Calculation of visibility and corresponding microwave attenuation

User manual to the program "visibility.exe"

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1. Introduction

The program "visibility.exe" enables the following to be computed:

1. Visual attenuation (visibility) on the basis of the known optical properties of atmospheric dust particles and their size distribution. The Mie theory for spherical particles is used, while there is a possibility to also take the surface electric charge of the particles into account. Except the visibility at the maximum spectral sensitivity of the human eye (555 nm), the software also allows the effective visibility involving the photopic eye sensitivity function to be calculated.
2. Microwave attenuation (in dB/km) for selected frequencies. The dust may be charged by electrons to a chosen potential at a chosen temperature.

All integrals in the code are calculated using the trapezoidal rule with an adaptive step size. This means that a minimum required relative precision of the result is defined and the integration step is adaptively decreased until the required precision is achieved. The relative precision is set to 0.001 and can be changed by modifying the preprocessor constant PRECISION in the file "visibility.c".

2. Program inputs

The program reads the input parameters from the command line as well as from the configuration files.

2.1 Command line parameters

In the command line the user enters the parameters that change frequently. This enables batch scripts for mass calculations to be efficiently written. The program expects the following parameters in the command line:

- The name of the file defining the dust size distribution function, its optical characteristics and density. The file description is below in subsection 2.3.
- The total mass of dust particles per unit of volume in μg/m^3. The program scales the size distribution function according to this value. The visibility *D* is typically 5-500 m in dust storms. To estimate the corresponding concentration of dust particles (in μg/m^3) one can use the simplified relation (9) from [Baddock,2014]:

$$m[\mu g/m^3] = \frac{4050}{D[km]} \quad (1)$$

  It is evident that the coefficient in Eq. (1) depends on the dust properties.

- The surface electric potential of the dust particles.

- The temperature of the dust particles.
- The value of the coefficient of proportionality in the relation $\gamma_S \propto \frac{k_B T}{\hbar}$
- The photopic/nophotopic switch, i.e., whether the effective visibility regarding the eye sensitivity function is to be calculated. This is a time-consuming computation, while a difference of such effective visibility against the visibility at the maximum spectral sensitivity (555 nm) is obviously negligible.

2.2 File "frequencies.dat"

This file defines the microwave frequencies (in GHz) for which the attenuation is to be calculated. The frequency values are written in the particular lines. An array of these values is allocated dynamically, and the number of frequencies is not limited.

2.3 File describing the size distribution and optical properties of dust particles

The name of this file is the first command-line parameter of the program "visibility.exe". The dust is fully characterized in this file and the user is expected to prepare separate files for typical regions (e.g., sahara.dat, india.dat, and so on). The typical content of the file is:

```
# This is a test config file for the "visibility" program
2                                  ... number of distributions (fractions) in
the dust - corresponding lines are below
6e2    0.03   0.33   2600   test_dust.dat... parameters (content [1/cm3], r0[mkm],
sigma(ln(r)), density [kg/m3], refr. index filename
4e0    0.8    0.3    2600   test_dust.dat
1e-3   1e3                         ... limits [mkm] of the dust distribution
```

The value in the first uncommented line represents the number of partial size distributions (fractions) of the dust. This is followed by one line of characteristic parameters for each fraction, while a log-normal distribution is assumed. For each fraction the following have to be set:

- The maximum value of the distribution function
- The position of the maximum (a corresponding particle radius) in μm
- The standard deviation
- The particle density in kg/m^3
- The name of the file containing the dependence of the refractive index on the wavelength.

A method for obtaining the mentioned parameters from published works is presented in Appendix 1.

In the last line, the limits for the particle radius have to be set. The upper boundary is important, because particles with large radii significantly affect attenuation in the optical and microwave range. A reasonable estimation of the maximum radius of particles floating in a dust storm is 0.1 – 1 mm.

All arrays are allocated dynamically, so there are no restrictions on the number of fractions. Of course, the more fractions there are, the longer the computational time.

2.4 Files describing the refractive index of dust particles

The files have a simple structure. There are three numbers in each uncommented line: the wavelength (in μm), the real part and the imaginary part of the refractive index. See the example:

```
# Test file for refractive index
# wavel [mkm]     real_part[-]      imag_part[-]
0.300 1.53  0.004
0.500 1.52  0.003
```

```
0.900 1.51  0.002
1e2   1.5   0.1
1e5   1.5   0.1
```

Values of the refractive index for other wavelengths not specified in the file are calculated by linear interpolation, or the boundary value is used, if the wavelength is out of the range. Arrays for the refractive index values are allocated dynamically; therefore, there are no file length limits.

A method for obtaining values of the refractive index from the literature is described in Appendix 2.

3. Program outputs

The running state of the computation is displayed in the console; the results are saved into two data files and one auxiliary file.

3.1 File "visibility.dat"

This file contains the detailed results of the computation, and its content is replaced by the new one upon a rerun of "visibility.exe". All the input parameters are initially stored in the file "visibility.dat"; therefore, this file enables all the inputs from the command line as well as from the input files to be acquired. Furthermore, the file contains the following computed data:

- The distribution functions of the particular fractions used and the resulting distribution function – appropriate for plotting the graphs dn/d(ln r).
- The visibility at 555 nm.
- If the flag "photopic" was on:
  - the effective visibility, including the spectral sensitivity of the eye
  - dependence of the visibility on the wavelength <400 nm – 800 nm>.
- The microwave attenuation for the frequencies defined in the file "frequencies.dat".

3.2 File "plot.dat"

The content of this file is not deleted after a new run of "visibility.exe". A new line containing the following data is added to the file:

- The name of the configuration file describing the size distribution of the dust.
- The mass concentration of dust particles (in μg/m^3).
- The visibility at 555 nm (in km).
- The effective visibility in km (if the flag "photopic" was on).
- The microwave attenuation values (in dB/km) for the selected frequencies given in the file "frequencies.dat".

The file "plot.dat" is suitable for plotting:

- The dependence of the attenuation on the frequency for various parameters.
- The dependence of the attenuation on various parameters for a particular frequency.
- A 3D-plot frequency-parameter-attenuation.
- The dependence of the visibility on the mass concentration of dust.

3.3 File "plotheader.dat"

In this file, a header belonging to the file "plot.dat" is generated after each run of "visibility.exe". This header contains a line with the name and another line with the column names. It is assumed that the frequency list defined in the file "frequencies.dat" does not change; otherwise, the content of the file "plot.dat" would be inconsistent.

Appendix 1 – size distribution parameters

Two specific size distribution functions of dust particles mainly occur in the literature:

- dn/d(ln r) – where n is the number concentration of particles which have the logarithm of their radius between the values ln r and ln r + d(ln r) (in 1/m^3). A graphical presentation of this function is such that the particle radius is on the horizontal axis on a logarithmic scale and dn/d(ln r) is on the vertical axis, which is obviously logarithmic, too.
- dV/d(ln r) – where V is the volume concentration of particles with logarithms of their radii between ln r and d(ln r) (a dimensionless value or a derived unit, for example $\mu m^3/m^3$).

The program "visibility.exe" requires the following parameters characterizing the distribution function dn/d(log r) of particular fractions:

- n_0 [1/cm^3] – the total number concentration of all particles
- r_0 [µm] – the position of the maximum
- the standard deviation σ

A method for obtaining these data from a plot of dn/d(ln r) is described below. This method is based on the lognormal distribution in the form

$$\frac{dn}{d(\ln r)} = \frac{n_0}{\sigma\sqrt{2\pi}} e^{-\frac{(\ln r - \ln r_0)^2}{2\sigma^2}} \qquad (2)$$

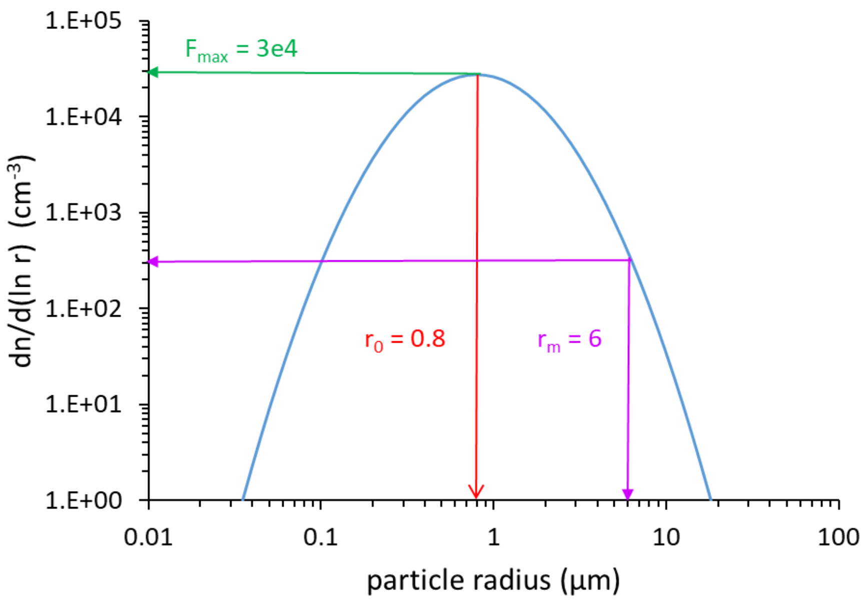


Fig. 1. Lognormal distribution function dn/d(ln r)

Step 1: Finding the maximum position r_0.

This value can be read directly from the graph (Fig. 1), r_0 = 0.8 µm.

Step 2: Finding the standard deviation σ.

We find the maximum value of the function (this is the value 3.10^4 marked in green in Fig. 1). Further, we find the value *m*-orders of magnitude smaller than the maximum, where *m* is arbitrary. In Fig. 1, the value 3.10^2, which is two orders of magnitude smaller (m = 2), is marked in violet. We determine the corresponding particle radius r_m = 6 µm. At this point, the ratio of the function value and the maximum value is equal

$$10^{-m} = e^{-\frac{(\ln\frac{r_m}{r_0})^2}{2\sigma^2}}$$

It gives

$$-m = -\frac{(\ln\frac{r_m}{r_0})^2}{2\sigma^2}\log e$$

and

$$\sigma = \sqrt{\frac{\log e}{2m}}\ln\frac{r_m}{r_0} \qquad (3)$$

For the values from Fig. 1, we get:

$$\sigma = \sqrt{\frac{\log e}{2\,.\,2}}\ln\frac{6}{0.8} = 0.66$$

Step 3: Finding of the total number concentration n_0.

We determine the maximum function value from the graph; this is $F_{max} = 3.10^4$ in Fig. 1. Eq. (2) directly yields:

$$n_0 = F_{max}\sigma\sqrt{2\pi} \qquad (4)$$

Thus, our example results $n_0 = 3.10^4$ x 0.66 x 2.51 = 5.10^4 1/cm^3.

Notes:

- With regard to the symmetry of the distribution, we can also read the value of r_m to the left of the maximum and replace the ratio r_m/r_0 by the ratio r_0/r_m in Eq. (3). It is also possible to use the square root of the ratio of the "right" and "left" of the value r_m as the ratio.
- Sometimes, the distribution function of particles is presented in the literature from their **diameter** instead of their radius. In such case, half of the diameter d_0 corresponding to the maximum has to be considered, instead of r_0. The standard deviation σ remains the same; the value of n_0 can also stay unchanged, because the program will always scale it according to the given total mass of the dust (see the last point).

- Only the mutual ratio of n_0 in the fractions is important, not the values themselves. The program "visibility.exe" scales the values of n_0 to achieve the required total mass concentration in μg/m^3.
- If we have only the plots of dV/d(ln r) available, we continue formally in the same way and determine the values r_{0v}, σ_v and n_{0v}. We then recalculate them to the required values using the relations presented in Table 1 in [Grainger, 2017]:

$$\sigma = \sigma_v$$
$$\ln r_0 = \ln r_{0v} - 3\sigma^2 \tag{5}$$
$$n_0 = \frac{n_{ov}}{\frac{4}{3}\pi e^{(3\ln r_0 + 4.5\sigma^2)}}$$

- For internal calculations of integrals in the program "visibility.exe", we do not actually need the function dn/d(ln r), but the function dn/dr. However, this function is obtained simply in the program:

$$\frac{dn}{dr} = \frac{dn}{d(\ln r)}\frac{d(\ln r)}{dr} = \frac{1}{r}\frac{dn}{d(\ln r)} \tag{6}$$

Appendix 2 – refractive index of dust particles

A complex refractive index for pure minerals in the optical range can be found in literature. In the radiofrequency range, the complex permittivity of a material is usually presented (the complex refractive index is the square root of the complex permittivity). Moreover, it is known that adsorbed water significantly affects dust permittivity as well as the microwave losses. The effect of relative humidity can be modelled by empirical relations presented, e.g., in [Sharif,2015]:

$$\varepsilon'(H) = \varepsilon' + 0{,}04H - 7{,}78.10^{-4}H^2 + 5{,}56.10^{-6}H^3 \tag{7}$$
$$\varepsilon''(H) = \varepsilon'' + 0{,}02H - 3{,}71.10^{-4}H^2 + 2{,}76.10^{-6}H^3$$

where $\varepsilon = \varepsilon' - i\varepsilon''$ is the effective relative permittivity and *H* is the relative humidity of the air in percentages.

To simplify the conversion of the complex permittivity to the refractive index (regarding the relative humidity), we have prepared the tool "eps2n.exe".

After it is launched, the real and imaginary part of the permittivity have to be entered, and the program will show a table of the complex permittivity and complex refractive index for various values of relative humidity:

```
Enter the numbers eps' a eps'' of the complex permitivitty eps' - i*eps'':
6.3485 0.0929

eps = 6.3485 - i * 0.0929
eps' - i *eps''         n' - i*n'':
rel.humidity[%]  eps'    eps''          n'      n''
0               6.3485  0.0929         2.51969 0.0184348
10              6.67626 0.25856        2.58433 0.0500246
20              6.88178 0.36658        2.62424 0.0698449
30              6.99842 0.43352        2.64672 0.0818976
40              7.05954 0.47594        2.65849 0.0895133
50              7.0985  0.5104         2.66602 0.0957232
60              7.14866 0.55346        2.6757  0.103424
```

```
70             7.24338 0.62168        2.69383 0.11539
80             7.41602 0.73162        2.72654 0.134166
90             7.69994 0.89984        2.77959 0.161865
100            8.1285  1.1429         2.85805 0.199944
```

We used the value 6.3485 – i*0.0929 for the microwave range permittivity of dry dust from Libya (Table IV in [Saleh,2010]) in the illustration.

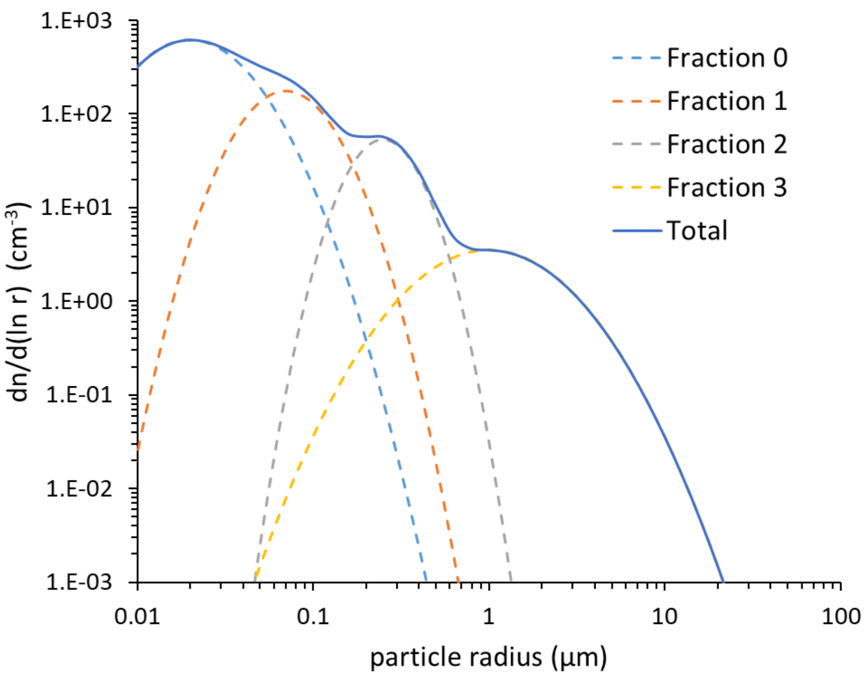
Appendix 3 – testing calculations

A3.1 Verification of the necessary range for the size distribution function

To test the program, we used the data on typical dust from North Africa (Algeria, Tunisia, Morocco, Libya). **The size distribution was taken from Fig. 3a in** [Denjean, 2016], where authors present the measured data and their model with four fractions. Using Eqs. (3) and (4) we found the parameters for the configuration file named "mediterian.cfg":

```
4      ... number of distributions (fractions) in the dust
1050   0.02  0.6   2600  mediterian_n.dat  ... parameters
230    0.07  0.46  2600  mediterian_n.dat
54.1   0.25  0.36  2600  mediterian_n.dat
7.6    1.0   0.76  2600  mediterian_n.dat
1e-2   1e2   ... limits [mkm] of the dust distribution
```

The corresponding distribution function (plotted from the file "visibility.dat" – output of the program "visibility.exe"):



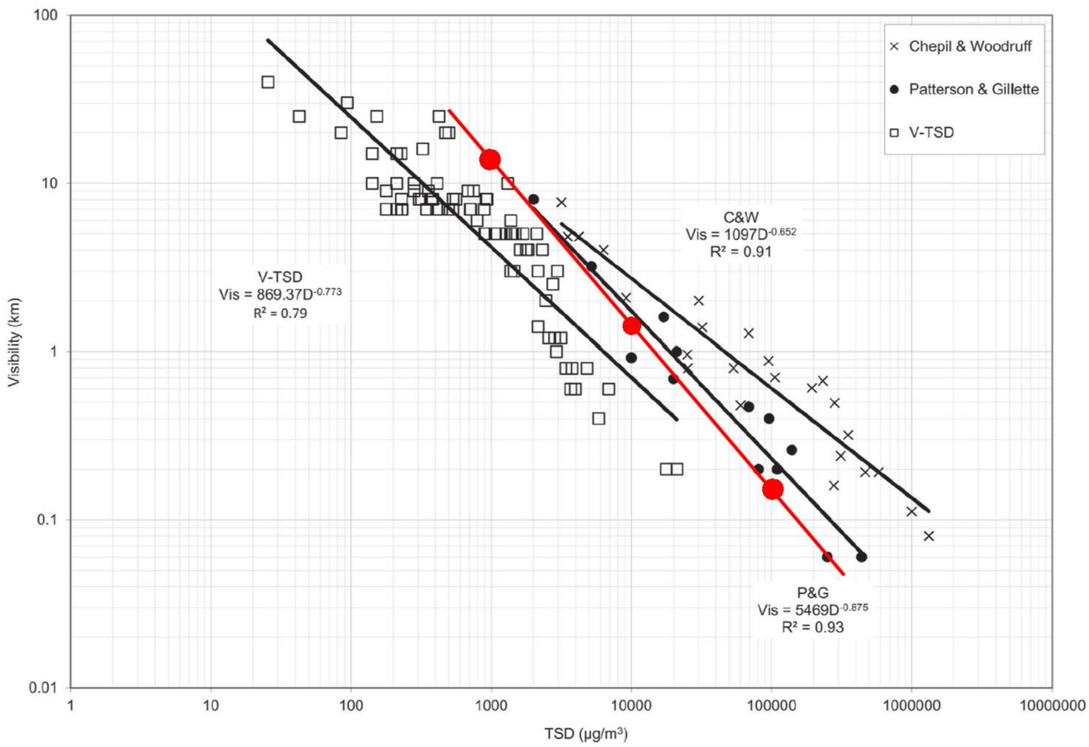
The particle density was set 2600 kg/m^3 (the typical value for minerals) and the refractive index in the optical range was equal to 1.53 – i*0.004 [Denjean,2016].

We set the range of the particle radius at **<0.01; 100> µm**, because the distribution function outside of this range decreases steeply. We verified that extending this range to <0.001; 1000> µm changed the calculated visibility by less than 0.1%, and the impact on the microwave attenuation was even smaller. **Thus, the upper limit of the particle radius equal to 1000 µm (diameter of max. 2 mm) appears to be sufficient.**

A3.2 Comparison of calculated visibility with published data

We compared our visibility results (this means the integral across the distribution function of dust) with Fig. 4 in [Baddock,2014], where the dependences of the visibility on the total mass concentration of dust (in µg/m3) coming from various authors are presented.

The visibility values at 555 nm calculated for our model of dry and uncharged dust are entered into the figure as red circles. Our results confirm the conclusions of Baddock [Baddock,2014], that the visibility is inversely proportional to the dust content in the air (in µg/m^3). It has to be noted here that our program omits Rayleigh scattering; therefore, our large visibilities (over a few kilometers) are overestimated. However, the Rayleigh scattering on air molecules is negligible in comparison with the scattering by dust particles in dust storms.



Therefore, we can state that the visibility calculated according to our model for north African dust is in good agreement with the measured data published by other authors.

A3.3 Comparison of the standard and effective visibility

In the next step, we compared the visibility calculated at 555 nm with the effective visibility regarding the eye spectral sensitivity, both calculated for the typical mass concentration 1000 µg/m^3:

Visibility at 555 nm: 15.506 km

Effective visibility: 15.498 km

The difference is less than the computational precision 0.1% (i.e. 0.015 km). We tried to compare both the visibilities under various circumstances and the difference was not greater than 1% even for extreme cases (very large particles, very small particles, monodisperse particles, ...). **Therefore, we consider the long-running calculation of the effective visibility unnecessary.**

A3.4 Microwave attenuation – assessment of the imaginary part of permittivity

The calculation of microwave attenuation does not differ from the same calculation in the optical range (that is from the visibility calculation):

$$A[\text{dB/km}] = -10*\log(\exp(-b*1000)) = 4343*b \qquad (8)$$

where b is the volume extinction coefficient in m^{-1}.

The only difference is a change of the refractive index and the wavelength. But the problem is that **published values of the imaginary part of dust permittivity differ significantly**.

For example, Saleh (Table IV in [Saleh, 2010]) introduces the value 6.3485 – i*0.0929 for the permittivity of dry dust in Libya in the microwave range. As was shown in Appendix 2, high humidity (100%) can increase the imaginary part of the permittivity by one order of magnitude. But some authors present even greater values of permittivity. Elabdin summarizes the values from several authors (Table 1 in [Elabdin, 2009]), which are extensively higher, and yet not for the unreal humidity 100%:

Frequency Band	ε'	ε''	Reference
S-band	4.56	0.25	Ghobrial [22]
X-band	5.73	0.42	Ghobrial and Sharief [23]
Ku-band	5.5	1.3	Ruike [24]
K-band	5.1	1.4	Ruike [24]
Ka-band	4	1.33	Ruike [24]
W-band	3.5	1.64	Ruike [24]

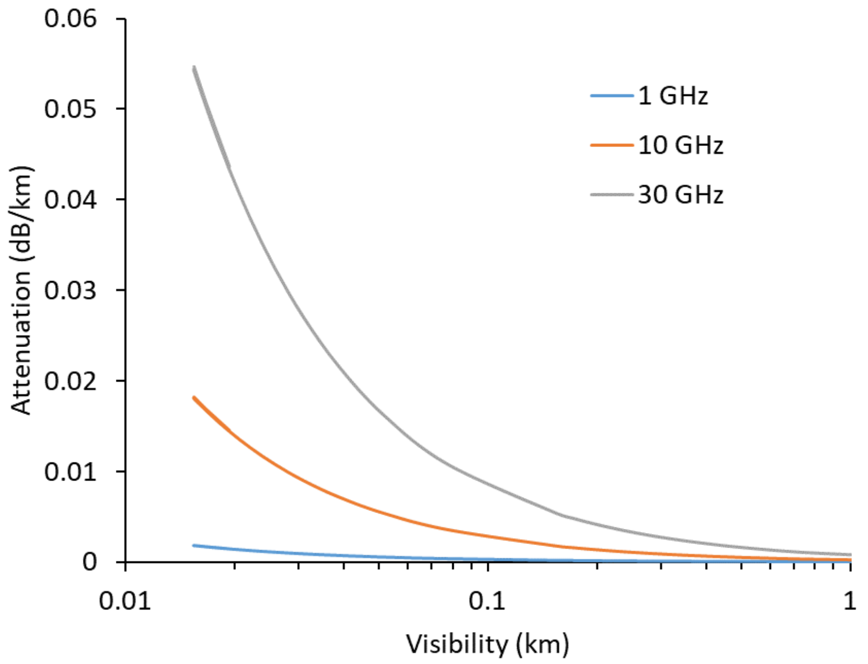
However, the one-order difference in the imaginary part of the permittivity leads up to a one-order difference in the attenuation (in dB/km), which put great emphasis on the accuracy of the material permittivity data.

A3.5 Microwave attenuation – influence of large particles

The main difference between a "normal" atmospheric aerosol and the aerosol during a dust storm is the presence of relatively big particles floating in the air during the storm. These would settle quickly under normal meteorological conditions.

The testing calculation for the "normal" aerosol was conducted for dust from Libya at a relative humidity of 40% (see Appendix 2):
n = 2.65 – i * 0.089.

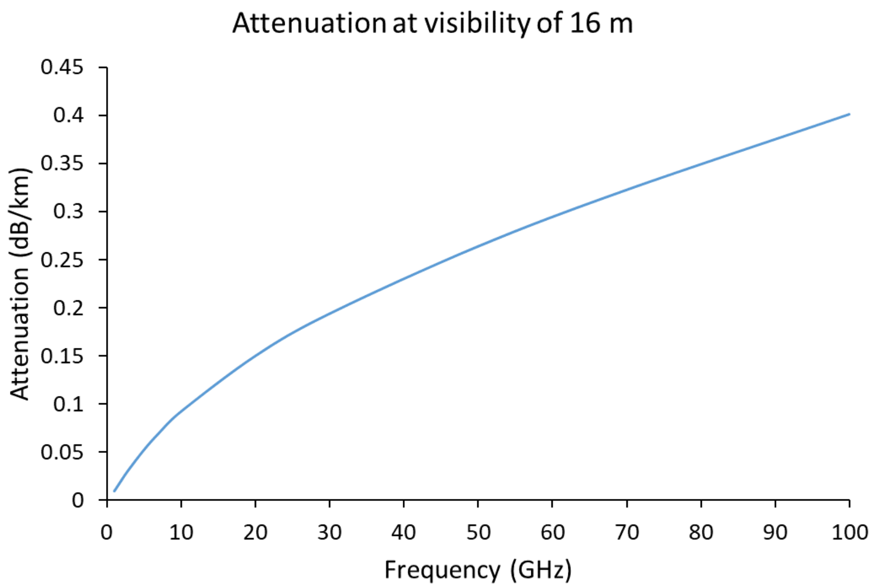
The dependence of attenuation on visibility (a plot from the data in the output file "plot.dat"):



The calculated values are much smaller than the values measured during dust storms. For example, Elabdin [Elabdin,2009] introduces the measured attenuation of 0.14 dB/km for the frequency 40 GHz at the visibility 0.625 km. Our result for the "normal" aerosol is 0.0017 dB/km.

Upon considering the particle electric potential of 50 V, the attenuation sharply increased to a value of 0.0056 dB/km (at the same visibility and frequency) but this value, too, is one-order smaller than the observed attenuation.

The next figure illustrates the dependence of the attenuation on the frequency at a visibility of 16 m and at the potential 50 V:



The values should have a magnitude of a few decibels per kilometer according to experiments.

Looking for the cause of the discrepancy between attenuation during a dust storm and on normal days we also changed the imaginary part of the refractive index and the electric potential of dust grains, but we were unable to achieve the measured values.

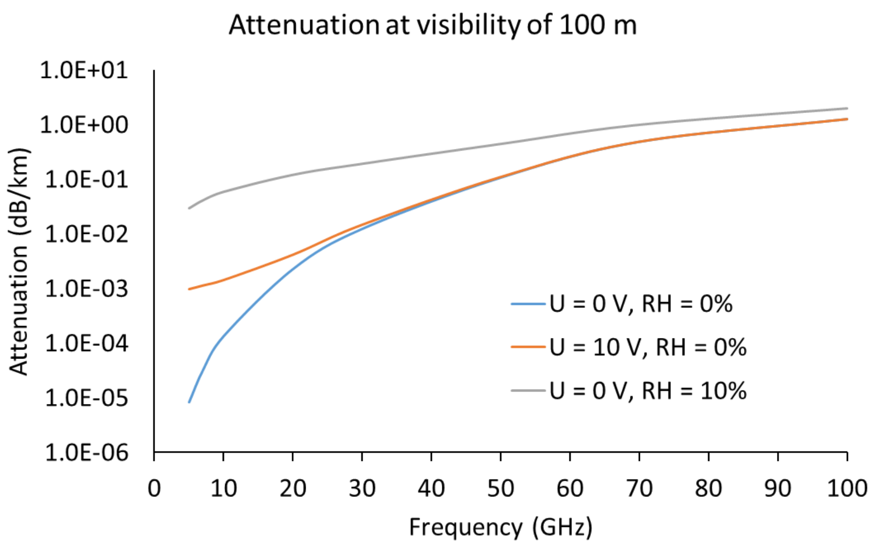
Therefore, we concluded that the main reason should be the presence of large particles during dust storms, when the typical dimension of dust/sand particles is obviously 1 – 100 µm (e.g. [Fadil,2018]), whereas in the calm atmosphere it is obviously 0.1 – 10 µm (see Appendix 3.1). Kandler has already pointed out that the particles with relatively large radii appear in the atmosphere during dust storms [Kandler, 2009]. We took the size distribution observed during a dust storm in Morocco from his paper (Table 4 in [Kandler, 2009]), when the largest fraction (r_0 = 76.95 µm), formed predominantly by SiO_2, increased:

content [1/cm3],	r0[µm]	sigma(ln(r))
367.8	0.0353	0.703
117.9	0.372	0.582
3.839	0.866	1.313
0.03189	76.95	0.3228

Conversion of that paper's data to our parameters: r_0 <- d_0/2, sigma <- ln(sigma), n_0 <- n_0.

This is the same distribution that we used in [Kocifaj, 2015]. The refractive index in the optical range was taken from Table 6 in [Kandler, 2009]. The real part of the microwave permittivity was set again at 6.3485 for the Libyan dust (Table IV in [Saleh, 2010]). Since, however, the largest fraction, made up of low-loss SiO_2, has the biggest effect on the microwave attenuation (Rayleigh scattering), we considered the imaginary part equal 0 (**a lossless dielectric**).

The results of calculations for the potential U = 0 V and U = 10 V and for the humidity H = 0% and H=10% (a typical desert value) are in the following figure.



One can see that we were able to reproduce the results from [Kocifaj, 2015] (the increase of the attenuation by two orders of magnitude at roughly 10 GHz, the small changes at frequencies over 50 GHz), which also corresponds to the observed attenuations during dust storms. It is interesting that the effect of the humidity on the attenuation is even more significant (at lower frequencies).

The attenuation values themselves, taking into account the humidity effect, are in good agreement with the results in [Fadil, 2018]. Fadil's calculations for H = 0% provide significantly higher attenuation, because Fadil considered a relatively high imaginary part of the refractive index of the dry material (we considered the lossless material).

Thus, for a good estimate of microwave attenuation, good knowledge of the size distribution of particles (mainly the fraction with the greatest average dimension) is necessary. The relative humidity also has a large effect on attenuation. All papers dealing with the effect of humidity on microwave attenuation refer only to the empiric relation from [Sharif, 2015].

References

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