A NOVEL GROUND-BASED MICROWAVE RADIOMETER FOR HIGH PRECISION ATMOSPHERIC OBSERVATIONS BETWEEN 10 AND 90 GHZ

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ABSTRACT

State-of-the-art microwave radiometers for probing water vapor, temperature and cloud liquid water do not show the high accuracy and stability which is needed for some applications like radio science or the assessment of turbulent weather conditions. Especially scientific experiments, performed in outer-space and missions to investigate other planets, are dependent upon high-precision transmission of data to receivers on Earth passing through the atmosphere, which is a big source of disturbance. Propagation and attenuation at frequencies between a few GHz and several tens of GHz are influenced by dry air as well as by water vapour and liquid water in form of clouds and rain. A precise and stable microwave radiometer to derive these properties has been developed – the Atmospheric Propagation and Profiling System ATPROP.

***Index Terms*—** Microwave Radiometer, radiation, full sky scanning, profiling, propagation parameters

1. INTRODUCTION

Atmospheric constituents like water vapor and clouds show a high spatial and temporal variability. On one hand it is of high interest for meteorological applications to better capture the turbulent structure of the atmosphere. On the other hand atmospheric constituents also control the propagation of electromagnetic waves. For radio science applications it is therefore important to accurately describe atmospheric disturbances.

A precise and stable microwave radiometer to observe the relevant atmospheric parameter has been developed in the frame of an ESA-ESTEC project: the Atmospheric Propagation and Profiling System (ATPROP). A new calibration technique using a fast cycling between target, Dicke Switch and noise diode enables highly precise and continuous measurements. A turntable combined with internal elevation mirrors allows flexible pointing, for example tracking individual satellites or mapping the spatial variability by volume scanning. ATPROP is able to detect tropospheric profiles of humidity and temperature as well as the integrated humidity. Using elevation scans, high resolution boundary layer temperature profiles can be measured. The possibility of elevation scans as well as azimuth scans enables the three dimensional detection of inhomogenities in clouds and water vapor. For the different applications, e.g. satellite ground stations and meteorology, retrieval algorithms for the calculation of attenuation at different frequencies, wet path delay, humidity, etc have been developed. After a brief technical overview (section 2) the theoretical accuracy is shown in section 3, examples of instrument evaluation during a test campaign are given in section 4 and the ability to describe horizontal inhomogeneities is illustrated in section 5.

2. TECHNICAL OVERVIEW

The radiometer provides 7 channels on the water vapor line (K_a-Band; 22.24-31.4 GHz) and 7 channels on the oxygen absorption complex (V-Band; 51.3-58 GHz) for detection of humidity and temperature profiles (similar to the Humidity and Temperature Profiler (HATPRO) [1]). Two additional channels have been added at the K_u-band (near 15 GHz) and at the W-band (near 90 GHz). The 90 GHz channel enhances the detection of cloud liquid water and (compared to HATPRO) improves the detection of clouds with lower liquid water path. The 15 GHz channel is favorable for detecting the onset of precipitation and quantity of rainfall for most conditions except the heaviest rain events.

The intensity and phase delay of satellite transmissions depends on atmospheric fluctuations as well as technical factors such as orbit instabilities of the spacecraft or thermally driven antenna distortions, etc. These technically related issues extend to time scales of thousands of seconds. Laboratory measurements with ATPROP could confirm an Allan Standard Deviation of 0.01 K@1000 s integration time for K_a band channels, and better than 0.04 K@1000 s for all other channels.

3. RETRIEVAL ACCURACY

Statistical retrieval algorithms are derived from a large data set of concurrent brightness temperatures and parameter of interest; e.g. attenuation, non-dispersive excess path length (EPL), integrated water vapor (IWV), liquid water path (LWP). The data base is based on a long-term radiosonde data set representative for the location of the microwave radiometer. Radio soundings only observe the profiles of pressure, temperature and humidity and therefore cloud liquid water profiles need to be diagnosed. Here we tested three different models which did not lead to significant differences retrieval in retrieval performance [2]. Therefore one cloud model and selected at least for the final retrieval development. In the radiative transfer the effect of atmospheric gases is described by the Rosenkranz model [3] and the one of clouds after Liebe [4]. Multivariate regressions employing higher order terms are derived following Löhnert and Crewell [2].

Because the test campaign took place at Cabauw, the Netherlands, we used a long-term (12-Years), high vertical resolution radiosonde data set from De Bilt, the Netherlands (52.06 N, 5.11 E, 4 m over msl). The manufacturer Vaisala specifies an overall accuracy of 0.5 K for temperature and 5 % for relative humidity in the troposphere. However, also depending on the launch personal, weather condition and transmission quality several problems in individual soundings can occur. Therefore, a sophisticated testing program has been developed in the frame of the ATPROP project and applied to the whole data set. In order to control the quality of the retrieval algorithms the dataset is split in two parts of nearly the same size. With the first part of the data set (training set) the algorithm is developed, while the second part is used as test data set for the algorithm derived from the training data set.

3.1. Attenuation

The total atmospheric attenuation is defined as the integral of the atmospheric extinction coefficient along the line of sight. Retrieval algorithms for attenuation at all frequencies between 10 and 90 GHz with 1 GHz spacing were developed.

Using all ATPROP channels as input for the retrieval algorithm, attenuation at all frequencies between 10 and 90 GHz can be retrieved to be better than 2%. *Table 1* illustrates the accuracy in attenuation retrieval at 22.24, 36.5 and 90 GHz. The attenuation at 36.5 GHz is of highest interest since it is not directly observed by ATPROP. If attenuation is derived from the two closest channels at 31.4 and 51.3 GHz the relative error is 3.7 %. It already reduces strongly to 2.5 % when the full K_a-band (but no V-Band channel) is used. Obviously the retrieval algorithm can extrapolate the line shape well. When all 16 ATPROP channels are used the quality improves even further to 1.5 %. Further studies for other frequencies confirm the strong benefit of using the 90 GHz and also the 15 GHz channel compared to a standard profiler.

Table 1: Statistical comparison of attenuation retrieval, test data set against retrieval, using single channels, the water vapor channels and all ATPROP frequencies.

Attenuation at	Frequencies	RMS in neper	Rel. error in %
22.24 GHz	22.24 GHz only	0.0031	2.27
	7 K_a band	0.0026	1.89
	All 16 frequencies	0.0021	1.55
36.5 GHz	31.4 GHz, 51.26 GHz	0.0041	3.72
	7 K_a band	0.0026	2.48
	All 16 frequencies	0.0016	1.54
90.00 GHz	90.00 GHz only	0.0072	2.20
	7 K_a band	0.0125	3.88
	All 16 frequencies	0.0027	0.84

3.2. Path Delay

In radio propagation applications the non-dispersive excess path length (EPL) or simply "path delay" is defined as the difference of the electrical path length and the geometrical straight-line distance of a ray propagating from the top to the bottom of the atmosphere along line of sight. For the construction of the training and test data set the path delay is calculated out of the atmospheric refractivity with different models for the calculation of refractivity. It has been found that all different variants of calculating the refractivity yields to very similar path delays with RMS errors of all different variants between 2.39 and 2.45 mm.

3.3. Integrated Water Vapor and Liquid Water Path

The benefit of 90 GHz channel is most prominent for the liquid water path due to its high sensitivity to cloud water. The accuracy of retrieval algorithms using only the K_a band frequencies and the K_a band frequencies added by 15 and 90 GHz is shown in *Table 2.* It can be seen that including the 90 GHz channel reduces the RMS from 17 g/m^2 to nearly the half. Including this frequency enables the detection of clouds with smaller liquid water content. The same effect can be found in the IWV but it is not of this strong dimension (*Table 2*).

Table 2: Statistical comparison of LWP and IWV retrieval, test data set against retrieval, using all water vapor (WV) channels added by the 15.3 and the 90.00 GHz channel and using only the water vapor channels.

Retrieved quantity	Frequencies	RMS in kg/m^2	BIAS in kg/m^2
LWP	7 K_a band	0.017	0.0005
	7 K_a band, 15, 90	0.0093	-0.0004
IWV	7 K_a band	0.43	0.0119
	7 K_a band, 15, 90	0.42	0.0164

3.4. Temperature and humidity profiles

The potential of a ground-based microwave temperature profiler to combine full tropospheric profiling with high resolution profiling of the boundary layer has been investigated by Crewell and Löhnert [5]. In comparison with tower and radiosonde data they could prove a significant improvement in the lowest kilometer by combining angular information from relatively opaque channels with zenith only information from more transparent channels.

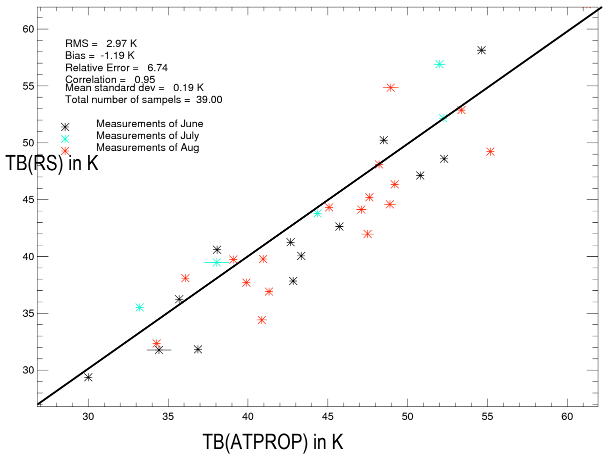

Figure 1 : Comparison of ATPROP measurements and De Bilt radiosonde measurements.

4. EVALUATION USING RADIO SONDES

Since mid April ATROP has been operated at the Cabauw Experimental Site for Atmospheric Research (CESAR) in the Netherlands. In order to evaluate the performance of ATPROP comparisons with the next radio sonde station (De Bilt) about 35 km are performed. All cloud free soundings between 01 June 2008 and 31 August 2008 have been used. As it can be seen in *Figure 1* exemplarily for the 22.24 GHz channel, the statistical comparison between ATPROP measurements and radio sounding shows a good correlation. The soundings show systematically higher values of 1.19 K. This bias is partly due to the special difference of the locations of ATPROP in Cabauw in a rural area and the more urban environment of De Bilt. Therefore the stronger deviations at frequencies affected more by water vapour might be explained by humidity variations and uncertainties in the gas absorption model.

Table 3: Statistical comparison of the brightness temperatures between ATPROP and the De Bilt radio soundings from June until August for all channels.

Channel in GHz	RMS in K	Bias in K	Rel Error in %	Corre-lation	Number of obs.
15.3	0.34	-0.11	3.57	0.91	20
22.24	3.72	-0.96	7.78	0.92	31
23.04	3.56	-0.84	7.86	0.92	30
23.84	3.04	-1.66	7.69	0.91	29
25.44	2.12	-1.75	7.13	0.90	29
26.24	2.15	-2.56	7.77	0.90	29
27.84	1.71	-2.04	7.27	0.86	29
31.40	1.63	-1.01	7.50	0.81	29
51.26	2.18	-2.64	1.88	0.74	29
52.28	2.00	-2.81	1.25	0.75	29
53.86	0.76	-1.95	0.30	0.97	32
54.94	0.35	0.77	0.12	0.99	32
56.66	0.38	0.29	0.13	0.99	32
57.30	0.40	0.15	0.14	0.99	32
58.00	0.41	0.46	0.14	0.99	32
90.00	4.19	-6.66	6.03	0.94	24

Table 3 shows the results of the statistical comparison of all soundings. At 26.24 GHz a relative large bias occurs. This is due to the fact that radio frequency disturbances occurred during tipping curve calibration. But further, it can be seen that no drifts of the radiometer can be noticed even though sky tipping calibration has been disabled all the time.

5. EXAMPLE OF ATPROP MEASUREMENTS

As an example *Figure 2* to *Figure 4* illustrate a single day, e.g. 19th June 2008 of ATRPOP observations data. Temperature and humidity profiles (*Figure*) of the whole day identify the time range of a frontal passage: air mass exchange can be clearly noticed around 13:00 UTC (red box all three plots, *Figure* , *Figure 3*). Volume scans (*Figure 4*) performed at regular intervals reveal the strong spatial inhomogenities in water vapor and liquid water path at 12:40, 13:08 and 13:36 UTC. Here the exchange of the air mass from North-West can be identified clearly and strong differences in both quantities can be found particularly at the two first time steps.

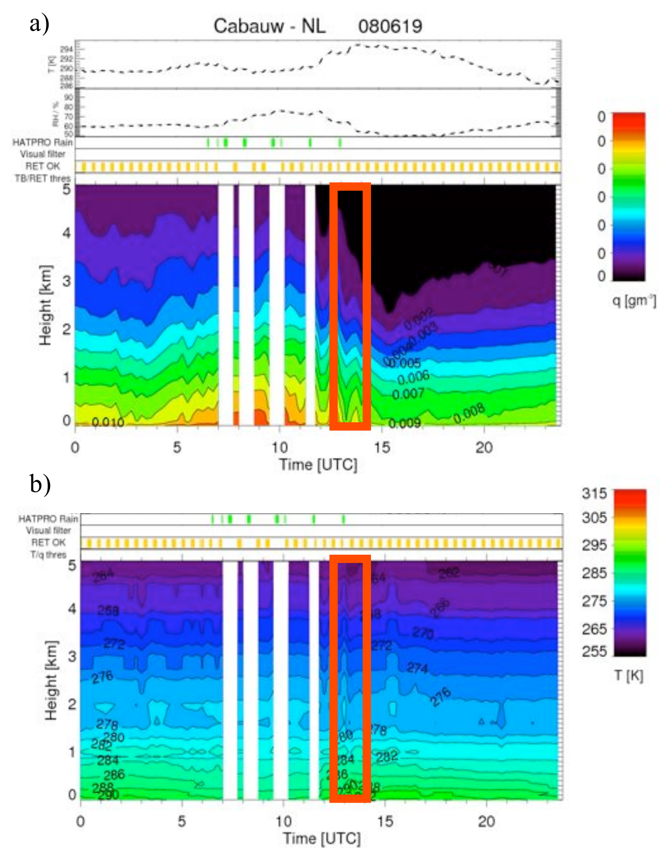

Figure 2: Time series of ATPROP profiles in Cabauw at 19.06.2008 (a) humidity, (b) temperature.

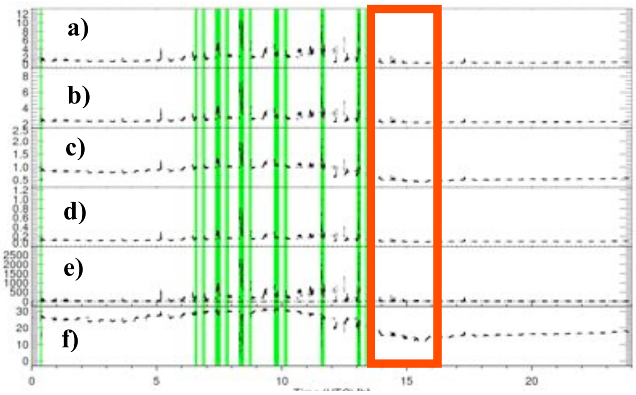

Figure 3: Time series of different quantities retrieved from ATPROP measurements (a) attenuation at 90 GHz, (b) attenuation at 51.8 GHz, (c) attenuation in 22.24 GHz, (d) attenuation at 15.3 GHz, (e) liquid water path in g/m^2, (f) integrated water vapor in kg/m^2.

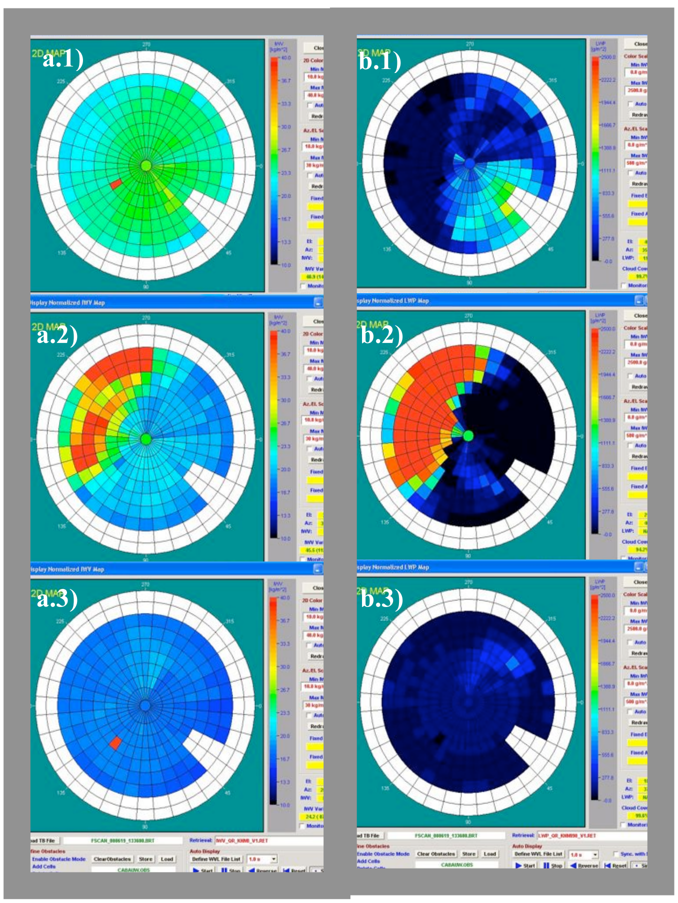

Figure 4: ATPROP full sky scans of (a) integrated water vapor in kg/m2, (b) liquid water path in kg/m2, (1) at 12:40 UTC, (2) at 13:08 UTC, (3) at 13:36 UTC

6. CONCLUSIONS

A novel microwave radiometer for investigating propagation and meteorological parameters has been developed. ATPROP is able to investigate the spatial and temporal variability of such parameters with high accuracy. Comparisons of ATPROP measurements with radio soundings have shown satisfactory performance. Further comparisons with other microwave radiometer (HATPRO) show a very high level of agreement (not shown here). The heated blower system works rather well and allows immediate observations past a rain event (*Fig. 3*). The 90 and 15 GHz channels improve IWV and attenuation retrieval even at frequencies which can not be measured directly as seen on the example of the attenuation at 36.5 GHz (*Table 1*). A novel feature of the system is the detection of spatial inhomogeneities.

11. REFERENCES

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