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The Tropospheric Products of the International VLBI Service for Geodesy and Astrometry

Robert Heinkelmann, Christian Schwatke

Deutsches Geodätisches Forschungsinstitut (DGFI)

Contact author: Robert Heinkelmann, e-mail: `heinkelmann@dgfi.badw.de`

Abstract

The IVS runs two tropospheric products: The IVS tropospheric parameter rapid combination monitors the zenith wet delay (ZWD) and zenith total delay (ZTD) of the rapid turnaround sessions R1 and R4. Goal of the combination is the identification and the exclusion of outliers by comparison and the assessment of the precision of current VLBI solutions in terms of tropospheric parameters. The rapid combination is done on a weekly basis four weeks after the observation files are released on IVS Data Centers. Since tropospheric and geodetic parameters, such as vertical station components, can significantly correlate, the consistency of the ZTD can be a measure of the consistency of the corresponding TRF as well. The ZWD mainly rely on accurate atmospheric pressure data. Thus, besides estimation techniques, modeling and analyst's noise, ZWD reflects differences in the atmospheric pressure data applied to the VLBI analysis. The second product, called tropospheric parameter long-term combination, aims for an accurate determination of climatological signals, such as trends of the atmospheric water vapor observed by VLBI. Therefore, the long-term homogeneity of atmospheric pressure data plays a crucial role for this product. The paper reviews the methods applied and results achieved so far and describes the new maintenance through DGFI.

1. Tropospheric Model of Radio Techniques

The general station dependent tropospheric model for the delay of radio waves propagating through the neutral atmosphere

$$d_{trop} = mf_h(\epsilon) \cdot ZHD + mf_w(\epsilon) \cdot ZWD + mf_g(\epsilon) \cdot [G_N \cos(\alpha) + G_E \sin(\alpha)] \tag{1}$$

accounts for non-dispersive delaying and bending effects through constituents of the Earth's atmosphere. The variables α and ϵ denote the azimuth and elevation angles of a specific observation at a VLBI antenna. The gradient mapping function mf_g can be taken from [9]

$$mf_g(\epsilon) = mf_h(\epsilon) \cdot \cot(\epsilon) \qquad \text{or} \qquad mf_g(\epsilon) = mf_w(\epsilon) \cdot \cot(\epsilon) \tag{2}$$

and the hydrostatic and wet mapping functions $mf_{h,w}$ are currently provided by [1][1]. For part of the atmosphere, the assumption of hydrostatic equilibrium approximately holds. The hydrostatic delay at zenith ZHD (mm) can be expressed analytically [3]

$$ZHD = \frac{2.2768 \cdot p}{1 - 0.00266 \cos(2\varphi) - 0.000280h} \tag{3}$$

depending on the surface air pressure p and the position (latitutde φ and orthometric height h) of the antenna reference point.

[1]http://ggosatm.hg.tuwien.ac.at/DELAY/

Water vapor shows rather different dipole characteristics and insufficient mixing with the other (dry) atmospheric gases. The wet delay is considered unknown and is estimated along with the other parameters by classical parameter estimation or filter techniques. The partial derivative of the zenith wet delay reads:

$$\frac{\partial d_{trop}}{\partial ZWD} = mf_w\left(\epsilon\right) \tag{4}$$

It is usually represented by constrained linear spline functions [8] or by a random walk stochastic process [7], respectively, in case of filter techniques.
The total zenith delay is the sum of the apriori (here: hydrostatic) and the estimated (here: wet) zenith delay

$$ZTD = ZHD + ZWD \tag{5}$$

2. The Role of Surface Air Pressure for Troposphere Modeling

While φ and h (eq. 3) can be approximated by their respective apriori values, ZHD depends almost entirely on the in-situ surface air pressure, which is usually recorded by meteorological sensors and provided for each observation, e.g., in the NGS file. In some cases, however, the meteorological records are missing, which is indicated by an invalid entry such as -999.99 hPa, or they are erroneous. Unlike temperature measurements, pressure measurements are most unlikely to be affected by artificial trends, such as urban growth or vegetation. Therefore, known inhomogeneities of the measured surface air pressure are mainly breaks of the running mean value due to calibration, replacement, or relocation of the sensor. The usage of inaccurate air pressure in VLBI analysis may have several effects on the estimated parameters:

1. ZHD will be wrong by about 2.3 mm per 1 hPa (eq. 3).
2. Since the hydrostatic and wet mapping functions are similar, the ZWD estimate absorbs most of the inaccurate ZHD and will be biased by about -2.1 mm per 1 hPa.
3. The rest, about -0.2 mm per 1 hPa, propagates into other parameters due to correlations, mainly into the height component of the station.

Following 1. and 2., ZTD (eq. 5) is also affected, by about 0.2 mm per 1 hPa. The estimate (ZWD) does not fully compensate for the wrong apriori (ZHD), because the hydrostatic and wet mapping functions differ. In the past there were approaches modeling the tropospheric delay with a single total mapping function, which would serve better for this particular purpose. Nevertheless, the usage of total mapping functions is significantly less accurate than the models separately accounting for hydrostatic and wet atmospheric constituents. Figures 1 and 2 display examples of ZWD and ZTD at two IVS sites. It is clearly visible that the ZWD differences between the IVS Analysis Centers become much smaller in the case of ZTD at Westford. At Zelenchukskaya, however, the ZWD differences almost totally remain at ZTD. Hence, much larger effects on the station coordinates are to be expected at this site.

For geodesy, 3. must be alarming since the primary geodetic parameters, the station coordinates, are affected. If the surface air pressure used in VLBI analysis deviates from its true value by 5 hPa, the effect on station coordinates will reach the 1-millimeter-level at most of the sites. Therefore, it is not sufficient to replace missing pressure values by a constant value or any simple atmospheric model. An appropriate way to substitute missing pressure values has been introduced by the authors before, cf. [6]. Since numerical weather models (NWM) such as NCEP or ECMWF

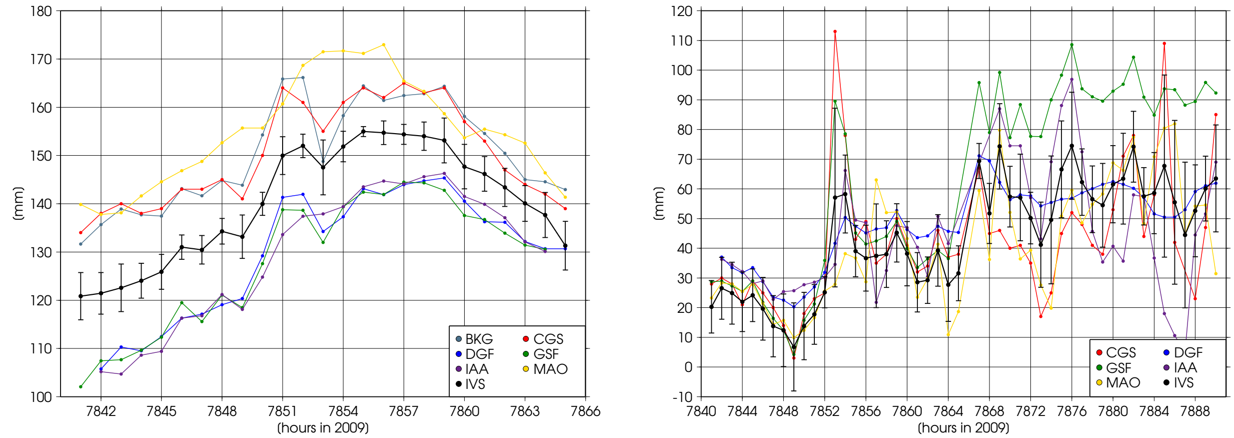

Figure 1. ZWD (mm): Westford, USA (left) and Zelenchukskaya, Russia (right). IVS line has error bars.

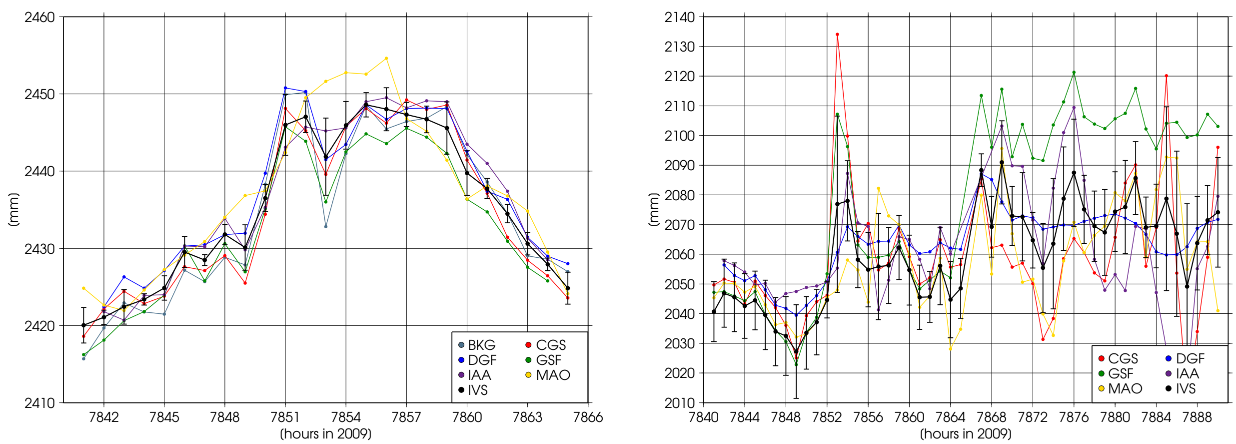

Figure 2. ZTD (mm): Westford, USA (left) and Zelenchukskaya, Russia (right). IVS line has error bars.

show inherent biases, too, it is questionable, whether pressure values interpolated from such models can provide the absolute accuracy target in general. If no particular accuracy is needed or no NWM is available, substitutes can be calculated from GPT [2].

3. Tropospheric Parameter Long-term Combination

- `http://www.dgfi.badw.de/index.php?id=196`
- Relevant publication: [5]
- Considered breaks (> 1 hPa) of the running mean value (Table 1) and outliers of pressure records (Table 2). A positive break in Table 1 means that the pressure values before the specified epoch are larger than the pressure values after the epoch until present day.

Table 1. Pressure breaks > 1 hPa at 8 frequently used observing sites

IVS site	epoch	break (hPa)
Algonquin Park	2003 Jan 17	-2.8
Gilmore Creek	1993 Jun 26	+1.4
Hartebeesthoek	1993 May 04	+15.5
Hobart (26)	1991 Dec 11	+17.4
Kokee Park	2003 Jun 17	+1.6
Ny-Ålesund	1998 Jul 01	+2.8
Shanghai (25)	1995 Apr 25	-7.6
Wettzell	1986 Aug 07	+1.9

Table 2. Possible outliers

solution	site	start epoch	end epoch
aus	all	2000.2	2001.1
	Fortaleza	2003.75	open
	Gilmore Creek	1984.0	1989.5
	Wettzell	1984.0	1989.0
iaa2007a	Westford	1999.4	2000.0
mao2005a	Fortaleza	2003.75	open
	Westford	2000.0	2001.0
	Wettzell	1984.0	1989.0
gsf2005a	Kokee Park	OHIG32, R&D-8	
	Wettzell	T2030, T2031, T2032, T2033	

4. Tropospheric Parameter Rapid Combination

- `http://www.dgfi.badw.de/index.php?id=194`
- Relevant publication: [4]
- Missing pressure records, outliers, and breaks (Tables 3–5) have to be considered.

Table 3. Missing pressure records (%) since 2002

site	%	site	%	site	%
Algonquin Park	0.6	Kokee Park	0.6	Svetloe	1.4
Badary	2.3	Matera	0.5	TIGO Concepción	0.7
Fortaleza	87.4	Medicina	2.6	Tsukuba (32)	0
Gilmore Creek	0	Ny-Ålesund	0.4	Westford	30.1
Hartebeesthoek	0.5	Onsala (60)	0	Wettzell	0
Hobart (26)	0.8	Shanghai (25)	1.5	Zelenchukskaya	38.9

Table 4. Possible outliers of IVS-R1 and R4

site	**outlier**
Fortaleza	$p = 0$hPa!
Hobart (26)	IVS-R1054
Matera	IVS-R4368
Westford	$p < 970$hPa, $p > 1030$hPa
Wettzell	$p < 900$hPa, $p > 970$hPa

Table 5. Pressure breaks w.r.t. current mean pressure since 2002

site	**epoch**	**break**
Algonquin Park	2003.08	1.6
	2004.5	4.0
	2004.9	2.1
	2006.16	5.1
Hobart (26)	2005.965	3.7
Svetloe	2004.0	-2.2
	2008.96	3.9
Tsukuba (32)	2005.0	0.6
Westford	2005.0	2.1
Zelenchukskaya	2007.5	11.4

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