IGS Tropospheric Products - Quality Verification and Assessment of Usefulness in Climatology

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IGS Workshop 2012 Olsztyn, 23--27 July 2012

Abstract

Poster concentrates around two main questions.
First is conformity study of ZTD of IPW in IGS tropospheric products (combination till 2006, final and ultra-rapid solutions by JPL, USNO, CODE), EPN tropospheric combination and meteorological water vapour data sources. Water vapour data come from radiosoundings, global numerical weather prediction model GFS (operated by NCEP) and sun photometer CIMEL 318.

Next topic is information potential contained in IGS tropospheric products for climatology and aerology.
Long time series of IPW (daily averaged) can serve as climate change indicator e.g.: relatively unique shape of such series in different climates. Long lasting changes in weather conditions - 'dry' and 'wet' years are also visible. The longer and more homogenous our series the better chance to estimate the magnitude of climatological IWV changes. The problems with GPS strategy and reference system changes can be solved by reprocessing (examples included). Next we adjust seasonal model to the series (LS method) for selected IGS stations. We apply two modes: sinusoidal and composite. Also two ways are tried: multi-year adjustment and every year separately (different are not only amplitudes but also phases). Even simple sinusoidal seasonal model of daily IPW values series clearly represents diversity of world climates. Residuals in periods up to 14 years are searched for some long-term IPW trend. For some stations & years such trends are quite clear, the following years not visible.
IPW from IGS tropospheric products can be treated also as information source for aerology: it demonstrates some clear physical effects evoked by station location (e.g. height and series correlation coefficient as a function of distance) and weather patterns like dominant wind directions. Also deficiency of surface humidity data to model IPW is presented for different climates.

Introduction

We can find several tropospheric solutions as part of the IGS poducts available in Data Centers repositories. These are: IGS combined product (till mid 2006, by G. Gend), IGS rapid combination (G. Gend), new IGS tropospheric product (from 2002 by Sung.H.Byun & Yoaz.E.Bar-Sever, JPL [1]), EUR - EPN combined product (by W. Soehne), IGS Analysis Centes individual solutions: CODE, SIO, NGS, JPL, EMR and EPN Analysis Centes solutions.

First we try to give some clues about quality of this solutions. Beyond simple statistical comprisons od ZTDs we use also some meteorological data - in the form of IPW.
IPW (Integrated Precipitable Water) sometimes defined simply as PW is interesting meteorological parameter describing quantity 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: kg/m^2. IPW can be calculated from ZTD by known procedure of separtating 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. On the other hand we can get IPW from veritcal humidity data: integrating water vapour density (from radiosounding data but also from numerical weather prediction models).
We have also some other techniques for IPW detection: WV radiometers and sun photometer. But the points equipped with them are quite sparse. From numerical weather predicton models we get IPW and ZTD for every station inside model grid.

$$IPW[mm] = IWV[kg/m^2] = \int \rho_v dh \approx \kappa \cdot \Delta^0_{trop,w} = \kappa \cdot ZWD = \kappa \cdot (ZTD - ZHD)$$

ZTD conformity analysis

Tropospheric combination provided us with easy mean to asses solution discrepancies for each station. Look for instance at weekly differences for REYK.

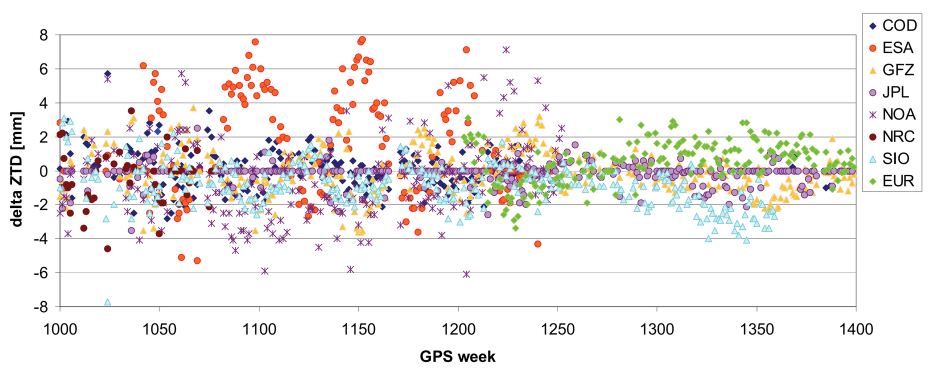


Fig. 1 Weekly ZTD biases of IGS Centers tropospheric solutions in relation to IGS tropospheric combination

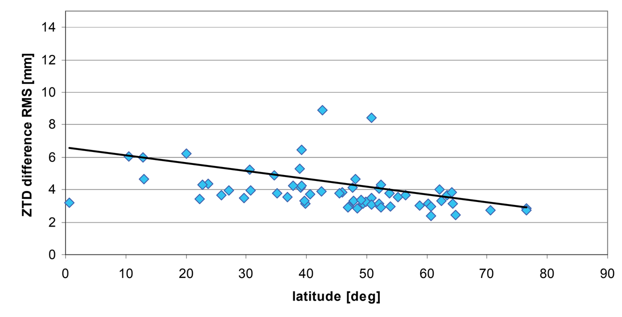


Fig. 2 Average ZTD difference RMS in 2010: CODE vs. new IGS tropospheric product in relation to station latitude

Tab. 1 Statistics of ZTD solutions: IGS(n) - new IGS tropospheric product, IGS(r) - rapis troposheric combination

year	ACs solutions	mean difference [mm]	mean absolute difference	difference STDEV	difference RMS	No. stations
2004	EUR-SIO	5.68	6.30	4.79	7.52	33
2005	EUR-SIO	1.91	8.47	13.80	14.37	28
2005	EUR-IGS(n)	6.47	7.06	4.75	8.22	24
2007	EUR-IGS(r)	-0.55	2.32	3.13	3.25	29
2007	IGS(n)-IGS(r)	0.15	3.20	4.24	4.45	44
2007	EUR-IGS(n)	0.09	2.61	3.38	3.64	30
2009	EUR-EMR	-0.32	2.52	2.95	3.24	10
2009	NGS-EMR	0.55	3.93	4.37	5.02	57
2009	EUR-JPL	-0.79	2.59	4.53	4.89	13
2009	EUR-NGS	-0.27	2.50	3.17	3.33	45
2009	NGS-IGS(n)	-0.06	3.16	3.97	4.22	50
2010	EUR-JPL	-0.16	2.73	5.82	6.06	14
2010	EUR-NGS	-0.29	2.14	2.79	2.97	45
2010	NGS-IGS(n)	-0.22	3.00	4.33	4.58	46
2010	COD-IGS(n)	0.21	2.86	4.24	4.44	63
2011	EUR-JPL	-0.50	2.66	5.55	5.79	16
2011	EUR-NGS	-0.21	2.12	2.66	2.87	44
2011	NGS-IGS(n)	-0.09	3.17	6.08	6.29	54
2011	COD-IGS(n)	-0.11	3.16	6.36	6.50	59

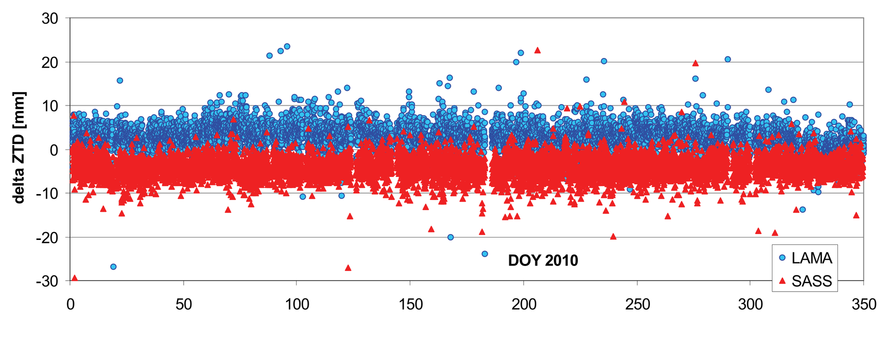


Fig. 3 ZTD differences for 2 stations:EPN tropospheric combination - IGS tropospheric product in 2010

Meteorological data for IPW verification

Most popular meteorological data to calculate IPW are free flying balloon radiosoundings (RAOBs) carried out 2 - 4 time a day in some points close to GNSS station. All comparisons from now are made in values of IPW.

Tab. 2 Comparison of selected radiosoundings and nearby GPS stations (three IGS tropo solutions) in 2011

radiosounding point		GPS	solution	distance [km]	RAOB point height [m]	bias [mm]	mean absolute bias [mm]	difference std dev [mm]	difference RMS [mm]	no of points
6610	SW PAYERNE	ZIMM 14001M004	cod	43.84	491	2.93	2.97	1.69	3.38	667
11520	CZ PRAHA-LIBUS	GOPE 11502M002	cod	29.21	303	2.31	2.38	1.68	2.86	1137
12374	PL LEGIONOWO	BOGO 12207M002	cod	12.47	96	1.11	1.64	1.9	2.2	259
12374	PL LEGIONOWO	JOZ2 12204M002	cod	34.79	96	1.2	1.6	1.64	2.03	718
12374	PL LEGIONOWO	JOZE 12204M001	cod	34.83	96	0.35	1.21	1.67	1.71	713
10393	DL LINDENBERG	POTS 14106M003	cod	73.09	115	1.07	1.57	1.75	2.05	306
10771	DL KUEMMERSRUCK	WTZR 14201M010	cod	76.5	418	1.31	1.72	1.78	2.21	1369
3238	UK Albemarle	MORP 13299S001	igs (n)	26.44	141	-0.45	1.2	1.66	1.72	321
11520	CZ PRAHA-LIBUS	GOPE 11502M002	igs (n)	29.21	303	2.27	2.32	1.52	2.73	1238
12374	PL LEGIONOWO	JOZ2 12204M002	igs (n)	34.79	96	1.35	1.66	1.53	2.04	720
12374	PL LEGIONOWO	JOZE 12204M001	igs (n)	34.83	96	0.41	1.29	1.76	1.81	730
12425	PL WROCLAW I	WROC 12217M001	igs (n)	18.35	122	0.37	1.12	2.53	2.56	684
17062	TU ISTANBUL/GOZTE	ISTA 20807M001	igs (n)	22.79	33	1.54	1.83	1.79	2.36	655
10393	DL LINDENBERG	POTS 14106M003	igs (n)	73.09	115	1.28	1.62	1.62	2.07	312
10771	DL KUEMMERSRUCK	WTZR 14201M010	igs (n)	76.5	418	1.49	1.61	1.08	1.84	417
6610	SW PAYERNE	ZIMM 14001M004	ngs	43.84	491	3.13	3.16	1.75	3.59	498
11520	CZ PRAHA-LIBUS	GOPE 11502M002	ngs	29.21	303	2.09	2.14	1.38	2.5	494
12374	PL LEGIONOWO	JOZE 12204M001	ngs	34.83	96	0.69	1.27	1.57	1.71	530

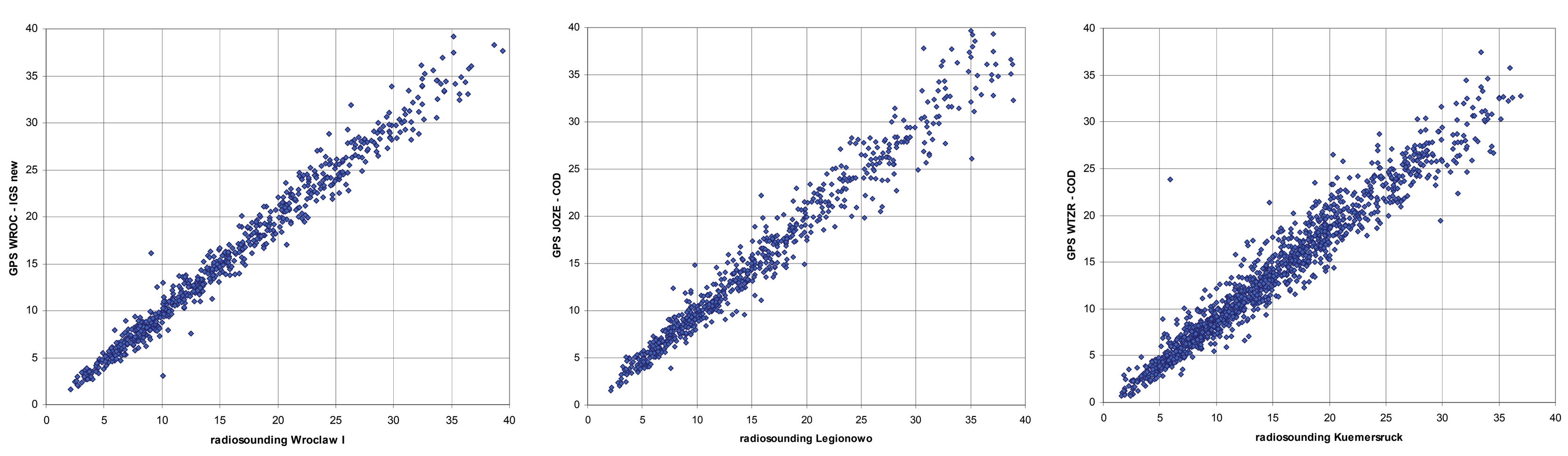
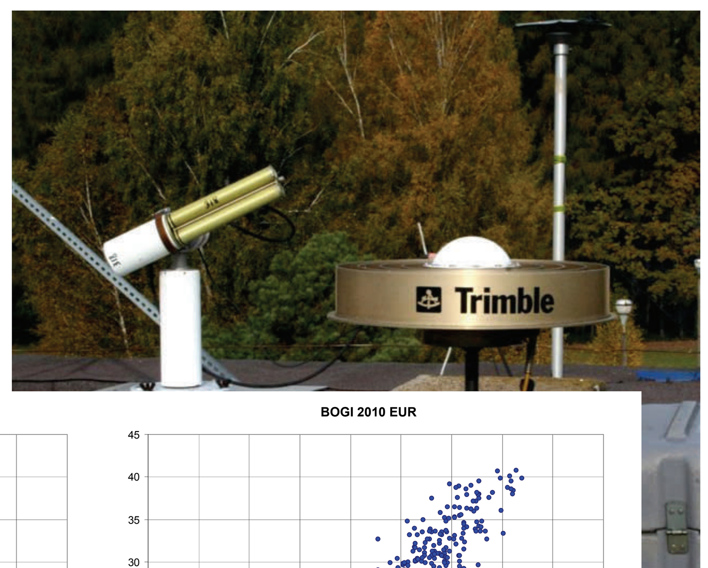
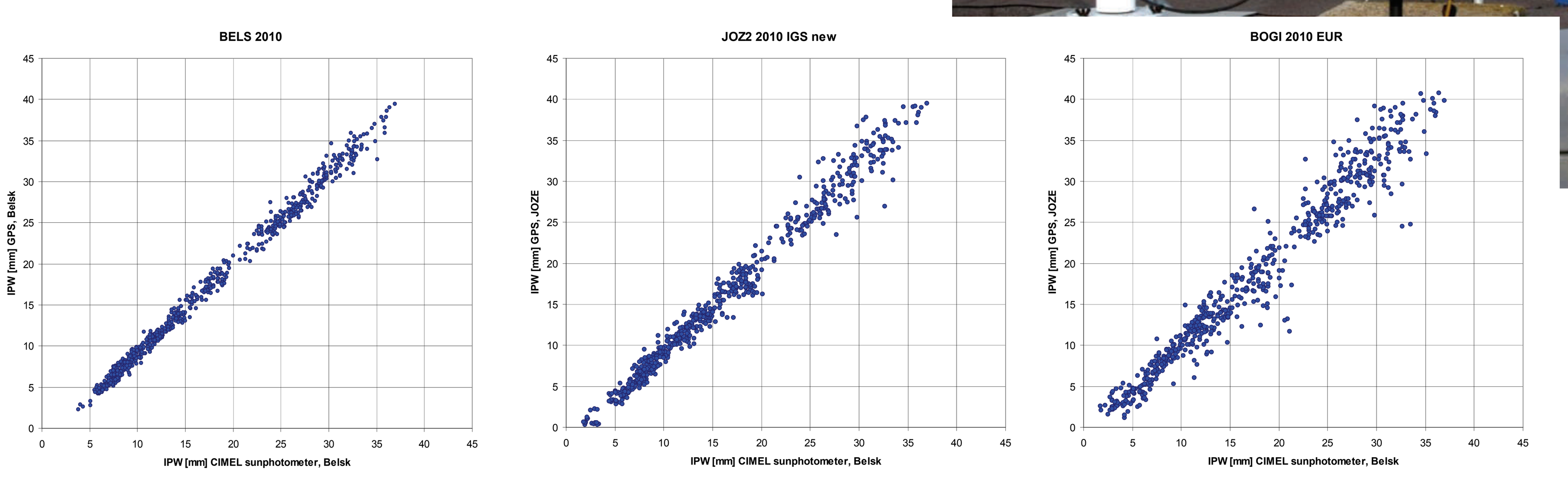


Fig. 4 IPW [mm] 2011 from radiosounding and GPS for 3 stations pairs with increasing distance: RAOB Wrocław - WROC (IGS (n)) - 18 km, RAOB Legionowo – JOZE (COD) - 35 km, RAOB Kuemmersruck – WTZR (COD) - 77 km.

Now You can compare this conformity with excellent results for other technique collocation for the same year 2010. This is sunphotometer. Polish Academy of Sciences operates CIMEL CF-318 sunphotometer at Central Geophysical Observatory in Belsk near Warsaw ($\lambda = 20°47'30"$, $\varphi = 51°50'12"$, h = 190.0 m), 33 km from JOZE in the frame of AERONET (AErosol RObotic NETwork) network coordinated by NASA & CNRS. There has been set up periodical GPS point BELS at the roof of the building of Central Geophysical Observatory Institute of Geophysics PAS in Belsk. Trimble 4000 SSE receiver has been permanently installed by our Department of Geodesy and Geodetic Astronomy (till May 2009 JOZE station receiver - one of the oldest in the whole network) and works permanently thereafter from July 2009. Decrease of correlation characteristic for COSMO-LM model comparisons with GNSS and GNSS vs. in situ technique is attained for Belsk-BOGI pair: distance 73 km!





Belsk CIMEL – BELS GPS correlation coefficient: 0.997 Belsk CIMEL - JOZ2 GPS (IGS): 0.988 Belsk CIMEL – BOGI GPS(EUR) : 0.979

Fig. 5 Belsk IPW: CIMEL-318 measurements and GPS BELS (WUT dedicated solution), JOZ2 (IGS solution) and BOGI (EPN combnation) in 2010

NWP model GFS as a source of IPW

As meteorological database to calculate ZTD and IPW we tested input fields (after assimilation) of GFS (Global Forecast System) model maintained by National Centers for Environmental Prediction (NCEP), grids after analysis are available 4 time a day (UT 00 06 12 18) in 0.5° resolution grid (720x181 nodes). We can use also first prognosis step (T+3h) to get 3-hour time resolution. Comparison have been made of IPW series from GFS model input fields and first prognosis steps with IGS final solution (USNO and JPL [1]). Direct comparison is possible only for sites equipped with meteorological sensors. But treating NWP input fields (after assimilation) as meteorological database we can calculate IPW for every station inside model grid.

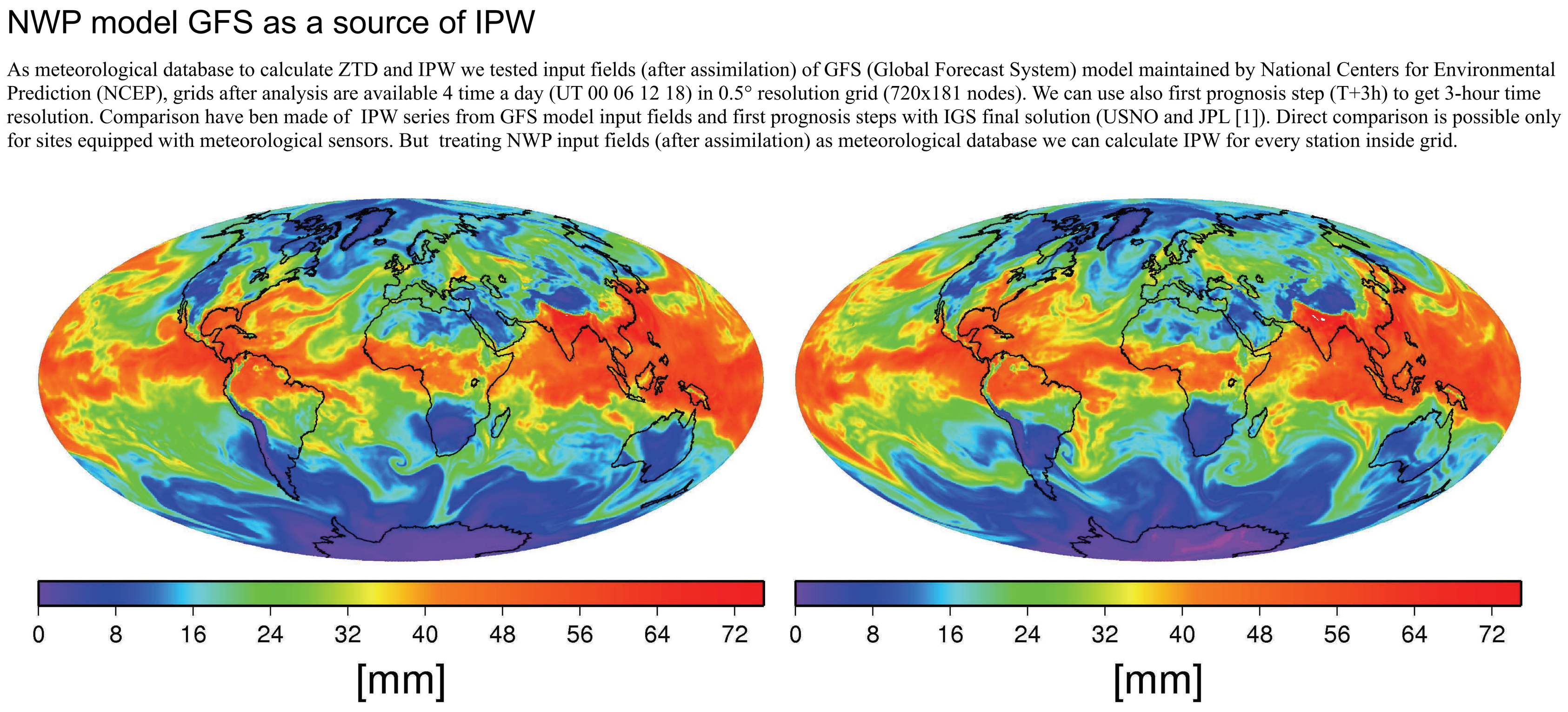


Fig. 6 IPW maps for 25 and 27 June 2011 12:00 UT from GFS global model (note: we need 2 day time step to see discernible change in global IPW pattern

IPW provided by GFS model show discrepancies similar to RAOBs at the distnce of about 50 km.. For IGS solution in 2011 we get mean bias of 0.1 mm (!), men absolute difference 2.5 mm, difference ZTD std. deviation 2.1 mm and difference RMS 3.1 mm. Let us look at three stations in different climates: QAQ1 (south Greenland), JOZE (Poland) and DARW (north Australia).

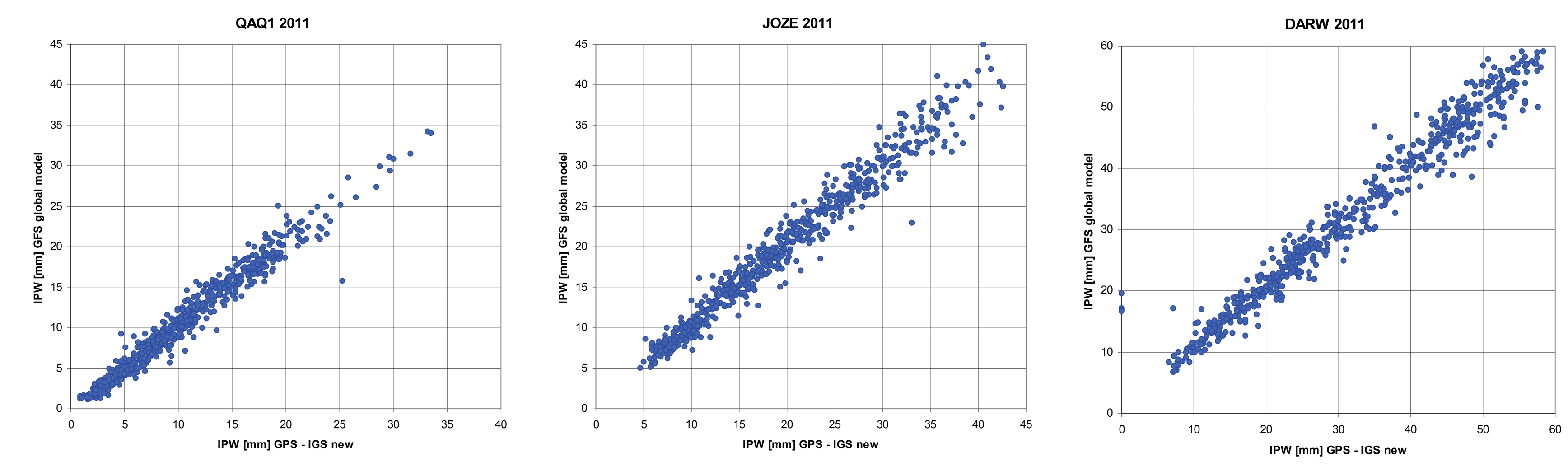


Fig. 7 IPW GPS (IGS new tropo product) vs. GFS global NWP model: QAQ1 (Greenland), JOZE (Poland) and DARW (Australia) in 2011

IPW from IGS tropospheric product in climatology

Daily averaged IPW values carry some climatological information. Below You see the series for GPS station pairs in different climates: HELG - Helgoland THU3, QAQ1 - Greenland, OHI2 - Antrarctica.

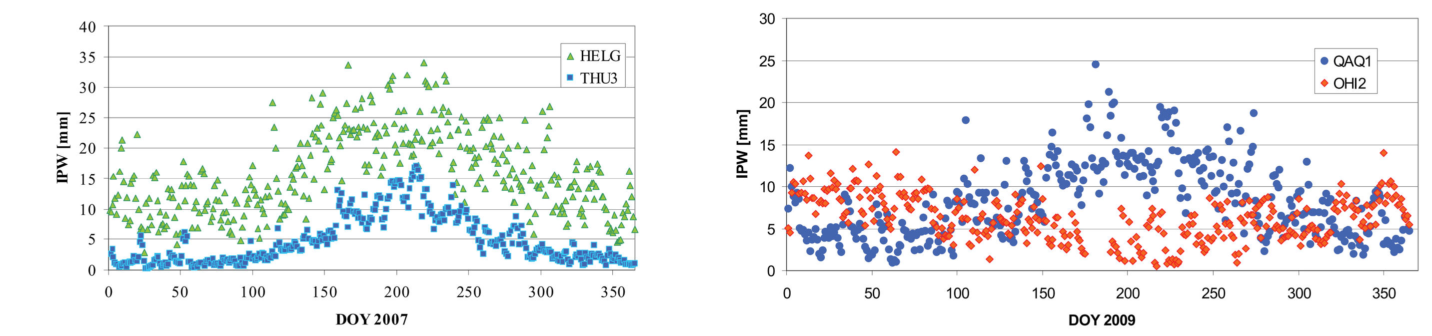


Fig. 8 IPW daily averaged for selected stations in 2007 and 2009

Simple model (sinusoid - amplitude and phase plus constant) has been adjusted to the series (LS method) for JOZE, and other selected stations. We use only stations equipped with meteo sensors - meteo data is required for IPW calaculation!
First we adjust every year separately – different are not only amplitudes but also phases. On the figures below we show the sinusoidal IPW model for some EPN stations. Note PDEL (Azores) distictive behaviour - station practically outside Europe.
Set of IGS stations of course show much bigger discrepancy. We can easily distinguish northern and southern hemisphere.

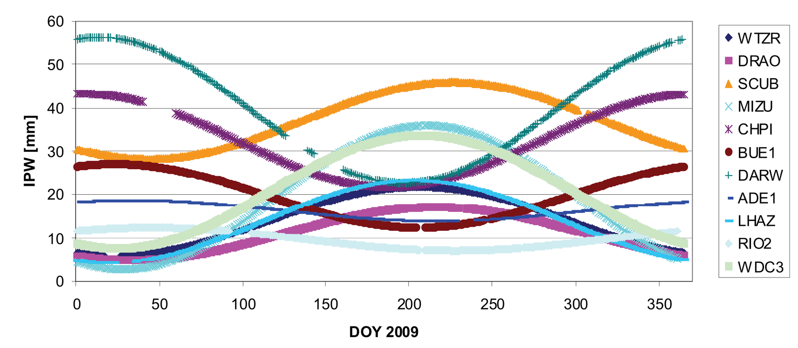


Fig. 9 IPW annual model for selected IGS stations in 2008 (CODE global solution)

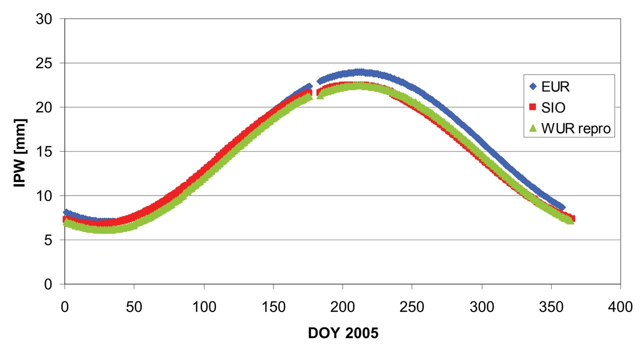


Fig. 10 Different GPS solutions for the same station (e.g. JOZE in 2005) gives divergent results: EUR - operational EPN tropospheric combination, SIO - IGS solution by SIO, WUR - WUT EPN LAC reprocessing campaign

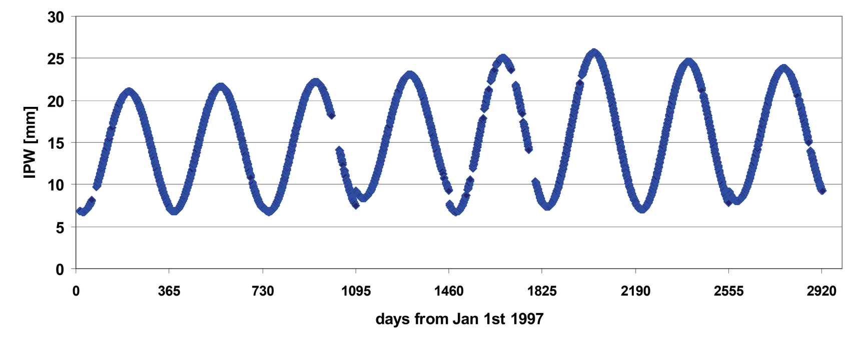


Fig. 11 results for 8 years (1997-2004) for JOZE from EPN combined solution, during first 5 years period we have got +0.6 mm/year IPW trend. For the following years not visible.

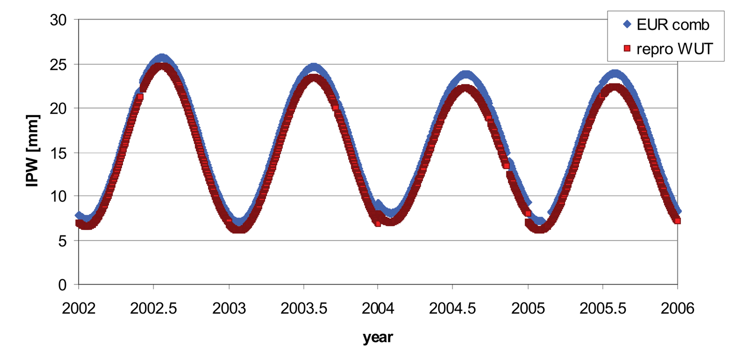


Fig. 12 Four year series of our IPW model for EPN nad reprocessed WUT ZTD's

Can we hope to find something of global change? First we will apply out model for multi-year series of ZTD from IGS and reprocessed solutions in search for some climate change signal in residuals (ver. 1). The second metod is to fit more complicated model: annual sinnusoid, semiannual sinusoid and linear trend at once in leat square approach (ver. 2).

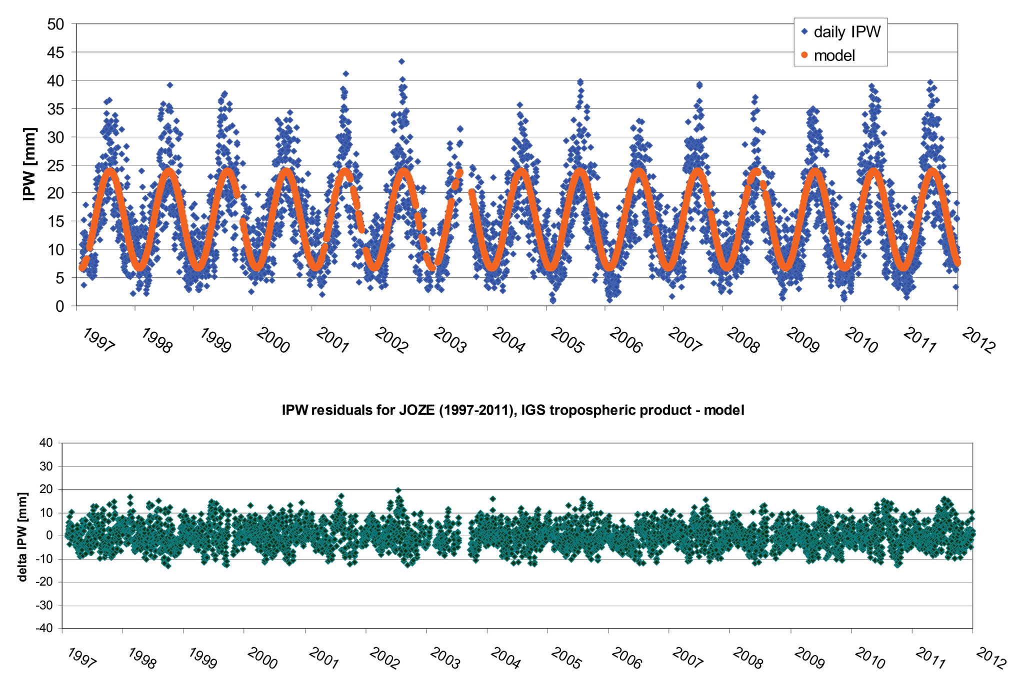


Fig. 13 Annual IPW model for JOZE (Józefosław, near Warsaw) from IGS tropospheric product and residuum

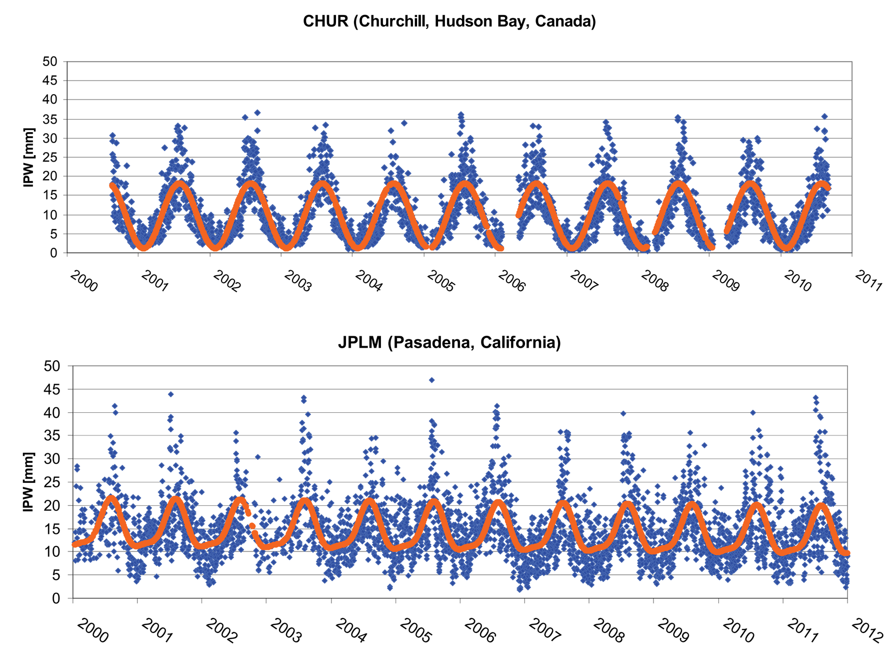


Fig. 14 Model fits better for northern mid-latitude stations e.g. CHUR (vers.1 - simple annual model) then southern stations e.g. JPLM (ver.2 - annual and semiannual sinusoids fitted)

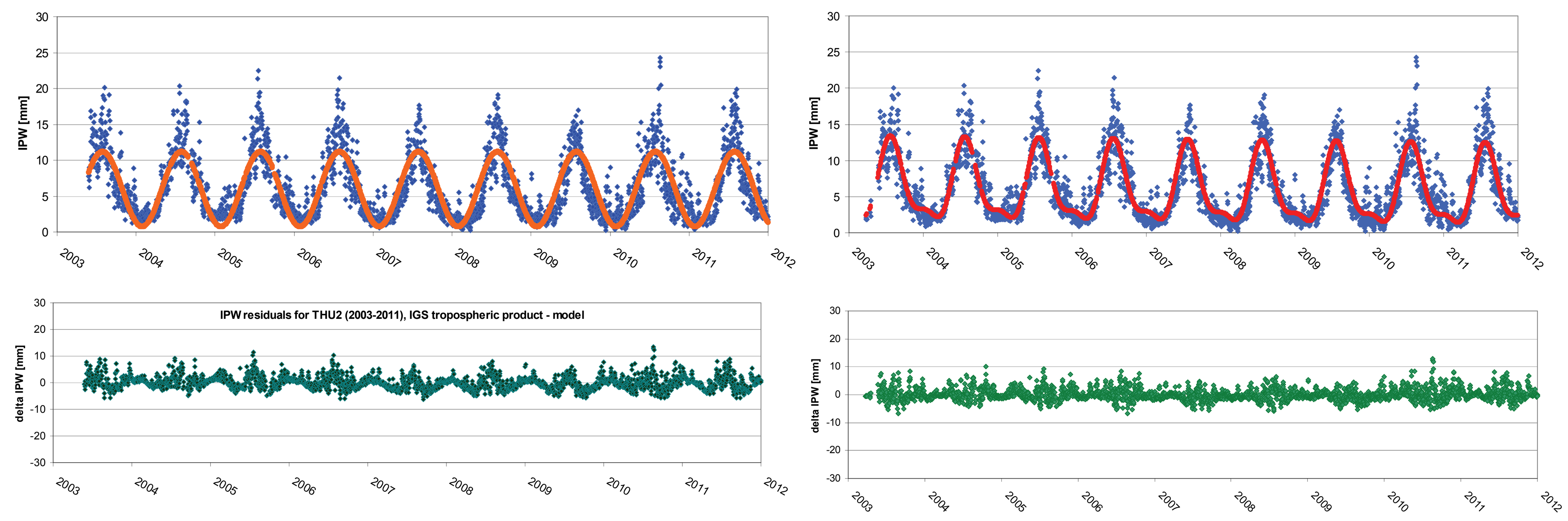


Fig. 15 Two version of annual IPW model for THU2 (Thule, Greenland) from IGS tropospheric product and residuum: ver.1 (annual sinusoid) - left, ver.2 (annual and semiannual sinusoids plus trend) - right

Tab. 3
Parameters of seasonal model adjusted to selected IPW series:
GNSS solution - IGS tropo product (if not listed)
ver1: annual sinusoid (plus mean level) and linear terend shown by the residuals
ver2: annual and semiannual sinusoids plus linear terend fitted together (LS method)

station	method	years	amplitude [mm]	IPW level [mm]	residuals RMS	location	IPW trend [mm/y]
joze	ver.1	1997-2011	8.6	15.3	5.1	Poland	-0.04
joze	ver.2	1997-2011	8.6	15.6	4.9		-0.04
joze EUR	ver.1	2002-2010	8.8	15.8	5.1		-0.11
joze WUT(r)	ver.2	1997-2011	8.5	15.0	4.9		0.03
fair	ver.1	1997-2005	8.2	9.9	4.5	Alaska	0.08
stjo	ver.1	1998-2009	8.6	15.0	6.7	New Foundland	-0.01
stjo	ver.2	1998-2009	8.6	15.4	6.5		-0.01
reyk	ver.1	1997-2011	5.0	12.2	4.1	Iceland	0.07
reyk	ver.2	1997-2011	5.1	10.6	4.0		0.13
reyk WUT	ver.1	1997-2011	5.1	11.6	4.1		0.13
qaq1	ver.1	2003-2010	5.5	9.7	4.0	Greenland	-0.17
thu2	ver.1	2003-2011	5.2	6.0	2.5	Greenland	-0.13
thu2	ver.2	2003-2011	5.2	6.5	2.1		-0.11
yell	ver.1	1998-2008	7.4	10.1	4.7	Yukon Territory	-0.08
chur	ver.1	2000-2010	8.4	9.6	5.1	north Manitoba	-0.12
chur	ver.2	2000-2010	8.4	10.3	4.8		-0.13
drao	ver.1	2000-2010	5.4	12.0	3.8	British Columbia	-0.16
drao	ver.2	2000-2010	5.4	12.8	3.7		-0.17
lama	ver.2	2001-2011	7.8	15.6	12.0	Poland, Masuria	-0.12
wroc	ver.2	2002-2011	9.1	16.6	4.9	Poland	-0.12
zimm	ver.1	1997-2011	7.2	13.3	3.9	Switzerland	-0.05
zimm	ver.2	1997-2011	7.2	13.6	3.9		-0.04
zimm EUR	ver.2	2002-2011	7.4	14.3	3.9		-0.18
wtzr	ver.2	1997-2011	7.5	14.2	4.2	Germany	-0.05
ista	ver.2	2002-2011	8.0	20.2	5.1	Turkey	-0.20
pdel	ver.2	2002-2011	6.1	23.9	5.9	Azores	-0.17
usno	ver.1	1997-2008	13.1	21.4	8.7	Washington DC	0.02
usno	ver.2	1997-2008	13.2	21.4	8.5		0.02
mdo1	ver.1	1997-2010	8.1	11.2	4.5	Texas	0.04
mdo1	ver.2	1997-2010	8.2	11.1	4.1		0.02
jplm	ver.1	2000-2011	4.9	14.4	5.6	California	-0.16
jplm	ver.2	2000-2011	4.9	15.3	5.5		-0.15
ohi2	ver.1	2002-2011	2.3	6.5	2.7	Antarctic Penisula	-0.17
ohi2	ver.2	2002-2011	2.3	7.4	2.6		-0.17

Appendix: IPW can not be modelled simply from sufrace meteo data.
There is only week correlation between IPW and absolute humidity or temperature. Especially for southern stations and oceanic climate but even for northern stations task seems impossible.

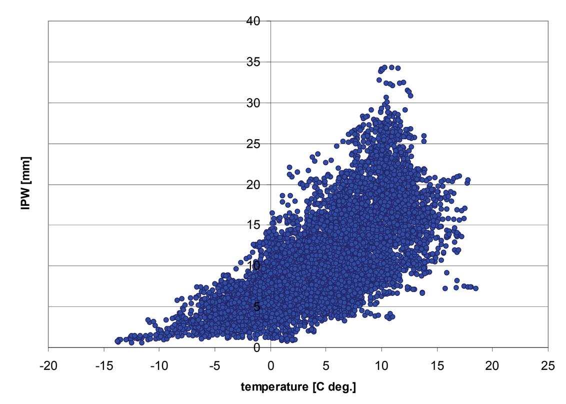


Fig. 16 IPW vs. surface temperature for QAQ1 (Greenland) in 2010, ZTD from IGS tropo product

Conclusions

1. IGS ZTDs show very good conformity in relation to EPN products from 2007 onwards.
2. Meteorological IPW (radiosoundings and sunphotometer) fits to IGS solutions, correlation diminishes quickly with distance. CIMEL sunphotometer data is most genuine source of IPW, as shows in situ observation campaign.
3. Long series of IPW can be useful for climatology. Unfortunately there are too little homogenous solutions spanning many years. IPW trend depends on solution minutes.
4. There are many inconsistencies and errors in meteo Rinex files on IGS/EPN servers. Most difficult part of this work was cleaning of meteo data.

References

[1] Sung H. Byun, Yoaz E. Bar-Sever: A new type of troposphere zenith path delay product of the international GNSS service. J Geod (2009) 83:367–373

Acknowledgements

- Polish Ministry of Science and Higher Education (National Science Center) – grant Nr N N526 074038
- IGS/EPN products developers
- Marcin Rajner (Warsaw University of Technology) - maps in GMT
- Aleksander Piotruczuk - Institute of Geophysics, Polish Academy of Sciences – BELS station maintenance and other help
- National Centers for Environmental Prediction (NCEP) - GFS model data
- University of Wyoming – radiosounding data
- NASA, AERONET (Brent Holben) – sunphotometer data analysis lev15/20

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