Middle Atmospheric Water Vapour Radiometer (MIAWARA): Validation and first results of the LAPBIAT Upper Tropospheric Lower Stratospheric Water Vapour Validation Project (LAUTLOS-WAVVAP) campaign

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[1] We present a validation study for the ground-based Middle Atmospheric Water Vapour Radiometer (MIAWARA) operating at 22 GHz. MIAWARA measures the water vapor profile in the range of 20–80 km. The validation was conducted in two phases at different geographical locations. During the first operational period the radiometer was operated at middle latitudes in Bern, Switzerland, and the measured water vapor profiles were compared with the HALOE satellite instrument. The agreement between HALOE and MIAWARA was for most altitudes better than 10%. In the second comparison phase, MIAWARA took part in the Lapland Atmosphere-Biosphere Facility (LAPBIAT) Upper Tropospheric Lower Stratospheric Water Vapour Validation Project (LAUTLOS-WAVVAP) campaign in early 2004 in the subarctic region of northern Finland. During this campaign, different balloon sondes probed the water vapor content in the upper troposphere and lower stratosphere. The stratospheric water vapor profiles of the fluorescent hygrometer FLASH-B and the NOAA frost point hygrometer mirror in the range of 20–26 km were compared with the lowermost retrieval points of MIAWARA. The agreement between the balloon instruments and MIAWARA was better than 2% for a total number of 10 comparable flights. This showed the potential of MIAWARA in water vapor retrieval down to 20 km. In addition, the northern Finland MIAWARA profiles were compared with POAM III water vapor profiles. This comparison confirmed the good agreement with the other instruments, and the difference between MIAWARA and POAM was generally less than 8%. Finally, the tipping curve calibration was validated with tipping curve measurements of the All-Sky Multi Wavelength Radiometer (ASMUWARA) which was operated 10 months side by side with MIAWARA. The agreement of the tropospheric opacity derived from these tipping curves agree within 1%.

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1. Introduction

[2] Water vapor is a key element in the Earth's radiative budget and in several chemical processes in the middle atmosphere. It is the most important greenhouse gas in the upper troposphere and contributes to the radiative cooling of the stratosphere by infrared emission. Therefore any trend in atmospheric water vapor will have implications for global warming. The effect of these water vapor changes depends on the altitude at which they occur [*Pierrehumbert*, 1995]. Water vapor is, as the source of the OH radical and the primary source of polar stratospheric clouds, also involved in ozone depletion processes.

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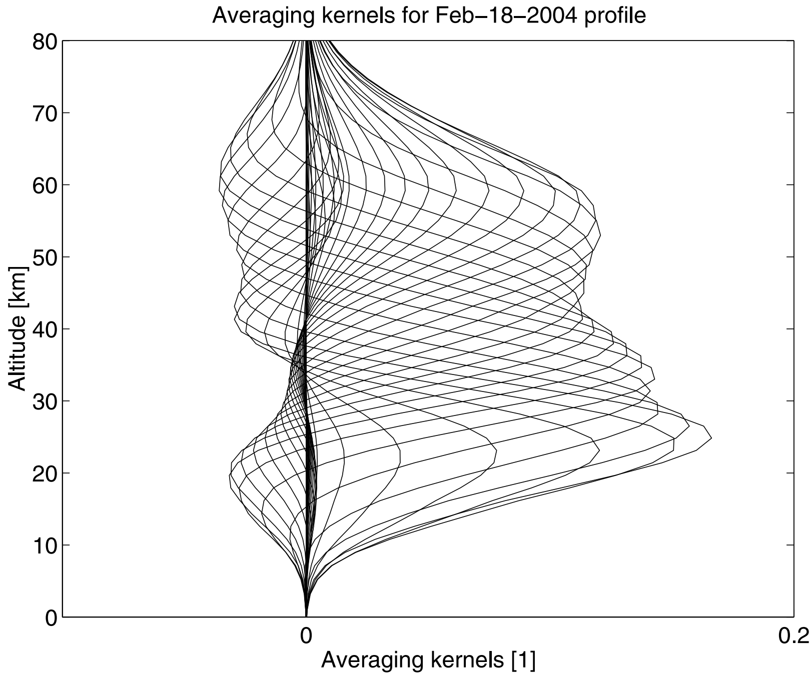

Figure 1. Averaging kernels for the profile retrieval of 18 February 2004.

[3] Different recent results show an increase in stratospheric water vapor in the last decades as reported by *Oltmans et al.* [2000], *Rosenlof et al.* [2001], and *Nedoluha et al.* [1997, 1998, 1999]. Some recent studies indicate a slowing down or a slight negative trend for the years 1999–2003 [*Nedoluha et al.*, 2003]. The reasons that led to this change in water vapor are still not fully understood.

[4] The Institute of Applied Physics of the University of Bern has developed a new ground-based radiometer which can, under conditions of low tropospheric opacity, measure water vapor profiles from 20 to 80 km. The radiometer called Middle Atmospheric Water Vapour Radiometer (MIAWARA) as described by *Deuber et al.* [2004] was designed for campaign use with a self-calibrating operation with the possibility to be used as a traveling standard in the future.

[5] In this paper we present our validation efforts for the water vapor profiles retrieved by MIAWARA. The validation phase consisted of two parts: Data from the first routine operation period of the instrument from December 2002 to November 2003, when the instrument was operated in Bern, Switzerland (46.95°N, 7.45°E, 550 m asl), were compared to vapor profiles measured by the HALOE instrument on the UARS satellite [*Russell et al.*, 1993; *Harries et al.*, 1996]. Second, MIAWARA took part in the LAUTLOS-WAVVAP campaign in early 2004 in Sodankylä, northern Finland (67.4°N, 26.6°E, 180 m asl) where various balloon soundings up to 26 km were performed. The water vapor measurements of the frost point hygrometer NOAA [*Oltmans*, 1985; *Vömel et al.*, 1995] and the fluorescent hygrometer FLASH-B [*Yushkov et al.*, 1998, 2000] allowed us to validate the lower altitudes of the MIAWARA retrieval and to check if the lower altitude limit of MIAWARA can reach 20 km under the good subarctic measurement conditions (dry troposphere). On 2 days the NOAA instrument was substituted by the newly developed (University of Colorado) Cryogenic Frost Point Hygrometer CFH, which is based on the NOAA frost point hygrometer. In addition the stratospheric profiles were validated with profiles from the POAM III satellite instrument [*Lucke et al.*, 1999].

2. Instrumentation and Retrieval of Profiles

[6] The ground-based radiometer MIAWARA measures the intensity of the pressure-broadened water vapor emission line at 22.235 GHz with an overall bandwidth of 1 GHz and a spectral resolution of 1.2 MHz for the broadband acousto-optical spectrometer and 40 MHz bandwidth with 14 kHz resolution for the narrow-band chirp transform spectrometer. The narrow-band spectrometer was in use in the instrument during the test period in 2002 and was definitively installed in the instrument in October 2004.

[7] The instrument is operated with a combined calibration scheme using tipping curve and balancing calibration. The concept of the instrument and the calibration technique as well as a validation of the calibration are described in detail by *Deuber et al.* [2004] and *Deuber and Kämpfer* [2004].

[8] The calibrated spectra were corrected for the tropospheric attenuation and the reference beam contribution according to the methods described by *Parrish et al.* [1988] and *Forkman et al.* [2003]. The water vapor profiles were retrieved from these corrected spectra using the optimal estimation method by *Rodgers* [2000]. As inversion algorithm we use the Qpack software [*Eriksson et al.*, 2005] which uses the Atmospheric Radiative Transfer Simulator (ARTS) [*Buehler et al.*, 2005] for the radiative transfer calculations. The spectral line parameters of the rotational transition at 22.235 GHz are used as given by *Janssen* [1993, appendix to chapter 2].

[9] In Figure 1 an example of the averaging kernels for the retrieved profile of 18 February 2004 are given. The

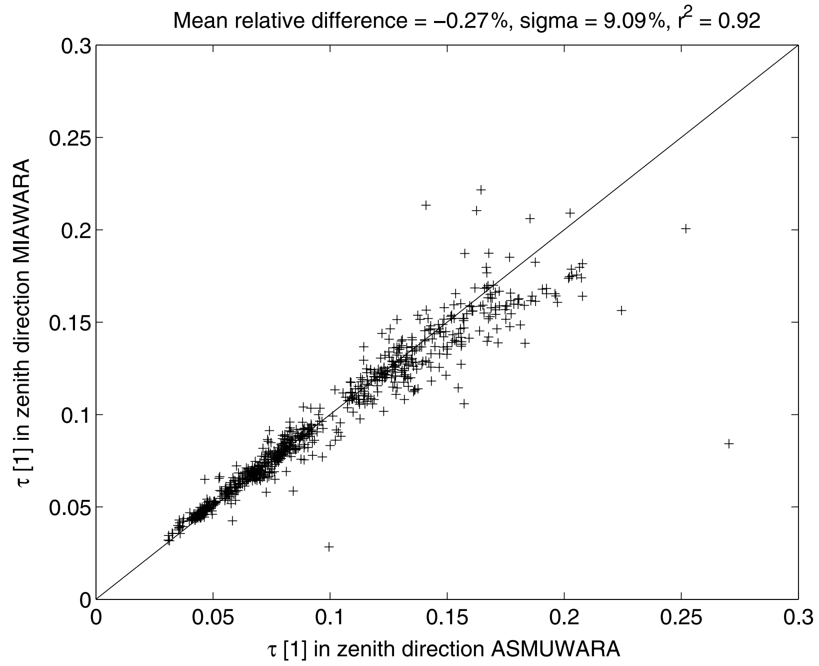

Figure 2. Comparison of opacities in zenith direction measured by the instruments MIAWARA and ASMUWARA during 2003 at Bern, Switzerland.

averaging kernels quantify the limited altitude resolution and the different sensitivity throughout altitude of the profile retrieval. From the averaging kernel the contribution of the a priori profile to the retrieved profile can be derived. For this validation study profiles where the a priori contribution was less than 30% have been considered.

3. Validation of the Tipping Curve Calibration

[10] The tipping curve measurements of MIAWARA as described by *Deuber et al.* [2004], resulting in the zenith direction opacity τ of the troposphere at 22 GHz, were validated at regular intervals using a liquid nitrogen cooled reference calibration load [*Deuber et al.*, 2004]. In addition to this liquid nitrogen reference method, we validated our measured opacities τ with the All-Sky Multi Wavelength Radiometer (ASMUWARA) [*Martin*, 2003]. This instrument is a combination of five radiometers at different frequencies for the detection of integrated water vapor, liquid water content and the temperature profile of the troposphere. ASMUWARA provides a radiometer channel (22.2 GHz ± 380 MHz) in the frequency range of MIAWARA. The calibration method of ASMUWARA includes also tipping curves. The algorithms for deriving the opacity τ were developed independently for the instruments MIAWARA and ASMUWARA. In the year 2003, these two instruments were operated side by side during almost 10 months. From this period the opacities in zenith direction of MIAWARA were compared to the zenith opacities of ASMUWARA in the same frequency band. In Figure 2 a scatterplot of all simultaneous measurements (time difference less than 1 hour) is shown. As visible from Figure 2 the agreement between these two instruments was very good. The mean relative difference $(\tau_{MIAWARA} - \tau_{ASMUWARA})/\tau_{ASMUWARA}$ was −0.27% with a standard deviation of 9.09% and a correlation of $r^2 = 0.92$. This difference is clearly within the reported uncertainty of the tipping curve measurements of MIAWARA resulting in an uncertainty of 10% in measurements of τ [*Deuber et al.*, 2004]. Removing the three most dominant outliers from the statistics, reduces the standard deviation to 7.5% and the correlation r^2 improves to 0.95. ASMUWARA also took part in the Comparison Campaign for Temperature Humidity and Clouds (TUC) and Measurement of Alpine Tropospheric Delay by Radiometer and GPS (MATRAG). These campaigns showed a good agreement of the ASMUWARA measurements with the other participating instruments of various techniques. First results of the MATRAG campaign are reported by *Häfele et al.* [2005].

[11] In Figure 3 a time sequence of this comparison for 3 days in February 2003 is shown. From Figure 3 it can

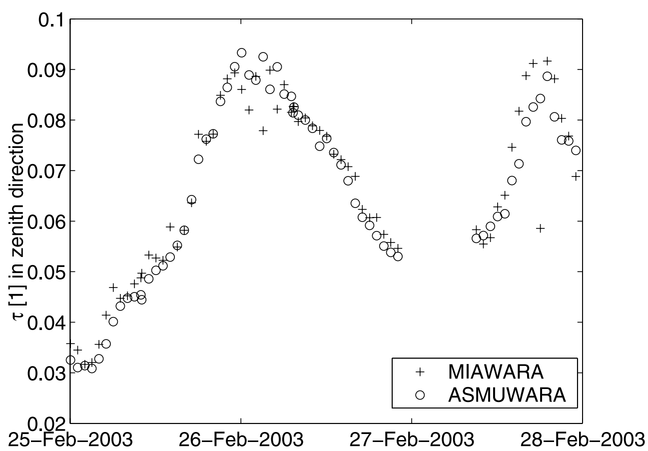

Figure 3. Time sequence of 3 days of hourly tipping curve measurements for the instruments MIAWARA (crosses) and ASMUWARA (circles).

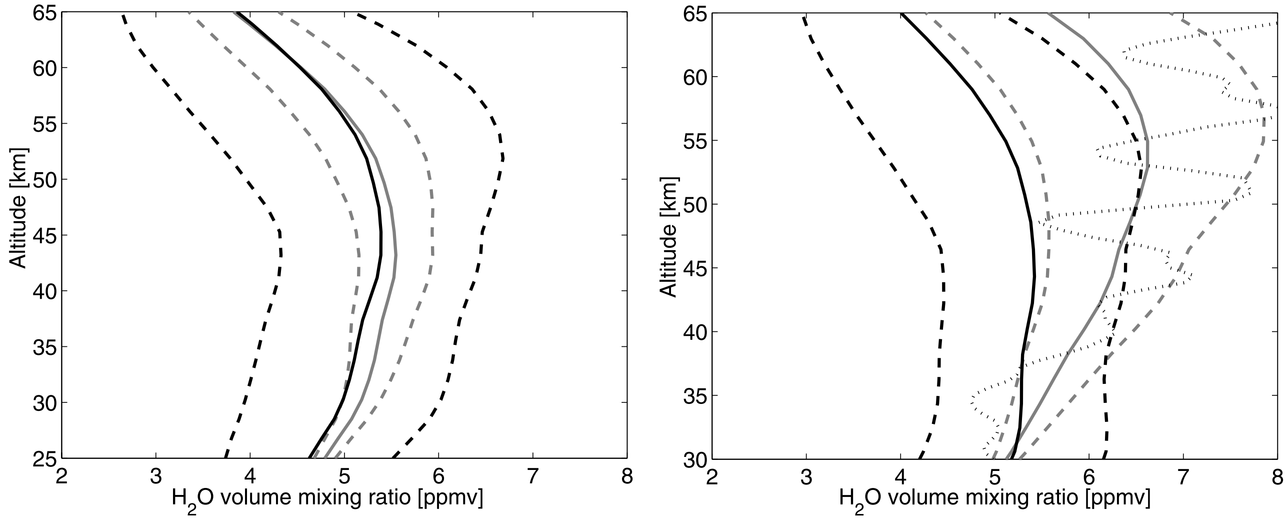

Figure 4. Comparison examples between MIAWARA and HALOE. The MIAWARA profile is represented by the solid line with measurement error (dashed line), and the convolved HALOE profile is given by the shaded line with corresponding errors (dashed shaded line). The dotted line in Figure 4 (right) represents the unconvolved original HALOE profile. (left) Comparison 17 February 2003: Δlat = −0.91, Δlon = −1.99. (right) Comparison 6 November 2003: Δlat = 1.42, Δlon = −6.24.

be seen that in general, the change in the tropospheric conditions, resulting in changes in τ, was nicely captured by both instruments.

4. Profile Measurements at Bern, Switzerland

[12] MIAWARA was in routine operation in Central Europe at Bern, Switzerland (46.95°N, 7.45°E, 550 m above sea level) from fall 2002 to fall 2003 and was reinstalled in Bern after the LAUTLOS-WAVVAP campaign (see section 5) in May 2004. During the first operational period MIAWARA retrieved approximately 100 water vapor profiles each integrated for one day. During this period the instrument was operated only with a broadband acousto-optical spectrometer (bandwidth: 1 GHz, 1725 channels). Therefore the altitude range for these profiles was limited to 25/30 to 65 km. The lower altitude limit depended on the integration time and on the tropospheric measurement conditions. A dry troposphere (resulting in a low opacity) is favorable as it tends to reduce the tropospheric influence on the spectrum and thereby allows for retrievals at lower altitudes. The effect of the dry troposphere results in a lower altitude limit for the retrieval of the subarctic measurements (see section 5) compared to the measurements at middle latitudes (this section) by 5 to 10 km.

[13] For this first operational period at Bern, the Halogen Occultation Instrument HALOE on the UARS satellite was chosen as a reference instrument. The HALOE instrument provides one of the longest spaceborne water vapor records and has been chosen as a reference instrument for various other validations and intercomparisons of ground-based measurements [e.g., *Nedoluha et al.*, 2003]. The validation and quality of HALOE water vapor measurements are described by *Harries et al.* [1996]. The HALOE data (version 19) were taken from the official UARS/HALOE data center Web page (http://haloedata.larc.nasa.gov/).

[14] In order to have a reasonable number of coincident measurements, all HALOE water vapor profiles with a latitudinal distance of ±5° and a longitudinal distance of ±40° were considered for this validation study. This resulted in 11 sunset and 12 sunrise HALOE profiles where MIAWARA profiles were available. The orbit of HALOE resulted in nonuniform distribution of the coincident profiles over all the measurement period. HALOE profiles were from December 2002, February/March 2003 and October/November 2003. During the summer months no coincident measurements were available due to very limited measurements of MIAWARA, as during summer 2003 extraordinary hot surface temperatures were recorded resulting in high tropospheric opacities. These tropospheric conditions allowed only very few retrievals of sufficient quality during the summer months and no MIAWARA profiles were available during the overpasses of HALOE. HALOE profiles were convolved with the MIAWARA averaging kernel matrix according to the method of *Tsou et al.* [1995] to account for the lower resolution and the a priori contribution of the microwave retrieval.

[15] The HALOE profiles were compared to 1-day averaged water vapor profiles measured by MIAWARA. Because of this integration time of the microwave spectra and the tropospheric conditions at Bern, the altitude coverage of the MIAWARA retrieval is in the range of 25/30 to 60 km. The integration of multiple days was not considered, as this would have decreased the basis of the statistics (for example, 4-day integration = 6 coincident measurements).

[16] Figure 4 shows two examples of the comparison between MIAWARA and HALOE. In Figure 4 (left) the profiles of 17 February 2003 are shown. For this day the agreement was better than 5% for all altitudes. In Figure 4 (right) the comparison of 6 November 2003 with poor agreement is shown. Most of the November 2003 profiles of HALOE, which are all measured at sunrise, show this distribution of water vapor almost linearly increasing

throughout the middle atmosphere as visible from the dotted high-resolution HALOE profile in Figure 4 (left). The MIAWARA instrument did not show this distribution and measured water vapor profiles with a maximum in the volume mixing ratio at approximately 45 km. In general, the profiles, even when they differed by more than 10%, were clearly within the measurement errors of both instruments. This is not the case for the profiles of 6 November.

[17] In Figure 5 the mean relative difference for all coincident measurements are given. The mean relative difference was calculated as

$$\Delta \mathrm{VMR}[\%] = 100 \cdot \frac{\mathrm{VMR}_{\mathrm{MIAWARA}} - \mathrm{VMR}_{\mathrm{HALOE}}}{\mathrm{VMR}_{\mathrm{HALOE}}} \quad (1)$$

[18] The relative difference for all 23 profiles (solid line) was in the range of 1.5% at 25 km and −11.5% at 65 km. The 2σ (dotted line) interval shows that the mean difference was not significant on a 2σ level at all altitudes. If the HALOE sunset (solid shaded line) and sunrise (dashed shaded line) measurements are analyzed separately, one can see from Figure 5 that the MIAWARA measurements seem to match up to 10% better to the sunset measurements.

[19] As mentioned in the discussion of Figure 4 the agreement was bad for several November 2003 coincidences. In that month the comparison with MIAWARA was based only on sunrise measurements of HALOE. The HALOE profiles of November differ by more than 100% in some altitude regions from the UARS HALOE/MLS water vapor climatology by *Randel et al.* [1998] in November at the latitude of Bern. Without the November measurements the mean relative difference between MIAWARA and HALOE improved and was better than −6.5%.

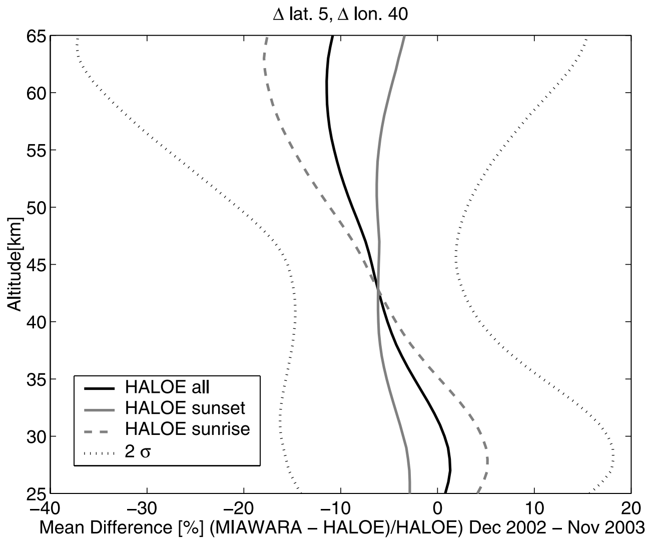

Figure 5. Mean difference for all 23 coincident MIAWARA and HALOE (convolved with MIAWARA averaging kernels) profiles from December 2002 to November 2003 (solid line) with 2σ of the mean value (dotted line). The difference was calculated separately for the HALOE sunset (solid shaded line) and sunrise (dashed shaded) measurements.

5. Measurements During the LAUTLOS-WAVVAP Campaign

5.1. LAUTLOS-WAVVAP

[20] The Lapland Atmosphere-Biosphere Facility (LAPBIAT) Upper Tropospheric Lower Stratospheric Water Vapor Validation Project (LAUTLOS-WAVVAP) campaign took part at Sodankylä in northern Finland between 29 January and 28 February 2004. Sodankylä is located north of the Polar Circle at 67.4°N, 26.6°E and 180 m above sea level. The major goal of this campaign was the validation of different sensors probing the water vapor content in the UTLS (upper troposphere-lower stratosphere) region. During the campaign launches of stratospheric balloon payloads were performed at the launch facility of the Arctic Research Centre of the Finnish Meteorological Institute twice each day. The small balloon payload, flown twice a day, consisted of the following sensors: Vaisala RS80 (H/A humicap), RS90 and RS92, Meteolabor Snow-white chilled mirror and Lindenberg Observatory FN-sonde. Large payloads, including the small payload sensors, fluorescent hygrometer FLASH-B, and either NOAA frost point hygrometer or University of Colorado (CU) Cryogenic Frost Point Hygrometer (CFH), were flown 13 times in the early evening (approximately at 17UT). In addition to the balloon sondes the radiometer MIAWARA and the airborne radiometer AMSOS [*Peter*, 1998; *Vasic et al.*, 2005] of the Institute of Applied Physics took part in the campaign. In this validation study for the MIAWARA radiometer we concentrated on the stratospheric sensors FLASH-B, NOAA frost point hygrometer and CU-CFH.

5.2. Comparison With Frost Point and FLASH-B Balloon Soundings

5.2.1. NOAA Frost Point Hygrometer and CU-CFH Sonde

[21] During the LAUTLOS Campaign both the NOAA frost point hygrometer and the CU-CFH were flown, however on different payloads. The current version of NOAA frost point hygrometer has been used with minor modifications since 1980. It allows measurements of the frost point temperature using a mirror with a uniform temperature distribution [*Oltmans*, 1985]. The instrument samples air in a 50 cm long and 2.5 cm diameter tube. The flow through this tube is about 5 m/s depending on the ascent/descent velocity of the balloon. The largest uncertainties in the frost point temperature measurement are the stability of the controller (<0.3°C), uniformity of the mirror temperature (<0.1°C), thermistor calibration (0.05°C), and self-heating of the thermistor (<0.05°C). The overall accuracy of this instrument is about 0.5°C in frost point temperature, or about 10% in mixing ratio. The vertical resolution is mostly determined by the response time of the instrument, which is typically between 10 and 30 seconds. Prior to the LAUTLOS campaign this instrument was successfully flown at Sodankylä in January and February 1996 [*Vömel et al.*, 1997] and during the winter of 2002/2003.

[22] The Cryogenic Frost Point Hygrometer (CU-CFH) is a new instrument, which was developed at the University of Colorado. It is based on the NOAA frost point hygrometer, but overcomes some of its limitations and at the same time significantly reduces power consumption and weight. The CU-CFH uses a digital feedback controller, which allows

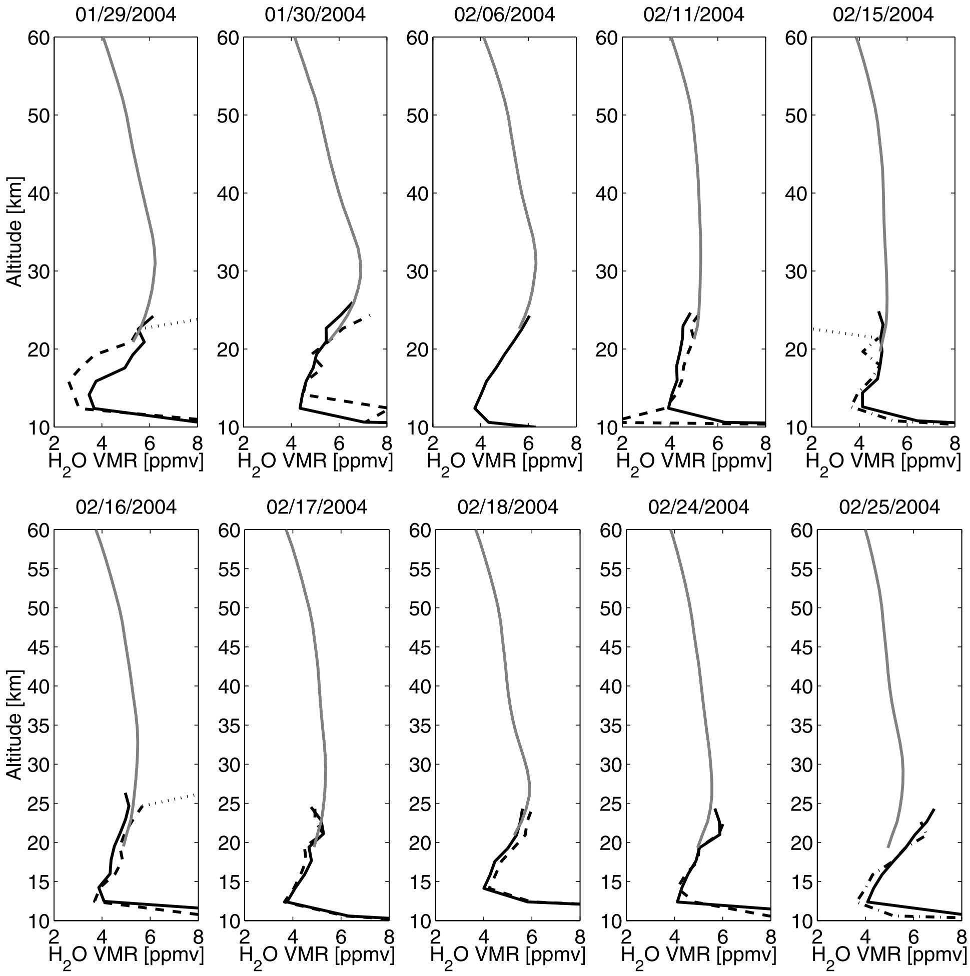

Figure 6. Comparison of MIAWARA (shaded line), NOAA(dashed line)/CU-CFH (dashed-dotted line) and FLASH-B (solid line) (balloon descent) profiles for different days. The solid dots are measurements by NOAA/CU-CFH which were not considered due to remaining wet contamination from the ascent or instrumental failure. The balloon profiles were reduced to the microwave retrieval grid using the Curtis-Godson equation. The CU-CFH sonde was flown on 15 and 25 February; on the other flights the older NOAA version was used.

the implementation of an advanced algorithm to maintain a constant frost layer. During LAUTLOS, CU-CFH instruments were flown for the first time to measure stratospheric water vapor, but encountered some hardware problems, which slightly reduced the accuracy of these measurements compared to the NOAA frost point hygrometer.

5.2.2. FLASH-B

[23] Sonde Fluorescent Advanced Stratospheric Hygrometer (FLASH-B) for balloon measurements (8–30 km) has been developed at Central Aerological Observatory, Russia. FLASH-B operates by photodissociation of H_2O molecules at Lyman-α (121.6 nm) followed by the measurement of the fluorescence of excited OH. The Lyman-α source of VUV radiation is a hydrogen discharge lamp. The OH fluorescence detection at 308 nm is achieved by a photomultiplier run in photon counting mode. The intensity of the fluorescent light as well as the instrument readings are directly proportional to the water vapor mixing ratio under stratospheric conditions (Pressure > 10 hPa) with negligible oxygen absorption. To avoid contamination, an open layout where the optics is looking directly to the outside is used. This coaxial optical layout allows reducing the size of the instrument for a total weight of 0.5 kg. However, this arrangement is suitable for nighttime measurements only at solar zenith angles greater than 98°. Long-term stability and calibration tests performed in the laboratory have demonstrated an accuracy of 8% for mixing ratios greater than 3 ppmv and 10% for 1 to 3 ppmv, a time resolution of one second for a power consumption of 6 Watts, including heating. Details of the hygrometer design and calibration procedures are given by *Yushkov et al.* [1998, 2000].

5.2.3. Measurements

[24] In Figure 6 the measured profiles of all 10 large payload flights where a corresponding MIAWARA profile was available are shown. The NOAA (dashed line)/CU-CFH (dashed-dotted line) and FLASH-B (solid line) profiles, which have a much higher vertical resolution than the microwave retrieval, were reduced to the MIAWARA retrieval grid using the Curtis-Godson equation [*Godson*, 1962] according to the method described by *Calisesi et al.* [2003].

Table 1. Agreement of MIAWARA With FLASH-B and NOAA/CU-CFH Measurements for the Different Retrieval Points of MIAWARA[a]

	FLASH-B	NOAA/CU-CFH	NOAA Only
20 ± 1.25 km			
Mean, %	−2.98	−0.97	−0.65
σ, %	6.61	10.07	3.84
Number of profiles	8	8	6
22.5 ± 1.25 km			
Mean, %	0.24	−2.57	−1.00
σ, %	8.79	7.13	6.07
Number of profiles	10	9	7
25 ± 1.25 km			
Mean, %	−0.14	−3.53	−3.45
σ, %	9.01	7.94	6.68
Number of profiles	10	9	7
Overall			
Mean, %	−0.33	−1.99	−1.71
σ, %	7.66	7.94	4.51
Number of profiles	10	9	7

[a]Relative difference in % (100 (MIAWARA (ppmv) − BALLOON (ppmv))/BALLOON (ppmv)).

[25] The microwave profile (solid shaded line) was considered for altitudes where the apriori contribution in the retrieved profile was less than 30%. Several balloon measurements suffered from a wet contamination during ascent due to snow, which accumulated during launch preparation and kept falling down from the balloon and parachute, and due to internal wetness of the instruments during ascent. Therefore only the data of the balloon descent were considered for this comparison. The dotted values in the NOAA/CU-CFH measurements for the flights on 29 January, 15 February, and 16 February were not taken into account as they clearly have a strong remaining wet contamination (29 January and 16 February) or almost zero ppmv values due to some instrumental problems (15 February). On 6 February the NOAA measurements failed above 15 km. The CU-CFH sonde was flown on 15 February and 25 February at the place of the NOAA sonde.

[26] In Table 1 the mean relative difference,

$$\Delta VMR[\%] = \frac{VMR_{MIAWARA} - VMR_{FLASH/NOAA}}{VMR_{FLASH/NOAA}} \quad (2)$$

for these 10 FLASH-B and 9 NOAA/CU-CFH comparisons with the MIAWARA instrument are given for different altitude ranges and the overall range of the overlapping altitudes. The agreement between the microwave radiometer and the balloon soundings was very good for both instruments. The mean difference over the entire altitude range of the overlap was −0.3% for FLASH-B and −1.99% for NOAA/CU-CFH with standard deviations of 7.66% for FLASH and 7.94% for NOAA/CU-CFH, respectively. If the NOAA measurements are analyzed without the CU-CFH flights the mean difference slightly improved to −1.71% (σ = 4.51%). The agreement in the different altitude layers was also generally better than 4% with a tendency of underestimation of the water vapor content by MIAWARA. These differences were clearly within the error of the MIAWARA water vapor profile in the range of 15–20% at this altitude region.

[27] In Figure 7 the evolution of the mean water vapor content as measured by the different instruments and the values of the modified polar vorticity according to *Lait* [1994] in the altitude range of 20 to 25 km are shown. From Figure 7 it is visible, that the changes between subsequent measurements were similar for all three instruments for most days. Especially the drop in the water vapor volume mixing ratio between 8 February and 15 February as well as the increase between 16 February and 18 February were captured by all instruments. The measurements were also nicely following the polar vortex situation over Sodankylä, as given by the PV values. As one would expect the water vapor mixing ratio is higher for high PV values and lower for low PV values in this altitude range. On 25 February the MIAWARA measurements show a very different behavior than the measurements by the balloon-borne sensors. During this day the PV distribution around 20 km was, in contrast to the previous days, very heterogenous in the vicinity of Sodankylä and the balloon flew not in the MIAWARA measurement direction. Therefore it is likely, that MIAWARA and the balloon instruments did not sample the air with the same PV signature.

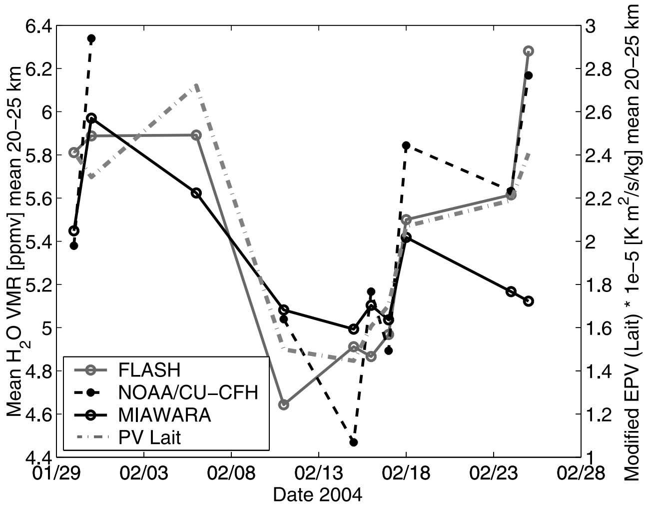

Figure 7. Evolution of the mean water vapor content between 20 and 25 km for the 10 days reported in Figure 6. MIAWARA (solid shaded line), NOAA/CU-CFH (dashed line), and FLASH-B (solid line) as well as PV values (dashed-dotted shaded line, right-hand axis). The measurement errors of the instruments in this altitude region are MIAWARA, 18%; FLASH-B, 8%; and NOAA/CU-CFH, 10%.

[28] The correlation coefficients for the different measured water vapor values, as illustrated in Figure 7, are listed in Table 2. The correlation improved when the 25 February values, which have a significantly higher difference between the MIAWARA and balloon profiles than all other days, were not taken into account. The correlation coefficient between MIAWARA and FLASH was 0.58 for

Table 2. Correlation Coefficients for the Measured Mean Water Vapor Mixing Ratio Between 20 and 25 km as Illustrated in Figure 7

	Correlation For All Days	Correlation Without 25 February
MIAWARA − FLASH	0.58	0.84
MIAWARA − NOAA/CU-CFH	0.70	0.88
NOAA/CU-CFH − FLASH	0.83	0.78

all days and 0.84 when 25 February was not considered. MIAWARA and NOAA/CU-CFH correlated with a coefficient of 0.7 and 0.88, respectively, when 25 February was not considered. The correlation coefficient of the balloon instruments FLASH and NOAA, which sampled the same air masses, was 0.83 and 0.78, respectively, without the 25 February flight. The correlation between MIAWARA and the balloon instruments, when the 25 February case was not considered, was in the same range or even slightly better than the correlation between the balloon instruments. These correlation coefficients were between 1.8 and 2.0 (including 25 February case) and 2.5 (without 25 February case) times larger than the standard deviation of the correlation coefficients if the measurements were analyzed randomly permuted. This indicates that the good correlation was not a random result and confirmed the very good agreement of the mean value of all 10 profiles as reported in Table 1.

[29] Analyzing the gradient of the measured mixing ratios with altitude (see Figure 6) in the overlapping region, one can see that it changes from day to day and that the three instruments (again with the exception of 25 February) measured similar gradients in the water vapor mixing ratio. This is an additional indication, that MIAWARA sampled sensitively the amount of water vapor in the altitude region between 20 and 25 km.

5.3. Comparison With POAM III Satellite Measurements

[30] In order to validate the MIAWARA LAUTLOS profiles throughout the entire stratosphere we compared the MIAWARA profiles between 20 and 50 km with POAM III water vapor measurements. The POAM III instrument is a visible/near infrared solar occultation photometer that measures several stratospheric constituents at high latitudes in both hemispheres (63°–88°S and 55°–71°N). A detailed instrument description is given by *Lucke et al.* [1999], and the retrieval methodology is described by *Lumpe et al.* [2002]. Detailed discussions of the expected uncertainties in the POAM III water vapor retrieval are given by *Nedoluha et al.* [2002a, 2002b] and by *Lumpe et al.* [2002]. The measurements have been validated by comparison with coincident measurements in the year 2000 SPARC Water Vapor Assessment [*Kley et al.*, 2000].

[31] As the measurements took part in the subarctic winter with changing polar vortex situations, the general coincidence criterium (Δlat = ±5°/Δlon = ±40°) as used for the HALOE comparisons was not suitable. We chose the equivalent latitude according to *Butchart and Remsberg* [1986] as coincidence criterium. The equivalent latitude is a vortex centered coordinate system based on the Ertel's potential vorticity (Epv) field, defined as the latitude that would enclose the same area between it and the pole as a given Epv contour. The equivalent latitudes computed for MIAWARA (solid line) and POAM III (shaded crosses) are given in Figure 8 for different potential temperatures θ. The equivalent latitude of the vortex edge (dashed line) according to *Nash et al.* [1996] is also plotted in Figure 8.

[32] The MIAWARA water vapor mixing ratio for a given day and altitude was compared to the POAM III profile if the difference in equivalent latitude was less than 5° and if both the MIAWARA and POAM measurements were in or outside the vortex. As for the HALOE comparison the

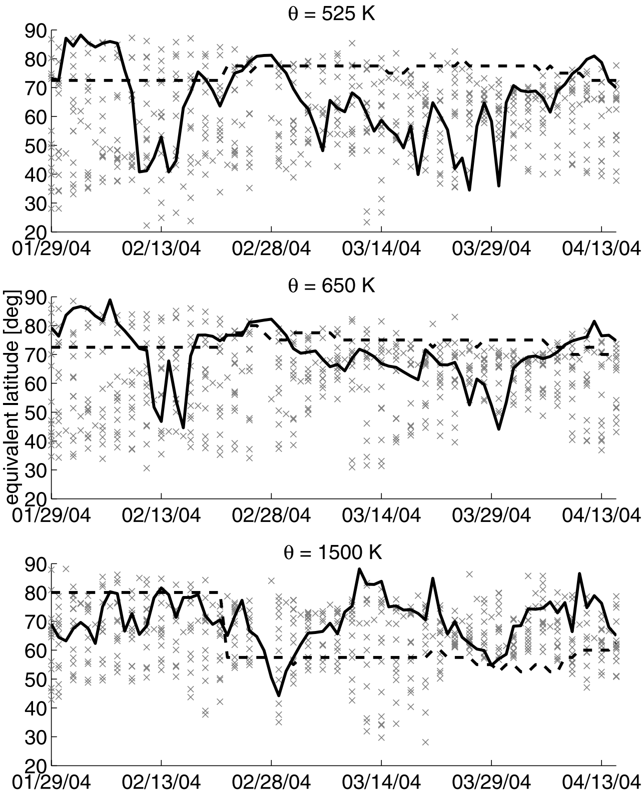

Figure 8. Location in equivalent latitudes of all POAM (shaded crosses) and MIAWARA (solid line) profiles for different altitudes (in units of potential temperature θ). The dashed line represents equivalent latitude of the polar vortex edge. The geographical latitude of Sodankylä, where MIAWARA was operated, is 67.38°N.

POAM III profile was convolved with the MIAWARA averaging kernel matrix. The comparison criteria resulted in 24 profiles to compare.

[33] In Figure 9 the mean relative difference for the MIAWARA and POAM comparison is shown. The difference was clearly better than 10% (maximum difference of −8.5%) with a negative bias of MIAWARA (solid line). The difference is not significant on a 2σ (dotted line) level for all altitudes. If the maximal difference in equivalent latitude is reduced to one degree the difference is smaller by about 3% (dashed line).

6. Conclusions

[34] The tipping curve calibration was validated by a comparison of the measured opacities by MIAWARA and the radiometer ASMUWARA, which were operated at the same location for 10 months. The agreement was better than 1% and clearly within the expected uncertainty of 10%. From this tipping curve comparison and the liquid nitrogen validations that were reported by *Deuber et al.* [2004] we conclude that our measurements of the tropospheric opacity were of good quality.

[35] Water vapor profiles measured by the Middle Atmospheric Water Vapour Radiometer MIAWARA between 20 and 65 km were validated with satellite measurements in

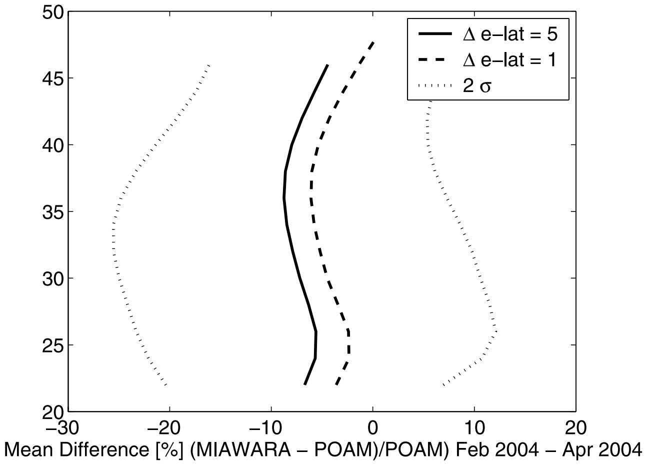

Figure 9. Mean relative difference for all coincident MIAWARA and POAM III (convolved with MIAWARA averaging kernels) profiles from 29 January 2004 to 15 April 2004 (Δ elat = 5°, solid line) with 2σ of the mean value (dotted line). The dashed line represents the difference with a stronger coincident criterion of Δ elat = 1°.

mid latitudes (HALOE) and with balloon-borne and satellite (POAM III) measurements in subarctic winter conditions.

[36] The mean difference to the other instruments was generally better than 15%, for most cases better than 10%, with a nonsignificant (2σ level) tendency of an underestimation of the water vapor mixing ratio by MIAWARA.

[37] The comparison in northern midlatitudes with HALOE showed a mean relative difference between +1.5% and −12%. If November 2003 measurements, which agree badly, were not taken into account, the difference was better than 6.5%. The difference of the MIAWARA measurements was 5 to 10% smaller for the sunset measurements than for the sunrise measurements.

[38] The comparison of MIAWARA with measurements of the balloon-borne instruments FLASH-B and NOAA/CU-CFH during the LAUTLOS-WAVVAP campaign in the Northern Hemisphere subarctic winter/spring 2004 showed a very good agreement between the MIAWARA measurements and the balloon-borne sensors between 20 and 26 km. The difference was less than −0.5% for FLASH and −2% for NOAA/CU-CFH. If the two flights of the new developed CU-CFH were not considered in the statistics, the mean relative difference between MIAWARA and NOAA improved to −1.7%. The measurements also correlated nicely to the evolution of the polar vortex in this altitude region. This excellent agreement with well known balloon-borne water vapor sensors proved that MIAWARA is able to retrieve water vapor mixing ratios down to 20 km under the favorable subarctic measurement conditions. No other ground-based water vapor radiometer has been able to retrieve profiles down to this altitude.

[39] Finally, the comparison of the LAUTLOS-WAVVAP MIAWARA measurements between 20 and 50 km with the POAM III satellite water vapor measurements confirmed the good agreement of the balloon intercomparison. The difference was generally better than −8.5% between 20 and 50 km.

[40] The comparison of MIAWARA profiles to different other water vapor measurements in midlatitudes as well as subarctic regions showed an agreement better than 10% between 20 and 65 km. Therefore we can conclude that MIAWARA measures water vapor profiles using the 22 GHz water vapor transition within the expected accuracy and is able to retrieve water vapor down to 20 km under favorable tropospheric conditions.

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