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Terahertz Signal Communication in South-East Asia: A Predictive Model to Estimate the Atmospheric Issues

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ABSTRACT

Millimeter wave and sub-millimeter wave signal propagation suffers due to absorptive and dispersive processes present in the atmosphere. Moreover, the resulting attenuation and temporal group delay increase in unfavourable weather conditions. This signal attenuation is one of the most common type of hazards in ultrafast wireless communication systems. Primarily the existence of suspended atmospheric particles, which are commonly referred as aerosols, is responsible for this scattering mechanism. The authors in this paper, have presented a comprehensive analysis of terahertz (THz) signal attenuation owing to different types of atmospheric scattering mechanisms in Indian subcontinent under tropical climatic belt. The frequency-dependent properties of the signal attenuation have been analysed using an indigenous-ly developed Non-Linear Terahertz Attenuation Model (NLTAM). The findings show that due to multiple-scattering from fog-based aerosols, the peak-attenuation level decreases from that of the single-scattering outcome. The nature of THz signal attenuation spectra in foggy atmosphere, agrees closely with experimental findings of the same, for near THz or IR signal transmission in adverse weather scenario in nontropical region. For the first time, the author has developed NLTAM simulator to study the THz signal attenuation for different scattering mechanisms under foggy atmosphere with low visibility, with special emphasis on Indian sub-continent and further report-ed a comparative analysis of single-scattering and multi-scattering effects.

Keyword: Terahertz, Mie-Theory, Extinction Coefficient, Radiation-Fog, Absorption, Multiple Scattering

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I. INTRODUCTION

The terahertz (100GHz-10000GHz) spectrum, which lies between the normal electronics and photonics bands of the electromagnetic spectrum, has seized a vast area of current study [1-4], particularly in the field of wireless communication, due to its diverse application. Terahertz technology provides a huge bandwidth and has a high channel capacity [5-6]. Terahertz (THz) waves can be extremely sensitive to adverse weather conditions when passing through the near-surface atmosphere[7-8]. In clear weather, the presence of atmospheric gases and aerosol turbulence might impede channel availability and link performance in THz communication[9-10].The primary restriction in THz communication is the high level of transmission loss caused by air absorption and signal scattering [11-12]. Various gas molecules, such as oxygen and water vapor in the atmosphere, can absorb the THz signal, but the presence of randomly positioned and randomly traveling finite and discrete aerosols and dust particles may cause scattering in THz transmission[13-14]. According to Fig. 1, the environment serves as a medium between the THz transmitter and receiver in a specific THz communication system. A number of atmospheric phenomena can interfere with THz wave transmission. As shown in Fig. 2, the current study aims to assess the extent of deterioration of THz signals transiting through a tropical fog-laden atmospheric medium. In general, the single scattering approach is used to determine the attenuation of an electromagnetic wave as it propagates through a random material [15]. Although this procedure is straightforward, the outcomes of these types of calculations can occasionally contain significant inaccuracies. It has been found that electromagnetic signal attenuation can be enumerated using single scattering technique under long visibility. On the other hand, the high density of aerosols in atmosphere lead to very poor visibility condition, in which the phenomenon of multiple scattering of electromagnetic signal becomes significant[16-17]. Fog is a common weather occurrence in which particles, water droplets or ice crystals are suspended in the air near the ground. Based on visibility and droplet size, it is categorized as haze, heavy fog, thick fog, or mist. Fog is divided as advection fog or radiation fog, depending on the origin and the process involved in its generation. Advection fog arises when warm, wet air flows over a cool sea surface. When the earth emits long wave terrestrial radiation, the air in the vicinity of the ground follows an adiabatic cycle, which initiates radiation fog in saturated atmosphere [18-19]. According to the Koppen-Geiger climate classification system[20-21], tropical climate is one of the five major climatic classifications. The tropical environment has an average temperature of roughly 650 degrees Fahrenheit.The climate zone of South-East Asia is primarily tropical [22-23], and in the Indian Subcontinent, radiation fog causes a loss in visibility below 1 km during the winter season. In the northern portion of India, beneath the tropical climatic region, the concentration of fog-based hydrometeors drops at a rate of approximately 1.5x105 particles/litre/hour during the daytime from mid-December to January [24]. This concentration varies more rapidly after sunset. In general, fog formation in the tropical climatic area is accumulation type[24], with aerosol particle diameter playing a significant influence. Furthermore, the chemical makeup of fog changes with geographic remoteness. Based on extensive investigations, the researchers discovered that in most cases, urban fog in the subtropical climatic area is anthropogenic, with hydrophilic ions abundant [25-26]. Because the particle size of fog-based aerosols ranges between 0.15 and 50 microns, the wavelength limit of submillimeter radiation is nearly equivalent to the diameter of tropical hydrometeors. The attenuation of the incoming THz signal owing to fog-particle scattering may be approximated using the Rayleigh or Mie-Scattering principle [15,27]. In tropical climates, fog may spread vertically up to 500 meters above the ground. The presence of liquid water in fog causes a fluctuation in the medium's refractive index, which leads to the absorption of incoming THz signals[28-31]. Discrete temporal variability has been seen in subtropical continental or radiation fog [32-33], resulting in multipath propagation and multiple scattering of the THz-wave. In this study, the authors evaluated the influence of both forward and back-scattered THz signals, and their spatial behavior is used to calculate the overall attenuation effect under multiple scattering.

It is worth noting that the Radiative Transfer (RT) theory for explaining the transition of electromagnetic energy in macroscopic media might be considered a milestone[34-35]. It makes several assumptions to form the foundation of the numerical back-up of the electromagnetic energy-transfer model. However, due to some special classical restrictions, the conventional RT model is unable to link with the Weak-Localization (WL) of coherent backscattering of electromagnetic waves. Furthermore, the radiative transfer equations describe the multiple scattering of classical electromagnetic signals, which are directly derived from Macroscopic Maxwell Theory[36]. As a result, traditional RT theory cannot be easily applied to evaluate the multiple-scattering phenomena of THz signals in a random and discrete medium under tropical climatic conditions. The authors have therefore included the improved radiative transfer equations into the newly constructed NLTAM model, taking into account the discrete microphysical approach, which is supported by vector radiative-transfer theory[36]. This model is unusual in that it includes the backdrop of geophysical separations as well as the influence of these separations on the atmosphere. To begin the temporal fluctuation of aerosol concentration along the course of propagation of the THz-wave in the discrete medium, the scientists used probability statistics to explore the wave-particle interaction more thoroughly. To make the study more realistic, several iterations with discrete-coordinate techniques were used. Although various studies on multiple scattering of sub-millimeter waves in poor weather conditions have been published in non-tropical climatic belts, no similar study has been published in tropical climates.

The presentation of this paper has been arranged as follows:

i. Single-scattering-based THz wave attenuation in tropical aerosols with climate-dependent bounds.
ii. Attenuation of THz waves due to multiple scattering in tropical aerosols under identical boundary conditions.
iii. Compare simulation results for both attenuation spectra.

iv. Validation of the newly designed physics-based non-linear THz attenuation simulator (NLTAM).

For the first time, the authors conducted a complete examination of THz signal attenuation in a tropical fog situation. It has been accomplished through the use of simulation tools, many of which have been created in-house. The authors have also validated this software. The simulation results are intended to assist Indian military personnel in establishing secure communication lines in densely fogged border areas.

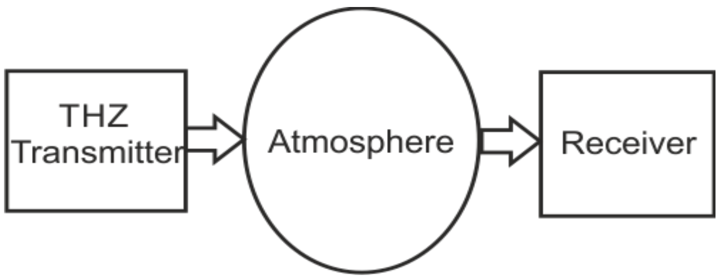

Fig.1. Schematic Block diagram of THz Communication System

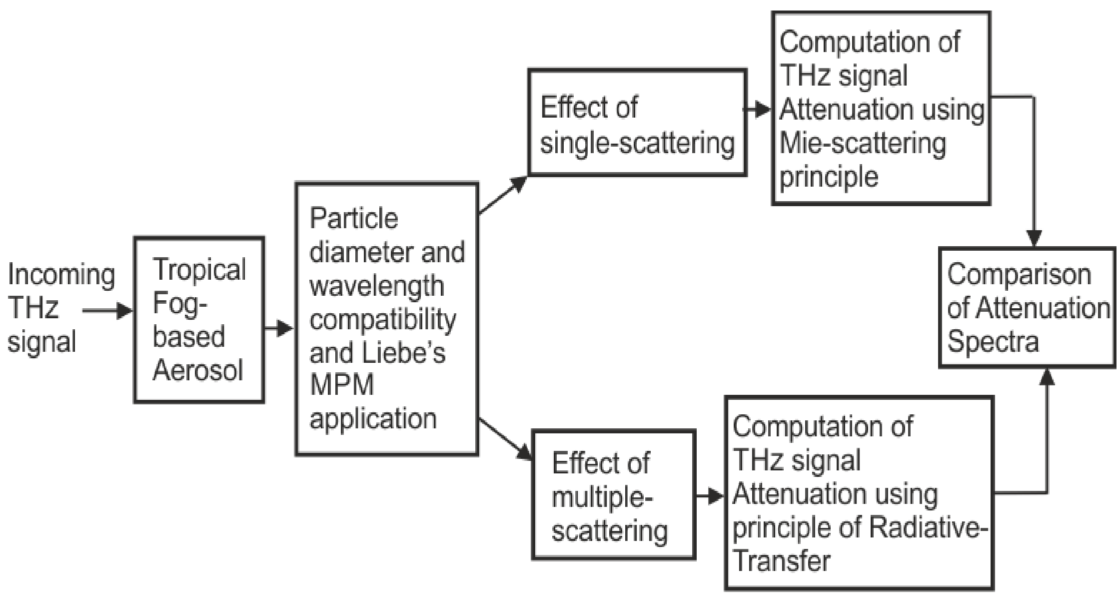

Fig.2. Work-flow diagram.

II. NUMERICAL ILLUSTRATIONS

The Non-Linear Terahertz Attenuation Model (NLTAM) is self-consistent and physics-based. This model is unusual in that it focuses on the influence of turbulent and time-varying atmospheric attitudes on wireless RF signals. As illustrated in Figure 3, distinct atmospheric types create phase and amplitude dislocations of the THz signal as it propagates through the atmospheric channel. The insulating properties of crystalline water molecules affect the refraction, dispersion, and absorption of submillimeter signals in a foggy atmosphere. Furthermore, the concentration of these particles varies with time in the Tropical Climate Area, resulting in either time-dependent partial or total absorption and scattering of the incident THz signal. Therefore, the attenuation of THz-wave in fog-laden atmosphere has a finite time-dependence. In the static medium, the THz Electric-field, subject to propagate a distance d, can be expressed in frequency domainas [15],

$$E(\theta, \varphi, d) = E_0(\theta, \varphi)e^{-j\Upsilon_f d} \quad (1)$$

where, in terms of angles s ϑ and φ, $E_0(\theta, \varphi)$is the maximum-intensity of the incoming E-field. ϒ_fas the frequency-dependent wave-number, can be supported by,

$$k_f = \frac{2\pi f}{c} r_f \quad (2)$$

where, r_f stands for the medium's complex refractive index and the free-space velocity of electromagnetic wave is c. Since, the dielectric properties of the medium define it'scomplex refractive-index, therefore, the generalized expression of the refractive-index can be given as[37-38],

$$r_f = \sqrt{(K_m)} = \sqrt{K_r + jK_i} \quad (3)$$

where, K_m stands for the complex permittivity of the medium through which the signal propagates. $K_r$and$K_i$denotethe real and imaginary parts of the permittivity respectively. On the other hand, the frequency of the incident signal controls the complex permittivity of the medium. The Double-Debye method is primarily utilised to derive this permittivity as[39-40],

$$K\_m = \sum_{t=1}^{2}\left[\frac{a_t}{(f_t^2 - f^2 - j\delta_t f)} - \frac{a_t}{(f_t)^2}\right] \quad (4)$$

where, f_1,f_2, δ_1,δ_2,a_1, $a_2$can be estimated from Liebe's Millimeter-wave Propagation Model (MPM)[39].

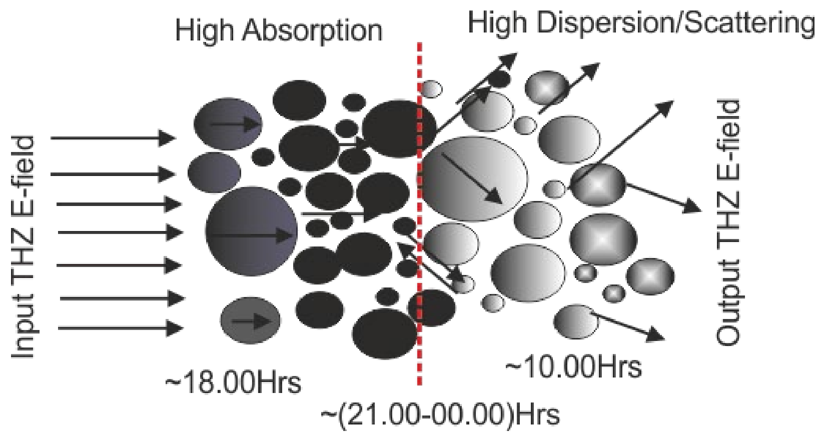

Fig.3. Proposed time-dependent dispersion scenario of THz-signal in Indian fog

A) Single Scattering of Terahertz Wave in Aerosols

Fog, as a specific form of aerosol, is often intensified by the condensation of Liquid Water Content (LWC) in the atmosphere. The relative humidity and density of LWC crystals in tropical climates varies from those in temperate climate zones. According to Liebe's MPM[38-39], the dispersive complex refractivity of the medium through which an electromagnetic signal of the appropriate frequency propagates may be described by the sum of frequency-dependent atmospheric restrictions. The authors of NLTAM considered the frequency-dependent complex refractivity of the dispersive medium as R(f), where,

$$R(f) = R_R + R_C + R_D + R_W + R_L \quad (5)$$

where,R_R represents the contribution of rain to refractivity, R_C initiates the continuum spectrum of water vapour, R_D stands for the non-resonant spectrum of dry air, R_W specifies the refractivity of suspended water droplets and R_L represents the contribution of moist air resonance.

Eq.(1) provides the solution to Macroscopic Maxwell's Equation in E-field, with the medium assumed to be homogeneous and isotropic. In general, the existence of an impediment along an electromagnetic signal's route causes the signal to disperse. To reduce the complexity of analysis resulting from the breakdown of the E-field into numerous back-waves owing to the scattering process, the concept of Single-Scattering is commonly used[41-43]. In NLTAM, the authors have started the simulation of the single scattering mechanism in the presence of fog-based particles, by treating the full E-field vector as,

$$\vec{E}(d, t) = \vec{E}_{inc}(d, t) + \vec{E}_{sca}(d, t) \quad (6)$$

where, $\vec{E}_{inc}(d, t)$ and $\vec{E}_{sca}(d, t)$stand for the incident and scattered components of E-field

vector, respectively.

Under single-scattering approach, it has been considered that size of water droplets, present to form radiation fog is regular(mainly spherical), so that the Mie-scattering theory can be easily incorporated[41-43]. The distribution of fog-particles for a particular dropletsize of radius, s, is considered to follow the Modified-Gamma Law[41-45]as

$$n(s) = as^{p}e^{-bs^{q}} \tag{7}$$

where, a, b, $p$and q are the parameters that mainly depend on the type of fog(advection or radiation).In tropical-climate, the mean radii of fog-based LWC crystals are centred around (10-20) micron. Beer-Lambert Lawcan be utilized to derive the relative spatial degradation of incident E-fieldin fog-ladenatmosphere. It is generally expressed as[40-44],

$$E(d) = E_0 e^{-\eta_{ext} dW} \tag{8}$$

where, the difference between incident and scattered Electric-fields is introduced by $E(d)$. The primary field-intensity is generally indexed by E_0, η_{ext}stands for the coefficient of mass extinction, which is measured in m^2/g and the concentration of LWC, is generally measured in g/m^3. The mass-extinction coefficient, which is a combination of scattering and absorption coefficients, plays a vital role in the measurement of single-scatter in attenuation of THz signal from fog-particles. The mass-extinction coefficient, under the utilization of extinctionefficiency μ_{ext} , has been simulated as[41-42],

$$\eta_{ext} = \frac{\int s^2(\mu_{ext}+\mu_{scint})n(s)ds}{\frac{4\tau}{3}\int s^3 n(s)ds} \tag{9}$$

The scintillation efficiency μ_{scint}has beenconsidered in Eq.(9) to incorporate the effect of air turbulence and humidity fluctuations[45-46]. The factor τ signifies the aerosol concentration in absorbing medium. Such beam variations, known as scintillations, reduce beam power and decrease connection performance. The terminal velocity of the aerosols in tropical climatic region, has been considered in the approximate range of 1.0m/s to 6.0 m/s depending on water concentration of the aerosols. To simulate the single-scattering attenuation-loss of THz signal in foggy-atmosphere, the authors have incorporated the expressions of scattering and absorption efficiencies as[41-44],

$$\mu_{sca} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)(|\alpha_n|^2 + |\beta_n|^2) \tag{10}$$

And $$\mu_{ext} = \frac{2}{x^2}\sum_{n=1}^{\infty}(2n+1)Re(|\alpha_n| + |\beta_n|) \tag{11}$$

Here, size-parameter is indicated by $x$and using standard expressions of Mieabcdparameters[41-42], α_n,$\beta_n$have been derived. In this simulator(NLTAM),the fog-based single-scattering attenuation of THz signal in fog, has been carried out by using the expression,

$$\text{Atn.(in dB/km)} = Z\int_0^{\infty} \mu_{sca} n(s)ds \qquad (12)$$

where, Z is about 5x10[3].

B) Single Multiple Scattering of terahertz wave in Aerosols

The size of aerosols seen in tropical fog is fairly consistent with the wavelength of terahertz radiation. As the most prevalent and practical scattering phenomena, multiple scattering must be studied. The difference between single and multiple scattering is shown in Fig 4. The impact of single-scattering by fogparticles is a virtually perfect scattering incidence, however the effect of multiple scattering is rather typical. In their novel NLTAM simulator, the scientists used modified Radiative-Transfer theory[36] and statistical analysis to investigate the consecutive backscattering of an incoming THz wave in random medium. The model analysis has been initiated by employing the FOLDY-LAX Equations in Eq.(6) to navigate the effect of local-excitations[35-36]within a certain volume in discrete medium. The Eq.(6) is re expressed as,

$$\vec{E}(\vec{r}) = \vec{E}_{inc}(\vec{r}) + \sum_{i}^{N=1} \vec{E}_{i}^{sca}(r) \qquad (13)$$

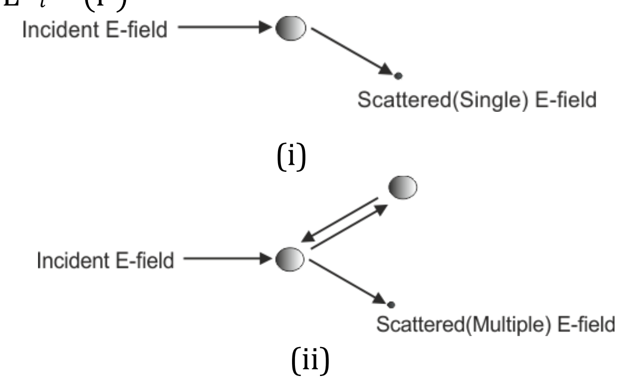

Fig.4. Different Scattering Mechanisms of THz wave in fog-based aerosols (i) Single (ii) Multiple.

The summation term, in Eq.(13), signifies all the water-droplets present in a finite group of aerosols. For numerical-computation with successive iterations, the authors have incorporated the operator-form of Eq.(13) , which is given as,

$$\vec{E} = \vec{E}_{inc} + \sum_{i=1}^{N} GT_i\vec{E}_i \qquad (14)$$

And $$\vec{E}_i = \vec{E}_{inc} + \sum_{j(\neq i)=1}^{N} GT_j\vec{E}_j \qquad (15)$$

In both of Eq.(14) and Eq.(15) $\mathcal{G}$ is Dyadic-Green operator, which has been incorporated in the simulation in order to specify the partial-scattering effect in between two distinct space vectors, r and r $_j$ of two different particles(here, aerosols)[47]. $\mathcal{T}_j$is the Lippmann-Schwinger operator. The tailor part of Eq.(15) can be re-expressed as,

$$\mathcal{G}\mathcal{T}_j\vec{E}_j = \int_{V} d\vec{r_1}\overleftrightarrow{G}(\vec{r},\vec{r_1}).\int_{Vj} d\vec{r_2}\overleftrightarrow{T_j}(\vec{r_1},\vec{r_2})\,\vec{E_j}(\vec{r_2}) \quad (16)$$

Utilising the above equations, the order of entire E-field with its expansion can be iterated as,

$$\vec{E}(\vec{r},t) = \vec{E}_{inc}(\vec{r},t) + \sum_{j(\neq i)=1}^{N} \mathcal{G}\mathcal{T}_j\vec{E}_{inc} + \sum_{\substack{j(\neq i)=1\\ l(\neq i)=1}}^{N} \mathcal{G}\mathcal{T}_j\mathcal{G}\mathcal{T}_l\vec{E}_{inc} + \sum_{\substack{j(\neq i)=1\\ l(\neq i)=1\\ m(\neq l)=1}}^{N} \mathcal{G}\mathcal{T}_j\mathcal{G}\mathcal{T}_l\mathcal{G}\mathcal{T}_m\vec{E}_{inc} + \cdots \quad (17)$$

The computation of the E-field under multiple-scattering effect, based on Eq.(17), has been carried out for a finite interval of iteration.

Authors have further incorporated the Henyey-Greenstein(HG) scattering phasefunction to determine the new direction cosine[48] of THz-photons after collision with LWC crystals present in the random-medium. As per HG-scattering phase function, the discrete scattering angle θ can be estimated as,

$$\theta = \cos^{-1}\left\{\frac{1}{2\bar{g}}\left[(1+\bar{g})^2 - \left(\frac{(1-\bar{g}^2)}{(1-\bar{g}+2\bar{g}S_t)}\right)^2\right]\right\} \quad (18)$$

Where,S_t is the mean radius of t-th scatterer. $\bar{g}$ is the mean-asymmetric factor, expressed as

$$\bar{g} = \frac{\int_0^\infty \pi s^2 Q_{sca}(s)n(s)g(s)\,ds}{\int_0^\infty \pi s^2 Q_{sca}(s)n(s)\,ds} \quad (19)$$

The symbols in Eq.(19) carry their usual significance. Using Eq.(18), the scattered E-field with varying direction-cosine can be established as

$$\vec{E}_i = \left|\vec{E}_0\right| \sum_{n=1}^{\infty} i^n \left\{\frac{2n+1}{n(n+1)}\right\} \left(\vec{M}_{oln}^{(1)} - i\vec{N}_{eln}^{(1)}\right) \quad (20)$$

The single-order vector wave-functions $\vec{M}_{oln}^{(1)}$ and $\vec{N}_{eln}^{(1)}$ can be expressed as

$$\vec{M}_{oln}^{(1)} = \begin{bmatrix} 0 \\ \cos\varphi.\,\pi_n(\cos\theta).\,j_n(srx) \\ -\sin\varphi.\,\tau_n(\cos\theta).\,j_n(srx) \end{bmatrix} \quad (21)$$

and

$$\vec{N}_{eln}^{(1)} = \begin{bmatrix} n(n+1).\,\cos\varphi.\,\sin\theta.\,\pi_n(\cos\theta).\,\frac{j_n(srx)}{srx} \\ \cos\varphi.\,\tau_n(\cos\theta).\,\frac{[(srx)j_n(srx)]'}{srx} \\ -\sin\varphi.\,\pi_n(\cos\theta).\,\frac{[(srx)j_n(srx)]'}{srx} \end{bmatrix} \quad (22)$$

The identities $\pi_n(\cos\theta)$ and $\tau_n(\cos\theta)$ are expressed as

$$\pi_n(\cos\theta) = \left(\frac{2n-1}{n-1}\right)\cos\theta.\,\pi_{n-1} - \left(\frac{n}{n-1}\right).\,\pi_{n-2} \quad (23)$$

And $$\tau_n(\cos\theta) = (n\cos\theta).\,\pi_n - (n+1).\,\pi_{n-1} \quad (24)$$

The angular Mie-Scattering cross-section for a particular phase-angle has been simulated by Eq.(17) and Eq.(20) to determine the attenuation level of THz signal under multiplescattering. To make the analysis of multiple-scattering more realistic, the authors have incorporated the space and time dependent aerosol distribution statistics in tropical climate area by considering the following equation

$$\frac{1}{u}\nabla_t\xi(\vec{r},t,\theta) + \hat{\Theta}\xi(\vec{r},t,\theta) + (\psi_{abs}+\psi_{sca})\xi(\vec{r},t,\theta) = \zeta_T N(\vec{r},t) + \psi_{sca}\int \xi(\vec{r},t,\theta)d\theta \quad (25)$$

- u is the velocity of THz-wave in space
- $\xi(\vec{r},t,\theta)$ is the flux-density of THz Electric field
- $\hat{\Theta}$ is the angular-scattering operator
- ψ_{abs} and ψ_{sca} are the space and time dependent fog-based absorption and scattering coefficients
- ζ_T stands for the transmission coefficient of THz signal through aerosol and $N(\vec{r},t)$ represents the space and time-dependent fog-density, especially in tropical-climatic belt

The entire space and time dependent electric field under multiple scattering of a THz signal in a fog-laden environment is enumerated by solving Eq.(25) with appropriate weather-dependent boundary conditions. The THz-attenuation rate under multiple-scattering is calculated by taking into account successive fogparticle collisions, with the mean free-path between two successive collisions assumed to have a finite probability distribution[48], allowing for THz-photon capture within a certain limit. If the rate of capture is taken as U(no. of THz photons/degree), then the overall attenuation (dB/km) may be represented as

$$\text{Attenuation(dB/km)} = \ln \frac{U}{Q_{ext}} \; {}^{-5^{\sigma}} \; {}^{2} \qquad (26)$$

Here, σ is the fitting-parameter which is < 2.

The Transmission Attenuation Rate per unit distance of THz transmission can be found out by taking the logarithm of Eq. (26). The workflow of NLTAM attenuation simulator of THz signal in tropical atmosphere has been presented in Fig. 5. It is evident from this algorithm that the THz attenuation spectra in continental fog, can be established by means of a comparative study, in which the single and multiple scattering mechanisms are jointly working. Based on the variation of THz wavelength in between 3mm to 30μm, the model initiates the simulation of attenuation employing Mie-scattering mechanism. In this case, the effect of back-scattering is ignored. The weather dependent size of absorbing hydrometeors are considered to be regular and necessary weather dependent boundary conditions including Liebe's MPM are applied to generate the continental fog based attenuation spectra of THz wave due to single-scattering. The data for every computational steps are recorded by the simulator. At the verge of the computation for simulation of single-scattering based complete attenuation spectra of THz signal (0.1THz to 10THz), the simulator jumps to the initial level once again and considers the effect of back-scattering. The Foldy-Lax Equations are incorporated with another set of boundaries. The effect of random media is improvised by tuning the mean-asymmetric factor values. The similar iteration process like the singlescattering mechanism for the entire THz frequency range, is followed in this case too and all the computational data are recorded. In the final step, the simulator displays the comparative outcomes of attenuation spectra of THz wave for both types of scattering effects out of tropical fog.

C) Single Scattering of Terahertz Wave in Aerosols

As discussed previously, the spherical droplet size of aerosols has been primarily considered by the authors to simulate single-scattering attenuation spectrum of THz signal from the continental fog-particles. Mie-Scattering theory in association with modified MPM, under appropriate weather dependent-boundary conditions have been applied in this simulator to yield the result, which has been shown in Fig. 6. This diagram-reveals that, in tropical climate condition, the peak-level of THz attenuation spectrum due to the presence of fog-particles, reaches approximately 1.5×10^6 dB/km within 2THz-4THz.Using the effect of

Mie-Scattering[20], the nature of this variation of attenuation, may be explained. It is also evident that, within the frequency range of 5THz to 10THz, the magnitude of THz-signal attenuation remains almost invariant at the level of~10.0x105 dB/km. The gradual decrease in the rate of attenuation is followed thereby.

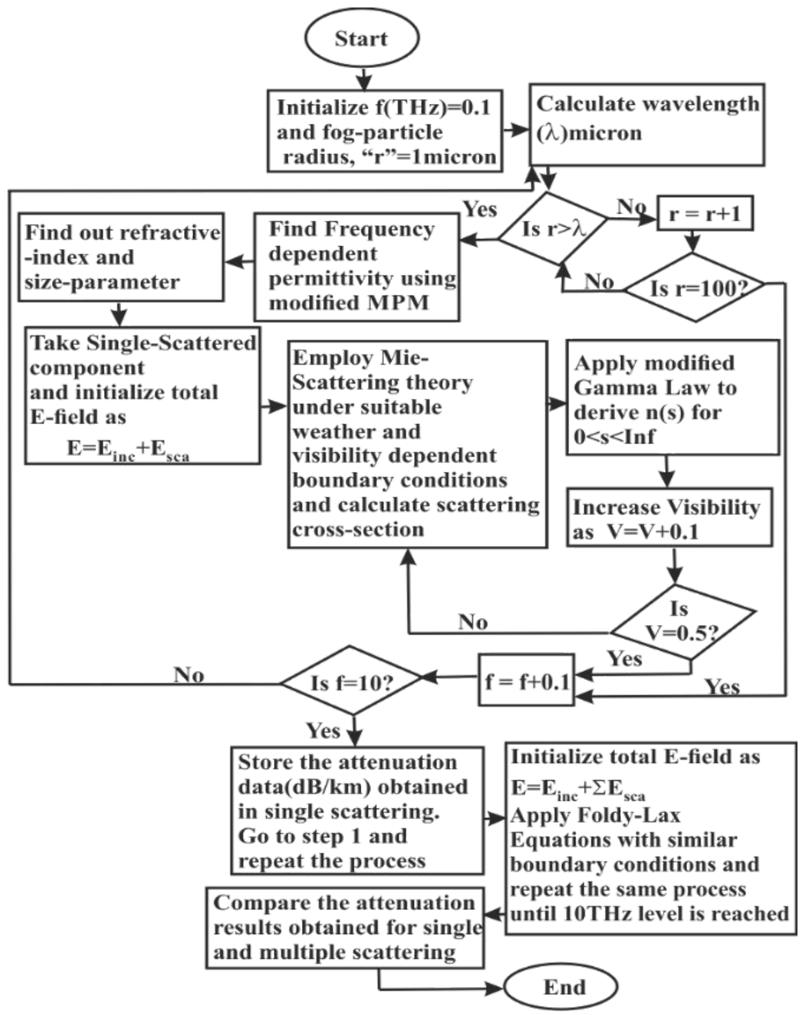

Fig.5.Algorithm to Simulate THz Signal Attenuation Spectra due to Tropical Aerosol Based Different Scattering Mechanisms (using NLTAM Simulator).

D) Attention Spectrum due to multiple Scattering of Terahertz Wave in Aerosols

The authors used the indigenously created physics-based non-linear NLTAM simulator to simulate multiple-scattering of THz waves in tropical foggy atmospheres, taking into account the influence of random medium. The sequential back-scattering process of the incoming THz signal in the fog-laden environment is described using modified Radiative-Theory, which includes Foldy-Lax equations. The irregularity in the scatterer-size has been given the highest priority. The authors have considered the effect of variable scattering angles in the simulation and the obtained attenuation spectrum is shown Fig.7 for two different mean-asymmetric factors ($\bar{g}$). As per this diagram it is clear that, the sharpness of multiple-scattering spectrum increases with $\bar{g}$, which can be explained in terms of the absolute dependence of scattering-angle on the asymmetric-factor, as described earlier. Figure 8 shows a comparative examination of THz-signal attenuation spectra resulting from single and multiple scattering effects caused by tropical fog particles. According to this graphic, the larger rate of reduction in THz-signal attenuation in multiple-scattering compared to single-scattering effect in tropical fog scenario illustrates the importance of back-scattering of THz wave in atmosphere. Figure 10 depicts the impact of Transmission Attenuation rate per unit distance of THz-signal due to multiple-scattering effect under a 500m visibility limitation. This graphic shows that after 3THz, the peak attenuation level of the THz signal in a fog-laden wireless medium declines. The nature of this fluctuation, as well as the modeling results, are quite similar to the actual data [47].

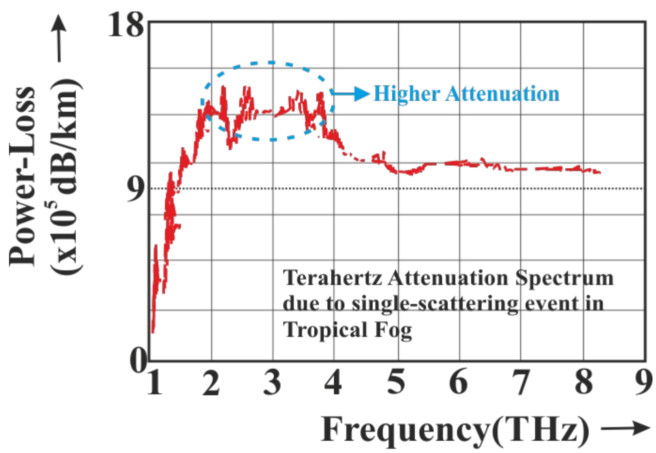

Fig.6. THz Signal Attenuation Spectrum (NLTAM simulated) caused by single-scattering from fog-based hydrometeors in tropical climatic conditions.

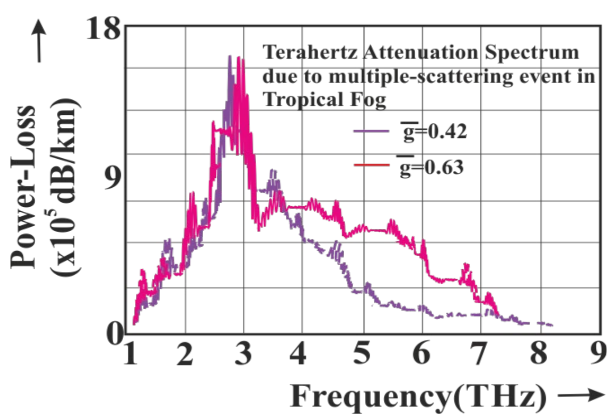

Fig.7. THz signal Attenuation Spectra (NLTAM simulated) because of multiple-scattering from fog-based hydrometeors in tropical climate condition. two one of a kind uneven factors were taken into consideration.

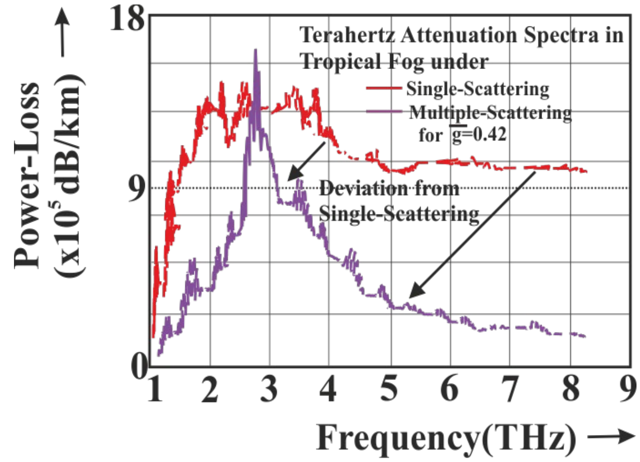

Fig.8. Evaluation of single and more than one-scattering attenuation spectra of THz sign in tropical weather , obtained from NLTAM simulator.

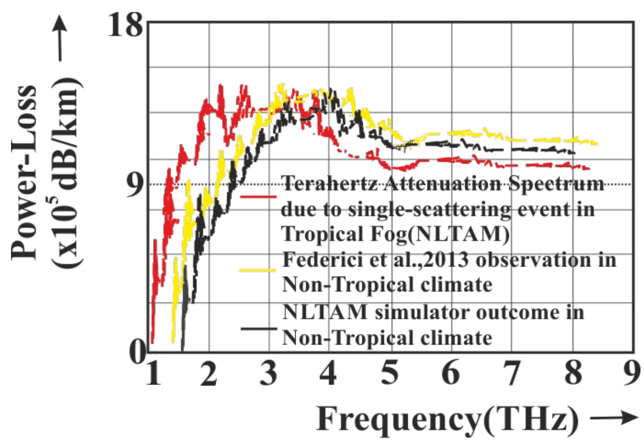

Fig.9. Comparative evaluation of experimental remark[20] of THz sign Attenuation and NLTAM simulated outcomes in tropical and non-tropical weather zones. The experimentally acquired non-tropical attenuation spectrum of THz signal because of single-scattering from fog-based totally aerosols, has been as compared with NLTAM simulated spectrum of the same in nontropical weather to validate the version.

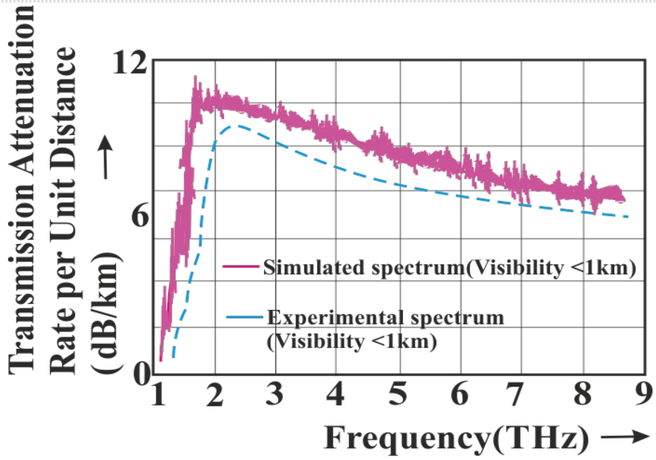

Fig. 10. Frequency changes how much sound gets weaker as it travels over short distances. The THz regime operates within an Indian fog scenario where visibility does not exceed 1 kilometre. The experimental observation [47], made under conditions where dust particles were present, was confirmed as well.

III. VALIDITY OF THE SIMULATOR

The researchers included several atmospheric factors into their NLTAM model for non-tropical weather conditions. Federici et al. 's experimental results were tested. The main evaluation of the model was done. The core analysis of the model was conducted. The fundamental assessment of the model was performed. The principal examination of the model took place. The initial investigation into the model was made. The basic test of the model was executed. The foundational study of the model was completed. The essential review of the model was undertaken. The primary scrutiny of the model was carried out. The central evaluation of the model was accomplished. The major examination of the model was achieved. The significant assessment of the model was attained. The substantial evaluation of the model was realized. The considerable examination of the model was reached. The notable review of the model was accomplished. [20] The important analysis of. The results show that the simulated effects at the highest point and in terms of THz absorption under foggy air conditions closely correspond to the actual measurements taken during experiments. This is illustrated by Fig. 9. The authors attempted to create a model that works well in tropical climates after validating it against non-tropical areas. Tropical atmospheric conditions were adjusted to create the model. The experts have never conducted any experiments up until now in the Indian subcontinent. To measure how much THz signals get weaker in India's area, this study uses computer simulations to create a model that shows how these signals lose strength when they pass through things. In the near future, an actual test will take place in India, serving as the basis for writing another research paper. Besides, see Fig. 10 The authors used the NLTAM simulator to show how the transmission attenuation rate changes with distance at terahertz frequencies in a foggy, tropical area with poor visibility, finding good agreement with experiments done during dust storms under similar conditions. In this manner, the model's validity is verified.

IV. CONCLUSION

The author now comprehensively examines how THz attenuation changes when scattered by various types of suspended water droplets in the tropical atmosphere for the very first time. The presence of fog in the air affects how well THz signals travel through it, depending on various conditions such as temperature and humidity levels, which can vary based on the amount of water vapor present. The Mie-Scattering theory allows calculating how an electromagnetic signal gets weakened by passing through tiny particles in the air, which is the basic way these particles scatter light. In most significant studies concerning the spread of electromagnetism. The signal travels through challenging conditions, highlighting the importance of the single scattering process. The authors revealed for the very first time how particles in fog affect how THz signals travel across India's region. Indigenous-developed and experimentally validated NLTAM simulators have been created. In an Indian tropical climate setting, when there's a single scattering of THz signals by atmospheric fog particles, their intensity decreases compared to multiple scattering events. The 2THz to 4THz frequency range has the greatest attenuation effect for both types of scattering phenomena. But the sharpness of the THz-signal's fall-rate in multiple-scattering is greater than that in single scattering. Besides, it has been demonstrated that adjusting the average asymmetry factor allows for achieving the peak level of THz attenuation spectrum. The statistical data about fog particles significantly influences the gradient observed in THz attenuation spectra when subjected to multiple scattering.

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REFERENCE

1. T. Nagatsuma, "Exploring sub-terahertz waves for future wireless communications", IEEE 31th Intl. Conf. on IRMMW and 14th Intl. Conf. on Terahertz Electronics, China, Vol.4, 2006.
2. E. Cianca, T. Rossi, A. Yahalom, Y. Pinhasi, J. Farserotu, C. Sacchi, "EHF for Satellite Communications: The New Broadband Frontier", Proc. of IEEE, Vol. 99, No. 11, pp. 18581881, 2011. 10.1109/JPROC.2011.2158765
3. W. Feng, Y. Li, D. Jin, L. Su, S. Chen, "Millimetre-Wave Backhaul for 5G Networks: Challenges and Solutions", Sensors, Vol. 16, No. 6, 2016. https://doi.org/10.3390/s16060892

4. T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, F. Gutierrez, "Millimeter Wave Mobile Communications for 5G Cellular: It Will Work!", IEEE Access, Vol. 1, pp. 335-349, 2013. 10.1109/ACCESS.2013.2260813
5. R. Piesiewicz, C. Jansen, D. M. Mittleman, T. Kleine-Ostmann, "Scattering Analysis for the Modeling of THz Communication Systems", IEEE Transactions on Antennas and Propagation, Vol. 55, No. 11, pp. 3002-3009, 2007. 10.1109/TAP.2007.908559
6. C. Jo rdens, M. Scheller, S. Wietzke, D. Romeike, C. Jansen,T. Zentgraf, K. Wiesauer, V. Reisecker, M. Koch, "Terahertz spectroscopy to study the orientation of glass fibres in reinforced plastics", Compos. Sci. Technol, Vol. 70, No. 3, pp. 472-477, 2010.
7. T. Wang, N. Zheng, J. Xin, Z. Ma, "Integrating Millimeter Wave Radar with a Monocular Vision Sensor for On-Road Obstacle Detection Applications", Sensors, Vol. 11, No. 9, pp. 8992-9008, 2011. https://doi.org/10.3390/s110908992
8. E. Hyun, Y.S. Jin, J.H. Lee,"A Pedestrian Detection Scheme Using a Coherent Phase Difference Method Based on 2D Range-Doppler FMCW Radar", Sensors, Vol. 16, No.1, 2016. https://doi.org/10.3390/s16010124
9. A.T. Pham, P.V. Trinh, V. V. Mai, N. T. Dang, C. T. Truong, " Hybrid free-space optics/millimeter-wave architecture for 5G cellular backhaul networks", IEEE Xplore, 2015. 10.1109/OECC.2015.7340269
10. T. Kamalakis, I. Neokosmidis,A.Tsipouras, T. Sphicopoulos,S.Pantazis, I. Andrikopoulos, "Hybrid Free Space Optical / Millimeter Wave Outdoor Links for Broadband Wireless Access Networks", IEEE Xplore, 2007. 10.1109/PIMRC.2007.4393998
11. J. Ma, L. Moeller, J. F. Federici, "Experimental Comparison of Terahertz and Infrared Signaling in Controlled Atmospheric Turbulence", Journal of Infrared Millimeter and Terahertz Waves, Vol.36, pp.130-143, 2015. https://doi.org/10.1007/s10762-014-0121-9
12. J. Ma, R. Shrestha, L. Moeller, D. M. Mittleman, "Invited Article: Channel performance for indoor and outdoor terahertz wireless links", APL Photonics, Vol. 3, Issue 051601, 2018. https://doi.org/10.1063/1.5014037
13. Y. Yang, M. Mandehgar, D. Grischkowsky, "Broadband THz signals propagate through dense fog", IEEE Photonics Technology Letters, Vol. 27, No. 4, pp. 383-386, 2015. 10.1109/LPT.2014.2375795
14. E. B.Moon, T. I. Jeon, D. R.Grischkowsky, "Long-Path THz-TDS Atmospheric Measurements Between Buildings", IEEE TRANSACTIONS ON TERAHERTZ SCIENCE AND TECHNOLOGY, Vol. 5, No. 5, pp. 742-750, 2015. 10.1109/TTHZ.2015.2443491
15. Y. Golovachev, A. Etinger, G. A. Pinhasi, Y.Pinhasi,"Propagation properties of sub-millimeter waves in foggy conditions", Journal of Applied Physics, Vol. 125, Issue 151612, 2019. https://doi.org/10.1063/1.5083711

16. R. Penndorf,"Angular Mie Scattering", Journal of the Optical Society of America, Vol. 52, No. 4, 1962.
17. B.Maronga, F.C. Bosveld, "Key parameters for the life cycle of nocturnal radiation fog: a comprehensive large-eddy simulation study", Quarterly Journal of the Royal Meteorological Society, 2017.https://doi.org/10.1002/qj.3100.
18. L.Yang, J. Wu Liu, Z. P. Ren,S.P.Xie, S. P. Zhang, S. H. Gao, "Atmospheric Conditions for Advection-Radiation FogOver the Western Yellow Sea", Journal of Geophysical Research: Atmospheres, 2018. 10.1029/2017JD028088
19. R. B. Myneni, C. D. Keeling, C. J. Tucker,G.Asrar, R. R.Nemani, "Increased plant growth in the northern high latitudes from 1981 to 1991", Nature, Vol. 386, pp. 698–702, 1997.
20. J. Federici, L. Moeller, K. Su, "Terahertz wireless communications", Elsevier, pp.156-214, 2013. https://doi.org/10.1533/9780857096494.1.156.
21. S. G. Shiyatov, "Rates of change in the upper treeline ecotone in the polar Ural mountains", Past Global Changes (PAGES), News 11(1), 2003.
22. G. K. SAWAISARJE, P. KHARE, C. Y. SHIRKE, S. DEEPAKUMAR, N. M. NARKHEDE, "Study of winter fog over Indian subcontinent : Climatological perspectives", MAUSAM, Vol. 65, No. 1, pp.19-28, 2014.
23. M. Mohan, S. Payra, "Aerosol Number Concentrations and Visibility duringDense Fog over a Subtropical Urban Site", Journal of Nanomaterials, 2014.http://dx.doi.org/10.1155/2014/495457
24. M. Mohan, S. Bhati, A. Rao, "Application of air dispersion modelling for exposure assessment from particulate matter pollution in mega city Delhi," Asia-Pacific Journal of Chemical Engineering, Vol. 6, No. 1, pp. 85–94, 2011.
25. K. Ali, G. A.Momin, S. Tiwari, P. D. Safai, D. M. Chate,P.S.P.Rao, "Fog and precipitation chemistry at Delhi, North India", Atmospheric Environment, Vol. 38, No. 25, pp. 4215-4222, 2004.
26. P. K. Pasricha, B. S. Gera, S. Shastri, H. K. Maini, "Role of the Water Vapour Greenhouse Effect in the Forecasting Of Fog Occurrence", Boundary-Layer Meteorology, Vol. 107, No. 2, pp. 469-482. 10.1023/A:1022128800130
27. Y.Golovachev,A.Etinger, G. A. Pinhasi, Y. Pinhasi, "Millimeter Wave High Resolution Radar Accuracy in Fog Conditions—Theory and Experimental Verification", Sensors, Vol. 18, No. 7, 2018.https://doi.org/10.3390/s18072148
28. C. F. Bohren, D. R. Huffman, "Absorption and Scattering of Light by Small Particles", Wiley, New York, 1998.
29. N. Balal, G. A. Pinhasi, Y. Pinhasi, "Atmospheric and Fog Effects on Ultra-Wide Band Radar Operating at Extremely High Frequencies", Sensors, Vol. 16, No. 5, 2016. https://doi.org/10.3390/s16050751
30. K. Y.Heo, S. Park, K. J. Ha,"Algorithm for sea fog monitoring with the use of information technologies", Royal Meteorological Society, 2012. https://doi.org/10.1002/met.1344

31. T. Kleine-Ostmann, T. Nagatsuma, "A Review on Terahertz Communications Research", Journal of Infrared Millimeter and Terahertz Waves, Vol.32, pp. 143-171, 2011.https://doi.org/10.1007/s10762-010-9758-1
32. S. Tiwari, S. Payra,M. Mohan, S. Verma, D. S. Bisht, "Visibilitydegradation during foggy period due to anthropogenicurban aerosol at Delhi, India", Atmospheric Pollution Research, Vol. 2, No. 1, pp. 116-120, 2011.
33. T. M. Peters, D. Ott, P. T. O'Shaughnessy, "Comparison ofthe Grimm 1.108 and 1.109 portable aerosol spectrometer to theTSI 3321 aerodynamic particle sizer for dry particles", Annals ofOccupational Hygiene, Vol. 50, No. 8, pp. 843-850, 2006.
34. P. T. Dat, A. Bekkali, K. Kazaura, K. Wakamori, M. Matsumoto, "Auniversal platform for ubiquitous wireless communications using radioover FSO system", Journal of Lightwave Technology, Vol. 28, No. 16, pp. 2258-2267, 2010.
35. D. Chakraborty, M. Mukherjee, "Self-consistent non-linear physics based predictive model for the computation of THz-signal attenuation in fog with varying visibility in tropical climatic zone", Microsystem Technologies, 2022.https://doi.org/10.1007/s00542-02205259-y.012345678
36. M. I. Mischenko, "MULTIPLE SCATTERING, RADIATIVE TRANSFER, AND WEAK LOCALIZATION IN DISCRETE RANDOM MEDIA: UNIFIED MICROPHYSICAL APPROACH", American Geophysical Union 46, 2008.
37. J. Federici, L. Moeller, "Review of terahertz and subterahertz wireless communications", Journal of Applied Physics, Vol. 107, 2010. https://doi.org/10.1063/1.3386413
38. T.Ku rner, M. Jacob, R. Piesiewicz,J.Scho bel, "An integrated simulation environment for the investigation of future indoor THz communication systems", Simulation, Vol. 84, pp. 123130, 2008.
39. H. J. Liebe, "Atmospheric EHF window transparencies near 35, 90, 140 and 220 GHz",IEEEXplore, Vol. 31, No. 1, pp. 127-135, 1983. 10.1109/TAP.1983.1143013
40. H. J. Liebe, G. A.Hufford, T. Manabe, "A MODEL FOR THE COMPLEX
41. PERMITTIVITY OF WATER AT FREQUENCIES BELOW 1 THz", International Journal of Infrared and MillimeterWaves, Vol. 12, No. 7, pp. 659-675, 1991. https://doi.org/10.1007/BF01008897
42. Q. Zhang, H. Wang, J. Ma, "On The Extinction Characteristics of Terahertz Wave in Fog", Joint International Mechanical, Electronic and Information Technology Conference (JIMET 2015), 2015.
43. M. Al Naboulsi, H. Sizun, F. de Fornel, "Fog attenuation prediction for optical and infrared waves", Optical Engineering, Vol. 43, No. 2, pp. 319-329, 2004.10.1117/1.1637611
44. X. Yu,S.Jia, H. Hu, M. Galili, T. Morioka, P. U. Jepsen, K. L. Oxenløwe, "160 Gbit/s photonics wireless transmission in the 300-500 GHz band", APL PHOTONICS, 2016. 10.1063/1.4960136

45. P. Duthon, M. Colomb, F. Bernardin, “Fog Classification by Their Droplet Size Distributions: Application to the Characterization of Cerema’s Platform”, Atmosphere, Vol. 11, No. 6, 2020. https://doi.org/10.3390/atmos11060596
46. K. Su, L. Moeller, R. B. Barat, J. F.Federici, “Experimental comparison of performance degradation from terahertz and infrared wireless links in fog”, Journal of the Optical Society of America A, Vol. 29, No. 2, pp. 179-184, 2012. https://doi.org/10.1364/JOSAA.29.000179
47. Y. Amarsinghe, W. Zhang, R. Zhang, D. M. Mittleman, J. Ma, “Scattering of Terahertz Waves by Snow. Journal of Infrared, Millimeter, and Terahertz Waves”, Vol. 41, pp. 215-224, 2020.https://doi.org/10.1007/s10762-019-00647-4
48. W. Hongxia, S. Honghui, Z. Xuanke, S. Xiaofang, W. Lianfen, Z. Yunfang, “Simulation of Multiple Scattering of THz Wave Propagation in Sandstorm”, Journal of Physics: Conference Series, Vol. 1437,2020. 10.1088/1742-6596/1437/1/012033
49. J. W. Hovenier, C. van der Mee, H. Domke, “Transfer of Polarized Light in Planetary Atmospheres”, Basic Concepts and Practical Methods, Springer Berlin, 2004.