Propagation Measurements at 19.7 and 99 GHz Using Ground-Based Radiometers

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Abstract—Radiometers are commonly used in order to assess the atmospheric propagation channel under low-attenuation and scatter-free conditions, with an increasing tendency toward using millimeter frequencies. In this letter, the interest is concentrated on the analysis of atmospheric attenuation measurements simultaneously obtained, under clear sky and the presence of clouds, by two independent and colocated ground-based radiometers at 19.7 and 99 GHz, in April of 2012 in Madrid, Spain. The experimental results obtained are in agreement with the estimations based on vertical meteorological profiles, and it is relevant to mention the high sensitivity to cloud liquid water provided by the measurements at 99 GHz. In general, the perspective of this work points toward the validity of using millimeter radiometry in propagation applications.

Index Terms—Atmospheric attenuation, clear sky, clouds, millimeter waves, radiometry.

I. INTRODUCTION

F rom the early work of Dicke in the field of radiometry, this technique has become a useful tool within the propagation community, due to the straight relation between incoming thermal radiation, expressed in terms of sky brightness temperature $T_b$ (in kelvins), and atmospheric attenuation $A_T$ (in decibels) caused by the medium. Advanced multichannel radiometers including channels above 90 GHz have been reported within the Earth science community [1], where the values of $T_b$ or atmospheric parameters are of main interest. As far as we know, there is a dearth of references about experimental measurements in terms of $A_T$ at W-band or above, primarily due to the absence of satellite beacon signals at these frequencies.

The present work is intended to discuss some results of measurements of $A_T$ at 99 GHz obtained by a ground-based radiometer, in the absence of rain, at a midlatitude site such as Madrid. Concurrent radiometric measurements at 19.7 GHz were also collected with a second colocated instrument with the purpose of comparing the behaviors of simultaneous time series. Validation of the measurements collected is discussed in terms of $A_T$ estimated from radiosonde observations (RAOBs). This validation approach has been extensively used in experimental campaigns by other researchers [2]–[4].

Section II provides an overview of the experiment, including a brief description of the radiometers and the meteorological database exploited. The main analysis of radiometric data is summarized in Section III. Results are discussed in Section IV, and conclusions are exposed in the last section.

II. INSTRUMENTS

A. Radiometers

The radiometer at 19.7 GHz is of the “total power” design, integrated into a ground station at the Universidad Politécnica de Madrid (UPM) [40.45° N, 3.71° W, 660 m above mean sea level (amsl)], aimed to measure the power level of the beacon signal of the Eutelsat HB13A (formerly HB6) satellite, along a slant path with an elevation angle of 40°. Due to the configuration of the whole system, several RF and IF stages are shared between the satellite receiver and the radiometer, in addition to a 1.2-m Cassegrain antenna with a half-power beamwidth (HPBW) of 0.95°. Due to the total power configuration, measurements of $T_b$ are affected by instabilities arising from different sources; thus, a reference noise source is periodically switched on for a few seconds in order to evaluate and remove some of these instabilities, particularly those resulting from the gain variations associated with temperature fluctuations. Further hardware details have been discussed in [5].

The 99-GHz radiometer [6] is the result of a collaborative work between several research groups within UPM. The instrument is an experimental prototype, located next to the 19.7-GHz beacon receiver (see Fig. 1). It includes a low-sidelobe horn antenna, with HPBW = 12.7°, whose azimuth and elevation angles are approximately equal to those of the beacon receiver antenna. The radiometer is a non ad hoc receiver, including commercial off-the-shelf components and in-house circuits [7]. It has a total power configuration, with two well-differentiated outdoor and indoor units. A hot-load calibration, which consists in placing an absorbing material at ambient temperature in front of the horn aperture, is carried out approximately each 40–60 min with the aim of compensating instabilities due to gain variations. An estimation of noise receiver temperature is achieved by measuring sky brightness temperature at two different elevation angles (i.e., 40° and 90°), in combination with hot-load calibrations.
B. Meteorological Data

On-site monitoring of meteorological conditions is achieved by using a colocated weather station recording continuously by surface parameters. External sensors allow room and equipment temperatures to be measured. One-minute rainfall rate data are obtained from a tipping-bucket rain gauge, joint with those collected by a laser optical disdrometer. Furthermore, vertical meteorological profiles from a 5-year RAOB database (2007–2011), routinely launched at 01:00 and 13:00 (local time), in the Madrid/Barajas Airport station (40.50° W, 633 m amsl), 14 km apart from the UPM premises, are available. Each profile is validated by preprocessing tasks including the identification of missing or invalid values. A layered atmospheric model is implemented, and the corresponding meteorological parameters at each layer are estimated by interpolation. Additionally, RAOBs performed during rainy conditions are discarded [8], obtaining a total of 3115 RAOBs under nonrainy conditions.

III. Radiometric Data Analysis

The volume of radiometric data at both frequencies was obtained between April 11 and 24, 2012, at the UPM premises, a period during which there was a predominant presence of clouds, being in some isolated cases accompanied by precipitations. Total and partial clear-sky conditions were only observed during a couple of days.

In order to convert the measurements of \( T_b \) (in kelvins) into atmospheric attenuation \( A_T \) (in decibels), the following well-known equation is used, which is valid in microwave and millimeter-wave radiometry for scatter-free and low-attenuation conditions [9], typically below 8 dB:

\[
A_T = 10 \log \frac{T_{m_r} - T_0}{T_{m_r} - T_b} \tag{1}
\]

where \( T_{m_r} \) (in kelvins) is the mean radiating temperature and \( T_0 \) is the cosmic background temperature (2.73 K). In a previous work in Madrid [10], it was shown that (1) can be used under clear sky or the presence of nonrainy clouds at frequencies around 100 GHz. With the purpose of continuously estimating

\[
T_{m_r} = 0.95T_{surf} \tag{2}
\]

and at 99 GHz [11]:

\[
T_{m_r} = 1.08337T_{surf} - 24.7784 \tag{3}
\]

where \( T_{surf} \) in kelvins is the surface temperature registered by the weather station. Expressions such as (2) and (3) are commonly obtained after statistical analysis of the values of \( T_{m_r} \) calculated from large RAOB databases in combination with absorption models.

One-second time series of \( A_T \) at 19.7 and 99 GHz were thus obtained by (1)–(3) from the experimental values of \( T_b \) measured by each radiometer along the slant path; the daily amount of valid data was defined by the intervals of time where hot-load calibrations in the 99-GHz radiometer were carried out. Short intervals corresponding to these calibrations were then removed.

IV. Results

Radiometric measurements of \( A_T \) are discussed in the following paragraphs. With validation purposes, individual \( A_T \) values estimated from RAOBs were used as indicators of the general behavior of the measurements, even if soundings were available only twice a day. Fig. 2 shows the \( A_T \) time series at the two frequencies, computed from the various RAOBs carried out during the radiometric campaign (April 11 and 24, 2012). Each value of \( A_T \) was obtained by adding the gas and cloud absorption contributions, calculated with the Liebe [12] and Salonen [13] models, respectively. Cosecant law was assumed in order to obtain the value of \( A_T \) along a slant path.

A. Attenuation Under Clear-Sky Conditions

Fig. 3(a) shows the experimental time series of \( A_T \) on April 16 at both radiometric frequencies. This day was the only one with clear-sky conditions throughout the entire day. At 99 GHz, the range of variations is comprised between 0.6 and 1.1 dB, with a relatively stable behavior suggesting that most of the gain fluctuations of the receiver were compensated by hot-load calibrations. At 19.7 GHz, \( A_T \) has a daily average between 0.1 and 0.2 dB. There is a good agreement among the measurements of \( A_T \) around the radiosonde launching at 13:00 and the estimated values of \( A_T \) from RAOBs at 19.7 GHz.
(0.2 dB) and 99 GHz (0.7 dB) at this time, shown in Fig. 2, as can be expected under clear-sky conditions, which are relatively stable in time and space.

During the interval of measurements of approximately 12 h, absolute humidity measured at the surface had a maximum value of 3.4 g/m³ and a minimum of 2.6 g/m³ [see Fig. 3(b)], which were the lowest during the experiment. Even though attenuation measurements describe a path-integrated parameter, at 99 GHz, a good degree of correlation between $A_T$ and surface absolute humidity variability can be observed. At 19.7 GHz, this correlation is not clearly observed because the smaller range of variations of $A_T$ is probably masked by the internal noise of the receiver.

### B. Attenuation Under Cloudy Conditions

During April 12 and 20, the sky was almost completely covered by low-altitude stratiform clouds. The experimental time series of $A_T$ of both days are shown in Fig. 4(a) and (b). The sporadic presence of light drizzle was detected by the laser disdrometer (registers not shown), with isolated peak values of rain intensity below 1.5 mm/h (instants are identified by the red circles in Fig. 4).

From Fig. 2, the corresponding RAOB-based $A_T$ values at 99 GHz at 13:00 in both days are 1.7 and 2.3 dB. Similarly, at 19.7 GHz are 0.3 and 0.4 dB. Visual inspection of Fig. 4(a) and (b) would suggest that the experimental data at this frequency are reasonably in agreement with the estimations based on RAOBs. Nevertheless, it should be taken into account that this comparison provides only a first approach about the validity of radiometric measurements. Indeed, differences with regard to $A_T$ from RAOBs are expected due to the dynamic nature of cloudy phenomena.

A “floor” attenuation level at both frequencies appears to be evident in the time series. It is expected that, after the passage of clouds with liquid water content, measurements tend to reach a stable level determined by the effect of gaseous absorption. From both figures, it is observed that this level is comprised between 1.1 and 1.5 dB at 99 GHz and between 0.3 and 0.4 dB at 19.7 GHz. These values are higher than the ones observed under clear-sky conditions on April 16. This is attributed to the higher levels of ground absolute humidity measured in both days, whose range of variations is comprised between approximately 5.5 and 7.5 g/m³ (registers not shown).

These floor levels suggest that receiver gain variations along the day are mostly compensated by the calibration procedures implemented for each instrument. However, it is worth mentioning that unexpected behaviors during some intervals of time, for example, between 11:00 and 11:20 in Fig. 4(a), would also suggest that a more performing compensation technique should be implemented in the 99-GHz radiometer as well as the necessity of a mounting with improved characteristics of thermal isolation and stability by cooling mechanisms.

The comparison of the time series at the two frequencies shows a significant degree of correlation with regard to the measurements carried out in the presence of light rain conditions [see the red circles in Fig. 4(a) and (b)], which would also be a good indicator of the performance of the two radiometers, as both frequencies are sensitive to rain. The 99-GHz radiometer features a high sensitivity to the presence of clouds along the path, with attenuation varying within a range of about 1.5–7 dB, that has a smaller correspondence in the measurements at 19.7 GHz, a frequency less sensitive to liquid water. The inspection of cosite rain gauge and disdrometer registers shows that intervals comprised between 11:00 and 16:00 on April 12 and between 15:00 and 19:00 on April 20 are characterized by the absence of precipitations. Within these intervals, some attenuation values at 99 GHz are even above those observed during light rain events. For example, on April 20 at 15:25 in
Fig. 4(b), the attenuation peak is about 7 dB, which could be caused by a strong presence of cloud liquid water along the path.

C. Retrieval of IWV and ILWC

The time series of $A_T$ at 99 GHz have been combined with those obtained at 19.7 GHz in order to retrieve the corresponding integrated water vapor IWV (in millimeters) and integrated liquid water content ILWC (in millimeters) parameters. The retrieval procedure, valid under the Rayleigh regime, is well known and based on the combination of attenuation measurements at two different frequencies, one sensitive to water vapor and the other one to liquid water, as follows [14]:

$$\text{IWV} = a_0 + a_1 A_{f1} + a_2 A_{f2}$$

$$\text{ILWC} = b_0 + b_1 A_{f1} + b_2 A_{f2}$$

(4)

where $A_{f1}$ and $A_{f2}$, expressed in decibels, are the zenith atmospheric attenuations, derived by the cosecant law, at the frequencies $f1$ and $f2$, i.e., 19.7 and 99 GHz. The retrieval coefficients $a_i$ and $b_i$, in millimeters for $i = 0$ and millimeters per decibel for $i = 1, 2$, are site-dependent parameters characterizing the physical properties of the atmosphere, also depending on temperature and frequency values. They have been computed by the method described in [14], using as input data the 5-year RAOB database and the already mentioned Liebe and Salonen models. The values obtained are $a_0 = -5.46$, $a_1 = 127.67$, $a_2 = -9.81$, $b_0 = 0.03$, $b_1 = -1.26$, and $b_2 = 0.29$.

As an example, the concurrent time series of $A_T$, IWV, and ILWC corresponding to April 13 are plotted in Fig. 5. During this day, sky conditions were characterized by the permanent presence of clouds, and no rainfall event was detected by the cosite rain gauge and disdrometer. However, a strong peak at 14:50 would suggest the presence of rain along the path, which is also confirmed by the 1.1 dB of attenuation at 19.7 GHz at that instant of time. In general, observable parameters under these conditions are erroneous. An anomalous behavior on the retrieval of ILWC is also observed during some short periods with negative values, which can be attributed to the presence of residual instabilities due to thermal effects affecting the total gain of both radiometers. The observed levels of ILWC during the periods comprised between 11:30 and 12:30, between 13:00 and 15:00, and between 16:00 and 18:00 provide evidence about the passage of clouds. The high sensitivity to the presence of ILWC is provided by the 99-GHz radiometer, whose measurements of $A_T$ are straightly related to the retrieval of ILWC. Moreover, the occurrence of cloudy events seems to be associated to an increase in the retrieved values of IWV, accompanied by the fastest variations of this parameter.

Statistics in the form of complementary cumulative distribution functions (CCDFs) of experimentally retrieved IWV and ILWC were calculated. Rainy periods were discarded by inspecting the rain gauge and disdrometer registers. Moreover, 124 RAOBs, corresponding to soundings launched at 13:00 during the months of April, were extracted from the 5-year data set, and CCDFs of IWV$^{\text{RAOB}}$ and ILWC$^{\text{RAOB}}$ (by the Salonen model) were obtained. This period has been selected in order to have a relatively large set of RAOBs, carried out under similar, but not identical, weather conditions as those of our experiment. The CCDFs are shown in Fig. 6. The ranges of variations of IWV and IWV$^{\text{RAOB}}$ in Fig. 6(a) do not show large departures from each other, with a maximum difference of 3 mm observed below 10% of the time and median values of IWV = 11.5 mm and IWV$^{\text{RAOB}}$ = 11.9 mm.

With regard to ILWC and ILWC$^{\text{RAOB}}$, the comparison in Fig. 6(b) must take into account that, as mentioned in Section III, the radiometric measurements were taken in a period with a much higher presence of clouds than what is usual in Madrid in this time of the year. The CCDF of ILWC shows nonzero values of liquid water for 70% of the time, compared to 40% for the period considered in the CCDF of ILWC$^{\text{RAOB}}$. It must also be noticed that the stability of the CCDFs is affected by the small number of RAOBs considered, as well as by the limited period in which radiometric measurements were taken, and that RAOBs and radiometers inherently measure different scenarios. Despite these limitations, it can be observed that both curves show similar values and slopes, although associated to higher time percentages in the case of the radiometric measurements. Once rain events were removed...
radiometric and RAOB-based estimations has shown a good agreement with regard to the ranges of values of $A_T$ observed and a good degree of coincidence when the measurements are carried out under clear-sky conditions. The radiometer allows the assessment of the propagation channel in a simple way, even at 99 GHz, for which atmospheric attenuation has been less studied. This frequency can provide sensitive measurements when cloudy scenarios are observed. An instrument such as the one presented in this letter could thus be a source of valuable data about the presence of clouds as well as about the absorption caused by liquid water in this frequency band.

Attenuation measurements at 19.7 and 99 GHz have been combined to retrieve IWV and ILWC values using a well-known procedure, not previously used with these frequencies. The results obtained are good indicators about the validity of using the method with this type of radiometric measurements.

**V. CONCLUSION**

Two low-cost and physically independent radiometers, working at 19.7 and 99 GHz and calibrated by simple procedures, have been used as propagation tools in order to estimate atmospheric attenuation $A_T$ under clear-sky and cloudy conditions. Both radiometers have provided good measurements of $A_T$, which have been compared with estimations obtained from RAOBs, in the absence of other alternatives to obtain direct measurements of atmospheric attenuation. The comparison has its own limitations, because of the distance between the sites and the limited availability of RAOBs, which are carried out only a few times daily. These limitations become more relevant under cloudy conditions. Nevertheless, the comparison of

**REFERENCES**


