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A Predictive Model for Attenuation and Phase Rotation in Mono- and Polydisperse Dusty Media at MW and mm-Wave Bands

Fowzi S. Alarabi [1]* , Hamza A. Juma [2]
[1] Department of Networks, Faculty of Information Technology, Elmergib University, Al-Khoms, Libya
[2] Department of Software Engineering and Information Systems, Faculty of Information Technology, Elmergib University, Al-Khoms, Libya

نموذج تنبؤي للتوهين ودوران الطور في الأوساط الغبارية أحادية ومتعددة التشتت في نطاق الموجات الميكروية والمليمترية

فوزي الصادق العربي [1]* ، حمزة علي جمعة شخطور [2]
[1] قسم الشبكات، كلية تقنية المعلومات، جامعة المرقب، الخمس، ليبيا
[2] قسم هندسة البرمجيات ونظم المعلومات، كلية تقنية المعلومات، جامعة المرقب، الخمس، ليبيا

*Corresponding author: fozuy.alarabi@gmail.com

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Abstract:

This paper presents a theoretical framework for predicting the attenuation and phase rotation of electromagnetic waves propagating in dusty storm environments. A mathematical model based on Rayleigh scattering theory and forward-scattering amplitude is developed for both monodisperse media (uniform particle-size distribution) and polydisperse media (exponential particle-size distribution). The model is used to evaluate the differential attenuation and phase shift of electromagnetic waves while explicitly accounting for non-spherical dust particles with different aspect ratios.

Published values of the dielectric constant and dust density in Libya are incorporated into the calculations across the X-, Ka-, V-, and E-bands. In addition, the study introduces an expression relating visibility to dust concentration and integrates it into the proposed models through visibility and frequency dependencies. Simulation results show strong agreement with selected published data. The results indicate noticeable differences in attenuation and phase behavior between mono- and polydisperse dry-dust media. These effects become more pronounced under severe visibility conditions or at shorter wavelengths, with the polydisperse medium exhibiting stronger impacts.

Keywords: Differential attenuation, phase rotation, monodisperse medium, polydisperse medium, dusty storm environments.

الملخص

تقدم هذه الورقة إطارًا نظريًا للتنبؤ بالتوهين ودوران الطور للموجات الكهرومغناطيسية المنتشرة في بيئات العواصف الغبارية. تم تطوير نموذج رياضي يعتمد على نظرية تشتت رايلي وسعة التشتت الأمامي لكلٍ من الأوساط أحادية التشتت (توزيع موحد لأحجام الجسيمات) والأوساط متعددة التشتت (توزيع أسي لأحجام الجسيمات). ويُستخدم النموذج لتقييم التوهين التفاضلي وإزاحة الطور للموجات الكهرومغناطيسية مع الأخذ في الاعتبار صراحةً الجسيمات الغبارية غير الكروية ذات نسب الأبعاد المختلفة.

تم إدماج القيم المنشورة لثابت العزل الكهربائي وكثافة الغبار في ليبيا ضمن الحسابات عبر نطاقات X وKa وV وE. بالإضافة إلى ذلك، تقدم الدراسة علاقة تربط مدى الرؤية بتركيز الغبار، وتدمجها في النماذج المقترحة من خلال الاعتماد على كلٍّ من مدى الرؤية والتردد. تُظهر نتائج المحاكاة توافقًا جيدًا مع بيانات منشورة مختارة، كما تشير النتائج إلى وجود

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فروق ملحوظة في سلوك التوهين والطور بين الأوساط الجافة أحادية ومتعددة التشتت. وتزداد هذه التأثيرات وضوحًا في ظروف انخفاض مدى الرؤية الشديد أو عند الأطوال الموجية الأقصر، حيث يُظهر الوسط متعدد التشتت تأثيرات أقوى.

الكلمات المفتاحية: التوهين التفاضلي، دوران الطور، وسط أحادي التشتت، وسط متعدد التشتت، بيئات العواصف الغبارية.

Introduction

The growing interest in studying the impact of sand and dust storms (SDST) on the performance of microwave and millimeter-wave links is driven by the rapid expansion of terrestrial and satellite microwave systems, as well as the increasing use of higher frequency spectra due to congestion in conventional frequency bands [1], [2]. To ensure the efficiency and reliability of high-frequency transmission links, the development of accurate propagation models that explicitly account for frequency and atmospheric visibility has become essential for assessing the effects of such phenomena.

Dust particles generated during SDST events degrade the quality of communication links by attenuating the transmitted signal along the propagation path. Several Libyan researchers [3]–[9] have investigated the impact of SDST on microwave link performance in Libya, particularly through the determination of the dielectric constant and particle density of sand and dust, parameters that are utilized in the present work.

Despite the extensive efforts devoted to investigating the effects of SDST on microwave and millimeter-wave propagation, most previous studies [4], [5], [7] have primarily assumed spherical particles and have not sufficiently addressed the influence of non-spherical dust geometries under both mono- and polydisperse conditions. Furthermore, the visibility-dependent relationship with dust concentration and its integration into scattering models remain insufficiently investigated in regional studies. This paper aims to bridge this gap by developing and validating a theoretical framework that incorporates non-spherical particle shapes, multiple size distributions, and frequency–visibility dependencies, thereby enabling more realistic predictions of SDST-induced effects on microwave (MW) and millimeter-wave (mm-wave) communication links in Libya.

Electromagnetic waves propagating through SDST environments experience attenuation and phase rotation, which may ultimately degrade communication system performance [2], [13]. Differential attenuation and differential phase rotation can arise in orthogonally polarized channels under such storm conditions due to the non-spherical geometry of dust particles [11].

Dust particles exhibit complex and irregular morphologies, for which the ellipsoidal approximation is commonly adopted [10], [20]–[24]. In a medium containing ellipsoidal dust particles, attenuation and phase rotation can be determined when the aspect ratios of the ellipsoids are specified. Accordingly, this paper investigates attenuation and phase rotation associated with ellipsoidal dust particles and introduces models for computing scattering coefficients under both mono- and polydisperse conditions. The forward-scattering amplitude formulation within the Rayleigh approximation is employed to derive the differential attenuation and differential phase shift during SDST events.

The proposed models are numerically implemented, and the results are presented through curves generated using Python and its associated libraries. These results are analyzed and compared with previously published data, followed by a discussion of the main findings.

Propagation Modeling in Ellipsoidal Particle Media

Attenuation and phase rotation in a medium containing ellipsoidal particles are modeled using the modified Rayleigh scattering approximation, which provides a rigorous analytical framework for describing the interaction between electromagnetic waves and non-spherical particles. In such scattering environments, these propagation characteristics can be expressed in terms of the imaginary and real parts of the complex refractive index, respectively [11], [12]. Accordingly, the attenuation coefficient and phase rotation for vertically and horizontally polarized waves are expressed as follows:

$$\alpha_{v,h} = kI_m(n_i)8.686 \times 10^3 \qquad [dB/km] \qquad (1)$$

$$\beta_{v,h} = kR_e(n_i)\left[\frac{180}{\pi}\right] \times 10^3 \qquad [deg/km] \qquad (2)$$

where k is the free-space wavenumber, and n_i represents the complex refractive index.

The development of attenuation and phase rotation models for SDST is based on the complex refractive index representation of the scattering medium. In such particulate media, the complex refractive index can be expressed in terms of the particle concentration and the forward-scattering amplitude as follows [13], [14]:

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$$n_i = 1 - i2\pi k^{-3}.N.S(0) \qquad (3)$$

where N denotes the dust particle concentration, and S(0) represents the complex forward-scattering amplitude.

By employing the Rayleigh approximation, the forward-scattering amplitude can be expressed as a complex quantity that simultaneously represents the magnitude and phase of the scattered electromagnetic field [22]–[24]. This formulation provides a convenient and accurate description of the scattering behavior of particles that are much smaller than the wavelength of the incident wave, and it serves as a basis for calculating the scattered power and polarization effects in various propagation scenarios and can be written as:

$$S(0) = ik^3.p_{s-i} \qquad (4)$$

where p_{s-i} represents the complex polarizability of the particle along the i-axis.

The propagation constants depend on the particle geometry and its orientation with respect to the wave polarization. For an ellipsoidal particle with the electric field applied along axis i (i =1,2,3), the complex polarizability p_{s-i} is given by [11]:

$$p_{s-i} = \frac{\upsilon}{4\pi}\varphi_i \qquad (5)$$

where:

$$\varphi_i = \frac{\varepsilon_r - 1}{1 + l_i(\varepsilon_r - 1)} \quad = \quad \acute{\varphi}_\iota - i\,\ddot{\varphi}_\iota \qquad (6)$$

where ε_r represents the dielectric constant of dry dust, as reported in [3], and l_i denotes the depolarization factors along the three principal axes of the particle.

For particles modeled as ellipsoids with three unequal axes, the relative volume υ of the dust particle is given by:

$$\upsilon = \frac{4}{3}\pi a^3 \qquad (7)$$

where a is the radius of the equivalent particle.

Substituting Eqs. (5) and (7) into Eq. (4), the forward-scattering amplitude under the ellipsoidal particle shape assumption can be expressed as:

$$S(0) = \frac{1}{3}ik^3.\varphi_i\,a^3 \qquad (8)$$

By substituting Eq. (8) into Eq. (3), the complex refractive index of the scattering medium takes the form:

$$n_i = 1 + \frac{2\pi}{3}a^3.\varphi_i.N \qquad (9)$$

The particle number concentration (number of particles per unit volume) is a parameter that is difficult to measure directly during SDST events. Therefore, it is commonly related to atmospheric visibility, which is the primary meteorological parameter used to characterize SDST conditions. Accordingly, attenuation and phase rotation are evaluated in this work as functions of visibility.

Several relationships between dust particle concentration and visibility have been reported in the literature [25]–[28] and widely used for modeling dust storm characteristics under different conditions. In this study, the dust particle concentration N is determined using the expression reported in [6].

$$N = \frac{2.369 \times 10^{-9}}{V^\gamma a^3} \qquad (10)$$

where V denotes the visibility in kilometers, and γ is a constant that depends on the climatic conditions and the origin of the storm, typically taken as 1.07 [10].

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Given the different descriptions of the scattering mechanisms associated with dust and sand particles during sand and dust storm events, attenuation and phase rotation models are developed for a medium containing ellipsoidal dust particles. The model formulation is performed for both mono- and polydisperse media.

In a Monodisperse medium, all particles are assumed to have identical geometrical dimensions and electromagnetic properties. By substituting Eq. (10) into Eq. (9), and then into Eqs. (1) and (2), the expressions for attenuation and phase rotation are obtained as follows:

$$\alpha_{v,h} = 9.026 \times 10^{-4} . \frac{f}{V^{\gamma}} .\ I_m(\varphi_i) \qquad [dB/km] \qquad (11)$$

$$\beta_{v,h} = 5.931 \times 10^{-3} . \frac{f}{V^{\gamma}} .\ R_e(\varphi_i) \qquad [deg/km] \qquad (12)$$

where f is the frequency in GHz, and $R_e(\varphi_i)$ and $I_m(\varphi_i)$ represent the real and imaginary parts of the i-th component of the dielectric constant, respectively. The indices i = 1, 2 correspond to horizontal polarization, whereas i =3 corresponds to vertical polarization.

To account for the more realistic case of a distributed dust particle size spectrum, the analysis of attenuation and phase constants is extended to a **Polydisperse medium**. In this scenario, ellipsoidal particles are characterized by a size distribution, typically represented by an exponential function, which captures the variability of particle sizes in SDST environments. The propagation coefficient K for a polydisperse medium is obtained as [11], [17]:

$$K = \frac{k}{3}\left[1 + \frac{12\pi N}{\beta^3}\ \varphi_i\right] \qquad (13)$$

For such a distribution, the mean particle radius is given by $a=1/\beta$ [11], where β denotes the slope parameter of the exponential distribution.

Substituting Eq. (10) and the above relation into Eq. (13), and then into Eqs. (1) and (2), yields the expressions for attenuation and phase rotation in a polydisperse medium.

$$\alpha_{v,h} = 5.416 \times 10^{-3} . \frac{f}{V^{\gamma}} .\ I_m(\varphi_i) \qquad [dB/km] \qquad (14)$$

$$\beta_{v,h} = 3.572 \times 10^{-2} . \frac{f}{V^{\gamma}} .\ R_e(\varphi_i) \qquad [deg/km] \qquad (15)$$

Differential Attenuation and Phase Rotation

The complex forward-scattering amplitude differs for horizontal and vertical polarizations due to the nonspherical geometry of the particles. This polarization-dependent scattering results in differential attenuation and phase rotation between the orthogonal linear components, which can induce cross-polarization effects [16]–[19].

The corresponding differentials in attenuation and phase between the horizontal and vertical polarizations are expressed as

$$\Delta_{\alpha} = \alpha_{h-}\,\alpha_{v} \qquad [dB/km] \qquad (16)$$

$$\Delta_{\beta} = \beta_{h-}\,\beta_{v} \qquad [deg/km] \qquad (17)$$

Results And Discussions

This section presents and discusses the results. The proposed models in (11), (12), (14), and (15) were evaluated using the required parameters at 0% moisture content, demonstrating very good agreement with the results reported in [11], [29]–[31].

The attenuation and phase rotation exhibit an approximately linear dependence on both frequency and atmospheric visibility when dust particles are modeled as ellipsoids. In particular, the attenuation decreases as visibility improves, reflecting the reduction in dust particle concentration. These results are obtained by solving the proposed model in (11),(12), using the depolarization factors l_1=0.213, l_2=0.329, and l_3=0.458. The corresponding numerical results are presented in Figs. 1, and 2.

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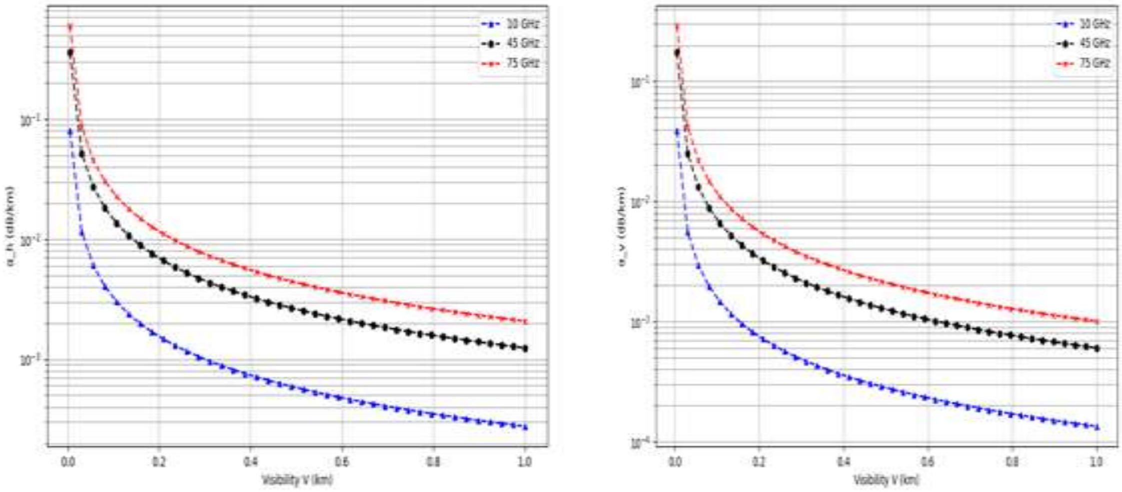
Figs. 1(a) and 1(b) illustrate the variation of the attenuation with visibility for the horizontal and vertical polarization components in a monodisperse medium.

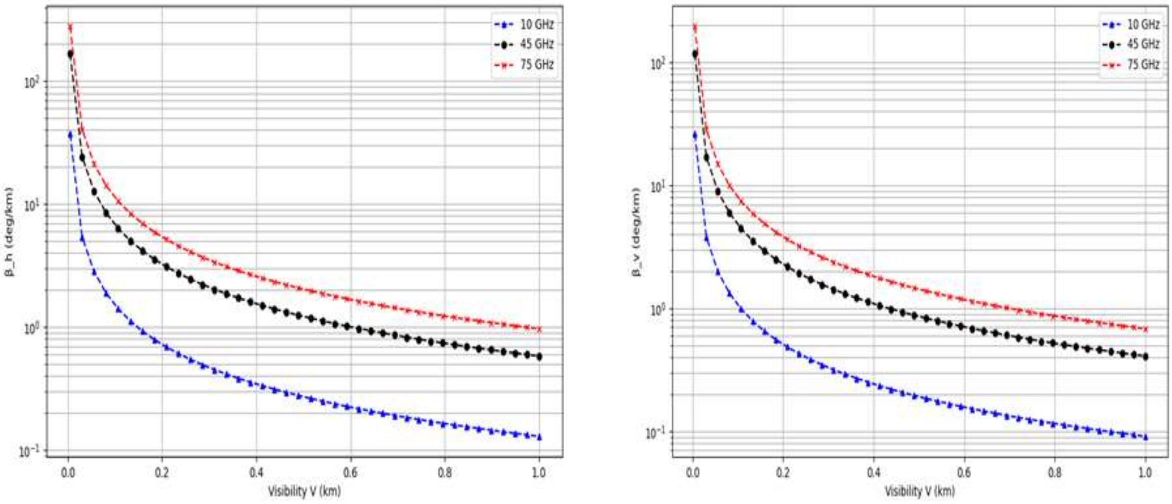


(a) horizontal polarization

(b) vertical polarization

Fig. 1. Attenuation vs. visibility (monodisperse medium) in MW and mm-wave bands

Similarly, Figs. 2(a) and 2(b) present the corresponding phase rotation variation for the horizontal and vertical polarization components.



(a) horizontal polarization

(b) vertical polarization

Fig. 2. Phase rotation vs. visibility (monodisperse medium) in MW and mm-wave bands

Application of the proposed model in (14) and (15) enables the evaluation of attenuation and phase rotation for a polydisperse medium based on the parameters specified in this paper. The resulting numerical variations are presented in Figs. 3 and 4.

Figs. 3(a) and 3(b) show the attenuation versus visibility for the horizontal and vertical polarization components in a polydisperse medium.

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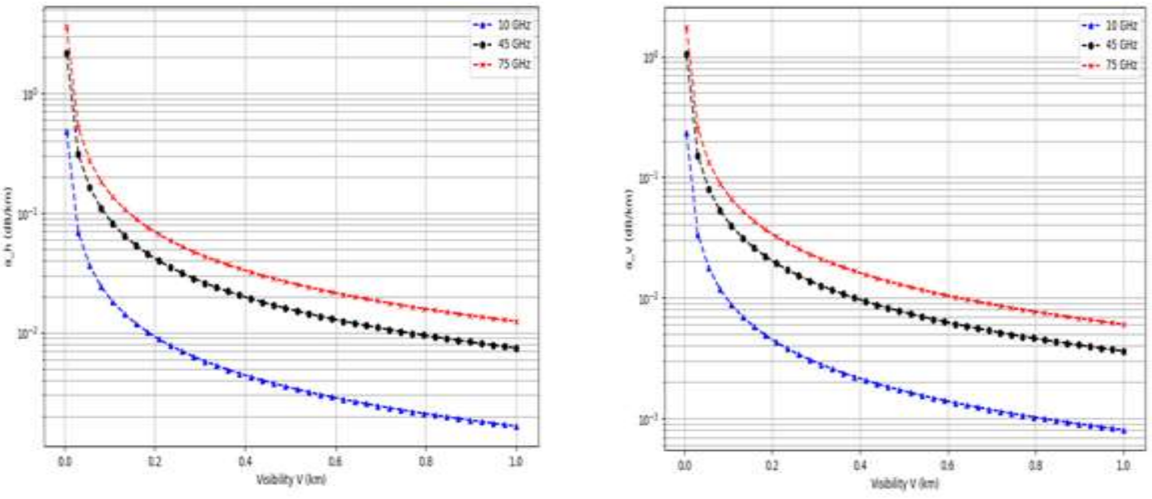
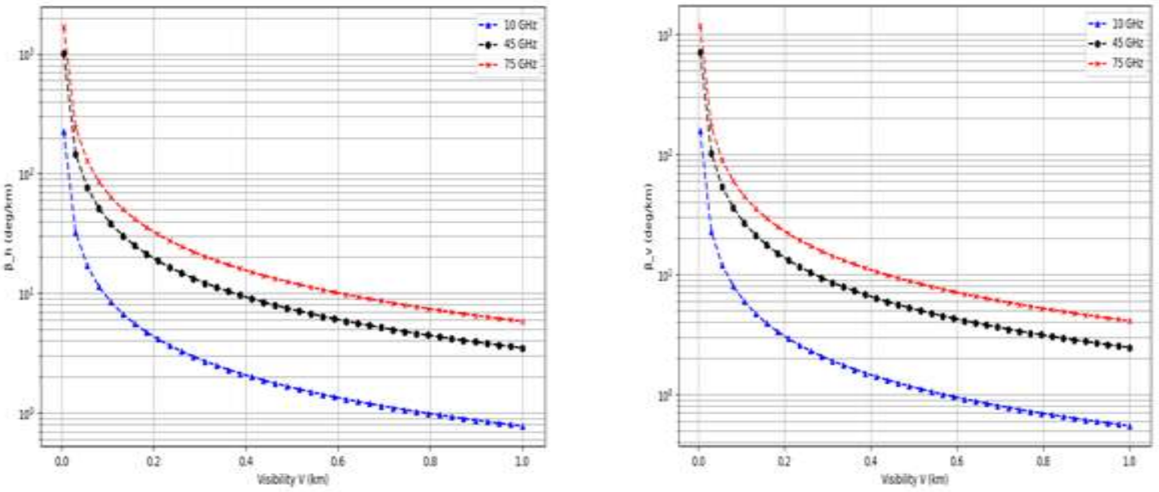


(a) horizontal polarization

(b) vertical polarization

Fig. 3. Attenuation vs. visibility (polydisperse medium) in MW and mm-wave bands**.**

Corresponding phase rotation variations for horizontal and vertical polarizations are presented in Figs. 4(a) and 4(b).



(a) horizontal polarization

(b) vertical polarization

Fig. 4. Phase rotation vs. visibility (polydisperse medium) in MW and mm-wave bands**.**

When dust particles are assumed to be ellipsoidal, they tend to align along their minor axis (the vertical axis) under stable atmospheric conditions. With this particle orientation, the differential attenuation and phase rotation can be determined using the expressions given in (16) and (17).

Figs. 5(a) and 5(b) illustrate the differential attenuation and differential phase rotation at frequencies of 10, 45, and 85 GHz for different visibility conditions.

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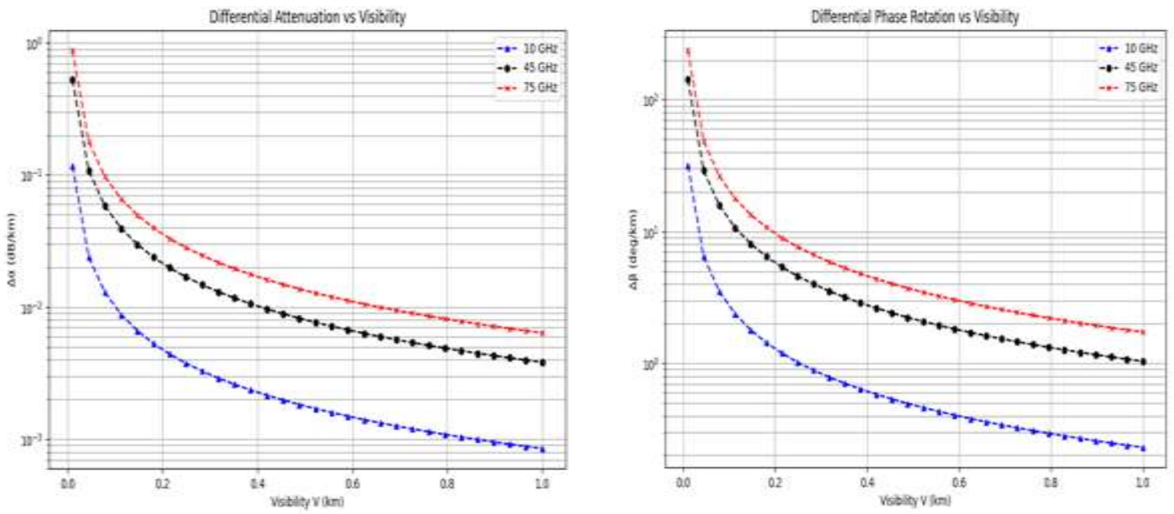

(**a**) Differential attenuation (b) Differential phase rotation

Fig. 5. Differential attenuation and phase rotation of polarized waves in MW & mm-wave bands.

Conclusion

This paper investigates microwave attenuation and phase rotation in SDST environments and proposes a predictive analytical model to estimate the attenuation and phase rotation induced by dry dust storms under various propagation conditions. The proposed formulations are presented in (11) and (12) for a monodisperse medium, and in (14) and (15) for a polydisperse medium. The models are derived based on the assumption of ellipsoidal dust particles, incorporating the relationship between particle concentration and visibility.

The results indicate that both attenuation and phase rotation increase with increasing dielectric constant and operating frequency, while decreasing with increasing visibility. These effects become more pronounced under severe dust storm conditions, particularly in the case of polydisperse particle distributions. The obtained results are further utilized to estimate the corresponding differential attenuation and differential phase rotation.

Based on the average behavior predicted by the proposed models, when visibility decreases from 400 m to 80 m at a frequency of 40 GHz, the attenuation increases from approximately 0.003 dB/km to 0.06 dB/km. Similarly, at 75 GHz, the attenuation increases from about 0.06 dB/km to 0.10 dB/km. These findings indicate that attenuation levels remain relatively low for propagation paths of approximately 1 km when visibility is around 20 m during dry dust storms. However, when visibility drops below 10 m, significant increases in differential attenuation and differential phase rotation are observed, which may lead to cross-polarization discrimination effects.

Overall, the proposed models and results provide valuable insights for the design and performance evaluation of microwave and millimeter-wave communication links, including emerging 5G and beyond-5G systems operating in environments affected by sand and dust storms.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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