TROPOSPHERIC DELAY IN GNSS AND METEOROLOGICAL ZTD AND IPW DATA SOURCES

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1. INTRODUCTION

This paper presents recent developments of research connected relevant to the several interesting results of ZTD and IPW time series comparisons and analyses. Zenith Tropospheric Delay solutions in the frame of EPN (EUREF Permanent Network): both individual LAC (Local Analysis Centre) and EPN combined product are treated as main GNSS data source. First some simple conformity indexes of these solutions are investigated. Next main attention is paid to IPW (Integrated Precipitable Water) - important meteorological parameter easily derivable from GPS tropospheric solutions (ZTD's). Unfortunately IPW values from various sources can be relatively problematic through various technical shortages. Many comparisons of EPN ZTD product with three meteorological water vapour data sources: radiosoundings, sun photometer (CIMEL, Central Geophysical Observatory Polish Academy of Sciences, Belsk) and input fields of operational numerical prediction model COSMO-LM (maintained by Polish Institute of Meteorology and Water Management) has been made.
Results which lead to the conclusion of GNSS IPW high quality are presented. Some other analyses show value of GPS IPW as a potential geophysical tool.

2. INSIDE STANDARD EPN TROPOSPHERIC DELAY PRODUCTS

Final tropospheric solutions of EPN Local Analysis Centers and EPN combined product should be a subject of minute analysis. Only some selected, especially interesting results are shown. Differences between individual LAC solutions (taken from EUR tropo combination made for EPN by Wolfgang Shöene) dramatically diminished in 2007 showing best conformity since the year 2003. Results from 2005 – period of new Bernese software version 5.0 introduction (in some LACs only) show greatest discrepancies. For many stations (e.g. JOZE) you can see quite a strange results. The cause of excellent conformity from the GPS week 1400 is in all probability cumulative effect of Bernese 5.0 almost exclusive 'reign', absolute antenna PCVs and ITRF2005/IGS05.
You can find interesting rule (for the years before 2007) that every LAC solution has its characteristic bias relatively to the others nearly constant in time. The same was already reported when compare IGS and EPN solutions (Kruczyk et al., 2004; Kruczyk, 2006). Slight but durable bias was typical for stations solved by several centres. Probable cause was different strategy and coordinates taken as fixed. This patterns changed in 2007 and sometimes reversed (Fig. 1 and 2). The graph in Fig. 3 shows extreme weekly discrepancies of different LAC's solutions for all GPS stations in Poland.

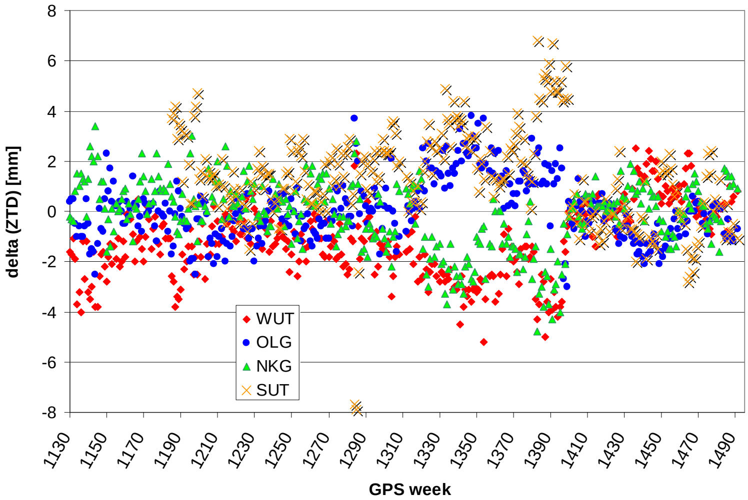

Fig. 1. ZTD weekly mean differences for JOZE (Jozefoslaw) taken from EPN combination file: EUR combined product - individual LAC.

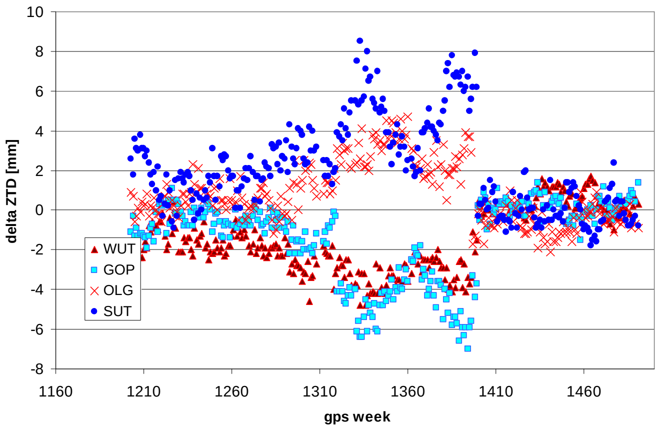

Fig. 2. ZTD weekly mean differences for KRAW (Krakow).

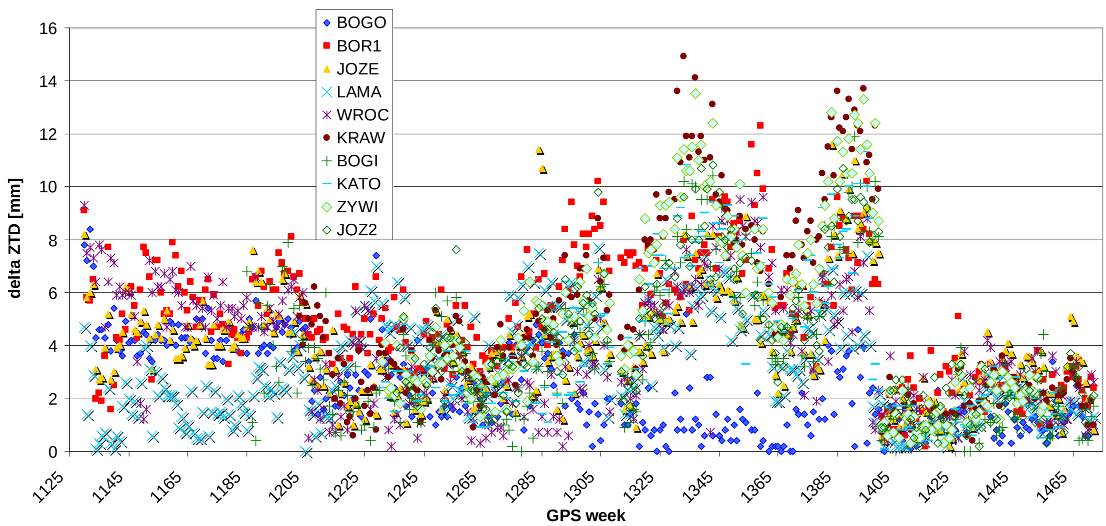

Fig. 3. ZTD weekly mean absolute differences: EUR combined product - individual LAC for all EPN stations in Poland.

Difference levels dramatically changed in 2007 or rather end of 2006 (around week 1400) as a cumulative results of Bernese 5.0, new strategies and ITRF2005 introduction. Now the biases are almost invisible. This 'revolution' in discrepancies will be illustrated by only one arbitrary chosen example of RIGA but it is recurring pattern for all stations (see Fig. 4)

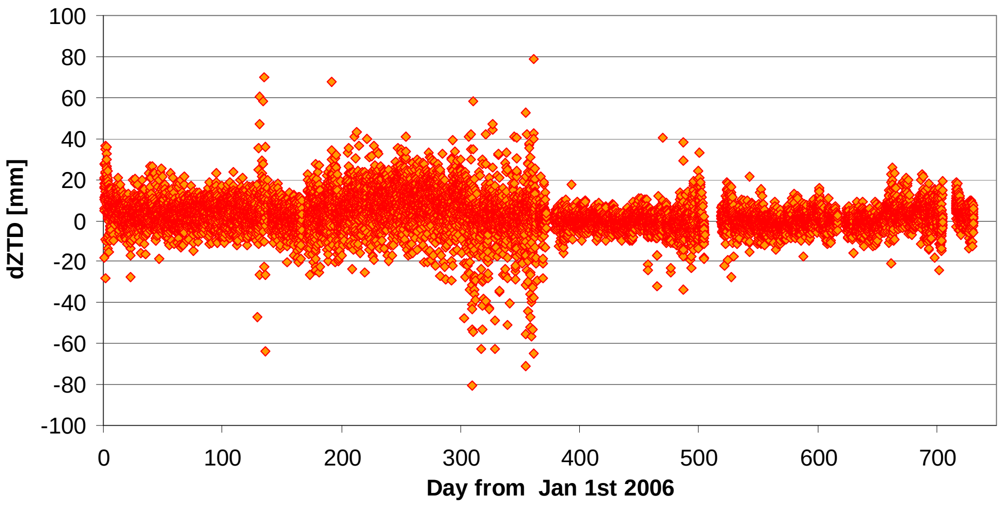

Fig. 4. ZTD difference of 2 EPN LAC (SUT-NKG) over 2 years.

Table 1. Yearly statistics of selected EPN LAC ZTD estimate differences.

YEAR	LAC'S	MEAN DIFFERENCE [MM]	MEAN ABSOLUTE DIFFERENCE	MEAN DIFFERENCE RMS [MM]	NO. STATIONS
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-NKG	-0.27	2.01	3.23	16
2007	COE-GOP	0.04	2.49	3.27	5
2007	COE-NKG	0.11	1.51	1.96	14
2007	COE-OLG	0.76	2.74	4.47	6
2007	COE-SUT	0.58	3.12	4.21	6
2007	OLG-NKG	-0.30	2.21	3.18	6
2007	OLG-SUT	-0.94	3.64	6.11	19
2007	SUT-NKG	0.04	3.22	4.50	7
2007	WUT-COE	0.49	2.14	3.27	12
2007	WUT-GOP	0.28	2.29	3.16	16
2007	WUT-NKG	0.63	1.57	2.09	15
2007	WUT-OLG	1.23	2.93	6.13	19
2007	WUT-SUT	0.41	2.99	4.21	16

For EPN Local Analysis Centres we can create some kind of quality-conformity indicator shown at the next page (years 2006 and 2007). Week 1400 quality jump sets completely new discrepancies levels for all Local Analysis Centres (refer Fig. 5).

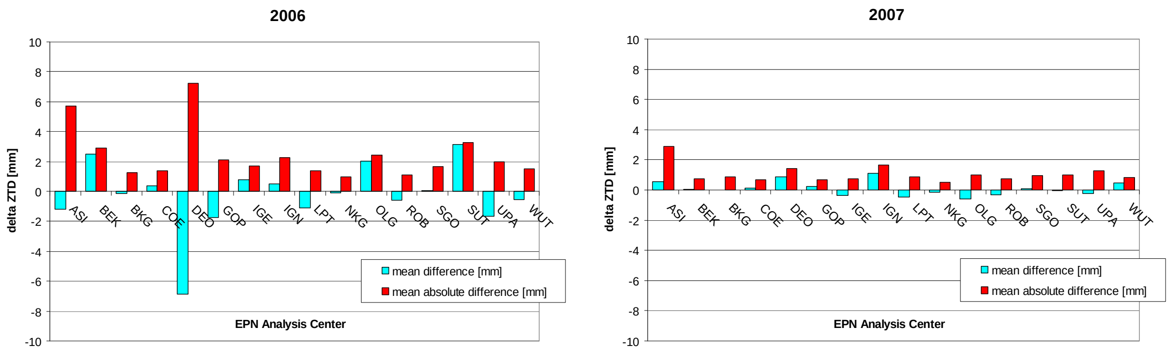

Fig. 5. LAC EPN tropospheric solution statistics in 2006 and 2007:
all LACs vs EUR combination; same scale.

3. ZTD IPW DATA FROM COSMO-LM NWP MODEL VS. GPS NETWORK DATA

Input fields of numerical weather prediction models (after assimilation/analysis) can be treated as a meteorological database. It has been tested for main synoptic model in Poland: COSMO-LM model maintained by Polish Institute of Meteorology and Water Management in Warsaw (data made accessible by A. Mazur).

The model has a grid of 183x161 points (about 14 km spacing), 36 vertical levels and is restarted twice a day (00 UT and 12 UT); data stored in the GRIB format. Grid has rotated equator and 0 meridian to minimize deformations making typical map projections inadequate – so the original grid is used for results mapping.

For all grid points zenith tropospheric delay was calculated and interpolated for all 120 EPN stations located in the model area. The ZTD map is of course dominated by topography due to dominant hydrostatic component (Fig. 6):

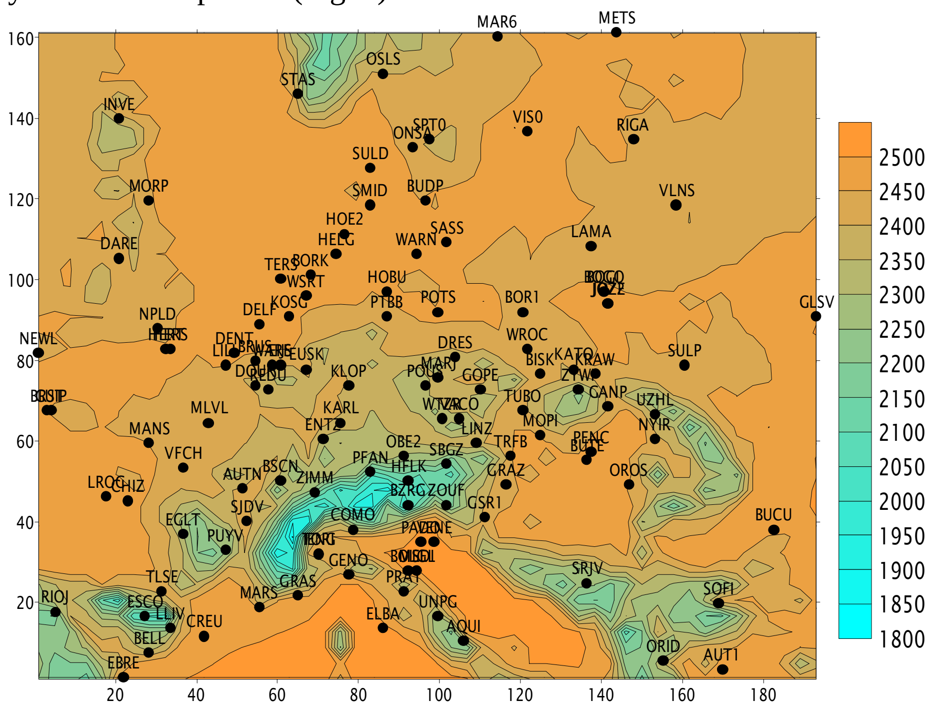

Fig. 6. Map of ZTD calculated from COSMO-LM input fields.

Now we can compare ZTD from COSMO-LM model and GPS solutions. The differences: EPN combined tropospheric product - COSMO-LM derived ZTD are shown in the whole 2007. You can see dramatic extremes for mountain stations. These differences turned out to be dependent on station height. Effect caused surely by relatively poor model topography. Correlation of ZTD differences for respective station and height differences (EPN station height minus interpolated in COSMO model grid for station coordinates) is amazing (see Fig.7).

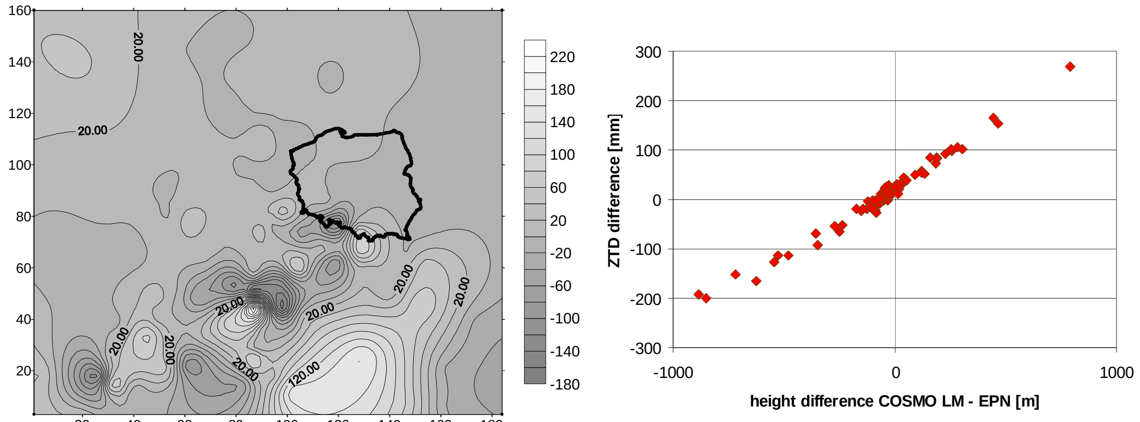

Fig. 7. ZTD differences [mm] map in 2007: EPN combined tropospheric product - COSMO-LM input fields derived ZTD averaged in the 12 months timespan (Jan-Dec 2007) on the left and ZTD differences [mm] for EPN stations inside COSMO model in relation to height difference: EPN height (logs) – height of model ground level for station coordinates (right).

Special procedure should be developed to take into consideration that phenomena in ZTD and IPW retrieval from numerical weather prediction model. By now assessment of ZTD differences from this two sources can be done by mapping difference RMS which has much less dramatic values (see Fig. 8).

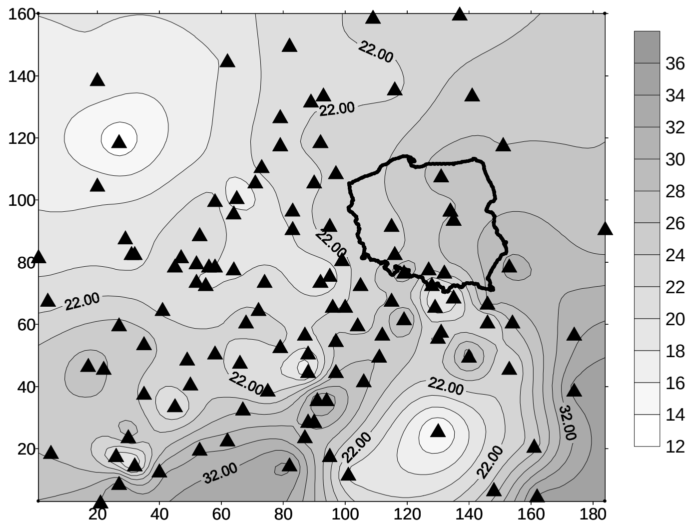

Fig. 8. ZTD differences RMS [mm] map in 2007
(EPN combined tropospheric product minus COSMO-LM input fields derived ZTD).

In the same way you can get IPW fields by numerical integrating vertical humidity data. Minute comparison of IPW from EPN combined tropospheric product and COSMO-LM input fields is possible only for 22 stations which record meteorological data. At the next pages there are set aside series of IPW for station JOZE in the 2007, XY plot for ORID (Fig. 9) and the table of differences for all stations. For most stations generally correlation is good (near 0.97) but some systematic 'scale' difference of 4-7 mm is present (COSMO model data too big or rather 'too wet'). In this case height difference is not a source of problems because humid air masses travel horizontally, whereas for ZTD pressure is decisive.

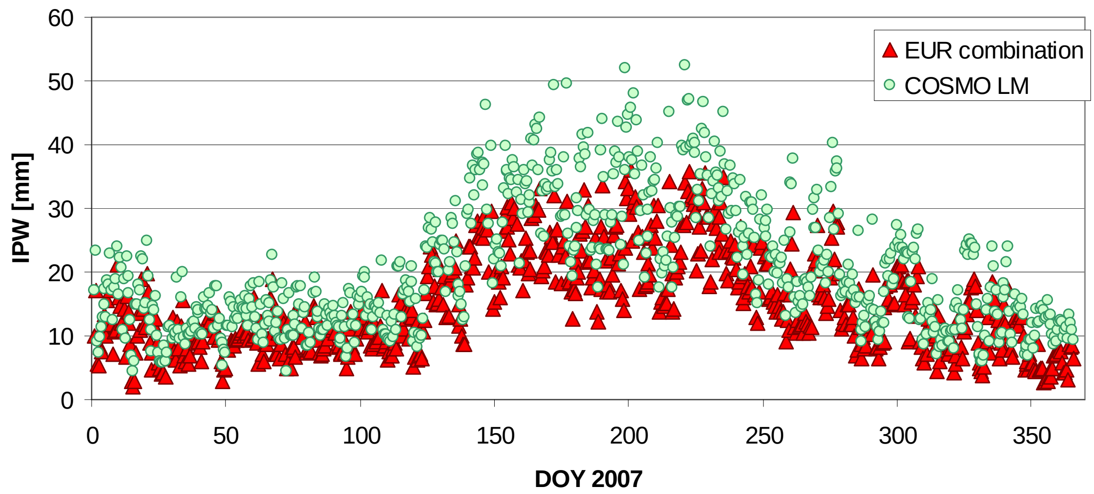

Fig. 9. Integrated Precipitable Water values for TUBO: derived from EPN combination and numerical weather prediction model COSMO-LM input fields – year 2007.

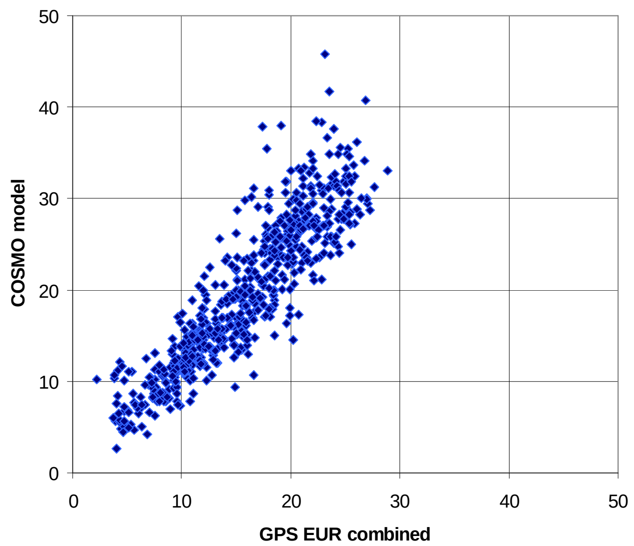

Fig. 10. IPW values [mm] from EPN combination and COSMO model for ORID in 2007 .

Table 2. IWV values from EPN combined tropospheric product and COSMO-LM weather prediction model comparison statistics in 2007.

STATION	MEAN DIFFERENCE: EUR COMB IPW - COSMO IPW [MM]	DIFFERENCE RMS [MM]	NUMBER OF POINTS
BACA	-7.35	4.66	720
BAIA	-5.40	3.84	661
BBYS	-1.62	2.30	203
BOGI	-6.62	3.88	686
BOGO	-7.00	3.99	662
BOR1	-5.95	3.45	346
BORK	-5.34	2.56	290
DEVA	-3.59	3.24	676
DRES	-5.63	3.28	432
EUSK	-5.00	3.07	679
GOPE	-6.32	3.89	672
HELG	-5.94	3.39	643
HERS	-6.51	2.96	700
HOE2	-6.28	3.18	720
JOZE	-6.69	4.03	667
JOZ2	-6.75	4.09	644
KARL	-6.19	3.42	442
KRAW	-5.64	3.40	670
MOPI	-9.95	4.90	385
MORP	-3.31	2.25	88
ORID	-3.75	3.85	634
POTS	-7.10	3.61	689
PTBB	-4.75	2.92	703
SASS	-7.64	3.42	715
SOFI	-5.80	3.98	574
TUBO	-5.60	3.44	720
WROC	-4.67	1.49	139
WTZR	-5.39	3.29	702
ZIMM	-5.55	3.24	689

4. IWV/IPW VERIFICATION BY AEROLOGICAL DATA

Integrated Precipitable Water values for some points can be validated by independent techniques: radiosounding observations (in Poland: Legionowo and Wrocław) and sunphotometer CIMEL CF-318 (Central Geophysical Observatory, Belsk near Warsaw, 33 km from JOZE) – results shown below for 2002 (Fig. 11) and 2005 (Table 3).

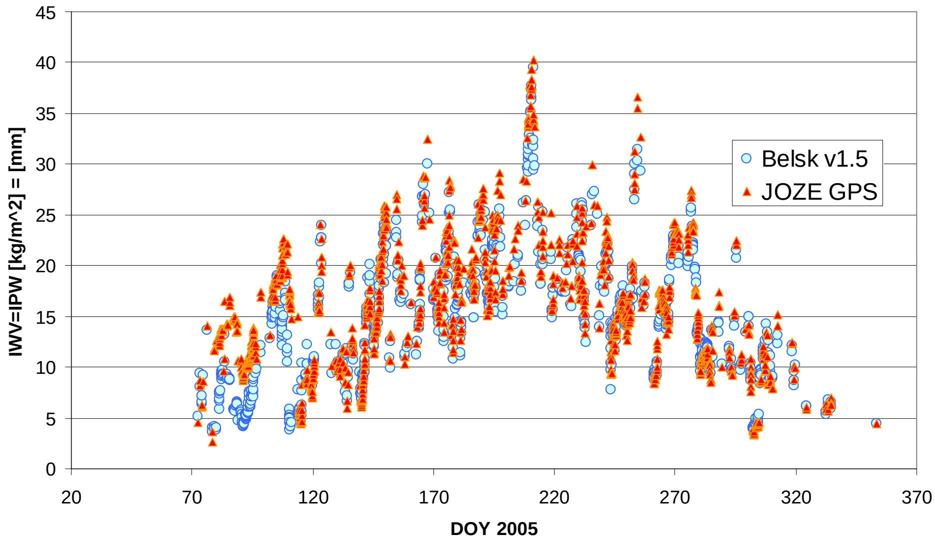

Fig. 11. Integrated Precipitable Water values validated by independent technique: sunphotometer CIMEL CF-318 (Central Geophysical Observatory, Belsk– results for 2005.

Table 3. GPS (EUR ZTD combination) and CIMEL sunphotometer (CSPHOT) IPW comparison; lev 15 - indicates application of corrections due to clouds, lev 20 also instrument corrections made by NASA (AERONET).

year	CSPHOT Belsk	JOZE GPS solution	IPW average difference [mm]	IPW average absolute difference [mm]	GPS estimates	CPHOT measurements
2002	lev15	EUR comb	-1.738	1.962	696	1807
2002	lev20	EUR comb	-1.694	1.930	661	1758
2003	lev15	EUR comb	-1.121	1.140	95	265
2003	lev20	EUR comb	-1.173	1.193	83	242
2004	lev15	EUR comb	-1.680	1.861	966	2583
2004	lev20	EUR comb	-1.649	1.827	835	2283
2005	lev15	SIO global	-1.255	1.827	1116	3235
2005	lev20	SIO global	-1.270	1.828	1068	3157
2006	lev15	WUT LAC	-1.772	1.961	968	2842
2006	lev20	WUT LAC	-1.199	1.217	41	110
2007	lev15	EUR comb	0.041	1.065	681	1811
2007	lev15	WUT LAC	-0.067	1.130	681	1811
2007	lev15	SUT LAC	0.052	1.066	678	1806

Conformity of sunphotometer and GPS derived IPW in 2007 (after periodic calibration) is really excellent. Even for the more distant station (BOGI – distance to Belsk nearly 64 km) we can see quite good results with slightly bigger dispersion (see Fig. 11).

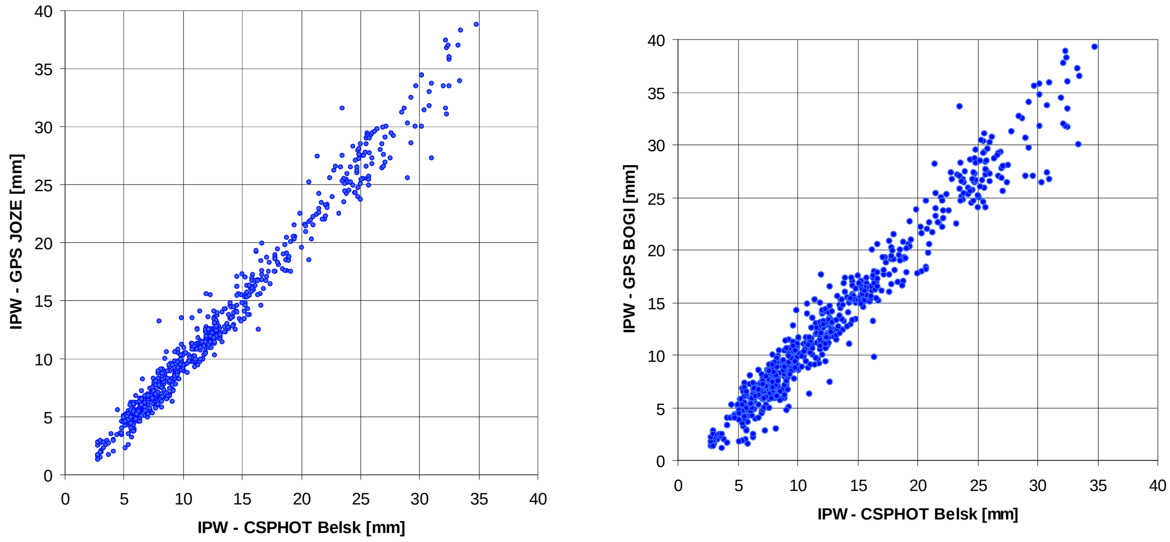

Fig. 12. Belsk CSPHOT vs. GPS JOZE (EPN comb.) and.GPS BOGI (EPN comb.) in 2007.

Radiosundings are regularly performed in 3 places in Poland, 2 of them are close to GNSS stations. IPW calculated from radiosounding profiles by simple algorithm was already presented (Kruczyk et al., 2004). This time values made available by Department of Atmospheric Sciences University of Wyoming are used. Here you see two examples of GPS (EPN) derived IPW and results of radiosounding compared (shown on Fig. 13 and 14). Soundings are performed twice a day at Legionowo (34 km from JOZE but only 9.5 km from BOGO/BOGI) – for both observatories IPW differences are at 1 mm level.

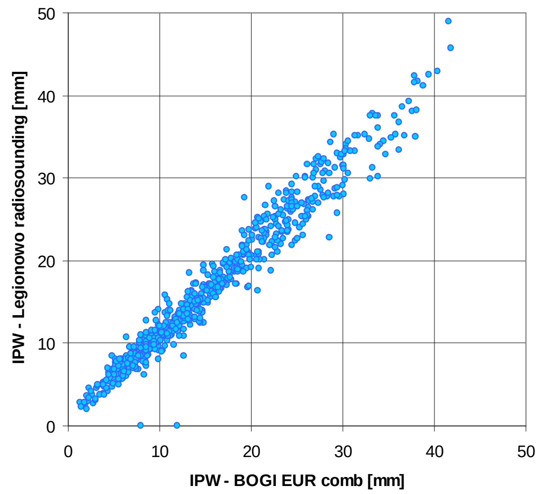

Fig.13. Legionowo radiosundings RAOBS vs. GPS EPN combination
for BOGI (Borowa Gora) in 2007.

For the midday soundings it is possible to validate also meteorological techniques until now treated as more credible than GPS derived values. The next graph compares radiosounding and sun-photometric IPW values – thus the area around Warsaw can serve as some inter-technique test area.

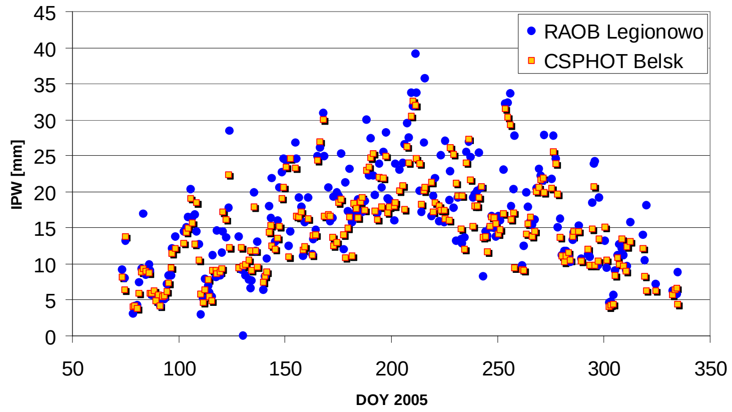

Fig. 14. Legionowo radiosundings RAOBS and Belsk CSPHOT in 2005.

5. ZTD AND IPW TIME SERIES ANALYSIS

ZTD and IPW series have been analysed in many ways in search for some geophysical effects. Among other conclusions worth mention is steady decrease of correlation coefficient as a function of distance: ZTD series correlations have been calculated for 2004, IPW for 2007 – less stations with meteo sensor.

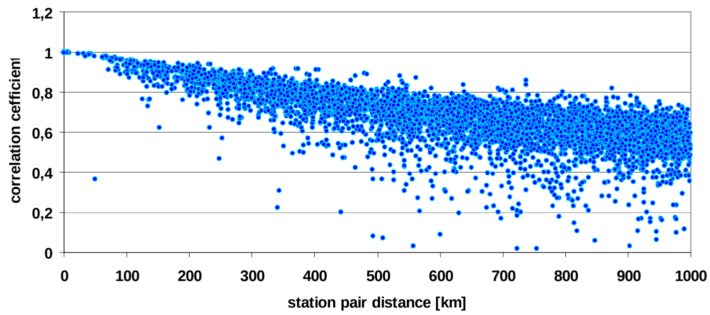

Fig. 15. Correlations of annual ZTD series correlations related to stations distance.

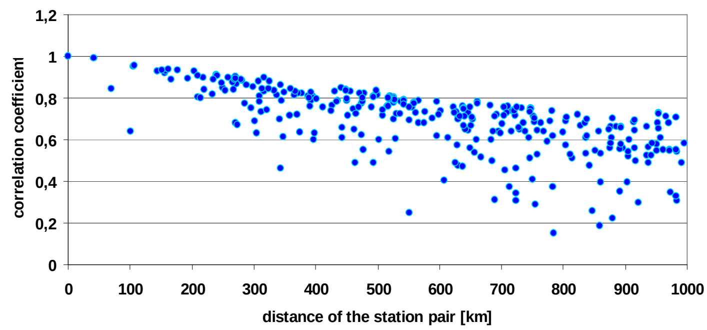

Fig. 16. Correlations of annual IPW series correlations related to stations distance.

In EPN there are 5 pairs of very close stations (distance several metes to over 100m) which are of course most correlated stations. BOGO & BOGI are very close (100 m) and correlated but show also systematic difference caused by 10 m height difference (BOGO – on the building roof). Analogical JOZE and JOZ2 pair shows also some periodic variations probably due to problems with JOZ2 receiver.

Similar situation exist for HERS and HERT (first on the 8 m mast). Case of two very close Italian double sites CAGL-CAGZ and MEDI-MSLM is very puzzling: points on the same level but different antenna-receiver sets (see Tab 4).

Table 4. ZTD series (from EUR comb) differences for closest stations.

station 1	station 2	mean ZTD difference	mean absolute ZTD difference	difference RMS [mm]	number of points	station 1 height [m]	station 2 height [m]
BOGO	BOGI	-2.71	3.13	2.74	8536	149.6	139.9
JOZE	JOZ2	0.17	2.05	3.02	7767	141.4	152.5
CAGL	CAGZ	5.66	5.74	2.53	7366	238.4	238.0
HERS	HERT	3.06	3.17	3.61	8518	76.5	83.3
MEDI	MSEL	-6.27	6.38	3.09	6011	50.0	49.3

Series of Integrated Precipitable Water obtained from ZTD values constitute interesting meteorological parameter coming from purely geometrical solution (so called GPS meteorology). The parameter shows weather patterns in the other manner than pressure or humidity.

Long series of IPW (daily averaged) can serve as 'climatological' information. In the figure 17 series of 11 years IPW could be seen for JOZE. Sinusoidal model has been adjusted to the series (LS method), every year separately – different are not only amplitudes but also phases. Figure 18 illustrates the results for 5 year period when I got +0.6 mm/year IPW trend. For the following years not visible. By the way +0.1°C/year trend for temperature keeps for the whole 11 year period.

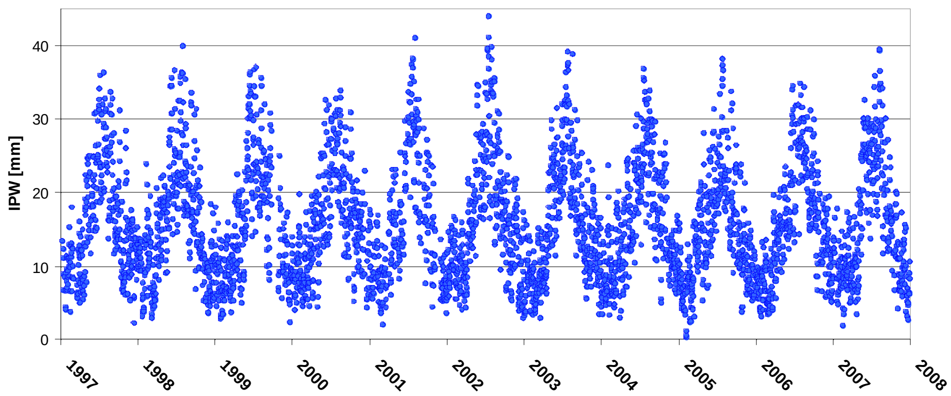

Fig. 17 Long series of daily averaged IPW values derived from EPN ZTD for JOZE

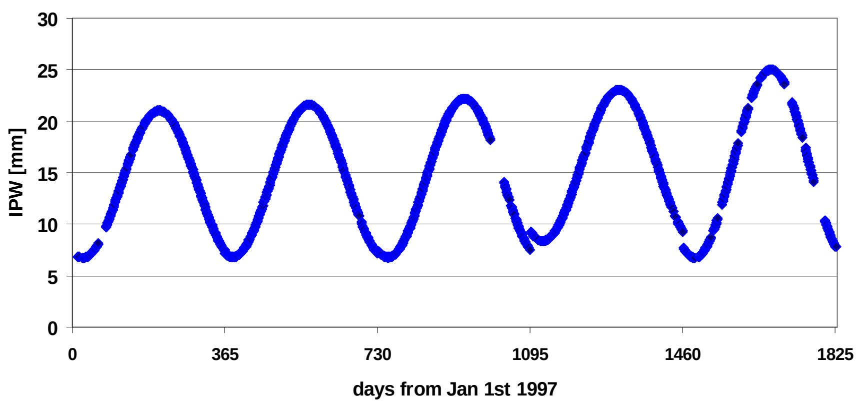

Fig. 18. Simple model of daily IPW values series (sinusoid + const) derived from IGS CODE ZTD solution for JOZE 1997-2001.

Some different climate features are visible in IPW series derived from EPN solutions. Oceanic climate for Helgoland is quite a distinct compared to arctic THU3 (Greenland, also on the seashore).

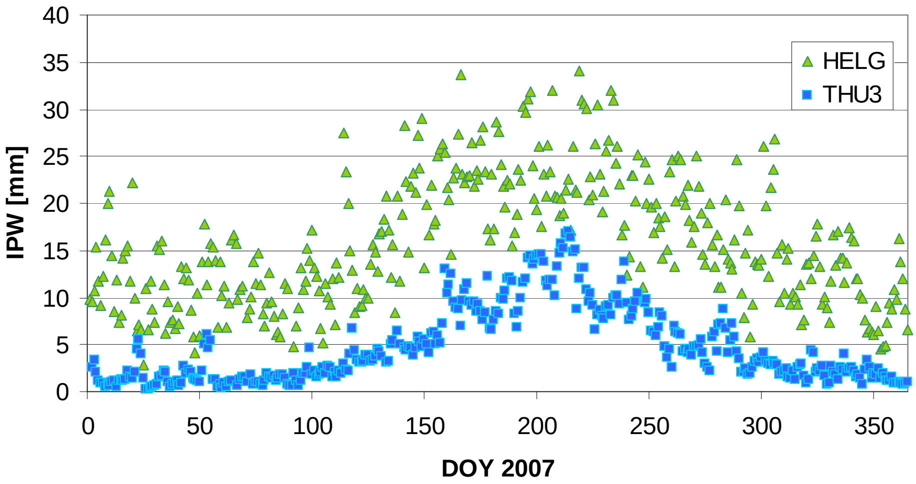

Fig. 19. Daily averaged IPW values for HELG and THU3 in 2007.

6. CONCLUSIONS

- EPN ZTD estimates have been much improved after GPS week 1400 (new strategy, software and reference frame).
- IPW coming from GPS (different static solutions mainly EPN) is of reliable quality compared with three meteorological water vapour data sources: radiosoundings, sunphotometer and input fields of operational numerical prediction model (NWP) COSMO-LM.
- Only CIMEL sunphotometer data seems more genuine source. IPW values from other sources can be much more problematic through various technical shortages.
- It is worth to emphasize that while inter-technique comparisons of directly measured IPW is attainable only for best equipped observatories, from NWP models treated as meteorological database you can obtain (calculate) ZTD and IWV for all stations independently from sparse RAOB network. Unfortunately procedure is not so straightforward.
- Numerical Weather Model topography is greatest concern for the proper ZTD derivation
- Other research show value of GPS IPW as a geophysical tool: clear physical effects evoked by station location (e.g. height and, ZTD series correlation coefficient as a function of distance) and weather pattern. Long (climatologic?) IPW series are especially intriguing.
- Lack of surface humidity data to model IPW extremely encourages to investigate information exchange potential between Numerical Model and GPS network derived values – which is needed for future development of weather prediction but also less laborious methods of GNSS precise positioning.

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