Journal of Computer Applications Technologies, Volume 1 (Issue 1: January - April, 2025): Pages 38-56
Published on: May 10, 2025

Journal of Computer Applications Technologies
ISSN: XXXX-XXXX (Online)
Vol: 01 **Issue:** 01
Contents available at: https://www.swamivivekanandauniversity.ac.in/jaca/

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 non-tropical 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

I. INTRODUCTION

The terahertz (100GHz-10000GHz) spectrum, located in between conventional electronics and photonics band of EM-spectrum has captured a wide area of modern research [1-4] especially in the field of wireless communication, owing to its versatile applicability. The bandwidth offered by terahertz technology is quite large and the channel capacity is also very high [5-6]. Terahertz (THz) waves can show a very high sensitivity to bad weather conditions, when subject to pass through near-surface atmosphere[7-8]. In clear weather, sometimes the channel availability as well as link performance of THz communication may be hampered due to the presence of at-mospheric gases and air- turbulence of aerosols[9-10].The prime

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constraint in THz communication is the high amount of propagation loss, that occurs due to atmos-pheric absorption and signal scattering[11-12]. Various gas molecules, like Oxygen, Water-vapor in atmosphere, can absorb the THz signal, while the existence of randomly positioned as well as randomly traversing finite and discrete aerosols and dust particles may lead to scattering effect in THz transmission[13-14]. As per Fig.1,the atmosphere, works as the medium between THz-Transmitter and Receiver in a particular THz communication system. The communication of THz wave through atmosphere can be disturbed by several atmospheric effects. As evident from Fig.2, the present work is aimed to characterize the level of degradation of THz signal, passing through Tropical fog-laden atmospheric medium. In general, the attenuation of electromagnetic wave, subject to propagate through a random medium is frequently calculated using the single scattering method[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].As per Köppen–Geiger climate classification system[20-21], the tropical climate is considered to be one of the most important among the five climate classes. The mean temperature level of tropical climate lies around 650F.The climatic belt of South-East Asia is largely tropical [22-23], and in the Indian Subcontinent, the effect of radiation fog is manifested by a reduction in visibility below 1km during winter season. In Northern part of India, under tropical climatic belt, the concentration of fog-based hydrometeors decreases at a rate of around 1.5x105 particles/litre/hour during day-time of Mid-December to January [24]. The rate of variation of this concentration increases after sunset. In general, the mode of fog-generation in tropical climatic belt is accumulation type[24] in which the particle diameter of aerosols plays a very important role. Besides, the chemical composition of fog also varies with geographical isolations. Based on rigorous studies, the researchers have found that in most of the cases, the urban-fog under sub-tropical climatic belt, is anthropogenic, where the hydrophilic ions are prevalent [25-26]. Since the particle size of fog-based aerosols lie in the approximate range of 0.15micron to 50micron, the wavelength limit of sub-millimeter radiation is found almost compatible to the diameter of tropical hydrometeors. The attenuation of the incident THz signal due to scattering from fog-particles may be estimated by incorporating Rayleigh or Mie-Scattering principle [15,27]. For tropical climatic area, fog can extend vertically to an altitude of 500m from ground surface. The presence of liquid water content in fog initiates variation of refractive-index in the medium that in turn leads to absorption of incoming THz signa l[28-31]. In sub-tropical continental or radiation fog, discrete temporal variability can be observed [32-33], which leads to multipath propagation as well as multiple-scattering of the THz-wave. The authors, in this work, have considered the effect of both forward and back-scattered THz signal and their spatial behavior is utilized to enumerate the total attenuation effect under multiple scattering.

It is noteworthy that, Radiative Transfer(RT) theory for describing the transition of electromagnetic energy in macroscopic medium can be regarded as a milestone[34-35]. It incorporates various assumptions to frame the base level of numerical back-up of electromagnetic energy-transfer model. But, owing to some specific classical limitations, the convention-al RT model fails somehow to link with the Weak-Localization (WL) of coherent back-scattering of electromagnetic waves. Besides, the radiative transfer equations narrate the multiple scattering of classical electromagnetic signals, which are obtained directly from Macroscopic Maxwell Theory[36]. Therefore, the conventional RT theory can't be directly incorporated to analyze the multiple-scattering phenomenon of THz-signal in a random and discrete medium under tropical climate region. The authors, therefore, have incorporated the modified radiative transfer equations in the newly developed NLTAM model, by considering the discrete microphysical approach, supported by vector radiative-transfer theory[36]. In this uniquely developed model the context of geophysical separations and the effect of these separations on atmosphere have also been included. To initiate the temporal variation of aerosol concentration along the path of propagation of THz-wave in the discrete medium, the authors have included the probability statistics to study the wave-particle interaction more comprehensively. Successive iteration including discrete-coordinate methods have also been incorporated to make the analysis realistic. Although, several research works on multiple-scattering of sub-millimetre wave in adverse weather condition under non-tropical climatic belt have been reported so far, no such work on the same for tropical-climate has been reported yet.

The presentation of this paper has been arranged as follows:

i. Single-scattering based THz wave attenuation in the presence of tropical-aerosols, where necessary climate dependent boundaries have been included.
ii. Multiple-scattering based THz wave attenuation in the presence of tropical-aerosols under similar boundary conditions.
iii. Comparison of the differences obtained throughout the simulation of both of the attenuation spectra.
iv. Validation of the uniquely developed physics based self-consistent non-linear THz attenuation simulator(NLTAM).

The authors, have reported a thorough analysis of THz-signal attenuation in tropical fog-scenario for the first time. It has been achieved through the simulation often indigenously developed tool(NLTAM). The validation of this software has also been established by the group of authors. It is expected that the simulation outcome would be helpful to the military people of India in establishing secure communication links in Border Area under dense-fog.

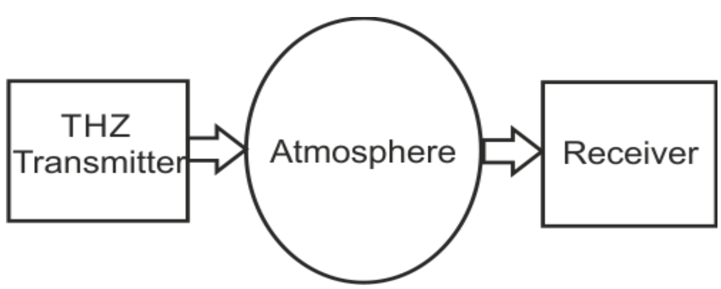


Fig.1. Block diagram of THz Communication System.

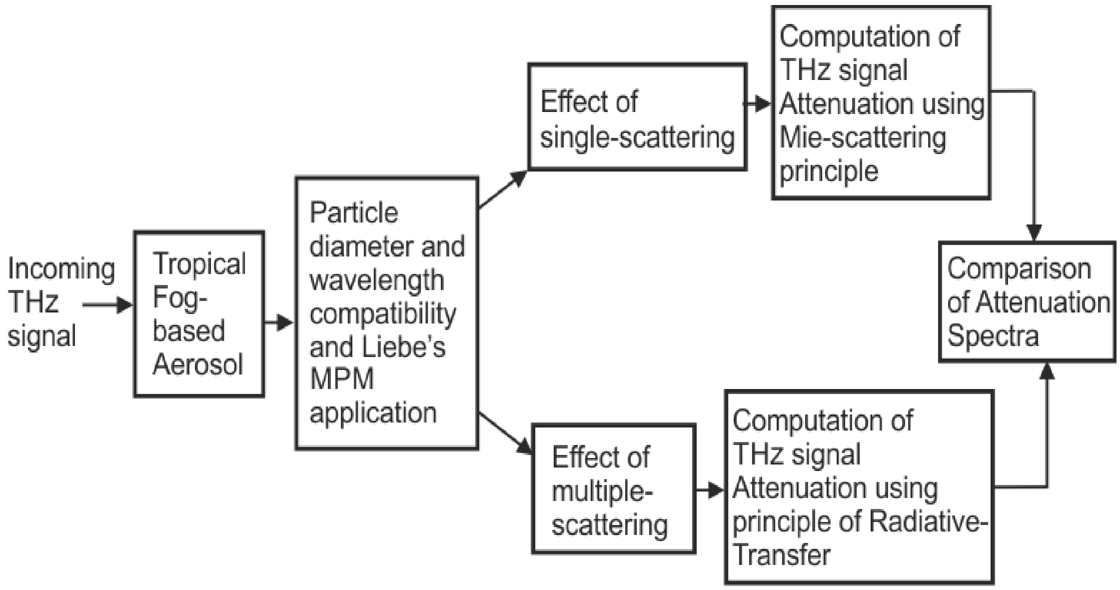


Fig.2. Work-flow diagram.

II. NUMERICAL ILLUSTRATIONS

The Non-Linear Terahertz Attenuation Model(NLTAM) is self-consistent and physics based. The uniqueness of this model lies mainly in its focus on the impact of turbulent and time-varying attitude of the atmosphere on wireless RF signal. As shown in Figure 3, the phase and amplitude-dislocations of THzsignalare generated by different atmospheric variants at the time of propagation through atmospheric channel. The refraction, dispersion and absorption of sub-millimetre signal, in the fog-laden atmosphere are governed by the insulating characteristics of crystalline water molecules. Besides, the concentration of these particles, in Winter, also vary with time in Tropical Climate Area, that leads to either time-dependent partial or complete 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],

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

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 permittivityas[39-40],

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

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].

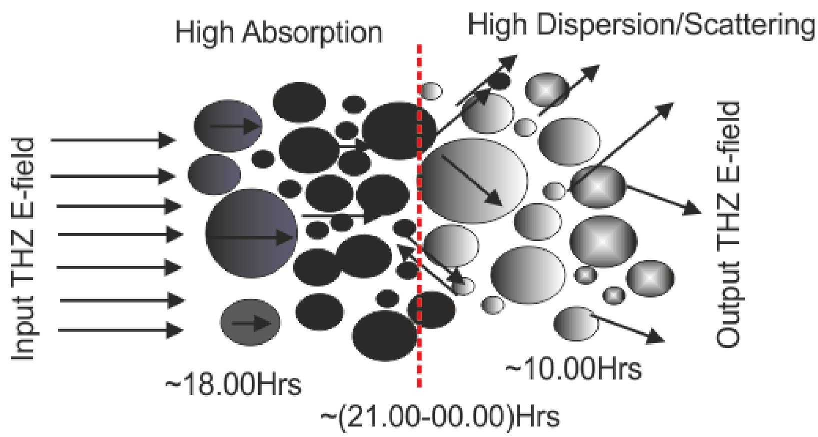


Fig.3. Proposed time-dependent dispersion scenario of THz-signal in Indian fog

A) Single Scattering of Terahertz Wave in Aerosols

Fog, as a particular type of aerosol, is generally enhanced by the condensation of Liquid Water Content(LWC) present in the atmosphere. The amount of relative-humidity as well as density of LWC crystals in tropical climate differ from temperate climatic zone. As per Liebe's MPM[38-39],thedispersive complex refractivity of the medium through which the electromagnetic signal of desired frequency is subject to propagate, can be characterized by the summation of frequency-dependent atmospheric constraints. The authors, in NLTAM, have considered the frequency-dependent complex-refractivity of the dispersive medium as R(f), where,

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

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.

The solution for Macroscopic Maxwell's Equation in E-field, considering the medium as homogeneous and isotropic, has been given in Eq.(1). In general, the presence of an obstacle along the path of electromagnetic signal propagation leads to the scattering of the signal. To simplify the complexity of analysis coming out of decomposition of E-field into innumerable back-waves due to scattering mechanism, the idea of Single-Scattering is generally taken into account[41-43]. In NLTAM, the authors have initiated the simulation of Single-Scattering mechanism in the presence of fog-based aerosols, by considering the entire E-field vector as,

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

where, $\vec{E}_{inc}(\vec{d},t)$ and $\vec{E}_{sca}(\vec{d},t)$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 droplet-size of radius, s, is considered to follow the Modified-Gamma Law[41-45]as

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

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],

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

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 extinction-efficiency μ_{ext} , has been simulated as[41-42],

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

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],

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

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

Here, size-parameter is indicated by $x$and using standard expressions of Mie-abcdparameters[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,

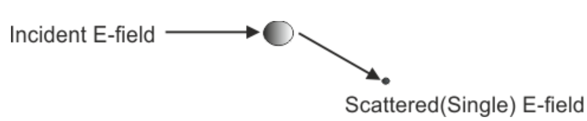
$$\text{Atn.(in dB/km)} = Z\int_0^{\infty} \mu_{sca} n(s)ds \quad (12)$$

where, Z is about $5\text{x}10^3$.

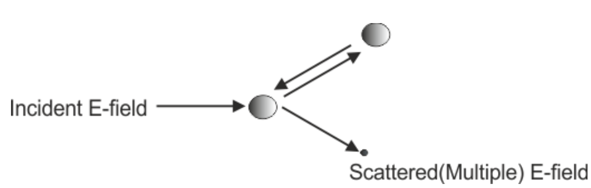
B) Single Multiple Scattering of terahertz wave in Aerosols

The dimension of aerosols present in tropical fog is quite compatible with the wavelength of terahertz radiation. Therefore, as the most common and practical scattering phenomenon, the multiple-scattering can be inevitably considered. The difference between single and multiple scattering has been presented in Fig. 4. The effect of single-scattering by the fog-particles can be chosen as an almost ideal scattering incidence, whereas, the effect of multiple scattering is very common. The authors, in their uniquely developed NLTAM simulator, have incorporated the modified Radiative-Transfer theory[36] along with statistical analysis to study the successive back-scattering of incident 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,

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



(i)



(ii)

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,

$$\vec{\mathrm{E}} = \vec{\mathrm{E}}_{inc} + \sum_{i=1}^{N} \hat{G}\hat{T}_i\vec{\mathrm{E}}_i \quad (14)$$

And $$\vec{\mathrm{E}}_i = \vec{\mathrm{E}}_{inc} + \sum_{j(\neq i)=1}^{N} \hat{G}\hat{T}_j\vec{\mathrm{E}}_j \quad (15)$$

In both of Eq.(14) and Eq.(15) $\hat{G}$ 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, $\vec{\mathrm{r}}$ and $\vec{\mathrm{r}}_{\mathrm{j}}$ of two different particles(here, aerosols)[47]. $\hat{T}_j$is the Lippmann-Schwinger operator. The tailor part of Eq.(15) can be re-expressed as,

$$\hat{G}\hat{T}_j\vec{\mathrm{E}}_j = \int_{V_j} d\vec{r_1}\overleftrightarrow{G}(\vec{r},\vec{r_1}).\int_{V_j} d\vec{r_2}\overleftrightarrow{T_j}(\vec{r_1},\vec{r_2})\,\vec{E}_j(\vec{r_2}) \quad (16)$$

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

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

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

The authors have further incorporated the Henyey-Greenstein(HG) scattering phase-function 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,

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

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

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

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

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

and

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

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

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

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

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 multiple-scattering. 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

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

where, u is the velocity of THz-wave in space, $\xi(\vec{r},t,\theta)$ is the flux-density of THz Electric-field, $\widehat{\Theta}$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 overall space and time dependent Electric-field under multiple-scattering of THz signal in fog-laden atmosphere is enumerated by solving Eq.(25) with appropriate weather dependent boundary conditions. The THz-attenuation rate under multiple-scattering is calculated by considering the successive collisions from the fog-particles, where the mean free-path between two successive collisions has been assumed to have a finite probability distribution[48], by which the THz-photon capture within a certain limit can be achieved. If the rate of capture be considered as U(no. of THz photons/degree), then the entire attenuation(dB/km) can be expressed as

$$\text{Attenuation(dB/km)} = \frac{-5^{\sigma}}{Qext} \ln U^2 \quad (26)$$

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 single-scattering 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.

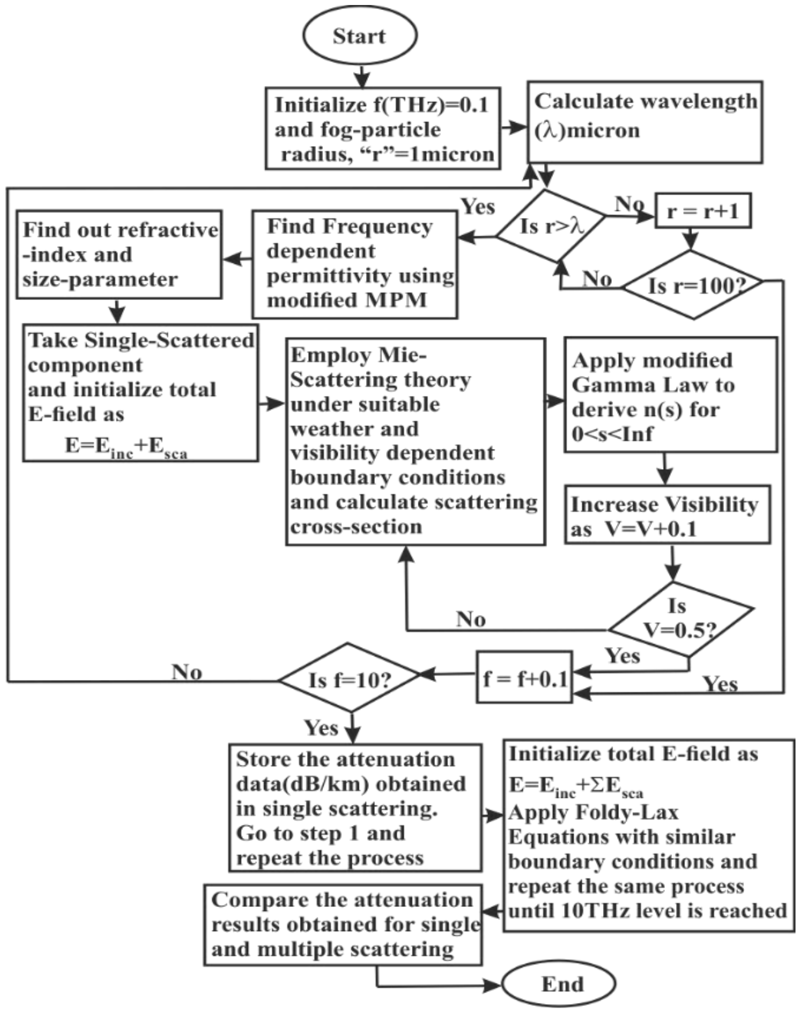


Fig.5.Algorithm to Simulate THz Signal Attenuation Spectra due to Tropical Aerosol Based Different Scattering Mechanisms (using NLTAM Simulator).

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

In the indigenously developed physics based non-linear NLTAM simulator, the authors have carried out the simulation of multiple-scattering of THz wave in tropical foggy-atmosphere, by considering the effect of random-medium. From the fog-laden atmosphere, the successive back-scattering mechanism of the incident THz signal, is enumerated by the application of modified Radiative-Theory, where, Foldy-Lax equations have also been included. 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. In Fig.8, the comparative analysis of THz-signal attenuation spectra out of single and multiple-scattering effects due to the presence of tropical fog-particles have been presented. As per this diagram the higher rate of decrease of THz-signal attenuation in multiple-scattering compared to single-scattering effect in tropical fog-scenario, indicates the significance of back-scattering of THz wave in atmosphere. Under 500m visibility constraint, the effect of Transmission Attenuation rate per unit distance of THz-signal out of multiple-scattering effect has been depicted in Fig. 10. This diagram establishes that after 3THz, the peak attenuation level of THz-signal in fog-laden wireless medium decreases. The nature of this variation and the outcome of simulation is in close vicinity with the experimental data[47].

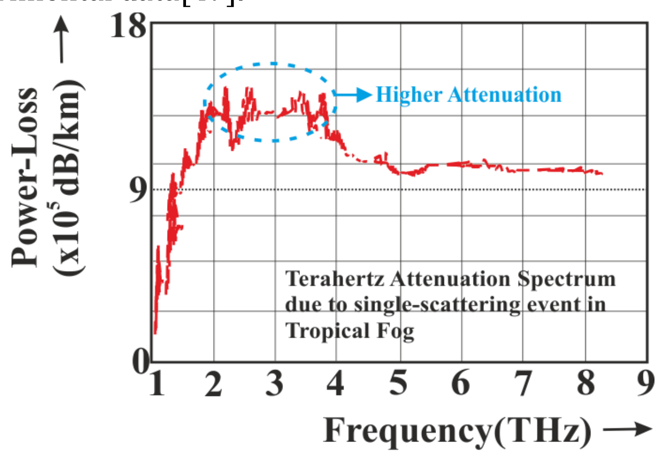


Fig.6. THz Signal Attenuation Spectrum (NLTAM simulated) due to single-scattering from fog-based hydrometeors in tropical climate condition.

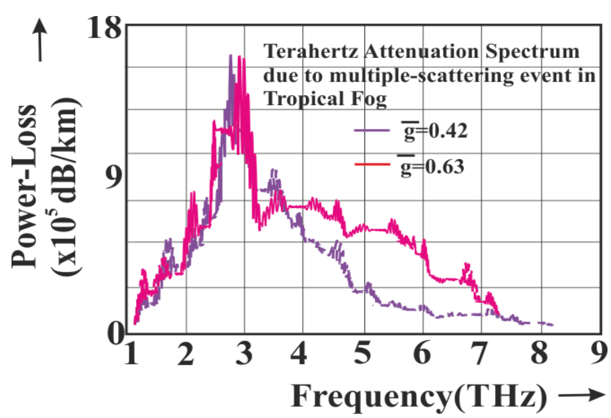


Fig.7. THz Signal Attenuation Spectra (NLTAM simulated) due to multiple-scattering from fog-based hydrometeors in tropical climate condition. Two different asymmetric factors have been considered.

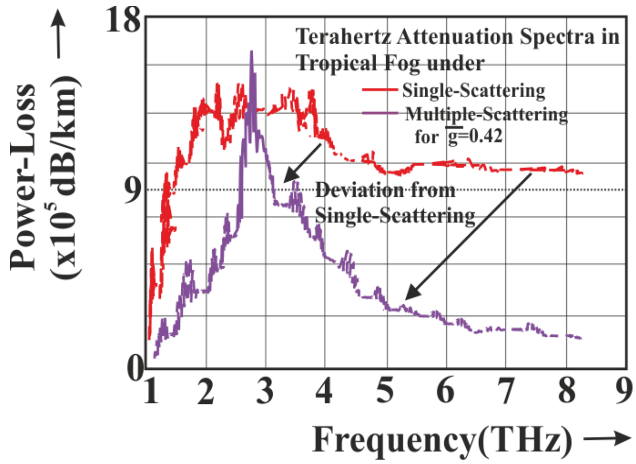


Fig.8. Comparison of single and multiple-scattering attenuation spectra of THz signal in tropical climate , obtained from NLTAM simulator.

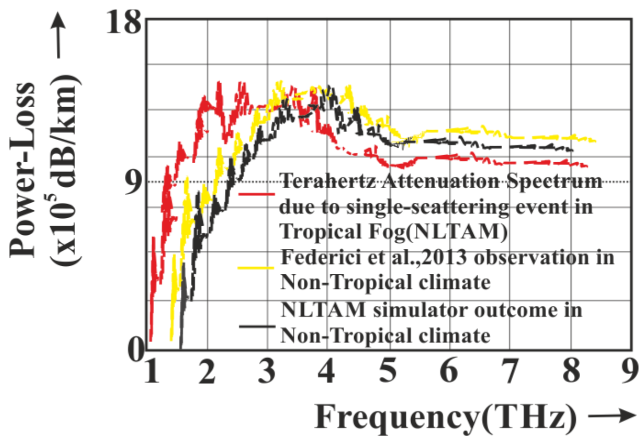


Fig.9. Comparative analysis of experimental observation[20] of THz signal Attenuation and NLTAM simulated outcomes in tropical and non-tropical climate zones. The experimentally obtained non-tropical attenuation spectrum of THz signal due to single-scattering from fog based aerosols, has been compared with NLTAM simulated spectrum of the same in non-tropical weather to validate the model.

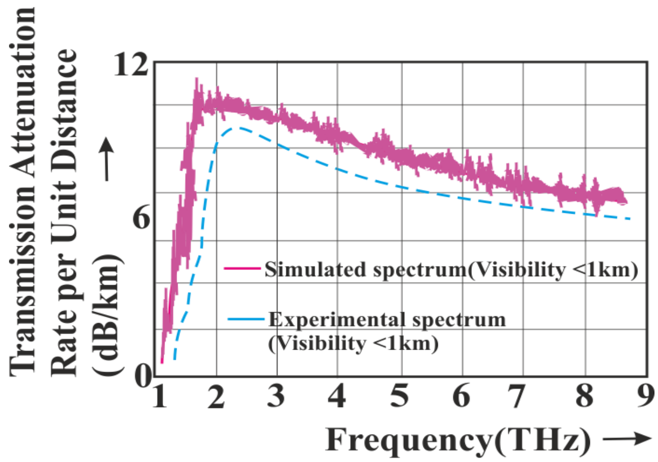


Fig.10. Frequency-dependent variation of Transmission Attenuation rate per unit distance at THz regime in Indian fog-scenario for less than 1km visibility. The Experimental observation [47]of the same in the presence of dust-particles constraint has been shown also.

III. VALIDITY OF THE SIMULATOR

Various atmospheric parameters of non-tropical weather domain have been initially incorporated by the authors in the NLTAM simulator. With experimental out-come of Federici et al. [20] the primary comparison of the model has been carried out. It is found that, the simulated outcomes on the peak level and nature of THz attenuation under foggy atmospheric conditions, matches well with the real-time experimental observations. This has been shown in Fig. 9. The authors, have tried to develop the model, compatible for tropical climate zone, when the validation, based on non-tropical boundaries, was completed. It has been achieved by incorporating necessary modifications in the tropical atmospheric parameters, essential for establishing the model. To the best of authors' knowledge, no experimental work is done till date in Indian Sub-continent. To estimate the THz signal attenuation in Indian Subcontinent, this project is carrying out the virtual experiment through the development of a physics based self-consistent Non Linear Terahertz Attenuation Model(NLTAM). A real time experiment, based on this, would be carried out in India in future, which can be treated as the scope of another research paper. Besides, in Fig. 10, the authors demonstrated the variation of Transmission Attenuation rate per unit distance with frequency of THz signal by NLTAM simulator, in fog-laden tropical climate under 500m visibility condition, where close-agreement with experimental observation under dust-storm for the same visibility has been found[47]. The validation of the model is performed in this way.

IV. CONCLUSION

The author, for the first time, has thoroughly studied the THz attenuation under different types of scattering mechanisms by the suspended water droplets of tropical atmosphere. The attenuation of THz signal in fog-laden atmosphere generally de-pend on different weather constraints and the concentration of hydrometeors. The Mie-Scattering theory enables to compute the aerosol-based attenuation of electro-magnetic signal due to single-scattering effect, that can be regarded as the fundamental scattering. Mostly, in the major research works on the propagation of electromagnetic. signal through adverse atmosphere, the emphasis is given on single-scattering mechanism. The authors, for the first time, have shown the effect of fog-particle based multiple scattering of THz signal in the Indian subcontinent. It has been achieved by their indigenously developed and experimentally verified NLTAM simulator. From this work, it is clear that, in Indian tropical climate scenario, the highest-level of THz signal attenuation due to single-scattering from atmospheric fog particles, de-creases in case of the multiple-scattering event. It is also evident that the frequency range of 2THz to 4THz can be considered as the highest attenuation zone for both of the scattering events. But the fall-rate of the THz signal attenuation spectrum in multiple-scattering is quite sharper compared to its single scattering counterpart. Besides, it is also shown that the tuning in the peak level of THz attenuation spectra can be achieved by the variation of mean asymmetric factor. The distribution statistics of fog-particles plays a major role in determining the gradient of THz-attenuation spectra under multiple-scattering.

ACKNOWLEDGEMENT

The author wishes to acknowledge DRDO, Ministry of Defence, Govt. of India, Dr. Moumita Mukherjee, Dean R&D and Principal Invstigator of DRDO Sponsored Project and Dr. U.C. Ray, Retd. Scientist-'G' and Advisor, SSPL-DRDO, Delhi for their technical support and valuable guidance in the development of the model.

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