



Improving the products of global GNSS data analysis by correcting for loading displacements at the observation level

Lin Wang¹, Daniela Thaller¹, Andreja Susnik^{2,3}, Rolf Dach³

1 Federal Agency for Cartography and Geodesy, Germany

2 Now at NERC Space Geodesy Facility, United Kingdom,

3 Astronomical Institute, University of Bern

Consitant GNSS (GPS+GLONASS) reprocessing in BKG based on CODE Final and reprocessed products

Table 1: summary of the GNSS network solution processing strategy; time span 1994-2018

A prior products	Orbits from CODE2015 REPRO 3-day-arc orbit (Susnik et al., 2016) till 2015.158 then IGS Final 3-day-arc orbit (Dach et al., 2018), corresponding Earth rotation parameters and coordinates in ITRF2014
observations	GPS only (Jan 1994-May 2003); GPS+GLONASS (May 2003 to 2018)
Static Gravity Field	EGM2008 (Pavlis et al., 2012)
Time variable Gravity field	GFZ AOD1B RL06 (Dobslaw et al., 2017) interpolated to 6h grid
Solid Earth Tides	IERS2010 Conventions (Petit & Luzum, 2010)
Atmosphere Tidal loading	S1 S2 tidal loading from Vienna APL model version 4
Ocean tidal loading	FES2004 (Lyard et al., 2006)
Constrains	No-Net-Translation and No-Net-Rotation to ITRF2014
ERP	24h intervals
Troposphere	Zenith path delays 2h resolution, a prior hydrostatic zenith path delay from Vienna Mapping function 1 (Boehm et al., 2006)
GNSS orbit	24h orbit arc, ECOM2 and stochastic orbit pluses at 12:00
Frame center	Center of Mass
Non-Tidal Loading	NTAL, CWSL and NTOL from GFZ loading grid interpolated to 6h grid (Dill & Dobslaw, 2013);

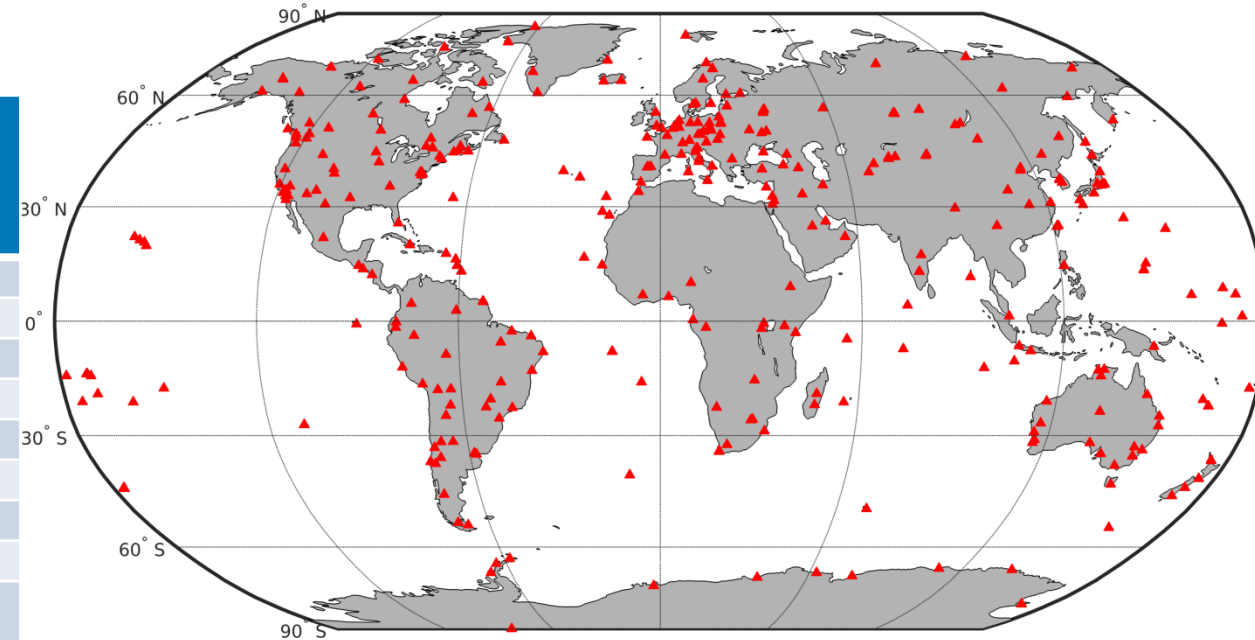


Figure 1: 426 GNSS stations from GNSS network which observed longer than one year duration. Stations which have shorter observation timespan is excluded from the statistics and amplitude discussions.

Station coordinates

Discontinuities, trend, offset and outliers are removed from time series analysis, without considering the spatial distribution.

Most station (more than 90% for all the directions) shows improved the repeatability.

Impacts in North direction: $CWSL \geq NTAL > NTOL$

Impacts in East direction: $NTAL > CWSL \geq NTOL$

Impacts in Up direction: $NTAL > CWSL > NTOL$

Table 2: mean RMS Reduction and the percent of stations which shows positive reduction among the GNSS network

	North (mm)		East (mm)		Up (mm)	
	RMS reduction	station %	RMS reduction	station %	RMS reduction	station %
RM NTAL	-0.12	91.5	-0.09	87.0	-0.56	91.5
RM CWSL	-0.13	82.5	-0.02	56.4	-0.12	65.6
RM NTOL	-0.03	78.1	-0.02	72.4	-0.09	77.8
RM ALL	-0.26	97.0	-0.11	91.5	-0.76	94.3

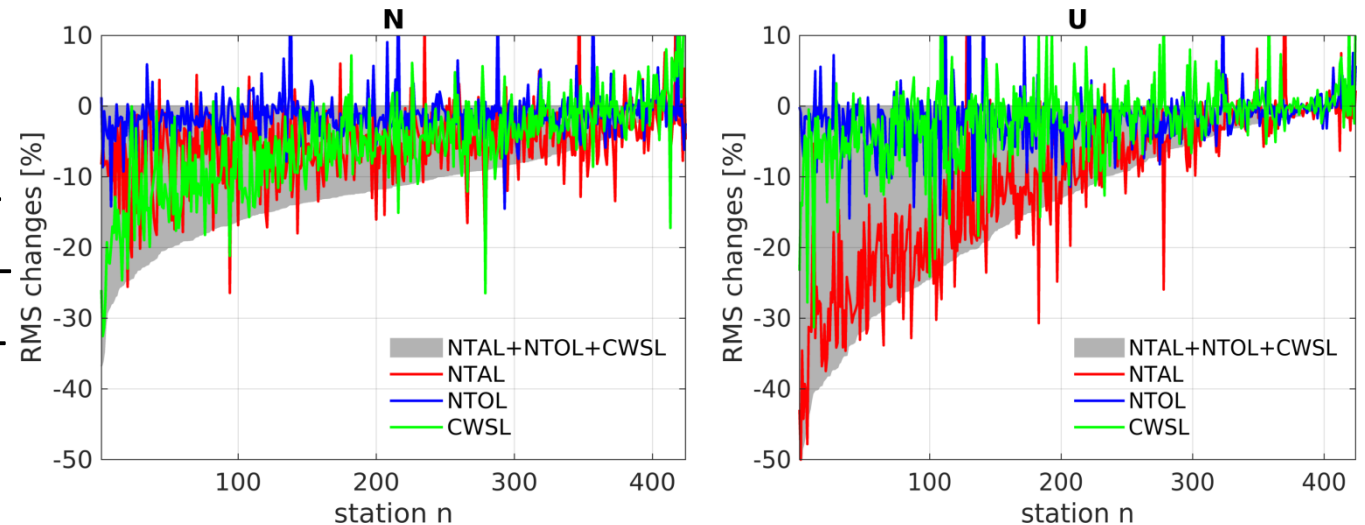


Figure 2: RMS reduction rate of all the solution sets. All the stations are sorted with the RMS reduction rate (in grey) in ascending order in the GNSS solution which removed all the NTAL, NTOL and CWSL effects. The corresponding RMS reduction of the GNSS coordinate RMS reduction of removing NTAL-only, removing NTOL-only and removing CWSL-only solution are in red, blue and green lines, respectively.

Stations coordinates

Annual amplitude (N E U) mm:
(1.3, 0.8, 2.0) -> (0.7, 0.6, 1.1)

Clear inter-seasonal variation
improvement introduced after
removing NTAL

Power Explained, from
 $1 - (\rho_2/\rho_1)^2$ ρ is mean annual amplitude
After correcting surfacing loading:
(68%, 47%, 68%)

Power Explained in Dong et al.
(2002): 31% in vertical direction

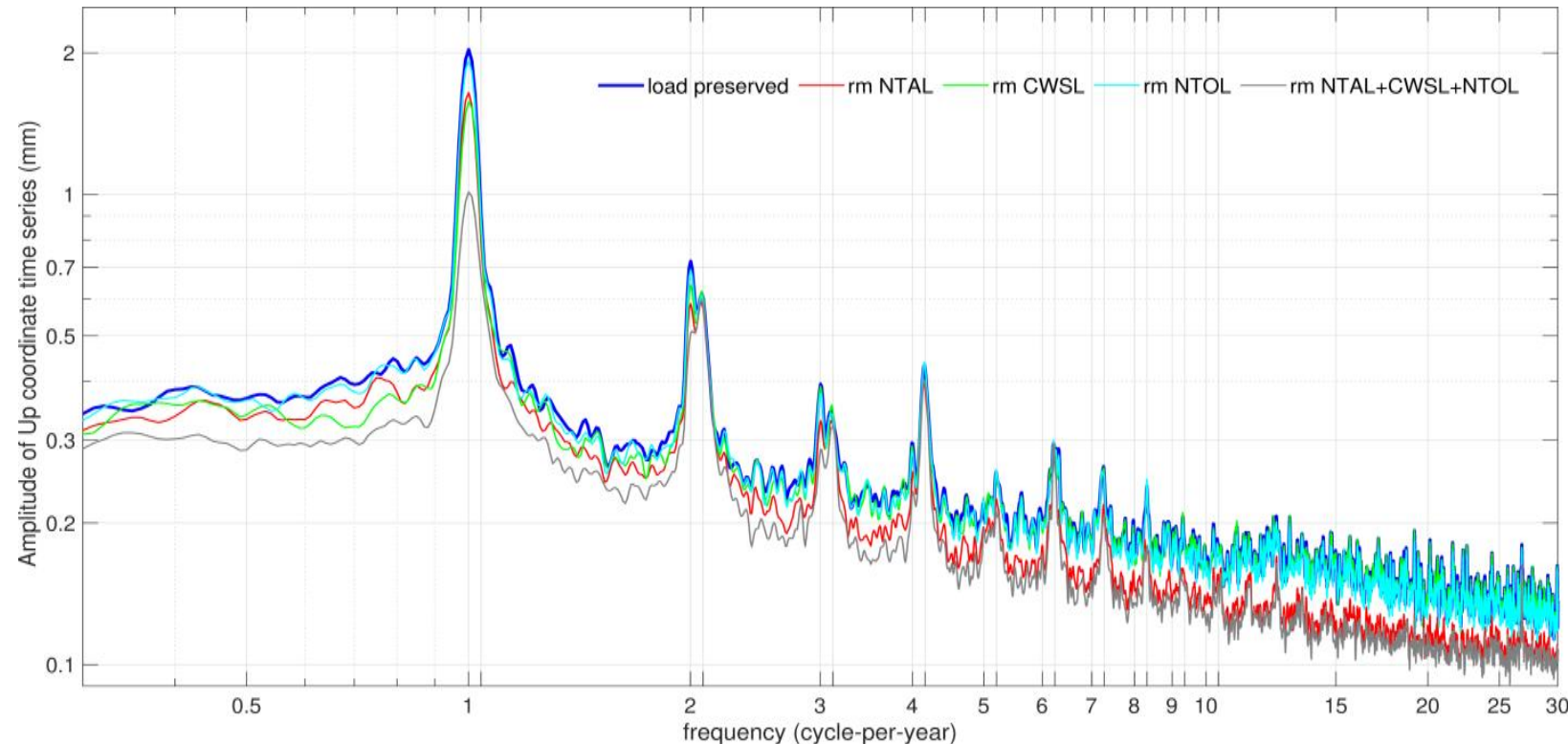


Figure 3: Stacked amplitude spectrum of GNSS coordinates. Ref (blue): all the loading components are preserved; NTAL (red), CWSL (green) and NTOL (cyan) are the GNSS coordinates after removing NTAL-only, CWSL-only and NTOL-only at the observational level, respectively. ALL(gray): GNSS solution after correcting all the NTAL, CWSL and NTOL together from the observations. The ticks after integer cycle-per-year harmonics are the first ten harmonic of the draconic frequency ($N \cdot 1.04$ cycle-per-year).

Surface loading can fully explain the major components in X and Y components.

Comparative effects from NTAL, NTOL and CWSL.

Z components are heavily impact from the orbit (Meindl et al. 2013), up to the year 2013, draconites significantly reduces after a full populated GLONASS satellite constellation.

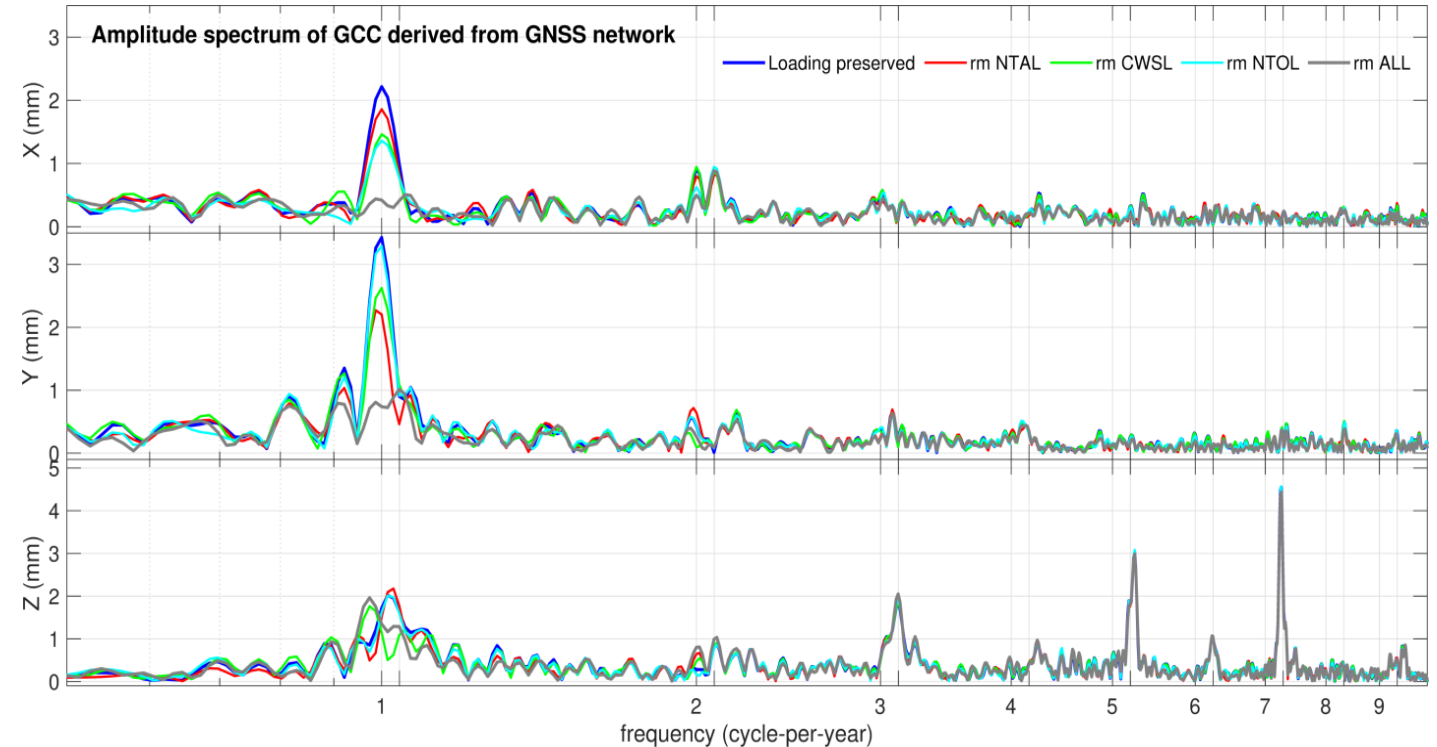


Figure 4: Geocenter amplitude spectrum of the GNSS solution set: reference solution (blue) loading displacement preserved, Geocenter motion derived after remove NTAL-only (red), CWSL (green) and NTOL (cyan), respectively. The gray lines are Geocenter after removing all the loading displacements (NTAL+CWSL+NTOL).

A posterior GCC ($d\mathbf{X}$) (Dach et al., 2011) vs GCC removal from observations:

- $d\mathbf{X}$ from grid is over-estimated.
- The $d\mathbf{X}$ from grid doubles the amplitude of $d\mathbf{X}$ from GNSS.

Annual amplitude can be full explained from surface loading, Explained Power (X Y): (95% 93%)

Semi-annual Explained Power (X Y): (72% 82%)

Major contribution (X Y): (NTOL 56%, CWSL 86%)

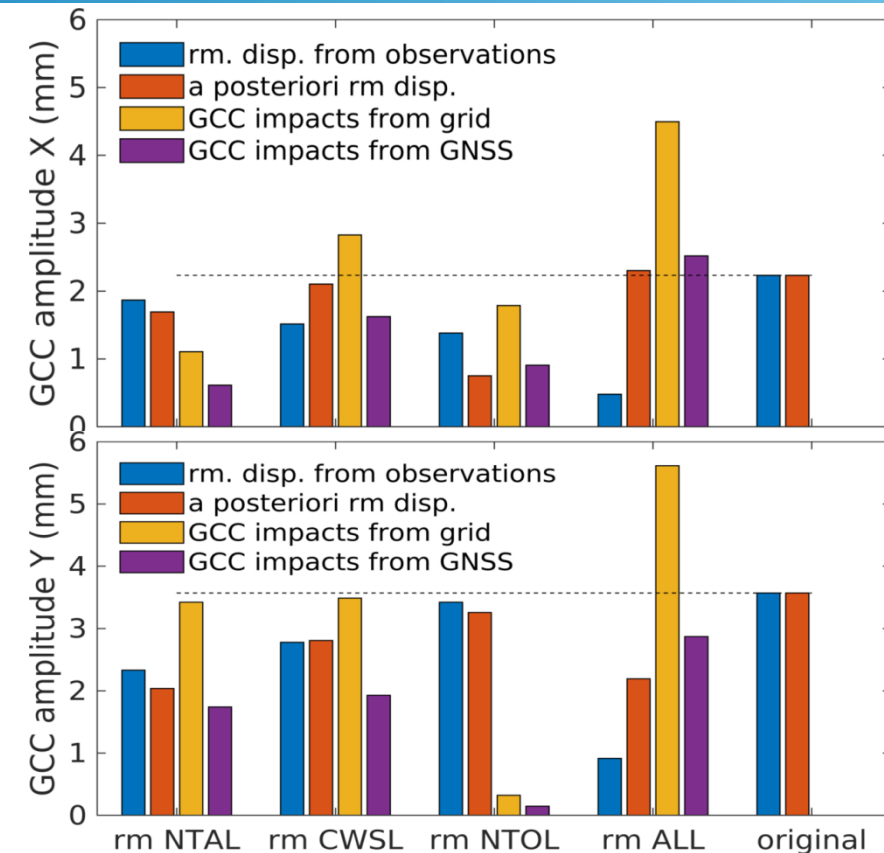


Figure 5: Annual amplitude of the Geocenter coordinates of all the GNSS solution sets. The dash lines are the annual amplitude estimated from the reference solution (original, loading displacements are preserved).

Earth Orientation Parameter

The geometrical impact of the polar motion from surface loading at tens μas scale of particular importance of ICRF3- ITRF transformation.

Biggest impact from NATL and NTOL

WRMS reduction is not significant comparing w.r.t. EOP C04 combined series (Bizouard et al. 2017), small improvement of the Xp and Yp at $\sim 0.5\mu\text{as}$ level

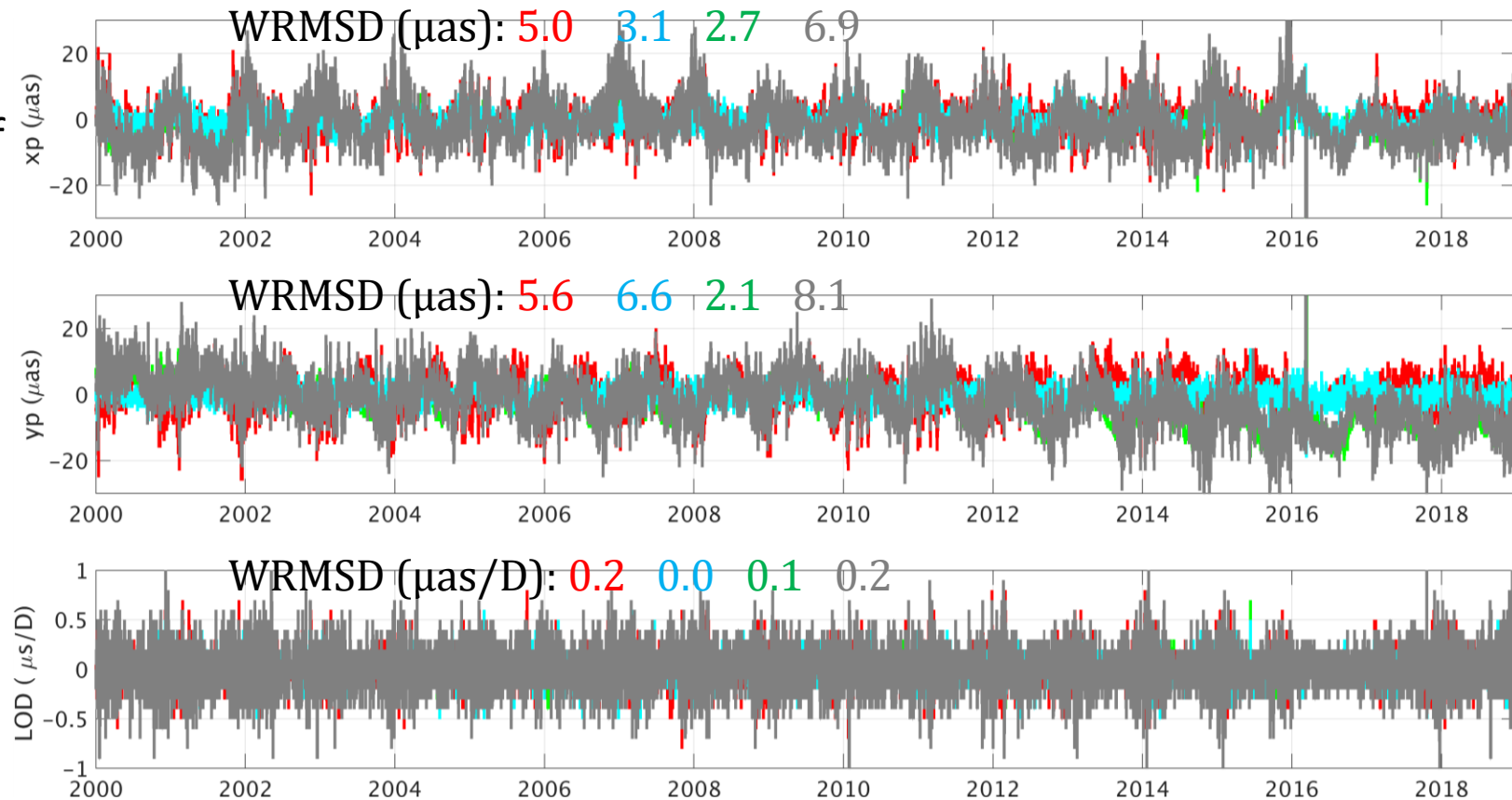


Fig. 6: Earth orientation parameters from difference loading grids with respect to No loading grid used. Right bottom numbers are the corresponding WRMSD of each solution. Red: NATL, green: CWSL, cyan: NTOL, gray: NATL+CWSL+NTOL.

Orbits improvements

Osculating elements are estimated from the misfit between two neighbor epoch -> an internal indicator for the orbit quality.

Consistent but small Improvement (up to sub-mm scale) is found in all orbit with one GLONASS exception.

A slight smaller effect comparing the EOPs are found in the direct comparison between the estimated precise orbits (w and w/o loading) in Rotational Helmer transformation parameters with amplitude of ± 15 . Sub-mm level in translation parameter.

Contribution dominated by NTAL and NOTL for the introduction of the inter-seasonal variations

Table 3: Position osculating elements for GPS and GLONASS satellites from the time span 2000-2018

Position osculating elements ($\epsilon_t = P_{t+1} - P_t$)	GPS satellites (mm)			
	$\bar{\epsilon}$	$ \bar{\epsilon} - \epsilon_r $	$\sigma(\epsilon)$	$\sigma(\epsilon - \epsilon_r)$
Ref.	51.929		36.286	
NTAL	51.924	-0.041	36.326	1.219
CWSL	51.924	-0.023	36.306	0.775
NTOL	51.939	-0.004	36.300	1.730
NTAL+CWSL+NTOL	51.902	-0.064	36.298	2.141
Position osculating elements ($\epsilon_t = P_{t+1} - P_t$)	GLONASS satellites (mm)			
	$\bar{\epsilon}$	$ \bar{\epsilon} - \epsilon_r $	$\sigma(\epsilon)$	$\sigma(\epsilon - \epsilon_r)$
Ref.	81.417		44.688	
NTAL	81.360	-0.026	44.642	2.122
CWSL	81.360	-0.008	44.643	1.467
NTOL	81.411	0.001	44.682	0.717
NTAL+CWSL+NTOL	81.348	-0.030	44.650	2.404

Conclusions

Significant impacts are found among in most of the reference frame variables and in most of them, a major improvement can be found in reducing the seasonal variations.

Most (> 90%) of the whole network shows an improvement in the coordinate estimation, a large portion (>50%) of the annual power can be explained from surface loading. Other processes such as other geophysical process not covered in this study can be the cause (e.g. oceanic pole tide, thermal elastic loading).

The seasonal variations in the Geocenter motion can be explained by the surface loading.

Tens of μas level influences are found in the estimated EOP caused from the surface loading.

Small but consistently persist improvements are found after correcting the loading displacement.

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Federal Agency for
Cartography and Geodesy



Thank you for your kind attention!

Bundesamt für Kartographie und Geodäsie
Organisationseinheit
Richard-Strauss-Allee 11
60598 Frankfurt am Main
Dr. Lin Wang
lin.wang@bkg.bund.de
www.bkg.bund.de
Phone: +49 69 6333 – 248