URSI AP-RASC 2019, New Delhi, India, 09 - 15 March 2019

On the Accuracy of Simplified Models for Water Vapor Attenuation Prediction at Ka band and Q band

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Abstract

The accuracy of the approximate prediction models included in recommendation ITU-R P.676 aimed at estimating the attenuation due to gases (water vapor and oxygen) from ground meteorological inputs is assessed. To this aim, the gaseous attenuation derived from a multi-channel radiometer installed at the experimental station of Spino d'Adda is used as reference. Two versions of the same recommendation are considered, defining different simplified expressions for the gaseous specific attenuation, but both taking advantage of the same equivalent height concept. Results, evaluated over a full year of data, indicate that the most recent model (version 11 of P.676) significantly underestimate the attenuation due to gases; on the contrary, the previous version of the recommendation turns out to be accurate enough to be used reliably in supporting the derivation of total tropospheric attenuation from the received beacon signal in electromagnetic wave propagation experiments, especially when no radiometric data are available at the site.

1. Introduction

The propagation of electromagnetic (EM) waves at frequencies above 1 GHz is impaired by atmospheric constituents. Among them, hydrometeors play the most relevant role, especially above 10 GHz [1], but also clouds and fog need to be taken into account; this is especially true in the light of the satellite communications systems to be deployed in the near future [2], which are foreseen to provide terabit capacity by exploiting frequencies in the Ka/Q and V bands [3].

Also atmospheric gases affect EM waves: for frequencies up to 1 THz, only water vapor and oxygen need to be taken into account. Though the attenuation level induced by these gases is in the overall quite limited (as an example, the specific attenuation amounts to roughly 0.1 dB/km at 30 GHz according to [4]), apart from small ranges around specific frequencies where resonant effects take place, their contribution cannot be neglected, being always present (differently from precipitation and clouds). In addition, the precise prediction of the attenuation due to gases is of paramount importance to derive with high accuracy the total tropospheric attenuation from the beacon signals received by ground stations during electromagnetic wave propagation campaigns [5], such as the ongoing Alphasat Aldo Paraboni scientific experiment [6].

The accurate estimation of the gaseous attenuation can be achieved by coupling vertical profiles of the atmosphere (e.g. obtained from radiosonde observations – RAOBS) with mass absorption models [5] or by using microwave radiometers (MWRs) [7]. While the former approach is of cumbersome implementation due to limited availability of atmospheric profiles (RAOBS are typically launched only twice a day at airports), MWRs are expensive instruments. As an alternative, simplified methodologies can be used to estimate the attenuation due to gases, which rely on limited and easily retrievable local information on the atmosphere. On the other side, due to their approximate nature, it is of key importance to assess the accuracy of these methodologies. This is the goal of this contribution, which focuses on the approximate prediction models (1-350 GHz range) included in Annex 2 of recommendation ITU-R P.676-11 [4] and ITU-R P.676-10 [8], both requiring as input the values of pressure (P), temperature (T) and relative humidity (RH) measured at ground level, while taking advantage of the equivalent height concept. The predictions obtained by these models are compared against the gaseous attenuation estimated, over one full year, by means of a multi-channel MWR installed at the experimental station of Spino d'Adda.

2. Water Vapor Attenuation Measurement

Included among the ancillary experimental equipment installed at Politecnico di Milano to support the Alphasat Aldo Paraboni scientific experiment [6], the RpG MicroWave Radiometer (MWR), located at the experimental station of Spino d'Adda, measures the brightness temperature (T_B) with 1-second integration time along the path to the Alphasat satellite (see Figure 1). The instruments includes 14 channels (ranging from 22.24 GHz to 58 GHz, i.e. covering the Ka band and part of the V band) enabling the estimation of the atmospheric attenuation, in nonrainy conditions, at any frequency in the centimeter and millimeter ranges, as well as the retrieval of the integrated water vapor (IWV) and of the integrated cloud liquid water content (ILW) along the path.

Figure 1. The radiometer installed at the experimental station of Spino d'Adda, during cold load calibration.

The MWR also features a weather station monitoring pressure (*P*), relative humidity (*RH*) and temperature (*T*) at ground level, with 1-second sampling time as well. Finally, vertical profiles of *P-RH-T* are also available, as collected twice a day using radiosondes launched at Milano Linate Airport (less than 25 km far from the radiometer).

In this work, the radiometric measurements are used to provide the reference attenuation due to gases A_G^{MWR}, against which the accuracy of the approximate methods included in recommendation ITU-R P.676 is evaluated. More specifically, A_G^{MWR} is calculated by removing the cloud attenuation A_C^{MWR} from the total tropospheric attenuation (in nonrainy conditions):

$$A_G^{MWR}(f) = A_T^{MWR}(f) - A_C^{MWR}(f) = A_T^{MWR}(f) - K_L^*(f)L \qquad (1)$$

In equation (1), $A_T^{MWR}(f)$ is the total attenuation at frequency *f*, obtained by linearly combining 5 of the 14 radiometric channels (23.84, 27.84, 31.4, 51.26 and 52.28 GHz):

$$A_{MWR}^{T}(f) = a_0 + \sum_{j=1}^{5} a_j \, A_{RAD}(f_j) \qquad (2)$$

In turn, the radiometric attenuation $A_{RAD}(f_j)$ is function of the brightness temperature at frequency f_j, of the cosmic background temperature T_C (typically set to 2.73 K in the cm- and mm-wave regions) and of the mean radiating temperature T_{mr} [7]

$$A_{RAD}(f_j) = 10 \log_{10}\left(\frac{T_{mr}(f_j) - T_C}{T_{mr}(f_j) - T_B(f_j)} \right) \qquad (3)$$

While TB is measured by the radiometer, T_{mr}, as well as the coefficients a_0 and a_j in (2) are calculated by using RAOBS-derived *P-RH-T* vertical profiles (collected at Linate Airport) as input to the TKK cloud detection method [9] and then to the MPM93 mass absorption model proposed by Liebe *et al.* [10]. First, $A_{RAD}(f_j)$ and $A_T^{MWR}(f)$ are calculated from the RAOBS profiles using these models, and afterwards the coefficients are regressed by inverting (2).

Finally, in (1) the cloud attenuation A_C^{MWR} is calculated using the liquid water mass absorption coefficient $K_L^*(f)$ and the liquid water content integrated along the path *L*: the former is extracted from recommendation ITU-R P.840-7 (equation (14)) [11], while the latter is retrieved again from the radiometric measurements using an inversion model similar to (2) [7].

As an example, Figure 2 shows the gaseous attenuation calculated using radiometric data on the 3rd of January 2015, at the two frequencies of the Alphasat Aldo Paraboni scientific experiment, namely *f* = 19.7 and 39.4 GHz [6].

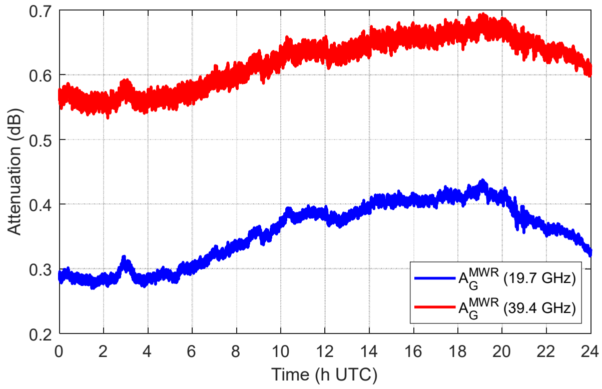

Figure 2. Gaseous attenuation A_G^{MWR} (3rd of January 2015) calculated using the radiometric data; frequencies of the Alphasat Alda Paraboni scientific experiment.

3. Water Vapor Attenuation Prediction: the Simplified Models

As an alternative to the use of ROABS profiles and mass absorption models, ITU-R defines in Annex 2 of recommendation P.676 approximate methodologies, valid in the 1-350 GHz range, to calculate the path attenuation due to water vapor and oxygen, A_V^{ITU} and A_{OX}^{ITU}, respectively. The rationale of both models is that the path attenuation can be calculated by simply multiplying the specific attenuation γ, calculated at the ground level, by an equivalent height, which takes into account the vertical profile of γ. As a result:

$$A_G^{ITU} = A_V^{ITU} + A_{OX}^{ITU} = \gamma_V h_V + \gamma_{OX} h_{OX} \qquad (4)$$

Regarding the two specific attenuations, which are function of *f*, as well as of *P*, *RH* and *T* at ground level, recommendation ITU-R P.676-10 (henceforth referred to as v10) defines, for both gases, simplified analytical expressions approximating the line-by-line absorption calculations of the MPM93 model, which is assumed in Annex 1 of the same recommendation as the theoretical reference providing the most accurate estimate of the attenuation due to gases in the full 1-1000 GHz range. On the other hand, in the attempt to increase the accuracy of the approximate methodologies, ITU-R P.676-11 (henceforth referred to as v11) introduced a change in the derivation of γ at ground level, which is now obtained using a simplified summation of the line-by-line expressions in Annex 1. Specifically, Zeeman splitting of oxygen lines and Doppler broadening of water vapor are not included, and only 9 out of the 35 water vapor lines are considered.

On the other hand, the formulas for the equivalent heights are the same for both models v10 and v11: besides on f, they also depend on P, RH and T at ground level. For the sake of brevity, the expressions for the approximate models are not reported here, but they can be found in [4] and [8].

As an example, Figure 3 shows the trend of the attenuation due to gases as estimated by both versions of recommendation ITU-R P.676; a clear difference is visible at both frequencies due to the different formulations of the specific attenuation in the two models: v11 provides prediction values that approximately half of those obtained with v10.

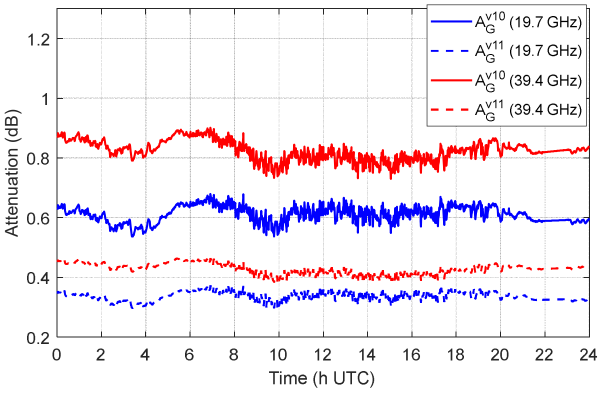

Figure 3. Gaseous attenuation A_G^{ITU} (2nd of June 2015) estimated using the simplified methodologies recommended by ITU-R in Annex 2 of [4] and [8].

4. Accuracy assessment

One full year of radiometric data (2015) have been employed to calculate A_G^{MWR}, which is used as reference to evaluate the accuracy of both ITU-R approximate models. Figure 4 and Figure 5 show the comparison between A_G^{MWR} and A_G^{ITU} on the 2nd of April 2015, for the Ka band and the Q band, respectively. These examples clearly indicate that v10 offers satisfactory prediction accuracy at both bands, while, on the contrary the model included in the most recent version of P.676 strongly underestimate A_G^{MWR}. This trend is likely due to change in the specific attenuation γ introduced in version 11, which would also require a modification of the equivalent heights h_V and h_{OX}, as they are of empirical nature.

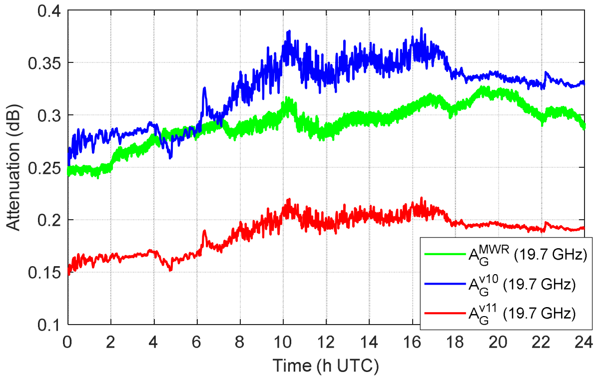

Figure 4. Comparison between A_G^{MWR} and the gaseous attenuation estimated by means of the ITU-R models (2nd of April 2015); Ka-band results.

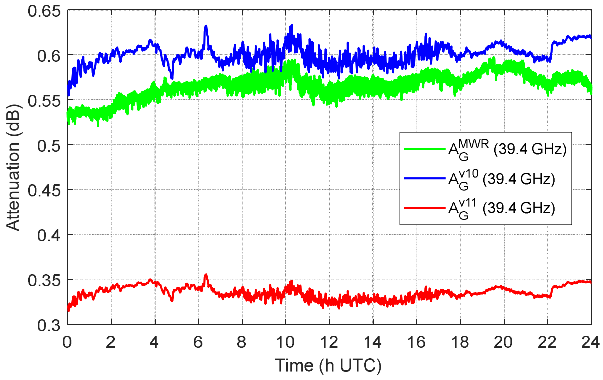

Figure 5. Comparison between A_G^{MWR} and the gaseous attenuation estimated by means of the ITU-R models (2nd of April 2015); Q-band results.

The accuracy trends in Figure 4 and Figure 5 are confirmed by the results reported in Figure 6 and Figure 7, which show, for each day of 2015, the mean (E) and root mean square (RMS) values of the prediction error ε (calculate every second) in (5).

$$\varepsilon(t) = A_G^{ITU}(t) - A_G^{MWR}(t) \qquad (5)$$

Overall, v10 shows high prediction accuracy, almost independent of the frequency (the average RMS of the error is around 0.06 dB for both bands), while the v11 model has a general tendency to underestimate A_G^{MWR} (average E of the error equal to -0.2 dB and -0.3 dB at Ka band and Q band, respectively). Moreover, the accuracy of v11 worsens in warmer months, with the RMS doubling its value when proceeding from January to August.

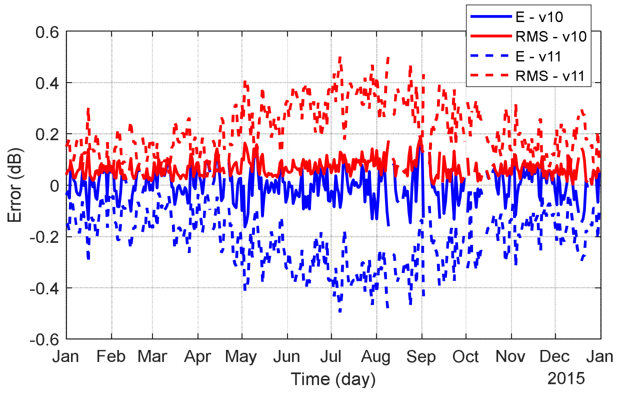

Figure 6. Mean (E) and root mean square (RMS) values of the prediction error (Ka band), for every day of 2015; results for both ITU-R models.

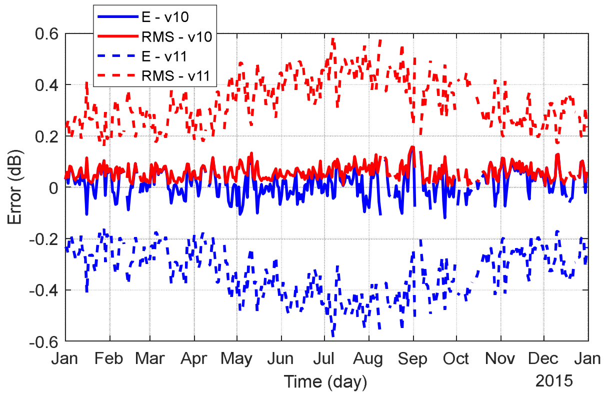

Figure 7. Mean (E) and root mean square (RMS) values of the prediction error (Q band), for every day of 2015; results for both ITU-R models.

5. Conclusions

This contribution has investigated the accuracy of the approximate models included in two latest versions of recommendation ITU-R P.676. The prediction methods aim at providing an estimate of the attenuation due to water vapor and oxygen (in the 1-350 GHz range) on the basis of the ground values of pressure, temperature and relative humidity. The accuracy of these models has been assessed using as reference the attenuation retrieved by the multi-channel radiometer installed at the experimental station of Spino d'Adda. Results, evaluated over one full year, indicate that the latest version of P.676 significantly underestimates the attenuation due to gases; on the contrary, findings show that the previous version of the recommendation is accurate enough to be used reliably to support the derivation of total tropospheric attenuation from the received beacon signal in electromagnetic wave propagation experiments, especially when no radiometric data are available at the site. Finally, results also point out that the attenuation trends estimated by the two ITU-R methods are very similar, but scaled by a factor, which can be probably introduced to "correct" the v11 model and thus increase its prediction accuracy. However, this is out of the scope of the present contribution, and will be investigated in future investigations on the topic.

6. References

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