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► **To cite this version:**

Erwan Motte, Philippe Ricaud, Mathieu Niclas, Benjamin Gabard, Fabrice Gangneron. A 22 GHz mobile microwave radiometer for the study of stratospheric water vapour. IGARSS, 2007, Barcelone, Spain. hal-00224731

**HAL Id: hal-00224731**

**<https://hal.science/hal-00224731>**

Submitted on 17 Mar 2021

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# A 22 GHz Mobile Microwave Radiometer for the Study of Stratospheric Water Vapor

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**Abstract**—We present a new compact ground-based microwave radiometer dedicated to the study of middle atmospheric water vapor. The instrument detects the  $6_{16} - 5_{23}$  H<sub>2</sub>O transition line at 22.235 GHz. This radiometer has been designed to be easily transported and operated during measurement campaigns in remote places. The first retrievals, performed with the MOLIERE inversion and radiative transfer software, show good agreement with MIAWARA, the 22 GHz Radiometer developed at the University of Bern, Switzerland, and the Microwave Limb Sounder instrument onboard the Aura satellite.

## I. INTRODUCTION

Water vapor (H<sub>2</sub>O) plays a major role in the climate system of the Earth since it is the main greenhouse species emitting in the infrared domain. The amplitude of the stratospheric H<sub>2</sub>O trend currently observed remains unexplained [1]. H<sub>2</sub>O is a key constituent of the mesospheric ozone chemistry and controls the formation of Antarctic stratospheric clouds involved in the ozone (O<sub>3</sub>) depletion process. Some satellite instruments measure or will measure H<sub>2</sub>O in the stratosphere and need ground-based measurements for validation. Currently only few instruments exist, mainly located in the northern hemisphere [2], [3], [4]. Most of them belongs to the Network for the Detection of Atmospheric Composition Change (NDACC).

We present a new compact ground-based radiometer for the study of stratospheric water vapor. The instrument detects the  $6_{16}$ - $5_{23}$  H<sub>2</sub>O transition line at 22.235 GHz. This microwave radiometer has been designed to be easily transported and operated during measurement campaigns. This Mobile Radiometer (MobRa) is the first step of a project aiming at the development of two instruments to be installed at the Reunion Island Observatory (21°S, 55°E) and at the Dome C Concordia station in Antarctica (75°S, 123°E). The scope of this project is to provide information about the long-term trends of water vapor in the tropics and at southern high latitudes.

The MobRa instrument and the measurement principles are detailed in section II. The scientific ground-segment including radiative transfer and inversion method is developed in section III. Preliminary results are presented in section IV.



Fig. 1. The MobRa instrument for the measurement of stratospheric H<sub>2</sub>O on the terrace of the Laboratoire d'Aérologie, Toulouse, France.

## II. INSTRUMENT

### A. Measurement principle

The MobRa instrument (Fig. 1) measures the intensity of the H<sub>2</sub>O microwave pressure-broadened emission line at 22.235 GHz [5]. In the atmosphere, as the pressure decreases exponentially with height, vertical profiles of water vapor can be retrieved from the line shape. The maximum retrieval height is limited by the spectrometer resolution and the Doppler broadening effect, while the lower retrieval height is limited by the instrument total bandwidth.

### B. Description

The instrumental block diagram of the MobRa instrument is presented in Fig. 2. It is a compact radiometer (1x1x1.2 m<sup>3</sup>, ~100 kg), designed to be easily transported and modified. The receiver is composed of a Potter horn having a 12° FWHM beamwidth, followed by an uncooled low noise High Electron Mobility Transistor (HEMT) amplifier exhibiting a noise figure of 1.5. The heterodyne single-side band (SSB) mixing stage downconverts the signal to the intermediate frequency (IF) band 1.6-2.5 GHz. The total receiver noise temperature of the

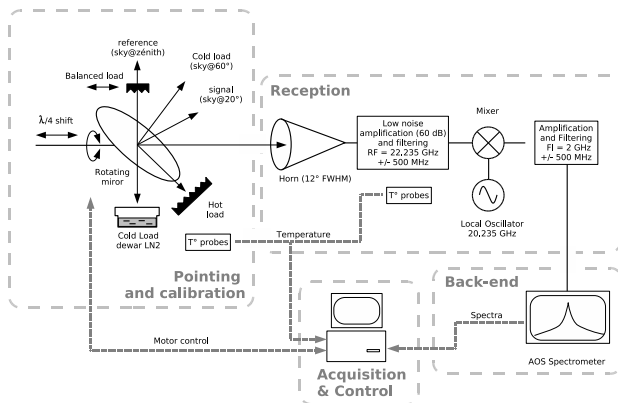


Fig. 2. The H<sub>2</sub>O MobRa instrument block diagram.

receiver  $T_{rec}$  is less than 200 K SSB and the total front-end amplification is about 80 dB. The front-end is in a temperature-controlled shielded enclosure. The signal is finally analyzed by an acousto-optical spectrometer (AOS) having an effective bandwidth of 850 MHz on 1,600 effective channels and an Allan variance stability of 10 s. Control and acquisition routines are operated from a standard PC running Labview.

### C. Measurement method

The radiometer uses the balanced beam-switching method described in [6], i.e. measures a difference  $[S - R]$  between a Signal beam  $[S]$  at low elevation, having a long pathlength in the atmosphere and a Reference beam  $[R]$  at high elevation. This method prevents the system to be sensitive to gain non-linearities and tropospheric opacity variations. In our case,  $[S]$  has an elevation ranging from 20° to 35°, depending on the tropospheric conditions, and  $[R]$  is directed towards zenith. A piece of microwave absorber ECCOSORB AN-74 is inserted into the reference beam to compensate for the lower atmospheric emission. Each  $[S - R]$  measurement cycle takes about 1 minute, including balancing, and corresponds to an effective integration time of about 10 seconds.

### D. Tropospheric properties

To be able to correct the measurement for the tropospheric contribution, we consider the troposphere as an isothermal layer of mean temperature  $T_{trop}$  and opacity  $\tau_{trop}$ .  $T_{trop}$  is estimated using only the ground temperature from the relation presented in [7]. Every 30 minutes, a so-called tipping-curve measurement is performed, scanning the sky at different elevations to derive  $\tau_{trop}$  according to the method described in [5].

### E. Calibration

The calibration of the measurement spectrum in brightness temperature (radiation intensity scaled in Kelvins, related to the intensity of the radiation emitted by a black body at a corresponding physical temperature) is done by observing two targets considered as black bodies

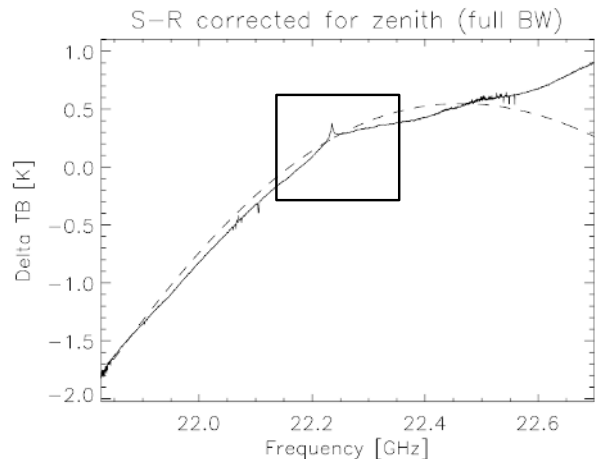


Fig. 3. Solid line: Full-Bandwidth spectrum measured after one day of integration. Dashed line: Fit of the tropospheric contribution. The bold square shows the effective bandwidth used for the retrieval of vertical profiles.

at different known physical temperatures. The *hot load* consists of a piece of ECCOSORB H1 microwave absorber at ambient temperature, and the cold load is a piece of ECCOSORB CV3 microwave absorber in liquid nitrogen (LN2). A calibration measurement is done every 15 minutes. The set up has been modified in order to be able to use sky at 60° elevation as a cold load. Nevertheless, preliminary results from this method are still showing rather large differences (10-20 %) with respect to LN2 cold load calibration.

### F. Baseline undulations

The so-called *baseline ripples* caused by reflections within the radiometer prevent the instrument from retrieving information in the lower stratosphere. The baseline ripples are periodic signals superimposed to the spectra. Their spectral period is directly related to the distance between the reflecting obstacles. In order to minimize these measurement artefacts, we installed a path-length modulator which translates the mirror subsystem back and forth.

### G. Level 1 processing

Level 0 individual spectra (raw uncalibrated  $[S - R]$  spectra) are filtered according to variations in gain, ground temperature, and then calibrated in brightness temperature and corrected for tropospheric attenuation and elevation dependence. Individual  $[S - R]$  spectra are then daily averaged, usually yielding to 3-4 hours of effective integration time per day, in order to reduce the noise level down to  $\sim 10$  mK, for a line amplitude of  $\sim 200$  mK. A typical 24 h-integrated spectrum is presented in Fig. 3. The remaining tropospheric contribution is removed by fitting to the whole spectrum a 5th-order polynomial function.

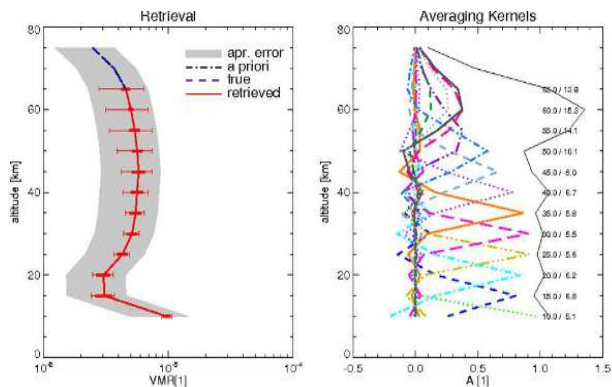


Fig. 4. (Left) Vertical profiles of  $\text{H}_2\text{O}$  corresponding to the *a priori* information (black), the true atmosphere (blue), and the retrieved information (red). The red thin horizontal lines correspond to the total error, the red thick lines correspond to measurement error, and the grey filled area is the *a priori* error. (Right)  $\text{H}_2\text{O}$  averaging kernels. The width at half maximum of the averaging kernels (representative of the vertical resolution of the measurements) together with the height where the averaging kernel is peaking are indicated on the right of each figure for altitudes where the measurement response is greater than 0.75, i.e. the *a priori* contamination is less than 25%.

### III. DATA ANALYSIS

#### A. Forward model and retrieval method

The generic Microwave Odin Line Estimation and Retrieval (MOLIERE) code [8] has been initially developed for the Odin satellite [9] and used in different ground-based projects, e.g.  $\text{O}_3$  at 110 GHz [10],  $\text{ClO}$  at 278 GHz [11]. The MOLIERE code is separated into a forward model and a retrieval code. The forward model includes modules for spectroscopy, radiative transfer and sensor characteristics (antenna, sideband and spectrometer). It also includes different shapes of baseline undulations from linear and quadratic to sine functions. The retrieval code is based upon the Optimal Estimation Method [12] and, coupled with the forward model, allows nonlinear retrievals according to a Newton Levenberg-Marquardt iteration scheme. An *additional noise* parameter can also be added to the random radiometric noise in order to cope with any spurious noise that cannot be fitted by an algebraic mathematical function.

Spectroscopic line parameters for the line-by-line calculations have been taken from the Verdandi database (<http://www.rss.chalmers.se/gem/Research/verdandi.html>), which merges frequencies, lines intensities, and lower state energies from the JPL catalogue [13] with pressure broadening parameters from the HITRAN compilation [14]. Only the  $6_{16} - 5_{23}$  transition at 22.235 GHz is considered in our study.

The *a priori* information for  $\text{H}_2\text{O}$  is provided by the Odin climatology set up for all the studies performed so far. Temperature, pressure, and altitude fields are provided by the ECMWF. The assumed *a priori* error for the retrieved mixing ratios corresponds to 75% of the climatological *a priori* mixing ratios. The *additional noise*

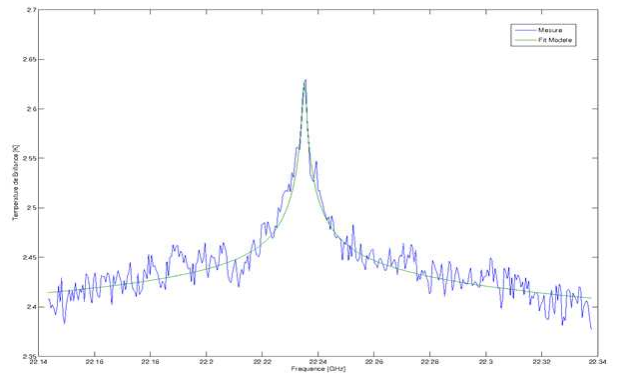


Fig. 5. 24-hour averaged spectrum within 200 MHz centered on the 22.235 GHz transition line as measured by the MobRa instrument over Bern, Switzerland on 18 July 2006 (blue line) and as estimated by MOLIERE (green line).

parameter is set to 50 mK. The maximum number of iterations is 3. A second-degree polynomial function is setup and estimated to reproduce the spectral baseline.

#### B. Error characterization

The vertical profile of estimated  $\text{H}_2\text{O}$  is presented in Fig. 4 together with the *a priori* profile and the *a priori* error. The right hand side also shows the  $\text{H}_2\text{O}$  averaging kernels. The width at half maximum of the averaging kernels can be considered as representative of the vertical resolution of the measurements. The sum of the elements of each averaging kernel (the measurement response) is an indication of the *a priori* contamination upon the retrieved information. We usually flag retrievals as good when the measurement response is greater than 0.75, meaning that the *a priori* information contaminates the retrieval by less than 25%. In a theoretical and optimal study, considering the true atmosphere as the *a priori* atmosphere, the vertical domain where  $\text{H}_2\text{O}$  can be retrieved is ranging from  $\sim 10$  km up to  $\sim 65$  km. The vertical resolution is ranging from  $\sim 5$  km in the lower stratosphere up to  $\sim 15$  km in the lower mesosphere. The total error on the  $\text{H}_2\text{O}$  profile is about 1 ppmv. The correlation between retrieved  $\text{H}_2\text{O}$  and the estimation of linear baseline is less than 10%.

### IV. PRELIMINARY RESULTS

A measurement and intercomparison campaign has been done at the University of Bern in July 2006. Measurements with MobRa in coincidence with MIAWARA, the 22 GHz microwave radiometer developed at the University of Bern [4] have been performed on the roof of the Institute of Applied Physics (IAP) building in Bern, Switzerland ( $47^\circ\text{N}$ ,  $7.5^\circ\text{E}$ ). We have also used the data from the Microwave Limb Sounder (MLS) instrument aboard the Aura satellite [15] averaged for each day within a  $10^\circ$  latitude  $\times$   $20^\circ$  longitude box centered on Bern.

One day of measurements (18 July 2006) is presented. The filtered data correspond to an effective integration

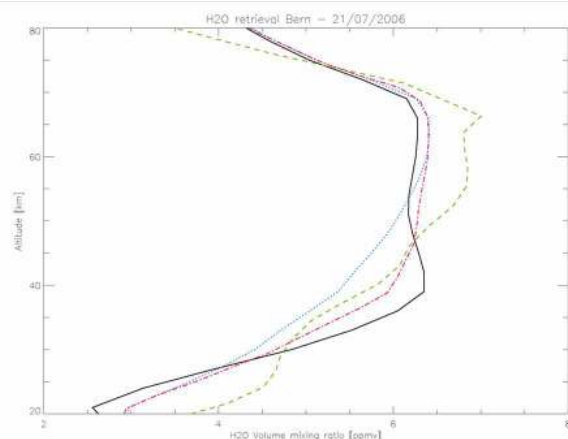


Fig. 6. H<sub>2</sub>O vertical profiles measured on 18 July 2006 over Bern (Switzerland) by the MobRa instrument (black line), the MIAWARA instrument (red dotted-dashed line) and the space-borne MLS instrument (green dashed line). The *a priori* H<sub>2</sub>O profile (blue dotted) is taken from ECMWF for the same day.

time of 50 minutes, yielding to a measurement noise of 20 mK. The spectrum used for the inversion is shown in Fig. 5. It has a total bandwidth of only 200 MHz centered on the 22.235 GHz transition line. The maximum total bandwidth of 850 MHz could not be used because of strong baseline ripples on the edges of the spectrum. The remaining tropospheric contribution has been removed using a 5th-order polynomial fit.

The vertical profile of the MobRa instrument has been retrieved with MOLIERE, using parameters described in section III. The retrieval of MIAWARA profile has been done with the Arts/Qpack inversion software [16], using the same *a priori* data. For both instruments, the vertical domain where H<sub>2</sub>O can be retrieved is ranging from 30 to 70 km. These two daily averaged profiles are compared to the averaged MLS measurements for the same day in Fig. 6. It has to be noticed that the vertical resolutions (not shown here) of the two ground-based instruments are quite similar (5-15 km) but differ from the MLS instrument (~2-3 km). This explains smoother ground-based profiles compared to the MLS profile. The precision of the measurements is ~1 ppm for all the instruments. There is an agreement among all these measurements to within 1 ppmv. Measured H<sub>2</sub>O is consistently higher than *a priori* H<sub>2</sub>O by about 0.5 ppmv for altitude ranging from 30-45 km. In the layer 45-70 km, MLS H<sub>2</sub>O is greater than ground-based H<sub>2</sub>O by about 0.5 ppmv. This indeed might be induced by the poor vertical resolution of ground-based instruments degrading with height.

## V. CONCLUSIONS

A new compact and mobile radiometer (MobRa) has been developed for measuring water vapor in the stratosphere by detecting the 22.235 GHz emission line. Although first measured spectra show strong undulations,

H<sub>2</sub>O can be retrieved from 30 to 70 km with a precision of 1 ppmv. On 18 July 2006, the daily-averaged MobRa H<sub>2</sub>O profile is in agreement with the coincident daily-averaged measurements by the ground-based MIAWARA and the space-borne MLS instruments. Improvements in the estimation of tropospheric opacity and in calibration procedure are required to lessen the amplitude of the baseline signal in the spectra and therefore to gain sensitivity in the lower stratosphere. Finally, vertical profiles of H<sub>2</sub>O will need to be further validated before we propose the MobRa instrument to be part of the NDACC.

## ACKNOWLEDGMENTS

The authors would like to thank Prof. N. Kämpfer and A. Haefle from the University of Bern for their help and welcoming during the intercomparison campaign. E. Motte's PhD thesis is funded by CNRS and CNES.

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