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بسم الله الرحمن الرحيم

Effects of Rain Particles on the Strength of the Electromagnetic Signals in the Microwave Regime

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Abstract

This report presents results from scattering and absorption by rain effects on the strength of the microwave signal at the X-band. The measurements of the signal strength are done by measuring the S12 parameters in different weather conditions: No rain, shower rain, and heavy including the wind effects. The measurement is done inside an artificial rain setup. The measurements are compared to their identical based simulations using CST MWS. The results are also quantitatively compared with results from Rayleigh theory that was reported in the literature.

I.Introduction

Mie Theory (Mie, 1908), known for almost one century, allows for exact modeling of wave propagation, absorption and scattering characteristics of spheres and of clouds of such particles, provided that the dielectric and magnetic properties of the particle are known. Water droplets of rain and clouds are nearly spherical, homogeneous, dielectric particles; thus, Mie Theory is quite appropriate for applications in atmospheric physics. Mie Theory has also been widely used for this purpose (e.g. Deirmendjian, 1969) to complement the results of Rayleigh scattering which are a much simpler formulation, but applicable for small size parameters ($x=ak<<1$, a= drop radius, k= wave number) only. Most published studies usually relied on old dielectric data, such as Ray (1972) - being especially inaccurate at frequencies above 10 GHz - and often the studies of Mie scattering were incomplete descriptions by considering one or another aspect, only, e.g. Olsen et al. (1978) gave a quantitative description of extinction by rain. Olsen's results were of recent interest (Mätzler 2002a) to quantify rain effects on radar signals. A useful set of parameters, allowing a larger range of applications (wave propagation, radiometer, monostatic radar), must include the extinction γ_{ext}, absorption γ_{abs}, and backscattering coefficient γ_b, respectively, including the scattering coefficient γ_{sca} from γ_{ext}-γ_{abs}; in addition, for modeling radiometer data with radiative transfer theory the full phase matrix is required as well or at least the asymmetry parameter $g=<\cos\theta>$ if a simplified method is applied, such as the few-stream models (Meador and Weaver, 1980). These parameters are computed and plotted by a set of MATLAB Functions, developed by Mätzler (2002b), based on the book of Bohren and Huffman (1983). The present report is an application of this software. The objective is threefold:

1- To extend the MATLAB functions to cloud and rain applications for general use in the 1 to 1000 GHz range (or to the optical range with an appropriate refractive model of water),
2- To prepare our research group for microwave radiometry of the rainy atmosphere,
3- To replace the rather inaccurate results of Olsen et al. (1978) by better ones and to complement them with more additional information.

Here, the presently assumed standard dielectric model of water will be applied (Liebe et al. 1991), and comparisons will be made with an alternative one (Liebe et al. 1993).

At a temperature of 300K, the two models coincide. They deviate just in one parameter, the permittivity at infinite frequency,

$$\varepsilon_\infty = \begin{cases} 3.52 + 7.52\theta; & \text{Liebe et al.(1991)} \\ 3.52\ ; & \text{Liebe et al.(1993)} \end{cases} \quad (1)$$

where θ =1-300/*T*, and *T* is the temperature in K. Thus, at frequencies *f* near or below 30 GHz, the difference between the two models is negligible.

The Marshall and Palmer (MP) drop-size distribution will be assumed:

$$N_{MP}(D) = N_0 \exp(-\Lambda D) \quad (2)$$

with the drop diameter *D*, the parameter Λ being given by (Sauvageot, 1992)

$$\Lambda = 3.67 / D_0 = 41R^{-0.21} \quad (3)$$

where *D*0 (cm) is the median diameter, *R* (mm/h) the rain rate, and *N*0 = 0.08 cm-4. Olsen et al. (1978) and de Wolf (2001) proposed renormalizations of the MP distribution to produce correct rain rates. Since these corrections are different, we will omit them here.

II. Single water droplets

2.1 Mie Efficiencies

Mie Theory requires the complex refractive index of water *m* as input parameter. Since the relative magnetic permeability of water is very close to 1, we can assume the relationship for non-magnetic materials

$$m = \sqrt{\varepsilon} \quad (4)$$

where ε is the complex relative dielectric constant (or permittivity) of liquid water. For ε we use the model of Liebe et al. (1991). The MATLAB function is called epswater. For the alternative model, Liebe et al. (1993), the MATLAB Function is called epswater93.

Mie Efficiencies of water droplets are computed at *T*=277K for two frequencies, using the MATLAB Function Mie_rain1. The results are shown versus drop diameter *D* in Figures 1 and 2. At the logarithmic scales, starting at *D*=10μm (a typical cloud drop size), the figures emphasize the Rayleigh regime with straight lines up to about 2 mm at 5 GHz and 0.3 mm at 94 GHz. This is the reason why rain-radar data at 5 GHz (e.g. Sauvageot, 1992) are usually interpreted in terms of Rayleigh scattering theory (van de Hulst, 1957, Ishimaru, 1978).

2.2 Comparison with Rayleigh Theory

To test the accuracy of the Rayleigh Approximation, the Mie and Rayleigh results are compared in Figure 3. It is observed that Rayleigh Theory underestimates absorption at *f*=5GHz at *D*=2mm (*x*≅0.1) by a factor of 1/2 already, and computations with an accuracy of 10% only reach to *D*=0.7 mm. For accurate modeling of microwave emission, absorption should be known to the 1% level. Thus, Mie Theory is needed in microwave radiometry of rain at 5 GHz and at all higher frequencies. For scattering and

Backscattering, on the other hand, the Rayleigh Approximation is valid (deviations < 25%) up to D=6 mm, thus covering the full range of rain drops. Since radar data are usually needed with an accuracy of about 1 dB (26%), the Rayleigh Approximation is sufficient for radar observations at 5 GHz. Note the slightly oscillatory behavior of the Mie backscattering efficiency around the Rayleigh curve in Figure 3. Similar results are found at 94 GHz (bottom graph of Figure 3). The underestimate of absorption of the Rayleigh curve by a factor of 1/2 is reached at D=0.5 mm ($x \cong 0.5$), i.e. at a 4 times lower value of D than at 5 GHz, whereas the frequency is higher by a factor of 19. This behavior is due to the relaxation spectrum of water. Again, for scattering, and especially for backscattering, the Rayleigh Approximation is useful up to higher D values, about 0.8 mm.

2.3 Comparison between Liebe'91 and Liebe'93

The two dielectric models, Liebe et al. (1991) and Liebe et al. (1993), give slightly different results. The difference increases with increasing frequency and with temperature decreasing from 300 K. Mie efficiencies and their differences between the two dielectric models at 277K are shown in Figure 4 for f=24 and 220 GHz, respectively, to produce correct rain rates. Since these corrections are different, we will omit them here.

2 Single water droplets

2.1 Mie Efficiencies

Mie Theory requires the complex refractive index of water m as input parameter.
Since the relative magnetic permeability of water is very close to 1, we can assume the relationship for non-magnetic materials

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2.4 Rain spectra

The results of the integration of the Mie Efficiencies over the drop-size distribution lead to the propagation coefficients, using the MATLAB Function Mie_rain3. Care has to be taken to select the best range of D values. The following parameters were found to be useful and to give accurate results with trapezoidal integration:

```
nsteps=501; dD=0.01*R^(1/6)/fGHz^0.05;
```

where nsteps is the number of steps in the numerical integration, starting at D=0,
and dD is the increment in dependence on rain rate R(mm/h) and frequency fGHz (GHz). The γj spectra of rain at 277K are shown in Figure 11 for rain rates R of 1 and 10 mm/h. These curves tend to increase frequency, either reaching saturation at the top or above the presented spectral range or a flat peak, especially for γb. The peak frequency decreases with an increasing rain rate. Another feature is the decreasing dominance of absorption with increasing frequency and rain rate.

2.6 Rain-rate dependence

The γj coefficients are shown versus rain rate, both in linear and logarithmic scales in Figures 12 to 17. These are quite smooth curves in both representations, sometimes being almost straight lines. The extinction coefficients can be used to check the approximate formula of Olsen et al. (1978), $\gamma ext \cong \alpha R \beta$, where α and β depend on frequency, drop-size distribution and temperature. For T=0, 10 and 20C, and for the dielectric water model of Ray

(1972), these parameters were given by Olson et al. (1978), and the tables are reprinted by Mätzler (2002a). However, when looking at Figures 12 to 17, it is clear that the Olsen formula cannot be very accurate as it require strait lines in the logarithmic representations. Therefore, Olsen's fits represent rough approximations of extinction, only.

2.7 Temperature dependence

The dependence of the propagation coefficients on temperature is shown by Figures 18 to 20, covering the frequency range, 5 to 94 GHz. The maximum sensitivity is found for absorption at the lowest frequency; this is a result of the rather strong temperature dependence of the lower relaxation frequency.

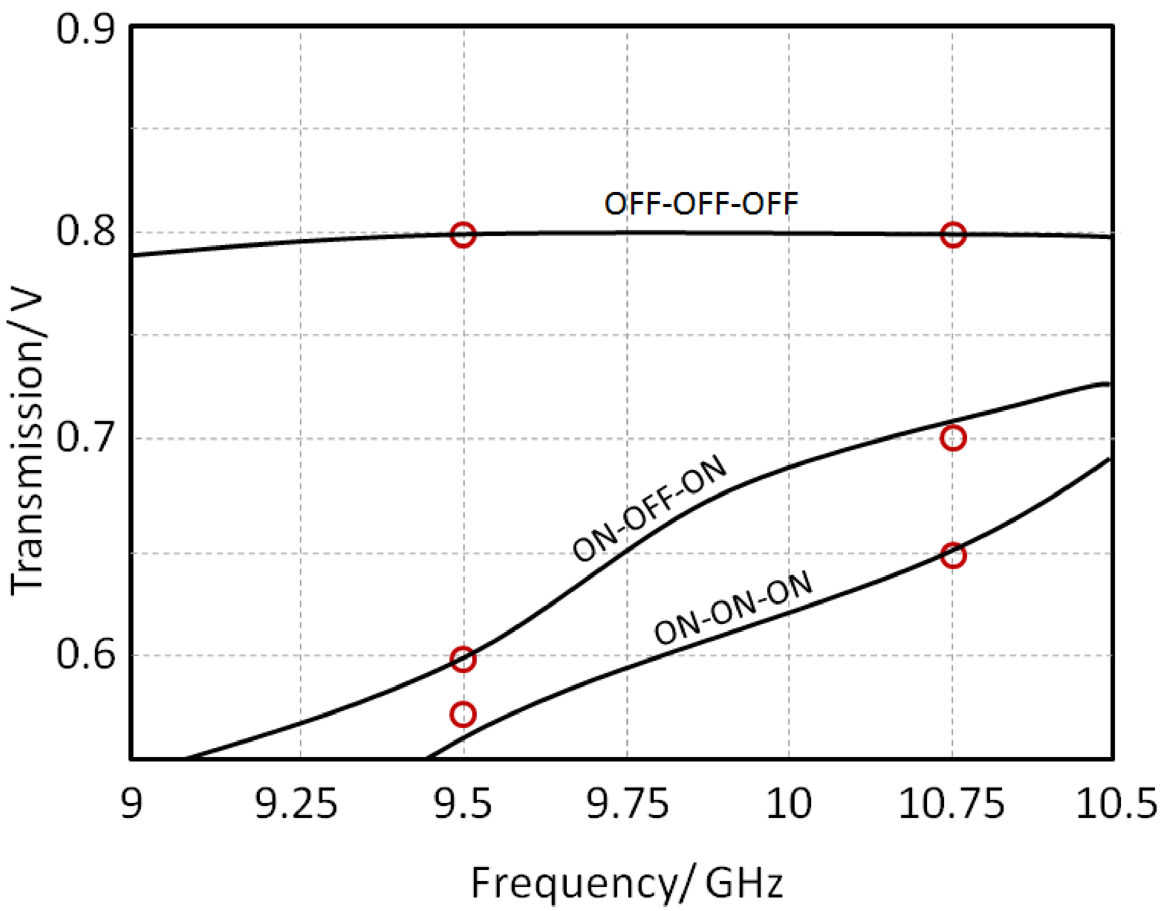
III. Results and Discussions

The measurements of the electromagnetic signals strength, scattering parameters, in the microwave region are listed in table 1.

Table 1: Scattering Measurements

Scattering Measurements at 9.5 GHz				
A	**B**	**C**	**S12 (V_{dc}) without wind**	**S12 (V_{dc}) with wind**
ON	ON	ON	0.58	0.65
ON	ON	OFF	0.58	0.75
ON	OFF	ON	0.59	0.65
ON	OFF	OFF	0.59	0.79
OFF	ON	ON	0.58	0.78
OFF	ON	OFF	0.59	0.78
OFF	OFF	ON	0.59	0.75
OFF	OFF	OFF	0.80	0.80
Scattering Measurements at 10 GHz				
A	**B**	**C**	**S12 (V_{dc}) without wind**	**S12 (V_{dc}) with wind**
ON	ON	ON	0.70	0.75
ON	ON	OFF	0.69	0.79
ON	OFF	ON	0.65	0.77
ON	OFF	OFF	0.75	0.79
OFF	ON	ON	0.70	0.79
OFF	ON	OFF	0.80	0.80
OFF	OFF	ON	0.80	0.75
OFF	OFF	OFF	0.80	0.80

V_{beam}=421 V
I_{beam}=26 mA
V_{rebel}=-241 V


0.9
0.8
0.7
0.6
Transmission/V
OFF-OFF-OFF
ON-OFF-ON
ON-ON-ON
9
9.25
9.5
9.75
10
10.75
10.5
Frequency/ GHz

IV. Conclusions

This report is a table and graphical presentation of scattering effects of rain in the microwave range. The presentation is as comprehensive as possible by giving all relevant parameters and showing all relevant dependencies. The graphs are instructive in the sense that they show how the different parameters behave, how they are related quantitatively and which drop-sizes contribute most. In addition, the results show that the feasibility of using numerical commercial software packages, using CST MWS, analyzing the scattering parameters. The absorption coefficient can be strongly underestimated by the numerical software.

References

1. Al-Behadili, Amer Abbood, et al. "Differential Microstrip Sensor for Complex Permittivity Characterization of Organic Fluid Mixtures." Sensors 21.23 (2021): 7865.
2. I. Bahl, and P. Bhartia, "Microwave Solid State Circuit Design", 2nd ed., Wiley, New York. (April 2003).
3. C. Caloz and T. Itoh, *Electromagnetic metamaterials: transmission line theory and microwave applications*. John Wiley & Sons, 2005.
4.T. A. Elwi, "Remotely controlled reconfigurable antenna for modern 5G networks applications," Microw. Opt. Technol. Lett., vol. 63, no. 8, pp. 2018–2023, 2021.
5.A. Nieuwoudt and Y. Massoud, "Optimizing the design of tunable spiral inductors for on-chip wireless applications," in 2006 IEEE Annual Wireless and Microwave Technology Conference, 2006, pp. 1–5.
6. S. R. Best, "A comparison of the performance properties of the Minkowski curve fractal and meander line monopole antennas,"Microwave and Optical Technology Letters, vol. 35, no. 4, pp.258–261, 2002.
7. S. S. Bor, T. C. Lu, J. C. Liu, and B. H. Zeng, "Fractal monopole- like antenna with series Minkowski -curves for WLAN dualband and circular polarization applications," Microwave and Optical Technology Letters, vol. 51, no. 4, pp. 876–880, 2009.

8. Slawomir, G.; Robert, S.; Krzysztof,W. Realization of High-Performance Broadband Quadrature Directional Couplers in UMS PH25 Technology. Electronics 2019, 8, 1520.
9. Hardinata, S.; Deshours, F.; Alquié, G.; Kokabi, H.; Koskas, F. Miniaturization of Microwave Biosensor for Non-invasive Measurements of Materials and Biological Tissues. IPTEK J. Proc. Ser. 2018, 29, 90–93.
10. Liu, W.; Sun, H.; Xu, L. A Microwave Method for Dielectric Characterization Measurement of Small Liquids Using a Metamaterial-Based Sensor. *Sensors* 2018, *18*, 1438.
11. Hao, H.; Wang, D.; Wang, Z.; Yin, B.; Ruan, W. Design of a High Sensitivity Microwave Sensor for Liquid Dielectric Constant Measurement. *Sensors* 2020, *20*, 5598.
12. Wei, Z.; Huang, J.; Li, J.; Xu, G.; Ju, Z.; Liu, X.; Ni, X. A High-Sensitivity Microfluidic Sensor Based on a Substrate Integrated Waveguide Re-Entrant Cavity for Complex Permittivity Measurement of Liquids. Sensors 2018, 18, 4005.
13. Liao, S.; Gao, B.; Tong, L.; Yang, X.; Li, Y.; Li, M. Measuring Complex Permittivity of Soils by Waveguide Transmission/Reflection Method. In Proceedings of the *IGARSS 2019—2019 IEEE International Geoscience and Remote Sensing Symposium*, Yokohama, Japan, 28 July–2 August 2019; pp. 7144–7147, doi:10.1109/IGARSS.2019.8900535.
14. Oliveira, J.G.D.; Pinto, E.N.M.G.; Silva Neto, V.P.; D'Assunção, A.G. CSRR-Based Microwave Sensor for Dielectric Materials Characterization Applied to Soil Water Content Determination. *Sensors* 2020, *20*, 255. https://doi.org/10.3390/s20010255
15. M. G. Mayani, F. J. Herraiz-Martínez, J. M. Domingo and R. Giannetti, "Resonator-Based Microwave Metamaterial Sensors for Instrumentation: Survey, Classification, and Performance Comparison," in *IEEE Transactions on Instrumentation and Measurement*, vol. 70, pp. 1-14, 2021, Art no. 9503414, doi: 10.1109/TIM.2020.3040484.

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