A Novel Ground-Based Microwave Radiometer for High Precision Atmospheric Observations Between 10 and 90 GHz (ATPROP - Atmospheric Propagation and Profiling System)

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INTRODUCTION

State-of-the-art microwave radiometers for probing water vapour, 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.

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, water vapour and attenuation. The beam can also be targeted on every specified satellite position. For the application of satellite ground stations, retrieval algorithms for calculation of dry and wet path delay and attenuation at different frequencies have been developed and implemented.

REQUIREMENTS OF ATPROP

The propagation of electromagnetic waves is controlled by atmospheric constituents like water vapour, oxygen, clouds and precipitation. Therefore, the accurate observation of these highly spatially and temporally variable species is not only of high interest for meteorological applications to better capture the turbulent structure of the atmosphere but as well for propagation studies. In order to completely describe the atmospheric signal over the 10-90 GHz range ATPROP needs to assess all relevant spectral features, e.g. the 22.235 GHz water vapour rotational line and the 60 GHz oxygen complex. Spectral observations along both features can be used to derive water vapour and temperature profiles, respectively [1, 2]. Atmospheric emission by cloud liquid water increases roughly with the frequency squared. Therefore, observations at a high window frequency, e.g. 90 GHz, are well suited to detect cloud attenuation and liquid water path (LWP) [3].

Additionally an infrared (IR) radiometer (8-12 µm) is beneficial to detect very thin clouds. In this wavelength range the atmosphere is nearly transparent with only slight contributions from water vapour and ozone. Since clouds strongly absorb infrared radiation the observed IR temperature is roughly proportional to cloud base temperature in cloudy conditions. In contrast to the MWR the IR is also sensitive to the presence of ice clouds. Precipitation causes strong attenuation and is complicated to treat as scattering of electromagnetic waves becomes important. Radiative transfer calculations based on realistic atmospheric scenarios [4] were performed in order to derive the most suitable ATPROP frequency for assessing precipitation with a focus on the transition between non raining and raining conditions. A frequency channel within the protected 15.3 GHz band was found most suitable since it combines the ability to observe a wide dynamic range of precipitation intensity and allows a smaller radiometer beam compared to lower frequency (longer wavelength) channels, e.g. 10 GHz, with reasonable aperture size.

A major issue is the capability of the ATPROP system to work (and retrieve sensible parameters) at various places on Earth, i.e. possible regions for ESA measurement campaigns are India, Polar Regions (both North and South Poles) or Earth Observation Ground stations (Svalbard, Kiruna, Fucino, MasPalomas). Therefore, an automatic system with high spatial and temporal resolution is required which is capable of operating in a stable way for long periods, in remote locations, under severe environmental conditions and with no or sporadic manned instrument control.

TECHNICAL OVERVIEW

ATPROP consists of two physically single but acquisition combined microwave radiometer units. The radiometers basically cover 4 frequency bands: 22-32 GHz (K-band), 51-58 GHz (V-band), 15.3 GHz (Ku-band) and 90 GHz (W-band) with a total number of 16 frequency channels. The first unit is similar to a commercially available RPG Humidity and Temperature Profiler (HATPRO) [5] combining 7 channels between 22.235 and 31.4 GHz (K-band) and 7 channels at V-band. The second unit combines a 15.3 GHz and a 90 GHz channel. All receivers have been designed in direct detection technology. Both units are mounted on a joint azimuth turntable. Elevation scanning is performed by internal mirrors. The profiler's architecture is comparable to a filter bank spectrometer which acquires the 7 channels all in parallel. Each channel is equipped with its individual band pass filter (BPF) and a total power detector for a 100% duty cycle operation.

A key feature which is realized in ATPROP for the first time is the calibration frontend comprising a noise injection section (gain drift calibration) and a magnetically switchable Dicke reference (system noise temperature drift compensation). The continuous calibration cycles (5 per second) are adjusted to yield an optimum radiometric resolution of <0.2 K RMS (one second integration time) and an excellent long term stability. Allan Variance measurements resulted in a noise reduction for integration periods of typically 4000 seconds (*Figure 1*), which makes the system ideal for precision wet delay determination. In addition the system can be calibrated manually by an external cold load filled with liquid nitrogen or via automated tipping curve procedures.

The optical resolution of each receiver package has been optimized for radiometer portability and the available observation modes. E.g. the temperature profiler (50-60 GHz band) HPBW is only 2°, so that the instrument is capable of performing boundary layer scans down to 5° elevation with high vertical temperature resolution of 50 m on the ground. The K-band radiometer beams have a beam width close to 4° (HPBW) which is a good compromise for a full sky scanning mode with approximately 400 point for full sky coverage. The 15.3 GHz channel has the widest beam width of 6.5°.

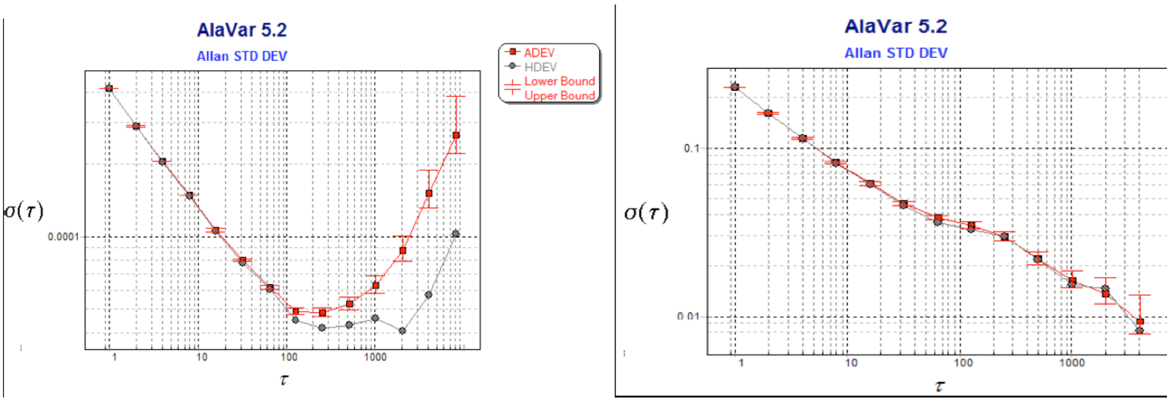

Figure 1: Allan variance of the 52.28 GHz channel with noise injection calibration (left) and combined noise/Dicke switch calibration (right). The noise injection only calibrates the receiver gain, leading to a typical stability of a few 100 s. By adding a Dicke switch standard the overall system stability is significantly improved by at least a factor of 10.

The instrument's temporal resolution is one second. The fast sampling rate is important for full sky scanning, LWP time series, cloud variability detection and satellite tracking schemes. The ATPROP software includes a tracking mode that reads RINEX navigation files in order to scan all visible GPS or Galilieo satellites for wet path delay in the line of sight, LWP and atmospheric attenuation. A single scan of 10 satellites takes about one minute. The receivers are thermally stabilized to better than 50 mK over the full operating temperature range (-35°C to +45°C). The instrument can be used under harsh environments and in high altitudes up to 6000 m. The system includes surface sensors for temperature, humidity and pressure, rain flag and a GPS clock. An IR radiometer is attached which can be manually tilted in elevation.

ACCURACY OF RETRIEVAL

ATPROPs frequencies have been chosen in a way that an optimal retrieval is achieved. Further, it was decided to use statistical retrieval algorithms since they are robust and can be applied in a timely fashion in contrast to physical retrieval algorithms. Using statistical algorithms the parameters of interest, e.g. attenuation, non-dispersive excess path length (EPL), integrated water vapour (IWV), liquid water path (LWP), can be derived from a large data set of concurrent brightness temperatures and the parameters, themselves. The data base is commonly based on a long-term radiosonde data set, which is 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 determined using a cloud model. Three different cloud models have been tested. At least for the final retrieval development the modified adiabatic cloud model described by [5] was selected. The radiative transfer also includes the effect of atmospheric gases. Two different model conceptions were taken into account. They are described by the Rosenkranz 98 [6] and Liebe 91 [7]. In this case the Rosenkranz 98 model is preferred. Multivariate regressions, employing higher order terms, are derived following Löhnert and Crewell 03 [8].

The quality and representativeness of the radio sonde data set is very important when reliable retrieval algorithms shall be developed. In the current example a long-term highly resolved (12-Years) data set from De Bilt, the Netherlands (52.06 N, 5.11 E, 4 m over msl), has been used. In the last years the radio sondes were of the RS92 type. 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 personnel, 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 [9].

The high resolution radio soundings of De Bilt are used as the data base for the retrieval development. They are available over a time range of 12 years from 1993 to 2005. Most of the time four soundings a day exist. In order to control the quality of the retrieval algorithms the dataset was split in two parts of nearly the same size. The first part of the data set is used to develop the algorithm; the second part serves as test data set. The years 93, 95, 97, 99, 01, 03 and 05 form the test data set; all the other available years are used to develop the algorithm. The developed algorithm is deployed to the test data set and will be compared to the results of the retrieval.

In order to determine the theoretical accuracy of the retrieval algorithms different sets of frequencies have been defined. These sets are arranged to link frequencies and retrieving parameter in an optimal way with respect to those parameters. For example it is not useful to apply V-Band channels retrieving IWV and LWP [8]. But for attenuation it is meaningful to give respect to all available frequencies – here all 16 ATPROP frequencies.

Integrated Water Vapour and Liquid Water Path

The accuracy of the retrieval algorithms mainly depends on the selected frequencies, which are used to build the algorithm. In order to detect the parameters, which are strongly controlled by the water vapour and dependend only little on the temperature profile of the atmosphere it is reasonable to exclude the frequencies along the slope of the oxygen line. The accuracy of retrieval algorithms using only the K-band frequencies and the K-band frequencies added by 15 and 90 GHz is shown in *SEQ*. For LWP it can be seen that including the 15/90 GHz channels reduces the RMS from 17 g/m^2 to nearly the half, which improves the accuracy of the algorithm significantly, e.g. from about 30 to 15 %. This strong reduction is due to the high sensitivity of the 90 GHz channel to cloud liquid water. Including this frequency strongly improves the detection limit and enables the detection of clouds with smaller liquid water content. The benefit of the 15 and 90 GHz channels is much less pronounced for IWV which can be retrieved with a relative error of about 5 % (*SEQ*).

Table 1: Statistical comparison of LWP and IWV retrieval, test data set against retrieval, using all K-band channels added by the 15.3 and the 90.00 GHz channel and using only the K-band channels

Retrieved parameter	Frequencies	RMS in kg/m^2	BIAS in kg/m^2
LWP	7 K band	0.0170	0.0005
	7 K band , 15, 90	0.0093	-0.0004
IWV	7 K band	0.43	0.0119
	7 K band , 15, 90	0.42	0.0164

Attenuation

The total atmospheric attenuation is defined as the integral of the atmospheric extinction coefficient along the line of sight and is usually expressed in dB. Retrieval algorithms for attenuation at all frequencies between 10 and 90 GHz with 1 GHz spacing were developed. Theoretically, it is possible to calculate the attenuation at a certain frequency from the observed brightness temperature using an estimate of the mean radiating temperature. However, it is not practicable to include a separate channel for every desired frequency in the instrument. Hence, it is necessary to generate retrieval algorithms for those frequencies which can not be measured. The quality difference of attenuation retrieved by miscellaneous frequency sets is shown in *SEQ* exemplarily for three frequencies. While 22.24 and 90 GHz, are measured directly by ATPROP the frequency of of 36.5 GHz lies between the observed K- and V-band frequencies. However, using all 16 ATPROP frequencies attenuation at this channel can be observed with similar relative accuracy (about 1.5 %) as at the directly observed freuquencies. .

Figure 2 shows that the inclusion of all ATPROP frequencies strongly improves the attenuation retrieval. Compared to the direct retrieval of attenuation from the single brightness temperature measurement at 90 GHz the RMS is reduced by more than a factor of two. If the attenuation at 90 GHz is extrapolated purely from K-band frequencies, e.g. the shape of the water vapor line, the RMS is increased by nearly a factor of 5.

Table 2: Statistical comparison of attenuation retrieval, test data set against retrieval, using single channels, the K-band channels and all ATPROP frequencies

Retrieved quantity	Frequencies	RMS in neper	BIAS in neper	Rel. error in %
ATT(36.5GHz)	31.4 GHz, 51.26 GHz	0.0041	-0.0005	3.72
	7 ku band	0.0026	-0.0001	2.48
	All 16 frequencies	0.0016	0.0000	1.54
ATT(22.24GHz)	22.24 GHz only	0.0031	-0.0002	2.27
	7 ku band	0.0026	0.0001	1.89
	All 16 frequencies	0.0021	0.0001	1.55
ATT(90.00GHz)	90.00 GHz only	0.0072	-0.0008	2.20

	7 ku band	0.0125	0.0007	3.88
	All 16 ATPROP frequencies	0.0027	-0.0001	0.84

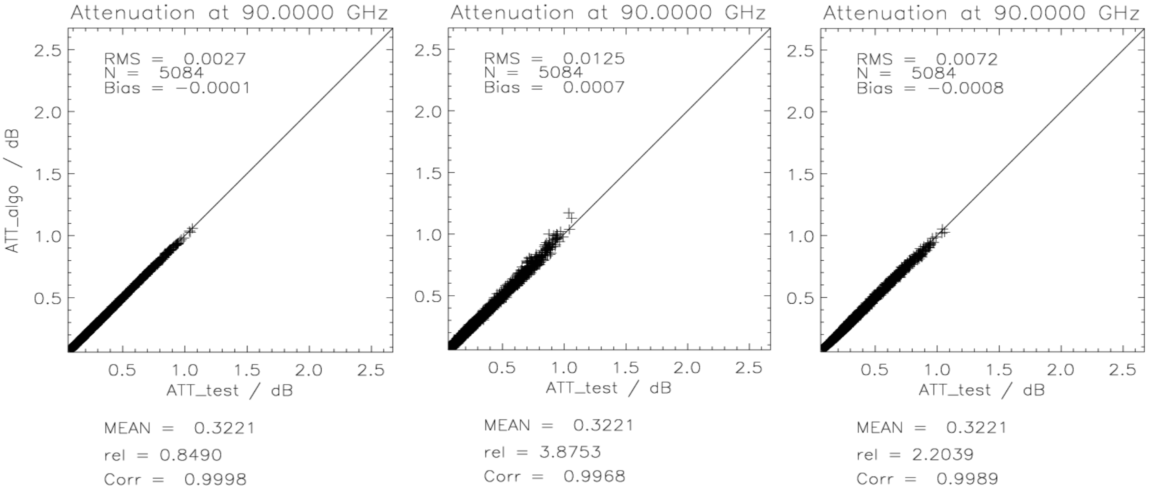

Figure 2: Performance of attenuation retrieval at 90 GHz, using a) all ATPROP frequencies, b) only K-band frequencies, c) 90 GHz only for training

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 a line of sight. In this study a technique is applied, where path delay is calculated out of the refractivity profiles of the atmosphere. This method is described in detail by [10]. Different coefficients k_n are used to calculate the refractivity profiles. Only marginally variations between the different calculation variants of this parameter and there for the path delay has been found. The RMS of the wet path delay appointed for all coefficient sets k_n varies between 2.385 mm and 2.445 mm, while the correlation converged to 1. Caused by the strong dependency of the wet path delay to the integrated water vapour the excess profit of the additional channels to the wet path delay is in the same order of magnitude like the IWV.

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 is investigated by [2]. The additional frequencies have only a marginal influence on the retrieval accuracy. In the free atmosphere no influence of the added 15 and 90 GHz can be found while inside the atmospheric boundary layer a marginally better retrieval accuracy for humidity is achieved. The accuracy increases round about 5%. For temperature profiles it is not beneficial to add the new frequencies. Both channels are not sensitive to oxygen emission. Thus, a decline of the results is the consequence of adding them to the retrieval.

EVALUATION USING OTHER MEASUREMENTS

Since April 15th 2008 ATPROP is measuring at the Cabauw Experimental Site for Atmospheric Remote Sensing (CESAR) in the Netherlands. The measurements are running nearly without interruption. This campaign serves to test the instrument under atmospheric conditions. Functionalities and the accuracy concerning the atmospheric conditions were tested in this phase.

In order to confirm the real accuracy of ATPROPs data it is mandatory to compare them with those of other instruments. Most suitable for a comparison are radiosondes because they provide a full vertical atmospheric profile by insitu measurements. It is difficult to get such detailed information of the atmospheric state by any other instruments. Unfortunately, the distance between sounding sites and the radiometer location is often rather large. In the current paper radio sondes of De Bilt are taken for the validation of ATPROP measurements. The site is about 30 km North East of ATPROPs location. Furthermore, the data sets of KNMIs HATPRO have been used to compare the results. HATPRO is located at the same site as ATPROP with the distance of only a few meters. In the following the comparison with these two data sets will be shown.

Table 3: Statistical comparison of the brightness temperatures between ATPROP and the De Bilt radio soundings from June until August 2008 for all channels.

Channel in GHz	RMS in K	Bias in K	Rel Error in %	Correlation	Number of measurements
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

Radio Sondes

For the comparison of ATPROP with the De Bilt radio soundings, all data between 01.06.2008 and 31.08.2008 have been used as input to a radiative transfer model in order to create synthetic brightness temperatures. As it is shown in *SEQ* for most channels, the statistical comparison between ATPROP bightness temperatures and radio sounding shows a good correlation. The soundings give systematically higher values of all channels except the 4 highest V-band channels. The upper K-band and lower V-band channels show larger biases over 2 K. This bias is partly due to the spatial distance between the locations of ATPROP in Cabauw and De Bilt, the location of radio sounding ascents. The direct environment has a big influence to all 16 channels. The brightness temperature at 58 GHz represents for example nearly the environmental temperature. With a relative error of 0.14 % a really good agreement between radiometer and radio sounding was found. The bias of 0.46 K can easily be explained by the different environmental conditions. Also the comparison at 15.3 GHz shows a good agreement with a bias of -0.11 K between sounding and radiometer measurements.

In
SEQ the results of the statistical comparison of all soundings can be found. At 26.24 GHz a relative large bias occurs. This is due to the fact that the sky tipping was switched off due to radio frequency interference. No drift of the radiometer was noticed even though sky tipping calibration has been disabled all the time (not shown here).

Hatpro

In order to produce a proper comparison between two instruments it is desirable to place the instruments next to each other. At CESAR different microwave radiometers are placed, amongst others also a Humidity And Temperature PROfiler (HATPRO). HATPRO consists out of the same channels like ATPROP except the 15/90 GHz module – as described before. The technical details differ marginally. Due to ATPROP possesses the calibration method with noise diode and a Dicke switch the measurements seem to be really stable. HATPRO does not possess this calibration method. HATPRO performs gain calibrations by pointing to an internal target instead.. A further difference of both dinstruments lies in the criteria used in the automatic tipping curve procedures. While ATPROP demands strong homogeneous atmospheric conditions for the sky tip HATPRO is less strict. This yields to frequent acceptances of sky tips and jumps in the time series of HATPRO, as it can be seen in *Figure 3*

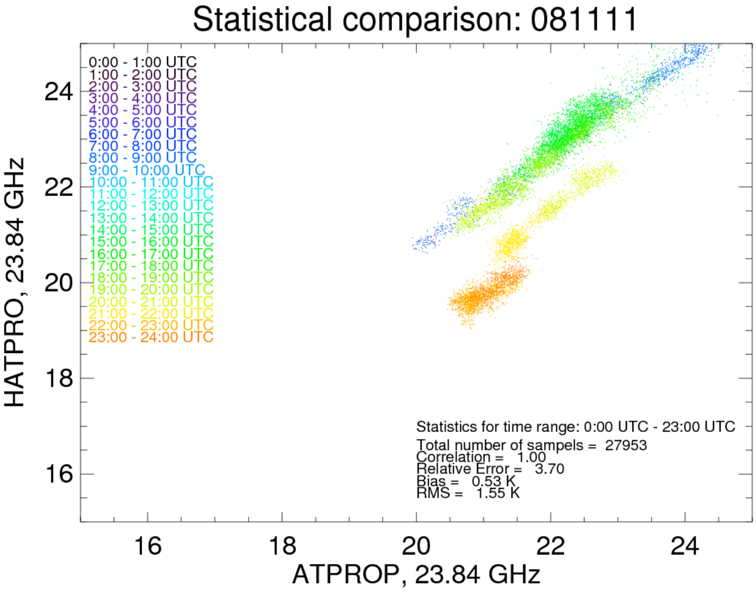

Figure 3: Comparison between ATPROP and HATPRO measurements for November 11th 2008, 23.84 GHz channel. Sky tips of HATPRO occurs at 15:48 and at 21:48 UTC

and *Figure 4*. The large shift at 21:00 UTC to 22:00 UTC in *Figure 3* marks exactly the time of HATPROs sky tips.

Since 10st of November both instruments are running in the same mode – performing only zenith measurements. The bias between -0.5 K and 0.6 K in the water vapour channels shows that both radiometers are measuring with high correlation, even during different weather conditions. Furthermore, it can be seen in *Figure 3* that the jumps due to sky dips do not occur in ATPROP measurements.

A summery of the statistical comparison between ATPROP and HATPRO is shown in *Table 4* and *Table 5*. For this comparison a time series of 13 days has been analysed. Both devices were operating with one sample per second. It has been given respect to all weather conditions. Relative errors between 3% and 6% in the K-band channels and mostly less than 1% in the V-band channels demonstrate good reproducibility of the different atmospheric conditions between both instruments, even if clouds are present.

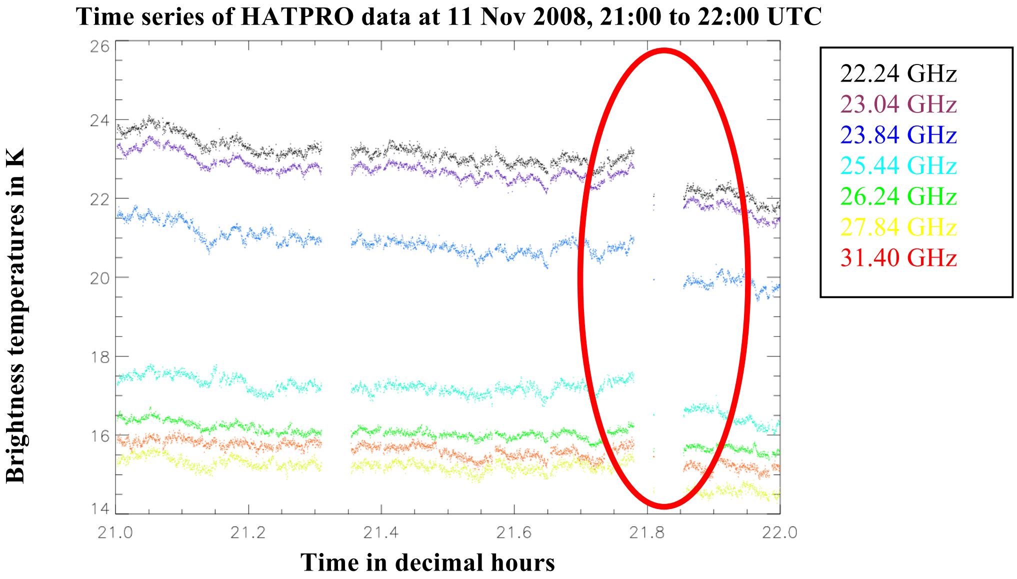

Figure 4 : **T**ime series of HATPRO data at November 11th 2008 between 21:00 and 22:00 UTC, sky tip is performed at 21.80 to 21.85 UTC marked by the red ellipse.

Table 4 : Statistical comparison of ATPROPs and HATPROs water vapour channels over the time range of 13 days

	22.24 GHz	23.04 GHz	23.84 GHz	25.44 GHz	26.24 GHz	27.84 GHz	31.4 GHz
Bias in K	0.17	-0.47	-0.49	0.07	-0.46	-0.43	0.58
RMS in K	1.23	1.23	1.27	1.15	1.62	1.2	1.29
Rel err in %	3.2	3.2	3.7	4.0	5.8	4.5	4.7
Correllation	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Table 5: The same as Table 4 for the oxygen channels

	51.26 GHz	52.28 GHz	53.86 GHz	54.94 GHz	56.66 GHz	57.30 GHz	58.00 GHz
Bias in K	5.31	1.29	0.75	1.07	0.68	0.84	0.96
RMS in K	1.29	1.05	0.55	0.43	0.39	0.39	0.43
Rel err in %	1.1	0.67	0.22	0,16	0.14	0.12	0.12
Correllation	1.0	1.0	1.0	1.0	0.99	0.99	0.99

CONCLUSIONS

ATPROP is able to investigate the spatial and temporal variability of different meteorological and propagation parameters. Comparison of ATPROP measurements with radio soundings are close to the theoretical accuracy. Comparisons with another microwave radiometer (HATPRO) show a very high level of agreement. The 90 and 15 GHz channels improve LWP, IWV, EPL and attenuation retrieval even at frequencies which can not be measured directly as seen on the example of the attenuation at 36.5 GHz (*SEQ*).

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