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Ground-based measurements of middle atmospheric water vapor at 183 GHz

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Abstract. We present here the first ground-based observations of stratospheric/mesospheric H_2O emission at the $3_{1,3} \rightarrow 2_{2,0}$ resonance (183.3101 GHz of central frequency). The spectra were obtained in January 1991 and January 1994 using the *Institut de Radioastronomie Millimétrique* (IRAM) 30-m radiotelescope located on Pico Veleta, Spain, (altitude 2870 m, latitude 37°N), during very dry tropospheric conditions (total precipitable water within the range 0.2-0.3 mm above the observation site). Microwave studies of stratospheric and mesospheric H_2O profile have been carried out so far mostly by means of observations of the weak $6_{1,6} \rightarrow 5_{2,3}$ resonance at 22.2351 GHz. Some measurements at 183 GHz were previously obtained from airborne observations. The water vapor abundance in the troposphere is, in most cases, so high that the atmosphere appears optically thick at 183 GHz. However, we show that emission from the stratosphere and mesosphere can be sometimes detected from the ground (allowing upper stratospheric and mesospheric water vapor profiles to be obtained). We use a generalized non linear radiative transfer code in order to perform a least squares fit of the observed spectra. The derived H_2O abundances are consistent with most measurements at 22 GHz. We suggest the possibility of carrying out this kind of observation in some selected sites during a significant fraction of the whole winter season. The required integration times to get a given signal-to-noise ratio are much shorter at 183 GHz than at 22 GHz.

1. Introduction

Water vapor plays an important role in the physics and chemistry of the middle atmosphere because it is a major source of radicals and a tracer molecule of stratospheric dynamics (due to a photochemical lifetime of several months for middle atmospheric regions). Water vapor in the upper stratosphere and lower mesosphere is mainly produced from the oxidation of methane. On the other hand, it is chemically lost by means of a slow reaction with $O(^1D)$, producing OH. This explains the long lifetime of H_2O in these regions and the importance of transport mechanisms for its overall distribution [*Russell*, 1987; *Le Texier et al.*, 1988].

Microwave ground-based measurements of middle atmospheric water vapor can be performed at 22 GHz on a regular basis [*Tsou et al.*, 1988; *Olivero et al.*, 1986; *Bevilacqua et al.*, 1990]. However, this line is very weak; typical emissions are, for example, ~100 times weaker than the mesospheric CO lines at 115 and 230 GHz. Long integration times (several hours) are thus necessary to infer the H_2O profile. The 183 GHz line, on the other hand, has an intensity S[300 K] = 2.254×10^{-12} cm^2Hz which is ~200 times larger than the one of the 22-GHz line. Therefore, this line is best suited for accurately measuring and monitoring the water vapor mixing ratio profile. It can be observed from aircraft and balloon experiments [*Peter and Künzi* [1988] observed it from aircraft providing information on water vapor at stratospheric and mesospheric levels). However, this line becomes usually optically thick when the radiation travels across the troposphere, preventing the stratosphere to be sounded from the ground. It has been suggested to observe the far wings of this line (less optically thick) by means of ground-based radiometry (in the region 140-181 GHz) to study water vapor up to ~8-10 km [*Schaerer and Wilheit*, 1979]. Such a technique has actually been employed by *Askne and Skoog* [1983]. From a satellite point of view, the problem is very different. In fact, actual and future meteorological instruments at nongeostationary satellite orbits use several channels in the region 183.31±7 GHz in order to retrieve the tropospheric humidity profile (Special Sensor Microwave/T2 actually on board DMSP satellites and AMSU-B on board TIROS-N at the beginning of 1997).

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In some selected dry areas, like Andalucia in Spain, and at high mountain sites, periods of time with very low-integrated water vapor amounts ($\leq$ 2 mm) occur during a significant fraction of the winter season. From the meteorological database of the Pico Veleta Observatory, the integrated tropospheric H_2O amount during 18% of the winter season (averaged data from 1984 to 1990) was less than 2 mm above the telescope site (2870 m of altitude). Under such conditions, a significant tropospheric transmission is expected even at the center frequency of the $3_{1,3} \rightarrow 2_{2,0}$ H_2O rotational line (183.3101 GHz) (see *Cernicharo et al.* [1990] and Table 1). As a consequence, stratospheric and mesospheric water vapor can be studied from the ground by means of spectroscopic observations at this frequency.

We present here the first report of ground-based detections of the stratospheric/mesospheric 183-GHz water vapor line from which the H_2O profile between ~30-65 km is inferred. The primary goal of our work is to demonstrate that measurements of the strong 183-GHz rotational resonance of water vapor could be achieved on a relatively frequent basis during wintertime in selected sites (above 2.5 km of altitude). For example, we suggest the Pico Veleta site (top at 3400 m), the Jungfraujoch station in Switzerland (3500 m), and the Mauna Kea Observatory in Hawaii (4200 m). This would allow us to study and monitor middle atmospheric water vapor with much shorter integration times than using traditional 22-GHz measurements.

This paper is organized as follows: We present in section 2 a description of the instrument and the observations, section 3 is devoted to the analysis of the data, discussions and conclusions are given in section 4.

2. Instruments and Observations

The H_2O 183-GHz observations presented in this paper were carried out in January 1991 and January 1994 using the 30-m IRAM radiotelescope at Pico Veleta, Spain (altitude 2870 m), at different elevations (from 25 deg. to 85 deg.). This instrument is normally devoted to astrophysical research. The initial goal of the observations was the search for maser emission of water vapor at 183 GHz from interstellar and circumstellar sources [*Cernicharo et al.*, 1990] which can only be achieved during very dry atmospheric conditions. Absolute calibration of the atmospheric emissivity was carried out using two absorbers at different temperatures: cold (liquid N_2) and warm(ambient). The Superconducting Insolator Superconducting (SIS) receivers were connected to two filterbanks, 512 x 1 MHz and 256 x 100 kHz for spectral analysis. The Half Power Beam Width (HPBW) at 183 GHz is ~20 arcseconds. The observable amount is an "antenna temperature" ($T_{sky,meas}$). It receives contributions coming from the ambient temperature T_{env} as well as the sky brightness temperature at the corresponding frequencies in the two bands of the receiver (T_{B_s} and T_{B_i}). It can be written according to

$$T_{sky,meas} = T_{env}(1-\eta) + \eta[G_S T_{B_s} + G_I T_{B_i}] \quad (1)$$

where η is the coupling coefficient of the antenna with the sky ($\eta \leq 1$), T_{env} is the ambient temperature, and G_S and G_I are the relative gains of the "signal" and "image" bands of the system (G_S+G_I=1). T_{env} and η are assumed to be the same for the signal and image sideband. In January 1991, the observations were performed in "lower sideband mode" (H_2O line observed in the lower sideband) with image sideband rejection. The parameters η and G_S were estimated to be 0.9 and 0.8, respectively. The 1991 spectra were folded with respect to their central frequency in order to increase the signal-to-noise ratio and to remove linear baseline effects. As a consequence, the usable spectrum has an effective coverage of 2 x 130 MHz only because the telluric line was not centered in the back end (the backend was centered at the expected central frequency for the

Table 1. Zenithal Atmospheric Transmission at the 183.310-GHz H_2O Line Above 2.9 and 4 km Altitude for Various Integrated H_2O Columns Above 2.9 km

Tropospheric H_2O (mm)		Zenith Atmospheric Transmission (ν_c= 183.310 GHz)							
		ν_c- 0 MHz		ν_c- 50 MHz		ν_c-100 MHz		ν_c-150 MHz	
2.9 km to ∞	4.0 km to ∞	2.9 km to ∞	4.0 km to ∞	2.9 km to ∞	4.0 km to ∞	2.9 km to ∞	4.0 km to ∞	2.9 km to ∞	4.0 km to ∞
2	1.154	0.013	0.047	0.014	0.053	0.015	0.055	0.015	0.057
1	0.577	0.103	0.201	0.117	0.226	0.120	0.230	0.123	0.236
0.5	0.289	0.296	0.416	0.335	0.465	0.340	0.472	0.345	0.479
0.3	0.173	0.452	0.557	0.510	0.623	0.517	0.631	0.523	0.637
0.1	0.058	0.689	0.744	0.776	0.830	0.786	0.840	0.792	0.846

The standard T(P) profile assumed in the calculations is U.S. Standard Atmosphere (1962) corresponding to midlatitudes and wintertime. For this profile temperature and pressure at 2.9 km are 262.1 K and 703 mbar. Water vapor was assumed to decrease exponentially with a scale height of 2 km. The absorption model used is taken from *Liebe*, [1993]. The second column gives the integrated H_2O amount above 4 km altitude, corresponding to the amount above 2.9 km given in the first column. This gives an idea of expected situations at observatories like Jungfraujoch and Mauna Kea.

observed astrophysical object, shifted from the telluric frequency due to the Doppler effect of the source). In January 1994, observations were made using upper sideband mode without image sideband rejection. In this case, η=0.9 and G_S/G_I=1.3. As a result of the intermediate frequency of the system (3.92 GHz), the image sideband in this mode is centered at around 175.47 GHz. As a consequence, an ozone resonance at 175.446 GHz showed up in the spectra via the image sideband and had to be taken into account in the retrieval. We assumed a U.S. Standard Atmosphere (1976) winter O_3 profile and, in order to reduce the errors associated with this assumption, we fitted only the high-frequency wing of the H_2O line, which is less contaminated by ozone.

In some cases, the 1994 raw data show the effects of standing waves that form between the different mirrors of the quasi-optical part of the system. The period of the ripples was ~20 MHz, and their amplitude was ~1 K. A Fourier transform analysis was performed to remove these waves. Figure 1 shows examples of obtained spectra after the data reduction along with the corresponding fits. Integration times for these observations are of the order of a few tens of seconds.

3. Data Analysis

Our inversion procedure consists in the calculation of brightness temperature for both receiver's bands using an atmospheric radiative transfer code. The results, as a function of the H_2O profile, are compared to the observations through equation (1). The H_2O profile is inferred only in a limited number of selected atmospheric layers, depending on frequency resolution and total bandwidth of the spectrum. In order to choose these layers, the Backus-Gilbert inversion procedure (see, e.g., *Rodgers*, [1976], *Bevilacqua and Olivero* [1988]) gives a natural way to predict vertical resolution, correlation between information from different layers, and error estimates. The idea is to find the abundance of the gas in a layer centered at z_j, optimize the vertical resolution and minimize the errors associated to channel noise. For this, we search a set of functions that minimizes a weighted sum of the error and the altitude range (related to the final vertical resolution) of the so-called averaging kernel (like a weighting function for the atmospheric gas under study). A Lagrangian multiplier γ acts as a trade-off parameter for

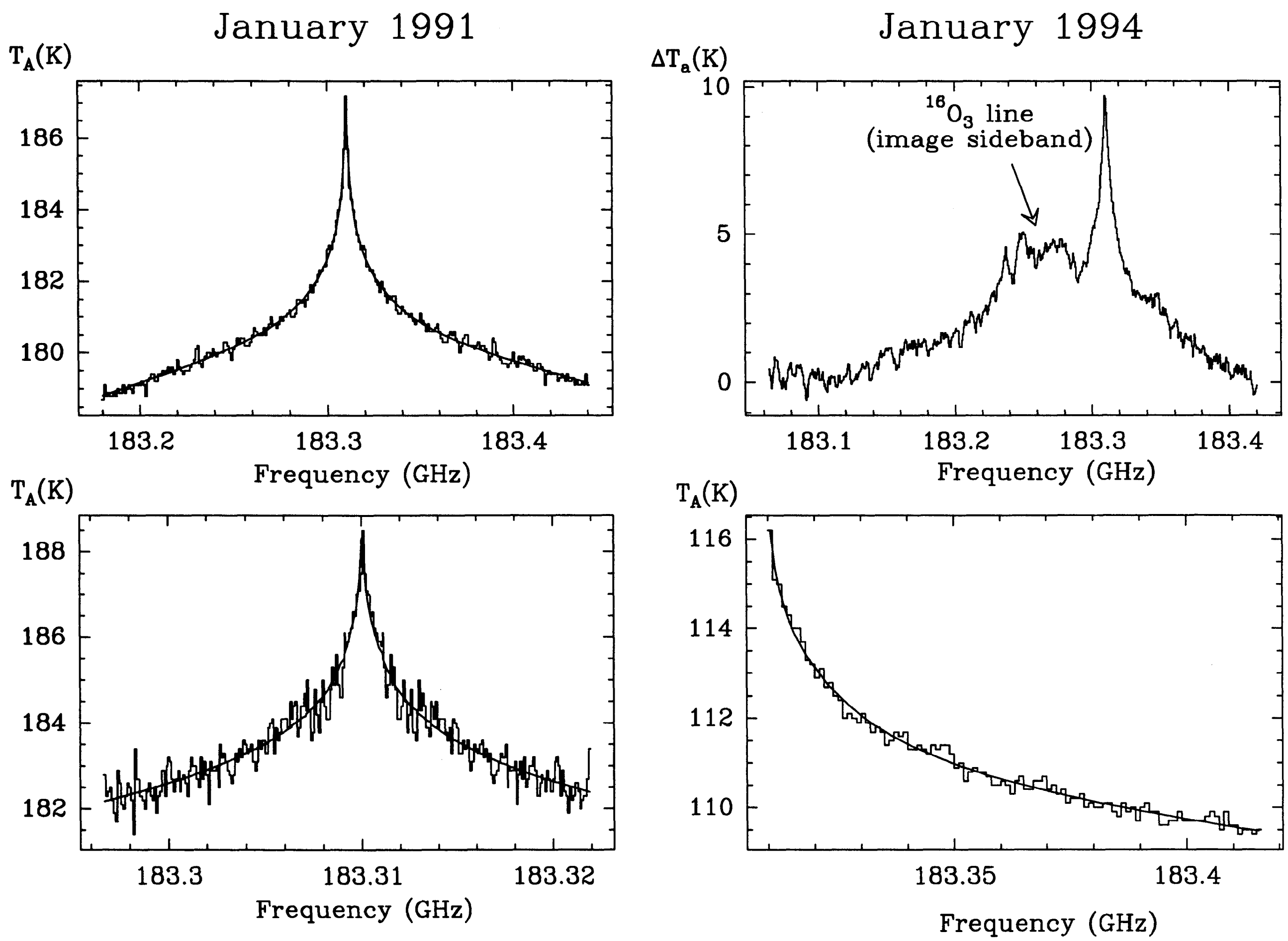

Figure 1. (left) Two spectra from January 1991 and the corresponding fits obtained from our inversion technique. (right) A spectrum from January 1994 showing the presence of an ozone line in the upper sideband (top spectrum). After the coaddition of several spectra taken at the same elevation, the inversion algorithm was applied to the less contaminated wing (bottom spectrum).

this weighting (see, in particular *Bevilacqua and Olivero* [1988]). The first step in the analysis is to calculate a set of H_2O weighting functions associated to the individual frequencies of the spectra. Figure 2 shows these functions normalized to unity. To compute them, the U. S. Standard Atmosphere (1976) was adopted, together with a standard water vapor profile described below, corresponding to 0.3 mm of precipitable water vapor above the observation site. As shown by *Bevilacqua and Olivero* [1988], the optimum averaging kernel functions fall within the central part (50-60%) of the altitude range covered by the weighting functions associated to the individual frequencies of the espectrum [see also *Rodgers*, 1976]. From this, we infer that the combination of the two spectrometers used during the 1991 observations shown in Figure 1 allows us to define the set of averaging kernel functions shown in Figure 2. In such averaging kernel functions, the trade-off is made mainly in favor of the accuracy at the expense of the vertical resolution. We propose from these calculations the use of three layers where H_2O amounts would be free parameters for the inversion procedure. We describe these layers in Table 2.

Correlations between the averaging kernels (A_j) of Figure 2, defined as

$$C = (\int_{\infty}^{0} A_j(z)A_k(z)dz)/[\int_{\infty}^{0} A_j^2(z)dz \cdot \int_{\infty}^{0} A_k^2(z)dz]^{\frac{1}{2}} \quad (2)$$

are equal to 0.292 for $A_{59.5km}$-$A_{46.5km}$, 0.066 for $A_{59.5km}$-A_{36km}, and 0.191 for $A_{46.5km}$-A_{36km}.

A similar analysis was performed for the January 1994 observations, leading to the use of only two layers in the case of the 1994 spectrum shown in Figure 1: 33-44 km and 44-56 km. The correlation between their averaging kernels ($A_{38.5km}$-A_{50km}) is 0.236. Differences between the number and vertical extent of the selected layers for the 1991 and 1994 data come from two factors: (1) only the 512 x 1 MHz back end was used in 1994 and (2) only 106 channels (and on one line wing only) were used for inversion of the 1994 spectrum shown in Figure 1. These layers are also described in Table 2.

Once this preliminary analysis is achieved, the H_2O amounts in the selected layers are varied in order to

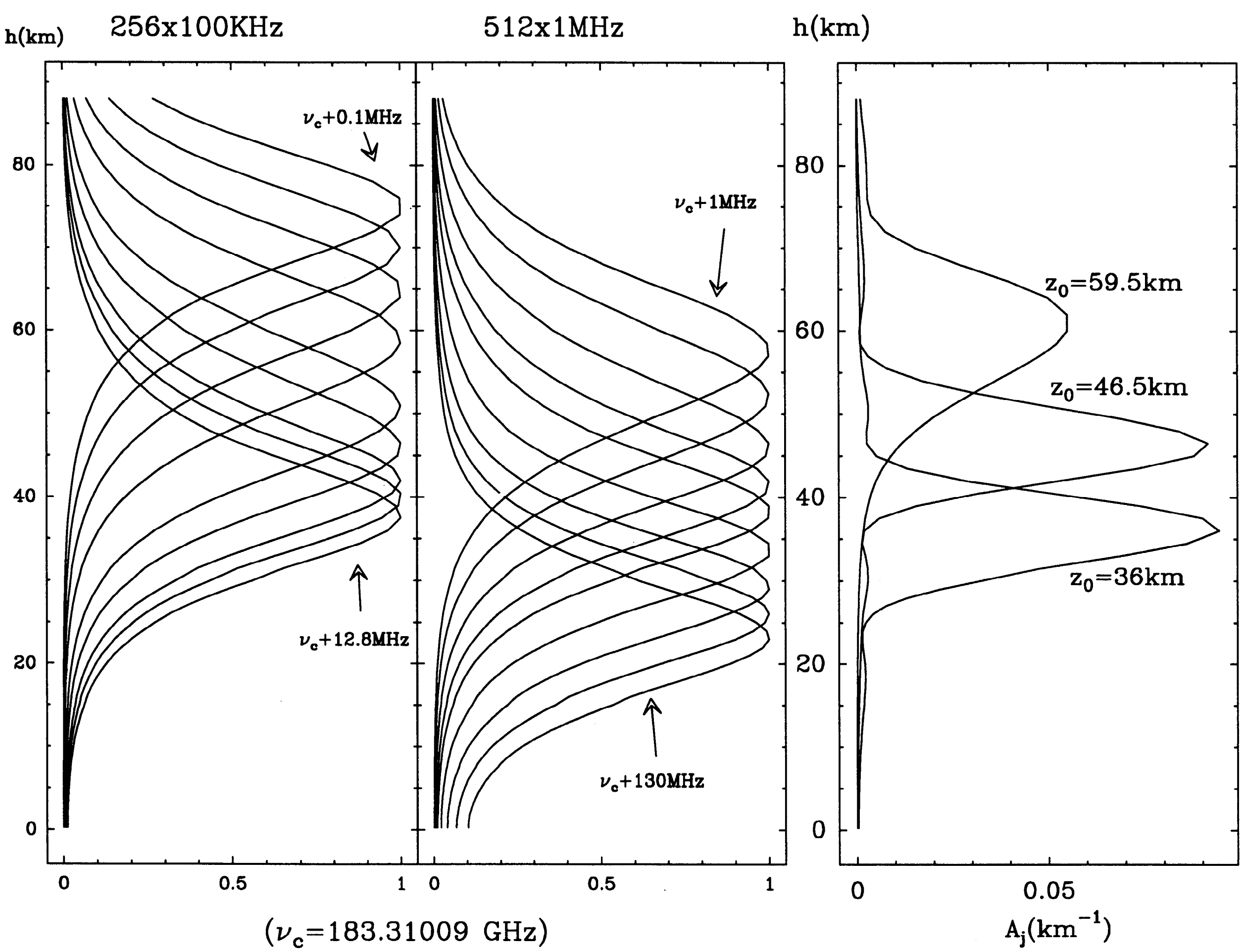

Figure 2. Normalized H_2O weighting functions corresponding to the two spectrometers used during the January 1991 observations and averaged kernels calculated from these weighting functions. This analysis allows to define the layers in which information on water vapor can be retrieved .

Table 2. Description of the Layers Selected for Retrieval of the H_2O Profile From January 1991 and January 1994 Observations

z_0	layer, km	Trade-off γ (K^2cm^7)[a]	$\mid R_i(\text{layer}) \mid$[b] $K^{-1}cm^{-3}$	H_2O density (cm^{-3}) (for 2 ppmv)
		January 1991: 230 x 1 MHz + 256 x 100 kHz		
36	31-41	10^{-16}	$7.75 \cdot 10^9$	$3.92 \cdot 10^{11}$
46.5	41-52	$5 \cdot 10^{-16}$	$2.88 \cdot 10^9$	$8.14 \cdot 10^{10}$
59.5	52-67	$5 \cdot 10^{-12}$	$5.58 \cdot 10^7$	$1.73 \cdot 10^{10}$
		January 1994: 106 x 1 MHz (One Wing)		
38.5	33-44	10^{-15}	$2.92 \cdot 10^9$	$2.77 \cdot 10^{11}$
50	44-56	$5 \cdot 10^{-16}$	$1.33 \cdot 10^9$	$5.18 \cdot 10^{10}$

[a] The trade-off parameter (γ) weights the errors associated with data noise and the vertical resolution obtained when calculating the averaged kernels (for more details, see *Bevilacqua and Olivero* [1988]). The limits of the selected layers are defined by the altitudes at which the averaged kernels are equal to half their peak value. Vertical resolution could be improved by about 2 km but at the expense of a large increase of the errors associated to spectral noise. The typical H_2O amounts given in the 5th column correspond to a middle atmospheric mixing ratio of 2 (ppmv). Calculations were performed using the same atmospheric profile of Table 1.

[b] From the rms noise in the measurements (in K), $\mid R_i \mid$ allows to quantify the error in the estimated H_2O amount for each layer (associated to an averaged kernel function).

fit the spectrum following a nonlinear iterative least squares algorithm. An additional free parameter in this procedure is the integrated tropospheric water vapor amount. This parameter is adjusted in order to account for the $T_{sky,meas}$ level of the end channels of the 1 x 512 MHz spectrometer. Specifically, we assume an exponentially decreasing H_2O mixing profile up to ~15 km with a scale height of the order of 2-2.5 km. Above 15 km, an initial profile is assumed, which has a constant water vapor mixing ratio with altitude. An a priori information on the T(P) profile is also required. We take the midlatitude winter U.S. Standard Atmosphere (1976) as our nominal profile, but we have also tested other profiles in order to estimate the errors associated

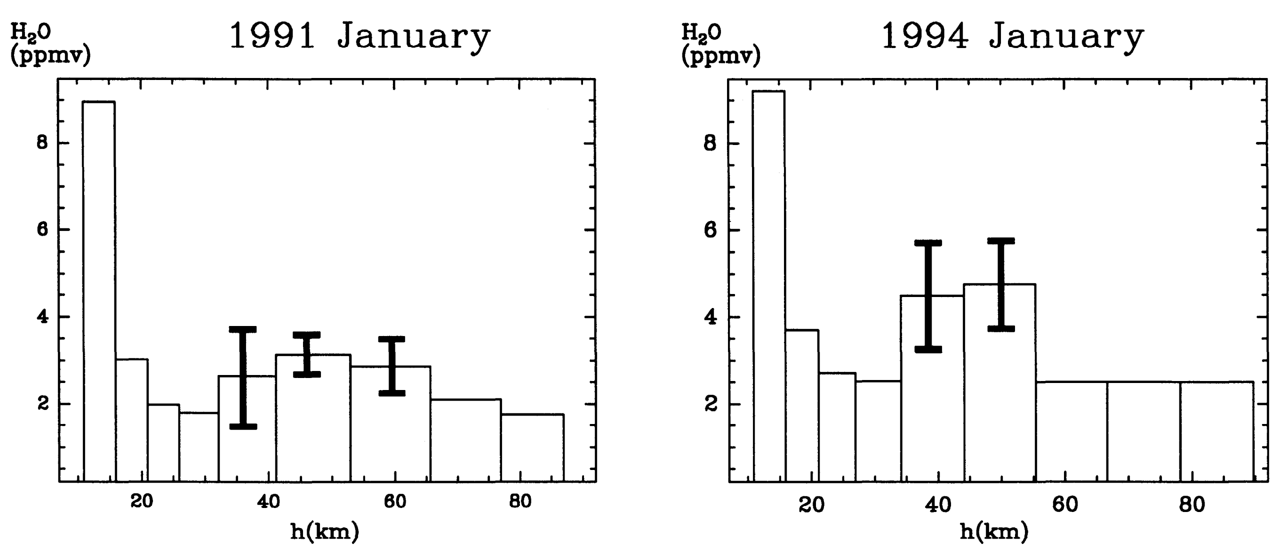

Figure 3. Water vapor profiles in ppmv retrieved from the observations presented in Figure 1: (left) January 1991; (right) January 1994. Boxes without error bars correspond to atmospheric levels where the shape of the H_2O mixing ratio is assumed as a priori information (however, the integrated amount in these layers is a free parameter, see section 3). For the layers in which the H_2O amounts are individually derived from the fit (see Table 2), the estimated error bars are given. Integrated tropospheric water vapor corresponding to the observations of Figure 1 was found to be around 0.25 mm.

to the choice of the T(P) profile. The Doppler broadening mechanism is taken into account at altitudes where it becomes nonnegligible [see *Rosenkranz*, 1993].

Figure 1 shows examples of observed spectra (after data reduction) taken in January 1991 and January 1994 and the corresponding fits. The calculated H_2O profiles from these spectra are shown in Figure 3. Boxes with error bars correspond to values found by the inversion algorithm. Figure 4 shows other 1994 spectra (of worse quality because of shorter integration time) and their corresponding fits. The main uncertainties on the retrieved mixing ratios come from the a priori information, the spectra noise, and the instrumental parameters.

3.1. Errors From a Priori Information

Using different atmospheric T(P) profiles within the U.S. Standard Atmosphere (1976) set as a priori information for the inversion procedure, we find an uncertainty of about ±10% on the retrieved middle atmospheric H_2O amounts for both the 1991 and 1994 spectra sets. The shape of the tropospheric water vapor distribution (assumed to exponentially decrease with altitude) could be a source of uncertainty to the retrieved H_2O amounts above 30 km (only the shape, because its integrated amount is calculated by the code). The reason for this is that the tropospheric contribution to the spectral shape is essentially flat over the ~200-MHz interval around the line center due to the relatively high pressures involved. The influence of the actual tropospheric H_2O profile on the line shape is therefore negligible (although it significantly affects the total level of atmospheric emissivity and the absorption of middle atmospheric information).

3.2. Errors From Spectra Noise

Under the assumption of zero correlation of the noise between the spectrometer channels, we have estimated the error due to channel noise using the method described by *Bevilacqua and Olivero* [1988] [see also *Rodgers*, 1976]. The typical noise level in our spectra is 0.1-0.2 K, inducing relative errors in the estimation of [H_2O] as small as ±3% in the worst case. Taking into account the existence of some correlation between the averaging kernels of the considered layers (see Figure 2), we estimate that this effect may contribute up to ±10% of error in the calculated H_2O mixing ratios for both data sets. We stress that improving the vertical reso-

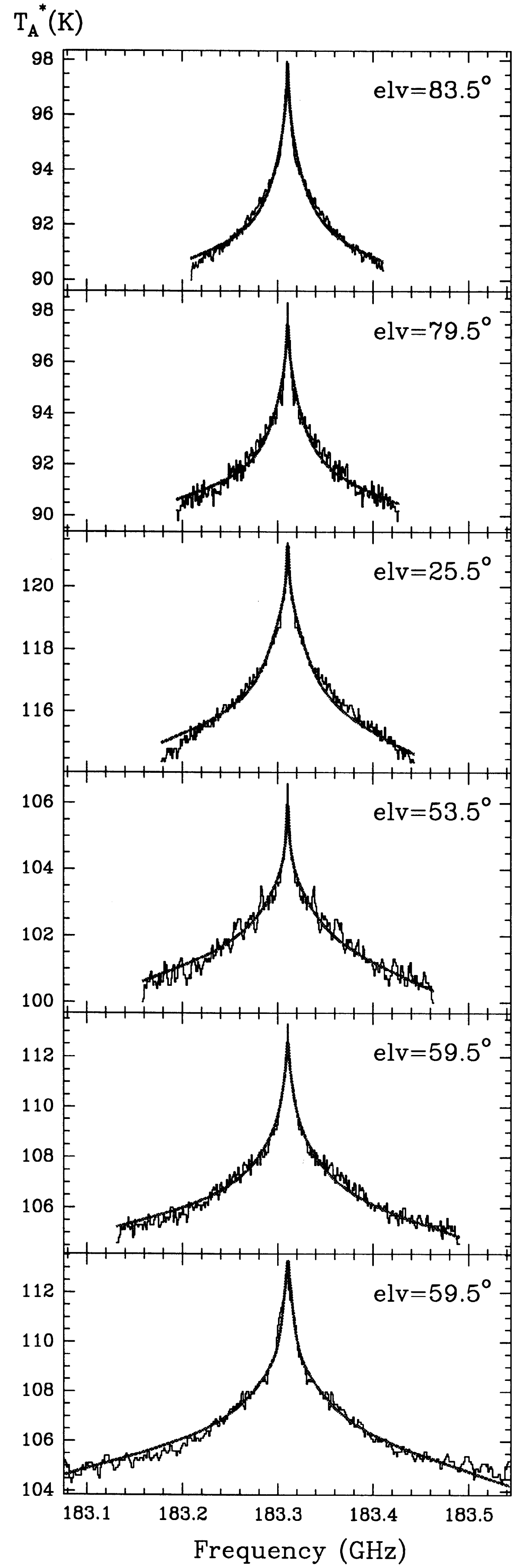

Figure 4. Other 1994 observations (after data reduction) and the corresponding fits obtained following the inversion procedure presented in this paper. Integrated tropospheric water vapor run from 0.18 to 0.3 mm, and the derived upper stratospheric and lower mesospheric water amounts are compatible with those presented for 1994 in Figure 3. Integration times are of the order of a few seconds.

lution from 10 to 8 km for the layer centered at $z_0 =$ 36 km corresponding to the low-resolution 1991 spectrum of Figure 1 would multiply this source of error by a factor of about 15 (see some examples in the work by *Bevilacqua and Olivero* [1988]).

3.3. Errors From the Instrumental Parameters

The most important source of errors is the calibration of the measurements. Assuming a satisfactory temperature stability of the two absorbers used for the calibration, the error mainly comes from the uncertainty in the coupling coefficient η and the relative gains of the bands of the receiver G_S (see equation (1)). These parameters are known within an accuracy of ~6%. In order to estimate the impact of this uncertainty, we have carried out the inversion for different values of η and G_S within a range of ±3% around the assumed values ($\eta = 0.9$ and $G_S = 0.8$). For the 1991 spectra shown in Figure 1, the calculated H_2O amounts show, because of this uncertainty, an error bar of ±35%. For the 1994 spectrum, the associated error is ±25%. Assuming that the total uncertainty is the quadratic sum of the individual uncertainties, and the existence of no other error sources, we obtain the error bars shown in Figure 3.

4. Discussions and Conclusions

Two sets of atmospheric observations of the 183.310-GHz H_2O line at different elevation angles have been analyzed. Results of individual fits are consistent with most previous measurements (see, for example, *Tsou et al.* [1988] and *Bevilacqua et al.* [1990] at 22 GHz) and models [see *Le Texier et al.*, 1988]. A good agreement is also found between our results of 1994 and the 183 GHz measurements of *Peter and Künzi* [1988] obtained with an airborne sensor at a flight level of 10 km. The lowest latitude reached by these measurements is 45 deg. N. At this latitude, they found H_2O mixing ratios in the range 4.0-5.3 parts per million by volume (ppmv) for altitudes between 25 and 60 km with a maximum at 50 km, to be compared with values between 3.5 and 6 ppmv that we find for 33-56 km for a latitude of 37°N.

For the first time to our knowledge the measurements presented in this paper allow us to study the middle atmosphere water vapor profile at 183 GHz from the ground. This demonstration of feasibility is the main interest of this admittedly limited set of observations. The observed atmospheric H_2O lines have been analyzed using a generalized nonlinear least squares fit in which the free parameters are the integrated tropospheric amount of water vapor and its abundance at some selected layers. Our observations prove that middle atmospheric H_2O amounts can be measured from the ground at 183 GHz. On the basis of the meteorological statistics at the Pico Veleta site, we propose that this kind of measurement can be done during a significant fraction of the winter season in some selected high mountain sites, that is above 2.5 km of altitude over dry areas (see Table 1). Observatories and meteorological stations at altitudes from 3.5 to 4.2 km are actually available. As a result of the relatively high intensity of the 183-GHz emission, much shorter integration times (a few times 10 seconds in our case) than for the 22-GHz H_2O emissivity observations (up to 24 hours, see *Bevilacqua et al.* [1990]) are required to achieve the same signal-to-noise ratio. Therefore, using the 183-GHz emission could allow a more accurate retrieval of the middle atmosphere H_2O profile than from 22-GHz measurements. At this last frequency, the work has also been carried out by means of solar absorption [*Olivero et al.*, 1986; *Tsou et al.*, 1988] due to the weakness of the line as well.

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