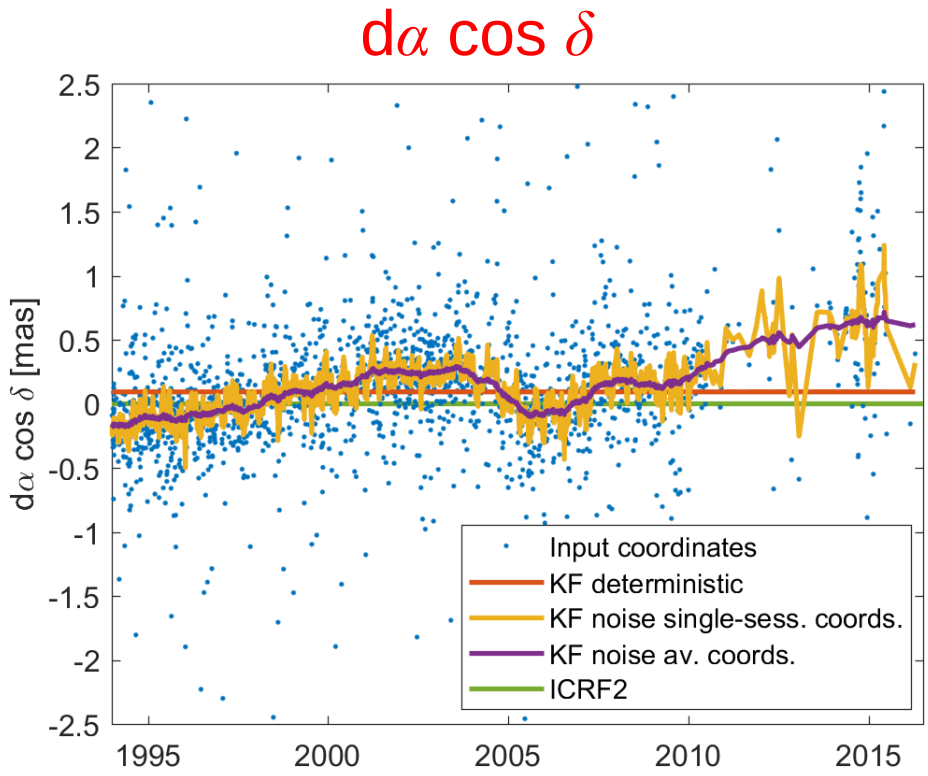
ICRF2 defining source

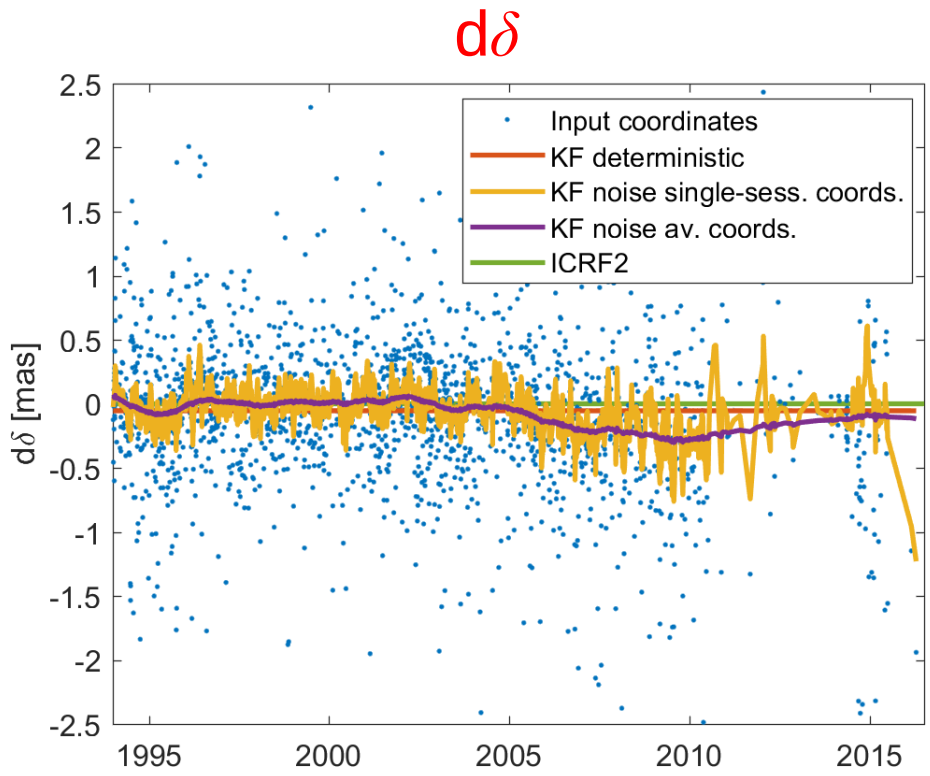
4C 39.25, right ascension



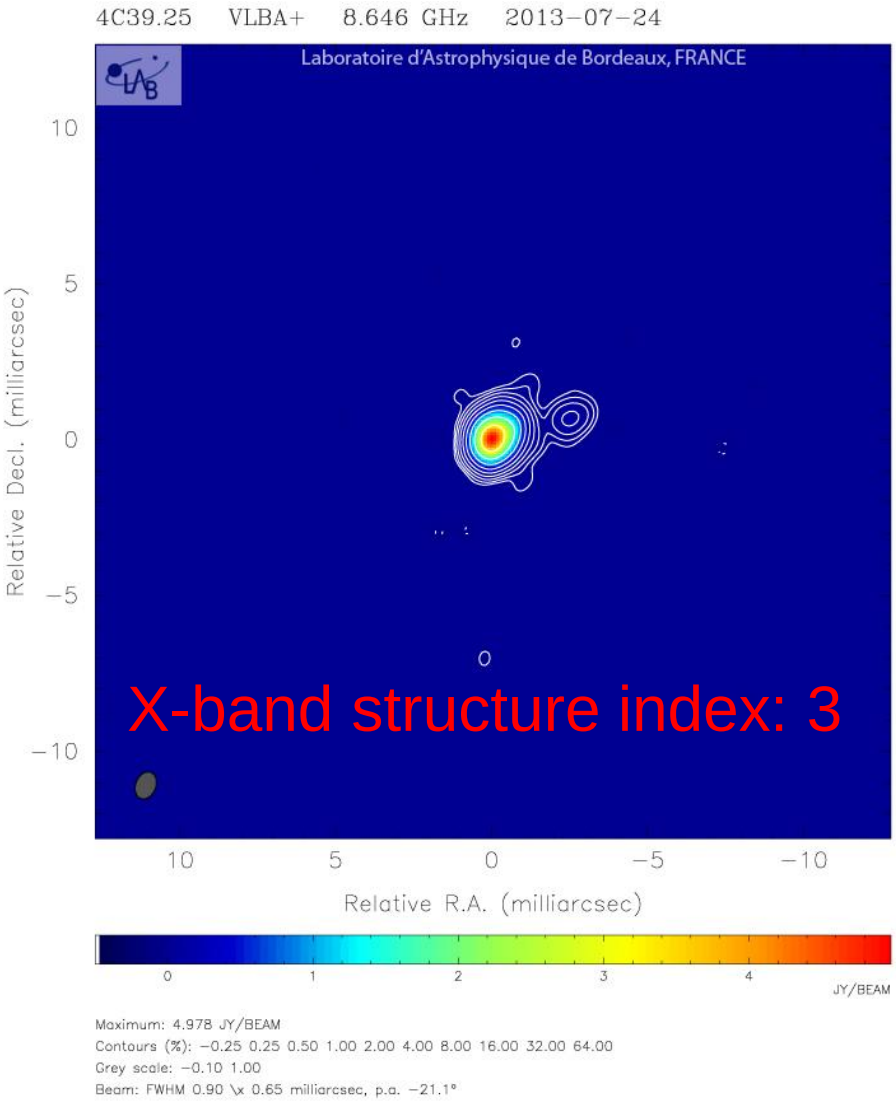
ICRF2 special handling source

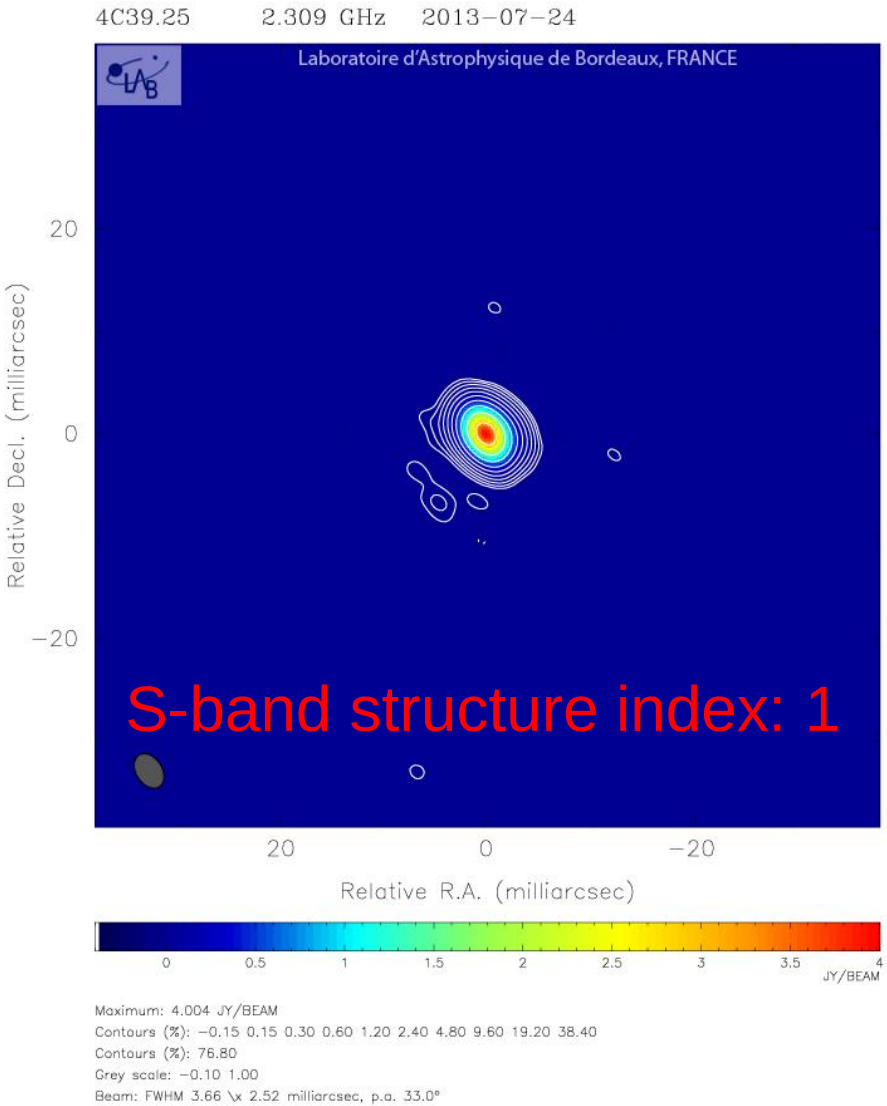
Kalman filter CRF solutions of 4C 39.25





Comparison to radio source images





Performance in VLBI analysis

- Implemented reference frame solutions in VLBI analysis software
  - Linear TRF – constant CRF
  - Linear + seasonal TRF – constant CRF
  - Kalman filter TRF – Kalman filter CRF

- Estimated parameters:
  - Station coordinates
  - Source coordinates
  - 5 EOP
  - Auxiliary parameters (clocks & troposphere)

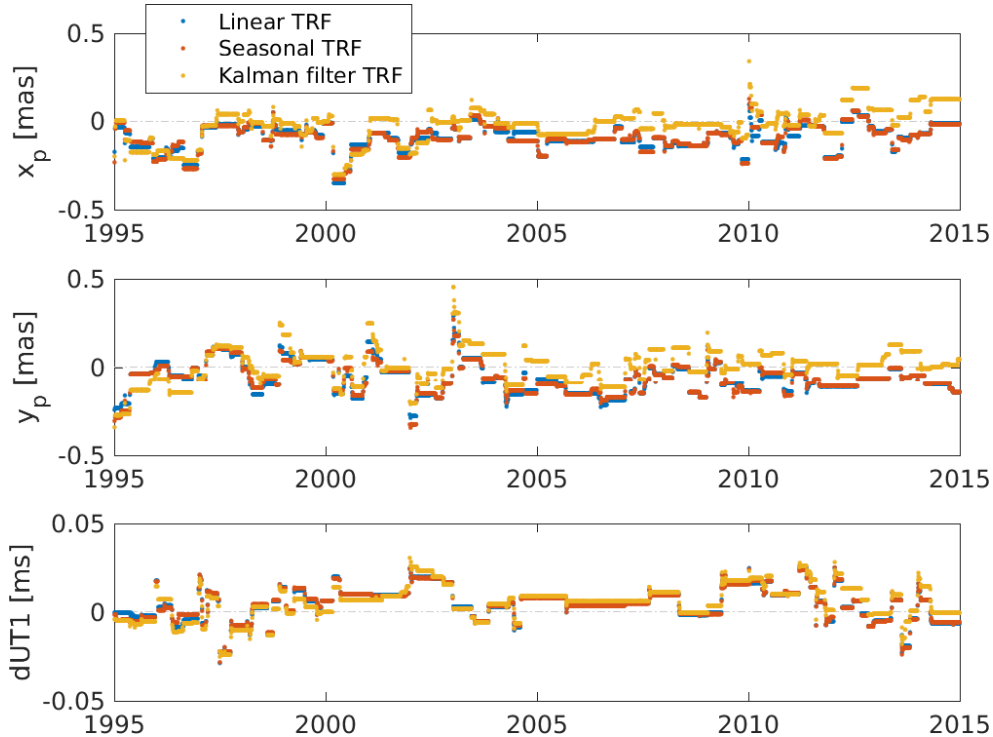
Earth orientation parameters

- Comparison of VLBI-estimated EOP with EOP from
  - ITRF2014
  - IERS 14 C04
  - DTRF2014
  - JTRF2014

Earth orientation parameters

- Comparison of VLBI-estimated EOP with EOP from
  - ITRF2014
  - IERS 14 C04
  - DTRF2014
  - JTRF2014

Differences w.r.t. ITRF2014
(moving medians w/ 30-day windows)



WRMS of differences

WRMS [µas] w.r.t. ITRF2014	x_P	y_P	dUT1
TRF linear	243	242	267
TRF seasonal	244	241	267
TRF Kalman filter	233	223	271
Δ(KF – seasonal)	-5%	-8%	+1%

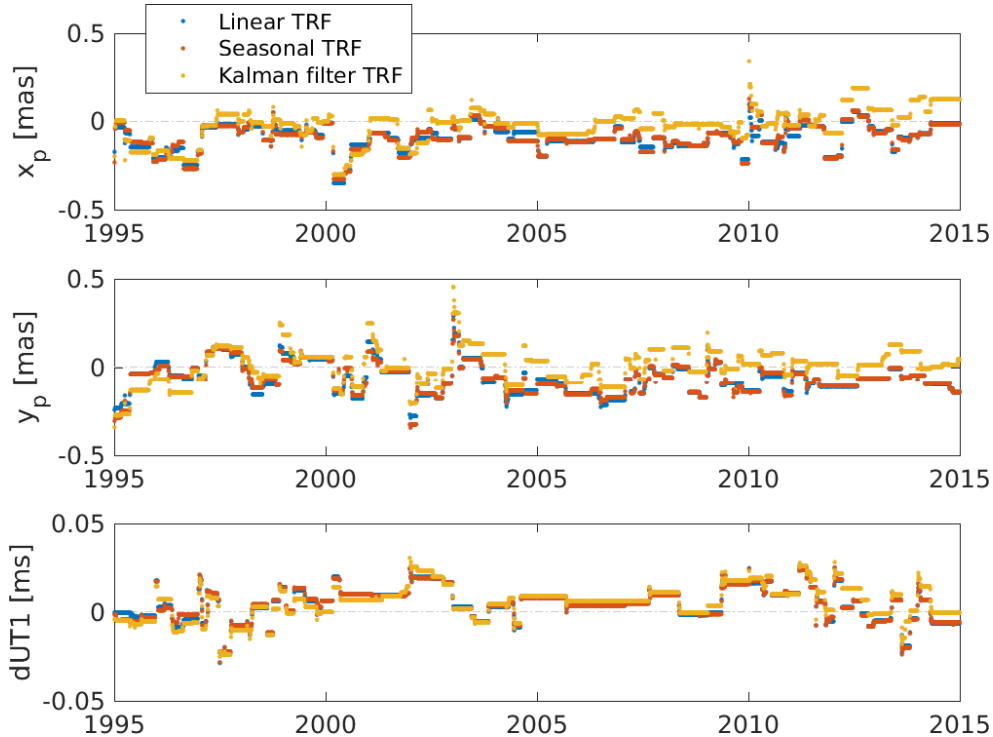
Earth orientation parameters

- Comparison of VLBI-estimated EOP with EOP from
  - ITRF2014
  - IERS 14 C04
  - DTRF2014
  - JTRF2014

WRMS of differences
after subtracting trend

WRMS [µas] w.r.t. ITRF2014	x_P	y_P	dUT1
TRF linear	224	219	354
TRF seasonal	225	218	353
TRF Kalman filter	229	225	357
Δ(KF – seasonal)	+2%	+3%	+1%

Differences w.r.t. ITRF2014
(moving medians w/ 30-day windows)



Earth orientation parameters

- Comparison of VLBI-estimated EOP with EOP from
  - ITRF2014
  - IERS 14 C04
  - DTRF2014
  - JTRF2014

WRMS of differences

WRMS [µas] w.r.t. 14 C04	x_P	y_P	dUT1	dX	dY
TRF linear	225	243	221	208	195
TRF seasonal	225	243	221	208	195
TRF Kalman filter	223	216	221	212	198
Δ(KF – seasonal)	-1%	-13%	0%	+2%	+2%

WRMS of differences
after subtracting trend

WRMS [µas] w.r.t. 14 C04	x_P	y_P	dUT1	dX	dY
TRF linear	209	211	217	208	194
TRF seasonal	210	211	217	208	194
TRF Kalman filter	214	215	222	211	196
Δ(KF – seasonal)	+2%	+2%	+2%	+1%	+1%

Source coordinates

a priori coordinates (from CRF)

$$\tilde{x} = x_0 + \Delta x$$

overall coordinates

estimated offsets

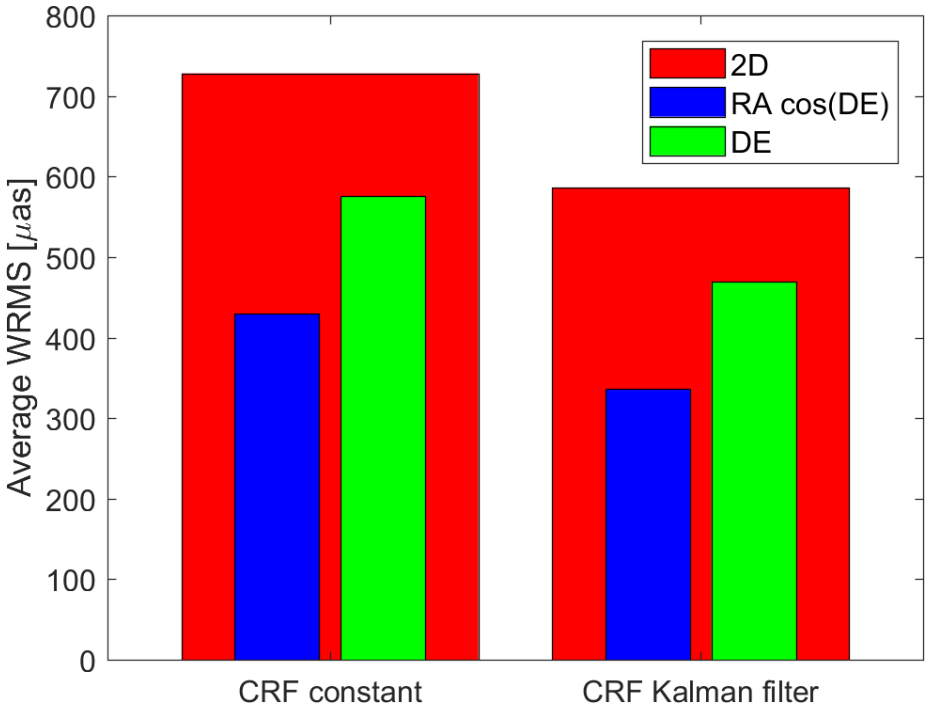
Source coordinates

a priori coordinates (from CRF)

$$\tilde{x} = x_0 + \Delta x$$

overall coordinates

estimated offsets



WRMS [µas]	RA cos(DE)	DE	2D
CRF constant	430	576	728
CRF Kalman filter	336	470	586
Δ(KF – constant)	-22%	-18%	-20%

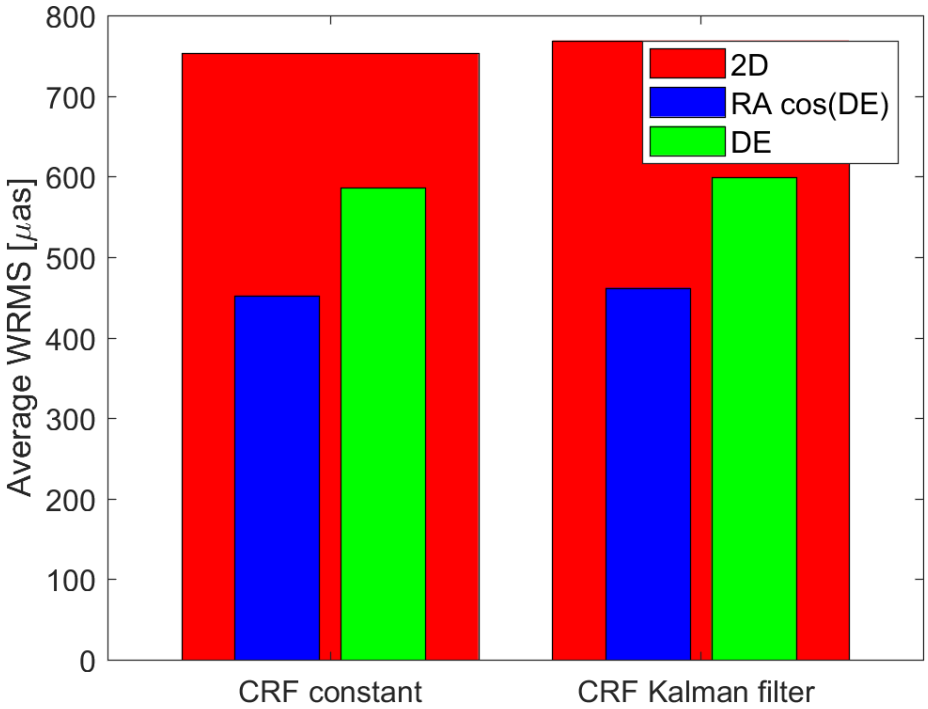
Source coordinates

a priori coordinates (from CRF)

$$\tilde{x} = x_0 + \Delta x$$

overall coordinates

estimated offsets



Coordinate repeatabilities:
WRMS after subtracting mean

WRMS [µas]	RA cos(DE)	DE	2D
CRF constant	452	586	752
CRF Kalman filter	462	599	769
Δ(KF – constant)	+2%	+2%	+2%

Conclusions

- Demonstration of a **Kalman filter CRF**
  - Time series approach to take into account **temporal variability**
- 2-level approach (LS + KF) for a **complete** CRF solution
- **Source-based noise model** from rigorous statistical analysis
  - Averaged coordinates to reduce artificial noise
- **Performance** in VLBI analysis:
  - Estimated offsets 20% smaller for Kalman filter solutions
  - EOP WRMS differs by ~5 µas, up to 30 µas
- **Outlook:** explore other approaches for determining the **noise model,** e.g. based on **source structure** information

  → with colleagues at UTAS!

Thanks for your attention!

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California Institute of Technology

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Acknowledgements
VLBI data: IVS (Nothnagel et al., 2015)
ICRF2: IVS / IERS / IAU
Radio source images: Bordeaux VLBI Image Database

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References I

- Krichbaum et al., IRAM, 1999.
- Ma et al., 2009: IERS Technical Note, No. 35, Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt a.M.
- Alan Marscher, 2006: Relativistic Jets in Active Galactic Nuclei and their relationship to the Central Engine, Proc. of Science, VI Microquasar Workshop: Microquasars & Beyond, Societa del Casino, Como, Italy, 18-22 Sep 2006.
- Nothnagel et al., 2015: The IVS data input to ITRF2014. International VLBI Service for Geodesy and Astrometry, GFZ Data Services. doi: 10.5880/GFZ.1.1.2015.002
- Karbon et al., 2016: The extension of the parametrization of the radio source coordinates in geodetic VLBI and its impact on the time series analysis, Journal of Geodesy. doi:10.1007/s00190-016-0954-1
- Wehrle et al., ASTRO-2010, no.310.

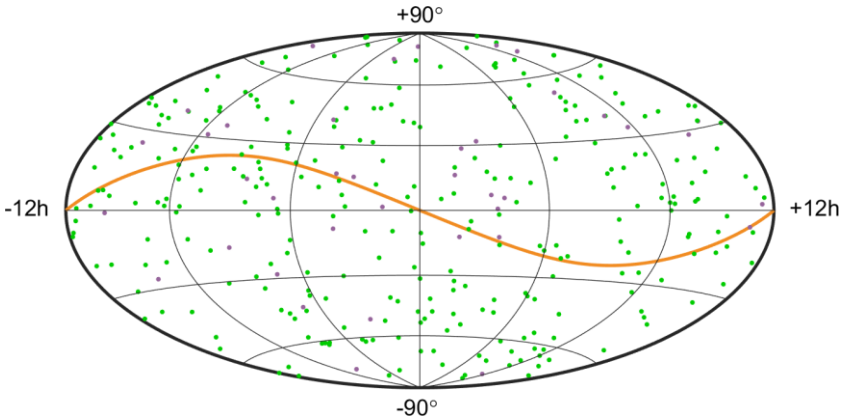
References II

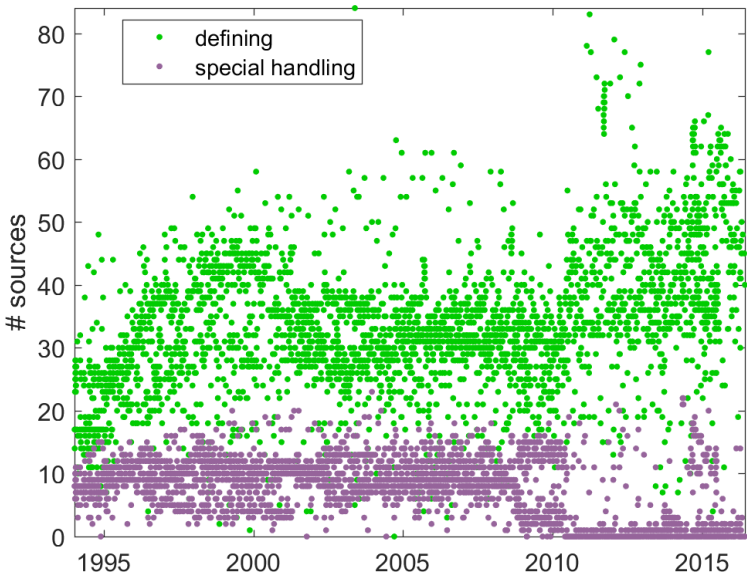
- Abbondanza et al., 2017: JTRF2014, the JPL Kalman Filter and Smoother Realization of the International Terrestrial Reference System. J. Geophys. Res. Solid Earth, submitted.
- Seitz et al., 2016: The new DGFI-TUM realization of the ITRS: DTRF2014 (data). Deutsches Geodätisches Forschungsinstitut, Munich, doi:10.1594/PANGAEA.864046
- Soja et al., 2017: A celestial reference frame based on Kalman filtering. In: "Proceedings of the 23rd European VLBI Group for Geodesy and Astrometry Working Meeting", R. Haas and G. Elgered (eds.), May 2017, Gothenburg, Sweden; ISBN 978-91-88041-10-4, 152-156.

Backup slides

VLBI data

- Limited data set selected for preliminary tests and investigations
- Time span: 1994 – 2016.5
  - Significant improvement of data quality in early 1990s
- 3118 IVS VLBI sessions
  - No regional sessions
- 334 radio sources
  - 295 defining
  - 39 special handling





New concept for terrestrial reference frames

DTRF2014

- Least-squares adjustment
- Input: normal equations
- Secular frame
- Optional loading displacement time series

[Seitz et al., 2016]

JTRF2014

- Kalman filter + smoother
- Input: station coordinates + covariances
- Time series frame

[Abbondanza et al., 2017]

New concept

- Least-squares adjustment
- Input: normal equations
- Secular frame
- Optional Kalman filter time series based on residuals of secular frame

Advantages

- User can choose which level (secular or secular + time series) depending on application
  - Secular: accurate predictions
  - Secular + time series: closer to "true" station coordinates
  - Both levels are consistent with each other

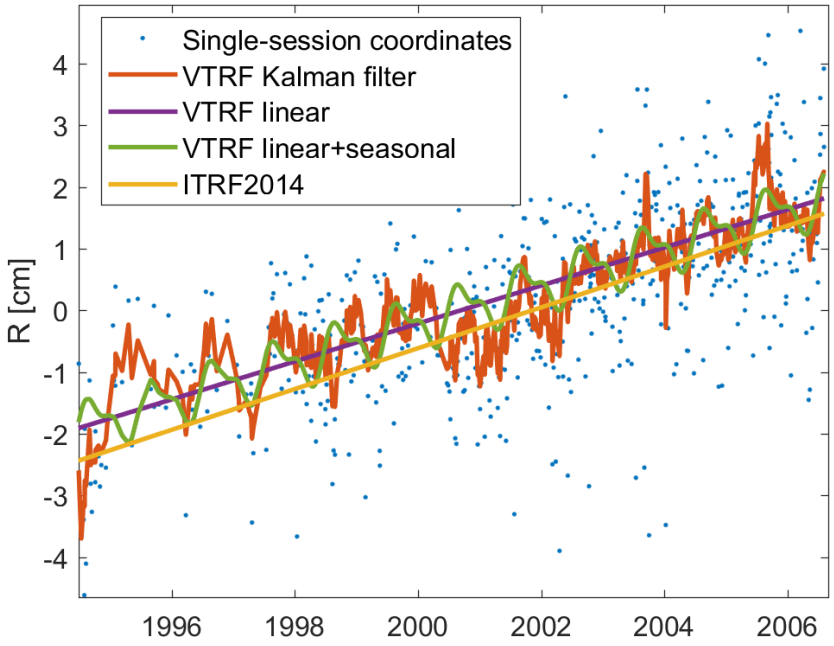
New concept

- Least-squares adjustment
- Input: normal equations
- Secular frame
- Optional Kalman filter time series based on residuals of linear frame

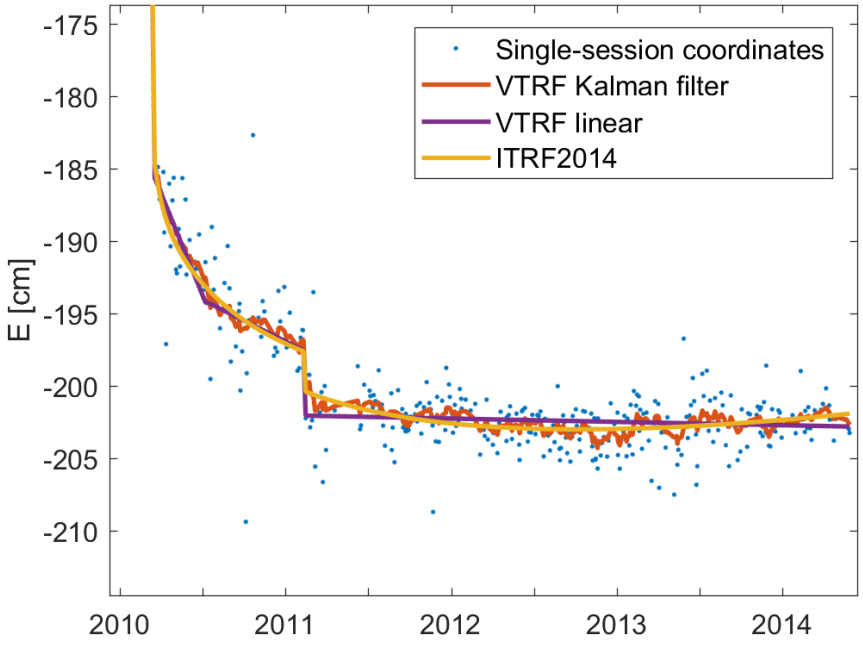
- Kalman filter solution instead of non-tidal loading time series:
  - Driven by space-geodetic observations
  - Non-tidal models not yet recommended by IERS Conventions

TRF solution examples

Algonquin Park, radial component



TIGO Concepción, East component



Station coordinates

a priori coordinates (from TRF)

$$\tilde{x} = x_0 + \Delta x$$

overall coordinates

estimated offsets

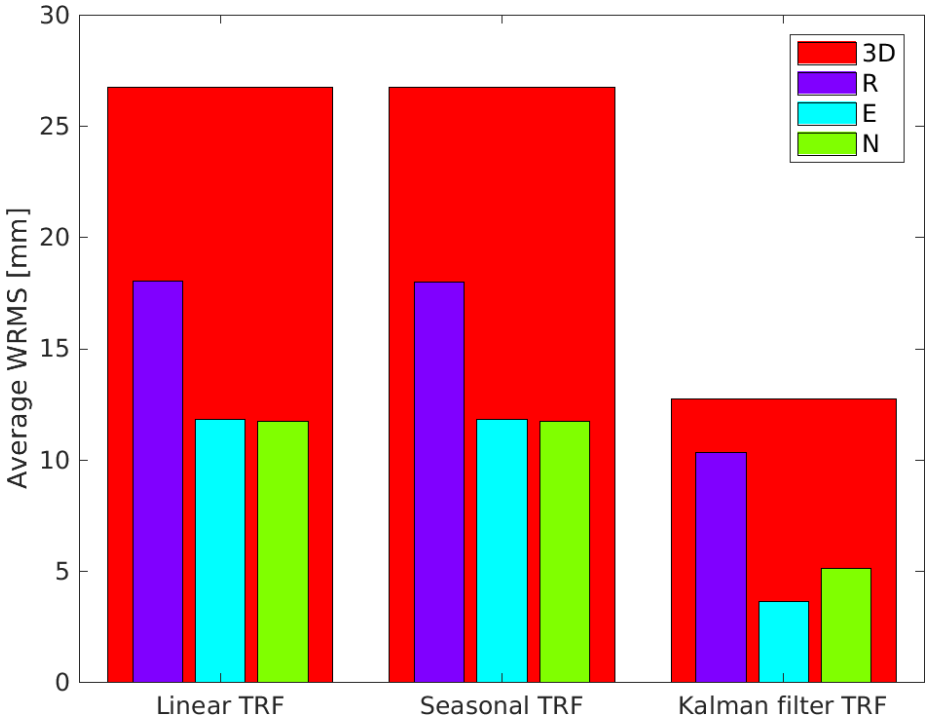
Station coordinates

a priori coordinates (from TRF)

$$\tilde{x} = x_0 + \Delta x$$

overall coordinates

estimated offsets



WRMS [mm]	R	E	N	3D
TRF linear	18.0	11.8	11.7	26.7
TRF seasonal	18.0	11.8	11.8	26.8
TRF Kalman filter	10.3	3.6	5.1	12.7
Δ(KF – seasonal)	-43%	-69%	-57%	-53%

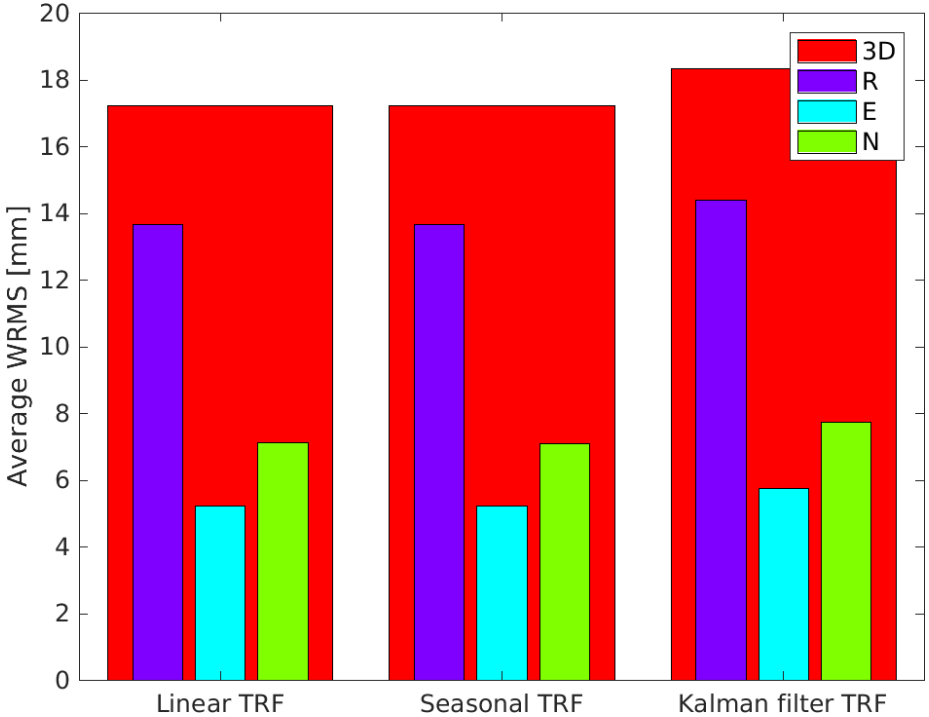
Station coordinates

a priori coordinates (from TRF)

$$\tilde{x} = x_0 + \Delta x$$

overall coordinates

estimated offsets



Coordinate repeatabilities:
WRMS after subtracting trends

WRMS [mm]	R	E	N	3D
TRF linear	13.7	5.2	7.1	17.2
TRF seasonal	13.7	5.2	7.1	17.2
TRF Kalman filter	14.4	5.8	7.7	18.3
Δ(KF – seasonal)	+5%	+12%	+8%	+6%