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Estimation of Millimeter Wave Attenuation Due to Rain Using 2D Video Distrometer Data in Malaysia

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Abstract

The increasing use of millimeter wave frequency bands requires a good understanding of the atmospheric channel. In equatorial regions, rain plays the central role in the impairment of millimeter wave propagation. Using large amounts of precise data collected by a two-dimensional video distrometer in Malaysia, the rain-specific attenuation of both vertically and horizontally polarized waves at the 38 GHz frequency was computed by applying the T-matrix technique. Good agreement is observed between these computations and fitted power law models from neighboring areas, but the ITU-R Recommendation P.838-3 significantly underestimates the rain-specific attenuation. The importance of including raindrop axial ratio in the calculation is revealed by differences among the local fitted coefficients for the vertically polarized estimations. The power law fit is provided, and the measurement is verified.

Keywords: *Millimeter Wave,Rain Attenuation, Equatorial Regions, Raindrop Size Distribution*

1. Introduction

As the world increasingly demands the higher bandwidths that millimeter waves can provide [1], precise prediction and estimation of their attenuation by atmospheric effects is crucial [2]. In equatorial regions like Malaysia, heavy precipitation is the dominant factor that reduces link quality and availability [3, 4]. To address this issue, a thorough understanding of precipitation drop size distribution (DSD), shape, fall velocity and macro-physical structure is required. The DSD is particularly important, because raindrops are comparable in size to wavelengths in the millimeter wave range; it is also known that hydrometeors are oblate spheroids with flattened bases, causing the rain-specific attenuation of millimeter waves to depend on their polarization. Linearly polarized waves are attenuated to a greater degree when the polarization is horizontal rather than vertical [5], and depolarization of the signal occurs when the polarization is orthogonal. A two-dimensional video distrometer (2DVD) can capture cross-sections of the drops [6], and therefore allows accurate measurement of these effects. However, that accuracy depends on the availability of not only rain data but also models that can estimate the introduced attenuation as well as attenuation data to validate these estimates. This article presents the estimated rain-specific attenuation of linearly polarized millimeter waves for terrestrial links, using a year of data collected by a fourth-generation 2DVD installed at the southernmost city of peninsular Malaysia [7]. Data gathered by co-located meteorological station and the older 38 GHz link [8] are used to validate the measurements.

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2. Distrometer Measurements

The 2DVD uses two line-scanning cameras to capture contour images and fall velocities of any particles pass through its 10 $\times$ 10 cm sensing area, providing information about shape, axial ratio, and canting angle. The relationship of raindrop axial ratio to equivalent diameter has been the focus of many studies [9, 10, 11, 12]. The 2DVD data computed from natural raindrops, shown in red in Figure 1, agree with [11] in that the axial ratio lies along the upper bound of the Beard-Chung model [10] and with [12] in that drops are slightly more spherical.

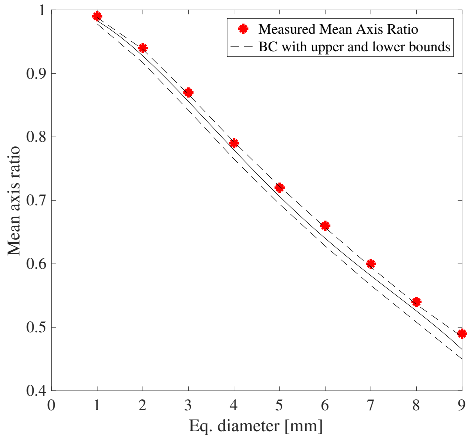

Figure 1. Relationship between natural raindrop mean axial ratio and equivalent diameter, compared with the upper and lower bounds of the Beard-Chung model [10].

The DSD, $N(D_i)$, is the number of drops per unit volume per unit drop diameter, which can be calculated from the drop data recorded by the 2DVD using

$$N(D_i) = \frac{1}{\delta t \times \delta D} \sum_{k=1}^{m_k} \frac{1}{A_k v_k}, \tag{1}$$

where δt is the integration time period (in this case, one minute), m_k resembles the number of drops within the drop size interval δD, and A_k and v_k are the effective area and the measured fall velocity of the drops, respectively. While, the rainfall rate R in mm/h calculated by dividing the rain amount computed from the quotient of the drop's volume and effective area by the corresponding time interval using

$$R = 3600 \frac{1}{\delta t} \sum_{i=1}^{n} \frac{V_i}{A_i}, \tag{2}$$

where n represents the total number of the visible drops within the period δt and V_i is the drop volume.

3. Rain-Specific Attenuation Calculation

The rain-specific attenuation depends on rain rate, one-minute-integrated DSD, drops shape, and wavelength and polarization of the operating frequency. The forward scattering amplitude can be computed using the T-matrix method [13], assuming drop shape is an oblate spheroid with an axial ratio as discussed in section 2., attenuation for horizontal and vertical (H and V) polarization in dB/km can be defined as

$$\gamma_{H,V} = 8.686 \times 10^3 \times \lambda \times \sum_{i=1}^{41} \mathrm{Im}(f_{H,V}(D_i)) N(D_i) \delta D_i, \tag{3}$$

where λ is the wavelength and $f_H(D_i)$ and $f_V(D_i)$ are forward scattering amplitudes for H and V polarization, respectively.

Figure 2 shows an example of rain-specific attenuation time series for the 38 GHz frequency from one event occurred on 29^{th} of April 2016. At the top of the figure, one-minute rain intensity calculated from distrometer data is shown in mm/h, followed by the calculated rain-specific attenuation for H and V polarization at 38 GHz in the middle of the figure and finally the difference between the two ($\gamma_H - \gamma_V$) at the bottom of the figure.

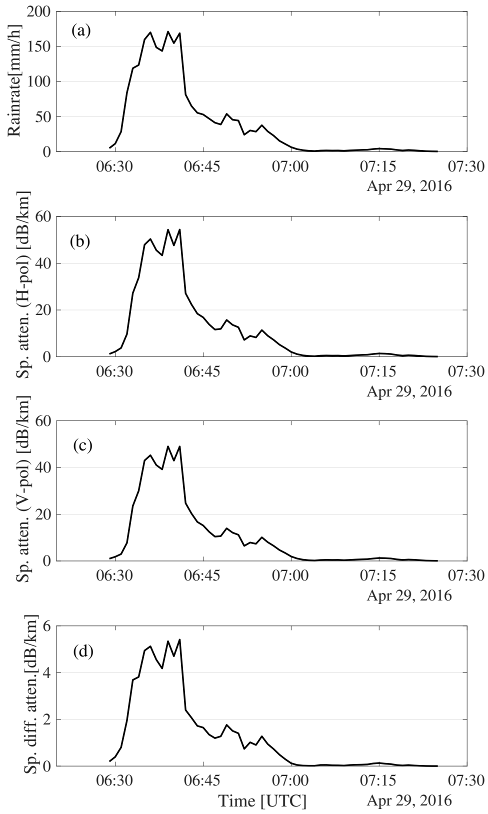

Figure 2. 2DVD measurements of one event at 38 GHz; (a)one-minute rainfall intensity, (b) rain-specific attenuation for H Polarization, (c) rain-specific attenuation for V polarization and (d) differential rain-specific attenuation.

Alternatively, the rain-specific attenuation can be approximated using a power law relationship, which uses coefficients as a function of wavelength and polarization to relate the calculated rain-specific attenuation in dB/km to the calculated one-minute rain rate in mm/h, given as

$$\gamma_{H,V} = k_{H,V} R^{\alpha_{H,V}}, \tag{4}$$

where k and α are the power law coefficients and R is the rain rate in mm/h. The ITU-R Recommendation P.838-3 [14] also provides a set of k and α values for the frequency range from 1 - 1000 GHz. However, due to high differences in the regional precipitation characteristics, plenty of authors recommended different local alternatives; within the study region, locally derived values are presented for Kuala Lumpur [3] and Singapore [15]. For the one year of 2DVD measurements the one-minute-integrated DSD is used to derive the specific attenuation at 38 GHz for H and V polarization, and the resulted power law fits presented in Table 1 and compared in Figure 3 with ITU-R P.838-3 and the locally derived coefficients values.

Table 1. Power law curve-fitting coefficients and their goodness of fits for the relationship between rain rate and rain-specific attenuation at 38 GHz computed from 2DVD data.

Polarization	k	α	R^2
Horizontal	0.400	0.935	0.997
Vertical	0.367	0.928	0.987

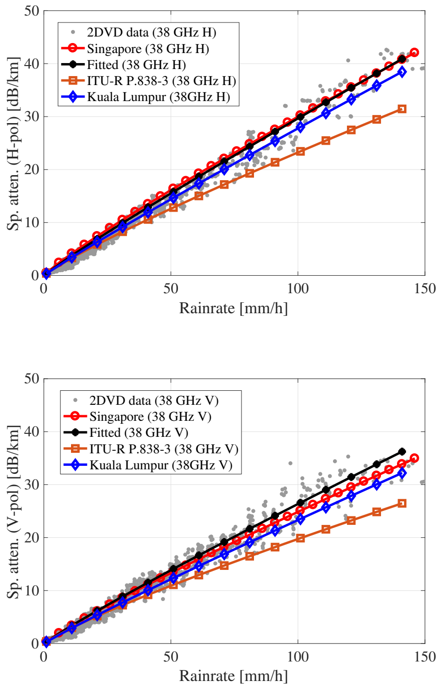

Figure 3. Specific attenuation from 2DVD in natural rain, with derived power law fit, compared with other fits from the ITU-R Recommendation P.838-3 [14] Kuala Lumpur data [3] and Singapore data [15].

In general, the ITU-R Recommendation P.838-3 rain-specific attenuation values unacceptably low compared with those from the 2DVD data, while a closer agreement was achieved by using the locally derived coefficients. The significant differences can be accounted for by the use of theoretical DSDs for different regions in the ITU-R Recommendation P.838-3, whereas the locally derived values are based on actual DSDs fitting using one-minute-integrated data. Furthermore, the drop axial ratio significant necessity in determining the rain-specific attenuation for H and V polarization, leads to noticeable differences in V polarization values calculated from the 2DVD data compared with other locally derived values. Additionally, there is a difference between the Kuala Lumpur and Singapore values, the latter of which are in line with the 2DVD horizontal values; we attribute this to the closer proximity of the 2DVD to Singapore than Kuala Lumpur.

4. Comparison of Attenuation Measurements

The data show that the ITU-R Recommendation P.838-3 underestimates the rain-specific attenuation by 6-25%. Table 2 compares the rain-specific attenuation values estimated for selected rain rates using the fitted coefficients from 2DVD data with those from the ITU-R Recommendation P.838-3 values.

Table 2. Comparison of the 2DVD and ITU-R Recommendation P.838-3 estimations of rain-specific attenuation dB/km at 38 GHz for H and V polarization, presented according to rain rate mm/h.

Rain rate (mm/h)	P838-3, H	2DVD, H	P838-3, V	2DVD, V
1	0.400	0.400	0.384	0.387
5	1.654	1.801	1.522	1.634
10	3.0483	3.444	2.754	3.110
25	6.840	8.112	6.030	7.277
50	12.605	15.510	10.908	13.846
100	23.231	29.653	19.733	26.343

To further quantify the 2DVD rain-specific attenuation results and examine the long-term effect of rain on terrestrial links, a comparison of its complementary cumulative distribution function (CCDF) with the fitting, as well as that of the ITU-R Recommendation P.838-3, is presented in Figure 4.

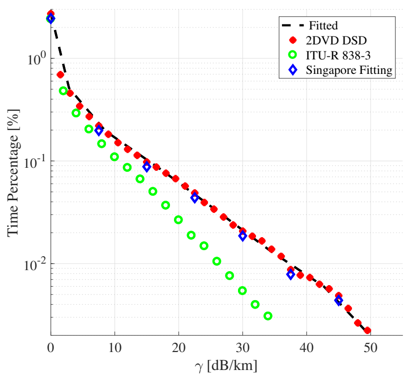

Figure 4. Comparison of rain-specific attenuation CCDFs of H Polarization at 38 GHz.

5. Conclusion

This article reports data gathered by a 2D video distrometer in Malaysia for the first time. The rain-specific attenuation of horizontally and vertically polarized millimeter waves has been computed from actual rain data using T-matrix calculations. The fitted power law has been compared with other fits from neighboring areas and the ITU-R Recommendation P.838-3. While the T-matrix calculations fitted power law are in good agreement with the local fitted laws, there is significantly lower agreement with the ITU-R recommendation, which might be due to the high variability of DSD in equatorial regions. This underlines the importance of local power law coefficients for the estimation of rain-specific attenuation. The raindrop axial ratio is also important; the discrepancies appeared in other fits of the vertically polarized data due to the use of older equipment and modeled axial ratios which do not represent the actual shape of raindrops. The local estimations can therefore provide better predictions as the world moves towards higher-frequency demands.

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