Tropospheric Delay (ZTD) and Precipitable Water data from COSMO model vs. geodetic GPS network data

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1 Introduction

Atmospheric refraction is topic of great concern in satellite geodesy. Refraction of Global Positioning System (GPS) L-band navigational signal manifests itself in the form of Tropospheric Delay. For the satellite in zenith, tropospheric delay (here Zenith Tropospheric Delay ZTD) on station at the sea level is around 2.3 m. Valuable geodetic coordinate solutions for antenna phase center should be at centimetre level (daily solutions). There are two approaches to eliminate tropospheric delay in GPS solutions (and other satellite positioning systems and VLBI). First is to model ZTD from surface meteorological parameters by means of rather coarse equations ([7], [4]) and next we transform it to satellite elevation by so called 'mapping function'; second emphasizes optimal construction and solution of observational equation system so tropospheric delay is estimated stochastically together with coordinates. Advanced GPS software practically mixes both methods [3] starting with model ZTD value and estimating values for each station in selected intervals (mostly 1 hour or as random walk). In some special cases WVR (Water Vapour Radiometers) are used to directly measure most variable (and problematic) part of atmospheric delay coming from water vapour.

In case of permanent GPS stations maintained for most precise scientific purposes (plate tectonics etc.) ZTD is also estimated for purposes of atmospheric research: so called 'GPS meteorology' [5]. Notion of 'GNSS meteorology' is more frequently used ($GNSS = GPS + Glonass + Galileo$). This new discipline is now quite advanced: in some cases at the level of operational assimilation of GPS data to numerical weather prediction models (e.g. NOAA RUC).

We describe several interesting results of IPW and ZTD time series comparisons and analyses. Greatest attention is paid to IPW (Integrated Precipitable Water) - important meteorological parameter easily derivable from GPS tropospheric solutions (ZTD's). We have made quite many comparisons of different static solutions (mainly IGS and EPN) and input fields of operational numerical weather forecast model COSMO (maintained by Polish Institute of Meteorology and Water Management).

2 Zenith Tropospheric Delay and Precipitable Water in satellite geodesy

Networks of GNSS receivers and dedicated solutions are coordinated in the frame of two organizations: IGS International GNSS Service (global reach) and European (EUREF) Permanent Network (EPN).

Total Zenith Delay above all stations in the network became one of the standard products of IGS (from 1998) and EPN (from 2001). It is created as a combination of individual

Local Analysis Center's solutions (EPN has 16 such centers and each station is calculated independently by 3-4 centers) or special solution using 'final' sub-products orbits, clocks etc. (IGS, [2]). In our paper we describe results of only these two official solutions, but many other are available or in development.

IPW (Integrated Precipitable Water) sometimes defined simply as PW describes quantity of water vapour in the vertical direction over station in mm of liquid water after condensation. Related parameter IWV (Integrated Water Vapour) is used more frequently - it has the same numerical value but another unit of measure: g/m^2. 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 ([1], [6]).

Separation of hydrostatic and wet part of delay involves using some model of ZHD (Zenith Wet Delay - in our work Saastamoinen formula with gravitational correction):

$$ZWD = ZTD - ZHD$$

Next we recalculate ZWD to IPW by

$$IWV \approx k \cdot ZWD$$

Coefficient k is given by equation

$$\frac{1}{k} = 10^{-6}(\frac{C_3}{T_m} + C_2')R_v$$

and has value of about $\frac{1}{6.4}$ $\{R_v$ is specific gas constant for water vapour, T_m - 'mean temperature', C_x are empirical coefficients given in many versions by different sources$\}$. Coefficient k depends on temperature profile but can be estimated by means of surface temperature at the GNSS station.

In short: ZHD is function of surface pressure (sometimes also temperature) and k of temperature. GPS meteorology needs stations to be equipped with meteorological device but it is true only for about 20% of EPN network. Fortunately in case of comparisons with COSMO results we can use values interpolated from model grid.

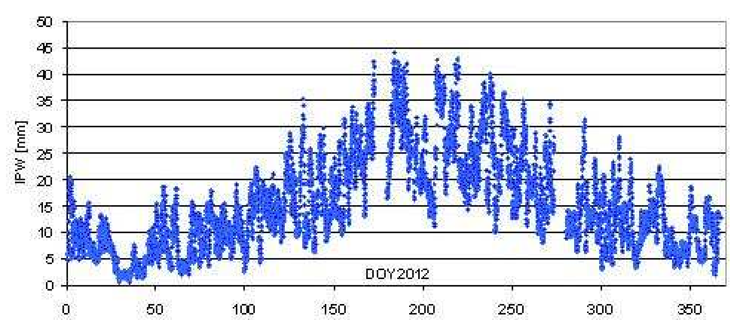

Figure 1: Precipitable water from EPN GNSS combined solution for station JOZE (Warsaw University of Technology Astro-Geodetic Observatory) in 2012

Most direct meteorological data to calculate IPW are free radiosoundings (RAOB) carried out 1 - 4 time a day in some cases at points close to GNSS station.

radiosounding point		GPS	distance [km]	RAOB point height [m]	bias [mm]	mean absolute bias [mm]	difference std dev [mm]	difference RMS [mm]	no of points
3238	UK Albemarle	MORP 13299S001	24.89	141	-0.65	1.11	1.39	1.54	325
6610	SW PAYERNE	ZIMM 14001M004	39.67	490	2.85	2.89	1.63	3.29	679
8522	PO Funchal	FUNC 13911S001	2.14	56	-0.59	1.2	1.49	1.6	319
11520	CZ PRAHA-LIBUS	GOPE 11502M002	25.87	303	2.43	2.47	1.56	2.89	1224
11747	CZ Brno/Prostejov	TUBO 11503M001	42.64	216	0.5	1.62	2.01	2.07	665
12120	PL LEBA	REDZ 12227M001	40.74	2	0.7	1.49	1.88	2.01	466
12374	PL LEGIONOWO	BOGI 12207M003	9.43	96	0.83	1.38	1.68	1.87	300
12374	PL LEGIONOWO	BOGO 12207M002	9.53	96	1.18	1.47	1.42	1.85	382
12374	PL LEGIONOWO	JOZ2 12204M002	33.85	96	1.07	1.46	1.51	1.85	718
12374	PL LEGIONOWO	JOZE 12204M001	33.96	96	0.53	1.23	1.6	1.68	722
12425	PL WROCLAW I	WROC 12217M001	12.73	122	0.2	0.91	1.2	1.21	681
16754	GR HERAKLION (AIR	TUC2 12617M003	103.03	39	1.28	2.51	2.82	3.1	348
17062	TU ISTANBUL/GOZTE	ISTA 20807M001	15.75	33	1.48	1.72	1.7	2.26	653
17130	TU ANKARA/CENTRAL	ANKR 20805M002	12.54	894	0.67	0.97	0.99	1.2	546
10200	DL EMDEN-FLUGPLAT	BORJ 14268M002	44.65	1	0.93	1.86	2.31	2.49	329
10113	DL Norderney	BORJ 14268M002	31.59	11	0.48	1.84	2.6	2.65	336
10035	DL SCHLESWIG	HOE2 14284M002	84.79	48	2.93	3.34	3.2	4.34	459
10393	DL LINDENBERG	POTS 14106M003	73.82	115	1.58	1.86	1.65	2.28	317
10410	DL ESSEN	EUSK 14258M003	82	152	0.61	1.32	1.63	1.74	145
10771	DL KUEMMERSRUCK	WTZR 14201M010	77.8	419	1.89	2.17	1.81	2.61	1373
4270	GL Narsarsuaq	QAQ1 43007M001	61.54	4	-0.1	1.13	1.55	1.55	715
4018	IS Keflavikurflug	REYK 10202M001	36.58	54	-0.18	0.86	1.18	1.19	691
26702	RU Kaliningrad	LAMA 12209M001	89.9	21	3.44	3.94	3.46	4.87	484

Table 1: Comparison of selected radiosoundings and nearby GPS stations (EPN combined tropospheric solution) in 2011. All results are given in values of IPW.

Note: mean bias for all 23 stations (RAOB - GNSS) is 1.05 mm, so GPS IPW values are on average smaller than radiosounding, (difference standard deviation 1.84 mm, difference RMS 2.27 mm)

3 Tropospheric Delay and Precipitable Water from COSMO model(s) (IMWM)

We can treat input fields of numerical weather prediction models (after assimilation/analysis) as a meteorological database. We tested this for main synoptic model in Poland: COSMO model maintained by Polish Institute of Meteorology and Water Management (IMWM) in Warsaw both in 14 km and 2.8 km resolution version.

The 14 km model has a grid of 183×161 points, 36 vertical levels (35 half-levels), the 2.8 km version 285×255 grid and 50 half-levels. Both are restarted twice a day (00 UT and 12 UT) so we use also first three forecast steps ($T + 3h$, $T + 6h$ and $T + 9h$) to get 3h temporal resolution.

Grid has rotated equator and 0 meridian to minimize deformations making typical map projections inadequate - so sometimes we use original grid for mapping results.

For all grid points we can calculate zenith tropospheric delay and interpolate it for about 160 EPN GPS stations located in the model area in two ways:

- hydrostatic (ZHD as function of surface pressure and station coordinates, ZWD integrated in vertical direction together with IPW)
- direct integration of refractivity profile utilizing one of formulas developed in geodesy ([8], [9] etc.).

$$ZTD = 10^{-6} \int N ds$$

For refractivity we used formula proposed by Thayer (1974):

$$N_m = (n_m - 1) \cdot 10^{-6} = 77.60\frac{p}{T} - 13\frac{e}{T} + 3.78 \cdot 10^5\frac{e}{T^2}$$

{p - pressure, T - temperature [K], e - water vapour partial pressure}

The ZTD map is of course dominated by topography:

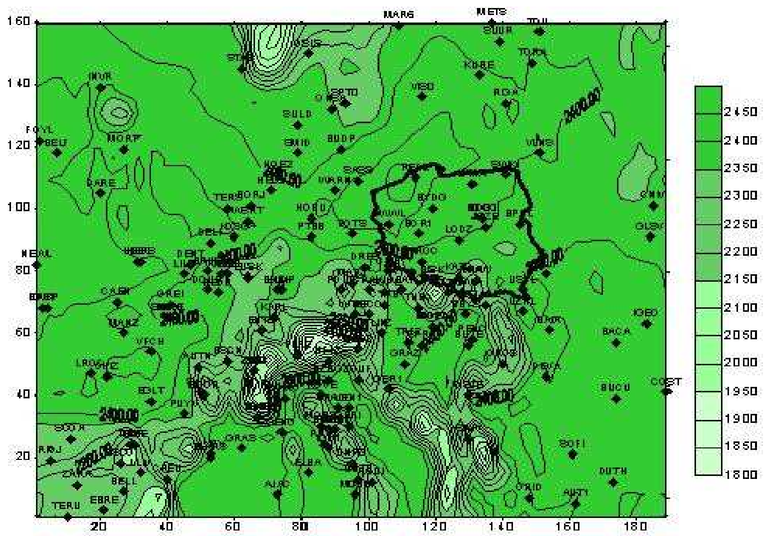

Figure 2: Map of ZTD [mm] calculated (hydrostatic method) from COSMO_14 fields May 17^{th} 2011 15:00 TU (first forecast step) in model grid

First results of comparisons: EPN combined tropospheric product - COSMO derived ZTD have shown dramatic extremes for mountain stations. We have found these differences 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 below.

4 Comparison of precipitable water and ZTD

Numerical weather prediction model grid can be treated as meteorological data database. We get IPW (or IWV) simply by numerical integration of vertical profiles of water vapour density (calculated from half-level temperature and specific humidity):

$$IWV = \int \rho_{wv}^k dh \approx \sum_{k=1}^{N}(h_{j+1} - h_j)$$

Now we can compare IPW from COSMO model and GPS solutions.

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Next we present selected results and visualizations of thorough comparisons of IPW. GPS (or $GNSS = GPS + Glonass$) IPW comes from from EPN and IGS solutions. COSMO IPW is integrated from input fields and first forecast steps in NWP models COSMO_14 and COSMO_2.8 in 2011 and 2012.

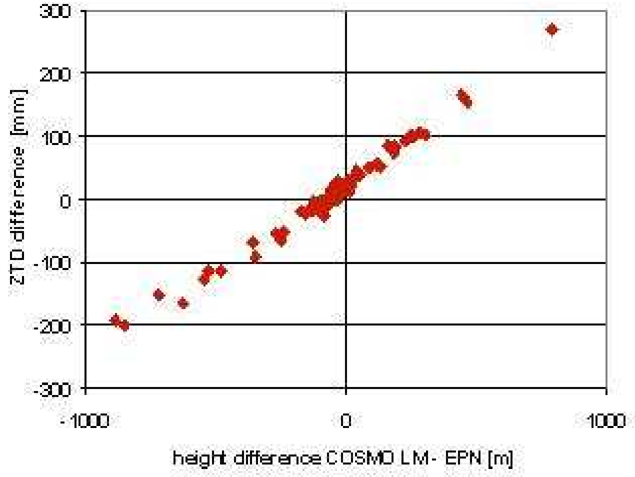

Figure 3: ZTD differences [mm] for EPN stations inside COSMO model in relation to height difference: EPN height (logs) - height of model ground level for station coordinates

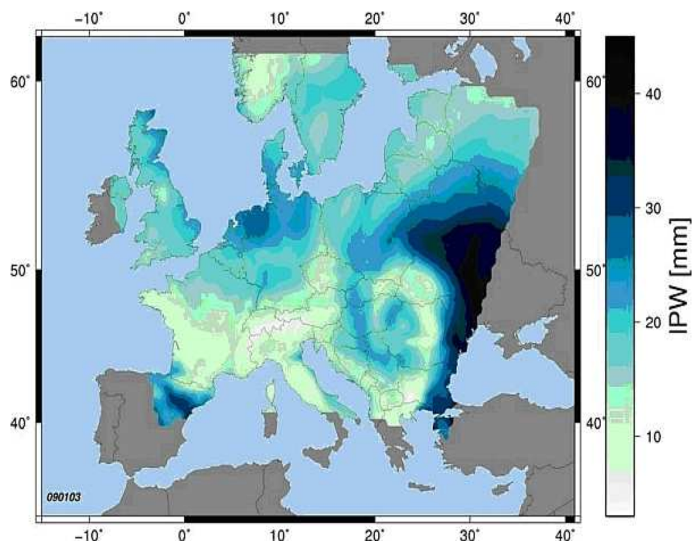

Figure 4: Maps of IPW [mm] calculated from COSMO_14 forecast: 2011 September 1^{st}, $03:00$ UTC

We analyse time dependence of IPW differences, spatial (geographical) distribution of IPW biases and standard deviations, also IPW biases height dependence (9).

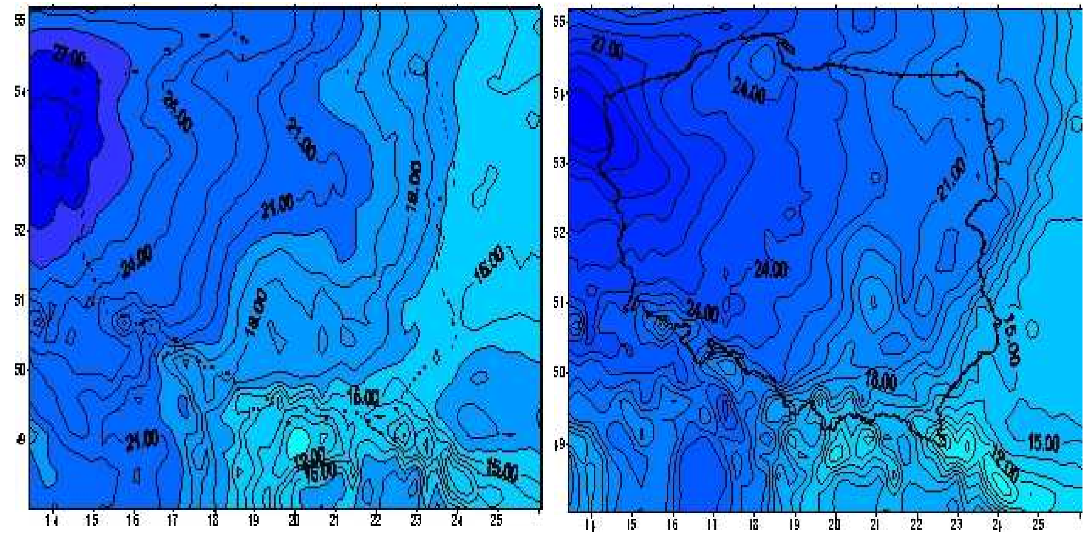

Figure 5: Maps of IPW [mm] calculated from COSMO_2.8 input fields: 2011 August 11 T = 00 UTC (analysis) and $T = 03$ UTC (first forecast step)

	GNSS	NWP model	GPS - NWP bias [mm]	mean absolute bias [mm]	difference std dev [mm]	difference RMS [mm]	stations
2011	EUR comb - station meteo	COSMO-LM_14	-0.85	2.25	2.21	2.88	38
	EUR comb - station meteo	COSMO-LM_14 ver II	-1.19	2.03	2.18	2.66	38
	EUR comb - model meteo	COSMO-LM_14	-0.87	2.07	2.34	2.74	163
	EUR comb - model meteo	COSMO-LM_14 ver II	-0.89	2.05	2.32	2.73	163
	EUR comb - station meteo	COSMO-LM_2.8	-1.06	1.87	2.06	2.44	19
	EUR comb - model meteo	COSMO-LM_2.8	-0.78	1.68	2.09	2.28	31
2012	EUR comb - model meteo	COSMO-LM_14	-0.68	1.94	2.29	2.63	159
	EUR comb - station meteo	COSMO-LM_14	-0.71	1.72	2.13	2.39	30
	EUR comb - station meteo	COSMO-LM_14 ver II	-0.74	1.73	2.13	2.41	30
	EUR comb - model meteo	COSMO-LM_14 ver II	-0.73	2.04	2.40	2.76	159
	EUR comb - station meteo	COSMO-LM_2.8	-0.46	1.50	1.99	2.12	18
	EUR comb - model meteo	COSMO-LM_2.8	-0.80	1.60	2.04	2.22	31
	IGS final - station meteo	COSMO-LM_14	-0.80	1.69	2.07	2.33	14
	IGS final - model meteo	COSMO-LM_14	-1.06	1.78	2.23	2.52	18

Table 2: Comparison of IPW standard ZTD solutions (EPN and IGS tropospheric product) and radiosoundings nearby GPS stations in 2011 and 2012. All results are given in values of IPW. Indicated source of meteo data for IPW separation and method of vertical integration (version II tests profile reconstruction using half-levels as layer boundaries - so we get double levels number).

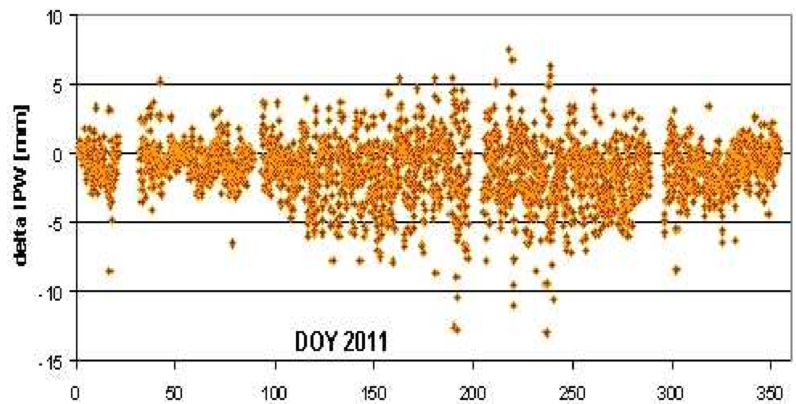

Figure 6: IPW difference: GNSS EUR for JOZE - COSMO_14 model in 2011

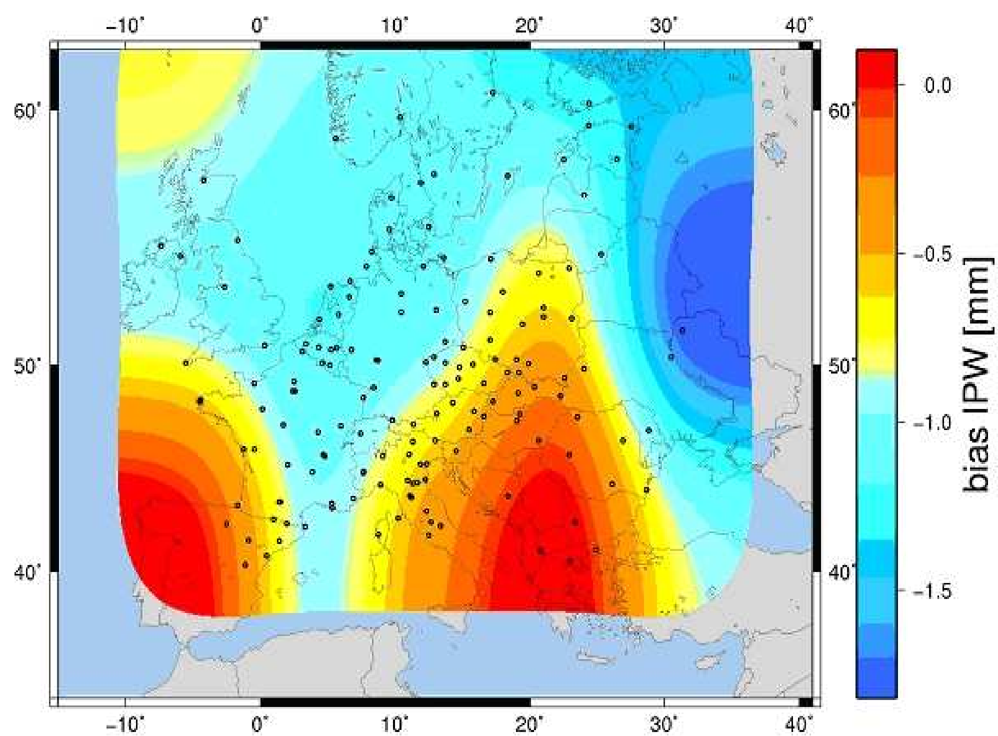

Figure 7: IPW difference (GNSS EUR tropospheric combination - COSMO_14; annual average) map for 2011, meteo from COSMO model; map area is wider than model area due to technical reasons.

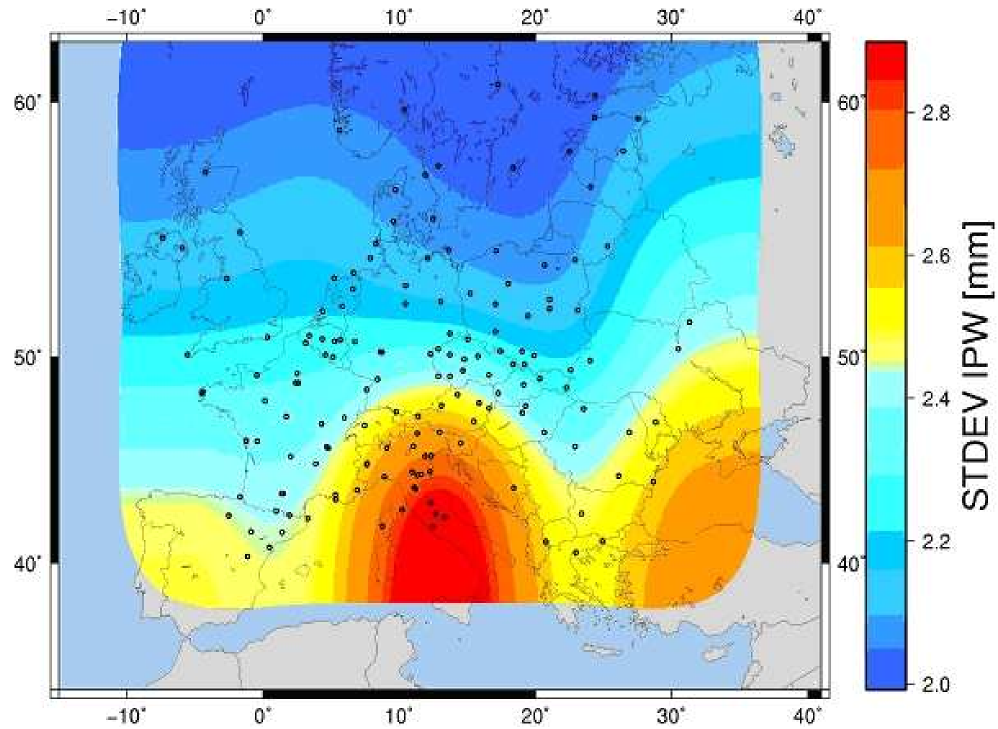

Figure 8: IPW difference standard deviation (GNSS EUR tropospheric combination - COSMO_14; annual average) map for 2011, meteo from COSMO model, version I

Separating analysis fields and forecast steps for comparison of IPW (GPS EUR vs. COSMO) we get to the conclusion that early forecast steps can be used as meteo database together with input fields (analysis).

forecast step	mean difference [mm]	mean absolute difference	difference STDEV
T=0	-0.76	2.04	2.33
T+3h	-0.79	2.07	2.36
T+6h	-0.93	2.08	2.33
T+9h	-0.98	2.10	2.32

Table 3: Comparison of IPW (GPS EUR vs. COSMO_14 in 2011) from input fields and first three forecast steps; T means here time.

Next interesting analysis is to relate IPW differences (comparison of GPS EUR vs. COSMO) to the station height. Linear regression would indicate some problems with pressure reference.

Let us look at 'model meteo' that is meteo data interpolated from COSMO model grid needed to calculate IPW from ZTD for each station inside model grid:

Surface atmospheric pressure from local meteo device at GNSS stations and values interpolated from COSMO model typically shows bias of 1 hPa, difference std. deviation 1 hPa. Surface temperature typical bias is 1 C degree, std. deviation 2 C degrees but sometimes greater. GPS stations meteorological devices are not always properly located: often on the building roof next to GPS antenna (This is also true for JOZE).

To the IPW analysis we add also several results of COSMO tropospheric delay (ZTD) fields comparisons with GPS estimates. This research is ongoing so we present only rough sketch

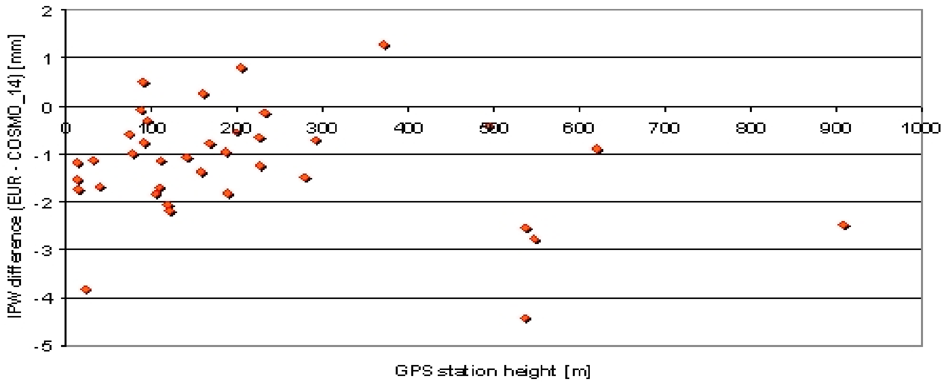

Figure 9: IPW difference (EPN tropospheric combined product COSMO_14, version II) height dependence in 2011

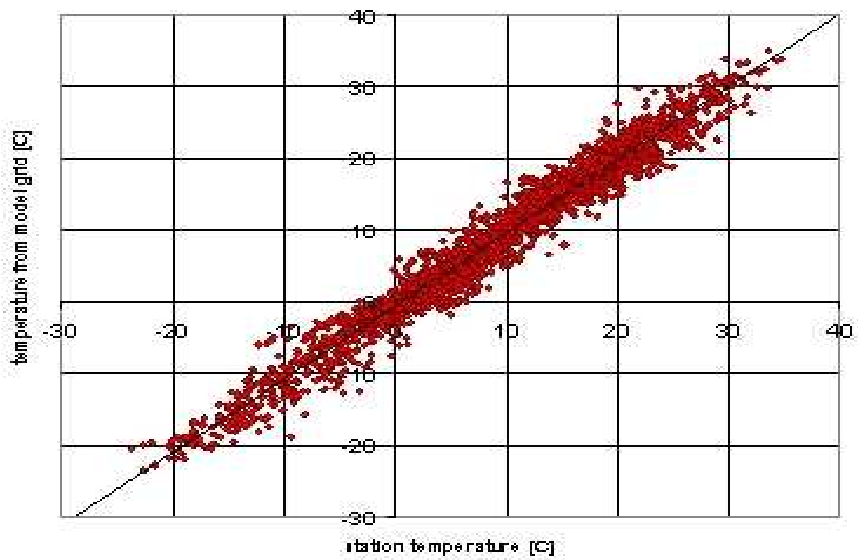

Figure 10: Temperature at JOZE GPS station (Józefosław south of Warsaw) vs. COSMO_14 model in 2012

of results.

station	GPS - COSMO bias [mm]	mean absolute bias [mm]	difference std dev [mm]	difference RMS [mm]	no of points	station ASL height [m]
BOGI	-1.91	2.32	2.09	2.83	214	109.1
BOGO	-2.1	2.34	1.89	2.83	523	118.8
BOR1	1.05	1.59	1.71	2	408	89
BPDL	-0.56	1.53	1.97	2.05	1116	167.5
BYDG	-0.59	1.66	2.14	2.22	854	73.8
DRES	-0.63	1.71	2.27	2.36	1135	159.3
GOPE	-2.06	2.4	2.41	3.17	1075	547.4
GWWL	-0.75	1.6	2.07	2.2	1126	90.8
JOZ2	-2.07	2.3	1.96	2.85	1136	120.9
JOZE	-1.06	1.68	1.96	2.22	1136	109.9
KATO	-0.45	1.5	2	2.05	1118	291.6
KUNZ	-2.33	2.66	2.22	3.21	1053	656.1
LAMA	-0.96	1.59	1.95	2.17	1108	157.7
REDZ	-0.67	1.52	1.93	2.05	1110	76.8
SWKI	-1.61	1.98	1.95	2.53	1120	188.5
TUBO	-2.31	2.59	2.4	3.34	997	279.6
USDL	0.18	1.48	2.04	2.04	1118	494.1
WROC	-0.91	1.68	2.14	2.32	1041	140.5
ZYWI	-0.37	1.46	1.97	2	1120	370.7

Table 4: Comparisons of IPW from EUREF tropospheric product (combination) and input fields and first forecast steps in COSMO_2.8 model in 2011 {for the GNSS stations minutes check: www.epncb.oma.be}

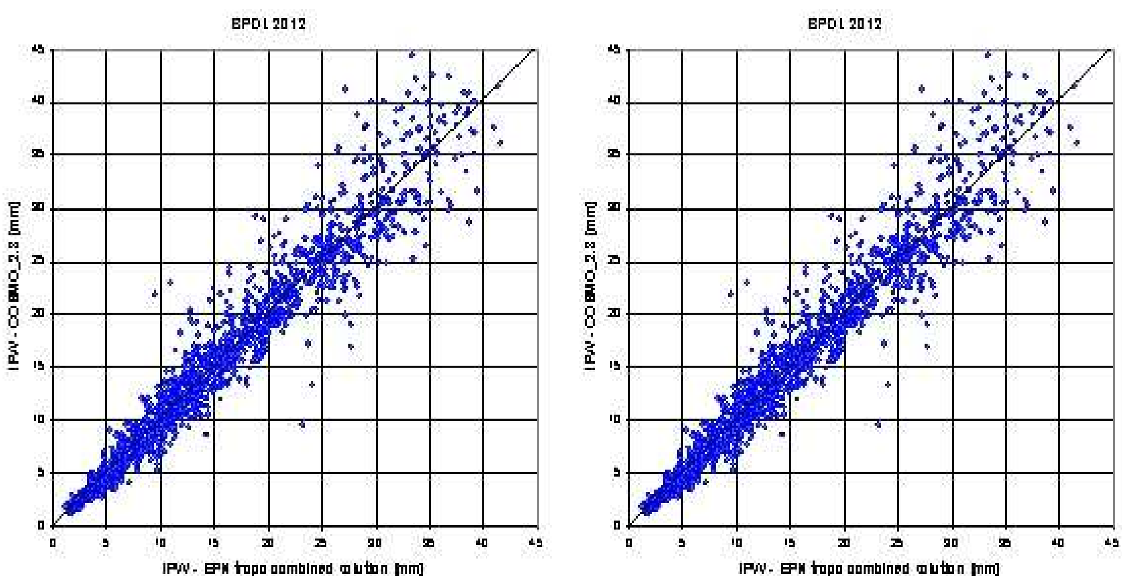

Figure 11: IPW comparisons GNSS EUR combined tropospheric solution for 2 GNSS stations in Poland vs. COSMO_2.8 model (version I) in 2012 BPDL (Bielsk Podlaski) and LAMA (Lamkówko, near Olsztyn); correlations are respectively: 0.966 and 0.973 but difference standard deviation in each case around 2 mm

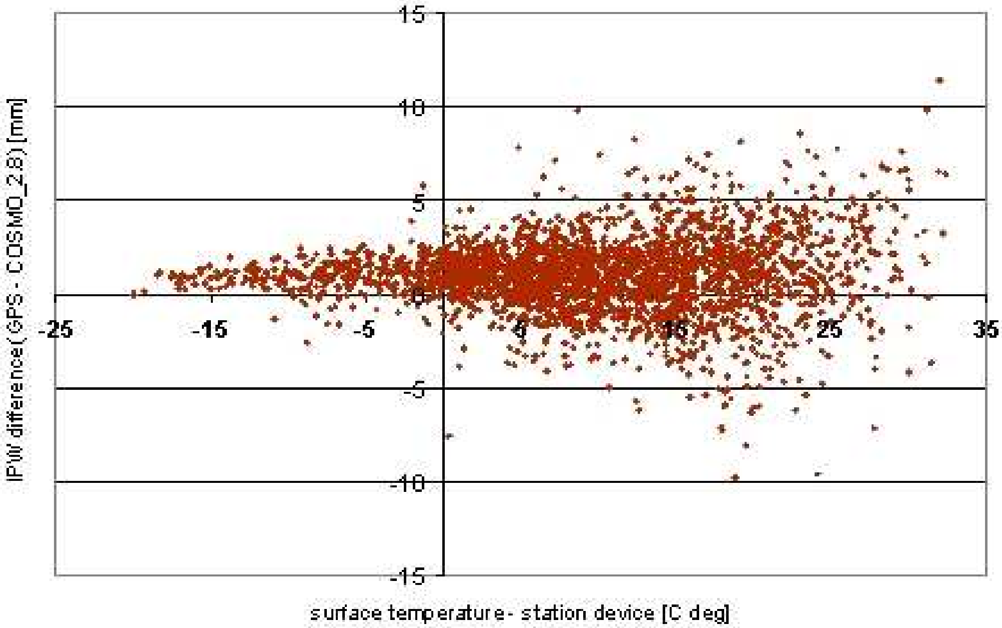

Figure 12: IPW difference (EPN tropospheric combined product - COSMO_2.8) temperature dependence in 2012

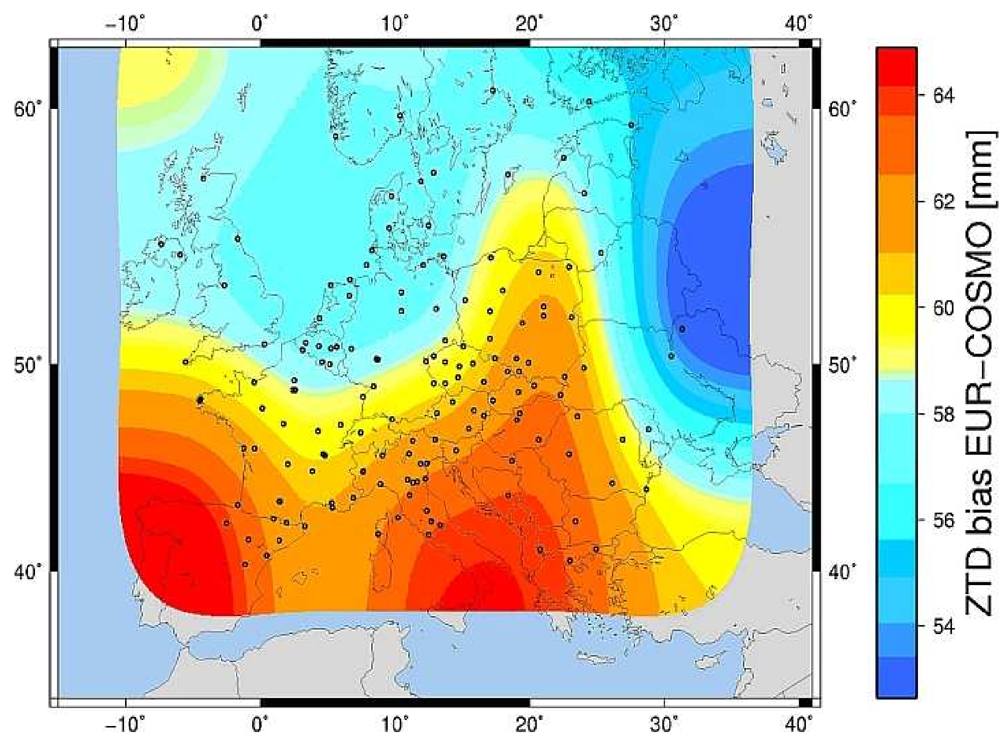

Figure 13: ZTD difference (GNSS EUR tropospheric combination - COSMO_14; annual average) map for 2012, ZTD integrated in the vertical profile

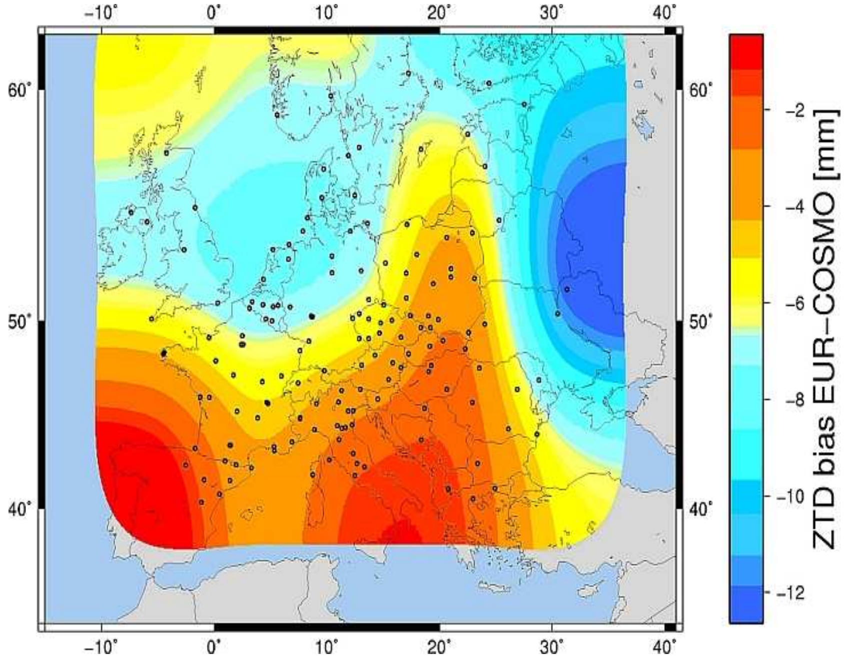

Figure 14: ZTD difference (GNSS EUR tropospheric combination - COSMO_14; annual average) map for 2012, ZTD calculated by hydrostatical method

Pattern of IPW difference distribution is clearly visible in hydrostatic ZTD difference. In the south we got greater IPW values in COSMO fields and so also greater wet delay ZWD and overall delay ZTD. Integration of refractivity by Thayer formula confusingly produces greater values of ZTD in the north. Relative discrepancies produced by direct integration is about 2.5% of ZTD in 14 km resolution model but below 1% (nearly 4 times smaller) for 2.8 km model!

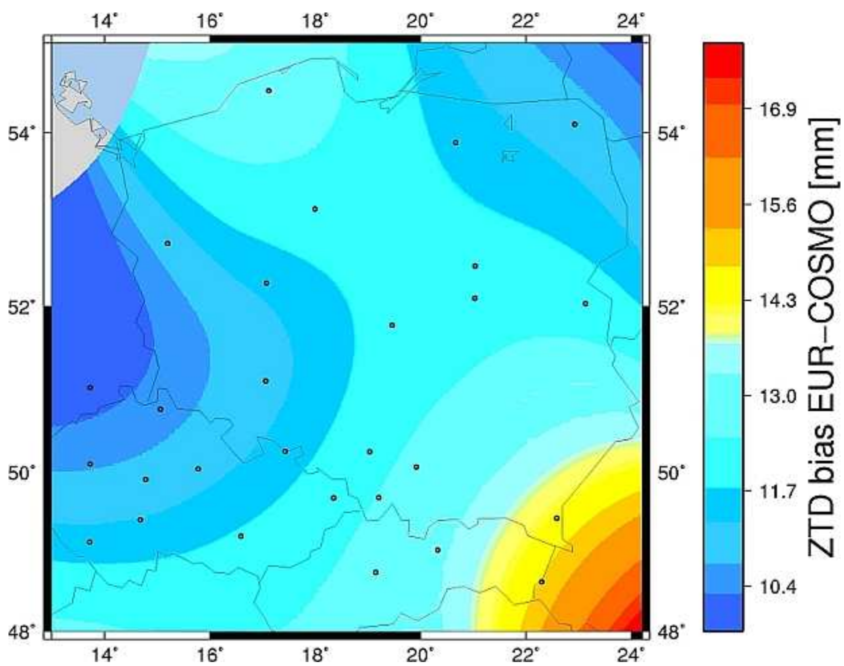

Figure 15: ZTD difference (GNSS EUR tropospheric combination - COSMO_2.8; annual average) map for 2012, ZTD integrated in the vertical profile, GPS stations indicated as small circles

ZTD bias can be result of poor quality of geodetic refractivity models (many of them were developed mostly for classic terrestial measurements), hybrid vertical coordinate in COSMO model or some numerical problems (e.g. numerical integration).

This effect should be further investigated.

5 Conclusions and Outlook

1. IGS and EPN zenith tropospheric delay (ZTD) recalculated to precipitable water (IPW) show good conformity in relation to COSMO model data. COSMO reveal positive IPW bias of about 1 mm (model is 'too wet').

2. Many factors affect both procedure of IPW derivation from COSMO model and calculation of IPW from tropospheric delay: most crucial is height adjustment, but even minor ones like water vapour density formula or barometric equation can affect IPWV on 1 mm level.

3. Using NWP models with dense grid does only slightly evidently improve IPW data, but greatly influences tropospheric delay (this effect will be investigated in next paper)

4. IPW coming from GPS (global and regional static solutions) is of good quality compared with independent meteorological water vapour data sources like radiosounding. In this case radiosoundings show positive bias close to 1 mm of IPW

5. There are many inconsistencies and errors and gaps in local meteorological data for GNSS stations (meteo Rinex) files on IGS/EPN servers. NWP models can be used instead for IPW derivation (COSMO is reliable but smoothed source of surface meteo data). For pairs GPS - RAOB correlation diminishes quickly with distance and height difference

6. GNSS networks provide us with vertically integrated humidity information (precipitable water) which can feed COSMO model (nudge water vapour content in right direction) in network much denser then RAOBs

7. Abundance of meteorological data from NWP and in accordance with them tropospheric delay information makes more and more crucial the question of their usefulness in GPS network processing. Tropospheric delay is smaller then delay caused by ionosphere but harder to eliminate so that contributes more to error budget in many positioning applications.

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- University of Wyoming - radiosounding data

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