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1. INTRODUCTION

Middle atmospheric water vapour plays a key role in the earth's radiative budget and in several chemical processes. Recent results in the published literature measured with different instrumentation indicate a positive trend of middle atmospheric water vapour in the range of 0.07 ppmv/yr [Oltmans et al. (2000)] to 0.15 ppmv/yr [Nedoluha et al. (1997); Nedoluha et al. (1998); Nedoluha et al. (1999)]. However the mechanisms leading to such an increase are not well understood. There is an urgent need for longterm high quality measurements of middle atmospheric water vapour. The concept of the newly built instrument MIAWARA (**M**iddle **A**tmospheric **W**ater vapour **R**adiometer) is designed to provide long-term ground-based measurements of middle atmospheric water vapour profiles. The first measurements with this instrument were carried out at Bern in the Swiss plateau (46.95 N / 7.45 E, 550 meters above sea level). Comparisons of the first retrieved altitude profiles from our ground-based instrument with the HALOE satellite are promising.

2. DESCRIPTION OF THE INSTRUMENT

The instrument MIAWARA (see figure 1) was developed at the Institute of Applied Physics of the University of Bern where it is currently operated. The instrument measures the 22.235 GHz emission line of the rotational transition of water vapour. The low tropospheric opacity at 22 GHz allows ground-based radiometric measurements of water vapour profiles from low altitude stations as Bern (550 m. asl). An overview of the instrumental setup is given in figure 2 and table 2. The setup of the instrument consists of the frontend (outside building) and the backend (inside building) connected by a 15 m coaxial cable. The signals from the atmosphere and the calibration loads (reference load, hot load, cold load) are fed into the corrugated horn-antenna by a large plane mirror, which can be shifted by a quarter of the wavelength between two successive measurements to minimise artefacts of standing waves. The instrument is operating in the single-sideband mode. The radio-frequency (RF) signal at 22.235 GHz is directly amplified by 2 low-noise amplifiers before being down converted to the intermediate-frequency (IF) at 2.1 GHz. The spectral analysis is currently achieved by an acousto-optical spectrometer (bandwidth 1 GHz, resolution 0.58 MHz)

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FIG. 1: The radiometer MIAWARA on the roof of the Institute of Applied Physics at Bern, Switzerland (46.95 N / 7.45 E, 550 m. above sea level).

and a chirp transform spectrometer (bandwidth 40 MHz, resolution 9.5 kHz). A detailed description of the instrument can be found in [Deuber (2001)].

We determine the water vapour spectrum by performing a so-called balancing-calibration [Janssen (1993)] using the sky as reference signal (zenith) and cold calibration target (60 degree elevation) [Nedoluha et al. (1995); Parrish et al. (1988)]. The use of the sky as calibration target and the correction of the middle atmospheric emission line due to tropospheric attenuation require knowledge of the tropospheric properties. We determine these properties with the same instrument while performing a so-called tipping curve calibration [Janssen (1993); Han and Westwater (2000)] on a hourly basis. This calibration technique is validated with periodic liquid-nitrogen calibrations. The results of both calibration techniques agree within $\pm 0.6\%$ [Deuber (2002)].

3. RETRIEVAL OF MIDDLE ATMOSPHERIC WATER VAPOUR PROFILES

The instrument measures the intensity of the pressure broadened water vapour emission line at 22.235 GHz. In microwave radiometry it is common to refer the signal intensity to the brightness temperature T_b according to Planck's law. The frequency dependent signal strength $T_b(f, s_0)$ detected on ground contains contributions from different emission altitudes according to the radiative transfer equation [Janssen (1993)]:

$$T_b(f, s_0) = T_0 e^{-\tau(f, s_1)} + \int_{s_0}^{s_1} ds' T(f, s') \alpha(f, s') e^{-\tau(f, s')} \quad (1)$$

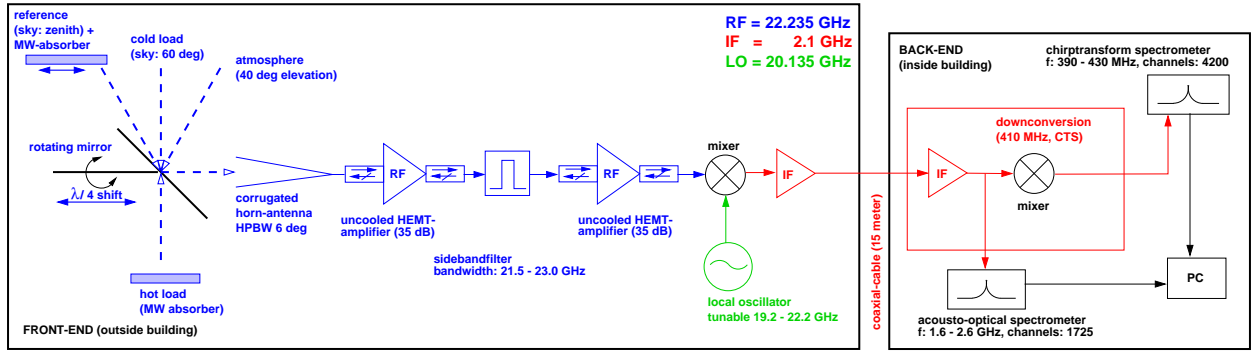


FIG. 2: Block scheme of the instrument.

| Calibration technique | Balanced calibration |
|------------------------------|---|
| Operational mode | Single sideband (SSB) 50 dB sideband suppression |
| Mirror | Plane mirror (gaussbeam optimised shape) |
| Antenna | Corrugated horn (HPBW 6 deg) |
| Receiver noise-temperature | 133 K SSB |
| Radio-frequency range | 21.735 – 22.735 GHz |
| Broadband spectral analysis | Acousto-optical spectrometer (f: 1.6–2.6 GHz, Δ f: 0.58 MHz) |
| Narrowband spectral analysis | Chirp transform spectrometer (f: 390–430 MHz, Δ f: 9.5 kHz) |

Table 1: Key parameter of the instrument

where $T_b(f, s_0)$ is the brightness temperature at the place of observation s_0 on the earth surface, s_1 the upper boundary of the atmosphere, $T(f, s)$ the signal strength along the integration path s and f the frequency. The opacity $\tau(f, s)$ is the integral of the frequency and path dependent absorption coefficient $\alpha(f, s)$.

$$\tau(f, s_1) = \int_{s_0}^{s_1} ds' \alpha(f, s') \quad (2)$$

The emission frequency of the rotational transition of water vapour is pressure broadened. Due to the exponential decrease of atmospheric pressure with altitude, the broadening of the retrieved line spectrum contains information from the emission altitude of the individual contributions to the measured signal $T_b(f, s_0)$ on ground [Janssen (1993)]. Therefore we are able to retrieve middle atmospheric water vapour profiles from the pressure broadened line in the range of 30 - 70 km using a re-

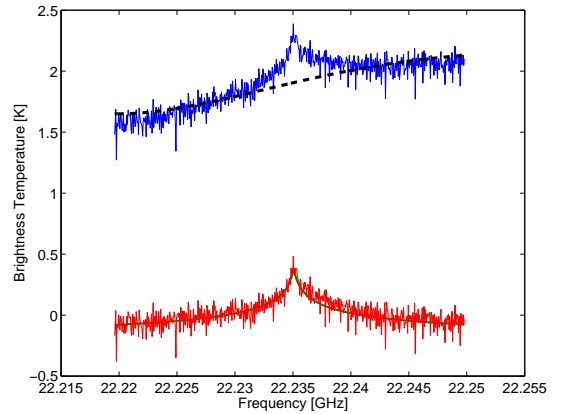


FIG. 3: Measured balanced 3-day average spectrum recorded by the narrowband spectrometer in August 2002 (integration time 4.6 hours). The measured spectrum (solid blue) is corrected for tropospheric attenuation. The spectrum (solid red) is corrected using the polynomial fitted baseline (dashed black). The fitted spectrum is used for the integration (solid green).

trieval algorithm based on Rodgers optimal estimation technique [Rodgers (2000)].

4. RESULTS

The instrument has started operation in winter 2001. During a first testing period a validation of the calibration method was performed [Deuber (2002)]. A good calibration is essential for the detection of the weak water vapour emission line at 22.235 GHz. The validation of the calibration was conducted using liquid nitrogen cooled calibration targets. This liquid nitrogen calibration is a widely spread and accepted standard for radiometric measurements [Ulaby et al. (1981)]. According these validation measurements we estimated a measurement error (neglecting systematical errors) of the retrieved balanced brightness temperature in the order of 1%

[Deuber (2002)].

Figure 3 shows a balanced spectrum measured by the narrow-band spectrometer in August 2002. The measurements were carried out at Bern, Switzerland (46.95 N / 7.45 E, 550 m. above sea level). The measured spectrum represents an integration of multiple spectra with an integration time of 4.6 hours. The original measured balanced spectrum (blue) is corrected for tropospheric attenuation using the method described in *Forkman et al. (2002)*. A polynomial baseline (dashed black) is fitted to the original balanced spectrum. The major contribution to this baseline originates from the tropospheric continuum, which could not be totally eliminated using the balanced calibration scheme. A smoothed spectrum (green) is fitted to the noisy baseline corrected measurement (red). The retrieved water vapour profile, that was inverted using the smoothed fit is shown in figure 5.

In figures 4 and 5 retrieved water vapour profiles for different months over Bern are presented. Both profiles are obtained from a 3 day-averaged spectrum. The retrieved profiles were compared to water vapour measurements of the HALOE satellite instrument.

4.1 Water Vapour Profile May 2002

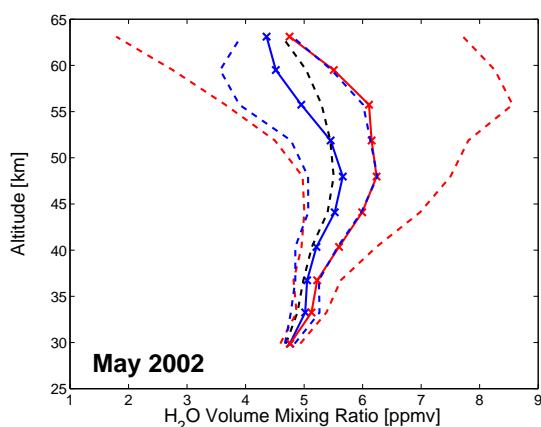


FIG. 4: Water vapour profile retrieved by a broadband spectrometer 3-day averaged spectrum in May 2002 (solid blue). The dashed blue lines represent the 2 times standard deviation for the observational error. The data is compared with a HALOE water vapour profile from April 10th 2002 at 44.95°N / 21.94°E (solid red) with plotted 2 σ of the HALOE measurement uncertainty (dashed red). The dashed black line represents the a priori profile used in the retrieval process.

The values for the obtained water vapour mixing ratios (solid blue) by the MIAWARA instrument for May 2002 using the broadband acousto-optical spectrometer (figure 4) are compared to a single HALOE water vapour profile (solid red) measured on April 10th 2002 at 44.95°N

/ 21.94°E (best coincident measurement in geographical location and time). The HALOE profile, which has a higher vertical resolution, is convoluted with the averaging kernel matrix and the a priori profile of the MIAWARA retrieval according to *Tsou et al. (1995)* to achieve an identical resolution of both profiles and to account for the a priori contribution in the MIAWARA retrieval. The profiles retrieved by MIAWARA and HALOE show an identical shape, but the MIAWARA mixing ratio values are slightly lower than those of HALOE (in the order of 0-1 ppmv). These differences are clearly within the large 2 σ uncertainties (dashed red) of the HALOE measurements. The HALOE measurement uncertainties are large, because the profile consists only of one HALOE sunset measurement. Due to the large measurement uncertainties in the HALOE profile and the not perfect temporal and spatial agreement of the MIAWARA and HALOE measurements only a qualitative comparison is possible in this specific case.

4.2 Water Vapour Profile August 2002

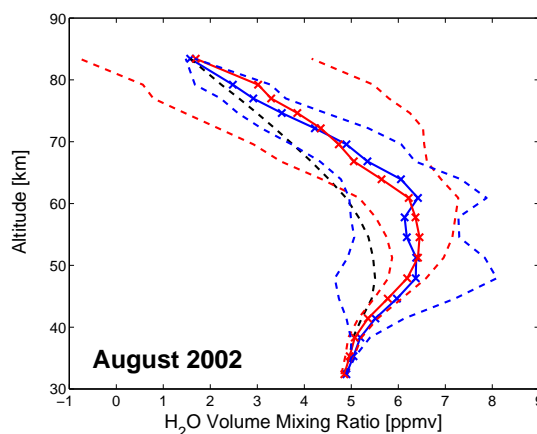


FIG. 5: Water vapour profile retrieved by a narrowband spectrometer 3-day averaged spectrum in August 2002 (solid blue). The dashed blue lines represent the 2 σ for the observational error. The data is compared with a 2-year mean HALOE 40°-50°N monthly mean water vapour profile for August 1998/1999 (solid red) with plotted 2 σ of the HALOE measurement error (dashed red). The dashed black line represents the a priori profile used in the retrieval process.

The values for the obtained water vapour mixing ratios (solid blue) by the MIAWARA instrument for August 2002 using the narrowband chirp transform spectrometer (figure 5) are compared to a two year average of HALOE 40°-50°N monthly zonal mean water vapour profiles (solid red). The HALOE profile is again convoluted with the averaging kernel matrix and the a priori profile of the MIAWARA retrieval according to *Tsou et al. (1995)* to achieve an identical resolution of both profiles and to

account for the apriori contribution in the MIAWARA retrieval.

The profiles retrieved by MIAWARA and HALOE monthly zonal means agree very well. The differences in the water vapour mixing ratios are clearly within measurement uncertainties (dashed blue (MIAWARA) and dashed red (HALOE)). The MIAWARA profile reports a double peak in the water vapour profile at approximately 47 and 62 kilometers that is not measured by the HALOE measurements. This double peak is also measured by a ground-based microwave radiometer located at the Onsala Space Observatory (Sweden) (*P. Forkman: personal communication 2002*). The single peak of the HALOE profile is located in between those peaks measured by MIAWARA at 55 kilometers.

5. CONCLUSION

The comparison of the obtained water vapour profiles by our instrument to HALOE monthly mean values show very good agreement for the measurements made in August 2002. The measurements taken in May 2002 show a slight underestimation of the water vapour amount in the middle atmosphere by the MIAWARA instrument compared to a single HALOE measurement on April 10th 2002. Nevertheless the MIAWARA measurements are clearly within the large HALOE measurement uncertainties. The differences may originate in the spatial and temporal distance of the MIAWARA and HALOE measurements.

Regarding these first results, we conclude that the MIAWARA instrument is suitable for longterm, ground-based water vapour measurements in the range of 30–80 kilometers.

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ACKNOWLEDGEMENTS

Beat Deuber's work was supported by the Swiss National Science Foundation under grant NCCR climate. We like to thank the Institute of Meteorology and Climate Research at Forschungszentrum Karlsruhe, Germany for lending us their chirp transform spectrometer, N. Lautié (Université de Bordeaux) for providing the HALOE monthly mean data, NASA Langley Data Center for providing the HALOE dataset for April 2002 and the ARTS / QPack developing team for providing the retrieval software.