# Efficient Calculation of Cloud Attenuation for Earth-space Applications

Lorenzo Luini and Carlo Capsoni

*Abstract*— **This contribution presents a simple and accurate approach to calculate cloud attenuation for Earth-space communication systems operating in the 20-200 GHz frequency range. The methodology relies on the use of the mass absorption coefficient for liquid water $a_W$, which is assumed to be independent of the site of interest. This finding, inferred from an extensive set of radiosonde observations collected in 14 locations throughout Europe, allows to devise a simple expression for $a_W$ as function only of frequency and, consequently, to efficiently calculate cloud attenuation. This indeed represents the main advantage of the approach, which, as a result, can take full advantage of global datasets of integrated liquid water content $W$ made available, for example, by Earth Observation sensors.**

***Index Terms*— Radio propagation, cloud attenuation, atmospheric effects**

## I. INTRODUCTION

Earth-space communication systems operating above 10 GHz are negatively affected by rain, which definitely plays the most significant role causing high attenuation to propagating electromagnetic waves. Though extremely detrimental, the presence of rain along typical Earth-space links is limited to approximately 5%–10% of the time in a year [1]; on the other hand, clouds cause a more limited impairment on the system, but are characterized by a much higher probability of occurrence (40%–80% of the yearly time in Europe). It is therefore important to investigate the effects of clouds on electromagnetic waves as well as to devise models to predict cloud attenuation statistics, especially when very high frequencies are considered (e.g. W band), strongly affected by the increasing extinction properties of liquid water droplets, and/or when low elevation links (e.g. 5° to 20°) are involved. Typical applications are high-latitude ground stations for GEO (Geostationary Earth Orbit) satellites, links to Earth Observation LEO (Low Earth Orbit) satellites and scientific space missions: in fact, whilst in the first and second cases the enhanced impact of suspended liquid water comes from the considerable increase in the liquid water $W$ integrated along the path, in the third case the presence of clouds is extremely critical because of the very limited system margin.

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Lorenzo Luini and Carlo Capsoni are with the Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133, Milano, Italy (e-mail: lorenzo.luini@polimi.it).

Some models developed in the past to predict cloud attenuation ($A_C$) receive as input meteorological quantities (e.g. the surface absolute humidity) and define empirical expressions whose coefficients have been regressed on existing measurements [2],[3]. Other more accurate and comprehensive models rely on some key features of clouds; in this class it is worth mentioning the DAH model [4], which classifies four types of clouds with different average properties (e.g. vertical and horizontal extent, water content) and probability of occurrence. The most acknowledged and accurate model for cloud attenuation prediction has been devised by Salonen and Uppala [5]. Also known as the TKK (Teknillinen KorkeaKoulu) model, this methodology originally requires as input vertical profiles of pressure, relative humidity and temperature (*P-RH-T*), derivable from radiosonde observations (RAOBS); however, also an approximate and more practical version of the TKK model has been introduced in [5] which, through the concept of liquid water content reduced to a fixed temperature, allows to estimate $A_C$ using as input an integrated quantity instead of complete vertical profiles [6].

Notwithstanding its good performance, the main drawback of the TKK model originates from the need to receive as input only reduced integrated liquid water data or, in other words, from the impossibility to take advantage of alternative (and possibly more accurate) cloud data as the ones provided by Earth Observation sensors (e.g. MODIS and CPR on-board the Aqua and CloudSat satellites, respectively) in terms of integrated liquid water content $W$. To overcome this limitation, this contribution proposes a different simplified yet accurate approach to estimate cloud attenuation that relies on the use of mass absorption coefficients and requires as input the integrated liquid water content $W$. Specifically, Section II describes in details how cloud attenuation can be calculated from RAOBS data, as well as using the approximate TKK model and the proposed methodology. The prediction accuracy of the latter approach is tested in Section III against a dataset of radiosonde observations collected in 14 European sites subject to different climates. Finally, Section IV draws some conclusions.

## II. CALCULATION OF CLOUD ATTENUATION

### A. *Exact methodology*

For propagation applications in the mm-/micro-wave region, cloud attenuation can be evaluated using the Rayleigh approximation to determine the extinction properties of suspended liquid water droplets. In fact, due to the small size of such droplets (assumed to be of spherical shape) with respect to the wavelength for frequencies below 300 GHz, the specific attenuation due to clouds $\gamma_C$ can be calculated as [5]:

$$\gamma_C(w,f,T) = K_l w \quad \text{(dB/km)} \tag{1}$$

where $w$ is the liquid water content in the cloud (g/m$^3$), whilst, according to the Rayleigh approximation and the double-Debye model for the dielectric permittivity of water $\varepsilon$, $K_l$ can be expressed as [5]:

$$K_l = \frac{0.819 f}{\varepsilon''\left(1+\eta^2\right)} \quad \text{(dB/km)/(g/m}^3\text{)} \tag{2}$$

In (2), $\eta = (2+\varepsilon')/\varepsilon''$, whilst $\varepsilon'$ and $\varepsilon''$ are the real and imaginary parts of the dielectric permittivity of water, respectively defined as:

$$\varepsilon'(f) = \varepsilon_2 + \frac{(\varepsilon_0-\varepsilon_1)}{1+(f/f_D)^2} + \frac{(\varepsilon_1-\varepsilon_2)}{1+(f/f_S)^2} \tag{3}$$

$$\varepsilon''(f) = \frac{f(\varepsilon_0-\varepsilon_1)}{f_D\left[1+(f/f_D)^2\right]} + \frac{f(\varepsilon_1-\varepsilon_2)}{f_S\left[1+(f/f_S)^2\right]} \tag{4}$$

where $T$ is the temperature expressed in K and:

$\phi = 300/T$,
$f_D = 20.09 - 142\,(\phi - 1) + 294(\phi - 1)^2$,
$f_S = 590 - 1500\,(\phi - 1)$,
$\varepsilon_1 = 5.48$, $\varepsilon_2 = 3.51$ and $\varepsilon_0 = 77.67 + 103.3\,(\phi - 1)$.

As is clear from the equations above, $K_l$ depends on the frequency $f$ and on the temperature $T$ of each layer in the cloud. As a consequence, the exact calculation of the path cloud attenuation $A_C$ requires the availability of full profiles of temperature and specific liquid water content. In turn, this information can be retrieved from radiosonde observations (RAOBS), typically collected worldwide at airports twice a day: whilst temperature $T$ is directly measured during the radiosonde ascent, together with relative humidity $RH$ and pressure $P$, the liquid water content $w$ can be estimated using the already mentioned TKK model [5], which, as a first step toward the calculation of the specific attenuation due to the suspended liquid water, identifies clouds and quantifies their density from *P-RH-T* profiles (full details on the well-established model and on its application can be found in [5]).

### B. Approximate solution

A viable way to simplify the calculation of $A_C$, currently adopted by ITU-R in recommendation P.840-6 [7], is to employ an effective value for the vertical integral of $w$ (much easier to handle than the whole profile), $W_{red}$, which embeds the information on the variation of temperature (and, thus, of the specific cloud attenuation) with height. As a result, the total path attenuation due to clouds can be calculated as [6]:

$$A = K_l(T_R)\,W_{red}(T_R) \quad \text{(dB)} \tag{5}$$

where $K_l(T_R)$ is the coefficient in (2) calculated for the reducing temperature $T_R$ and $W_{red}(T_R)$ is the integrated liquid water content reduced to $T_R$. In other words, equation (5) expresses the total path attenuation as if the temperature within the cloud were always 0 °C, regardless of the layers' height, and this deviation from the actual values of $T$ is taken into account by modifying $w$ into $w_{red}$ along the whole profile as follows [6]:

$$w_{red}(T_R) = w\frac{\int_{f\,\min}^{f\,\max}\gamma_C(w,f,T)\gamma_C(w,f,T_R)df}{\int_{f\,\min}^{f\,\max}\left[\gamma_C(w,f,T_R)\right]^2 df} \tag{6}$$

In order to ease the application of (5), statistics of $W_{red}$ are attached to recommendation ITU-R P.840-6 as calculated using the TKK model applied to *P-RH-T* profiles extracted from the ERA40 database with latitude/longitude grid resolution equal to 1.125°×1.125° [8]; in this case, $\Delta f$ = 10-60 GHz and $T_R$ = 0° C were chosen. Indeed, the application of (5) is tightly linked to such database, as this simplified approach cannot readily take advantage of alternative (and possibly more accurate) inputs, such as integrated liquid water content data provided by Earth Observation sensors (e.g. MODIS and CPR on-board the Aqua and CloudSat satellites, respectively). Moreover, a change in $T_R$ (as suggested in [6] to reduce the approximation error) and/or $\Delta f$ (e.g. to address frequencies higher than 60 GHz with minimum loss of accuracy) would require a full (and computationally heavy) reprocessing of the entire set of ERA40 *P-RH-T* vertical profiles (or of any equivalent global database).

### C. Alternative approximate approach

To overcome the above mentioned limitations, we propose an alternative approach to estimate cloud attenuation which involves the direct use of the mass absorption coefficient for liquid water, $a_W(f)$ in (7), widely employed in remote sensing applications to relate the integrated liquid water content $W$ to the associated attenuation at a given frequency $f$, $A_W$ [9]:

$$A_W(f) = a_W(f)W \quad \text{(dB)} \tag{7}$$

Fig. 1, which refers to the example of Milano/Linate airport, shows that $a_W$ represents the slope of the black regression line obtained from data derived from an extensive set of RAOBS. *P-RH-T* profiles are used on one side to derive the liquid water content with high vertical resolution (10 to 40 meters) by means of the TKK cloud detection algorithm [5],[9] and, on the other side, to separately calculate $A_W$ through the MPM93 mass absorption model proposed by Liebe *et al.* in [10]. This procedure has been applied to RAOBS collected routinely twice a day for ten years (1980-1989) in 14 sites ranging from Northern (e.g. Sodankyla, Finland) to Southern (e.g. Trapani, Italy) Europe, i.e. subject to very different climates.

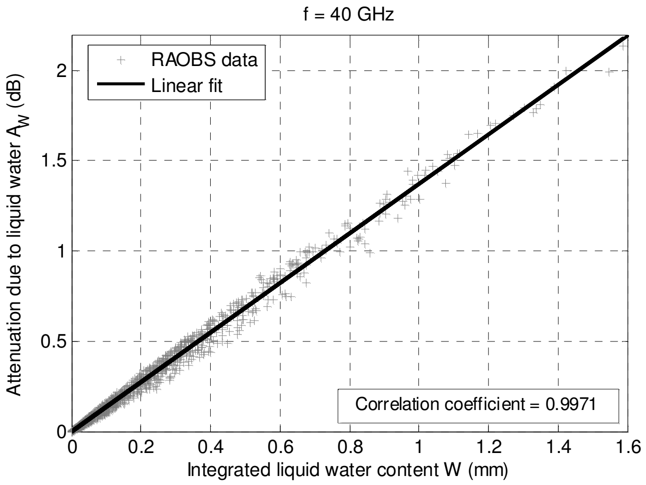


Fig. 1. Calculation of the mass absorption coefficient $a_W$ at 40 GHz using the RAOBS data collected at Milano/Linate airport (TKK and MPM93 models).

With this approach, the variation of the temperature within the cloud profile (and of the associated specific attenuation) is no more embedded in $W_{red}$ but is taken into account by the mass absorption coefficient $a_W$. This solution introduces the advantage of working with a physical quantity ($W$) instead of an effective one ($W_{red}$) which is of importance for applications involving low elevation links (e.g. high-latitude ground stations for GEO satellites and/or links to Earth Observation LEO satellites and deep-space probes), where the customary assumption of horizontal homogeneity for clouds (used in the ITU-R P.840-6 model as well) is no longer acceptable and, instead, the liquid water $W$ integrated along the path, taking into account the full vertical and horizontal distribution of $w$, is a requisite to obtain accurate results.

The differences in $a_W$ that were found when repeating the exercise in Fig. 1 for all the 14 different stations across Europe are negligible for the radiowave propagation applications addressed in this work. This indicates that, notwithstanding the difference both in the type and in the occurrence of clouds among the various sites, their vertical development, in terms of relationship between pressure, temperature and relative humidity, is similar. As a result, the following expression, depicted in Fig. 2 and valid for temperate climate, can be used to estimate $a_W$ as a function of frequency:

$$a_w^*(f) = \frac{0.819\left(a f^{b} + c f^{d} + e\right)}{\varepsilon''\left(1+\eta^2\right)} \quad \text{(dB/mm)} \tag{8}$$

where $a$ = 0.0155, $b$ = 1.668, $c$ = 14.8523, $d$ = 0.3885 and $e$ = -27.4863, 20 GHz $\le f \le$ 200 GHz, whilst the real and imaginary parts of the electric permittivity of water (see (3) and (4)) are calculated for $T = 0$ °C. The accuracy of (8) for the considered European sites is summarized in Fig. 3, which reports the highest values of the error $\delta$ as a function of $f$ (associated to Cagliari, Italy, and De-Bilt, the Netherland), being $\delta$ defined as $\delta(f) = 100[a_w^*(f) - a_w(f)]/a_w(f)$.

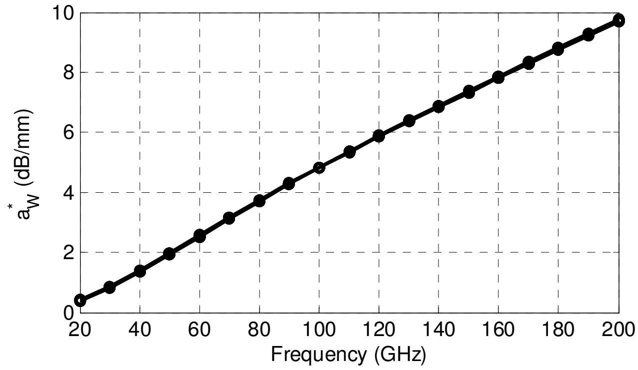


Fig. 2. Trend of the mass absorption coefficient $a_w^*(f)$ according to (8).

As a result, equation (8), which turns out to be a deviation from (2), can be used to calculate the cloud attenuation along the path $A_C$, for frequencies between 20 GHz and 200 GHz, as a function of $W$ values derived from different sources/models.

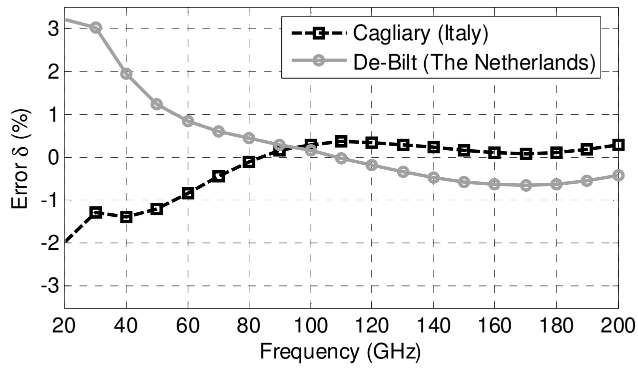


Fig. 3. Highest values of the error $\delta$ as a function of $f$ (Cagliari, Italy, and De-Bilt, the Netherlands).

## III. Performance Assessment

The accuracy of the method is tested in this Section against the set of European RAOBS measurements mentioned above. Fig. 4 shows an example of the zenithal cloud attenuation statistics (Complementary Cumulative Distribution Function, CCDF) at 100 GHz calculated according to the exact (i.e. exploiting the whole *P-RH-T* profile as input to the TKK and MPM93 models) and approximate (i.e. using (7) and (8)) methods for the RAOBS data collected at Milano/Linate airport from 1980 to 1989. The accuracy is quantified by the average (E) and root mean square (RMS) values (also reported in the legend of Fig. 4) of the following error figure [6]:

$$\varepsilon(P) = 100\frac{A^*(P) - A(P)}{A(P)} \quad (\%) \tag{9}$$

where $A^*(P)$ and $A(P)$ are the cloud attenuation values extracted from the approximate and exact attenuation statistics, respectively, relative to the same probability level $P \geq 0.01\%$.

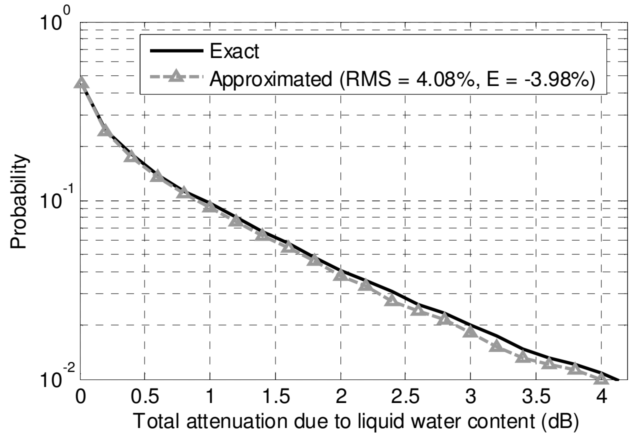


Fig. 4. Zenithal cloud attenuation CCDF at 100 GHz calculated according to the exact (black solid line) and approximate (dashed gray line with triangles) methods for the RAOBS data collected at Milano/Linate airport.

Fig. 5 gives an overall hint of the accuracy of the method by reporting the mean E ($\psi_E$) and mean RMS ($\psi_{RMS}$) values as a function of frequency. Results indicate a very accurate prediction performance (overall $\psi_{RMS}$ = 3.4%), which has some dependence on the frequency ($\psi_{RMS}$ = 5.2% and $\psi_{RMS}$ = 1.4% around 60 GHz and 170 GHz, respectively). On the other hand, negligible variation of $\psi_{RMS}$ is found from site to site in Europe, which confirms the appropriateness of the site-independent expression for $a_W^*(f)$ defined in (8).

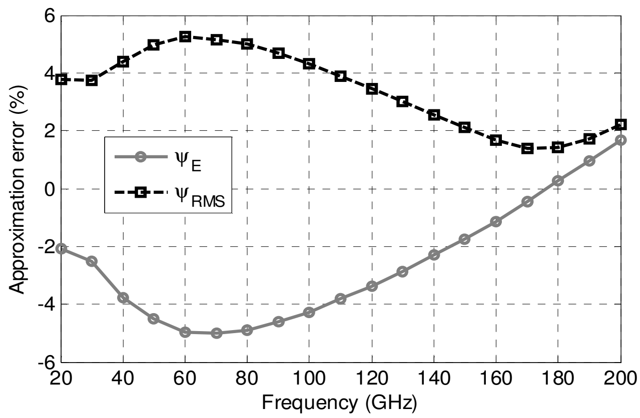


Fig. 5. Mean E ($\psi_E$) and mean RMS ($\psi_{RMS}$) as a function of frequency (average over all stations).

## IV. Conclusions

A simple and accurate approach to calculate cloud attenuation $A_C$ for Earth-space communication systems operating in the 20-200 GHz frequency range is presented and assessed here. The model is the result of a thorough analysis on high resolution RAOBS data collected in several locations for many years in Europe. We have proposed a simple analytical expression for the mass absorption coefficient of liquid water $a_W$ that is function of frequency and is independent of the site of interest. The knowledge of $a_W$ and of the integrated liquid water content $W$ is thus sufficient to calculate cloud attenuation in any site subject to temperate climate. Tests on the accuracy of the method in predicting $A_C$ show a very good performance (overall RMS of the approximation error $\varepsilon$ equal to 3.4%) which is slightly dependent on frequency (RMS of $\varepsilon$ ranging between 1.4% and 5.2% in the 20-200 GHz band) but not on the site. The main advantage of the proposal lies in the possibility to exploit different datasets of $W$ e.g. provided by Earth Observation sensors. This, in turn, is of key importance for applications involving low elevation links (e.g. high-latitude ground stations for GEO satellites and/or links to Earth Observation LEO satellites and deep-space probes), where the customary assumption of horizontal homogeneity for clouds is no longer acceptable and, instead, the liquid water $W$ integrated along the path, taking into account the full vertical and horizontal distribution of $w$, is a requisite to obtain accurate results.

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