Effects of non-tidal loading applied in VLBI reference frames

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Outline

- description of input data
- correcting for non-tidal loading (NTL) in TRF computation
- impact of NTL on VLBI-only TRF
- application of TRF in single-session solutions
- discussion of impact in VLBI
- conclusions

Input data: VLBI observations

- basis: all VLBI sessions for the ITRS 2020 realization (24h sessions of the years 1979-2020 with at least 3 antennas participating). 5,860 sessions could be processed.
- legacy observations only, i.e. no combination with the new VLBI Global Observing System (VGOS).
- VLBI observation and normal equations set up with the Radio Interferometry component of our DGFI-TUM Orbit and Geodetic parameter estimation Software (DOGS-RI).
- underlying geophysical and technique-specific models partly changed w.r.t. the IVS contribution to the ITRS 2020 realization.
- e.g., ITRF2020 used for a priori antenna positions, new model EOT20 by DGFI-TUM used for ocean tides.
- radio source positions are fixed, tropospheric and clock parameters are reduced.

Input data: non-tidal loading (NTL)

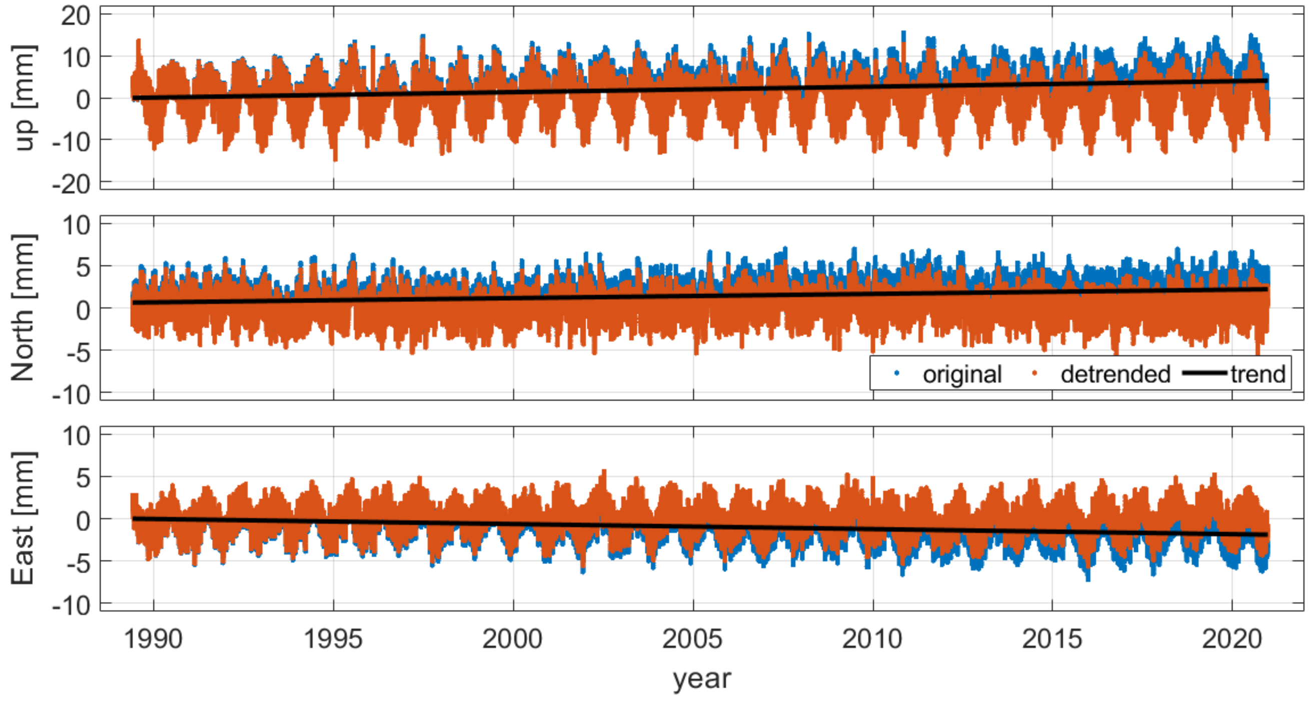
- contribution (in terms of site displacements) of the Global Geophysical Fluid Center (GGFC) to the ITRS 2020 realizations.

- time series of displacements (for, e.g., VLBI station NOTO below) contain trends, mainly due to the hydrological loading part.

- trends removed before application in our secular TRFs, to not separate velocities.

- site displacements obtained by con-volving weighting Green's functions with pressure anomalies from models:

loading part	underlying model
atmospheric	ECMWF ERA5
oceanic	TUGO-m or inverted barometer
hydrological	ECMWF ERA5



TRF computation

- **VLBI-only TRFs by combination of session-wise, datum-free normal equation systems.**
- **datum constraints M_D: NNT and NNR conditions w.r.t. DTRF2014.**

DOGS-RI

observation and normal equations per session s:

$$A^s\,\Delta x^s = b^s - f(x_0^s) = l^s$$
$$N^s = (A^s)^T P^s A^s$$
$$y^s = (A^s)^T P^s l^s$$

datum-free normal equations

DOGS-CS

re-parametrization of station positions per session s:

$$p(t^s) = o(t^0) + (t^s - t^0)\, d$$
$$A^s \Delta p^s \leftarrow (A^s \quad A^s B^s) \begin{pmatrix} \Delta o \\ \Delta d \end{pmatrix}$$
$$N^s \leftarrow \begin{bmatrix} N^s & N^s B^s \\ B^s N^s & B^s N^s B^s \end{bmatrix}, \quad y^s \leftarrow \begin{bmatrix} y^s \\ B^s y^s \end{bmatrix}$$

stacking of session-wise normal equations:

$$M = \sum_{s=1}^{q} N^s, z = \sum_{s=1}^{q} y^s$$
$$\Delta x = (M + M_D)^{-1} z$$

Correcting for NTL at observation level

- **epoch-wise site displacements due to NTL directly applied in the functional model in DOGS-RI => new model $\tilde{f}$.**
- **new partial derivatives $\tilde{A}^s$, normal matrices $\tilde{N}^s$, $\tilde{M}$ and right-hand-sides $\tilde{y}^s$, $\tilde{z}$.**

DOGS-RI

new observation and normal equations per session s:

$$\tilde{A}^s \Delta\tilde{x}^s = b^s - \tilde{f}(x_0^s) = \tilde{l}^s$$

$$\tilde{N}^s = \left(\tilde{A}^s\right)^T P^s \tilde{A}^s$$

$$\tilde{y}^s = \left(\tilde{A}^s\right)^T P^s \tilde{l}^s$$

new datum-free normal equations

DOGS-CS

re-parametrization of station positions per session s:

$$\tilde{p}(t^s) = \tilde{o}(t^0) + (t^s - t^0)\tilde{d}$$

$$\tilde{A}^s \Delta\tilde{p}^s \leftarrow \begin{pmatrix} \tilde{A}^s & \tilde{A}^s B^s \end{pmatrix} \begin{pmatrix} \Delta\tilde{o} \\ \Delta\tilde{d} \end{pmatrix}$$

$$\tilde{N}^s \leftarrow \begin{bmatrix} \tilde{N}^s & \tilde{N}^s B^s \\ B^s \tilde{N}^s & B^s \tilde{N}^s B^s \end{bmatrix}, \quad \tilde{y}^s \leftarrow \begin{bmatrix} \tilde{y}^s \\ B^s \tilde{y}^s \end{bmatrix}$$

stacking of session-wise normal equations:

$$\tilde{M} = \sum_{s=1}^{q} \tilde{N}^s, \tilde{z} = \sum_{s=1}^{q} \tilde{y}^s$$

$$\Delta\tilde{x} = \left(\tilde{M} + M_D\right)^{-1} \tilde{z}$$

Correcting for NTL at normal equation level

- **session-wise average site displacements $\bar{\delta}^s_{NTL}$ used to correct the right-hand-sides y^s of the normal equation systems in DOGS-CS.**
- **matrices A^s, N^s and M unchanged, intra-session resolution of displacements lost.**

DOGS-RI

observation and normal equations per session s:

$$A^s\,\Delta x^s = b^s - f(x_0^s) = l^s$$
$$N^s = (A^s)^T P^s A^s$$
$$y^s = (A^s)^T P^s l^s$$

(old) datum-free normal equations

DOGS-CS

correction of right-hand-sides:

$$\tilde{f}(x_0^s) \approx \bar{f}(x_0^s) = f(x_0^s) + A^s\,\bar{\delta}^s_{NTL}$$
$$\Rightarrow \quad \bar{y}^s = y^s - N^s\,\bar{\delta}^s_{NTL}$$

re-parametrization of station positions per session s:

. . .

stacking of session-wise normal equations:

$$M = \sum_{s=1}^{q} N^s,\ \bar{z} = \sum_{s=1}^{q} \bar{y}^s$$

$$\Delta\bar{x} = (M + M_D)^{-1}\,\bar{z}$$

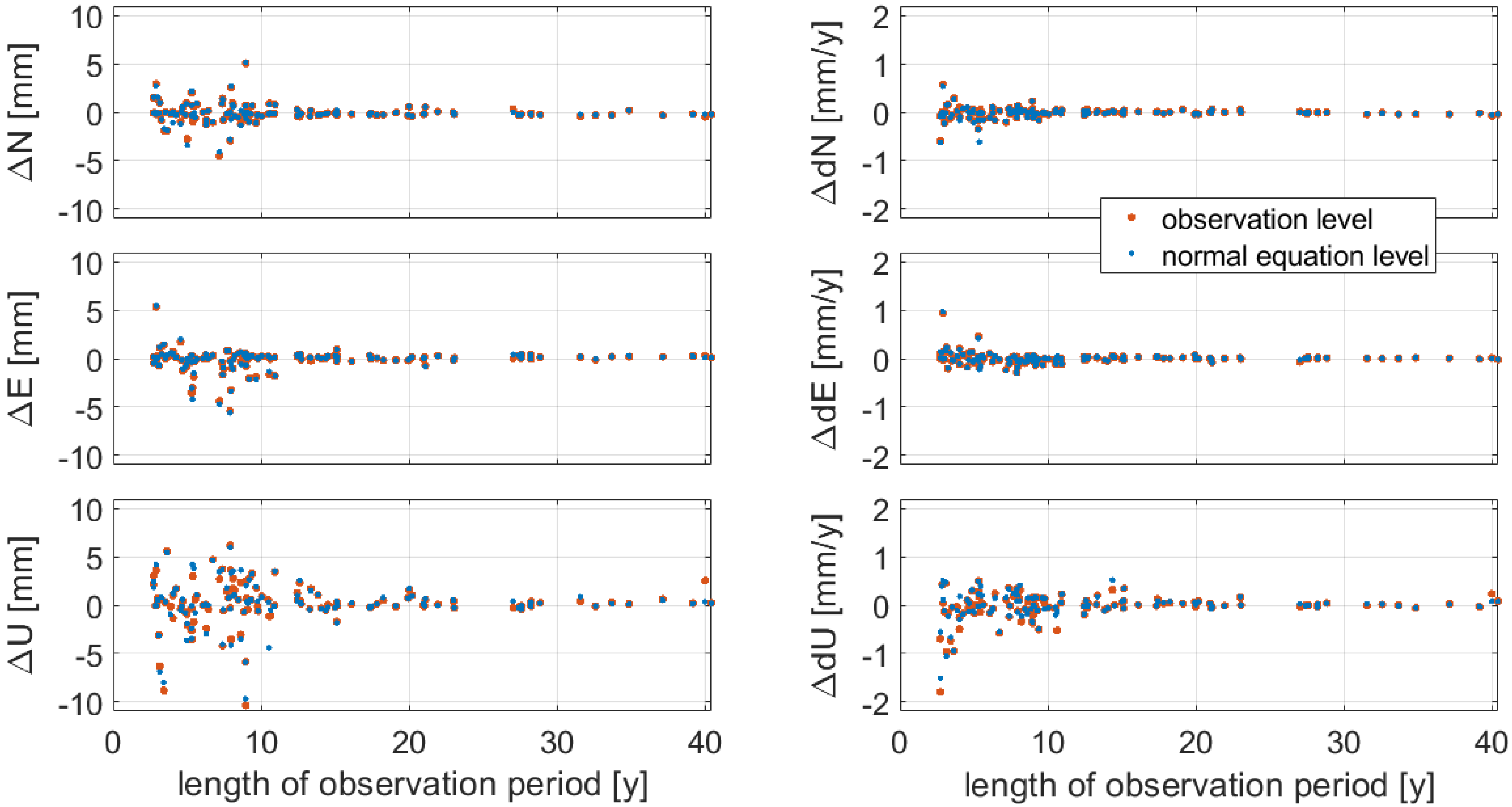
Impact of NTL: estimated antenna motions

- **linear motions of 83 stations with at least 20 sessions and 2.5 years of data estimated.**
  When correcting for NTL, antenna offsets change by a few mm, antenna velocities by less than 1 mm/y.

- **changes largest for antenna heights, like site displacements largest for vertical direction.**

- **hardly any changes for antennas with observation history greater than about 15 years.**

- **results very similar for the distinct application levels.**



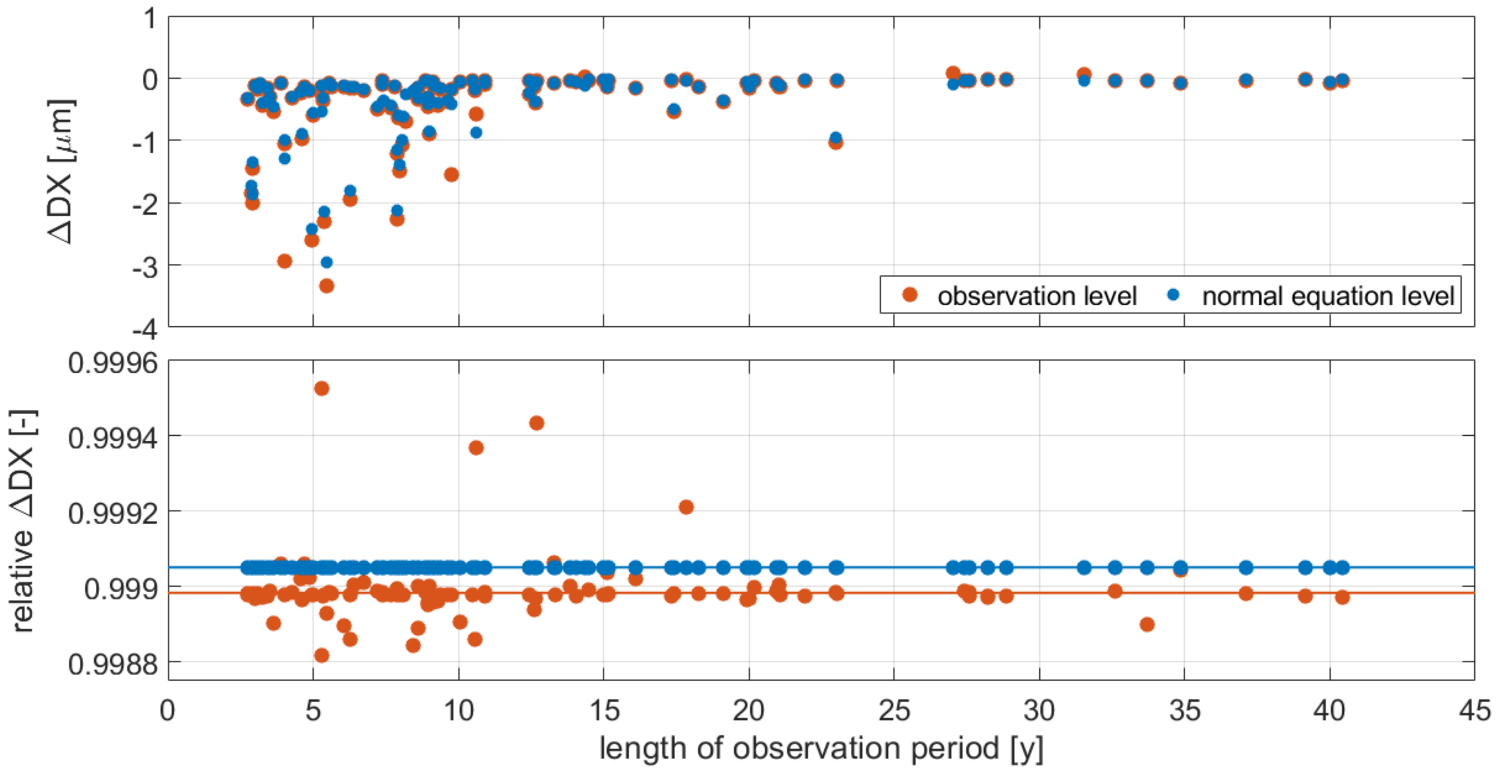
Impact of NTL: formal errors

- formal errors of antenna offsets and velocities only change with the new partial derivatives in $\widetilde{\boldsymbol{M}}$ and the a posteriori variance factors $\hat{\sigma}_0^2$:

$$C_{\hat{x}\hat{x}} = \begin{cases} \hat{\sigma}_0^2 \,(M + M_D)^{-1} & \text{(no NTL; normal equation level)} \\ \hat{\sigma}_0^2 \,(\widetilde{M} + M_D)^{-1} & \text{(observation level)} \end{cases}$$

- relative changes in formal errors dominated by $(\hat{\sigma}_0^{NTL})^2 / (\hat{\sigma}_0^{no\ NTL})^2$.

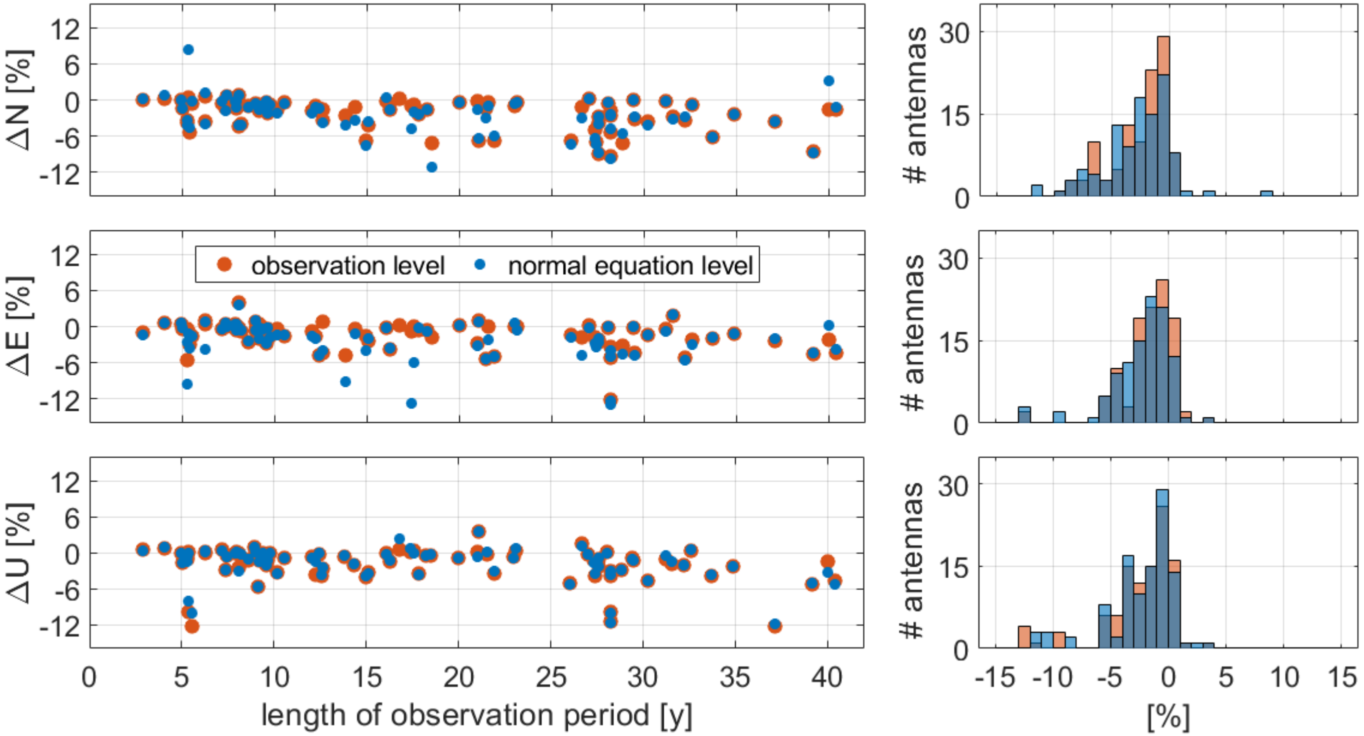
scenario	$\hat{\sigma}_0^2$
no NTL	1.1804
NTL at observation level	1.1792
NTL at normal equation level	1.1793



Antenna position residuals

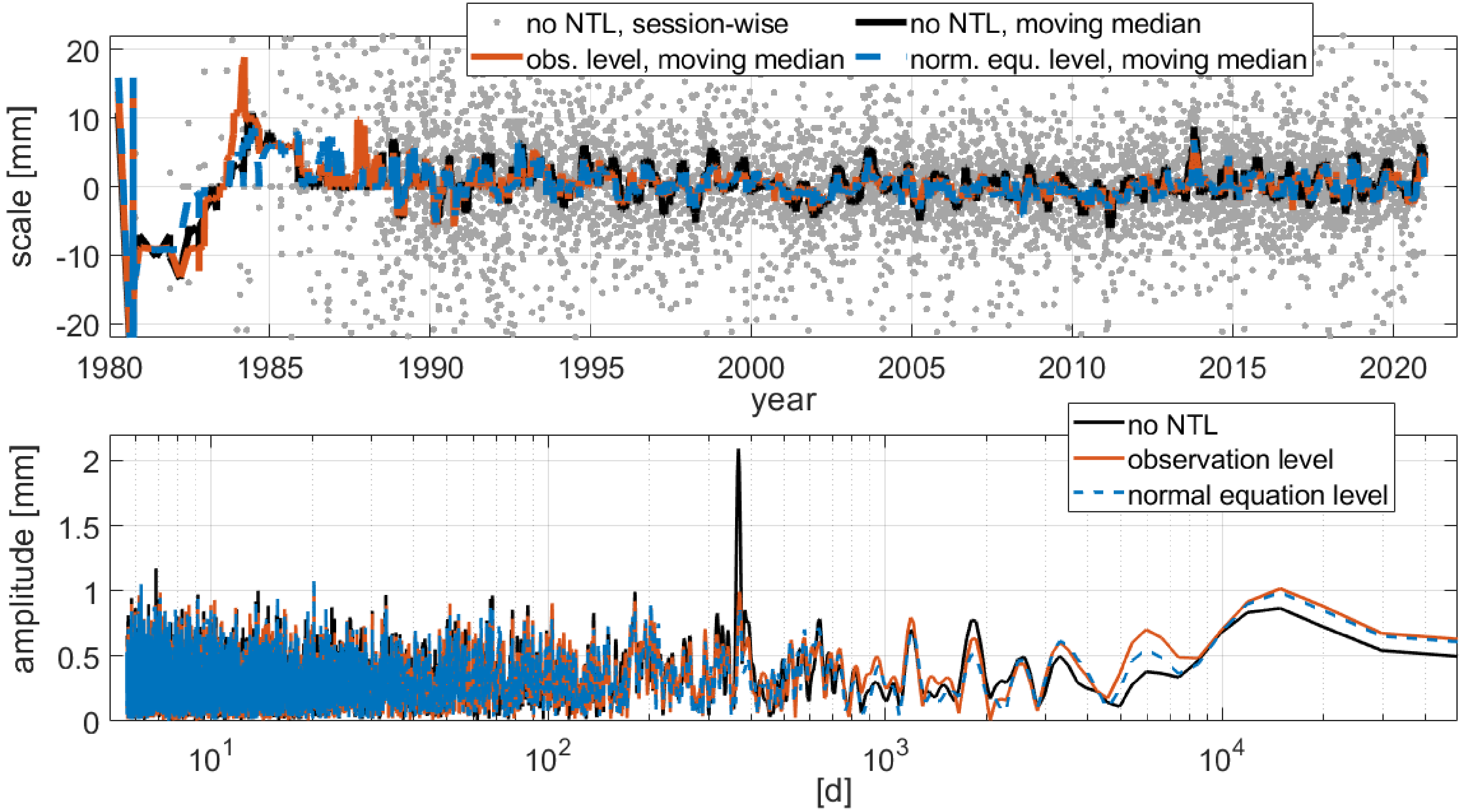
- new single-session solutions computed by replacing a priori frame ITRF2020 by the respective TRFs. Datum-constraints hence align new solutions to our TRFs.

- WRMS values of residuals of single-session antenna positions w.r.t. corresponding TRFs systematically reduced by application of NTL at either level:



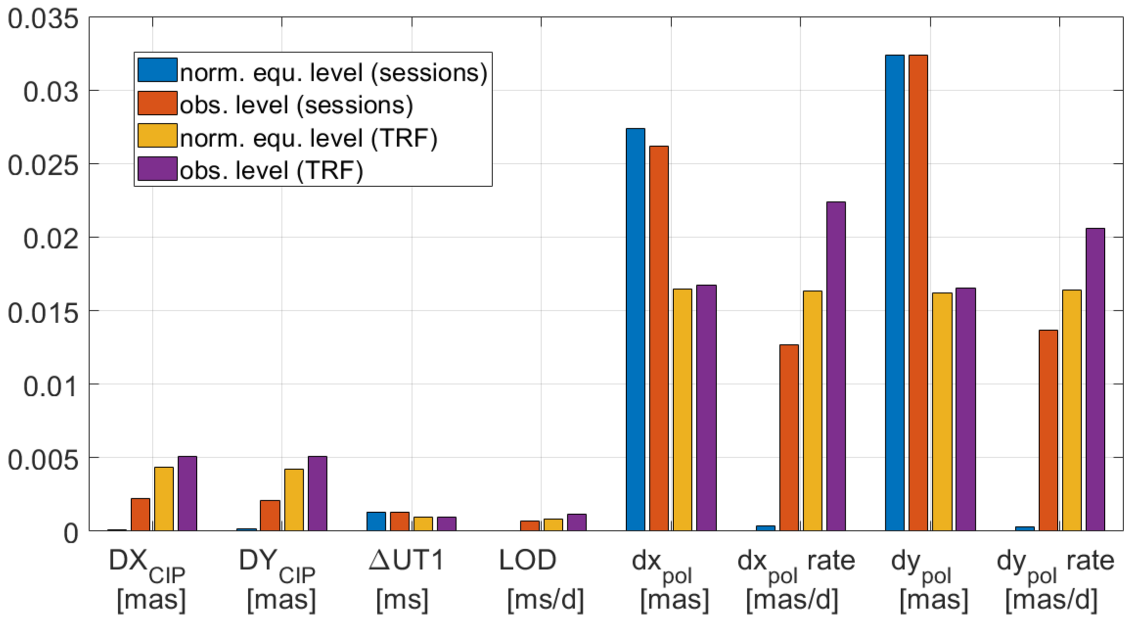
Intrinsic scale

- **annual amplitude for scale parameter of Helmert-transformation between single-session solutions and respective TRFs reduced (2.1 to about 0.95 mm) by the application of NTL at either level:**



Earth orientation parameters (EOP)

- figure: WRMS values of differences between EOP estimated with and without correcting for NTL, for both TRF and single-session solutions.
- larger discrepancies of results for distinct application levels, in particular for Earth rotation parameter (ERP: polar motion and ΔUT1) rates and celestial pole offsets.
- rates sensitive against intra-session variation in site displacements, which is lost at normal equation level.
- differences in nature of estimated EOP between TRF (less scatter in time series) and single-session solutions (more scatter).
- TRF: EOP (especially ERP offsets) correlated between session epochs, more substitution of the impact of NTL between offsets and rates.
- EOP differences between TRF and single-session solutions slightly smaller when NTL applied.



Discussion of impact in VLBI

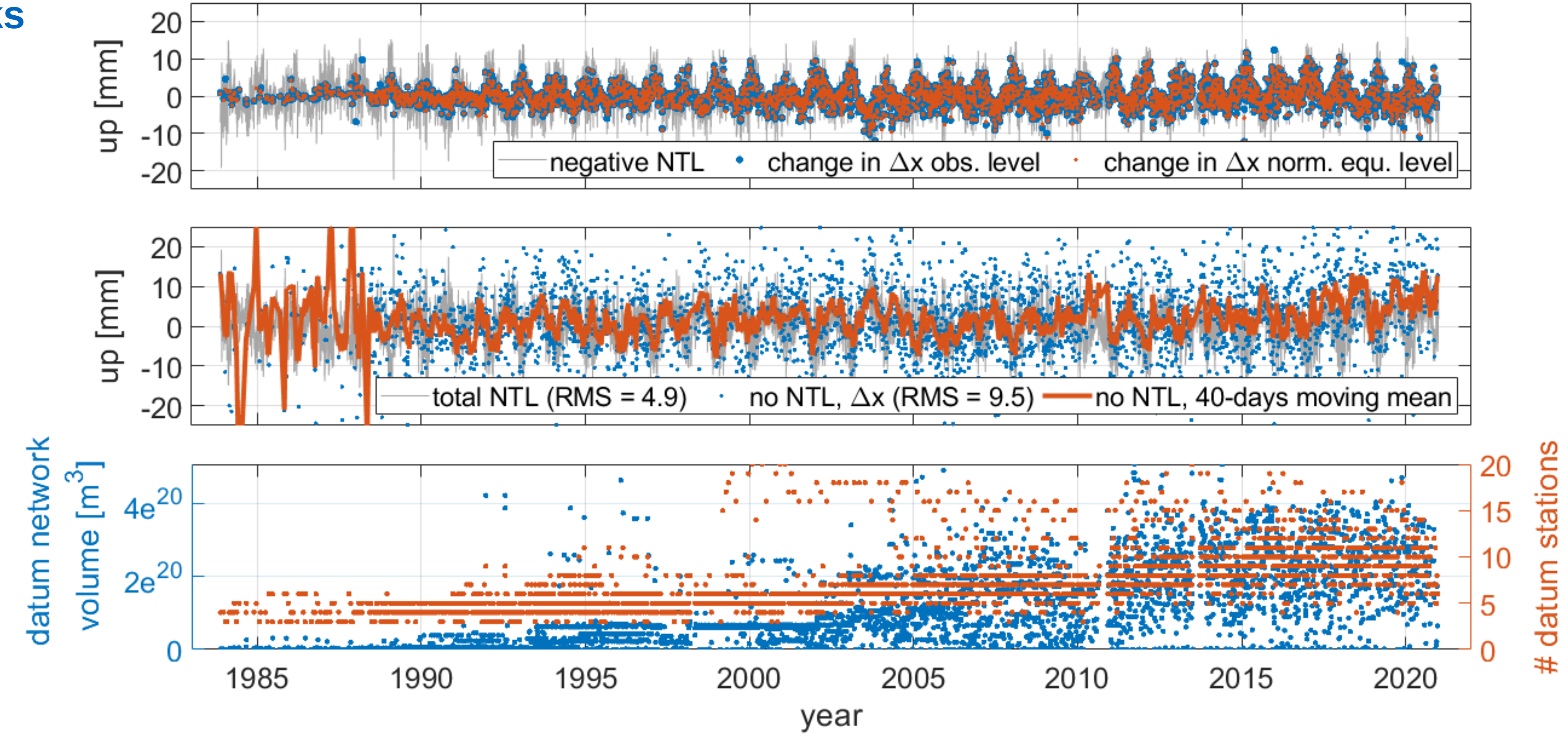
- ideally, change due to NTL in estimated antenna corrections per session equal to the (average) negative site displacement (compare top panel in figure for VLBI antenna WETTZELL): $\Delta\bar{x}^s - \Delta x^s = -\bar{\delta}^s_{NTL}$

- equality strongly depends on network of datum stations in sessions (bottom panel).

- heterogenity of session networks further contributes to variability of corrections, which is larger than that of the site displacements (middle panel).

- together: hard for NTL to make a larger impact yet.

- different for VGOS, and more homogeneous networks?



Conclusions

- correcting for NTL in VLBI-only TRFs is beneficial, since there are systematic positive effects.
- stations with short observation histories are affected most, those with very long histories mainly in single-session solutions only.
- scatter of antenna position residuals and seasonal signal in the (instrinsic) scale parameter are reduced.
- the application level of site displacements (observation vs. normal equation level) is minor relevant, except for jointly estimated EOP with their epoch-wise parametrization.
- a reason for the small (compared to, e.g., GNSS) impact of NTL is probably the (datum) station network heterogenity.
- with VGOS, the impact of NTL might become larger.
- consistently correcting all geodetic space techniques for NTL also improves the DTRF.

THANK YOU VERY MUCH FOR YOUR ATTENTION!

ARE THERE ANY QUESTIONS?