

International GNSS Service (IGS) Troposphere Products and Working Group Activities

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SUMMARY

The International GNSS¹ Service (IGS), a federation of 200+ international agencies, pools GNSS measurements, data-processing facilities and scientific expertise to generate the highest-possible-accuracy positioning, timing and geophysical estimates in support of science research needs.

One of its major activities is to coordinate the continuous acquisition of GNSS measurements at 400+ carrier-phase GNSS receivers worldwide. Among the geophysical quantities of interest to the IGS is the excess path delay encountered by GNSS signals as they traverse the lower part of the atmosphere, the troposphere, en route to these receivers. The troposphere contains about 75-80% of the mass of the atmosphere and is the layer where most clouds are found and almost all weather occurs.

The IGS conducts two troposphere-related programs: production of IGS Final Troposphere Estimates and operation of the IGS Troposphere Working Group. These activities have since 2011 been coordinated by the US Naval Observatory (Washington, DC). In this paper we provide an overview of the IGS, review the production/applications of IGS Final Troposphere Estimates, and provide information about the goals and activities of the IGS Troposphere Working Group.

The IGS computes so-called “IGS Final Troposphere [delay] Estimates” for most of its GNSS receivers. Zenith troposphere delay and north/east gradients are estimated every 300 s. An individual data file providing values for 0000-2355 GPS Time is produced for each GNSS receiver. The values are provided three weeks after measurement because their estimation requires IGS Final Orbits, Clocks and EOPs. In 2014, 326 site-files were produced each day on average; 12.3 million files were downloaded. Researchers worldwide perform climate and meteorology studies using these estimates.

The goal of the IGS Troposphere Working Group is to improve the accuracy and usability of GNSS-derived troposphere estimates. It has approximately 50 members and meets twice per year. Its current major project is the creation of a database/website performing continuous, automated comparisons of troposphere estimates obtained from independent techniques e.g., GNSS, VLBI and radiosondes. The group is also supporting an initiative to standardize the *tropo_sinex* file format used to exchange troposphere-delay estimates.

¹ Global Navigation Satellite System, e.g., GPS (USA), GLONASS (RU)

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1. INTRODUCTION

The International GNSS² Service (IGS), a federation of 200+ international agencies, pools GNSS measurements, data-processing facilities and scientific expertise to generate the highest-possible-accuracy positioning, timing and geophysical estimates in support of science research needs.

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The IGS conducts two troposphere-related programs: production of IGS Final Troposphere Estimates and operation of the IGS Troposphere Working Group. These activities have since 2011 been coordinated by the US Naval Observatory (Washington, DC). In this paper we provide an overview of the IGS, review the production/availability/applications of IGS Final Troposphere Products, and provide information about the goals and activities of the IGS Troposphere Working Group.

2. OVERVIEW, IGS AND ITS ACTIVITIES

2.1 IGS Overview

The mission of the IGS is to provide on an openly available basis the highest quality GNSS data, products, and services in support of the terrestrial reference frame; Earth observations and research; positioning, navigation, and timing (PNT); and other applications that benefit the scientific community and society.

Founded in 1994, it operates a global network of GNSS ground stations, data centers, and data analysis centers to provide data and data-derived products in support of these applications. For example, the IGS Reference Frame Coordinator determines tracking site coordinates and velocities in the International Terrestrial Reference Frame (ITRF), and organizes the IGS contribution to ITRF.

² Global Navigation Satellite System, e.g., GPS (USA), GLONASS (RU)

IGS products include: GNSS satellite ephemerides, earth rotation parameters, tracking station coordinates/velocities, satellite and tracking station clock information, zenith tropospheric path delay estimates and global ionosphere maps. The IGS also has working groups charged with performing, staying abreast of or implementing research on improving these products.

To learn more about the IGS and its activities, please visit <http://igs.org>.

2.2 IGS Receiver Network

The foundation of the IGS is a global network of over 400 permanent, continuously operating, dual-frequency carrier-phase receivers recording measurements from one or more of the following systems: GPS, GLONASS, Galileo, BeiDou, QZSS³, SBAS⁴. A representation of this network is shown in Fig. 1.

Receiver data are archived at four IGS global data centers and multiple regional data centers, all of which are publically accessible. Analysis centers regularly process the data and contribute products to the Analysis Center Coordinator, who produces the official IGS combined products.

3. OVERVIEW, IGS TROPOSPHERE ACTIVITIES

3.1 Why the IGS estimates tropospheric delay

Dual-frequency carrier-phase GNSS measurements can be used to provide centimeter-level (or even millimeter-level) ground-station positioning. However, to achieve that accuracy, the excess path delay of radio signals as they pass through the (non-vacuum) troposphere must be accounted for in the data-processing scheme. The excess troposphere path delay of GNSS signals coming from the zenith direction is typically about 2.2 m. It can be tens of meters for signals arriving from low-elevation angles.

Processing techniques have evolved for estimating zenith troposphere delay from GNSS measurements. The resulting estimates can then in turn be used to estimate atmospheric water vapor content, which then can be used for meteorology and climate studies. The IGS now computes troposphere estimates primarily in support of atmospheric science.

Three equations demonstrate the evolution of troposphere delay from nuisance parameter to science:

A GNSS measurement made at receiver i from satellite m , with satellite m having elevation and azimuth angles (e_i^m, A_i^m) ⁵ as measured at receiver i , can be written at a given epoch to first order as:

³ Quasi-Zenith Satellite System

⁴ Satellite Based Augmentation System, e.g., EGNOS

⁵ A_i^m is measured from north and is positive to the east.

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Fig 1. IGS GNSS-Receiver Tracking Network

$$L_i^m = r_i^m + c \cdot [dt^m - dt_i] + T_i^m + dE_i^m \quad (1)$$

where L_i^m is the measurement expressed in distance units, r_i^m is the satellite-receiver distance, dt^m and dt_i are the satellite and receiver-clock errors, T_i^m is the excess path delay in distance units experienced by the radio signal as it passes through the troposphere, and dE_i^m indicates measurement noise. (First-order ionosphere delay errors are assumed removed through linear combination of the dual-frequency measurements.)

Measurements from multiple GNSS satellites are simultaneously tracked by the receiver. Even if obtained simultaneously, each of these measurements will have a different troposphere delay because the associated signal took a different path through the troposphere. Estimation of these individual slant delays (T_i^m) is costly and difficult from a “degrees-of-freedom” standpoint: each satellite-receiver path has its own value, this value is correlated with the receiver/satellite clock errors (as well as station height), and both the slant delay and the receiver/satellite clock errors change every measurement epoch.

The estimation of troposphere delay for a given location and epoch is therefore simplified by combining the satellite measurements to compute zenith troposphere delay, Z , and in most cases, a pair of north and east gradients (G_N , G_E) characterizing atmospheric azimuthal asymmetry. Z can be decomposed into two components: hydrostatic (“dry”) component Z_d driven largely by air pressure, and wet component Z_w , driven by atmospheric water vapor and

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temperature. Z_d , at approximately 2 m the larger of the two, can be estimated from global atmospheric models (rather than from GNSS measurements) accurately enough for most geodetic applications. The smaller Z_w , approximately 0.1 – 0.25 m, changes rapidly and is highly localized; it therefore cannot be modeled with sufficient accuracy and must be estimated from the GNSS measurements.

A mapping function, mf , with dry, wet and gradient components mf_d , mf_w and mf_g , uses the elevation and azimuth angles e^m_i , A^m_i from which the signal arrived, to relate slant delay T^m_i to zenith values (Z_d , Z_w , G_N , G_E). (In a very simple situation, one could write $T^m_i = mf \cdot Z$, with $mf \equiv \csc(e^m_i)$). Then:

$$T^m_i = mf_d(e^m_i) \cdot Z_d + mf_w(e^m_i) \cdot Z_w + mf_g \cdot \cot(e^m_i) \cdot [G_N \cdot \cos(A^m_i) + G_E \cdot \sin(A^m_i)] \quad (2)$$

(Bar-Sever *et al.*, 1998), where the impact of azimuthal asymmetry – the A^m_i dependence – has been confined to the third right-hand-side term.

Once Z_w has been estimated from the combined satellite measurements, it can be related to precipitable water vapor PWV by a simple proportionality constant $\Pi(T_m)$:

$$PWV = \Pi(T_m) \cdot Z_w, \quad (3)$$

(Bevis *et al.*, 1992) where T_m , the weighted mean temperature of the atmosphere, can be estimated from global weather models or measurements.

This GNSS-derived PWV can then be used as input to atmospheric models.

3.2 IGS Troposphere Estimates and Working Group

The IGS Troposphere Working Group (IGS TWG) was founded in 1998. The United States Naval Observatory (USNO) assumed chairmanship of the WG as well as responsibility for producing IGS Final Troposphere Estimates (IGS FTE) in 2011.

Dr. Christine Hackman chairs the IGS TWG. Dr. Sharyl Byram oversees production of the IGS FTEs. IGS FTEs are produced within the Earth Orientation Department GPS Analysis Division, which also hosts the USNO IGS Analysis Center.

3.2.1 Production and use of IGS Final Troposphere Estimates

USNO produces IGS Final Troposphere Estimates for most of the stations of the IGS network. Each 24-hr site results file provides five-minute-spaced estimates of total troposphere zenith path delay, north, and east gradient components.

Fig. 2 shows an example of the zenith troposphere delay values obtained for six IGS stations on 30 June 2012. Fig. 3 shows the number of receivers for which USNO computed IGS FTEs 2011-4. In 2014, USNO produced IGS FTEs for 326 receivers per day, on average. IGS FTE

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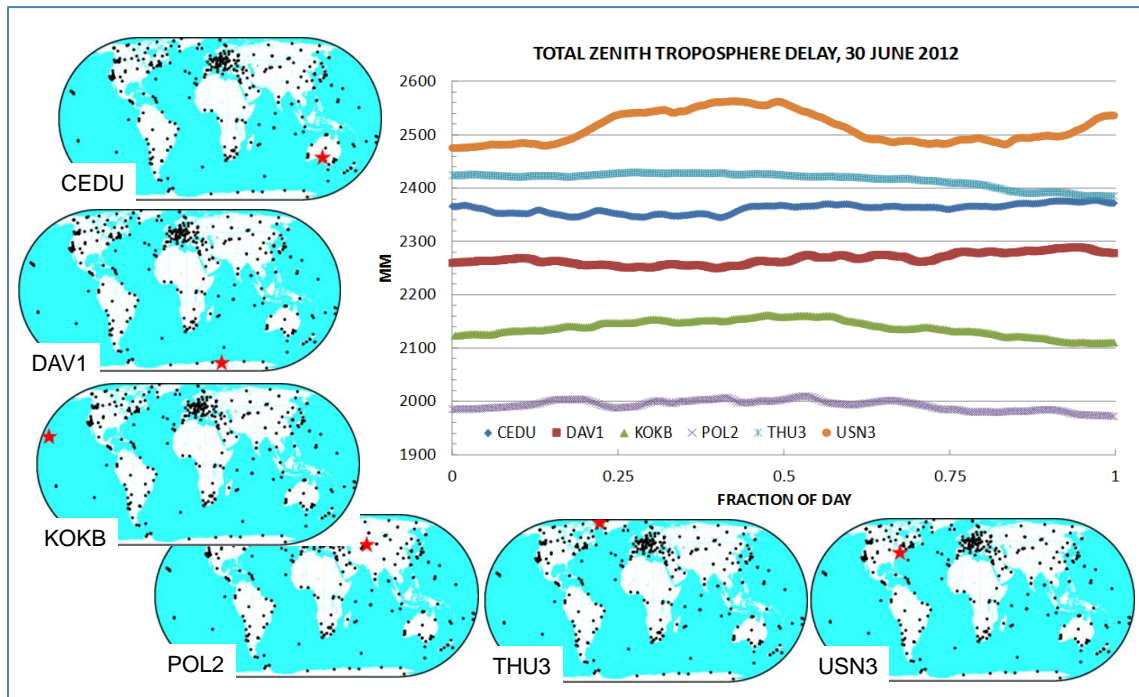


Fig 2. IGS Final Troposphere Estimates (zenith delay) for six IGS network stations, 30 June 2012. “Fraction of day” is with respect to GPS Time.

files can be downloaded from <ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd>.

IGS Final Troposphere estimates are generated via *Bernese GPS Software 5.0* (Dach *et al.*, 2007) using precise point positioning (PPP; Zumberge *et al.*, 1997) and the GMF mapping function (Boehm *et al.*, 2006) with IGS Final satellite orbits/clocks and earth orientation parameters as input. Each site-day’s results are completed approximately three weeks after measurement collection as the requisite IGS Final orbit products become available. Further processing details can be obtained from Byram and Hackman (2012). Transition to the newer *Bernese GNSS Software 5.2* is expected in 2015.

IGS FTEs are used as a benchmark for researchers testing their own troposphere-delay or PWV estimates; see, for example Teke *et al.* (2011) and Wang *et al.* (2013). Users downloaded 12.3 million IGS FTE files in 2014 (Noll, 2015).

The IGS has updated the physical models and reference frames used to compute/realize its products several times over its 20-year history. For example, in 2008, the IGS changed the system by which it represents the location of the electrical phase centers from which satellite antennae transmit and at which receiver antennae receive L1 and L2 frequency signals. Such model and reference-frame changes can introduce subtle changes in IGS estimates which can then create problems for scientists wishing to use IGS products to study multi-year phenomena.

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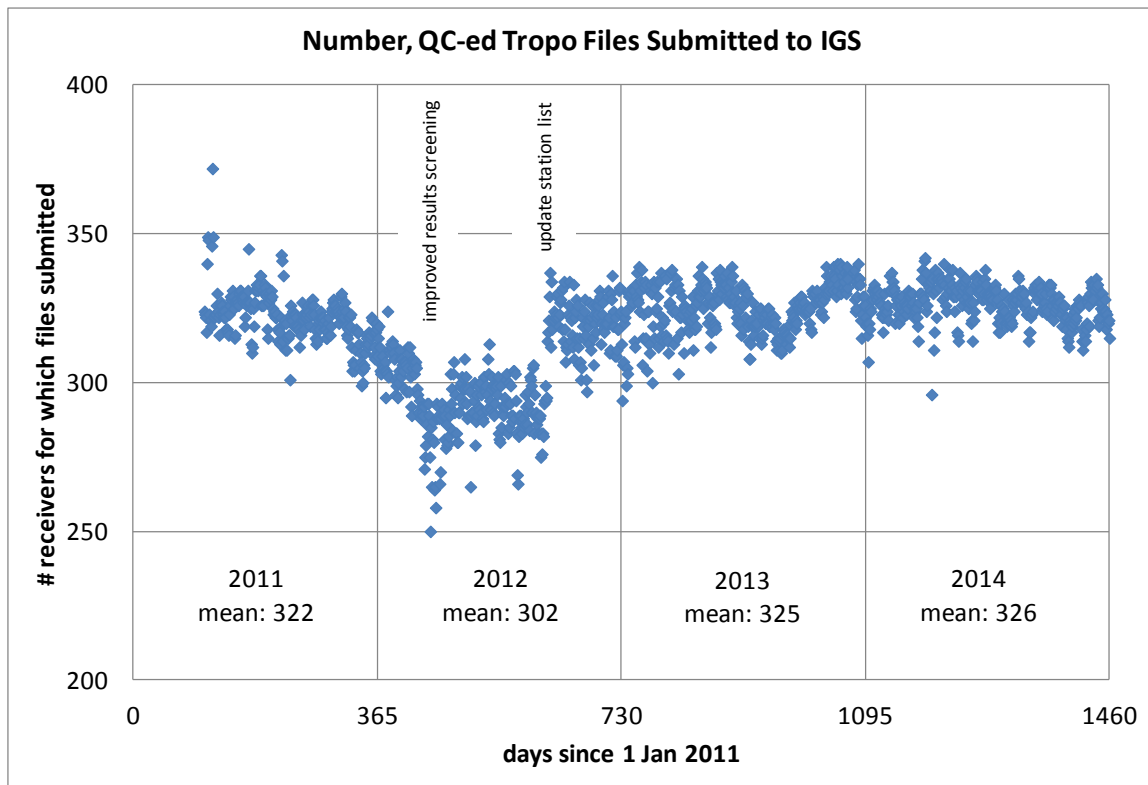


Fig 3. Number of IGS receivers for which USNO produced IGS Final Troposphere Estimates, 2011-4. (Estimates were produced by Jet Propulsion Laboratory up through mid-April 2011.)

The IGS addresses this problem by periodically re-computing all of its products – e.g., satellite orbits, earth orientation parameters, satellite and receiver clock-correction estimates, and troposphere estimates – over the entire timespan of its GNSS-measurement database. The troposphere estimates computed in the first of these reprocessing efforts, “Repro 1,” can be downloaded from <ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd/repro1>. The second of these IGS efforts, “Repro 2”, is underway. USNO plans to compute the corresponding *Repro 2* troposphere estimates once the requisite *Repro 2* satellite orbits, satellite clock and EOP estimates are complete.

The IGS estimates GNSS-related parameters, e.g., satellite orbits, satellite-clock corrections, in 24-hour batches, causing discontinuities to appear between parameter values computed at the end of one 24-hr measurement block and the beginning of the next. (The GNSS measurements themselves are recorded continuously.) IGS FTEs exhibit such “day-boundary discontinuities” of about 4-7 mm RMS (depending on location), complicating IGS FTE use in certain meteorological applications. Research is ongoing at Technische Universität München to characterize and then minimize these discontinuities. Steps forward were made in a bachelor’s thesis by Gauges (2014), who, in studying day-boundary discontinuities at 30 locations, observed that the RMS discontinuity size at a given location was ultimately linked

to the size of the zenith troposphere delay itself. A procedure to minimize the discontinuities is under development.

3.2.2 Activities and structure of the IGS Troposphere Working Group

The IGS Troposphere Working Group is currently comprised of 50+ members from around the globe. It meets twice per year: once in the fall in conjunction with the American Geophysical Union (AGU) Fall Meeting (San Francisco, CA, USA; December), and once in the spring/summer, either in conjunction with the European Geosciences Union (EGU) General Assembly (Vienna, Austria; April) or with the biennial IGS Workshop (location varies; dates typically June/July). Meetings are simulcast online so that members unable to attend in person can participate. Members can also communicate using the IGS TWG email list.

The goal of the IGS Troposphere Working Group is to improve the accuracy and usability of GNSS-derived troposphere estimates. It works toward this goal by coordinating (a) technical sessions at the IGS Analysis Workshop and (b) working-group projects.

IGS Workshop technical sessions coordinated by the IGS TWG

The IGS Workshop takes place in even-numbered years. The IGS TWG sponsors three sessions per workshop: an oral plenary session in which three speakers present big-picture projects related to estimation or application of GNSS-based troposphere estimates, a poster session in which maximum participation is sought in order to foster technical exchange, and an IGS TWG splinter meeting.

At the 2014 IGS Workshop, for example, the plenary session featured the following presentations:

- On the COST Action GNSS4SWEC⁶ project, which uses GNSS-derived troposphere estimates for severe-weather forecasting: *Advanced Global Navigation Satellite Systems Tropospheric Products for Monitoring Severe Weather Events and Climate (GNSS4SWEC)*, Guerova *et al.* (2014)
- On the World Meteorological Observation GRUAN⁷ project, which (among other things) uses GNSS-derived troposphere values to study climate change: *Global Precipitable Water Trend and its Diurnal Asymmetry Based on GPS, Radiosonde and Microwave Satellite Measurements*, Wang *et al.* (2014)
- On the (IGS-coordinated) development of a database/website automating the comparison of troposphere estimates derived from independent techniques (e.g.,

⁶ European Cooperation in Science and Technology (COST) Advanced Global Navigation Satellite Systems Tropospheric Products for Monitoring Severe Weather Events and Climate: http://www.cost.eu/COST_Actions/essem/Actions/ES1206

⁷ GCOS (Global Climate Observing System) Reference Upper Air Network: <http://www.gruan.org>

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GNSS, VLBI, radiosondes, and weather models): *Development Towards Inter-Technique Troposphere Parameter Comparisons and Their Exploitation*, Douša et al. (2014).

The poster session meanwhile featured 18 contributions – 10 or so is more typical for this workshop – and the splinter meeting featured presentations on current WG projects, plus discussion of past/future direction.

The 2014 IGS Workshop troposphere-related posters can be viewed at <http://igs.org/workshop/posters>; scroll down to "PS05: Estimation and Application of GNSS-Based Troposphere Delay." The plenary presentations can be viewed at <http://igs.org/workshop/plenary>; scroll to "PY09: GNSS-Derived Troposphere Delays."

IGS Troposphere Working Group Projects

As mentioned previously, the goal of the IGS Troposphere Working group is to improve the accuracy and usability of GNSS-derived troposphere estimates. One way to assess the accuracy of GNSS-derived troposphere estimates is to compare these estimates to those obtained for the same time/location using independent measurement techniques, e.g., VLBI, DORIS, radiosondes, or from numerical weather models.

The IGS TWG has therefore since 2012 been coordinating the creation of a database/website to automatically and continuously perform such comparisons.

Dr. Jan Dousa, Geodetic Observatory Pecny (GOP; Czech Republic) has been spearheading the development of the database (Dousa and Gyori, 2013; Gyori and Dousa, 2015), with contributions from other scientists at GOP and at GeoForschungsZentrum (GFZ; Germany). This database is nearly complete: it already can (and does) download and compare troposphere values from a wide variety of sources, compensating for horizontal and vertical separation of measurement locations. Development of the website by which users can view/access the values is underway as well, with USNO augmenting initial GOP efforts. USNO has also begun contributing to database development, as well as the sourcing of auxiliary databases/servers.

In 2014, a grant proposal, *Automated Intra- and Inter-technique Troposphere Estimate Comparisons*, made to the Kontakt II Czech-US research partnership by Dr. Dousa with supporting documents authored by WG chair C Hackman, was funded.

This funding supports, in addition to other items, travel to the US for joint US-Czech work on the database/website. Dr. Dousa thus worked with USNO scientists on further website/database development during a Kontakt II funded USNO site visit 2-14 Nov 2014. Such short, focused co-work visits enable large steps forward, e.g., the installation of a second database at USNO, familiarization of USNO staff with database features, and USNO-GOP joint work on designing interface structure.

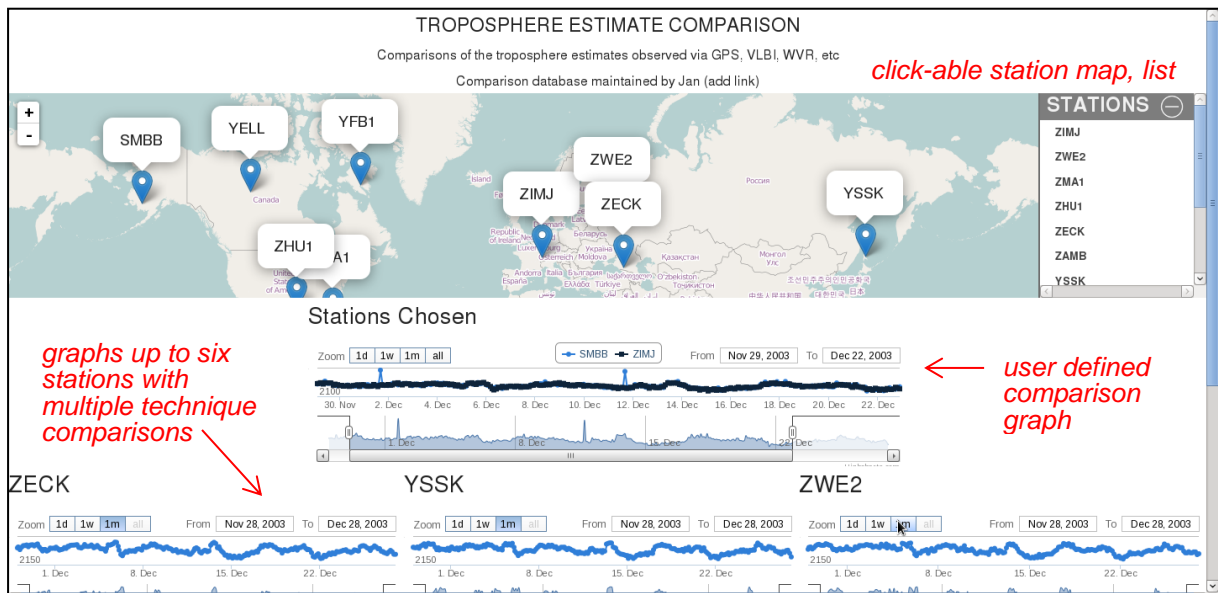
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Fig. 4 illustrates how the user interface to the website/database might appear. Completion of



GOP-TropDB - TropModel online service

The formular serves for calculation of site-specific tropospheric parameters, conversion factors or other auxiliary meteorological parameters for scientific applications.

Currently, the following limitations for the service are applied:

- Scope: 20 sites
- Period: 366 days (1 year)
- Interval: 1990 - present (delayed by 3-4 months)
- Sampling: 1s - 21600s (6h)

Notes: This is an **experimental** service! Any feedback is appreciated at jan.dousa@pecny.cz. We acknowledge the availability of the ERA-Interim dataset provided by [ECMWF](#).

E-mail:

Parameters: ZTD ZHD
 ZWD P
 T Tm

Period: from: to: YYYY-MM-DD

Sampling rate: integer [seconds] ... for parameter sampling

Model:

Coordinates: site_id X Y Z [remark]

Job notice: request comment

Fig 4. Early drafts, two parts of user (website) interface to troposphere-comparison database. Top: user can choose locations and sources for which s/he would like to compare values. Bottom: user can request measurement files.

this project is expected in 2016. This system has received interest from climatologists/meteorologists, e.g., those associated with the GRUAN and COST Action ES1206 GNSS4SWEC projects, as it will simplify quality-comparison and perhaps acquisition of data used as input to their studies.

The IGS Troposphere Working group is also supporting a project to standardize the so-called "tropo_sinex" format in which troposphere delay values are disseminated and exchanged. At issue is the fact that different geodetic communities (e.g., VLBI, GNSS) have modified the format in slightly different ways since the format's introduction in 1997. To take one simple and relatively benign example, text strings *STDEV* and *STDDEV* are used to denote standard deviation in the GNSS and VLBI communities respectively. Such file-format inconsistencies hamper inter-technique comparisons.

This project, spearheaded by IGS Troposphere WG members R Pacione and J Dousa, is being conducted within the COST Action GNSS4SWEC Working Group 3. This COST WG consists of representatives from a variety of IAG⁸ organizations and other communities; its work is further supported by the EUREF Technical Working Group⁹ as well as E-GVAP¹⁰ expert teams. The WG is currently defining in detail a format able to accommodate both troposphere values and the metadata (e.g., antenna height, local pressure values) required for further analysis/interpretation of the troposphere estimates.

4. HOW TO OBTAIN FURTHER INFORMATION

4.1 The IGS

To learn more about the IGS, visit: <http://igs.org>

4.2 IGS Troposphere Final Estimates

IGS Final Troposphere Estimates can be downloaded from:
<ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/zpd>

For technical questions regarding them, please contact Dr. Sharyl Byram at sharyl.byram@usno.navy.mil or Dr. Christine Hackman, christine.hackman@usno.navy.mil.

4.3 IGS Troposphere Working Group

To learn more about the IGS Troposphere Working Group, you may...

-contact Dr. Christine Hackman at christine.hackman@usno.navy.mil,

⁸ International Association of Geodesy

⁹ http://www.euref.eu/euref_twg.html

¹⁰ EUMETNET EIG GNSS Water Vapour Programme; <http://egvap.dmi.dk/>

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-visit its website (under development): <http://igs.org/projects-working-groups/twg>, and/or

-subscribe to its email list: <http://igscb.jpl.nasa.gov/mailman/listinfo/igs-twg>

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BIOGRAPHICAL NOTES

Christine Hackman is head of the Earth Orientation Department at the United States Naval Observatory in Washington, DC USA. The department, which provides earth-orientation-parameter estimates/predictions for defense and civilian applications, also hosts the IERS Service Rapid Service/Prediction Centre. Prior to this, she was chief of the USNO Earth Orientation Department GPS Analysis Division which serves as an analysis center for the IGS, computes 16 sets per day of GPS/GLONASS-based satellite orbits, clock-synchronization and earth-orientation parameters, and produces IGS Final Troposphere Estimates. Dr. Hackman chairs the IGS Troposphere Working Group, directs the IERS Rapid Service/Prediction Centre, and is a member of the IGS and IERS governing boards. Her science interests include high-precision satellite-based geodesy, timing, geophysics, atmospheric sciences, and relativity. She holds a PhD in physics from the University of Colorado.

Guergana Guerova is an associate professor at the Sofia University, Sofia, Bulgaria. She received a MSc degree in meteorology from Sofia University and PhD in applied physics from University of Bern. Her research interest is in monitoring short and long-term variation of GNSS derived water vapour in particular for application in monitoring fog, intense precipitation, hail storms and heat waves. She is Marie Curie IRG Fellow (2011-2014) and vice chair of COST Action ES1206 GNSS4SWEC (2013-2017).

Sharyl Byram is an Astronomer in the GPS Analysis Division of the Earth Orientation Department at the U.S. Naval Observatory (USNO) in Washington, DC USA. She is currently the manager of the Troposphere Estimation project at the USNO and coordinates the

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production of the International GNSS Service (IGS) final troposphere products. Additionally, she is involved with the maintenance and improvement of the USNO's contribution to IGS rapid and ultra-rapid GPS products. She holds a BS and a MS in Aerospace Engineering from the University of Cincinnati and a PhD in Aerospace Engineering from the University of Michigan.

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