New Analysis and Estimations of Atmospheric Attenuation at 100 GHz using Meteorological Data in Madrid

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***Abstract*—Atmospheric propagation at frequencies within the THz domain are deeply affected by the influence of the composition and phenomena of the troposphere. This paper is focused on the estimation of first order statistics of total attenuation under non-rainy conditions at 100 GHz. With this purpose, a yearly meteorological database from Madrid, including radiosoundings, SYNOP observations and co-site rain gauge, have been used in order to calculate attenuation due to atmospheric gases and clouds, as well as to introduce and evaluate a rain detection method. This method allows to filter out rain events and refine the statistics of total attenuation under the scenarios under study. It is expected that the behavior of the statistics would be closest to the ones obtained by experimental techniques under similar conditions.**

I. Introduction

The THz band covers a broad frequency range comprised between 100 GHz and 10 THz, which corresponds to wavelengths from 3 mm to 30 μm, respectively. A great research effort within this domain is currently concentrated on technological issues as well as several promising applications. An important number of exhaustive reviews on these subjects can be found in the literature [1], [2]. Along with the growing interest on this band, the study of the strong influence of the atmosphere on the propagation at frequencies above 100 GHz is essential for some emerging research areas, as THz communications [3], or more well-known applications, as ground-based radiometry applied to atmospheric sciences studies [4].

The TeraSense project [5] is a collaborative initiative joining the efforts of sixteen spanish research teams specialized into different scientific and technologic areas; the project aims to increase the knowledge on several submillimeter sub-bands and to develop experimental instruments from a radio perspective, including design and measurement of antennas, design of circuits, as well as simulation and modelling of radiation-matter interaction. Within this framework, a series of studies are being developed at Universidad Politécnica de Madrid (UPM), currently focused on propagation on non-scattering atmospheric conditions at 100 GHz and also 300 GHz. This study is carried out in parallel with the implementation of a ground based radiometer at 100 GHz allowing sky brightness levels to be measured and thus total attenuation values to be retrieved.

Under the atmospheric conditions mentioned, radiation absorption effects are fundamentally caused by the presence of gases and clouds. Gaseous attenuation is evaluated as the sum of the effects of water vapor and oxygen, using well established physical-basis models [6], [7]. Cloud attenuation is evaluated under the Rayleigh approximation, which is considered valid up to 300 GHz for small water particles, typically those with radii below 30 μm [8]. Therefore, absorption caused by water droplets in clouds is linearly related to cloud liquid water content. The calculation of this atmospheric parameter as well as the detection of cloud layers can be performed through a variety of cloud detection algorithms detailed in the literature [9]–[11].

Yearly cumulative distributions functions (CDF) of total attenuation at 100 GHz, using radiosoundings data, have been obtained and reported in a recently work [12]. These kind of first order statistics are typically one of the tools used in order to evaluate channel propagation characteristics. Since the scenario under study is a non-scattering propagation medium, the previously obtained statistics could be refined discarding those radiosoundigs carried out during rain conditions.

The present contribution aims to introduce a rain detection procedure using available meteorological data sources, which are briefly described in Section II. Following, the proposed method is described and evaluated in Section III. In Section IV the method is used with recently processed data from radiosundings of year 2011, in order to improve yearly statistics of total attenuation along a zenith path under non-scattering conditions. At the end of the present paper, some valuable conclusions and future works are discussed.

II. Meteorological data

A variety of meteorological data are regullarly collected and registered in some specific sites in Madrid. In the present research, data from Barajas Airport station (40.50 N; 3.57 W; 633 m amsl) have been analyzed. Madrid is located in the central area of the Iberian Peninsula. It is characterised by having continental climate, with hot and dry summers and cold winters. In the following paragraphs, an overview of relevant aspects concerning the different meteorological data sources having been exploited in this work is summarized.

A. Radiosoundings

Vertical profiles of temperature, pressure and relative humidity are available from radiosonde balloons launched routinely twice a day (00 and 12 UTC). These parameters are used as input data of the above mentioned gaseous and cloud attenuation models. A selection and check procedure has been established with the aim of identifying non-existing and invalid soundings. With this purpose, considerations about the minimum and maximun height attained by the radiosonde, as well as non-realistic or missing parameters along the path have been verified. The possible horizontal displacement of the radiosonde during its ascent, due to the effect of wind, has not been analyzed.

B. SYNOP observations

Surface synoptic reports (a.k.a SYNOP reports) are man-made weather observations, registered generally four times a day (00, 06, 12 and 18 UTC). As it is well-standardized by the World Meteorological Organisation (WMO), the information about meteorological conditions provided by these reports is coded according to the alpha-numeric data format FM-12 [13].

A decoding process of these data is carried out with the aim of extracting useful meteorological information at the moment of the observation. Specifically, a set of relevant information relative to the presence of rain events is extracted from the following decoded parameters:

- SYNOP Present Weather parameter (ww code): Numerical code describing weather conditions at observation time.
- SYNOP Liquid Precipitation parameter (RRR code): It represents the liquid precipitation amount in (mm) during the previous 6 h (for reports registered at 00 and 12 UTC) or 12 h (for reports registered at 06 and 18 UTC) before the SYNOP observation.

III. Rain Detection Method

The detection method proposed below allows to filter out radiosoundings carried out under rain conditions. At the frequencies of interest, these kind of atmospheric scenarios would be responsible of scattering effects caused by the interaction between radiation and water particles. As consequence, high attenuation values would be expected due to extinction processes, expressed as the sum of absorption and scattering contributions.

The following considerations have been taken into account in order to define the method:

- Given a series of yearly atmospheric profiles from radiosoundings, it is not possible to easily separate rain and non-rain events analyzing the IWC (Integrated liquid Water Content), expresssed in (mm), of each profile. This frequency-independent parameter is calculated integrating the liquid water content, w_c in (gm^{-3}), along a path. The parameter w_c is typically estimated using one of the previously mentioned estimation models of cloud attenuation [9]–[11].
- In order to detect the presence of rain in Barajas, co-site rain gauge data would be the most reliable source of information. However, rainfall data measured by this kind of instruments is not always available.

TABLE I
SUMMARY OF RAIN DETECTION CRITERIA BASED ON SYNOP PARAMETERS

Criterion	Description
CR1	Present Weather Parameter (at 00 and 12 UTC): Rain at Observation Time
CR2	Liquid Precipitation Parameter (at 00 and 12 UTC): Accumulated Rain in previous 6 h $> 1\,\mathrm{mm}$
CR3	Liquid Precipitation Parameter (at 06 and 18 UTC): Accumulated Rain in following 6 h $> 1\,\mathrm{mm}$

- As a consequence of the previous consideration, the Present Weather and Liquid Precipitation parameters, decoded from SYNOP reports, are evaluated in order to identify rain conditions.

In addition to the above considerations, the proposed identification algorithm makes use of the IWC value for each time-coincident radiosounding launching and SYNOP observations. Due to the well behavior of the Salonen model [9] in Madrid's climate, observed during previous experiments [14], it has been used to detect the presence of clouds and to estimate IWC along a zenith path.

Based on the SYNOP Present Weather and the SYNOP Liquid Precipitation parameters, a set of three identification criteria, hereinafter denominated as CR1, CR2 and CR3, have been defined. Table I summarizes the information analyzed by each criterion in order to discard probable rain conditions events. Besides, an IWC threshold, IWC$_{th}$ = 0.1 mm, has been introduced with the aim of evaluating those probable falsely detected events by CR2 and CR3. In some cases these soundings could be associated to almost zero or thin-cloud related IWC values [15].

In summary, a rain event is identified if one of the conditions below is verified:

1) CR1 is satisfied during SYNOP observation.
2) IWC $>$ IWC$_{th}$ during events detected by CR2 and CR3 (and not previously detected by CR1).

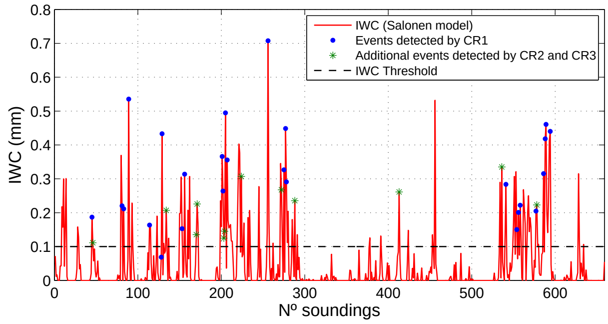
An in-depth description and details about the method here proposed can be found in a previous work recently reported [16].

Fig. 1a shows an example of the use of the method. Yearly IWC time series, corresponding to data of 2011, has been obtained and plotted using a total of 659 meteorological profiles. This volume of data has been analyzed using the above mentioned conditions in order to identify probable rain conditions during radiosoundings. Finally, the events to be discarded have been clearly determined. CR1 is established as the most reliable rain presence identifier. CR2 and CR3, in combination with IWC$_{th}$, allow the detection procedure to be complemented, specially for those events not-detected by CR1 having high IWC values, probably associated to rain conditions.

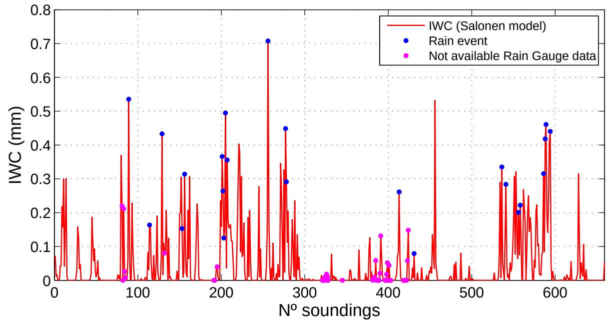
IV. Evaluation and results

A. Evaluation of the method using co-site rain gauge data

Time series of cummulated rain, expressed in (mm), with an integration time of 10 minutes, have been provided by the



(a)



(b)

Fig. 1. Rain events identified by a) CR1, CR2 and CR3, using IWC_{th} = 0.1 mm, and b) Co-site rain gauge data. Year 2011

public spanish meteorological agency, AEMET, for year 2011. This kind of information, which could not always be available for the period under study, has been used in order to evaluate the rain identification method by comparing its results with those obtained by the rain gauge.

With the aim of identifying the presence of rain during the ascent of the radiosonde balloon, cumulated rain values around the time of launching have been analyzed. Then, the following considerations have been taken into account:

- Launching of radiosondes is not carried out on time every day. According to [17], balloons would be launched between 45 and 30 minutes earlier than the estimated time (i.e. 00 and 12 UTC) reported in meteorological literature.
- In addition to the issue previously remarked, it must be taken into account the time elapsed until the sonde reaches a theoretical rain height, typically assumed in Madrid as 3.0 km amsl. As a first approximation, a balloon ascent velocity of 300 m/min has been considered [17].
- Thus, a time interval of 70 minutes before and 20 minutes later the theoretical launching time is proposed. A rain event is considered existent as long as the cummulative rain value within the period is higher or equal to 0.1 mm.
- If the previous condition is not verified, then the event is not classified as rain condition.

On the basis of the previous discussion, yearly rain gauge data was analyzed. Rain events were identified and they have been plotted on the same IWC time series previously obtained, as it is shown in Fig. 1b. Some missing rain data have also been discovered during this analysis, and for very particular cases, this non-available data coincided with events detected

TABLE II
SUMMARY OF RAIN DETECTION CRITERIA BASED ON SYNOP PARAMETERS

Events detected by Rain Gauge	**Events detected by CR1 + CR2 + CR3**	**Coincident events between both methods**
23	36	22

by the SYNOP criteria.

A first visual comparison between Fig. 1a and 1b allows to observe a good agreement on the detection of events, specially for those with IWC values above 0.1 mm. Below this value, the rain gauge almost not identify rain conditions. Table II sumarizes the results obtained during the simultaneous evaluation. The number of radiosoundigs to be filtered out using (CR1 + CR2 + CR3) is higher than the events identified by the rain gauge. However, assuming that cummulative rain analysis is the most reliable source of rain presence detection, it is observed that approximately 95% of these events are detected by the SYNOP criteria.

B. *CDF of total atmospheric attenuation at 100 GHz*

The CDF of total attenuation, A_T in (dB), along a zenith path has been calculated at 100 GHz using all valid vertical profiles for the period of 2011. Total attenuation for each event, expressed as the sum of the absorption effects of atmospheric gases and clouds, has been calculated using the ITU-R line-by-line method and Salonen model, respectively. Following, the method of identification based on the criteria has been used in order to filter out radiosoundings carried out during rain conditions. Then, a new CDF of total attenuation has been computed with non-discarded events. With the aim of comparing both CDF's, the obtained one using all radiosoundings has been defined as reference curve. Both statistic distributions have been plotted in Fig. 2.

On the whole, the variations between the reference level and the cumulative distribution obtained after the filtering process are considerable. Total attenuation values exceeded between 1 and 10% of time are in the order of 1.8 and 2.8 dB for the filtered CDF. After discarding rain events, the predicted value of A_T exceeded 20% of time is about 1.3 dB, which is quite consistent with a similar observation noticed in an previous interannual study carried out for years 2007 to 2010 [18].

As it was pointed out in previous paragraphs, a greatest number of events are filtered out by our SYNOP criteria-based method with respect to those identified as rain conditions by the rain gauge. With the aim of gaining a better understanding of the effect of this difference on the result obtained, a CDF of total attenuation was computed discarding those events simultaneously detected both by the rain gauge and by our method. The resulting CDF has also been plotted in Fig. 2.

After examiming the set of three first-order statistics shown in Fig. 2, it can be observed that even though some more events have been discarded by the method, the two filtered CDF's are quite similar. Very small differences are observed for percentages of time comprised between 2% and 20%, typically associated to cloudy conditions. Based on the definition of the method, some events associated to cloudy conditions,

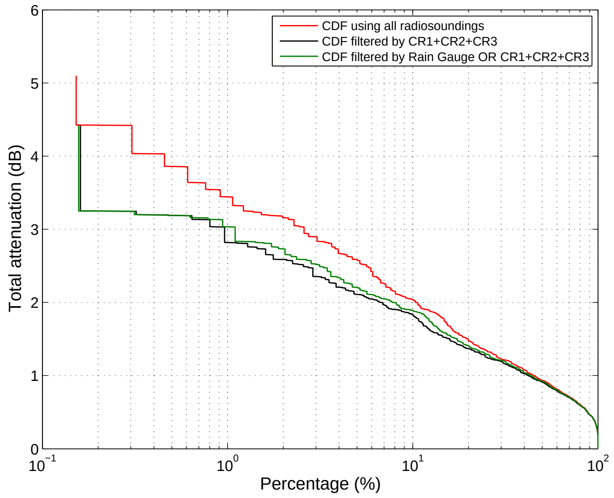


Fig. 2. CDF's of total attenuation at 100 GHz for year 2011. A set of three different CDF's is observed aiming to analyze the effect of discarding events.

non responsible of precipitations, have been filtered out.

V. Conclusions

Meteorological data from Barajas Airport in Madrid, for the period of 2011, have been used to develop an atmospheric propagation study at 100 GHz considering non-scattering conditions. Radiosoundings have been used to extract meteorological vertical profiles and therefore estimate yearly IWC time series. Then, based on parameters extracted from co-site SYNOP reports and defining an IWC threshold, a rain detection method has been introduced. The method has also been evaluated by comparing the number of events detected both by the method and by a co-site rain gauge. Furthemore, the evaluation has included a comparison between CDF's of total atmospheric attenuation.

After the evaluation of the method, it can be concluded that differences between statistics distributions of total attenuation filtered by the SYNOP criteria or by the rain gauge data, are not significant. Therefore, in the case of unavailability of rain gauge data, detection based on co-site SYNOP data have demonstrated that can be useful to identify events probably associated to rainy conditions. The proposed identification criteria and the use of an IWC threshold can be considered as a suitable method to filter out these kind of events, that could be associated to important attenuation values.

It is expected that yearly cummulative statistics of total attenuation filtered by the SYNOP criteria, would be closest to the ones obtained from yearly experimental measurements campaigns under clear sky or cloudy conditions. A validation of this method in other spanish locations, with different climate conditions, is foreseen in following stages of this research.

From an experimental point of view, a radiometer at 100 GHz is currently in operation at our premises. This instrument has been developed in collaboration with a research team from the TeraSense project, with the aim of estimating atmospheric attenuation values under non-scattering conditions. These experimental estimations could be compared with computed levels as the reported ones in the Section IV of this paper. To the best of our knowledge, this 100 GHz propagation-oriented study in this climate region would be the first of its kind to be carried out.

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