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A two-level approach to VLBI terrestrial and celestial reference frames using both least-squares adjustment and Kalman filter algorithms

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California Institute of Technology

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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
- 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
- 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

New concept for celestial reference frames

ICRF2

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

[Fey et al., 2015]

Kalman filter CRF

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

[Soja et al., 2017]

New concept

- Least-squares adjustment
- 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
- 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

VLBI data

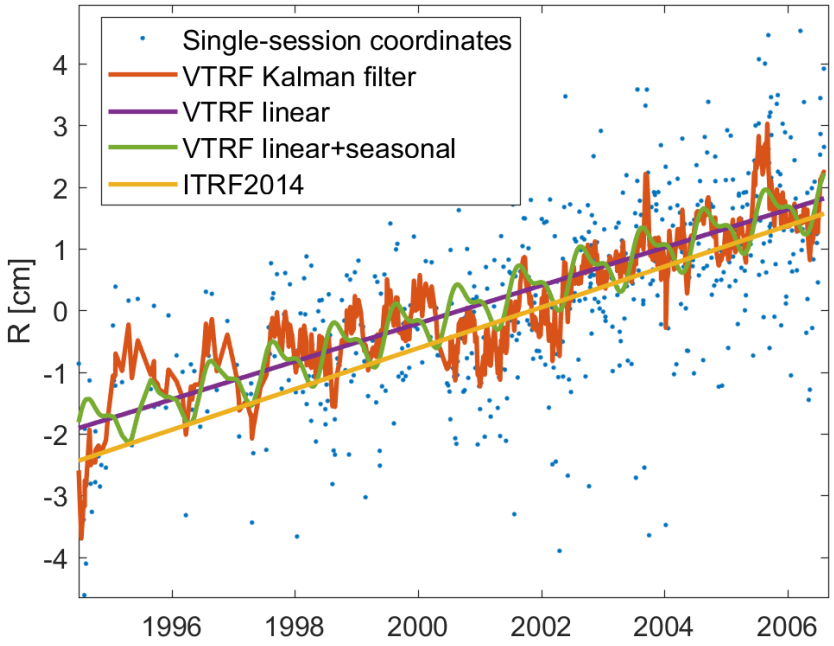
- 1980 – 2016.5
- 5446 IVS-VLBI sessions

- Secular frame
  - 136 VLBI stations (22 used for datum definition)
  - 4097 radio sources (1178 used for datum definition)
  - Seasonal signals: only estimated for datum stations

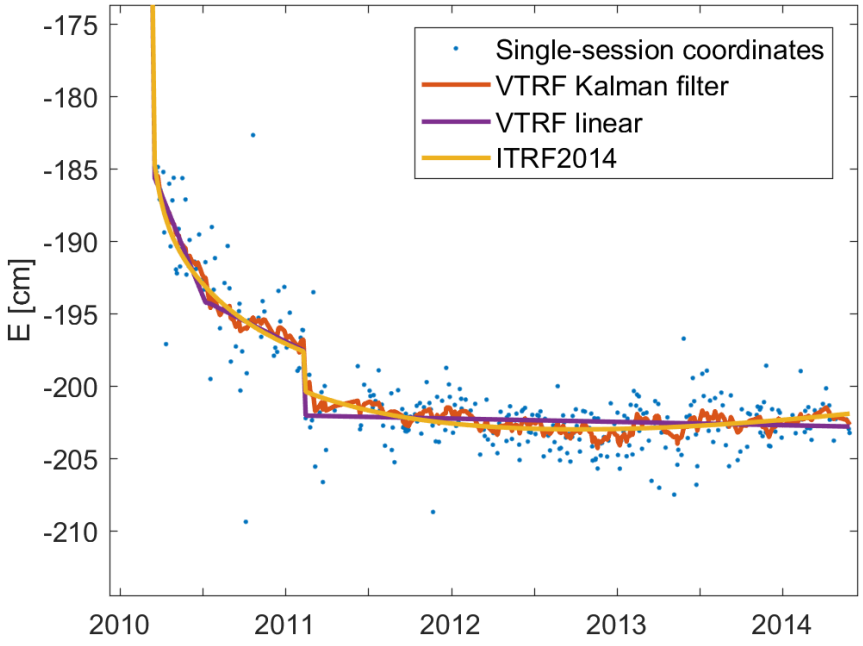
- Time series frame
  - 119 VLBI stations
  - 822 radio sources

TRF solution examples

Algonquin Park, radial component

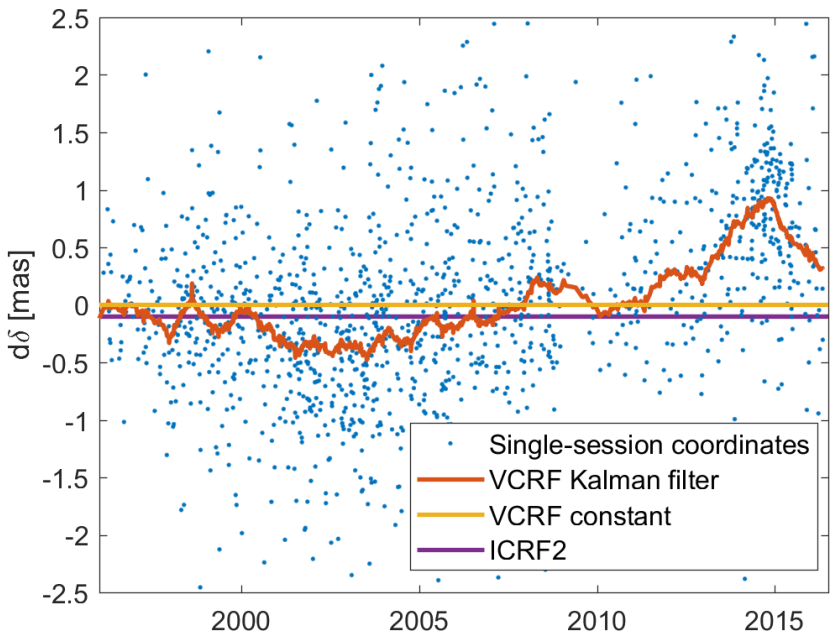


TIGO Concepción, East component

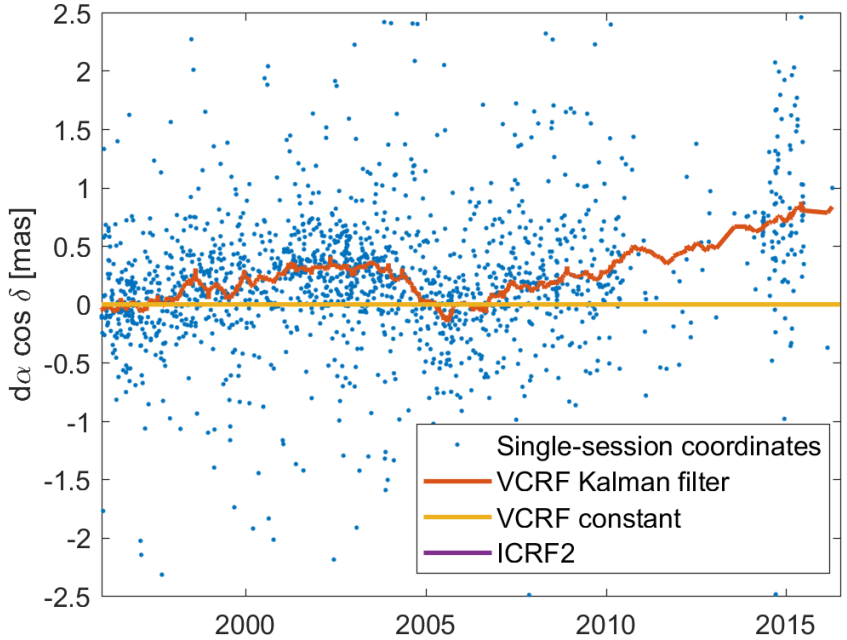


CRF solution examples

0119+115 (defining), declination



4C 39.25 (special handling), right asc.



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)

Station coordinates

a priori coordinates (from TRF)

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

overall coordinates

estimated offsets

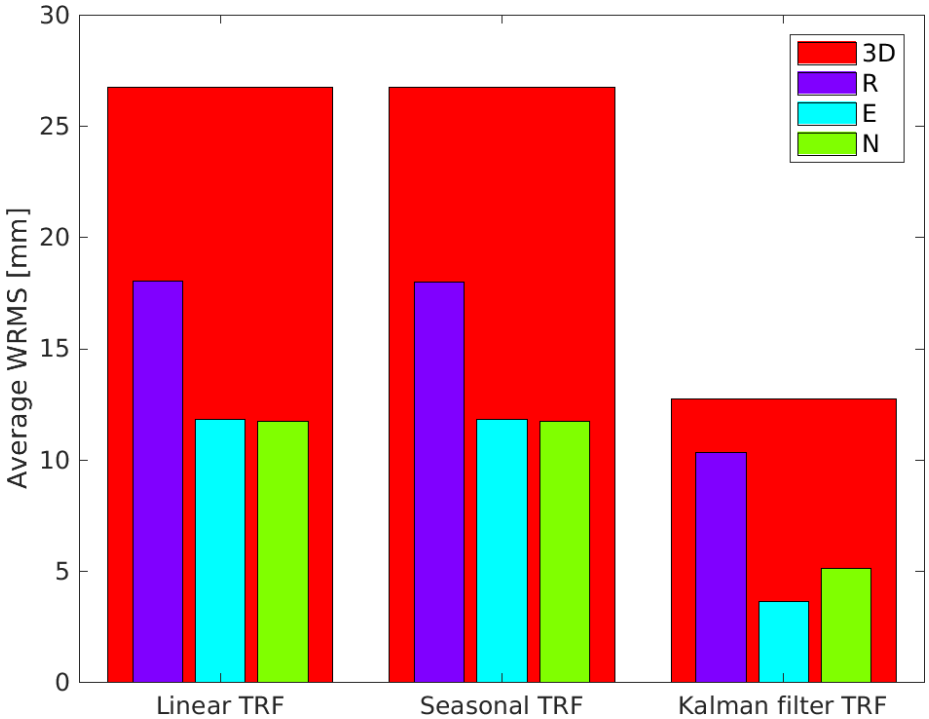
Station coordinates

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%

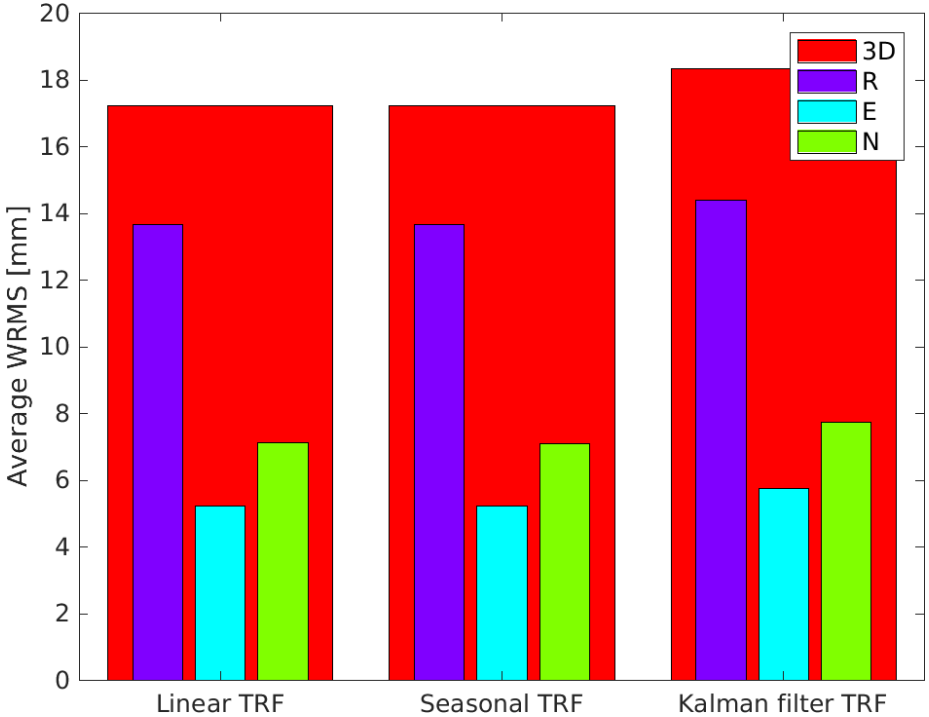
Station coordinates

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%

Earth orientation parameters

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

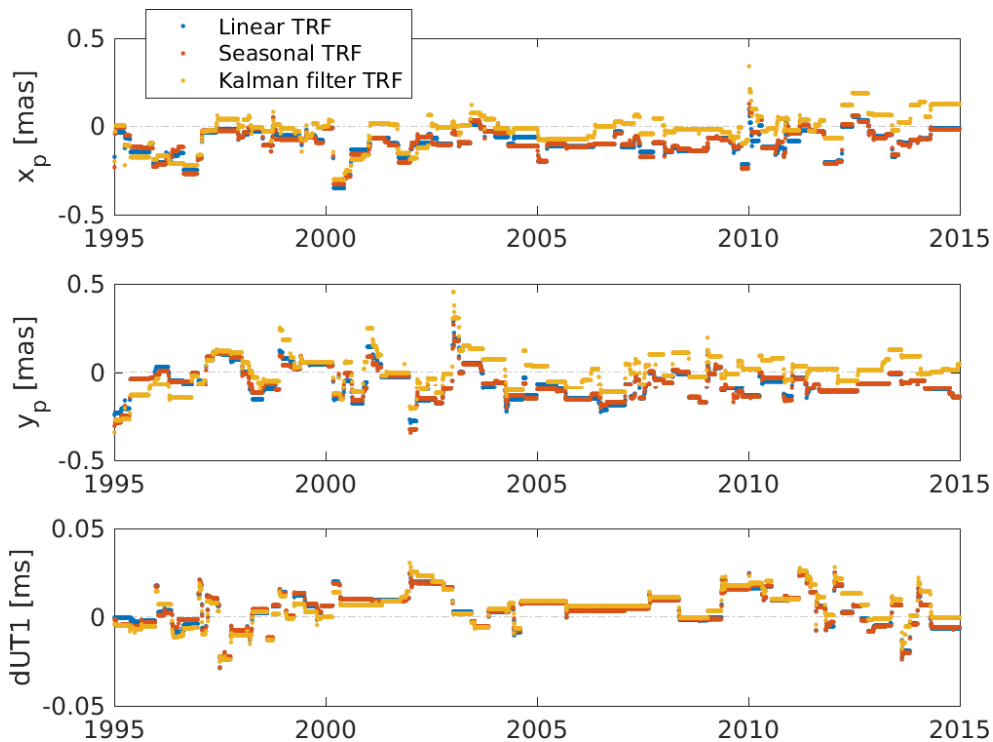
Earth orientation parameters

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

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%

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



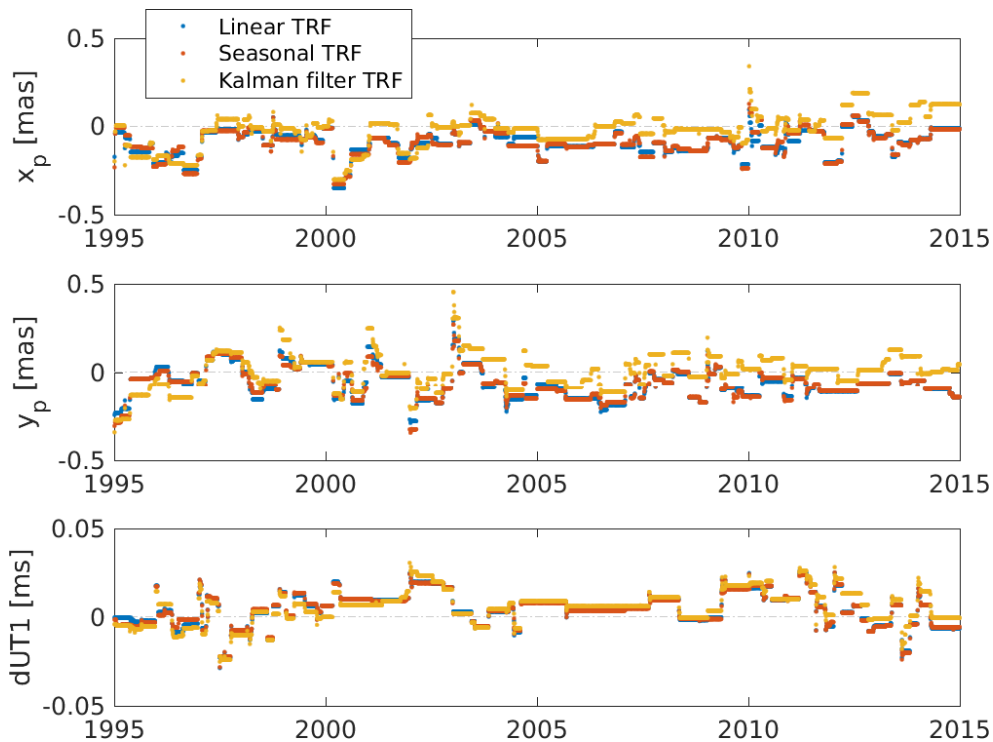
Earth orientation parameters

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

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

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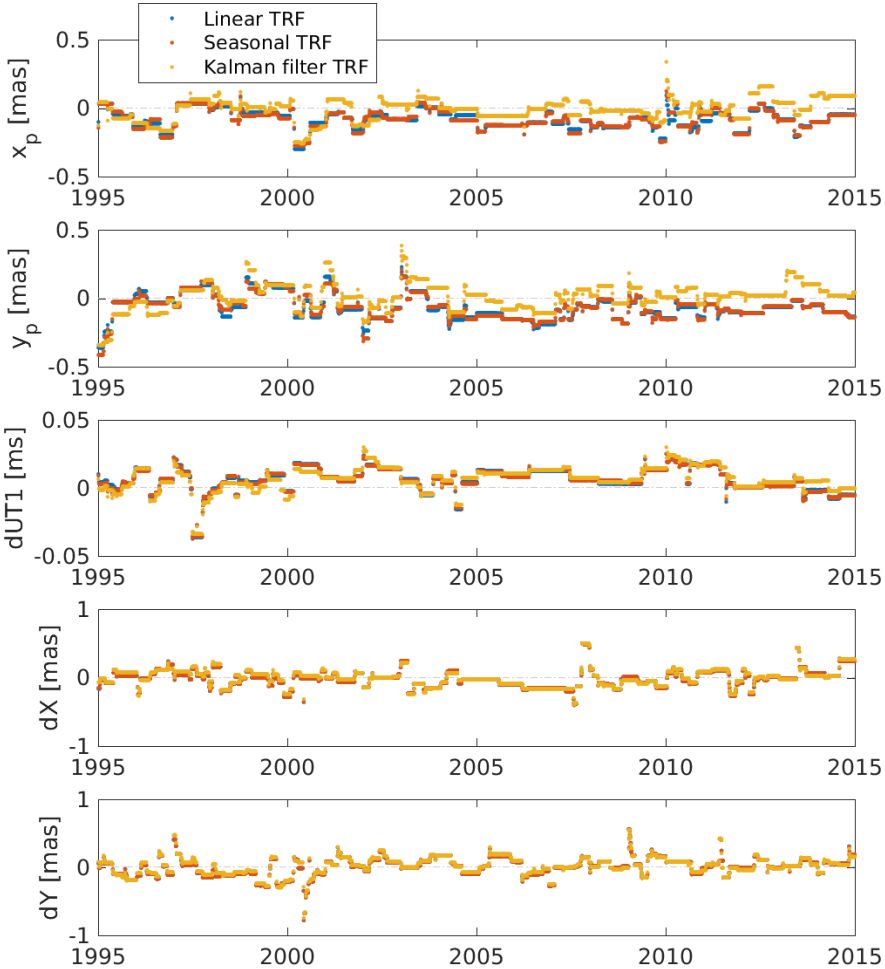


WRMS of differences

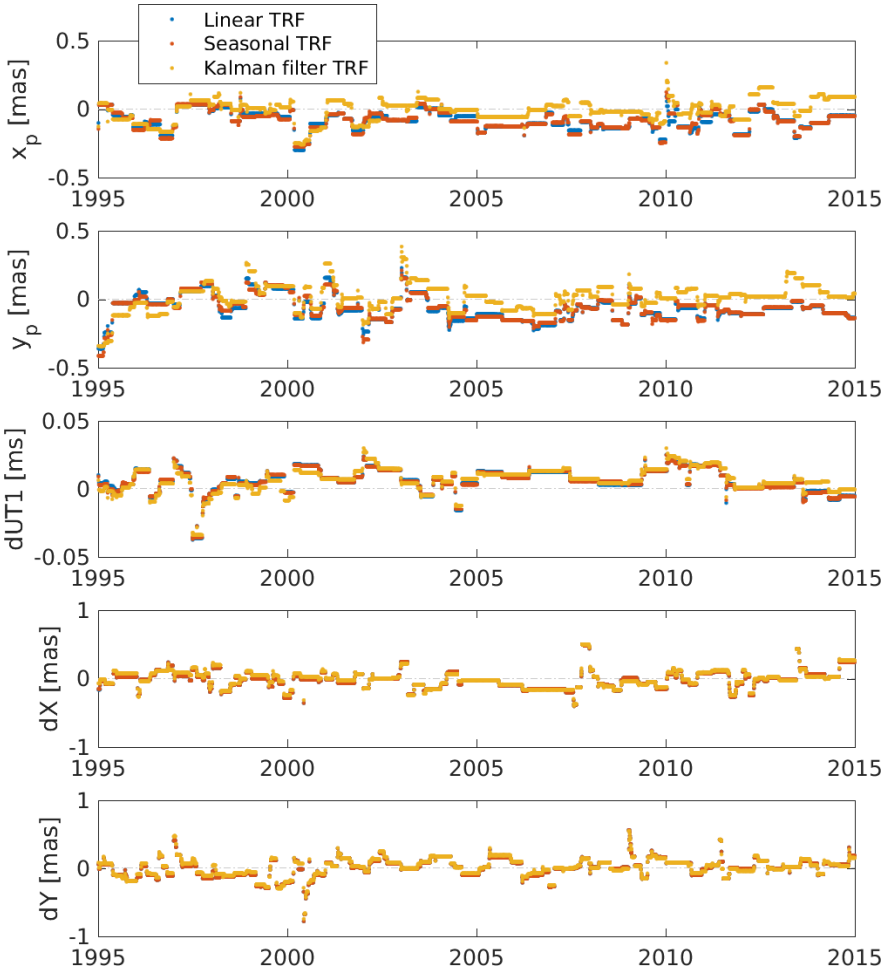
WRMS [µas] w.r.t. DTRF2014	x_P	y_P	dUT1	dX	dY
TRF linear	243	240	690	378	378
TRF seasonal	243	239	690	378	378
TRF Kalman filter	226	219	692	377	380
Δ(KF – seasonal)	-8%	-9%	+0%	-0%	+1%

Earth orientation parameters

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

WRMS of differences
after subtracting trend

WRMS [µas] w.r.t. DTRF2014	x_P	y_P	dUT1	dX	dY
TRF linear	221	216	690	377	377
TRF seasonal	222	215	689	377	377
TRF Kalman filter	225	219	691	377	380
Δ(KF – seasonal)	+1%	+2%	+0%	0%	+1%



Earth orientation parameters

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

WRMS of differences

WRMS [µas] w.r.t. JTRF2014	x_P	y_P	dUT1
TRF linear	249	257	301
TRF seasonal	250	256	301
TRF Kalman filter	233	223	309
Δ(KF – seasonal)	-7%	-15%	+3%

WRMS of differences
after subtracting trend

WRMS [µas] w.r.t. JTRF2014	x_P	y_P	dUT1
TRF linear	220	215	297
TRF seasonal	221	215	297
TRF Kalman filter	223	221	301
Δ(KF – seasonal)	+1%	+3%	+1%

Earth orientation parameters

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

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

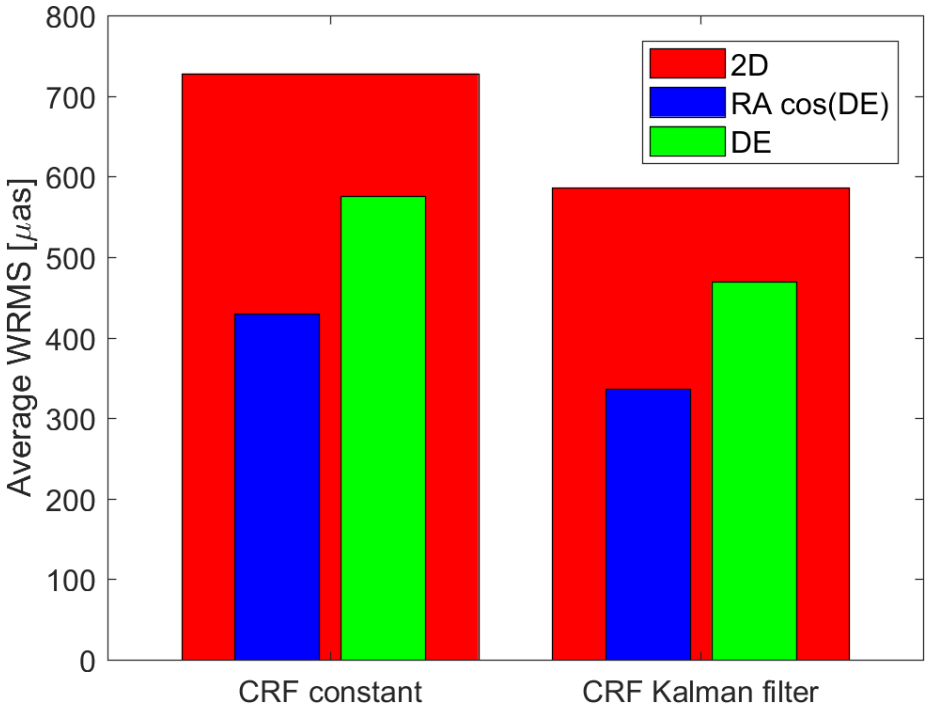
Source coordinates

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%

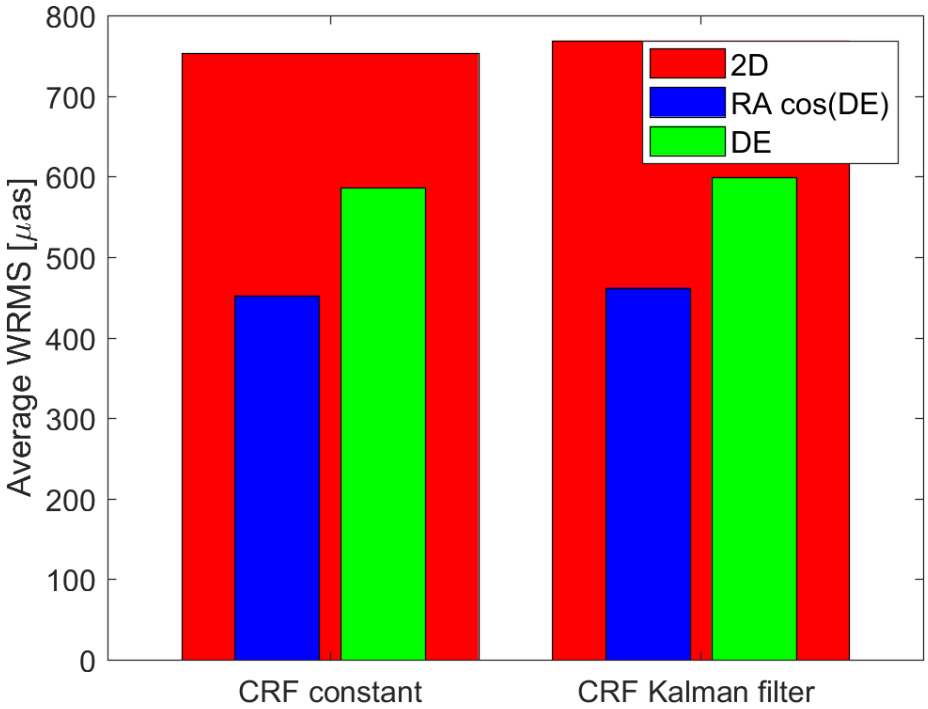
Source coordinates

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

- First implementation of a **2-level TRF and CRF**
  1. Least-squares secular frame
  2. Kalman filter time series based on residuals
- Advantage: **user can choose** depending on application

- **Performance** in VLBI analysis:
  - Estimated offsets 20-50% smaller for Kalman filter solutions
    - KF can follow coordinates much more closely
  - Repeatabilities for Kalman filter solutions 2-6% larger
    - Repeatabilities based on linear assumption
  - EOP: VLBI solutions WRMS differs by ~5 µas, up to 30 µas
    - External EOP time series also differ by a similar amount

Thanks for your attention!

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VLBI data: IVS (Nothnagel et al., 2015)

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- Nothnagel et al., 2015: The IVS data input to ITRF2014. International VLBI Service for Geodesy and Astrometry, GFZ Data Services. http://doi.org/10.5880/GFZ.1.1.2015.002
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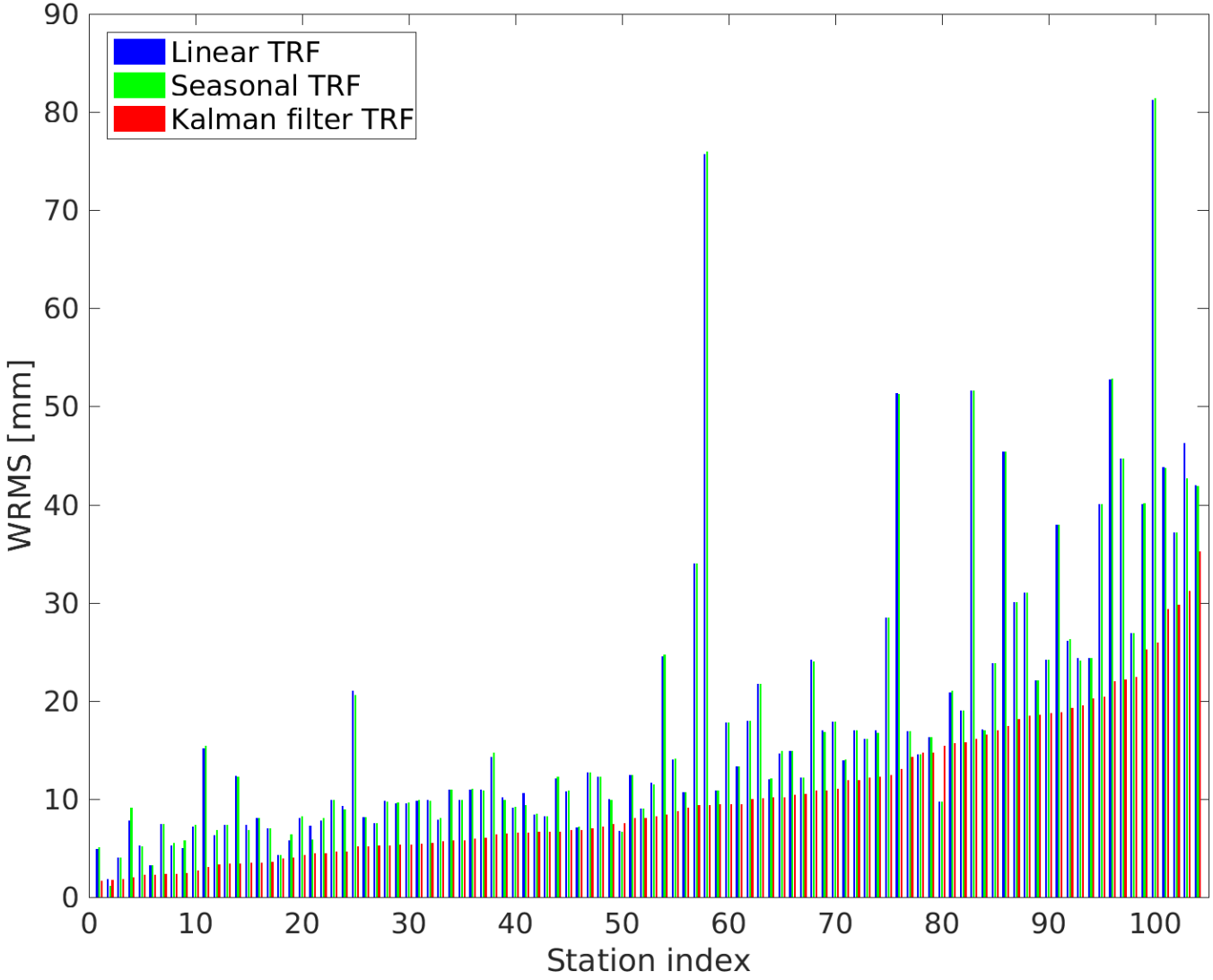
- Seitz et al., 2016: The new DGFI-TUM realization of the ITRS: DTRF2014 (data). Deutsches Geodätisches Forschungsinstitut, Munich, doi:10.1594/PANGAEA.864046

Backup

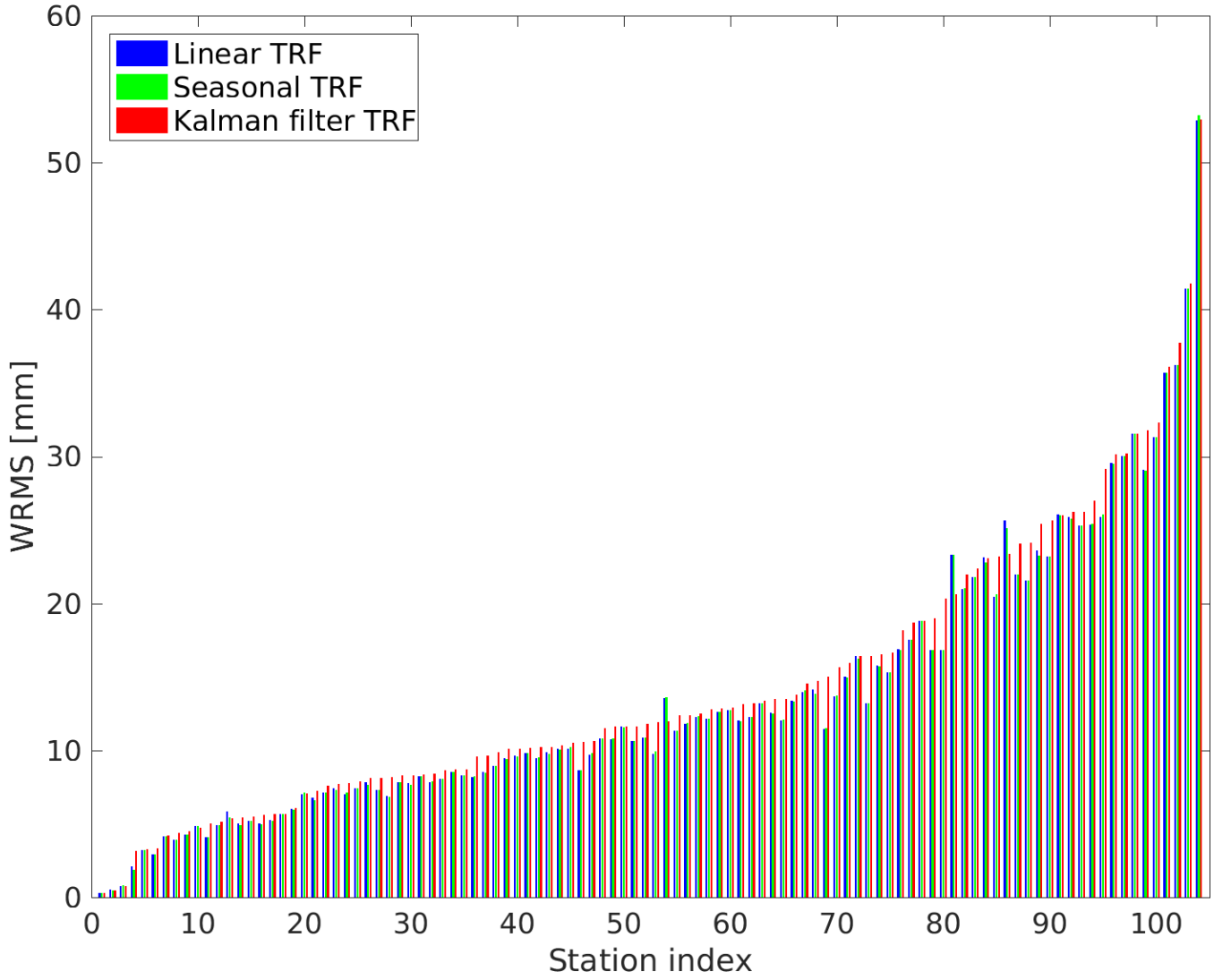
Individual estimated offsets (radial)

Sorted by WRMS of KF solution



Individual
stat. repeatabilities
(radial)

Sorted by WRMS
of KF solution



EOP 14C04

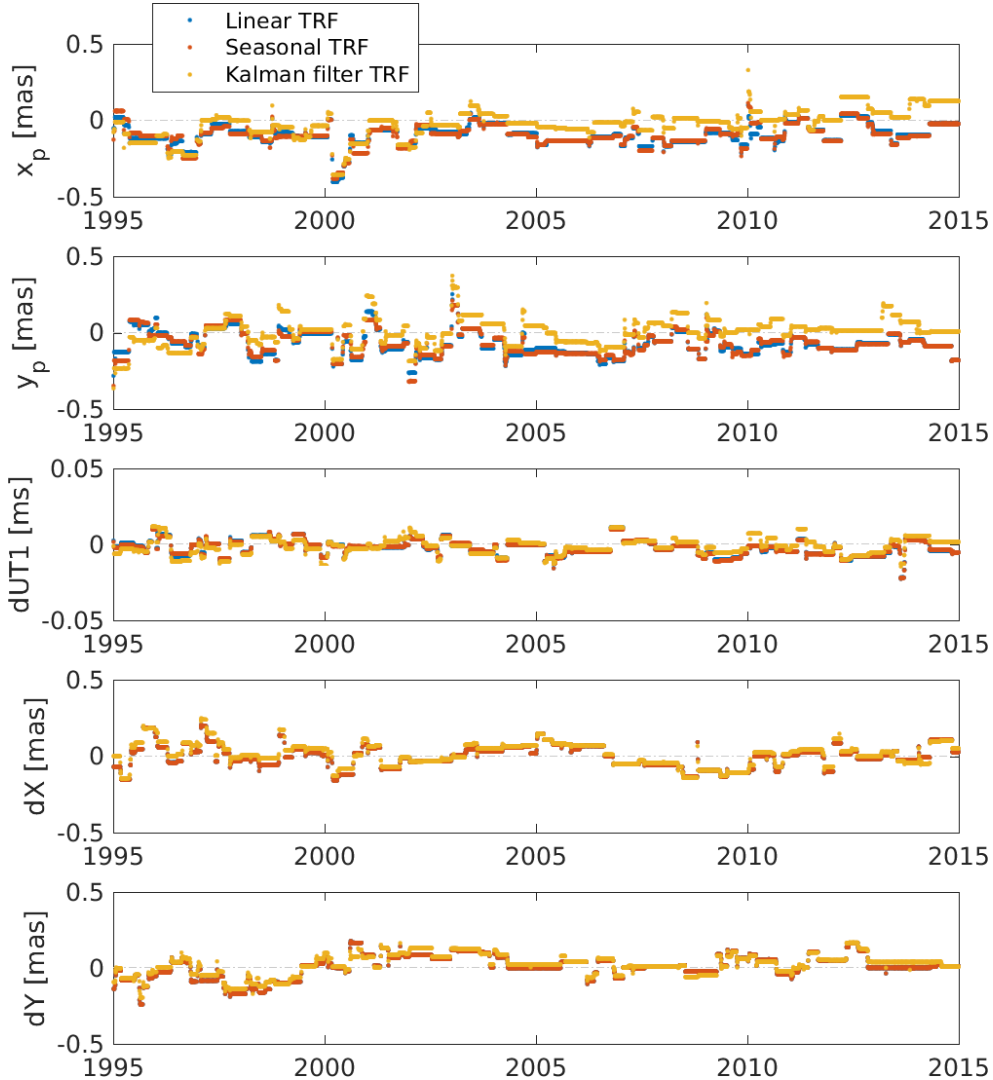
Estimated station & source coordinates

WRMS [muas] w.r.t. C04 14	x_P	y_P	dUT1	dX	dY
Linear TRF	225	243	221	208	195
Seasonal TRF	225	243	221	208	195
Kalman filter TRF	223	216	221	212	198
KF - seasonal	-1%	-13%	0%	+2%	+2%

Fixed station & source coordinates

WRMS [muas] w.r.t. C04 14	x_P	y_P	dUT1	dX	dY
Linear TRF	137	164	121	75	75
Seasonal TRF	138	164	121	75	75
Kalman filter TRF	158	162	119	87	87
KF - seasonal	+13%	-1%	-2%	+14%	+14%

EOP 14C04



Plotted are:
30 day moving medians

EOP ITRF2014

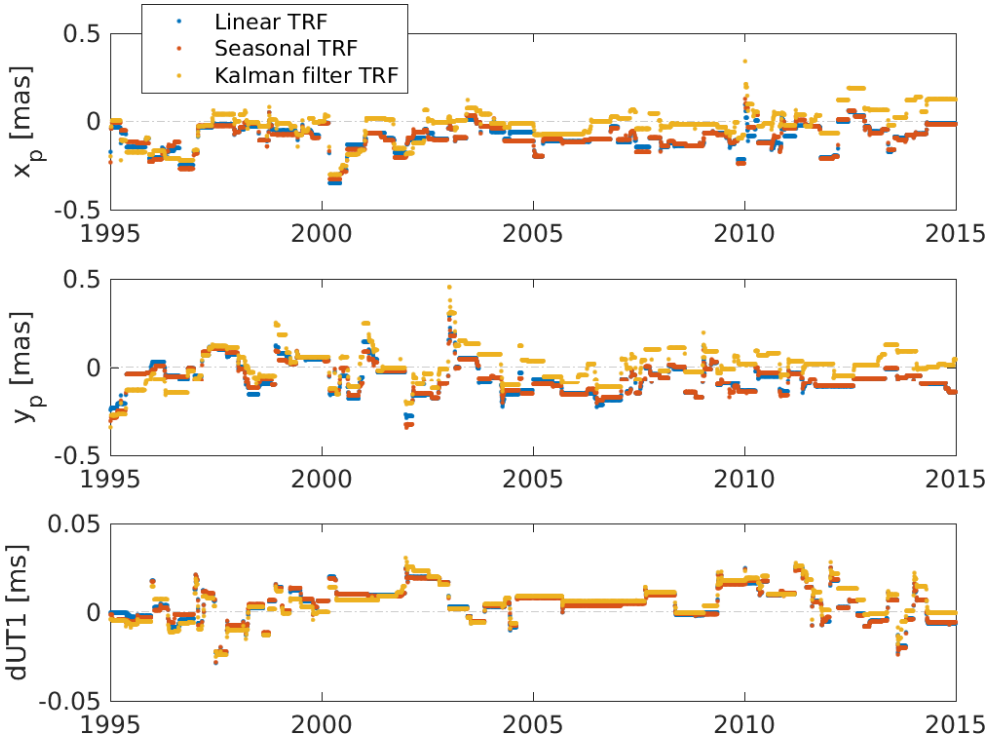
Estimated station & source coordinates

WRMS [muas] w.r.t. ITRF2014	x_P	y_P	dUT1
Linear TRF	243	242	267
Seasonal TRF	244	241	267
Kalman filter TRF	233	223	271
KF - seasonal	-5%	-8%	+1%

Fixed station & source coordinates

WRMS [muas] w.r.t. ITRF2014	x_P	y_P	dUT1
Linear TRF	146	153	175
Seasonal TRF	147	153	175
Kalman filter TRF	160	160	188
KF - seasonal	+8%	+4%	+7%

EOP ITRF2014



Plotted are:
30 day moving medians

EOP DTRF2014

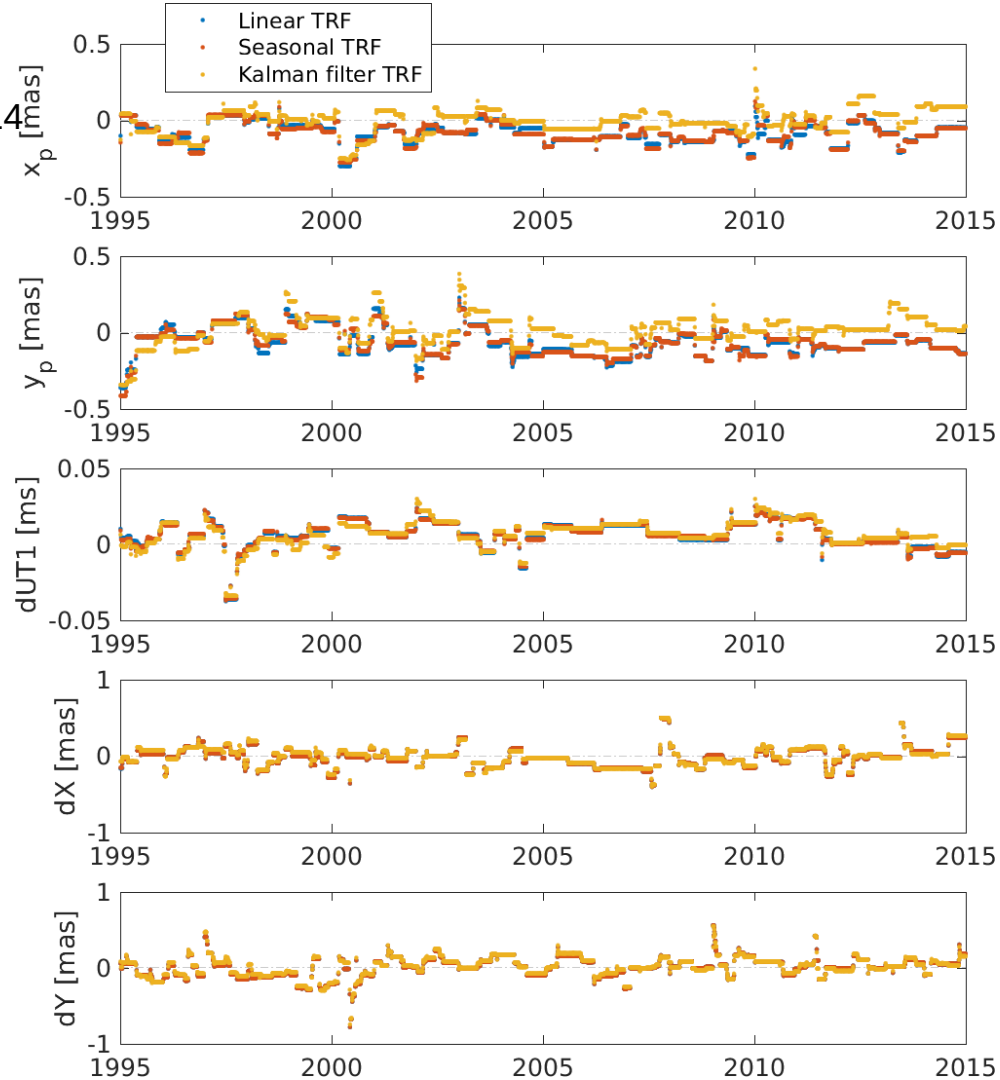
Estimated station & source coordinates

WRMS [muas] w.r.t. DTRF2014	x_P	y_P	dUT1	dX	dY
Linear TRF	243	240	690	378	378
Seasonal TRF	243	239	690	378	378
Kalman filter TRF	226	219	692	377	380
KF - seasonal	-8%	-9%	+0%	-0%	+1%

Fixed station & source coordinates

WRMS [muas] w.r.t. DTRF2014	x_P	y_P	dUT1	dX	dY
Linear TRF	147	155	460	329	322
Seasonal TRF	149	155	460	329	322
Kalman filter TRF	152	158	462	325	326
KF - seasonal	+2%	+2%	+0%	-1%	+1%

EOP DTRF2014



Plotted are:
30 day moving medians

EOP JTRF2014

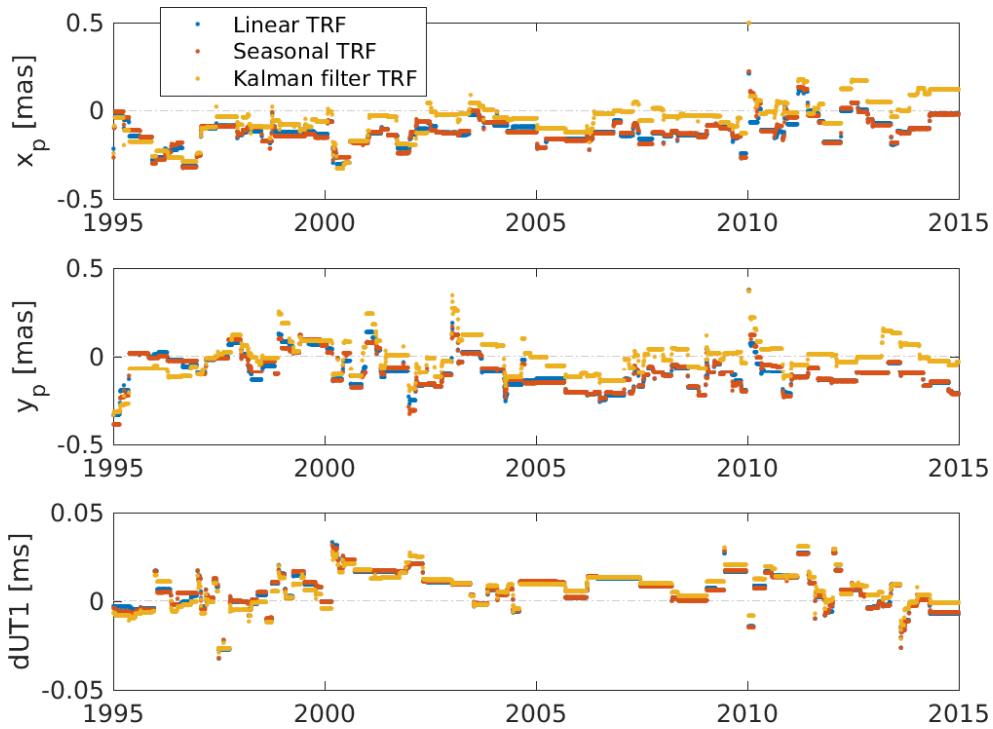
Estimated station & source coordinates

WRMS [muas] w.r.t. JTRF2014	x_P	y_P	dUT1
Linear TRF	249	257	301
Seasonal TRF	250	256	301
Kalman filter TRF	233	223	309
KF - seasonal	-7%	-15%	+3%

Fixed station & source coordinates

WRMS [muas] w.r.t. JTRF2014	x_P	y_P	dUT1
Linear TRF	158	180	249
Seasonal TRF	160	180	249
Kalman filter TRF	163	164	266
KF - seasonal	+2%	-10%	+7%

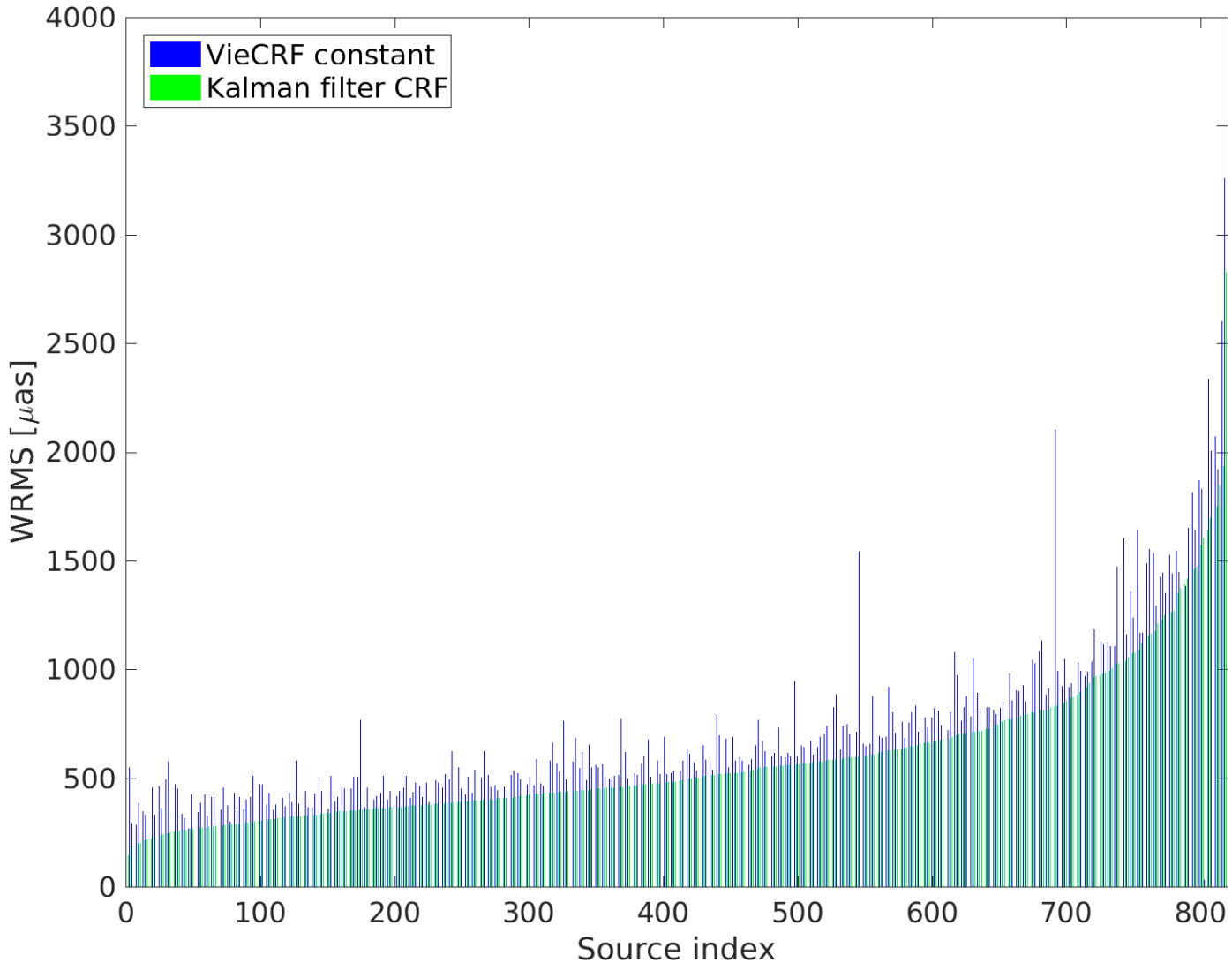
EOP JTRF2014

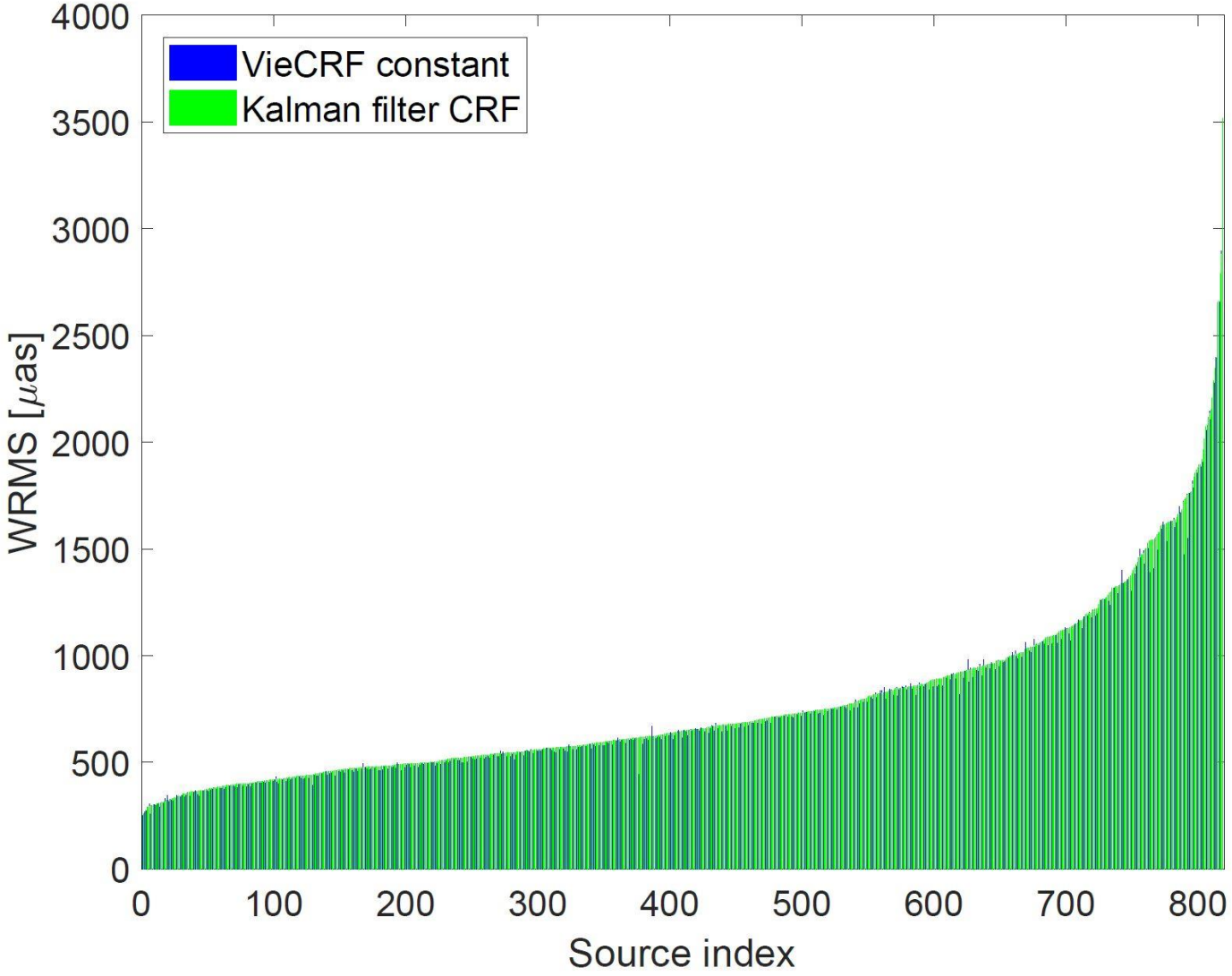


Plotted are:
30 day moving medians

Individual estimated offsets (2D)

Sorted by WRMS of KF solution



Individual
coord. repeatabilities
(2D)

Sorted by WRMS
of KF solution