

Experimental validation of heavy rain attenuation in E-band based on climate wind tunnel measurements at 77 GHz

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Abstract Attenuation measurements through extreme rain in a climate wind tunnel are carried out to benchmark the possibility of wireless data transmission at 77 GHz during adverse weather conditions. Based on a network analyzer and external E-band mixers, the propagation loss at 77 GHz is obtained over a distance of 180 m using a corner reflector at the end of a 90-m tunnel. Comparing the results to prediction models like the ITU-R P.838, a large deviation of several tens of dB/km was found for high rain rates when the drop size distribution is neglected. In the paper, the authors use known attenuation models based on rain drop distribution functions to explain the high measured attenuation during the testing, demonstrating a large variation of specific attenuation under heavy rain at high microwave frequencies.

Keywords Broadband communication · Propagation measurements · Rainfall effects · Millimeter wave communication · Attenuation measurement · Millimeter wave propagation

1 Introduction

In the last years the volume of data transmission has been strongly increasing. Therefore, the available bandwidth in the microwave regime is crowded and new techniques, effective codes or new frequency bands need to be acquired for data transmission. One of the future broadband communication bands is the E-band (71–76 and 81–86 GHz) with a regulated bandwidth of 10 GHz [10]. In cases where optical links are not cost efficient or fail due to bad weather conditions, a millimeter wave link can preserve high data rates.

At microwave frequencies the propagation effects are known and given by ITU-R recommendations such as [8] for rain attenuation. Underlying models for rain attenuation and the calculation of specific attenuation are given in [7] for various frequencies and rain rates. Previous investigations at high frequencies are field tests in the E-band [5] and at 120 GHz reported by [6]. The tests at 120 GHz show deviations of the attenuation of several tens of dBs, but due to a large number of measurement points the mean values meet almost exactly ITU-R predicted attenuation. The E-band test over 2 years in [5] also indicate large deviation of attenuation prediction at high rain rates in the E-band. In both cases the drop size distribution was not known and the rain rates are minute data from a single spot, while the rain cannot be considered to be uniform over a large distance. So no further conclusions for different conditions can be drawn. Field tests of E-Band or W-Band microwave propagation for the verification of the rain models are very important for the design of future satellite missions, since measured data are only available up to 50 GHz [15].

Here, we are using a climate wind tunnel with a length of 90 m to measure the rain attenuation under severe rain

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conditions with controlled rain rate over the entire distance [3], which is not possible in free field. Nevertheless, this method will not address improvements of the accuracy of statistical models. It will be used to demonstrate and verify wireless propagation through severe rain and to evaluate the possibility of calculation of the specific attenuation through controllable conditions with an existing model base. Additionally, it can be tested if such a climate wind tunnel can be used for propagation testing in the microwave range. The available rain valves allow only the testing of very high rain rates of 33, 43 and 105 mm/h, where the distribution of the rain rate over the tunnel can be controlled very accurately by the water distribution system of the climate tunnel.

A literature survey turns out that the values of rain attenuation in E-band vary from 12 to 28 dB/km using ITU-R and other reported experiments for a rain rate of 33 mm/h at 77 GHz [4, 11, 14, 17]. In our measurement, we obtain 24 dB/km rain attenuation. In order to investigate these extreme attenuation ranges, the authors use known rain drop distribution functions [13, 14, 18, 19] and the data of natural rain events extracted from [4, 11, 14, 17]. From a measured drop distribution we try to extract the model parameters to show that the measured attenuation in the climate wind tunnel can be reproduced by the models provided in literature [13, 14, 18, 19].

2 Experimental setup

To measure the attenuation at 77 GHz we are using a four-port Agilent PNA-X network analyzer connected to a 77-GHz E-band transmission link. The chip set from [1] together with the IQ-mixers [2] are mounted into a water proof housing together with a 45.7 dBi cassegrain antenna system. As shown in Fig. 1a the ports of the PNA are connected to the I and Q ports of the E-band mixers.

In a distance of 90 m within a climate wind tunnel of the rail tec arsenal (RTA), Vienna, Austria, a corner reflector sends back the signals from the PNA to the E-band receiver front end. The number of points and the sweep time of the PNA-X are set up to form a radar detecting the reflection of the corner as peak in the time domain.

Due to the high gain antennas used in the setup, the only reflections seen by the PNA-X are the corner reflector, the tripod and the backside wall forming a ripple in the transmission S parameters. Therefore, we use a time-domain gating during post-processing for isolating the strongest reflection caused by the corner reflector.

At the roof of the climate wind tunnel, segments of rain valves are installed generating heavy rain. In our case rain rates of 33, 43 and 105 mm/h can be produced under stable conditions over the entire 90 m length of the tunnel,

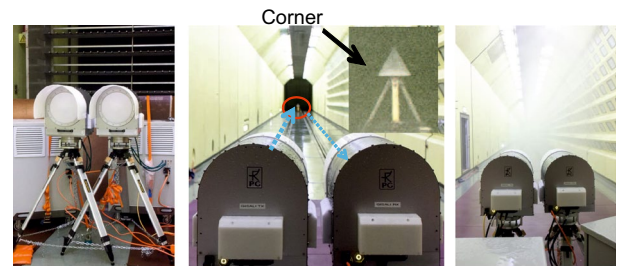
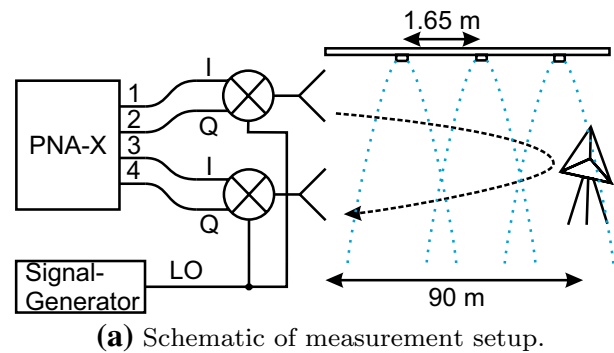


Fig. 1 Measurement setup for the rain attenuation measurement in a 90-m climate wind tunnel under severe rain conditions

giving a measurement distance of 180 m. The separation of the rain valves is 1.65 m, combined into six sections with a section length of 15 m each. The tripod is set to the middle of the tunnel where the rain distribution is expected to be uniform over the whole distance. From [3] this is true for a path within a diameter not exceeding 1 m. The high-gain antennas with a half power beam width of only 0.972° (i.e., an antenna gain of 45.7 dBi) keep the transmission path within this range. During the rain attenuation experiments, the wind within the tunnel was turned off to ensure undisturbed, controlled rain fall over the entire distance.

The picture of the setup within the tunnel is given in Fig. 1b. On the left-hand side the front view of the receiver and transmitter housing on tripods are shown. Underneath the white radome a cassegrain antenna is fed by the mixer waveguide modules. The middle picture shows the climate wind tunnel with the corner in a distance of 90 m. The roof-mounted rain system allows to generate controlled heavy rain conditions as shown in the picture on the right hand side.

In the following, the S parameters reference plane is set to the mixer ports. The measured S_{41} refers to the signal sent from port 1 (I-Port of the Tx mixer) to port 4 (Q-port of the Rx mixer). In the following this S_{41} would be called QI .

The local oscillator signal for the mixers is generated by a signal generator at 9.6 GHz and is multiplied to 76.9 GHz by a frequency multiplier by eight [12], mounted within the water proof housing.

For the attenuation measurements the phase information from the IQ-mixers can be neglected. Therefore the total energy is used for the evaluation. This means that the signals sent from one port are summarized after reception.

$$\begin{aligned} I &= \sqrt{|II|^2 + |QI|^2} \\ Q &= \sqrt{|QQ|^2 + |IQ|^2} \end{aligned} \tag{1}$$

All data at all rain rates set within the climate wind tunnel are compared to a reference measurement taken under dry conditions after turning off the rain to take into account possible wetting of the corner reflector surfaces. To get mean values the measurements are averaged over ten measurements. The sweep time is 50 ms with 16 k-points and a sweep bandwidth of 20 GHz.

Finally, the measured attenuation is scaled to 1 km for comparison with the specific attenuation from different rain attenuation calculations.

3 Rain attenuation

We are calculating the attenuation from a given rain drop distribution measured by the RTA with a laser optical disdrometer. The idea is to calculate the specific attenuation by integration over the scattering at each rain drop within the volume of the microwave transmission path as it is shown in [7] and recommended in [8].

The specific attenuation A in dB/km is described as the integration over the drop size distribution η :

$$A = 4.343 \times 10^{-3} \int_0^\infty \eta(D) \sigma_{\text{ext}}(D, m, \lambda) dD, \tag{2}$$

where D is the rain drop diameter in mm. σ represents the scattering cross-section of the water spheres in the rain, depending on the drop diameter, the index m and the wavelength λ . σ of Eq. (2) is described as:

$$\sigma_{\text{ext}} = Q_{\text{ext}} \pi \left(\frac{D}{2} \right)^2, \tag{3}$$

where Q_{ext} is the extinction cross-section from the Mie scattering theory and can be further expanded to

$$Q_{\text{ext}}(D, m, \lambda) = \frac{\lambda^2}{2\pi} \sum_{n=1}^\infty (2n + 1) \text{Re}(a_n + b_n), \tag{4}$$

where a_n and b_n are the Mie scattering coefficients. They are functions of D , λ and m [9].

It is obvious that all parameters in Eq. (2) depend on accurate description of the rain drop size distribution (DSD) $\eta(D)$, forming a model to describe the number of drops of a certain diameter within a volume. For rain estimation in weather radars early models described the distribution as exponential distributed raindrops [13].

This model was further expanded by [14, 19] and [18] inserting a gamma function and additional multiplication with D , reducing the drop counts for low drop diameters. We use the modeled rain events from [14, 19] and compare the attenuation with our results. Then we use a measured rain drop distribution from RTA to extract model parameters to describe the rain in the climate tunnel with the DSD model from [19]. The DSD for the following calculations is

$$\eta(D) = N_0 D^m e^{-\Lambda D}, \tag{5}$$

where N_0 , Λ and m are functions of the rain rate in [19] and are found iteratively in Sect. 4 of this paper by fitting it on measured values provided by RTA.

4 Rain distribution fitting

The evaluations of the measured data resulted in large deviation from the predicted values using the ITU models for rain attenuation [8]. The rain produced in the climate wind tunnel is not shaped like average rain estimated in the standard models provided by the ITU, where the rain drop distribution is estimated to medium values over a large number of measurement, which do not represent single events but give average values for attenuation prediction.

With measured cumulative probabilities (CP) of the rain drop size in the center of the tunnel, the rain drop distribution can be calculated with

$$\text{CP}(D) = \int_0^D \eta(D) dD, \tag{6}$$

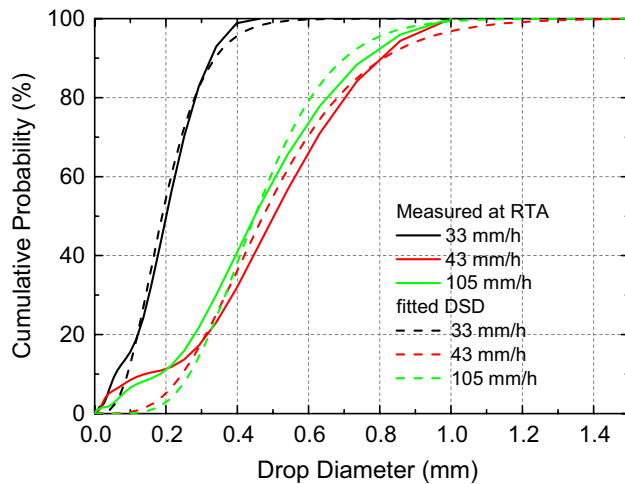
normalized to 100 % by division with the maximum value of the CP-function.

Our approach for the rain distribution fitting is as follows:

- Fit CP function by finding N'_0 , m and Λ for the $\eta(D)$ function given in Eq. (5). Here, N'_0 is only a start value for the next step, since the comparison with a normalized function gives only the correct shaping parameters m and Λ .
- Find N_0 by calculation of rain rate using Eq. (7) with the previously found parameters. The approach is an

Table 1 Fitting parameters used for the fitted drop size distribution

Rainrate (mm/h)	m	Λ	N_0/N_T
33	3.46	21.24	66.79×10^9
33 (6:00–12:00) [14]	7.05	9.25	3955
43	4.06	9.9	14.44×10^7
43 (6:00–12:00) [14]	6.84	8.91	4894
105	6.5	15.79	8.42×10^{10}
105 (6:00–12:00) [14]	6.16	7.87	10,042

**Fig. 2** Comparison of measured cumulative drop size probability with the fitted functions

iterative process, increasing N'_0 until Eq. (7) gives the wanted rain rate.

- Calculate the attenuation A

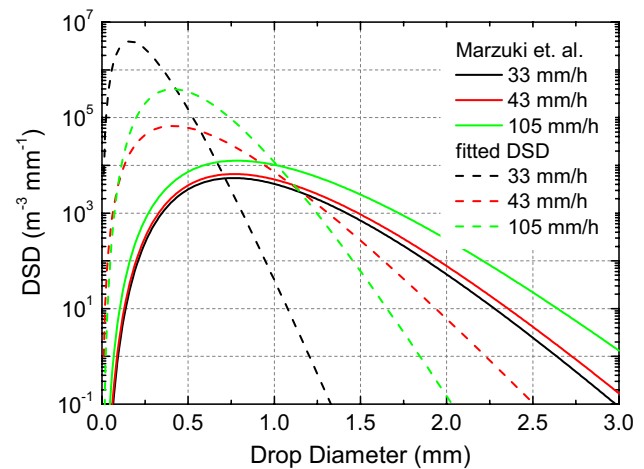
From [14, 18] the rain rate can be calculated with Eq. (7)

$$R = 6\pi \cdot 10^{-4} \int_0^{\infty} v(D) D^3 \eta(D) dD, \quad (7)$$

where $v(D)$ is the particle size dependent falling speed of the droplets in still air. It can be approximated by the calculation [16]:

$$v(D) = \begin{cases} 4 \cdot D(1 - e^{-12D}), & \text{for } D \leq 0.6 \text{ mm} \\ 9.65 - 10.43e^{-0.6D}, & \text{for } D \geq 0.6 \text{ mm} \end{cases} \quad (8)$$

With the found values of m , Λ and N_0 the DSD of the given rain rate in the tunnel experiment is fully described. All values are summarized in Table 1 together with the closest values from [14] compared to our measured attenuation. To show the effectiveness of the fitting, all three CPs at the measured rain rates (solid lines) are compared with the calculated CPs (dashed lines) in Fig. 2.

**Fig. 3** Comparison of measured (*solid*) drop size distributions for the measured rain rates in the wind tunnel for both, fitted values and values from [14]

The comparison of the fitted DSDs is showing a good match with the measured cumulative probabilities for the three generated rain rates in the climate wind tunnel. For lower particle sizes the fit cannot model the plateau type of size distribution of the measured drop sizes. For a better understanding this part of the density is neglected to use known rain drop size distributions.

For a comparison the DSD of both, Marzuki et.al. with the values where the attenuation was close to our measurements and the fitted parameters are plotted in Fig. 3. The values for the measured rain events from [14] indicate that the mean drop size of the valves in the wind tunnel is lower than in real rain. This leads to higher number of droplets for getting comparable rain rates.

For the rain rates of 43 and 105 mm/h the valves are bigger than the valves used for the 33 mm/h rain. To compensate the small particle sizes of only 500 or 250 μm , the number of particles is very high compared to real rain of the same rain rate.

5 Experimental results

The measured attenuation values (triangles) at 77 GHz are plotted versus the rain rate in Fig. 4. Due to the big valves in the climate wind tunnel only very heavy rain rates could be tested. Compared to the ITU-R P.838 values the measurements show more than doubled specific attenuation than predicted by theory. The ITU recommendation is a fit for average natural rain events. In contrast to natural rain, the rain in the wind tunnel consists mostly of very small drops with a very high density.

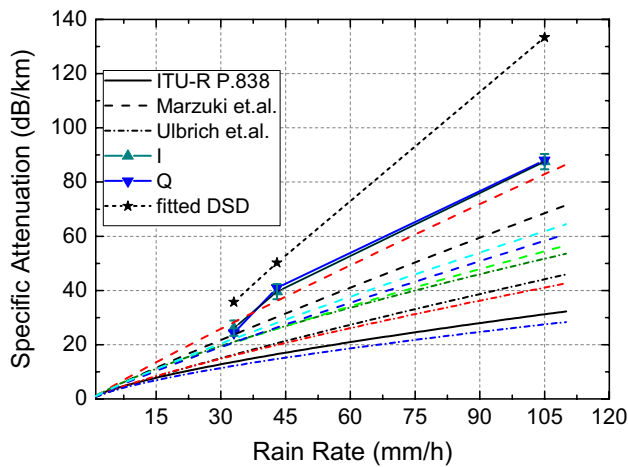


Fig. 4 Specific attenuation of microwave propagation at 77 GHz for different rain models over the rain rate. The measured points are inserted together with the calculated attenuation from the fitted DSD

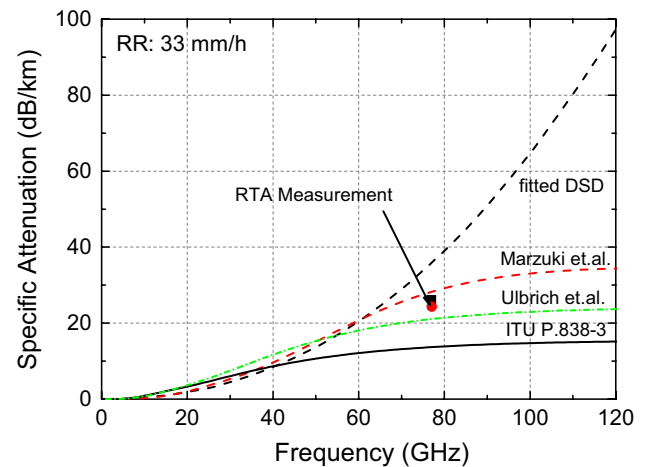


Fig. 5 Specific rain attenuation in dB/km versus frequency for various rain attenuation models and rain events at a rain rate of 33 mm/h

Table 2 Comparison of specific attenuation values at 77 GHz

References	33 mm/h	43 mm/h	105 mm/h
[19]	12.2–21 dB/km	14.7–26 dB/km	27.5–51.7 dB/km
[14]	20–28 dB/km	26–36 dB/km	54.5–83 dB/km
ITU-R [8]	13.7 dB/km	16.5 dB/km	31.2 dB/km
Fitted DSD	35.7 dB/km	50.2 dB/km	133.4 dB/km
Measured	26 dB/km	41 dB/km	88 dB/km

Since the ITU recommendation only enables the calculation of statistical attenuation we plotted the attenuation given by parameters found in previously investigated natural rain events. For each event an attenuation versus rain rate plot can be generated at 77 GHz. All of these curves are plotted using the values given by [14] (long dashed), while the dash-point lines are calculated from values given in [19].

Both sets of data are giving a wide range of attenuation values for heavy rain conditions, where the closest match is the 6:00–12:00 data from [14], also given in Table 1. Additionally, the variation of attenuation values is summarized in Table 2. At every measured rain rate the calculated values give various attenuation values spread over 10–30 of dB/km.

At 33 mm/h the closest match to a rain event from [19] is a thunderstorm reported in [17]. All other rain events where the parameters are given by [19] result in lower attenuation values. This indicates that the tested rain in the tunnel behaves like severe thunder storm events [19] or tropical rain events [14], which deliver the closest possible match to the measured data.

In Fig. 4 the stars represent the calculated attenuation from Eq. (2) with the fitting parameters given in Table 1 set into Eq. (5). Although the values for the DSD should be close to the measurement a large deviation between measurement and fitted DSD can be observed. Several simplifications of the model can be the source for the deviation.

- The rain model calculates attenuation for totally uniform rain, which is not the case in reality, even in the climate chamber. The rain in the chamber is concentrated in the center of the tunnel with a deviation of 7 mm/h for 33 and 43 mm/h and 22 mm/h for 105 mm/h.
- The attenuation uses Mie scattering which is not proportional to rain drop size changes. This may lead to overestimated attenuation due to the very small drop sizes and high density of droplets in the RTA tunnel.
- The N_0 value is critical for the attenuation calculation. In the case of the fitted DSD the absolute N_0 values are calculated with Eq. (7). The unknown pressure in the rain valves and within the tunnel could not be used during calculation. This may lead to a calculation error of N_0 , leading to a deviation of the calculated attenuation.

6 Attenuation prediction

To show the behavior of the specific attenuation versus frequency the models are now used to calculate the estimated attenuation at millimeter wave frequencies. Figure 4 shows that the deviation of attenuation at high rain rates is much higher than at low rain rates. In most cases the attenuation is well described at rain rates below 5 mm/h.

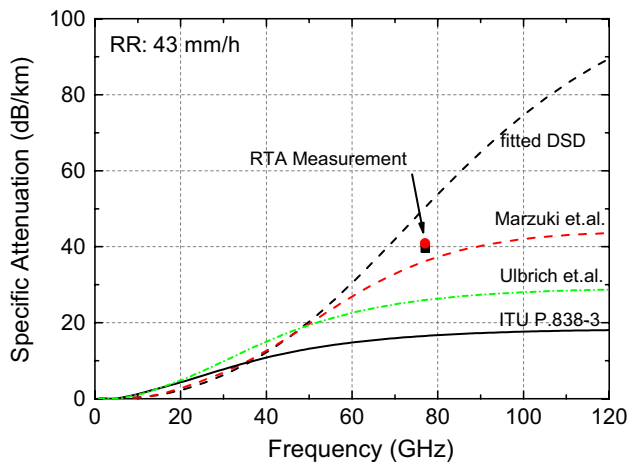


Fig. 6 Specific rain attenuation in dB/km versus frequency for various rain attenuation models and rain events at a rain rate of 43 mm/h

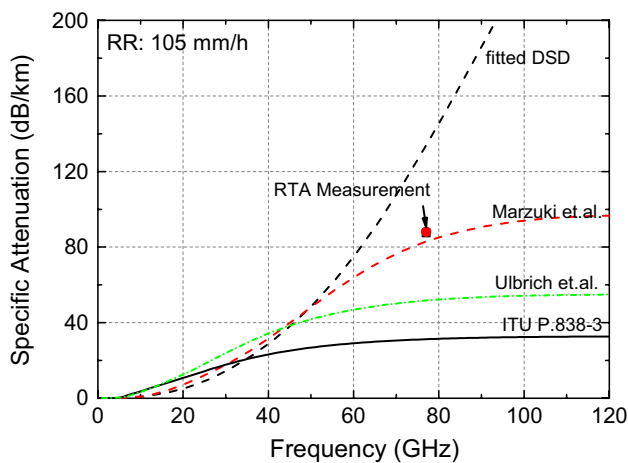


Fig. 7 Specific rain attenuation in dB/km versus frequency for various rain attenuation models and rain events at a rain rate of 105 mm/h

Figures 5, 6 and 7 show the calculated specific attenuation versus frequency. In all plots the attenuation shows only a slight deviation at frequencies below 50 GHz.

A plot of the attenuation versus frequency for a rain rate of 33 mm/h is given in Fig. 5. Obviously the calculated data from the fitted DSD reaches extreme values at high frequencies. This is due to the high drop density due to the small drop size in the tunnel at this rain rate. Although the ITU only gives 15 dB/km of attenuation, two real events with similar attenuation to the measurement could be found in literature (dashed lines).

Increasing the rain rate to 43 mm/h (Fig. 6) the fitted DSD showed the lowest N_0 values after value extraction.

For completeness the data of the extreme high rain rate of 105 mm/h is plotted in Fig. 7 versus the propagation

frequency. Here the data of the natural and artificial rain events show even higher deviation from the ITU prediction than in the plots before.

Overall the rain in the wind tunnel from the attenuation point of view behaves like heavy rain rate tropical rain. Similar rain was identified by [14]. The large deviation of attenuation values show that at high rain rates the link performance depend on the drop distribution of the individual rain event. The ITU provides values for average rain but does not cover extreme events. In the latter case, the individual rain deviations in the drop size matter at high rain rates and high frequency.

7 Conclusion

Based on transmission measurements in a climate wind tunnel under controlled rain rates, the specific attenuation at 77 GHz was measured. Under these test conditions, a large deviation from the ITU models was found. Evaluation of the underlying models of rain drop distributions results in a large variance of attenuation for rain rates over 5 mm/h and frequencies over 50 GHz. The measurements and investigations of the drop size depicts that individual rain events can show large attenuation difference to the ITU-R calculations due to rain drop size deviation. For the design of highly reliable links, the individual regional rain has to be taken into account into the link budget since the standard models cover statistical rain events and represent a fit over a large range of rain events. Due to the limitations of the test setup to extreme conditions and very small drops, future experiments of microwave propagation in a climate wind tunnel designed for traffic experiments would need a technical revision of the rain valves in the tunnel.

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