Tropospheric delay from EPN reprocessing by WUT LAC as valuable data source – in comparison to operational EPN products and aerological data

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Abstract. Standard EPN tropospheric products still show some discrepancies, prominent especially before GPS week 1400. It was one of the motives of massive reprocessing projects organised in the frame of both IGS and EPN. WUT LAC is one of Analysis Centers actively participating in EPN Reprocessing Campaign. Both operational tropospheric products and reprocessing campaign were manifold analysed. Properties of information carried in ZTD estimates were investigated both in ZTD solutions and in the form of IPW (Integrated Precipitable Water). Independent aerological data sources - radiosounding and CIMEL-318 sunphotometer were used for external verification. Authors demonstrate some results convincingly demonstrating value of reprocessed tropospheric product. Tropospheric solutions from reprocessing compared to meteorological data demonstrate better conformity. Most important application of long series ZTD's of uniform quality is climatology. Search for climate change signal in IPW series is possible only with a reliable tropospheric solution. Reprocessing campaign results meet this requirement.

Keywords: GPS, tropospheric delay, IPW, water vapour, sunphotometer

1 Introduction

Tropospheric Delay (the path delay caused by the neutral part of the Earth's atmosphere) estimation is standard procedure in geodetic

GPS solutions of highest accuracy (Hugentobler *et al.* 2001). Zenith Tropospheric Delay (ZTD) above all stations in the network from GPS final solution is one of standard products of and EPN (EUREF Permanent Network) and IGS. It is created by every Analysis Center (AC) of EPN (e.g. WUT LAC from GPS week 1137 - May 2001) in so called tropospheric solution. Combined product is also created as a combination of individual AC solutions from 2001 by BKG. Wide known fact is that Zenith Tropospheric Delay (ZTD) from GPS network solution can be separated into hydrostatic part (it is a function of surface pressure) and 'wet' part which can be transformed into IPW - most precisely if we can calculate coefficient dependent upon mean temperature in troposphere (Hoffmann-Wellenhof *et al.*, 1997; Bevis *et al.*, 1994; Rocken *et al.*, 1993). Our team has been investigating ZTD and IPW properties and reliability since the beginning of EPN special project dedicated to tropospheric solution. Many details were already reported (Kruczyk, 2006, 2008; Kruczyk *et al.*, 2001, 2004). This paper summarizes latest research concentrated on verification of GPS reprocessing by WUT LAC tropospheric product.

Abundance of meteorological data in form of tropospheric delay information makes crucial the question of their usefulness in meteorology and as climate change indicator.

2 Tropospheric delay products conformity

Warsaw University of Technology Local Analysis Center (WUT LAC) in the frame of EPN project creates daily tropospheric solution of their network (apart from coordinate solution) already since GPS week 1137. These are routinely sent to BKG (Bundesamt für Kartographie und Geodäsie, Frankfurt am Main) data center and are included to combined tropospheric product made for EPN by Wolfgang Söhne.

Discrepancies of 17-18 separate current LAC solutions can be assessed in several ways. Here we show some two interesting visualizations. Most efficient way is to analyse weekly biases of individual LAC solution in the relation to EPN tropospheric combination. Most Polish stations are included in solution by 3-4 LAC's.

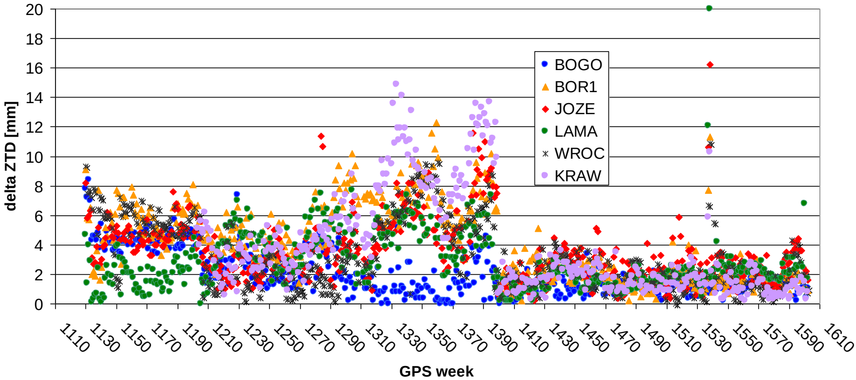

Figure 1. *Mean weekly ZTD biases: maximum of LAC solutions for selected (oldest) stations in Poland from the beginning of EPN*

Weekly differences combination - LAC solution show entirely changed patterns in subsequent periods. Apparently the discrepancies of individual EPN AC's ZTD solutions are much smaller after GPS week 1400 (December 2006). The conclusions can be drawn from picture of weekly discrepancies of all solutions available for 6 GPS stations in Poland with longest history in EPN (BOGO, BOR1, JOZE, LAMA, KRAW, WROC) on Figure 1.

Differences between individual LAC solutions (taken from EUR tropospheric combination) dramatically diminished in 2007 showing best conformity since the year 2003. Results from 2005-2006, period of new Bernese software version 5.0 introduction and processing strategy changes is characterized by the greatest discrepancies. We can assume as interesting rule for the years before 2006 that every LAC solution has its characteristic bias relatively to the others nearly constant in time. Probable cause is different strategy and coordinates taken as fixed. The same was already reported by us when compare IGS and EPN solutions: slight but durable bias for stations solved by several centers. This patterns dramatically changed in 2007 or rather end of 2006 (start from week 1400) as a cumulative results of Bernese 5.0, new strategies and ITRF2005 introduction. Now the biases are hardly visible. We can analyse also combined biases and difference standard deviations for all

Table 1. *Comparison of selected LAC solutions in the years 2005-07: averaged biases, mean absolute difference and difference standard deviation for all common stations in selected LAC pairs tropospheric solutions*

year	LACs	MD* [mm]	MAD†	DS‡	No. stations
2005	COE-NKG	−0.13	2.19	3.13	14
2005	COE-OLG	−5.29	7.62	7.91	6
2005	COE-WUT	0.01	2.75	3.84	10
2005	SUT-NKG	4.49	6.74	7.08	7
2005	SUT-WUT	5.80	7.47	7.21	15
2005	WUT-GOP	1.12	2.98	3.63	18
2005	WUT-NKG	−0.24	2.03	2.88	16
2005	WUT-OLG	−5.00	6.63	6.82	20
2006	COE-NKG	0.28	1.69	2.23	14
2006	COE-OLG	−2.97	4.95	6.95	6
2006	COE-WUT	0.28	2.04	2.84	12
2006	SUT-NKG	4.20	6.51	7.53	7
2006	SUT-WUT	5.20	6.93	7.54	18
2006	WUT-GOP	1.30	2.96	3.69	19
2006	WUT-NKG	−0.27	2.01	3.23	16
2006	WUT-OLG	−2.46	4.32	6.66	20
2007	COE-NKG	0.11	1.51	1.96	14
2007	COE-OLG	0.76	2.74	4.47	6
2007	COE-WUT	−0.49	2.14	3.27	12
2007	SUT-NKG	0.04	3.22	4.50	7
2007	SUT-WUT	−0.29	3.08	4.30	17
2007	WUT-GOP	0.24	2.26	3.08	19
2007	WUT-NKG	0.74	1.79	2.46	17
2007	WUT-OLG	1.20	2.83	4.38	19

*mean difference
†mean absolute difference
‡difference standard deviation

common stations for two given LAC networks. On the Table 1 averaged biases for years 2005-2007 and arbitrarily selected LAC pairs solutions (Analysis Centers working out most stations in Poland).

Most important conclusion from EPN ZTD series monitoring is dramatic decrease of differences between individual LAC solutions in 2007 (solutions after GPS week 1400 showing best conformity since the year 2003). Note that bias is greatly diminished but difference standard deviation only slightly reduced. Results from 2005 - period of new Bernese software version 5.0 introduction in some LACs only show greatest discrepancies. The cause of excellent conformity from the GPS week 1400 is in all probability cumulative effect of Bernese 5.0 almost exclusive use, absolute antenna PCVs (Phase Center Variations) and new reference frame ITRF2005/IGS05.

3 ZTD/IPW from EPN reprocessing campaign

Problematical year 2006 became object of the pilot project realized by special group of EPN for reprocessing. Pilot project proposed in October 2008, initiated in 2009 has been completed in November 2010 (see Völksen, 2011). Encouraging results from both Pilot Project and IGS global reprocessing campaign (completed in 2010 and delivering needed by products like orbits) led to massive reprocessing campaign EPN-Repro1 in 2011. The aim of this important project is to recalculate of all the old observations in the period of 1996-2005 with the use of contemporary models: e.g. absolute antenna phase centers and reference frame ITRF2005. WUT LAC is also part of the reprocessing team (Liwosz *et al.*, 2010, Liwosz, 2010). First aim is consistent precise coordinates and velocities set for the management of the ETRS (Draft Charter for the EUREF Working Group on Reprocessing of the EPN, Völksen, 2009) but ZTD are also estimated. We present here some selected results of tropospheric solution in WUT reprocessing.

We can further investigate the differences between reprocessed and operational solution on the Table 3 in case of WUT LAC solutions: operational (of 2005) and reprocessed (in 2011).

During the year 2006 tracking the ZTD differences we can see switch over from ITRF2000 to ITRF2005 as a clear leap in the DOY 309 visible for all stations (see figure 4).

At the end let us summary comparison results of the two GPS tropospheric solutions by WUT LAC: WUT reprocessing and at the time WUT LAC results (made by M. Figurski).

4 Reprocessing IPW verification by meteorological data

IPW (Integrated Precipitable Water) sometimes defined simply as PW is interesting meteorological parameter describing quantity

Table 2. *Comparison of EPN tropospheric combination and WUT reprocessing in 2004*

station	MD	MAD	DS	points	station	MD	MAD	SD	points
BOGI	16.92	16.92	4.87	7776	LAMA	9.56	9.57	3.81	8701
BOR1	9.13	9.17	4.06	8747	MORP	10.10	10.11	3.56	6121
DARE	11.95	11.98	4.41	7361	REYK	7.52	7.67	4.10	7792
DELF	7.67	7.70	3.55	8606	SASS	14.11	14.11	3.59	7853
DENT	9.12	9.16	4.27	8640	SODA	9.81	9.85	3.91	7211
DOUR	8.27	8.37	3.92	8680	SPT0	8.89	8.90	3.28	8765
EUSK	8.98	9.00	3.98	8682	SRJV	9.74	10.29	7.12	2612
HELG	13.05	13.05	3.65	8663	SULD	8.41	8.42	3.25	8681
HOFN	9.97	10.00	3.70	8777	TERS	7.93	7.95	3.42	8550
JOZ2	12.99	13.19	6.45	8157	TRO1	7.74	7.76	3.08	8616
JOZE	8.75	8.83	4.72	8623	TUBI	12.51	12.56	5.57	8616
KATO	14.93	14.93	5.10	7754	WARE	8.17	8.23	4.18	8595
KIRO	7.69	7.70	2.93	7048	WARN	12.14	12.14	3.52	7756
KIRU	10.04	10.05	3.24	7904	WSRT	8.13	8.18	3.91	8653

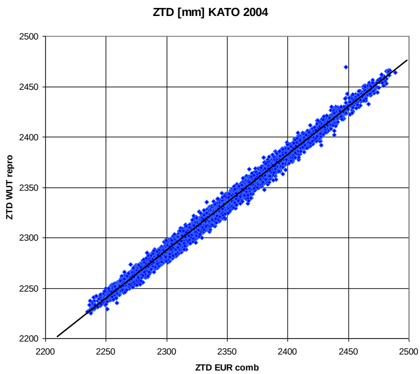

Figure 2. *ZTD KATO station in 2004: EPN combined solution (of original LAC tropospheric contributions) and WUT LAC reprocessing results for 2004*

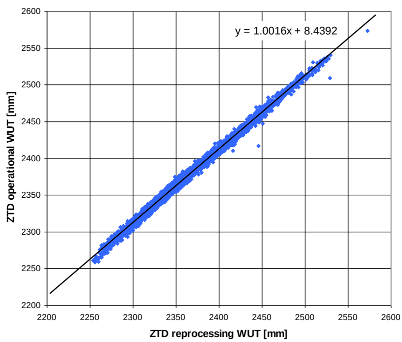

Figure 3. *ZTD for BOGI (Borowa Góra) station in 2005: WUT reprocessing tropospheric solution and WUT LAC operational solution (of the time) in 2005*

Table 3. *Comparison of combination and WUT reprocessing and WUT operational solution in 2005*

station	ΔZTD [mm]	AD	DS	ΔRMS [mm]	points
BOGI	−12.32	12.33	3.23	12.73	8345
BOR1	−5.23	5.39	3.11	6.09	8705
DARE	−10.46	10.5	3.75	11.12	7136
EVPA	−8.92	8.99	3.9	9.74	1135
GLSV	−7.69	7.75	3.41	8.41	8345
HOFN	−9.41	9.48	4.03	10.24	8590
JOEN	−8.89	8.91	2.76	9.3	8617
JOZ2	−9.16	9.2	3.33	9.75	7436
JOZE	−5.47	5.66	3.62	6.56	8386
KATO	−11.7	11.7	3.3	12.16	7112
KELY	−9.87	10.98	8.4	12.96	5850
KHAR	−8.17	8.27	3.66	8.95	6820
KIRU	−7.36	7.45	3.48	8.14	8199
LAMA	−7.85	7.87	3.01	8.41	8615
NYA1	−5.63	5.65	2.45	6.14	8519
POUS	−8.06	8.08	3.26	8.69	1848
SASS	−11.77	11.78	3.01	12.15	8398
SPT0	−7.53	7.54	2.82	8.04	8152
SULD	−6.83	6.86	2.93	7.43	8349
THU3	−6.75	6.8	3.29	7.51	8463
VARS	−6.22	6.26	2.54	6.72	8120

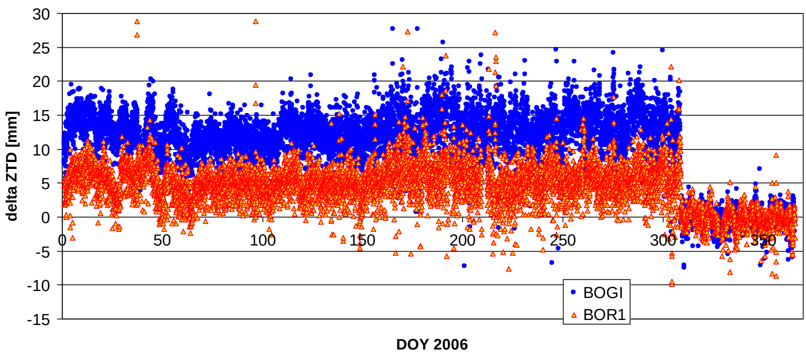

Figure 4. *ZTD difference for BOGI and BOR1 station: WUT LAC original solution tropospheric contribution to EPN minus WUT LAC reprocessing results for 2006.*

Table 4. *Comparison of yearly differences of the two GPS tropospheric solutions by WUT LAC: WUT reprocessing and at the time WUT LAC results (number of common stations also listed)*

year	ΔZTD [mm]	AD	DS	ΔRMS [mm]	stations
2002	−8.58	9.00	5.03	10.16	12
2003	−9.12	9.33	4.55	10.32	19
2004	−10.08	10.26	4.92	11.29	19
2005	−8.35	8.45	3.49	9.11	21
2006	−7.18	7.46	4.43	8.47	20

of water vapour in the vertical direction over station in mm of liquid water after condensation. Related parameter IWV (Integrated Water Vapour) is also used which has the same numerical value but another unit of measure: g/m2. IPW can be calculated from ZTD by known procedure of separating ZHD (Zenith Hydrostatic Delay) and recalculating obtained ZWD (Zenith Wet Delay) by numerical coefficient dependent on so called 'mean temperature' in vertical profile of atmosphere (Bevis *et al.*, 1994; Rocken *et al.*, 1993).

Radiosunding observations by free flying balloons are performed regularly twice a day by Polish Institute of Meteorology and Water Management at Legionowo (station no 12374, 34 km from JOZE but only 9.5 km from BOGO/BOGI). We use IPW calculated from radiosounding profiles by Department of Atmospheric Sciences University of Wyoming. Here you see some examples of GPS (EPN) derived IPW and results of radiosoundings performed at Legionowo and several other observatories (Table 5 for year 2005). Even when bias (JOZE GPS - RAOB Legionowo) is bigger for reprocessed values (year 2006 in Table 6) difference standard deviation, and difference RMS have been diminished.

Next technique is CIMEL CF-318 sunphotometer at Central Geophysical Observatory IGF, PAS in Belsk near Warsaw ($\lambda = 20°47'30''$, $\varphi = 51°50'12''$), 33 km from JOZE (only one point in Poland). This device is operated in the frame of AERONET (AErosol RObotic NETwork) coordinated by NASA & CNRS. Multichannel radiometer measures many air properties (mostly aerosoles) registering absorption lines of solar spectra and gives also IPW values. This genuine

Table 5. *Comparison of radiosounding IPW and various GPS solutions (EPN tropospheric combination, WUT reprocessing and SIO global) in 2005*

radiosunding point	GPS station (dist. [km])	ΔIPW	AD	DS	points	GPS sol.
10035 SCHLESWIG	HOE2 14284M002 (82.82)	−1.36	3.07	4.34	262	EUR
10035 SCHLESWIG	HOE2 14284M002 (82.82)	0.30	2.92	4.43	270	WUT repro
10410 ESSEN	EUSK 14258M003 (81.27)	0.22	2.02	2.95	232	EUR
10410 ESSEN	EUSK 14258M003 (81.27)	1.11	2.25	2.89	262	WUT repro
12374 LEGIONOWO	JOZE 12204M001 (34.83)	−1.07	1.73	2.22	643	EUR
12374 LEGIONOWO	JOZE 12204M001 (34.83)	0.09	1.29	1.73	696	WUT repro
17062 ISTANBUL/GOZTE	ISTA 20807M001 (22.79)	−1.95	2.29	1.96	599	EUR
17062 ISTANBUL/GOZTE	ISTA 20807M001 (22.79)	−0.83	1.68	2.14	669	SIO
11520 PRAHA-LIBUS	GOPE 11502M002 (29.21)	0.08	1.65	2.51	1 377	SIO

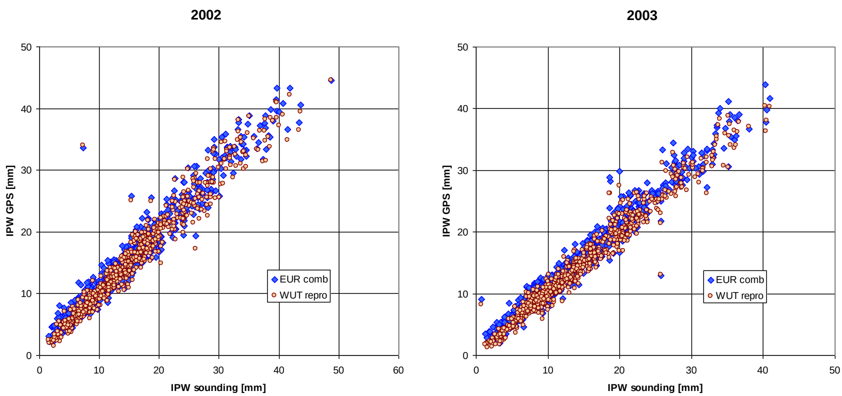

Figure 5. *Legionowo radiosounding IPW vs. GPS JOZE in 2002 and 2003: dark points - original EPN combination, bright points - WUT LAC reprocessing.*

Table 6. *Comparison of radiosounding IPW and selected GPS solutions (EPN tropospheric combination, WUT reprocessing and WUT operational) in 2002-2006*

GPS solution	year	IPW diff. [*mm*]	MD	DS	diff. RMS [mm]	points
EUR comb	2002	−0.71	1.57	2.09	2.21	684
WUT repro	2002	0.11	1.29	2.03	2.03	686
EUR comb	2003	−0.97	1.49	1.77	2.02	714
WUT repro	2003	0.04	1.14	1.60	1.60	710
EUR comb	2004	−0.99	1.61	1.92	2.16	679
WUT LAC	2004	−0.85	1.52	1.91	2.09	660
WUT repro	2004	0.21	1.26	1.79	1.80	667
EUR comb	2006	−0.17	1.59	2.03	2.04	609
WUT repro	2006	0.78	1.42	1.73	1.90	623

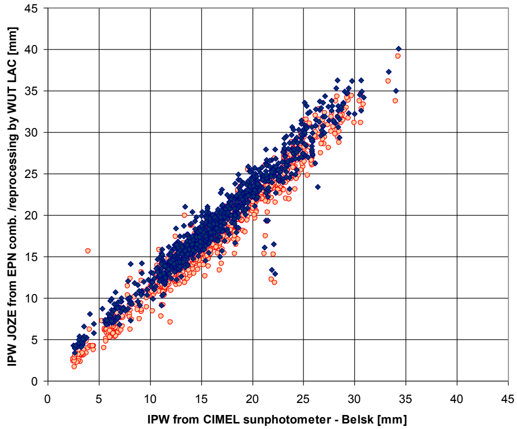

Figure 6. *Belsk* CIMEL-318 *sunphotometer* IPW *vs.* GPS JOZE *in 2006: dark points - original* EPN *combination, bright points -* WUT LAC *reprocessing.*

source of IPW data and can be utilized for external verification of GPS tropospheric solutions, e.g. reprocessing. Tropospheric estimates after reprocessing with use of new software, models and reference frame result are less biased. This was confirmed with the help of sunphotometer data for 2006. Bias after reprocessing is two times lower then before and close to 1 mm (see figure 6).

All IPW calculations from ZTD in this work utilise Saastamoinen model with gravitational correction for Hydrostatic Delay and model of mean temperature from (Bevis *et al.* 1994).

5 Reprocessing ipw series importance in climatology

IPW is a meteorological parameter and daily averaged series of IPW values carry some climatological information as shown for two stations in different climates (Kruczyk, 2008). Simple model (sinusoid plus constant) has been adjusted to the series (LS method) for JOZE, and other selected stations. First we adjust every year separately - different are not only amplitudes but also phases. We can also adjust multi - year seasonal variability if we search for steady trends (climate change). On the figures below we show some

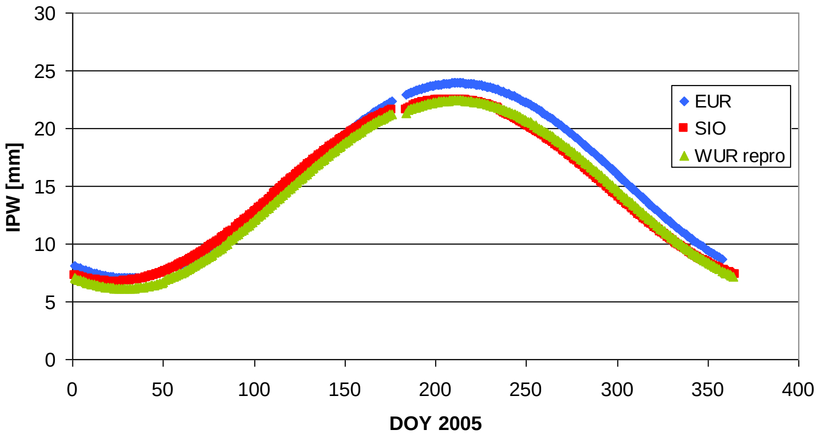

Figure 7. *Sinusoidal seasonal IPW model from three different tropospheric solutions for JOZE in 2005: EUR - operational EPN tropospheric combination, SIO - IGS solution by SIO, WUR - WUT EPN LAC reprocessing campaign.*

examples of the sinusoidal IPW model. What is worrying different GPS solutions for the same station (e.g. JOZE in 2005) gives divergent results: EUR - operational EPN tropospheric combination, SIO - IGS solution by SIO, WUR - WUT EPN LAC reprocessing campaign (figure 7).

Next we illustrate discrepancies between operational EPN solution and reprocessed ZTD's: four year series of our IPW model for EPN and WUT LAC reprocessing tropospheric delay.

To search for climate change signal we will apply out model for multi-year series of ZTD from WUT LAC, WUT LAC reprocessed, EPN combined (EUR), and IGS solutions and calculate IPW trend in residuals.

Changing type of solution we get quite different results. Careful final solutions is available only after reprocessing campaign. Keep in mind: water vapour is both greenhouse gas and climate change indicator (content rises with average temperatures).

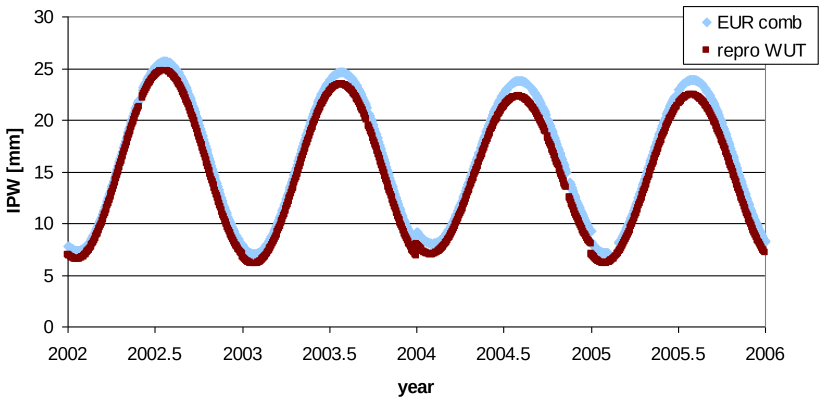

Figure 8. *Sinusoidal seasonal IPW model from two different tropospheric solutions for JOZE in 2002-2005 period: EUR - operational EPN tropospheric combination, WUR - WUT EPN LAC reprocessing campaign. Sinusoid adjusted for every year separately.*

Table 7. *Parameters of seasonal model (sinusoid plus mean level) adjusted to selected IPW series, and linear trend shown by the residuals.*

station & solution	years	amplitude [mm]	IPW level [mm]	residuals RMS	IPW trend [mm/y]
JOZE WUT repro	1997-2006	8.5	15.2	5.1	-0.05
JOZE WUT repro *	1997-2010	8.5	15.2	5.1	0.02
JOZE WUT operational	2002-2010	8.8	15.7	5.1	-0.08
JOZE EUR	2002-2010	8.8	15.8	5.1	-0.11
JOZE IGS **	1997-2010	8.5	15.3	5.1	-0.06
REYK WUT repro	1997-2006	3.8	12.8	7.9	0.20
REYK IGS **	1997-2010	4.8	12.4	4.8	0.09
REYK WUT	1997-2010	3.8	12.8	7.4	0.14

* WUT reprocessing campaign till 2006, WUT LAC operational from 2007
**IGS combination till 2005, IGS tropospheric product by JPL from 2006 (Byun and Bar-Sever, 2009)

6 Conclusions

1. EPN ZTD estimates from different LAC have been much improved and show better conformity after GPS week 1400 thanks to new reference frame, strategy (absolute PCV's) and software (Bernese 5.0 in all but one LAC). Earlier data requires reprocessing.

2. Tropospheric solutions from WUT LAC reprocessing campaign and at the time solutions (both operational WUT LAC and EPN combined product) shows significant discrepancy: about 1 cm.

3. Radiosundings and CIMEL sunphotometer data as a independent source of IPW shows improved quality of ZTD from WUT reprocessing campaign.

4. GPS IPW can be used as a climatological tool but only after reprocessing.

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