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Determination of Tropospheric Parameters by VLBI as a Contribution to Climatological Studies

Johannes Böhm [1], Harald Schuh [2], Volker Tesmer [3], Harald Schmitz-Huebsch [4]

[1] *Institute of Geodesy and Geophysics, Gußhausstraße 27-29, A-1040 Wien*
[2] *Institute of Geodesy and Geophysics, Gußhausstraße 27-29, A-1040 Wien*
[3] *Deutsches Geodaetisches Forschungsinstitut (DGFI), Marstallplatz 8, D-80539 Munich, Germany*
[4] *Deutsches Geodaetisches Forschungsinstitut (DGFI), Marstallplatz 8, D-80539 Munich, Germany*

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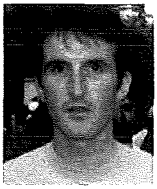
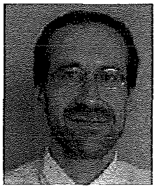
Johannes Boehm and Harald Schuh, Wien, Volker Tesmer and Harald Schmitz-Huebsch, München

Abstract

As consistent VLBI observations at various stations over the whole globe have been carried out since 1984, it is possible to determine long time series not only of baseline vectors and Earth orientation parameters, but also of tropospheric parameters. Time series of wet zenith delays provide information about trends and periodic variations of the amount of water vapour in the troposphere. At Wettzell (Germany) there is a trend of ~+0.7 mm/year in the wet zenith delay which corresponds to ~+0.1 mm/year precipitable water vapour. Additionally, periodic variations in the time series are revealed by Fourier and wavelet analyses, and information about the precipitable water provided by the ECMWF (European Centre for Medium-Range Weather Forecasts) is used to evaluate the VLBI estimates.

Kurzfassung

Erst in den letzten Jahren wurde erkannt, dass die troposphärischen Laufzeitverzögerungen, denen die Signale der VLBI (Very Long Baseline Interferometry) und GPS unterworfen sind, nicht nur Störgrößen bei der Bestimmung geodätischer Parameter (Stationskoordinaten, Erdorientierungsparameter, ..) sind, sondern auch wertvolle Informationen für Meteorologie und Klimatologie liefern können. Zum Beispiel lässt sich aus dem feuchten Anteil der Laufzeitverzögerung in Zenitrichtung der Wasserdampfgehalt über der Station mit hoher Genauigkeit bestimmen. Im Gegensatz zu GPS ist eine Auswertung der VLBI-Experimente in genäherter Echtzeit noch nicht möglich; andererseits aber überdecken die zur Verfügung stehenden konsistenten VLBI-Reihen troposphärischer Parameter einen erheblich längeren Zeitraum. Für manche Stationen existieren Zeitserien seit Beginn der 80er Jahre. Daraus können langzeitliche Trends bestimmt werden und somit auf eine Zu- oder Abnahme des Feuchtegehalts der Troposphäre geschlossen werden. An der Station Wettzell (Bayerischer Wald, Deutschland) wurde der Trend für die letzten 20 Jahre zu ~+0.7 mm/Jahr bestimmt, was einer Zunahme des ausfällbaren Wassers von ~+0.1 mm/Jahr entspricht. Dies stimmt wiederum sehr gut mit der am Boden gemessenen durchschnittlichen Temperaturzunahme von +0.13 °C/Jahr an der Station Wettzell überein, da eine höhere Temperatur der Troposphäre auch eine erhöhte Speicherung von Wasserdampf erlaubt. Zusätzlich werden periodische Variationen in den Zeitserien mit Fourier- und Waveletanalysen ermittelt. Dabei zeigen sich neben den zu erwartenden saisonalen Schwankungen auch andere Perioden, die je nach Station unterschiedlich stark ausgeprägt sind. Schließlich werden die VLBI-Ergebnisse der Feuchte mit Daten des ECMWF (European Centre for Medium-Range Weather Forecasts) verglichen, wobei eine sehr gute Übereinstimmung zu erkennen ist.

1. Introduction

The total path delay for an observation at the elevation angle (consists of the hydrostatic and the wet part. Each of these parts is the product of the delay in zenith direction and the corresponding mapping function. Assuming azimuthal symmetry at a VLBI station, the total path delay in the neutral atmosphere (L(() can therefore be modelled as:

$$\Delta L(\varepsilon) = HZD \cdot mf_h(\varepsilon) + WZD \cdot mf_w(\varepsilon) \quad (1)$$

HZD hydrostatic zenith delay
WZD wet zenith delay
$mf_h(\varepsilon)$ hydrostatic mapping function
$mf_w(\varepsilon)$ wet mapping function

In standard VLBI analyses, the wet zenith delay (WZD) is estimated, while the other three parameters (HZD, mfh, mfw) are assumed to be known. Since consistent VLBI observations have been carried out for about 20 years, long time series of the wet zenith delays at various stations can be determined and used for climatological studies. Table 1 gives an overview of the VLBI stations that have been used for these investigations. On the average, 24 h geodetic VLBI sessions have been performed every 4th to 5th day, which yields a temporal coverage between 19% and 25%.

Station	latitude	temporal coverage	1st observation in the year
Wettzell, Germany	49°	25%	1984
Fortaleza, Brazil	−4°	20%	1993
Westford, Mass., U.S.A.	43°	19%	1984
Kokee Park, Hawaii, U.S.A.	22°	24%	1993
Gilcreek, Alaska, U.S.A.	65°	21%	1984

Table 1: Overview of selected VLBI stations, their latitudes, temporal coverage by VLBI sessions and the year of the first observation that was included in the analyses.

In VLBI analysis, wet zenith delays are estimated in the least-squares fit for each station of the observing session with a temporal resolution of 1 or 2 hours. The accuracy level of the absolute values is at about ± 5 mm [1]. In contrast to GPS, meteorological parameters are recorded at all VLBI stations, which is very valuable if we want to separate the hydrostatic and wet delays.

The contribution of GPS-derived wet zenith delays to climatology derived from nearly continuous GPS observations since 1994 has been reported recently [3], [2]. Since the spatial coverage of these observations is much denser than that of VLBI, it allows also regional studies. However, GPS-derived wet zenith delays can suffer from antenna phase center variations, multipath effects and the replacement of antennas or radomes. Thus, a comparison with wet zenith delays determined by VLBI at selected stations seems adviseable, in particular because a better long-term stability of the latter can be assumed due to the higher stability of the celestial and terrestrial reference frames used in VLBI.

2. Accuracy of the terrestrial reference frame

In order to detect significant trends in the wet zenith delays, the terrestrial reference frame has to be sufficiently accurate. This requirement is above all due to the high correlation of about −0.4 between station heights and zenith path delays, i.e. if a station height is wrong by +10 mm, the zenith path delay at this site will be shifted by about −4 mm (see Figure 1). If one assumes that the station coordinates of Fortaleza are error-free, that both stations are fixed in the analysis and that the observation is taken in zenith direction, an error of the station height coordinate of Wettzell (vertical arrow) will be fully transferred (with opposite sign) into an error of its wet zenith delay. As in typical VLBI sessions the observations are taken at elevations down to ~5°, the correlation decreases from −1 to about −0.4.

As this paper focuses on linear trends and periodic variations of the wet zenith delays rather than on absolute values, the station velocities and their standard deviations are of primary importance in this context. Two different terrestrial reference frames were applied to check the impact of their differences on the trends observed in wet zenith delays. In addition to the ITRF2000, which is a combined solution of VLBI, GPS, SLR, and DORIS measurements, a terrestrial reference frame purely determined by VLBI (DGFI02R02) was used for the analyses of the VLBI sessions. While the imprecision of the DGFI02R02 velocities is about ± 0.1 mm/year and that of the ITRF2000 is about ± 0.5 mm/year, the differences in station height velocities between both realizations do not exceed 0.8 mm/year for the subset of stations treated here (Table 2). Thus, ± 0.8 mm/year can be considered as a rough estimate of the inaccuracy of the terrestrial reference frame.

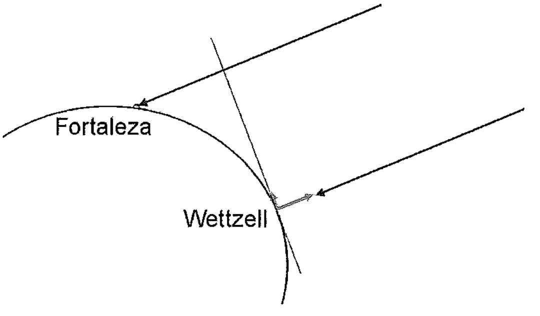


Figure 1: Geometry of a VLBI observation. The arrows at Wettzell mark horizontal and vertical errors in the station coordinates (see text).

Gilcreek	Kokee Park	Westford	Fortaleza	Wettzell
0.5	−0.5	0.8	0.8	0.1

Table 2: Differences in station height velocities between ITRF2000 and DGFI02R02 in mm/year (ITRF2000 minus DGFI02R02).

The maximum deviation of 0.8 mm/year in station height velocity corresponds to about −0.3 mm/year in the wet zenith delay. Thus, if the linear trend in WZD exceeds ~0.3 mm/year, it can be assumed as significant as far as the accuracy of the reference frame is concerned. To check this statement, different analysis strategies were compared: Fixing the coordinates to ITRF2000 and DGFI02R02 and calculating free network solutions with respect to both terrestrial reference frames yields similar trends for the wet zenith delays which will be presented in the following section.

3. Analysis and results

For this investigation, all 24 h geodetic VLBI sessions were analyzed that have been carried out since 1984. The VLBI software package OCCAM V 5.1 (Titov et al., 2001, [4]) was applied using the Gauss-Markov model for the least-squares adjustment. The wet zenith delays were estimated as 1 h piecewise linear functions, the elevation angle cutoff was set to 8°, and the ITRF2000 was fixed.

3.1. Linear long-term trends in wet zenith delays

Six-hour values of the wet zenith delays were extracted by interpolating between the two closest hourly estimates (Figure 2a) to allow comparison with meteorological data from numerical weather models (Figure 4a,b). In these data, e.g. at Wettzell (Germany) a linear trend was estimated to 0.83 mm/year and a big seasonal variation can be seen ranging from 0 mm (on some winter days) to 200 mm (on some summer days).Then mean seasonal values were determined. On the basis of these seasonal values, the overall rate of the wet zenith delays was estimated to +0.7 mm/year at Wettzell (Figure 2b). It is slightly different from the trend of the original time series, due to the different averaging processes within the computation of the seasonal values. The trend at Gilcreek (Alaska) for the time period 1989–2001 was determined to +0.3 mm/year (Figure 2d). Following the conclusion of section 2, the trend at Wettzell is significant, i.e. above the possible influence of the chosen reference frame. Multiplication of the observed rate by the length of the time series yields a change of 12.6 mm in 18 years. For the other VLBI stations the determination of reliable linear trends was not possible because either the time series were too short (Fortaleza, Kokee Park) or the seasonal wet zenith delays were too noisy (Westford). Figure 2c shows the averaged winter

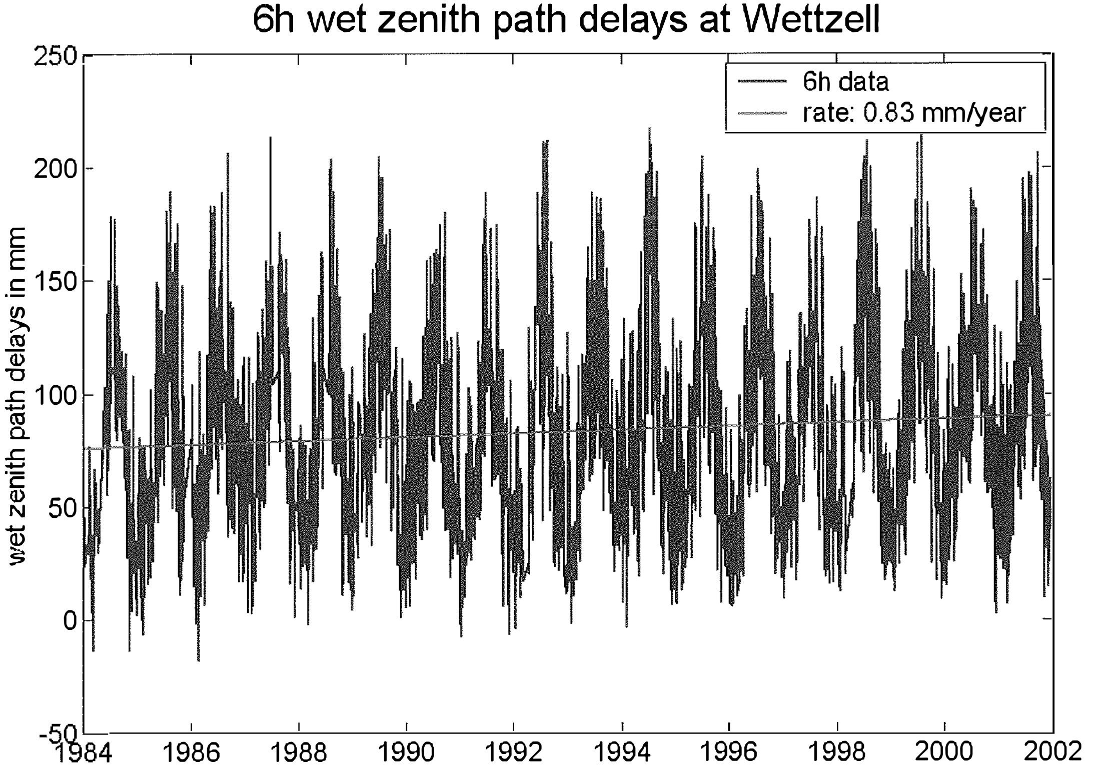


Figure 2a: 6 h wet zenith delays at Wettzell since 1984.

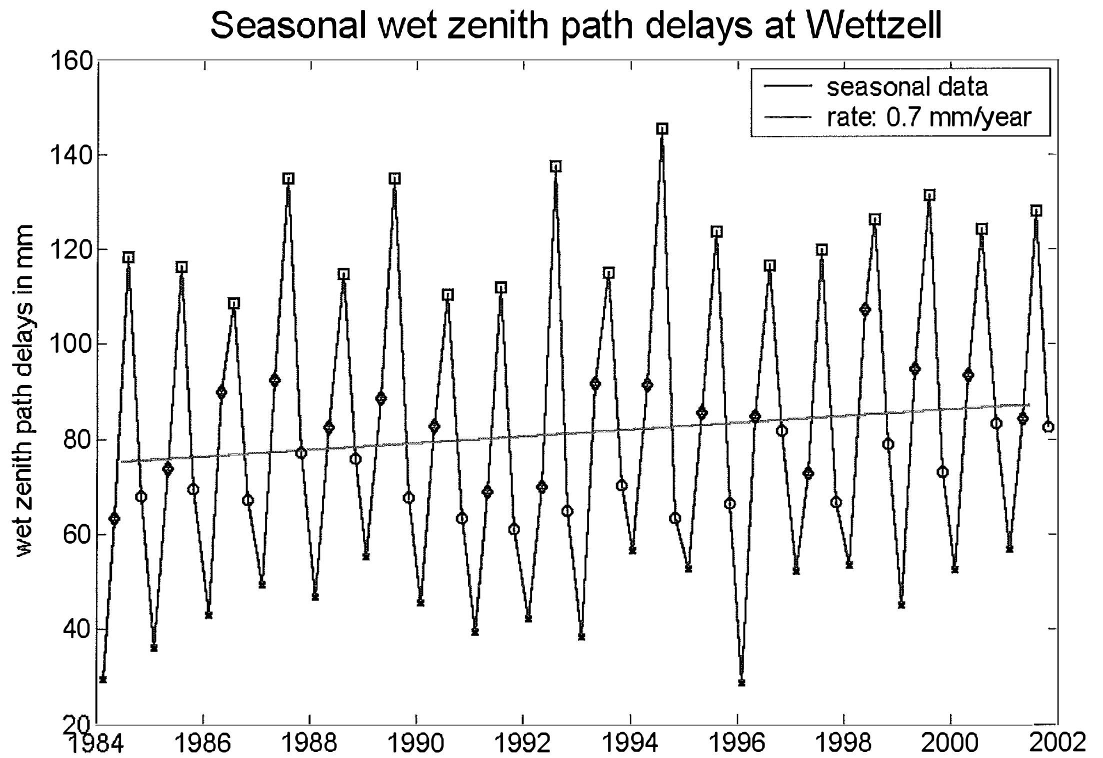


Figure 2b: Mean seasonal values of the wet zenith delays at Wettzell. The linear trend is estimated to 0.7 mm/year. Different markers are used for the seasons (◊ spring, □ summer, ○ autumn, × winter).

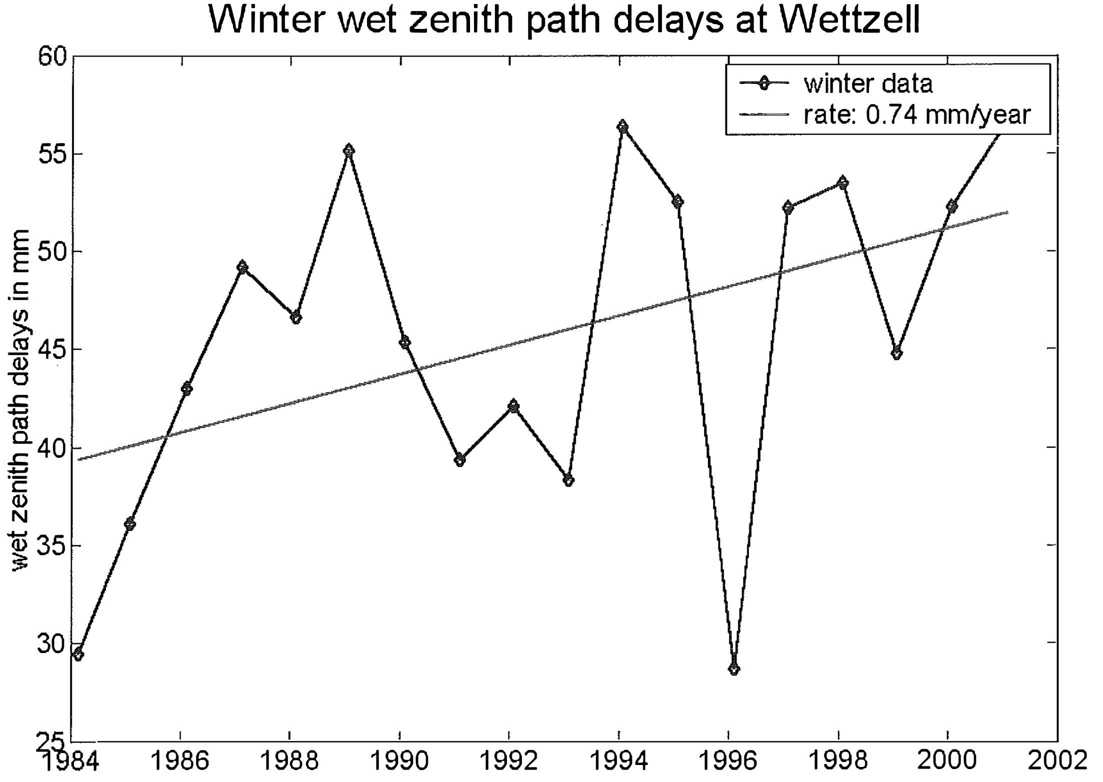


Figure 2c: Wet zenith delays at Wettzell in winter. In 1983/84 and 1995/96 the winters were extraordinarily dry (= cold).

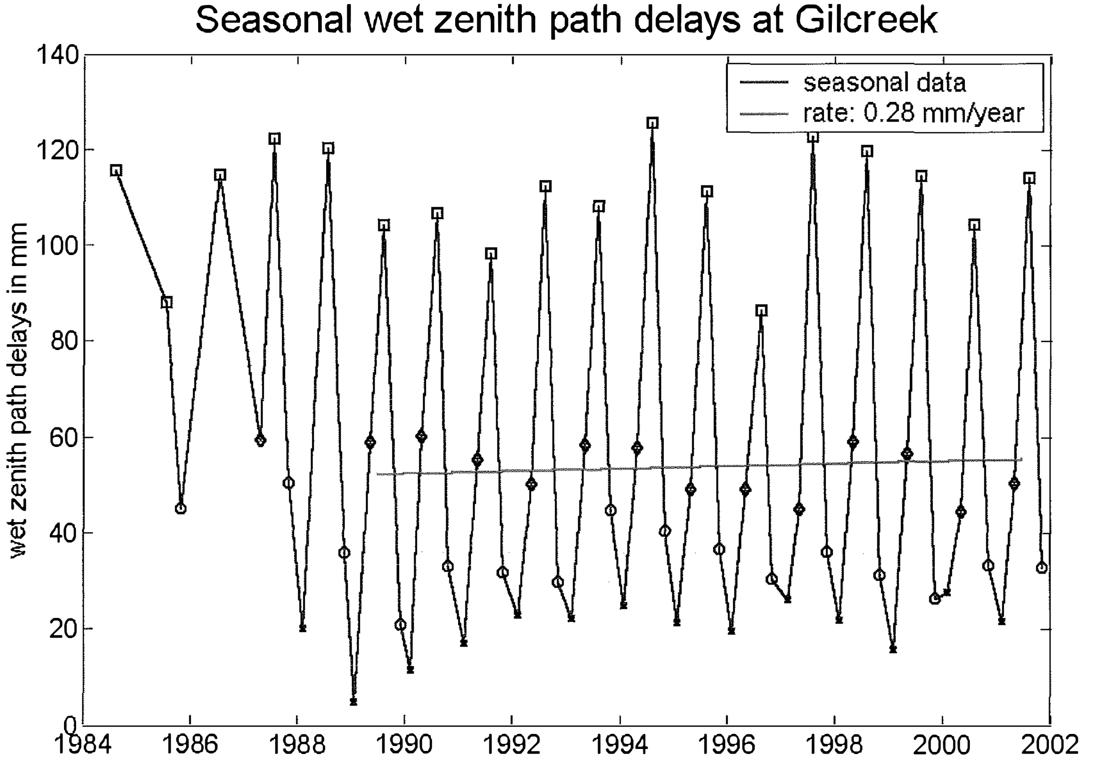


Figure 2d: Mean seasonal values of the wet zenith delays at Gilcreek. The linear trend is estimated to 0.3 mm/year. Different markers are used for the seasons (◊ spring, □ summer, ○ autumn, × winter).

WZD values at Wettzell with a linear trend of 0.74 mm/year. The lowest average WZD were obtained for winter 1983/84 and 1995/96. Meteorological records at Wettzell station confirm that these winters were extraordinarily cold and dry.

3.2. Climatological interpretation of trends in the wet zenith delays

Although wet zenith delays cannot be directly derived from meteorological data recorded at a site, there are equations that yield approximate values, e.g. by Moran et al. (2001, [6]):

$$WZD \approx \frac{e}{T^2} \text{ [m]}, \quad (2)$$

where e is the water vapour pressure in hPa and T is the temperature in K. The VLBI databases comprise information about the temperatures and the relative humidities recorded close to each radiotelescope. At Wettzell, since 1984 the relative humidity has been rather constant at about 80% whereas the temperature has increased by about 0.13 K/year. The relative humidity f is defined by

$$f = \frac{e}{E(T)}. \quad (3)$$

As the saturated water vapour pressure E(T) is increasing with rising temperature, the water vapour pressure e is increasing with rising temperature, too, if f is kept constant. Although (2) implies that the wet zenith delays are decreasing with increasing temperature, the influence of the increase in e (see (3)) is dominating over this effect. Using a mean temperature of 15 °C and a mean relative humidity of 80%, (3) and (2), applied for an increase in the temperature of 0.13 K per year, yield an increase in the wet zenith delay of 0.9 mm/year, what is close to the results from VLBI (0.7 mm/year to 0.8 mm/year).

t in °C	e in hPa (see (3))	T^2 in K^2	WZD in mm (see (2))
15.00	13.635	83030	124.8
15.13	13.750	83105	125.7

Table 3.:Change in the WZD after one year, when the temperature is rising by 0.13 K and the relative humidity is constant at 80 %.

3.3. Periodic variations in the wet zenith delays

Classical Fourier analyses and wavelet transformations of the six-hour time series were performed to find periodic variations of the wet zenith delays. The Fourier spectra show wide peaks at the annual periods for tropical stations (Fortaleza, Kokee Park) (Figure 3b, plots at left side) and sharp peaks for stations in mid-latitudes (Wettzell, Westford). This is due to the fact that there are no pronounced differences between the seasons in the tropics, while the large seasonal differences of the temperatures for continental stations are mirrored in the strong annual variations of the wet zenith delays.

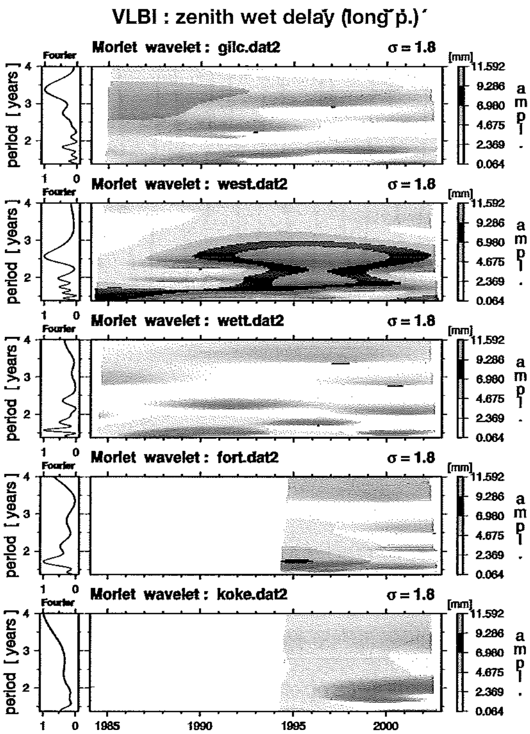


Figure 3a: Fourier and Morlet wavelet spectra for periods between 500and 1460 days for the VLBI stations Gilcreek (gilc.dat2), Westford (west.dat2), Wettzell (wett.dat2), Fortaleza (fort.dat2) and Kokee Park (koke.dat2).

The wavelet analyses do not only provide information about the main periods of the wet zenith delays but also about their temporal variations:

- strong annual periods at all stations with variable amplitudes (Figure 3b),
- irregular variations at 1.6–1.7 years (Figures 3a),
- irregular variations with periods between 30 and 90 days (Figure 3c);

the strongest of these variations occurred at Westford, in particular with periods shorter than 50 days.

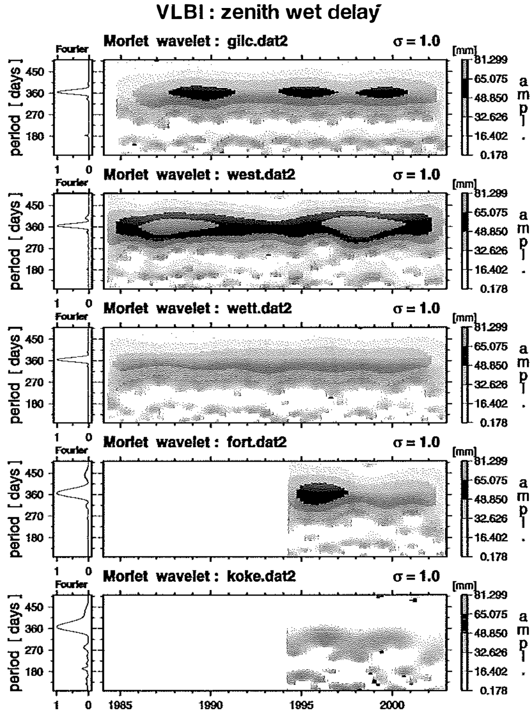


Figure 3b: Fourier and Morlet wavelet spectra for periods between 100 and 500 days for the VLBI stations Gilcreek (gilc.dat2), Westford (west.dat2), Wettzell (wett.dat2), Fortaleza (fort.dat2) and Kokee Park (koke.dat2).

4. Comparison with ECMWF data

The European Centre for Medium-Range Weather Forecasts (Reading, UK) provides meteorological data at six-hour intervals. The precipitable water is the parameter that is comparable to the wet zenith delay WZD. Firstly, the wet zenith delay has to be transformed into the integrated water vapour IWV (units kg/m^2):

$$IWV = WZD \cdot \Pi \tag{4}$$

The parameter Π is as follows:

$$\Pi = \frac{10^6 \cdot M_w}{\left(k_2{}' + \frac{k_3}{T_m}\right) \cdot R} \tag{5}$$

where

$$M_w = 18.0152 \frac{kg}{kmol}$$

$$k_2{}' = 17 \pm 10 \frac{K}{hPa}$$

$$k_3{}' = 373900 \pm 1200 \frac{K^2}{hPa}$$

$$R = 8314.34 \frac{J}{kmol \cdot K}$$

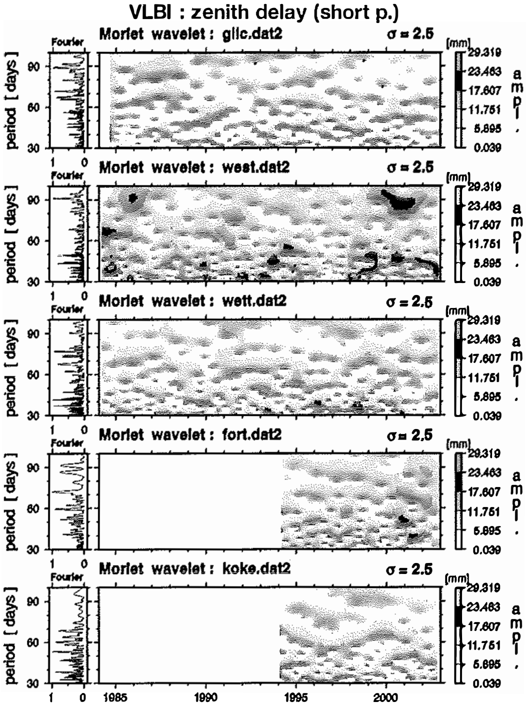


Figure 3c: Fourier and Morlet wavelet spectra for periods between 30 and 100 days for the VLBI stations Gilcreek (gilc.dat2), Westford (west.dat2), Wettzell (wett.-dat2), Fortaleza (fort.dat2) and Kokee Park (koke.dat2).

M_w is the molar mass of water, k_2' and k_3 are empirically determined coefficients, T_m is the mean temperature above the station, and R is the general gas constant. With the density of liquid water ρ_w, the precipitable water PW (units: m) can be determined:

$$PW = IWV/\rho_w \qquad (6)$$

The precipitable water can be approximated by the formula

$$PW \approx 0.15 \cdot WZD. \qquad (7)$$

The comparison between precipitable water from VLBI and ECMWF, which is available since 1994, shows a very good agreement at the level of ± 1.85 mm corresponding to a zenith delay of ~12 mm (Figures 4a,b). Compared to the standard deviation of ± 1.85 mm (precipitable water) the bias between the time series is very small (0.44 mm PW or 3 mm WZD).

5. Conclusions and outlook

The investigations presented here reveal a systematic increase of the wet zenith delays at Wettzell in the past two decades. This trend is significantly above the potential influence of the chosen terrestrial reference frame. Thus, the results obtained from VLBI might be useful for cli-

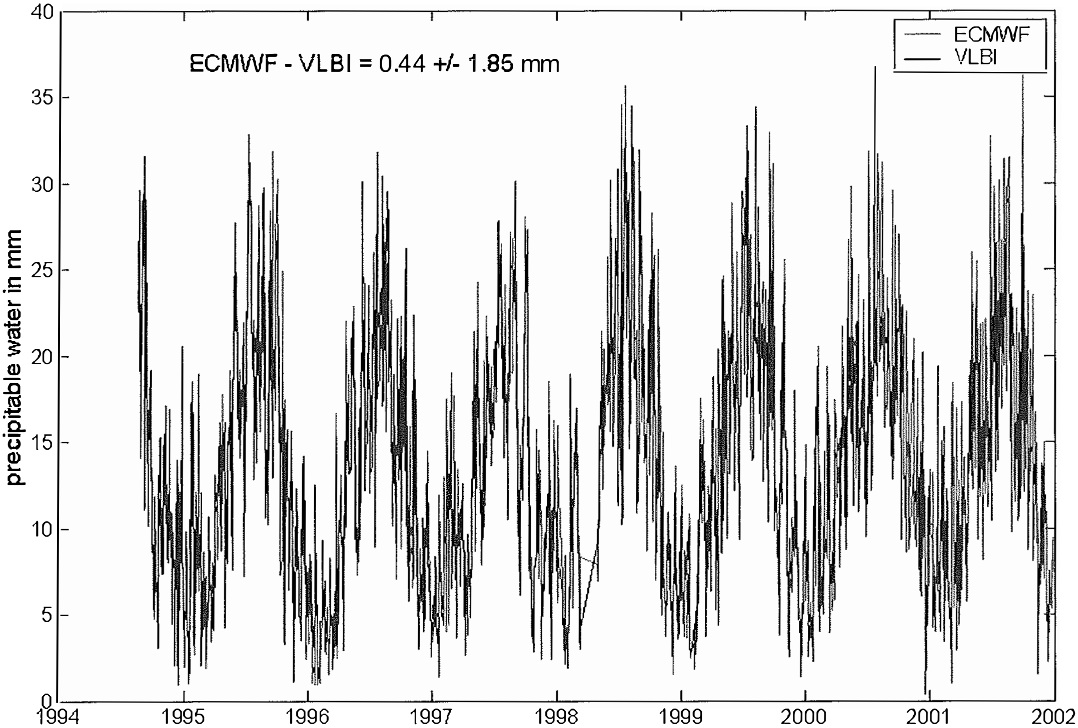


Figure 4a: Precipitable water from ECMWF and VLBI at Wettzell (1994–2002).

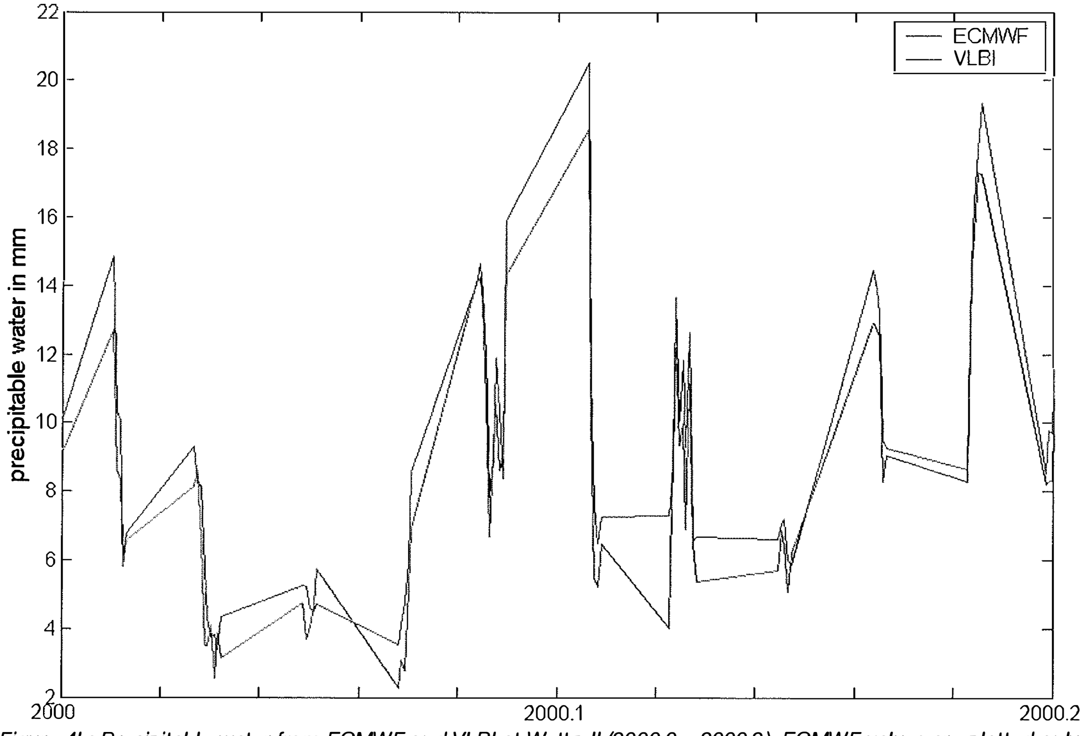


Figure 4b: Precipitable water from ECMWF and VLBI at Wettzell (2000.0 – 2000.2). ECMWF values are plotted only when VLBI values are available.

matological studies. A closer look remains to be taken at the other VLBI sites to possibly detect similar features in the time series of the tropospheric parameters. Similarily to the comparison with data from ECMWF, the tropospheric zenith delays can be compared with those provided by IGS [5]. Moreover, GPS-derived zenith delays can be used to fill the gaps between the results of VLBI and to finally obtain a robust combined time series.

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Contact

Dipl.-Ing. Johannes Boehm, Univ.-Prof. Dr. Harald Schuh: Institute of Geodesy and Geophysics (IGG), Vienna University of Technology, Gusshausstrasse 27–29, A-1040 Vienna. email: jboehm@luna.tuwien.ac.at, hschuh@luna.tuwien.ac.at

Dipl.-Ing. Volker Tesmer, Dr. Harald Schmitz-Huebsch: Deutsches Geodaetisches Forschungsinstitut (DGFI) Marstallplatz 8, D-80539 Munich, Germany. email: vtesmer@dgfi.badw.de, schmihue@dgfi.badw.de