Determination of the Coefficients "a" and "b" of the K-R Relationship for Accurate Measurement of Water Quantity Using Cellular Links in Burkina Faso

ABSTRACT

Electromagnetic waves emitted between antennas interact with the atmosphere, undergoing absorption, scattering, and emission processes. Previous studies have shown that the relationship between specific attenuation (K) due to rain of these microwaves and the precipitation rate (R) can be modeled by an empirical power law. The coefficients "a" and "b" of this relationship, linking microwave signal attenuation to precipitation rate, vary depending on frequency, temperature, raindrop size distribution, and other parameters. Thus, it is crucial to obtain data adapted to specific geographical and environmental conditions for accurate rainfall rate assessment.

In this study, we first determined the values of "a" and "b" using data from a disdrometer installed in Nazinga, Burkina Faso. These values were used in the relationship to determine rainfall rates. The Pearson correlation coefficient between the different series of values of the rain is over 0.9. A comparison of the cumulative rainfall rates determined with the data from a rain gauge at Bobo Dioulasso airport was made. There is a perfect correlation between the values determined in Nazinga and those of Doumounia et al., 2019 with bias values ranging between -3,31 and 0.61 depending on the frequency value and its polarization.The discrepancy between the series of values and those of the rain gauge highlights the need to take local conditions into account when determining the values of "a" and "b" for a better determination of rainfall rates.

Keywords: Attenuation, Microwave link, Rain rate, Signal, Telecommunications

1. INTRODUCTION

Accurate measurement of water quantity is essential for effective agricultural planning, irrigation management and the sustainability of water resources. In Burkina Faso, a West African country with a semi-arid climate, a reliable estimate of the amount of precipitating water is particularly crucial due to seasonal variations and the effects of climate change. Accurate rainfall measurement is a major challenge for many operational and research applications. Unfortunately, traditional measurement and monitoring methods, such as rain gauges, ground-based radar and satellites, are often insufficient, particularly in low-income countries [1], [2].

The rain gauge remains the most commonly used tool for measuring ground precipitation, essentially providing a point measurement. However, it is crucial to note that there is a growing delay in the transmission and subsequent processing of rain gauge data to the Global Precipitation Climatology Center. Additionally, regular maintenance visits are necessary for these rain gauges, resulting in significant costs to protect them against obstructions. As for weather radar, the costs of installation and operations are too expensive for these countries. Satellite rainfall products are more and more used but still present some biases [3]. Moreover, acquiring these data remains a costly process, particularly for low-income countries [1], [2], [4].

A promising alternative is to exploit commercial microwave link attenuation measurement to estimate rain rate. This method has been tested for the first time in West Africa by Doumounia et all.2014 [1]. The principle is simple, when the signal traverses precipitation, it undergoes additional attenuation caused by the absorption and scattering of electromagnetic radiation by water droplets. This additional attenuation can be exploited to estimate the amount of rain fallen between the two antennas. However, the reliability of processing methods needs improvement due to the opportunistic nature of CML data [1], [5].

This paper presents the results of the values of the coefficients "a" and "b" of the K-R relationship from data obtained from a disdrometer installed in Nazinga, Burkina Faso. A comparison of the obtained values with other data sources is conducted. These different values of "a" and "b" are then used in the K-R relationship to determine the rainfall rate for given attenuation values of a link. A comparison of the determined rainfall rates is also performed.

2. MATERIAL AND METHODS

2.1 material

2.1.1 Study Area

The study area is the Nazinga Reserve, also known as the Nazinga Ranch, a protected area covering an area of 913 km², located near the town of Pô in the southern part of Burkina Faso. Situated in the Sudanian zone of the country, this region has an average annual temperature of 27.80 °C and an average annual precipitation of 925.98 mm, calculated over a period of 30 years. The highest temperatures are generally recorded between March and April, reaching around 31 °C, while the lowest temperatures occur in August, around 25.29 °C [6]. The area outlined in green in Figure 1 represents the Nazinga region.

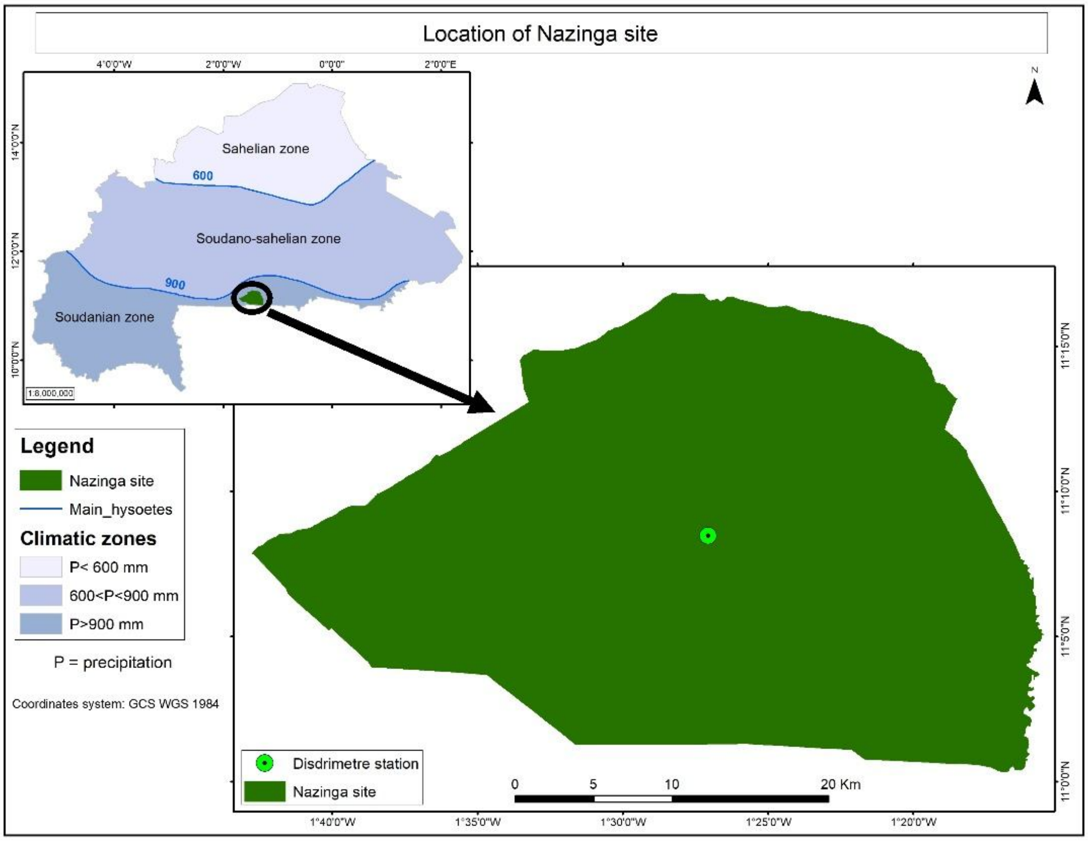

Fig.1. Map illustrating the Nazinga site.

2.1.2Disdrometer Data

To accurately estimate the rainfall rate from commercial microwave telecommunication links, it is necessary to determine the constants "a" and "b", which depend on parameters such as temperature, frequency, and raindrop size [7]. To obtain precise measurements tailored to different areas, a disdrometer was installed by WASCAL in the Nazinga region of Burkina Faso. The disdrometer used in Nazinga is an OTT Parsivel model, a sophisticated device designed to measure the size and velocity of precipitation particles, primarily raindrops. It operates using optical and electronic sensors to detect the size and fall speed of individual raindrops passing through its measurement area. Data collection took place from October 1, 2016, to September 26, 2017, over a period of about one year. The data were recorded with a temporal resolution of 1 minute. The OTT Parsivel2 disdrometer recorded various information such as the average fall speed of precipitation V in (m/s), the rainfall rate (R in mm/h), the number concentration of the drops in the unit volume per diameter (N(D), the type of particles detected, and the atmospheric conditions during the measurement period.

2.1.3Microwave Attenuation Data

For this study, we use a 13 GHz link with horizontal polarization and a length of 1.278 km in the city of Bobo Dioulasso, as we do not have a CML network in the city of Nazinga. Converting microwave link (CML) attenuation data into rainfall rates is challenging because CMLs are an opportunistic data source and are not specifically designed for rainfall observation [8]. Therefore, the processing of CML data significantly impacts the quality of the generated rainfall information and must be done carefully. Most CML research groups have developed their own methods, tailored to their needs and datasets. An overview of these methods is provided by Chwala and Kunstmann (2019) [9]. In the following subsections, we will describe how to convert microwave signal attenuation due to rain into rainfall rates.

2.2Methodology

2.2.1 Specific attenuation (k)

The specific attenuation k defines the attenuation experienced by the electromagnetic signal per unit length traveled. It is caused by absorption and scattering by all water droplets contained per unit volume of air. Specific attenuation can be calculated by integrating the Drop Size Distribution (DSD) and the attenuation cross-section from the equation defined below [10]:

$$k = 4{,}343 \times 10^3 \int_0^\infty C_{ext}(D) N(D) dD \qquad \text{(Eq.1)}$$

Where k is the specific attenuation expressed in [dB/km], $C_{ext}(D)$ is the extinction cross-section of diameter D [mm], and N(D) is the number of raindrops per unit volume of air.

2.2.2Rain Rate (R)

The rainfall rate R, expressed in (mm/h), which characterizes the flow of rainwater falling to the ground, is related to the granulometry and the fall velocity of the droplets according to the following equation[11], [12]:

$$R = 6\pi \times 10^{-4} \int_0^\infty D^3 V(D) N(D) dD \quad \text{(Eq.2)}$$

$$V(D) = 3{,}78 D^{0{,}63} \qquad \text{(Eq.3)}$$

Where V (m/s) is the fall velocity, approximated as a function of the average diameter of the water droplets D (m), and N(D) is the number of raindrops per unit volume of air.

2.2.3K-R relationship

The technique for estimating precipitation from path-integrated rain attenuation is based on the well-known empirical relationship between specific attenuation k (in dB/km) and rainfall rate R in (mm/h) [10]:

$$k = aR^b \qquad \text{(Eq.4)}$$

The pre-factor "a" and the exponent "b" depend on the microwave frequency, polarization, water droplet temperature, and the raindrop size distribution along the path. Using the k-R relationship, rainfall rates can be deduced from the path-integrated attenuation measurements provided by the CMLs.

2.2.4Drop Size Distribution(DSD)

The disdrometer records the values of the previously mentioned parameters and stores them in txt files, which are then converted to CSV files. Data processing is performed using the Python programming language. After structuring the data from the CSV files generated by the disdrometer, they are filtered to retain only the data corresponding to precipitation (rain). The rainfall intensity R (in mm/h) is calculated using the DSD, which gives the number of raindrops per unit volume for different drop sizes, according to equation (Eq.2). The specific attenuation k (in dB/km) is also calculated from the DSD. It is given by equation (Eq.1) where the he extinction cross-section $C_{ext}(D)$ is calculated using the T-matrix method for non-spherical raindrops developed by Waterman (1965) [13]. The values of the coefficients "a" and "b" were determined by linear regression using the specific attenuations k and the rainfall rates R calculated for frequencies ranging from 1 to 100 GHz in both vertical and horizontal polarization.

2.2.5Calculation of bias between different K-R relationships and the Pearson correlation coefficient between the corresponding rainfall.

The bias between the different K-R relationships and the Pearson correlation coefficient between the corresponding rainfall are calculated using equations (Eq.5) and (Eq.6), respectively.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(P_i - Q_i) \qquad \text{(Eq.5)}$$

where
n is the number of data pairs,
P_i is the predicted or estimated value,
Q_i is the observed or measured value.

$$PCC = \frac{cov(R_i,R_j)}{\sigma(R_i)\times\sigma(R_j)} \qquad \text{(Eq.6)}$$

Where R_i and R_j are daily rains from different values of a and b. $cov(.)$ is the covariance function, $\sigma(.)$ is the standard deviation function.

3. RESULTS AND DISCUSSION

3.1 The values of "a" and "b" derived from the Nazinga DSD

The coefficients "a" and "b" are constants used to define the relationship between specific attenuation (K) and rainfall rate (R) in the context of microwave precipitation measurement, particularly in empirical models. Coefficient "a" indicates how much an increase in rainfall rate leads to an increase in attenuation. In other words, "a" measures the magnitude of the effect of rainfall on microwave signal attenuation. A higher value of "a" indicates greater sensitivity of attenuation to precipitation. Coefficient "b" determines the nature of the relationship between specific attenuation (K) and rainfall rate (R). When "b" is close to zero, the relationship is more linear, whereas higher values of "b" imply an exponential or non-linear relationship. Figure 2 presents the values of "a" and "b" for frequencies ranging from 1 to 100 GHz in vertical and horizontal polarizations, determined from the Nazinga DSD. It is observed that "a" values increase with frequency, while "b" values increase to a peak near 1, then decrease with frequency[14].

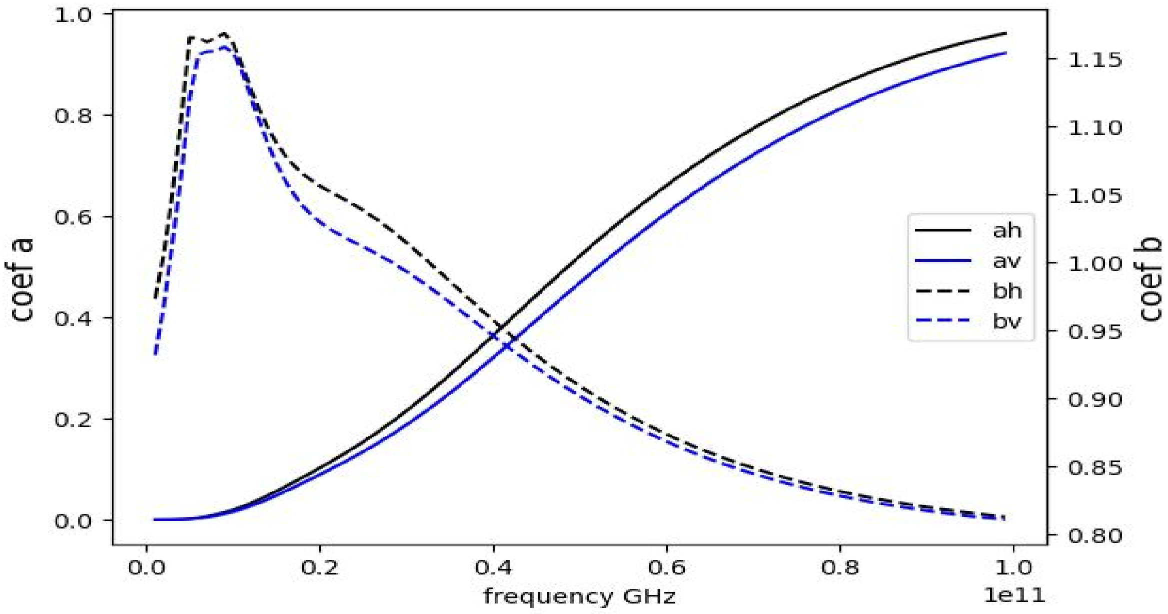

Fig.2.Values of "a" and "b" for the K-R relationship, determined using the Nazinga DSD.

3.2Comparison of "a" and "b" derived from DSD with other data sources

Figure 3 compares the K-R relationship using different values of "a" and "b" at frequencies of 7 GHz and 13 GHz. A strong correlation is observed between ITU values and those determined at Nazinga for the 7 GHz frequency in both vertical and horizontal polarizations. However, the values of "a" and "b" used by Doumounia et al.,2019 [15] in Burkina Faso, specifically in the Kaya area in the North-Central region, with a 7 GHz CML link, diverge not only from the DSD data but also from those of the ITU. This highlights the need for dense disdrometer coverage in Burkina Faso to accurately determine "a" and "b" values specific to each area.

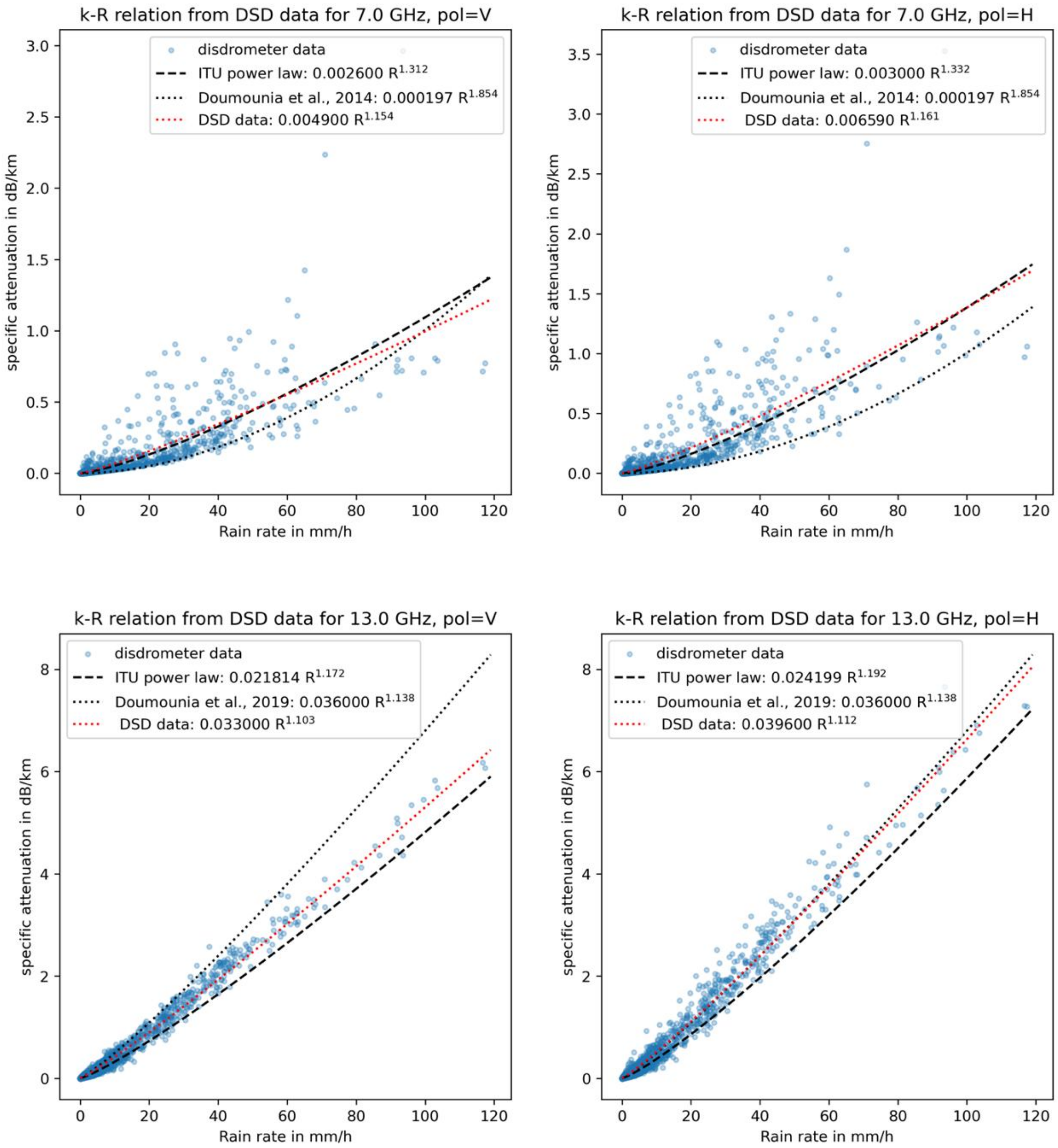

Fig.3.Evolution of the K-R relationship for different frequencies and polarizations

3.3Bias between the different K-R relationships

Table 1 shows the values of the bias between the different K-R relationships and the Pearson correlation coefficient between the corresponding rainfall. The Pearson correlation coefficient between the different series of values of the rain is over 0.9. The low bias values show good agreement between the different rainfall data sets. It should be noted that these positive and negative values of the bias show an under- and over-estimation from one K-R relation compared to the other.

Table 1. Calculation of biases between different K-R relationships and the Pearson correlation coefficient between the rainfall

	ITU & DSD_data	ITU & DOUMOUNIA	DSD_data & DOUMOUNIA
Bias (7 GHz, Pol. V)	**2,16**	**-1,16**	**-3,31**
Bias (7 GHz, Pol. H)	**-0.79**	**-0.86**	**-0.06**
Bias (13 GHz, Pol. V)	**-1.77**	**-1.16**	**0.61**
Bias(13 GHz, Pol. H)	**-0.79**	**-0.86**	**-0.06**
PCC	**0.98**	**0.99**	**0.99**

3.4Comparison of rainfall rate from the K-R relationship with different values of "a" and "b"

The climate of this area of Bobo Dioulasso is of the southern Sudanian type, characterized by annual rainfall between 900 and 1100 mm, with precipitation spanning four to six months. The daily rainfall rate is about 100 mm. It should be noted that this region of Burkina Faso, like others, suffers from a lack of reference precipitation monitoring instruments. The available rainfall data, if any, are not exploitable, likely due to a lack of follow-up. Additionally, the available rainfall data are from periods when CML data and CML coverage were not available in the same area. Therefore, we will compare the cumulative daily rainfall rates derived from CML for different values of "a" and "b" for the K-R relationship at a frequency of 13 GHz in horizontal polarization in this subsection. Figure 4 provides a representation of the cumulative rainfall rates derived from different values of "a" and "b" for the K-R relationship at 13 GHz in horizontal polarization and the rainfall data from the Bobo Dioulasso airport rain gauge over the same period. There is a good dynamic among the different series of values. The Pearson correlation coefficient between the different series of values of the rain is over 0.9 as mentioned above. However, an overestimation of rainfall rates is noted with the ITU values compared to the rain gauge data from Bobo Dioulasso airport over the entire period considered. Table 2 shows the value of the bias between the different cumulative rainfall rates.As shown in Table 2, the bias between the rainfall rates from the ITU values and the local rain gauge is 27.61. This confirms the overestimation of rainfall rates when using ITU values in this area of Burkina Faso.

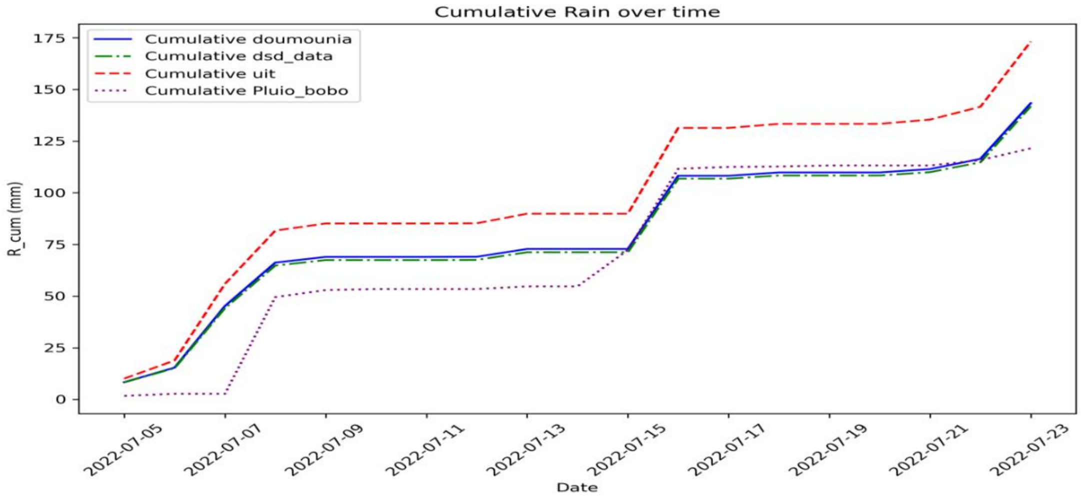

Fig.4.Comparison of cumulative rainfall rates derived from different values of "a" and "b" for the K-R relationship at 13 GHz in horizontal polarization

Table 2. bias between different cumulative rainfall rates

	Pluio_bobo & DOUMOUNIA	Pluio_bobo & DSD_data	Pluio_bobo & ITU
Bias in the cumulative rainfall	**9.55**	**8.21**	**27.61**

4. CONCLUSION

In a context where accurate precipitation measurement in Africa remains a major challenge for many operational and research applications, this study has contributed to determining the values of the constants in the K-R relationship. The use of the OTT Parsivel disdrometer proved to be an effective solution for obtaining precise and reliable measurements of precipitation characteristics. Data collection over a period of approximately one year, with a high temporal resolution of 1 minute, provided detailed information on particle fall velocity, rainfall rate, and other relevant parameters.

From these data, we were able to determine the values of the constants "a" and "b" for frequencies ranging from 1 to 100 GHz. Comparing these values with other data sources highlighted the importance of locally determining the values of "a" and "b" to improve rain rate estimation. Additionally, a comparison of precipitation data obtained from different values of the "a" and "b" parameters for a given attenuation was performed. The Pearson correlation coefficient between the different series of values of the rain is over 0.9.

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