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Atmospheric Measurement Techniques Discussions

Intercomparison of atmospheric water vapor soundings from the differential absorption lidar (DIAL) and the solar FTIR system on Mt. Zugspitze

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Abstract

We present an intercomparison of three years of measurements of integrated water vapor (IWV) performed by the mid-infrared solar FTIR instrument on the summit of Mt. Zugspitze (2964 m a.s.l.) and the nearby near-infrared differential absorption lidar (DIAL) at the Schneefernerhaus research station (UFS, 2675 m a.s.l.). The solar FTIR turned out to be one of the most accurate and precise IWV sounders in recent work (Sussmann et al., 2009) and is taken as the reference here. By calculating the FTIR-DIAL correlation (22 min coincidence interval, 15 min integration time) we derive an almost ideal slope of 0.99(1), a correlation coefficient of $R = 0.99$, an IWV intercept of 0.056(42) mm (1.8% of the mean), and a bias of 0.097(26) mm (3.1% of the mean) from the scatter plot. By selecting a subset of coincidences with an optimum temporal and spatial matching between DIAL and FTIR, we obtain a conservative estimate of the precision of the DIAL in measuring IWV which is better than 0.1 mm (3.2% of the mean). We found that for a temporal coincidence interval of 22 min the difference in IWV measured by these two systems is dominated by the volume mismatch (horizontal distance: 680 m). The outcome from this paper is twofold: (1) The IWV soundings by FTIR and DIAL agree very well in spite of the differing wavelength regions with different spectroscopic line parameters and retrieval algorithms used. (2) In order to derive an estimate of the precision of state-of-the-art IWV sounders from intercomparison experiments, it is necessary to use a temporal matching on the shorter 10-min scale and a spatial matching on the smaller 1-km scale.

1 Introduction

Water vapor is a key component of the atmosphere (Kiehl and Trenberth, 1997; Trenberth et al., 2007). Its distribution plays a major role for both meteorological phenomena and climate. One of the big challenges in climate research is to identify long term changes of the water vapor distribution, especially in the upper troposphere and lower

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stratosphere (UT/LS). In this altitude region, small changes of the water vapor concentration can already result in a heavy impact on the radiative balance (Harries, 1997). Consequently, highly accurate sounding techniques are needed.

For measuring integrated water vapor (IWV) solar Fourier-transform infrared spectrometry (FTIR) only recently turned out to be one of the most accurate and precise ground-based remote sensing techniques (Sussmann et al., 2009) and this was confirmed by follow-on intercomparison studies (Pałm et al., 2010; Schneider et al., 2010): Tabl 1 in Sussmann et al. (2009) shows that FTIR is comparable with or better than other state-of-the-art IWV sounding techniques, such as GPS, microwave radiometers, Raman lidars, or sun photometers (e.g. Morland et al., 2006; Fiorucci et al., 2008). The precision of FTIR for IWV was estimated to be better than 0.05 mm (2.2%), and a perfect matching to radiosonde response characteristics (scatter plot with slope ≡1) could be achieved by applying a dedicated Tikhonov-based spectral inversion scheme to the FTIR data; this retrieval was utilized for a harmonized study of the decadal trends in IWV above the Zugspitze and Jungfraujoch FTIR stations (Sussmann et al., 2009).

Profiling water vapor throughout the entire troposphere with a differential absorption lidar (DIAL) still is under development due to the technically demanding requirement of using tunable narrow-band high-power laser light in the near-infrared spectral domain. The DIAL system on Mt. Zugspitze is, to our knowledge, the first and only water vapor DIAL covering the entire free troposphere (Vogelmann and Trickl, 2008). Large discrepancies between different sets of spectral line parameters were reduced by recent investigations (Ponsardin and Browell, 1997; Schermaul et al., 2001; Mérienne et al., 2003; Tolchenov and Tennyson, 2008; Rothman et al., 2009). The LUAMI (Lindenberg Upper Air Methods Intercomparison) campaign in which the Zugspitze DIAL participated stimulated further efforts for refining the retrieval (Wirth et al., 2009). Thus, the intercomparison of DIAL-derived IWV with a validated, highly accurate, and precise method like FTIR is an important step to verify the DIAL spectroscopic parameters employed and the goal of this paper. At the same time, this intercomparison provides an estimate of the precision attainable by the DIAL measurements for IWV.

Section 2 will present the set up for the intercomparison experiment which is based on the Zugspitze FTIR system installed in 1995 on the Zugspitze summit at 47.42° N, 10.98° E, 2964 m a.s.l. (Sussmann and Schäfer, 1997) and the DIAL which began its routine operation at the nearby Schneefernerhaus in 2007 (680 m southwest of the summit, 2675 m a.s.l.). Section 3 will describe the intercomparison data set comprising 3 years of coincident measurements which will be utilized in Sect. 3.1 to derive the bias, intercept, and slope from a scatter plot. Section 3.2 will show the optimization of the spatio-temporal coincidence criteria as a basis for the subsequent estimation of the precision of the DIAL. Section 4 will give the summary and an outlook.

2 Instruments and intercomparison setup

2.1 Zugspitze solar FTIR system

Solar absorption FTIR spectrometry uses the direct radiation from the sun in the mid-infrared range as a light source. The FTIR provides total columns of a variety of atmospheric trace gases. Additionally, information on the vertical distribution of trace gases can be derived (typically 1–4 degrees of freedom) from the changes of the infrared spectral line shapes with pressure and temperature. Due to its principle, the solar FTIR measures slant columns/profiles pointing towards the actual position of the sun. The FTIR instrument located on the summit of Mt. Zugspitze is based on a Bruker IFS125HR interferometer and is described in detail by Sussmann and Schäfer (1997) (Table 1). The retrieval of IWV is based on the algorithm SFIT 2 (Pougatchev et al., 1995), which is the standard code within the Network for the Detection of Atmospheric Composition Change (NDACC). An FTIR retrieval optimized for IWV was developed recently by Sussmann et al. (2009). In brief, a dedicated set of 3 micro-windows was set up (see Table 1 for detailed information), and by using the new water vapor spectroscopy by Toth and coworkers implemented in HITRAN 2000 (Rothman et al., 2003) a spectral fit down to the noise could be achieved for the first time without systematic residuals due to spectroscopic errors (Sussmann and Camy-Peyret, 2002, 2003). As a result the precision of the FTIR retrieval for IWV could be estimated to be better than 0.05 mm (2.2% of the mean), and a perfect matching to the response characteristics of radiosonde-based IWV measurements could be achieved (scatter plot with slope ≡1) by tuning the regularization strengths of a Tikhonov-based spectral inversion scheme applied to the FTIR data; this retrieval has proved its usefulness via a harmonized study of the decadal trends in IWV above the Zugspitze and Jungfraujoch FTIR stations (Sussmann et al., 2009).

2.2 Differential Absorption Lidar (DIAL)

The DIAL method is a laser-based remote sensing technique providing number-density profiles of trace gases. In atmospheric sounding, this method has been applied mainly for ozone and water vapor and benefits from the specific molecular absorption of the trace gas to be measured. The Zugspitze/Schneefernerhaus DIAL system and the retrieval of water vapor profiles are described in more detail by Vogelmann and Trickl (2008). In brief, this DIAL is operated with single absorption lines in the 817-nm band of H_2O (Table 1) for ground-based water vapor profiling in the free troposphere. Two wavelengths are used, λ_{on} which is placed right in the center of an adequate absorption line and λ_{off} which is nearby, but outside of any line wings, if possible. Both are emitted into the sky in alternating sequence (pulse length ≈2 ns, repetition rate 20 Hz) with a pulse energy of up to 250 mJ. Their backscatter is collected by a large receiver telescope (0.65 m mirror, fixed zenith view) and, after electronic detection, stored in different registers of a transient recorder (20 MHz). In most cases, the lidar return from the free troposphere is pure Rayleigh backscatter. The water-vapor concentration is then retrieved by calculating the differential absorption from the two lidar returns. A vertical resolution of 50 m to 300 m is adapted dynamically to a vertical range from 2.95 km to ≈12 km a.s.l., respectively. The system yields a very narrow-band laser emission (≤220 MHz) with a high spectral purity (>99.9%) and, thus, meets the demanding requirements (Bösenberg, 1998). Narrow-band daylight filtering yields a full daytime measurement capability. The spectral data by Ponsardin and Browell (1997) are used for the calibration because of the successful validation of the line parameters by DIAL measurements (Ferrare et al., 2004).

2.3 Setup

Mt. Zugspitze is located on the northern rim of the Alps and overtops its surroundings by far. The site is above or in the upper part of the moist boundary layer during most of the year. This allows for sensitive spectroscopic measurements of water vapor throughout the free troposphere due to reduced absorption losses. As shown in Fig. 1, the FTIR instrument is located on the summit of Mt. Zugspitze at an altitude of 2964 m a.s.l. The DIAL instrument is located at the Schneefernerhaus research station (UFS) on the steep southern slope of Mt. Zugspitze at an altitude of 2675 m a.s.l., 680 m southwest of the FTIR instrument. This allows for a good spatial matching, if FTIR measurements are selected with the solar azimuth angle pointing towards the DIAL location. Furthermore, the DIAL is located 289 m below the FTIR. This is a very advantageous situation for the intercomparison experiment, because geometrical restrictions by the lidar telescope optics do not allow for the detection of water vapor closer than about 300 m to the lidar. Thus, the vertical measurement range of the Zugspitze DIAL starts approximately 300 m above the instrument, which is exactly the altitude where the FTIR spectrometer is located.

3 Intercomparison results

The intercomparison data set comprises 342 lidar profiles of the years 2007–2009. In the same time period 3544 IWV measurements from the solar FTIR instrument were obtained. It was shown by Sussmann et al. (2009) that it is crucial for IWV intercomparison experiments to choose strict temporal matching criteria on the minutes time scale because of the high variability of IWV. Reducing the temporal coincidence interval of course is a trade-off against the number of available coincident measurement pairs as shown in Fig. 4 of Sussmann et al. (2009). Using a coincidence interval of 22 min as a starting point we derive a scatter plot with 178 pairs (Fig. 2). In this scatter plot two types of outliers had to be eliminated. The first type refers to cases of a very high concentration of free-tropospheric aerosol which can lead to an overdrive in the lidar receiver. This was observed during strong Saharan dust events and during heavy winter storms when windblown snow from the ground reached the field of view of the receiver optics in the far field range (typically above 3300 m a.s.l.). The second type refers to cases of strongly perturbed humidity profiles compared to a standard profile with widespread and very dry layers below 4 km a.s.l. This was observed during stratospheric intrusion events during the winter season. We presume this to be caused by the FTIR retrieval algorithm which cannot resolve vertical structures of the water-vapor profile on small vertical scales below one kilometer. The type-one outlier was detected in 17 cases, the type-two outlier in 9 cases.

3.1 Bias and slope

From Fig. 2 we derive bias and slope, see Table 2. Briefly, IWV values measured by the DIAL and the FTIR are highly correlated ($r = 0.99$) as expected from the high variability ($\leq$0.5 mm to $\geq$10 mm). The slope is 0.99 and the intercept −0.056 mm (1.8% of the mean). The overall bias is −0.097 mm which means a relative bias of 3.1% compared to the average IWV of 3.15 mm above Mt. Zugspitze. This 3.1% bias probably is mainly the result of the limitation of the measurement range of the DIAL to the troposphere. Under clear sky conditions, the range of the DIAL ends at the tropopause, while the FTIR instrument also observes the water vapor in the stratosphere. Although the stratospheric water vapor contributes only about 1% to the IWV above sea level (Seidel, 2002), it contributes in the order of 3% to the mean IWV observed above an altitude of 3 km. (About two thirds of the sea-level water-vapor column are located below an altitude of 3 km.) Note that both FTIR and DIAL slopes and biases found in our study are in extraordinary agreement when keeping the completely differing measurement

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principles in mind (differing retrieval algorithms, differing spectroscopic line parameters).

3.2 Precision

In order to derive a conservative estimate for the precision of the DIAL for IWV measurements we have to optimize the spatio-temporal matching with the FTIR. The spatial matching varies with daytime because of the sun-pointing observation geometry of the FTIR (Fig. 1). To achieve an optimum volume matching of the FTIR with the lidar, a subset of the coincident pairs of Fig. 2 is taken into account, i.e., only pairs with FTIR solar azimuth angles of $210^\circ \pm 6^\circ$ are used. The result is shown in Fig. 3. An extension of the FTIR solar azimuth interval to $210^\circ \pm 10^\circ$ already significantly increases the standard deviation of the differences between FTIR and DIAL for short temporal coincidence intervals as indicated by the upper curve in Fig. 3. As expected, the standard deviation between DIAL and FTIR IWV values is smallest for the shortest temporal coincidence intervals (0.05 mm at 5 min) and increases with increasing interval length (>0.5 mm at 1000 min). This corresponds to the results of Sussmann et al. (2009), where two side-by-side FTIR-instruments were intercompared at Jungfraujoch (Switzerland). At Jungfraujoch a standard deviation of 0.07 mm was obtained for the shortest coincidence intervals, which is in the same order as shown here.

To estimate the precision of the DIAL, we analyze the standard deviation in the case of optimum volume matching and acceptable temporal matching (see Fig. 3, lower curve). A temporal coincidence interval of 18 min, together with a solar azimuth interval of $210^\circ \pm 6^\circ$, leads to 9 pairs with a standard deviation of 0.11 mm. Stricter spatio-temporal coincidence criteria yield even smaller standard deviations, but with a statistically insufficient number of pairs. From

$$\sigma_{\mathrm{IWV}} = \sqrt{\sigma^2_{\mathrm{DIAL}} + \sigma^2_{\mathrm{FTIR}}} \tag{1}$$

and $\sigma_{FTIR} \leq 0.05$ mm (Sussmann et al., 2009) we conclude that the precision of the DIAL is better than 0.1 mm. Thus, the DIAL can compete with the upper echelon of water vapor remote sounding techniques.

4 Summary and outlook

Intercomparison of FTIR and DIAL IWV measurements produced two major results: First of all, the slope (0.99(1)), correlation ($R = 0.99$) and intercept (–0.056(42) mm, 1.8% of the mean) obtained from the DIAL-FTIR scatter plot are almost ideal. The overall bias was found to be 0.097(26) mm (3.1% of the mean). This is a small value, but it can still be explained by the measurement range of the DIAL, which ends at the tropopause, while the FTIR IWV includes stratospheric water vapor as well. From this, it maybe concluded that the effective bias is much smaller than 3.1%. This fact as well as the almost ideal slope s of the correlation line ($s = 0.99$, $R = 0.99$) indicate that the spectroscopic parameters used for the retrieval of both the DIAL and the FTIR instrument are highly consistent. Quantitative spectroscopy of the molecular line parameters was derived independently for FTIR by Toth et al. (1998); Toth (1998, 2000), and, for the DIAL by Ponsardin and Browell (1997), respectively. The agreement (Fig. 2) reflects the high quality of both retrieval algorithms (Vogelmann and Trickl, 2008; Sussmann et al., 2009).

Secondly, the precision of the DIAL in measuring integrated water vapor was estimated to be better than 0.1 mm (relative measurement error of 3.2%). This value is nearly comparable to the precision of the FTIR (<0.05 mm) and this means that the DIAL is one of the best remote water-vapor sounders in the field of competition (see Table 1 in Sussmann et al., 2009).

Using the diurnally changing spatial overlaps between the solar FTIR and the DIAL we found that a spatial mismatch of <1 km is required to derive the (<0.1 mm) precision of state-of-the-art IWV sounders. This complements the finding by Sussmann et al.

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(2009) that a temporal matching in the order of 10 min or better is required for the same purpose.

Our goal was to examine the quality of water-vapor measurements with the DIAL from a technical point of view. As a side effect, Fig. 2 provided some indications as to the spatio-temporal variability of IWV. In the future, it is planned to derive quantitative information about the three-dimensional field of the spatio-temporal variability of IWV above the Zugspitze by further exploiting the outstanding geometrical arrangement of both instruments with their different observation geometries. This will be the subject of subsequent work.

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Table 1. Specifications of the FTIR and the DIAL on Mt. Zugspitze.

	FTIR	DIAL
geographical coordinates	10°59′8.7″ E 47°25′15.6″ N	10°58′46.8″ E 47°25′0″ N
altitude a.s.l.	2964 m	2675 m
vertical range a.s.l.	above 2.96 km	2.95 km–12 km
typ. integration time	15–20 min	14–16 min
wave number [cm^{-1}]	micro windows 839.5–840.5 849.0–850.2 852.0–853.1	ν_{on} 12236.560 12237.466 12243.537

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Table 2. Intercomparison results of DIAL versus FTIR (this work) and FTIR versus FTIR (side-by-side experiment; Sussmann et al., 2009).

instruments	DIAL–FTIR		FTIR–FTIR	
	precision	bias	precision	bias
[mm]	≤0.1	0.097(26)	≤0.05	0.02(1)
[% of mean]	≤3.2	3.1(8)	≤2.2	0.96(52)
slope	0.99(1)		1.001(7)	

Discussion Paper | Discussion Paper | Discussion Paper | Discussion Paper |

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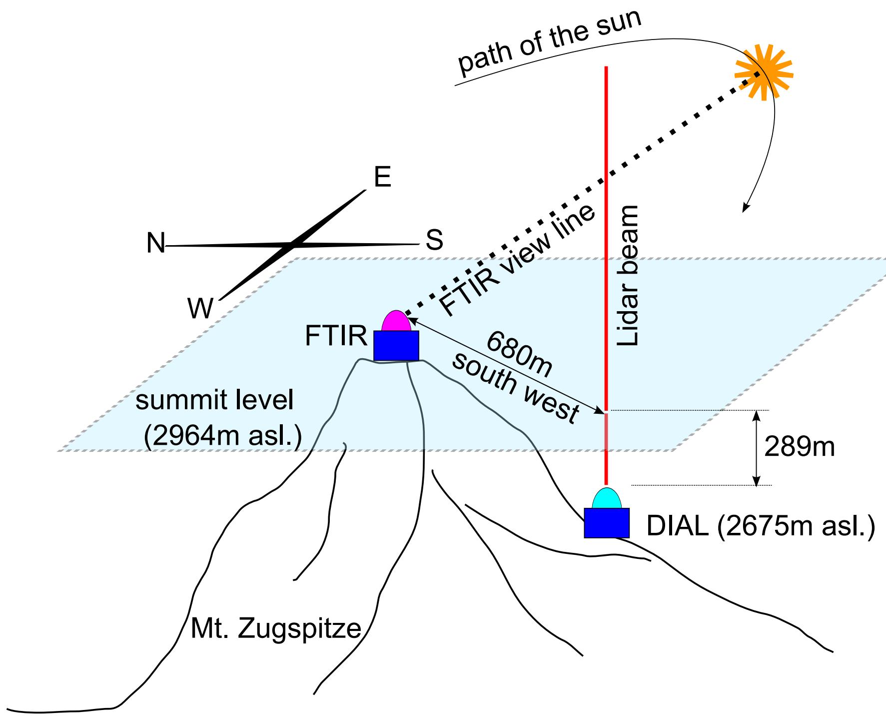

Fig. 1. Collocation of the FTIR and the DIAL on Mt. Zugspitze. The volume matching of the FTIR instrument and the DIAL peaks in the early afternoon at an azimuth of ≈210°.

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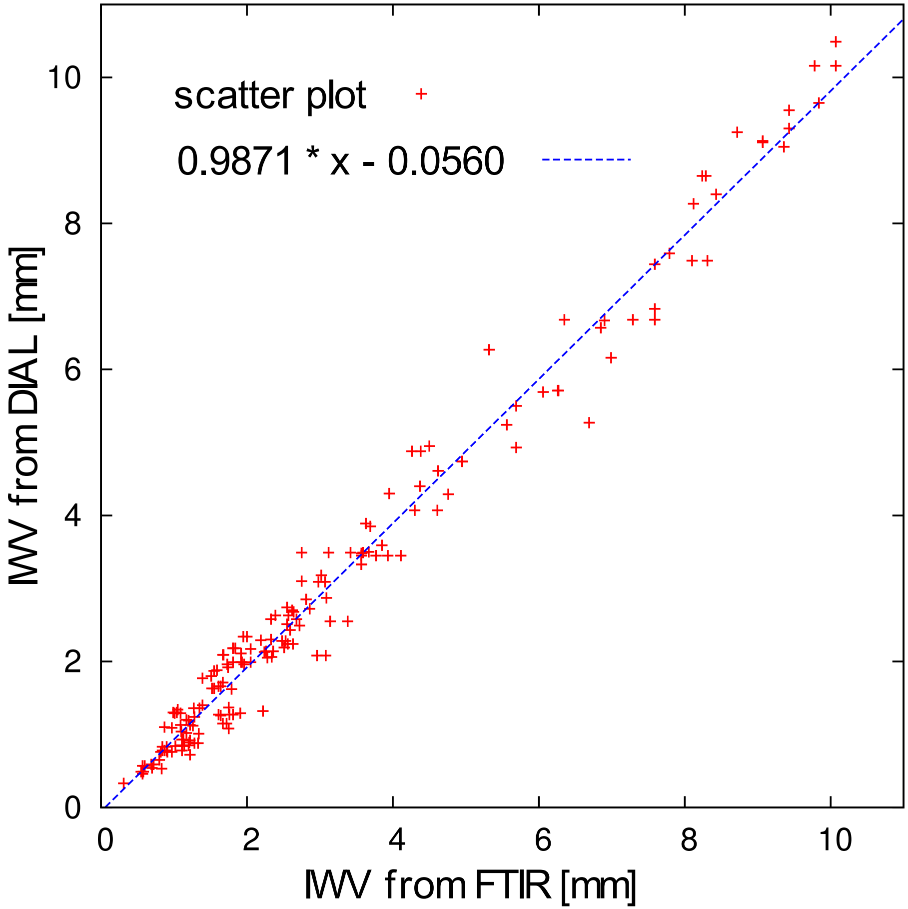

Fig. 2. Scatter plot of all FTIR and DIAL measurements, considering pairs of all day times within a coincidence interval of 22 min.

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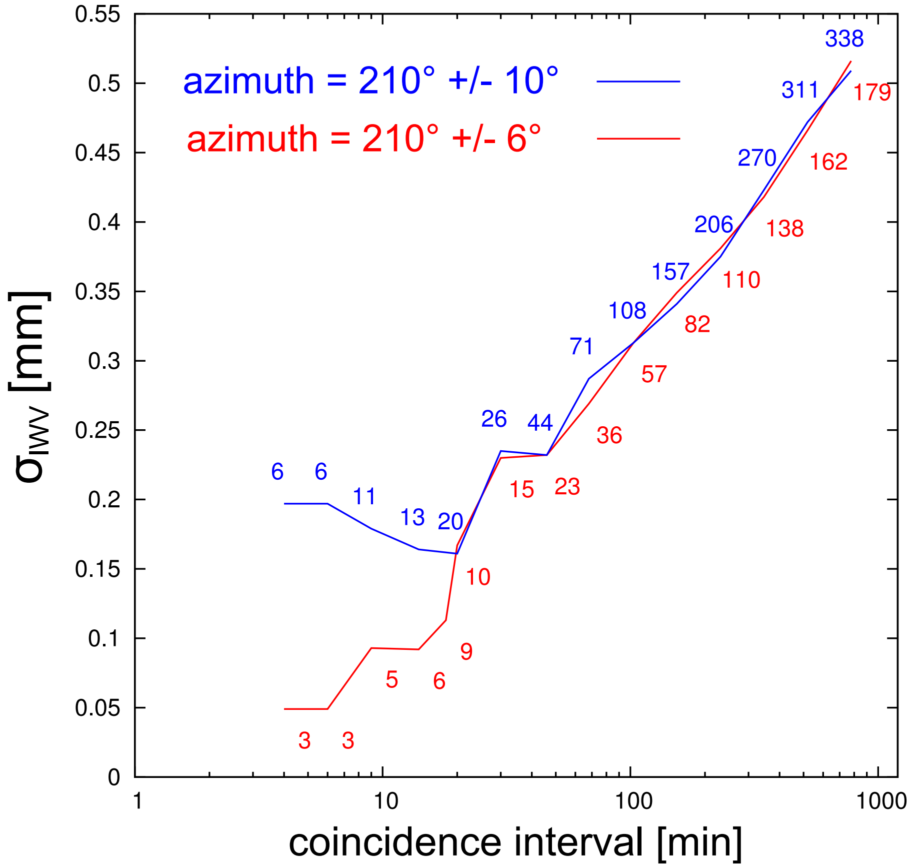

Fig. 3. σ_{iwv} as a function of the coincidence interval. Only FTIR measurements within an azimuth interval of $210^\circ \pm 6^\circ$ were taken into account for the lower curve, while the upper curve is for an increased interval ($210^\circ \pm 10^\circ$). Numbers indicate the amount of coincident pairs.

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