Development of Ground Equipment for Atmospheric Propagation Assessment from 10 up to 90 GHz (ATPROP)

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***Abstract*—The "Atmospheric Propagation and Profiling System" (ATPROP) advanced ground-based microwave radiometer, for radiowave propagation assessment at Ku, Ka, Q/V and W bands has been developed. The design of ATPROP is based on the requirements of SatCom, SatNav systems and Space Science Missions. ATPROP consists of two independent subsystems, operating at Ka band, near the 60 GHz oxygen absorption band and at 15/90 GHz. ATPROP has a full non-GEO satellite tracking capability and uses switched Dicke references to improve stability. Its performance allows to accurately derive atmospheric attenuation, sky noise, wet delay, and cloud, vapor and air temperature profiles.**

I. INTRODUCTION

TODAY satellite-based systems such as telecommunication, navigation and earth observation are fundamental to the course of modern life. In order to guarantee an unrestrained functionality of those systems, the assessment of atmospheric propagation effects and meteorological parameters is a key issue. Radio propagation in the Earth's atmosphere is affected by the atmospheric constituents, mainly gases and hydrometeors, which interact with electromagnetic radiation. The goal of this study is to assess radio propagation in the spectral range from 10 to 90 GHz, a spectral region which is becoming more and more important for the applications mentioned above.

For this purpose a highly stable microwave radiometer system (ATPROP, Fig. 1) has been designed, constructed and tested which allows the investigation of

- Sky noise due to emission of atmospheric components such as gases and hydrometeors
- Atmospheric attenuation due to gases and hydrometeors
- Atmospheric excess path length mainly due to atmospheric gases

II. REQUIREMENTS

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 ARPROP needs to assess all relevant spectral features, e.g. the 22.235 GHz water vapor rotational line and the 60 GHz oxygen complex. Spectral observations along both features can be used to derive water vapor 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 region the atmosphere is nearly transparent with only slight contributions from water vapor 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

Fig. 1. ATPROP during the test campaign at the remote sensing site of Cabauw, The Netherlands. The radiometer unit in the back is a HATPRO and the lower unit in the front contains the 15.3 GHz (larger window) and 90 GHz (smaller window) radiometer.

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.

III. TECHNICAL SPECIFICATIONS

ATPROP consists of two physically single but acquisition combined microwave radiometer units (Fig. 1). 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 filterbank spectrometer (Fig. 2) 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 (Fig. 3) 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 approx. 400 point for full sky coverage. The 15.3 GHz channel has the widest beam width of 6.5°. 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.

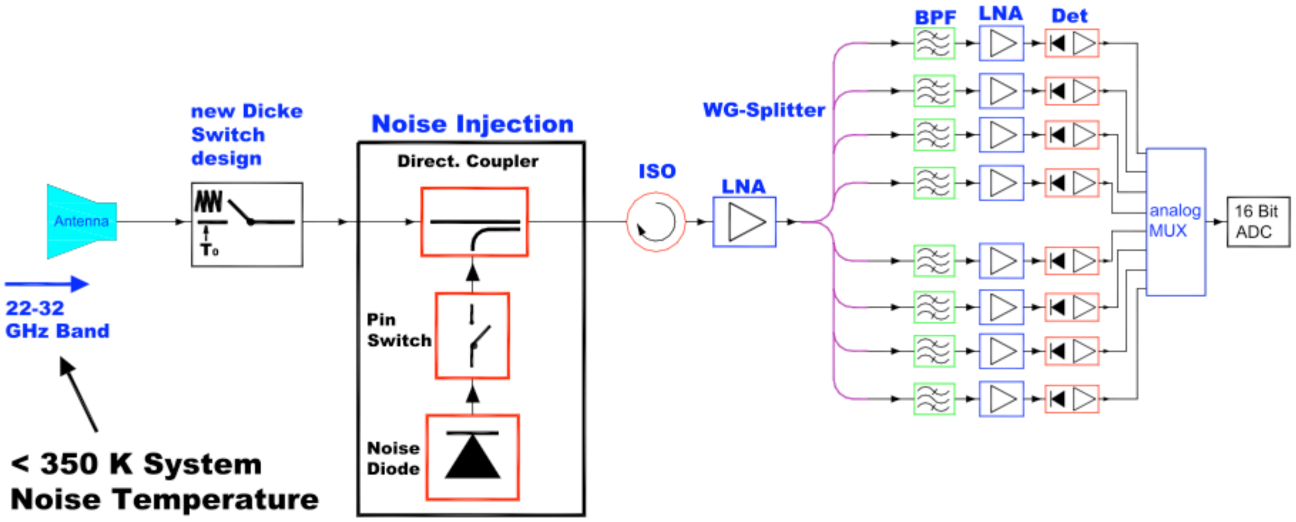

Fig. 2. Sketch of ATPROP receiver (K-band as example) layout with combined Dicke Switch and noise injection auto-calibration frontend. The signal is directly amplified by low noise amplifiers (LNA). The filterbank is realized in waveguide (WG) technology with individual filters (BPF) and detectors (DET).

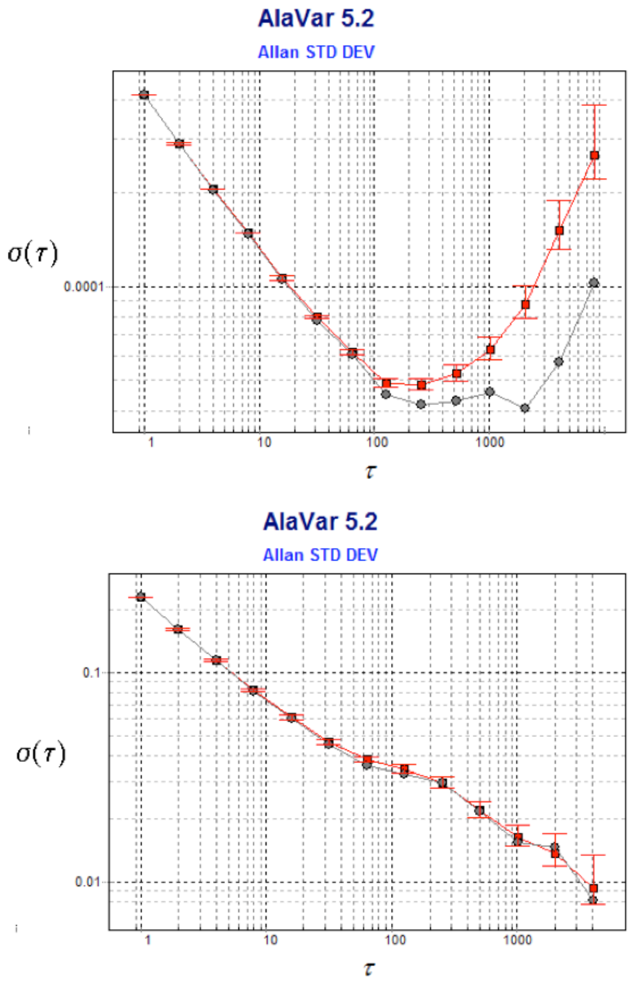

Fig. 3. Allan variance of the 52.28 GHz channel with noise injection calibration (top) and combined noise/Dicke switch calibration (bottom). The noise injection only calibrates the receiver gain, leading to a typical stability of a few 100 s. By adding a Dicke switch standard the overall system stability is significantly improved by at least a factor of 10.

IV. RETRIEVAL ALGORITHMS

ATPROP frequencies have been chosen to allow accurate retrievals of attenuation between 10 and 90 GHz, wet path delay, liquid water path (LWP), integrated water vapour (IWV) from the observed brightness temperatures (sec. 2). In order to allow for robust and computationally efficient retrievals statistical algorithms have been developed following [6]. Synthetic brightness temperatures are simulated by a radiative transfer model from a large set of realistic atmospheric profiles and linked to the designated propagation or atmospheric parameter. Realistic noise is added to the synthetic brightness temperatures before a multivariate regression including quadratic terms is performed. The statistical retrieval coefficients are then implemented in ATPROP's software. For the test campaign at Cabauw, The Netherlands, 12 years of high resolution radio soundings at De Bilt were used as data base. At other locations another representative radiosonde station or atmospheric model data have to be considered. A special quality check routine was developed to identify erroneous soundings. Cloud liquid water profiles were diagnosed from the soundings using the modified adiabatic approach. One half of the dataset was used as training set to derive the regression coefficients while the second half was used to assess the theoretical performance.

The analysis of the test data reveals the benefit of ATPROP's frequency combination (Table 1). Even at frequencies not explicitly measured attenuation can be retrieved to better than 2 %. For example attenuation at 36 GHz (not covered by ATPROP) can only be derived with 3.7 % relative error from the two closest ATPROP frequencies (31.4 and 51.3 GHz) while the combination of all 16 frequency channels improves the retrieval by more than a factor of 2 to 1.54 %. Integrated water vapour has an accuracy of about 0.4 kg/m^2 corresponding to about 25 mm in wet path delay. The benefit of the 90 GHz channel can be demonstrated by looking at the theoretical LWP accuracy using standard K-band frequencies (~17 g/m^2) and the frequency combination including the 90 GHz channels (~9 g/m^2). The information content of the water vapor line on the vertical humidity distribution is limited to about two independent layers [7]. For the temperature profile the situation is slightly better with a vertical resolution of about 1 km at 1 km height degrading with increasing height. When so-called boundary layer scans using observations at elevations between 5 and 90° are performed the retrieval qualityfor the lowest 1500 m of the troposphere is significantly improved compared to zenith mode with an error <0.5 K [8].

Table 1. Theoretical accuracy for attenuation retrievals at selected frequencies. Different combinations of input frequencies are considered. The number of input frequencies is given in parenthesis.

Attenuation at	Input frequencies	RMS in neper	Rel. error in %
36.5 GHz	31.4 GHz & 51.26 GHz	0.0041	3.72
	K band (7)	0.0026	2.48
	All (16)	0.0016	1.54
22.24 GHz	22.24 GHz (1)	0.0031	2.27
	K band (7)	0.0026	1.89
	All (16)	0.0021	1.55
90 GHz	90 GHz		
	K band (7)	0.0125	3.88
	All (16)	0.0027	0.84

V. ATMOSPHERIC OBSERVATIONS

ATPROP has been installed at Cabauw, The Netherlands on the 16th of April and been operated in various testing modes. Fig. 4 shows a typical time series of all 16 brightness temperatures observed in zenith mode on 20 July 2008 as well as some derived quantities. While the first hours of the day were characterized by clear sky and few thin clouds (LWP < 100 g/m^2) several rather strong rain events happened around noon leading to saturation at 90 GHz (brightness temperatures approach environmental temperature). Here the advantage of the 15.3 GHz becomes clear whose maximum temperatures do not exceed 150 K. During peak precipitation no sensible retrieval of geophysical parameters can be performed (see negative spikes in IWV in Fig. 4) because water drops on the radom lead to an additional emission signal. This effect is more pronounced at the higher the frequencies. The rather short duration of the disturbances illustrates the good performance (and importance) of ATPROP's in-build heated blowers

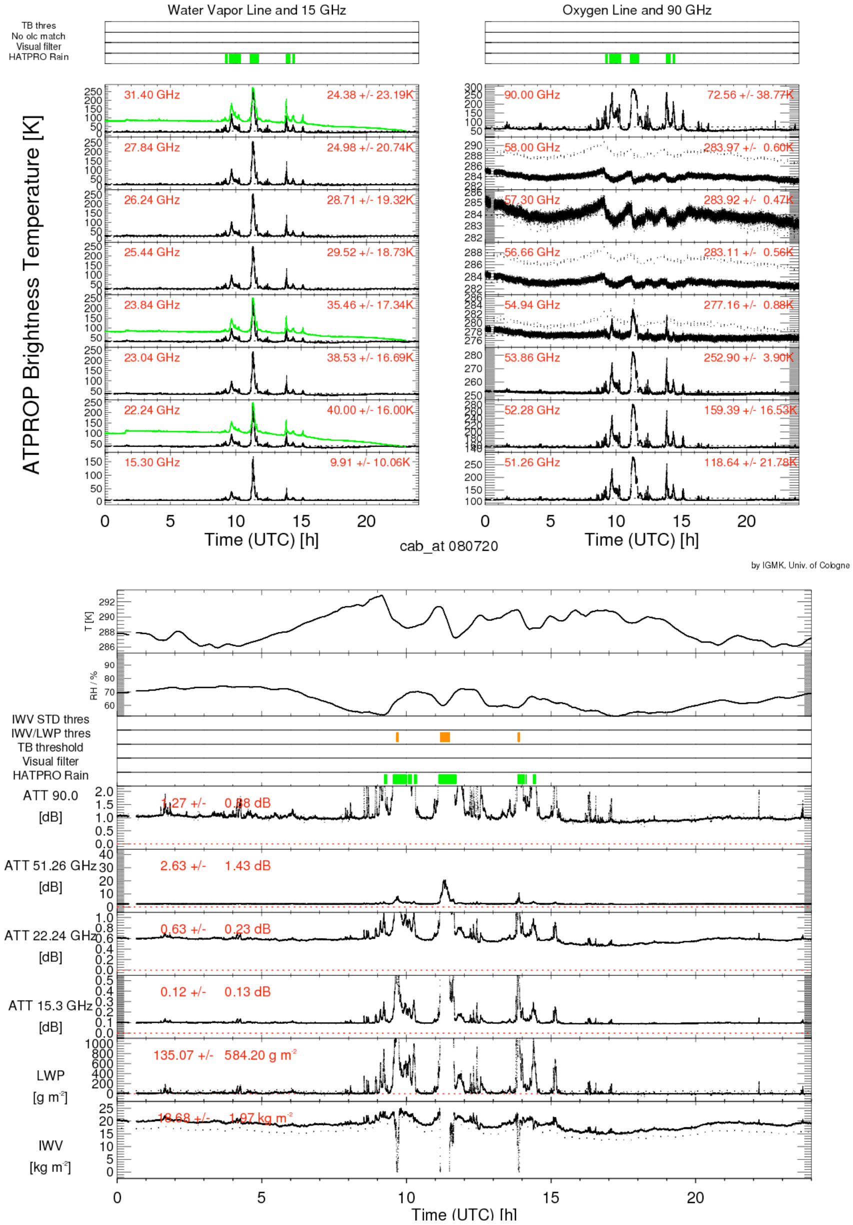

Fig. 4. Time series of ATPROP brightness temperatures observed at 16 frequencies on 20 July 2008 at Cabauw (top). In addition, brightness temperatures observed by the RESCOM radiometer (slightly different frequencies) are shown in green. The conspicuous single dots with enhanced brightness temperatures visible especially at 54.9, 56.7 and 58 GHz are due to one uncalibrated measurement at the beginning of each 10 min measurement interval. The problem has now been fixed. Attenuation at different frequencies, LWP and IWV (bottom) derived from brightness temperatures together with environmental temperature, humidity and rain flag (green).

which can quickly dry the radome. This becomes even more clear then ATPROP brightness temperatures are compared to whose measured by ESA's RESCOM radiometer (Fig. 4). Rain events took place on July 19th and lead to the fact that at midnight on July 20th RESCOM's brightness temperatures were strongly enhanced as water contaminated the optical part of the radiometer. Only towards the end of the day the RESCOM radiometer's brightness temperatures approach those of ATPROP.

ATPROP provides the opportunity to perform volume scans which can provide an overview of the full hemisphere (Fig. 5). This is rather interesting since approaching frontal systems or cloud streets become visible which can not be identified from continuous zenith observations. Inhomogeneity can be rather strong, e.g. more than a factor of 10 in attenuation, and is also interesting for meteorogical boundary layer studies [9].

In order to assess the quality of ATPROP observations, comparisons with KNMI's HATPRO were performed which showed an RMS of less than 0.5 K on clear sky days. Comparisons with the RESCOM radiometer showed a poorer performance with values between 0.4 and 1.2 K. Furthermore, brightness temperatures were compared to synthetic ones computed from corresponding radiosonde launches at De Bilt (~30 km away). While the agreement was rather good (~0.4 K) at the higher oxygen channels which reflect the temperature of the lower atmosphere the channels along the water vapour line showed a poorer performance. This can be explained by the stronger variation of humidity between rural and urban environment.

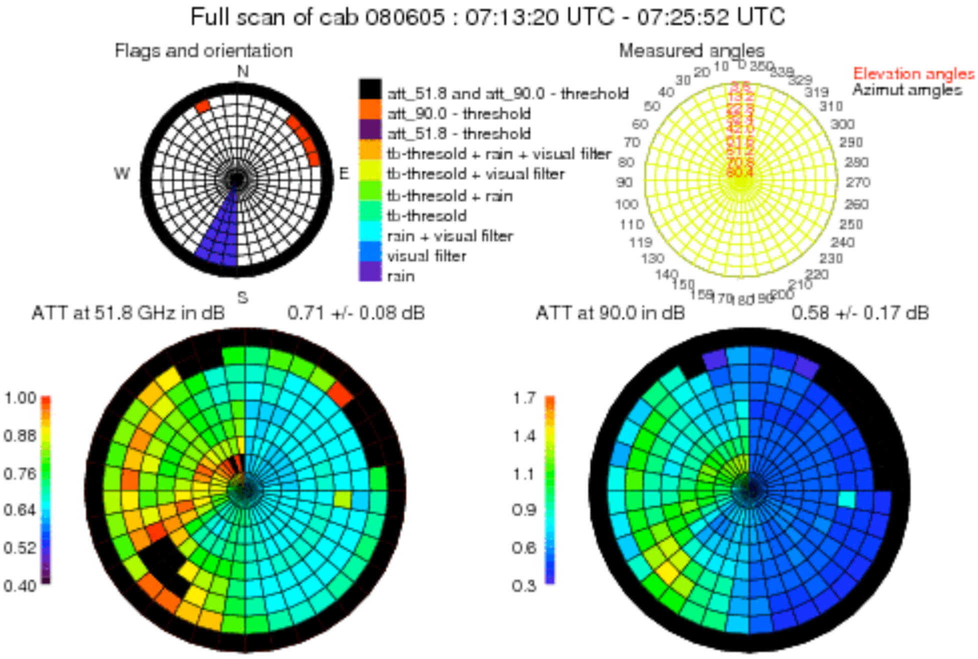

Fig. 5. Attenuation at 51.8 (bottom, left) and 90 GHz (bottom, right) derived from an ATPROP volume scan on 5 July2008, 7:20 UTC at Cabauw, The Netherlands. The observed azimuth and elevation scans are shown at the top right. Dubious observations are identified through a number of tests and flagged correspondingly (top left).

VI. CONCLUSIONS

The "Atmospheric Propagation and Profiling System" (ATPROP) has been designed, constructed and tested to allow an accurate assessment of propagation conditions between 10 and 90 GHz. It employs a unique set of frequency channels by combining a standard profiling system with additional channels at 15 and 90 GHz. The first channel frequency should allow an enhanced performance for determining attenuation in the transition phase between non-raining clouds to precipitation. On the other hand the 90 GHz channel is most suitable for detecting clouds with low water content.

All frequency channels point in the same azimuth and elevation direction. The software allows various observation modes including zenith pointing, boundary layer scans, full sky mapping as well as tracking of GPS/Leo satellites. All ATPROP channels include a novel calibration concept including a Dicke switch and noise diode injection. This allows a highly stable operation over long time periods. In addition, a high duty cycle can be achieved with no interruptions necessary for relative or tipping curve calibrations.

ATPROP has been installed and tested at Cabauw, The Netherlands, where a large number of state-of-the-art remote sensing instruments is continuously operated. Further analysis will therefore focus on synergetic use of ATPROP, cloud and precipitation radar, lidar, total sky imager etc in order to describe the atmospheric state as complete as possible. Especially the characterization of the longterm radiometer stability and the use of volume scans for characterizing the larger environment around Cabauw will be a future challenge.

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