International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 9
***Article Received:** 25 July 2023 **Revised:** 12 September 2023 **Accepted:** 30 September 2023*

A Channel Model Suitable for Employing Efficient Beam Steering on Tropospheric Communication Links

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Abstract - Tropospheric communication systems find extensive use in both civil and military applications for long distance point to point communication. 21st century warfare requires high performance tropo systems capable of supporting high data rates for real time communication between various fighting elements. Most of the research and development for enhancing performance of tropo systems, has been in minimizing propagation loss due to fast-fading of channel. Limited progress has been made to overcome slow, diurnal and seasonal, changes in troposphere, which lead to considerable signal attenuation. Beam steering can be used to minimize slow fading loss in tropospheric links, enhancing their performance. Transmitter and receiver antenna beams should be dynamically steered in order to point to the tropospheric heights that are most conducive for propagation at any given time, for receiving maximum power. This paper discusses prominent tropospheric channel models and examines their suitability for beam steering. Dinc's ray-based model can be used for employing beam steering in tropospheric links. It employs a ray-based approach for determining powers received due to signal propagation at different tropospheric heights using real world data of atmospheric parameters obtained from NASA's LIDAR experiment. However, Dinc's model needs certain modifications for exact representation of tropospheric turbulence and its propagation characteristics. A modified ray-based channel model has been presented in this paper, derived by making required changes in Dinc's model. Simulation results, showing a comparison of transmission loss obtained from modified model and Dinc's model with widely used ITU-R P.2001 model, are presented in the paper for validation. The paper also presents calculation of received power for different heights using modified model, validating its suitability for beam steering. Real world atmospheric parameters have been obtained from Indian Meteorological Department (IMD) for validation process. Received powers obtained for different heights using modified model have been compared to determine the most favourable heights for signal propagation. Knowledge of favourable heights for different times of a day in different seasons, can be used to steer transmit and receive antenna beams towards the favourable heights, at any given time and day, resulting in efficient beam steering.

Keywords - Tropospheric propagation phenomenon; fading in tropo channel; beam steering in tropospheric link; tropospheric channel models; modified ray based tropo channel model.

I. INTRODUCTION

Tropospheric communication, popularly known as tropo communication, can be defined as propagation of radio frequencies ranging from 0.3 GHz to 30 GHz, using tropospheric inhomogeneities, to establish communication between two points well beyond the horizon, as far as several hundred kilometres.

Troposphere is an inhomogeneous region of atmosphere extending from ground level up to 8-14 km. The inhomogeneities, a mixture of gaseous concentrations and small atmospheric layers, have higher refractive index than immediate surrounding region. The volume formed by intersection of transmit and receive antenna beams is known as common volume. Fig. 1 shows that when a transmitted Radio Frequency (RF) beam strikes the tropospheric inhomogeneities present in the common volume, incident electromagnetic energy is scattered or reflected in all directions. The energy scattered or reflected towards receiving antenna makes transmission of information possible. Study of tropospheric propagation takes following phenomenon into account [1]:

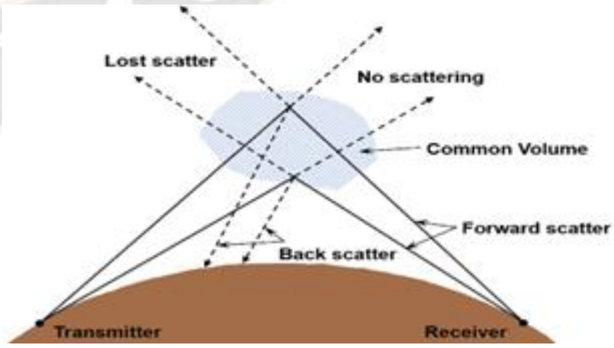

Figure 1. - Tropospheric propagation phenomenon

- *Long Term Changes (Slow Fading).* They comprise seasonal, monthly and hourly variations in refractive index of troposphere due to upward or downward movement of inhomogeneities. This leads to change in the bending of transmitted rays producing major variations in the path attenuation and hence, the received power level.

- *Short Term Changes (Fast Fading).* Transmit and receive antenna beams can be considered to be comprising of multiple rays. Random, rapid and statistically independent variations in tropospheric refractive index particularly close to earth surface, result in continuous fluctuation in the angel of arrival and signal strength received via different rays. Short-term behaviour considers periods from less than a minute to several minutes.

Extensive research has led to development of various techniques, like space, frequency and angle diversity combining, for overcoming fast fading [2]. However, similar progress has not been made in overcoming slow fading. It should be noted that annual variations of tropospheric received signal can be as high as 20 dB while diurnal variations can range from 5 to 10 dB, depending on the climatic conditions of the region [3]. Main reason for slow fading is large sized (60ft high) static antennas used in conventional tropo systems, which produce narrow transmit and receive beam, forming a common volume at fixed heights of troposphere. However, heights of troposphere favourable for propagation, change during the day and with the seasons.

Beam steering can minimize slow fading loss by dynamically directing the antenna beams towards favourable heights of troposphere, thus receiving high power at all times. This increases link availability and helps achieve higher data rates, enhancing the performance of tropo communication systems. A discussion of prominent tropospheric channel models is required to identify the model suitable for employing beam steering. Such a model should be able to obtain powers received after signal propagation through different tropospheric heights, thus indicating the most favourable height for beam steering at any given point of time.

II. PROMINENT CHANNEL MODELS

Tropospheric channel models are based on either of the two postulates; scattering from a turbulent atmosphere or incoherent reflections from patchy elevated layers. However, both the theories are based on a common belief that tropospheric propagation is made possible by refractive index variations due to tropospheric inhomogeneities.

A. Models Based on Scattering Theory

Booker and Gordon model [4] together with Bello model [5], forms a complete theoretical channel model based on scattering theory.

1) Booker and Gordon Model: When a layer of air flows past over a neighbouring layer, smooth flow of these layers becomes turbulent and leads to formation of eddies, which then act as scatterers for the incident RF radiation. Size of eddies (scatterers) is proportional to scale of turbulence (*l*), which further depends on time correlation of atmospheric temperature and average velocity of wind as per a study by university of Texas [6]. Scale of turbulence is considered to vary from 10 metres in a turbulent troposphere to 10 cm under stable conditions [7].

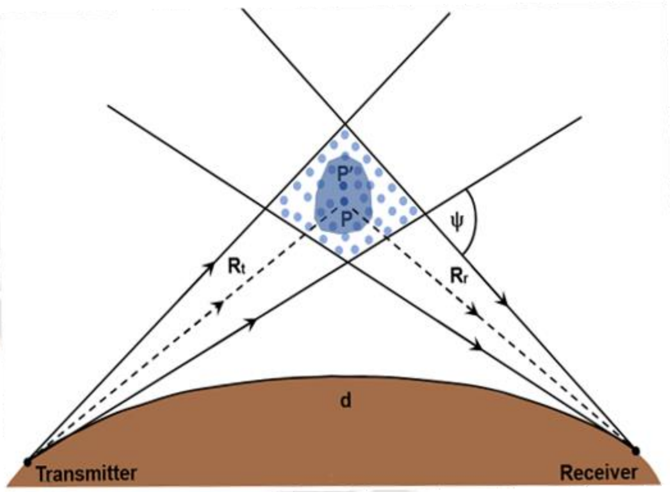

Figure 2. – Link for Booker and Gordon Model

Booker and Gordon have assumed the size of scatterers to be homogeneous throughout the common volume.

Table I. Link Geometry and System Variables for Booker and Gordon Model

Notation	Explanation
P_t	Transmitted Power
R_t , R_r	Distance of dV from TX / RX antenna
d	Arc distance from TXR to RXR
l	Scale of turbulence
A_t, A_r	TX/RX antenna aperture area, both taken equal to A
λ	TX wavelength
X	Angle between direction of TX electric field and line joining scattering volume to the receiver
ψ	Angle between direction of scattered radiation and incident radiation, also known as scatter angle.

Common volume has been divided into macroscopic elements of volume dV having dimensions much larger than *l* and microscopic elements of volume dv having dimensions much smaller than *l*. One such macroscopic volume element is shown as shaded region in Fig. 2, containing multiple microscopic elements like P, shown as dots. Notation for link geometry and system variables and their explanation is given in Table I.

Scattering Cross Section (SCS) of a macroscopic element is power scattered by scatterers contained in its volume dV into a unit solid angle, given by radar range equation, as:

$$\text{SCS} = \frac{P_t}{4\pi R_t^2}\frac{4\pi A_t}{\lambda^2}\ \sigma(\psi, X)\ dV \tag{1}$$

$\sigma(\psi, X)$ is the power scattered per unit solid angle from a unit volume for unit incident power density. Total power received has been obtained by multiplying equation (1) with solid angle

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subtended by the receive antenna (A_r/R_r^2) and integrating over the entire common volume V:

$$P_r = \frac{P_t\,A^2\sigma(\psi,X)}{\lambda^2} \int_V \frac{dV}{R_t^2 R_r^2} \quad (2)$$

$\sigma(\psi, X)$, is given as:

$$\sigma(\psi,X) = \frac{\overline{(\Delta\epsilon/\epsilon)^2}\,(2\pi l/\lambda)^3\ \sin^2 X}{\lambda[1+\{(4\pi l/\lambda)\,\sin(\psi/2)\}^2]^2} \quad (3)$$

where $\overline{(\Delta\epsilon/\epsilon)^2}$ is the mean square deviation of capacitance for a microscopic volume element, given as:

$$\overline{(\Delta\epsilon/\epsilon)}^2 = 4 * 10^{-12}\,(\Delta M)^2 \quad (4)$$

where ΔM is the mean square deviation from mean of refractive index, having different values at different heights. Taking $\sigma(\Theta, X)$ as constant in the entire common volume, integral in (2) has been evaluated as λ^2/Ad, giving power received as:

$$P_r = \frac{P_t\,A\sigma(\psi,X)}{d} \quad (5)$$

2) Bello Model: Bello derived expression for power delay spectrum of tropo communication channel, based on Booker and Gordon's work [4]. The model considers a multipath received signal, having short term stationary Gaussian envelope for signal received over each independent path, with combined signal having a Rayleigh probability density [8,9]. Link geometry used by Bello for derivation of channel model is given in Fig. 3, while notation of various variables used and their explanation is given in Table II.

As seen from (1), power scattered by a common volume element is proportional to its volume and $\sigma(\psi, X)$. Bello gives the relationship between $\sigma(\psi, X)$ and ψ as [10]:

$$\sigma(\psi) \sim \frac{1}{\psi^5} \quad (6)$$

In absence of definitive knowledge, $\overline{(\Delta\epsilon/\epsilon)^2}$ has been assumed to decrease with height h, above the earth's surface. Power received after scattering from a scatterer of volume dv, has been given using radar range equation, as:

$$dP_r \sim \frac{GH}{(4\pi)^2\,{R_t}^2\,{R_r}^2}\frac{dv}{h\,\psi^5} \quad (7)$$

Loci of scatterers providing delays of $z,\ z+dz$ and so on, are concentric ellipses in two dimensions and prolate spheroid shells in three dimensions, as shown in fig. 3. This division of common volume into different regions providing different delays, was a significant improvement of Bello model over

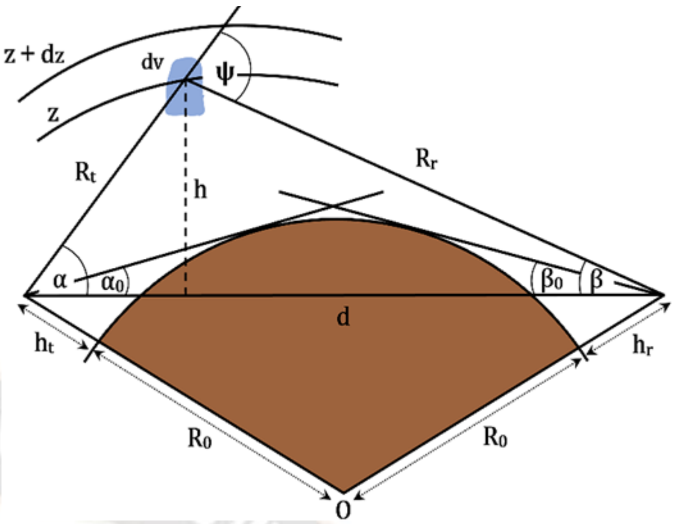

Figure 3. Link geometry for Bello model

Table II. Link Geometry and System Variables for Bello Model

Notation	Explanation
R_t, R_r	Distances of scatterer from TX and RX antenna respectively
h	Height of scatterer from straight line joining TX and RX antenna
h_t, h_r	Height of TX and RX antenna respectively
d	Straight line distance between TX & RX antenna
R_0	Actual radius of Earth
G, H	Gain patterns of TX and RX antenna respectively
ψ	Scatter angle
α, β	Elevation angles of a scatterer from TX and RX antenna respectively
α_0, β_0	Elevation angles of respective horizons from TX and RX antenna respectively
z, $z+dz$	Loci of all scatterers providing delay of z and $z+dz$ respectively
δ	Normalized path delay given as α/β

Booker and Gordon model which considers common volume as one whole. Power received at the receiver from all the scatterers providing delays in interval $(z, z+dz)$, calculated by integrating (7) over the volume of the shell enclosed by the curves z and $z+dz$, has been given as:

$$P_r \sim \frac{1}{\delta^{1+\frac{m}{2}}} \int_{\alpha_0/\sqrt{2\delta}}^{\sqrt{2\delta}/\beta_0} \frac{G\left(x\sqrt{2\delta}-\alpha_0\right) H\left(\sqrt{2\delta}/x-\beta_0\right)}{x\left(x+\frac{1}{x}\right)^3} \quad (8)$$

$G\left(x\sqrt{2\delta}-\alpha_0\right)$ and $H\left(\sqrt{2\delta}/x-\beta_0\right)$ are the vertical gain patterns, assuming that maximum gain occurs at α_0, β_0 and no scattering takes place for $\alpha < \alpha_0$ and $\beta < \beta_0$. Power Delay Profile (PDP) has been determined by evaluating (8) for each delay interval $(z, z + dz)$, $(z + dz, z + 2dz)$ etc. and plotting it against the average delay for each interval. Frequency Correlation Function (FCF) has been determined by evaluating Fourier Transform of the corresponding delay spectra with the help of digital computers.

B. Friis Model Based on Reflection Theory

Friis et al, in 1957, proposed that RF waves propagate through troposphere due to uncorrelated reflections from discontinuous layers [11], formed by sharp variations in atmospheric refractive index gradient, both vertically and horizontally [12]. Fig. 4 gives basic link geometry for explanation of reflection theory. Table III gives notation and explanation of geometry parameters. Number and size of the reflecting layers and amount of change in refractive index gradient at the boundary of these layers, determine the level of received power. Different layer sizes; large, small and intermediate, have been considered, with latter being the most prevalent. Layer dimensions b and c have been taken as equal, such that $\sqrt{2a\lambda} < b < \sqrt{2a\lambda}/\Delta$. Power received after reflection from all the layers present in common volume has been given as:

$$P_r = P_t \frac{A_t\, A_r\, N\, b^2}{2\, \lambda^3\, a^3} \int_V \Delta^2 q^2\, dV \quad (9)$$

Δ is the grazing angle given as ρ/a. Reflection coefficient (q)

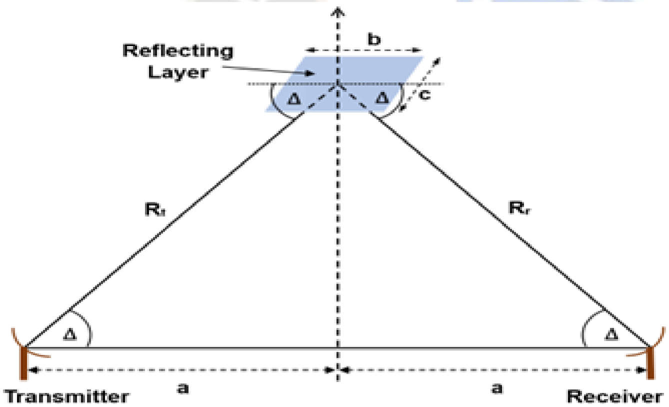

Figure 4. Link geometry for Friis model

has been determined using method given in relevant publications [13,14,15]. Idealized antenna patterns have been used for evaluating (9). The final expression for received power is given as:

$$P_r = \left[\frac{P_t\, \lambda^2}{4a^2\alpha^4}\right]\left[\frac{4M\lambda}{3\theta^4}\right]\left[\frac{\frac{\alpha}{\theta} f\left(\frac{\alpha}{\theta}\right)}{2+\frac{\alpha}{\theta}}\right] \quad (10)$$

where $M \approx 2000\, b^2 k_1^2 N$ with k_1 as change in the gradient of dielectric constant for a layer at height of 1600 meters.

Table III. Link Geometry and System Parameters for Friis Model

Notation	Explanation
R_t, R_r	Distances of reflecting layer from TX and RX antenna respectively
b, c	Layer dimension in plane of common volume and perpendicular to it.
N	Number of layers in unit common volume
$2a$	Distance from TXR to RXR
A_t, A_r	Aperture areas of TX and RX antennas
V	Common Volume
ρ	Twice the height of layer above Earth's surface
α	Vertical beam angles of TX/RX antenna beams
θ	Elevation angles of lower edge of both TX/ RX antenna beams
λ	Transmit signal wavelength

C. Prediction Models

Scattering theory gained more prominence as compared to reflection theory and became the basis for development of widely used prediction models. These models help in predicting maximum propagation loss for a tropospheric radio link, for different percentages of time, to determine if the given link will be able to provide required service all through the year. A comprehensive model for predicting transmission loss for tropospheric paths based on the scattering theory, was presented in Technical Note no. 101 [16] issued by National Bureau of Standards (NBS) in 1965. NBS model became the basis for various recommendations by Radiocommunication sector of International Telecommunication Union (ITU-R), such as ITU-R P.452 [1], P.617 [3] and P.2001 [17]. ITU-R

P.452-16 gives transmission loss for non-exceeding percentages of time from 0.001% to 50% of an year. Troposcatter, compared to diffraction and ducting, is the predominant propagation mechanism when considered over long periods of times. Hence, ITU-R P.617-5 gives transmission loss for time percentages in excess of 50%.

ITU-R P.2001 is the most comprehensive recommendation as it considers non-exceeding time percentages from almost 0% to 100%. Transmission loss for a troposcatter link, not exceeded for p% of time, has been given as:

$$L = M + L_{freq} + L_{dist} + L_{coup} - Y_p \quad \text{dB} \quad (11)$$

Notation and explanation of various parameters used in ITU-R P.2001 model is given in Table IV.

Table IV. Link Geometry and System Parameters for ITU-R P.2001 model

Notation	Explanation
M	Meteorological structure parameter in dB
L_{dist}	Distance dependent loss
d_c	Curved path distance between TXR & RXR in kms
ψ	scatter angle in milliradians
L_N	Loss term dependent on common volume height
γ	Atmospheric structure constant
a_e	Mean effective Earth radius in kms
L_{freq}	Frequency dependant loss
f	Centre frequency of transmitted signal in GHz
L_{coup}	Aperture to medium coupling loss
$G_{t,r}$	Gains of TX/ RX antenna

L_{freq} is given as:

$$L_{freq} = 25\log_{10}(f) - 2.5[\log_{10}(0.5f)]^2 \quad \text{dB} \quad (12)$$

L_{dist} is given as:

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$$L_{dist} = \max\left\{\begin{matrix} 10\log_{10}(d_c) + 30\log_{10}(\psi) + L_N, \\ 20\log_{10}(d_c) + 0.573\psi + 20 \end{matrix}\right\} \text{ dB} \quad (13)$$

L_N is given as:

$$L_N = 20\log_{10}(5 + \gamma H) + 4.34\gamma h_{trop} \quad \text{dB} \quad (14)$$

where H and h_{trop} are given as:

$$H = 0.25 \cdot 10^{-3}\, \psi d_c \quad \text{m} \quad (15$$

$$h_{trop} = 0.125 \cdot 10^{-6}\, \psi^2 a_e \quad \text{m} \quad (16)$$

L_{coup} is given as:

$$L_{coup} = 0.07\exp\,[0.055(G_t + G_r)] \quad \text{dB} \quad (17)$$

Parameter Y_p, not exceeded for p% of time is given as:

$$Y_p = C\, Y_{90} \quad \text{dB} \quad (18)$$

where,

$$C = 1.26[-\log_{10}\{(100 - p)/50\}]^{0.63} \quad p \geq 50$$
$$C = -1.26\{-\log_{10}(p/50)\}^{0.63} \quad p < 50 \quad (19)$$

Different regions of earth are designated to six different climatic zones, that can be ascertained from a file included with the recommendation. Y_{90}, in dB, is calculated using one of the equations given in the recommendation, as per the climatic zone in which the link falls. Values of M and γ are obtained from ITU-R P.2001 as per applicable climate zone for the link.

D) Ray Based Channel Model

The channel model developed by Dinc et al [18] uses ray-based approach which splits the transmit and receive antenna beams into smaller contiguous sub-beams, stacked vertically. Received power and path delay are calculated for each sub-beam, to estimate PDP of the channel. Link geometry used for ray theory model is given in Fig. 5. The notation and explanation of the parameters used in the model are given in Table V.

Each pair of corresponding transmit and receive sub-beams enclose a portion of common volume, having a differential SCS. Based on the studies of SCS [19,20] and index of refraction [21], size of scatterers has been considered as 1-10 µm. Since, the size of scatterers is much smaller than the wavelength of signal used in tropo systems (few cms), Rayleigh scattering approximation has been used for derivation of expression for differential SCS, given as [19]:

$$\sigma_V(\alpha,\beta,n) = 2\pi k^4 \cos^2(\psi)\, \phi(\alpha,\beta,n) \quad \text{m}^2 \quad (20)$$

k is the wave number given as 2π/λ. $\phi(\alpha,\beta,n)$ is the Kolmogorov spectrum given as [19]:

$$\phi(\alpha,\beta,n) = 0.33\, C_n^2\big(2k\sin(\psi/2)\big)^{-11/3} \quad (21)$$

C_n^2 is the refractive index constant structure, representing strength of atmospheric turbulence, given as [21]:

$$C_n^2 = 2.8\ (\delta n/\delta z)^2\, L_0(h)^{4/3} \quad (22)$$

L_0, outer scale of turbulence, has been modelled as a random

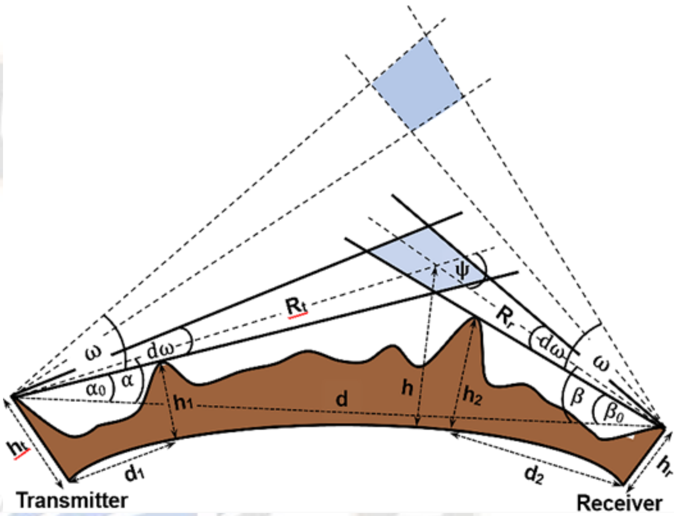


Figure 5. Link geometry for Ray Based Channel Model

Table V - Link Geometry and System Variables for Ray Based Model tropospheric channel.

Notation	Explanation
P_t	Power transmitted in any sub-beam
d	Straight line distance from TXR to RXR
d_1, d_2	Straight line distance from TXR/RXR to their respective horizons
h_1, h_2	Height of TX/ RX horizons
h_t, h_r	Height AMSL of TXR/ RXR
R_t, R_r	Average distance of common volume, formed by a sub-beam pair, from TXR/RXR
G_t, G_r	TX and RX antenna gains
ω_t, ω_r	Elevation beam width of TXR/RXR
$d\omega$	Elevation beam width of any sub-beam
α_0, β_0	Elevation angle of lower edges of TX/RX beams
α, β	Elevation angle of centre ray of lowest TX/RX sub-beam
ψ	Scatter Angle
ρ	Polarization mismatch factor
$L_0(z)$	Outer scale of turbulence

variable lying between 3-100 m with a uniform probability density. $\delta n/\delta z$ is the vertical gradient of refractive index, given as:

$$\left(\frac{\delta n}{\delta z}\right) = \left(\frac{\delta N}{\delta z}\right) * 10^{-6} \quad (23)$$

where N is the refractivity of air for microwave frequencies, given as [1]:

$$N = \frac{77.6}{T}\left(P + 4810\frac{e}{T}\right) \quad \text{N-units} \quad (24)$$

T is atmospheric temperature in degree Kelvin, P is atmospheric pressure in millibars (mb) and e represents vapour pressure in mb, given as:

$$e = \frac{P}{\varepsilon} w \quad \text{mb} \quad (25)$$

w represents amount of water in air in g/kg and ε is the ratio of molecular mass of water vapour to air, taken as 0.622.

Differential common volume enclosed by each corresponding pair of transmit and receive sub-beams, is given as:

$$dV_c(\alpha,\beta) = \frac{{R_t}^2 \, {R_r}^2 (d\omega)^2}{\sqrt{{R_t}^2 + {R_r}^2} \;\; sin\,(\psi)} \quad \text{m}^3 \quad (26)$$

Received power for any sub-beam has been given using radar range equation as:

$$P_r(\alpha,\beta,n) = \frac{P_t G_t G_r \; \sigma_V(\alpha,\beta,n) dV_c(\alpha,\beta) \; \rho}{4\pi^3 R_t(\alpha,\beta)^2 \; R_r(\alpha,\beta)^2} \quad \text{W} \quad (27)$$

Final expression of power received in any sub- beam, using expressions of $\sigma_V(\alpha,\beta,n)$ from (20) and $dV_c(\alpha,\beta)$ from (26) in (27), is given as:

$$P_r(\alpha,\beta,n) = \frac{P_t G_t G_r \, \pi^2 (d\omega)^2 \;\; cos^2(\psi) \; (\delta n/\delta z)^2 L_0(z)^{4/3} \rho}{21.64 \, \lambda^2 \sqrt{{R_t}^2 + {R_r}^2} \;\; (sin\,\psi\,)\big(2k \; sin\,(\psi/2)\big)^{11/3}} \quad \text{Watts} \quad (28)$$

Path delay and received power for each smaller beam are calculated to determine the PDP of the troposcatter channel. Dinc's model calculates vertical gradient of refractive index from atmospheric pressure (P), temperature (T) and water vapour mixing ratio (w) recorded during NASA's African Monsoon Multidisciplinary Analyses (NAMMA) Light Detection and Ranging (LIDAR) experiment [22]. Hence, Dinc's model is a realistic model of tropospheric channel which portrays actual propagation conditions of troposphere at different heights, calculating $\delta n/\delta z$ from real world measurements of atmospheric parameters rather than taking a uniform value of $\delta n/\delta z$ or assuming a statistical relationship between $\delta n/\delta z$ and height.

III. MODIFIED RAY BASED CHANNEL MODEL

Dinc's ray-based channel model needs certain corrections and changes for exact portrayal of tropospheric propagation conditions. Differential SCS used by Dinc, given in (20), is applicable for sound waves [19]. Expression of SCS for EM waves is given from [19] as:

$$\sigma_V\,(\alpha,\beta,n) = 2\pi k^4 \; sin^2(X) \; \varphi(\alpha,\beta,n) \;\; \text{m}^{-1} \quad (29)$$

where X is the angle between direction of incident electric field and the direction from the common volume formed by sub-beams to the receiver. For forward scattering, X is equal to 90˚, hence $\sin^2(X)$ is always 1.

Expression for turbulence spectrum used by Dinc's model, given in (21), is based on Kolmogorov spectrum technique. The expression takes into account both, the size of scatterers and their scattering properties. Scattering properties are represented by C_n^2 which further depend on outer scale of turbulence and refractive index gradient as seen in (22). Size of scatterer, l, is related to turbulence wave number, κ, as $\kappa = 2\pi/\, l$. κ has been taken as $2k \sin(\psi/2)$ in (21). Angle ψ is different for different sub-beams sets, as can be seen in fig. 5, but does not change with time. However, the size of scatterers even within a given sub-beam common volume is not constant with time due to successive breaking of large sized inhomogeneities into smaller ones [23]. Size of scatterers can be considered to lie between inner scale of turbulence l_0 and outer scale of turbulence L_0 and correspondingly, κ lies between $2\pi/L_0$ and $2\pi/l_0$. Value of L_0 lies between 10-100 m and l_0 between 1-10 mm [21]. Hence, (21) can be modified as:

$$\phi(\alpha,\beta,n) = 0.33 \; C_n^2 \, \kappa^{-11/3} \;\; m^3 \quad (30)$$

where, κ is taken as a uniformly distributed random number with limits $2\pi/L_0$ and $2\pi/l_0$.

Expression of differential common volume used in Dinc's model, given in (26), needs to be corrected and is given from [23] as:

$$dV_c(\alpha,\beta) = \frac{1.206 \, {R_t}^2 \, {R_r}^2 \; \omega \; (d\omega)^2}{\sqrt{{R_t}^2 + {R_r}^2} \;\; sin\,(\psi)} \quad \text{m}^3 \quad (31)$$

where ω is the elevation as well as azimuth beamwidth of both transmit and receive antenna beams, while $d\omega$ is the elevation beam width of any transmit or receive sub-beam. Incorporating (29), (30) and (31) in (27), the modified expression for received power is obtained as:

$$P_r(\alpha,\beta,n) = \frac{P_t G_t G_r \, \pi^2 \; \omega \; (d\omega)^2 \; (\delta n/\delta z)^2 L_0(z)^{4/3} \rho}{17.96 \, \lambda^2 \sqrt{{R_t}^2 + {R_r}^2} \;\; (sin\,\psi\,) \; \kappa^{11/3}} \quad \text{Watts} \quad (32)$$

IV. SUITABILITY FOR BEAM STEERING

Beam steering on tropospheric link involves two steps. First one is calculation of received power for different tropospheric heights at different times of a day and in different seasons. Second is identification of favourable heights which give maximum received power at different times of day in different seasons. Analysis of diurnal and seasonal pattern of refractive index gradient and optimum tropospheric heights, over a period of few years, can help in determining the heights which are more likely to deliver higher powers at different times of a day, in different seasons. Hence, on any given day and time, transmit and receive antenna beams can be steered to these favourable heights for obtaining maximum received power. Weather of a place, on a given day and time, cannot be expected to be exactly same as that for preceding years. Therefore, only a coarse beam steering can be carried out based on prior knowledge of favourable heights. A separate beam may be used, for real-time scanning of favourable heights, for finer beam steering. However, prior knowledge of favourable heights makes beam steering faster and more efficient.

Booker and Gordon model and Bello model together present a comprehensive tropospheric channel model based on scattering theory. They introduced the concept of scattering cross section which has been used by many future models. As per these models, received power depends on size and scattering properties of scatterers. Size of scatterers is proportional to scale of turbulence, while, scattering properties are decided by mean square deviation of capacitance, $\overline{(\Delta\epsilon/\epsilon)}^2$. However, Booker and Gordon model being basic in nature considered common volume to be homogenous having scatterers with uniform size and properties. Though, Bello model divided common volume into vertically stacked locally homogenous sub volumes, but it assumed $\overline{(\Delta\epsilon/\epsilon)}^2$ to be inversely proportional to height, rather than calculating its actual value from atmospheric parameters at different heights. Hence, both these models do not depict actual scattering conditions at different tropospheric heights. Therefore, they cannot be used for determining received powers for different tropospheric heights and for beam steering.

Friis model introduces reflection theory, in contrast to scattering theory, as the basis for determining received power on a tropospheric channel. However, being elementary in nature, it also considers the common volume to be homogenous with uniform size, tilt and reflection coefficient of atmospheric layers. Hence, the model does not provide actual representation of tropospheric conditions and cannot be used for determining differential power received from different heights. Hence, the model cannot be used for beam steering.

Prediction models are statistical models based on large data sets of meteorological observations and experimental records of received power, collected over a number of years for a large number of tropospheric links, located in different parts of world. Atmospheric and meteorological structure parameters like M and γ, used by the models are averaged both geographically and in time and maybe different from present values for a link due to climatic changes over the years. Moreover, these models use an approach suitable for fixed beam tropo systems and do not present a direct method for determining the received power from different heights. Thus, prediction models cannot be used for beam steering.

Ray-based channel model determines received power for different sub-beams using actual values of $\delta n/\delta z$, obtained from real world measurements of meteorological parameters. Since, common volumes formed by different sub-beams are vertically stacked and represent scattering conditions at different heights of troposphere, ray-based model can be used to obtain power received due to signal propagation at different tropospheric heights. The approach given in the model can be extended to tropospheric heights even beyond the extent of default common volume (formed by antenna beams pointing just above their respective radio horizons). Thus, both Dinc's model and modified ray-based channel model can be used to determine optimum pointing heights for efficient beam steering on a tropospheric communication link. However, modified model is an improvement over Dinc's model as it gives a more exact representation of tropospheric turbulence for propagation of EM waves.

V. METHODOLOGY FOR VALIDATION

Validation of modified ray-based channel model has been done on two aspects. First is comparison of transmission loss obtained using modified model with transmission loss obtained from Dinc's ray-based model and widely used ITU-R P.2001 model. Second is calculation of received power for different heights using the modified model to establish its employability for beam steering.

A 100 km tropospheric link between two sites located in Gujarat, India, with common volume formed over Ahmedabad (Gujarat) has been considered for the validation process. Link has been synthesised using Tropo Link Implementation Planning Software (TLIPS) developed by Defence Research and Development Organization (India). The link falls in climate zone 4 as determined from ITU-R P.2001. Various parameters of the synthesized link used for calculating transmission loss are given in Table VI. Meteorological parameters are recorded at height differences of around 150 m by various meteorological observatories. Hence, transmit and receive antenna beams have been considered to consist of 10 sub-beams each, which gives a common volume height of approximately 150 m for each sub-beam. This gives at least two values of refractivity N for each sub-beam common volume required for calculating $\delta n/\delta z$. Calculation of received power for each

Table VI – Parameters used for Validation Process

Parameter	ITU-R P.2001	Dinc's Model	Modified Model
P_T	-	2000W	2000W
P_t	-	200 W	200W
M	128.5 dB	-	-
γ	0.27	-	-
f	5 GHz	-	-

International Journal on Recent and Innovation Trends in Computing and Communication
ISSN: 2321-8169 Volume: 11 Issue: 9
***Article Received:** 25 July 2023 **Revised:** 12 September 2023 **Accepted:** 30 September 2023*

λ	-	0.06 m	0.06 m
d_c	157.42 km	-	-
a_e	9193.43 km	919343 m	919343 m
α	-	5.8e+03 rad	5.8e+03 rad
β	-	6.8e+03 rad	6.8e+03 rad
ψ	12.546 mrad	0.0125 rad	0.0125 rad
$d\omega$	-	3.1e-03 rad	3.1e-03 rad
G_t, G_r	38.97 dB	7.89e+03	7.89e+03

sub-beam in Dinc's model and modified model requires scatter angle, distances R_t and R_r, outer scale of turbulence, turbulence wave number and vertical gradient of refractive index for each sub-beam. Scatter angle for i[th] sub-beam is calculated as:

$$\psi_i = \psi + i \cdot 2d\omega \qquad (33)$$

Distances R_t, R_r for i[th] sub-beam are calculated as:

$$R_{ti} = d\,\frac{\sin\beta_i}{\sin\psi_i}\ \text{m} \quad \text{and} \quad R_{ri} = d\,\frac{\sin\alpha_i}{\sin\psi_i}\ \text{m} \qquad (34)$$

where,

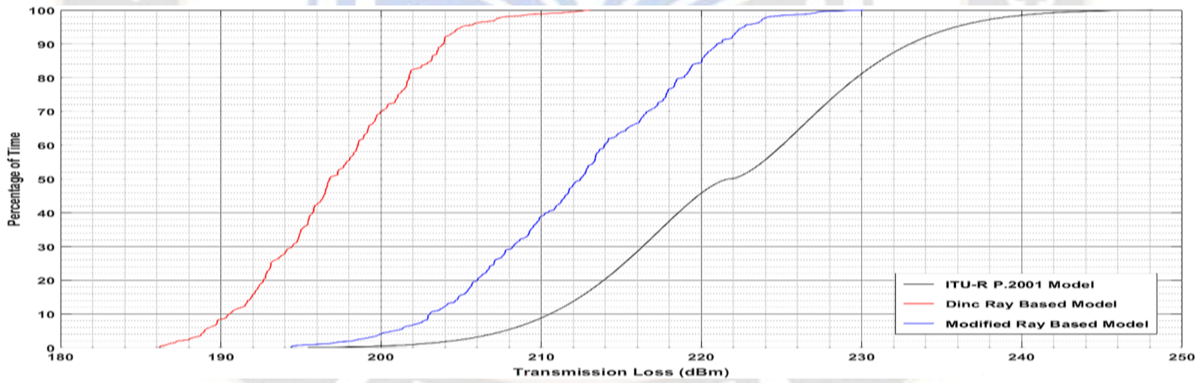
$$\alpha_i = \alpha + i \cdot d\omega \quad \text{and} \quad \beta_i = \beta + i \cdot d\omega \qquad (35)$$

Received power for each sub-beam is calculated using Monte Carlo simulations with sufficient number of iterations. $L_0(z)$ and κ are chosen randomly, from within their respective limits, for each iteration.

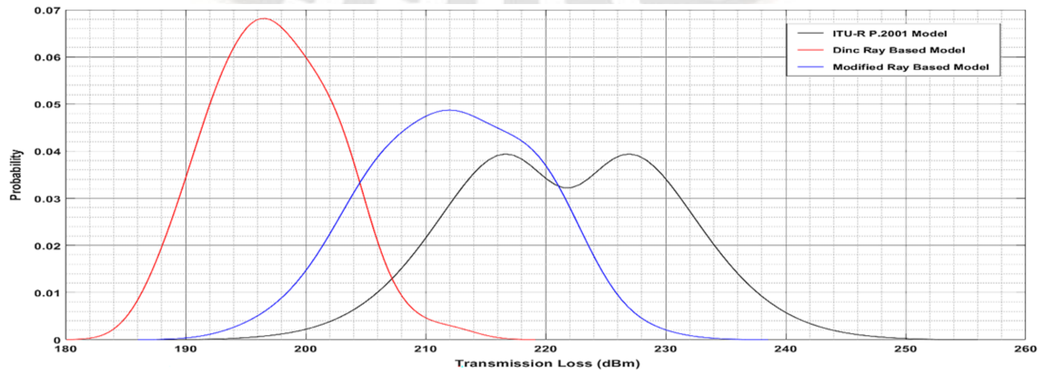
Calculation of vertical gradient of refractive index requires meteorological parameters like atmospheric pressure, temperature and vapour pressure. Meteorological data recorded at 05:30 a.m. every day, for different heights, has been obtained from observatory of Indian Meteorological Department (IMD) located at Ahmedabad, for years 1990 to 2021. Data of year 2006 has been used for validation due to its high height resolution and availability for all days of the year. N is obtained for different heights in common volume formed by each set of corresponding transmit and receive sub-beams using (24). $\delta n/\delta z$ is calculated for successive heights using (23). An average value of $\delta n/\delta z$ is calculated for each sub-beam set if more than two values of N are obtained in a sub-beam common volume. Received power for each sub-beam set is calculated for Dinc's model and modified model using the sub-beam average of $\delta n/\delta z$ in (28) and (32), respectively. Total received power (P_R) at 05:30 a.m. for all days of year 2006, is obtained for both the models by adding received powers of all sub-beams. Transmission loss is finally obtained as $10\log_{10}(P_T/P_R)$, with P_T as the total transmitted power.

VI. RESULTS

Fig. 6 shows CDF and PDF plots of transmission loss for different days of year 2006, obtained using Modified model, Dinc's model and ITU-R P.2001 model. Slight levelling of



(a) CDF plots of transmission loss for year 2006 obtained using different models



(a) CDF plots of transmission loss for year 2006 obtained using different models

Figure. 6 - Comparison of transmission loss obtained from Dinc's model and Modified model with ITU-R P.2001 model

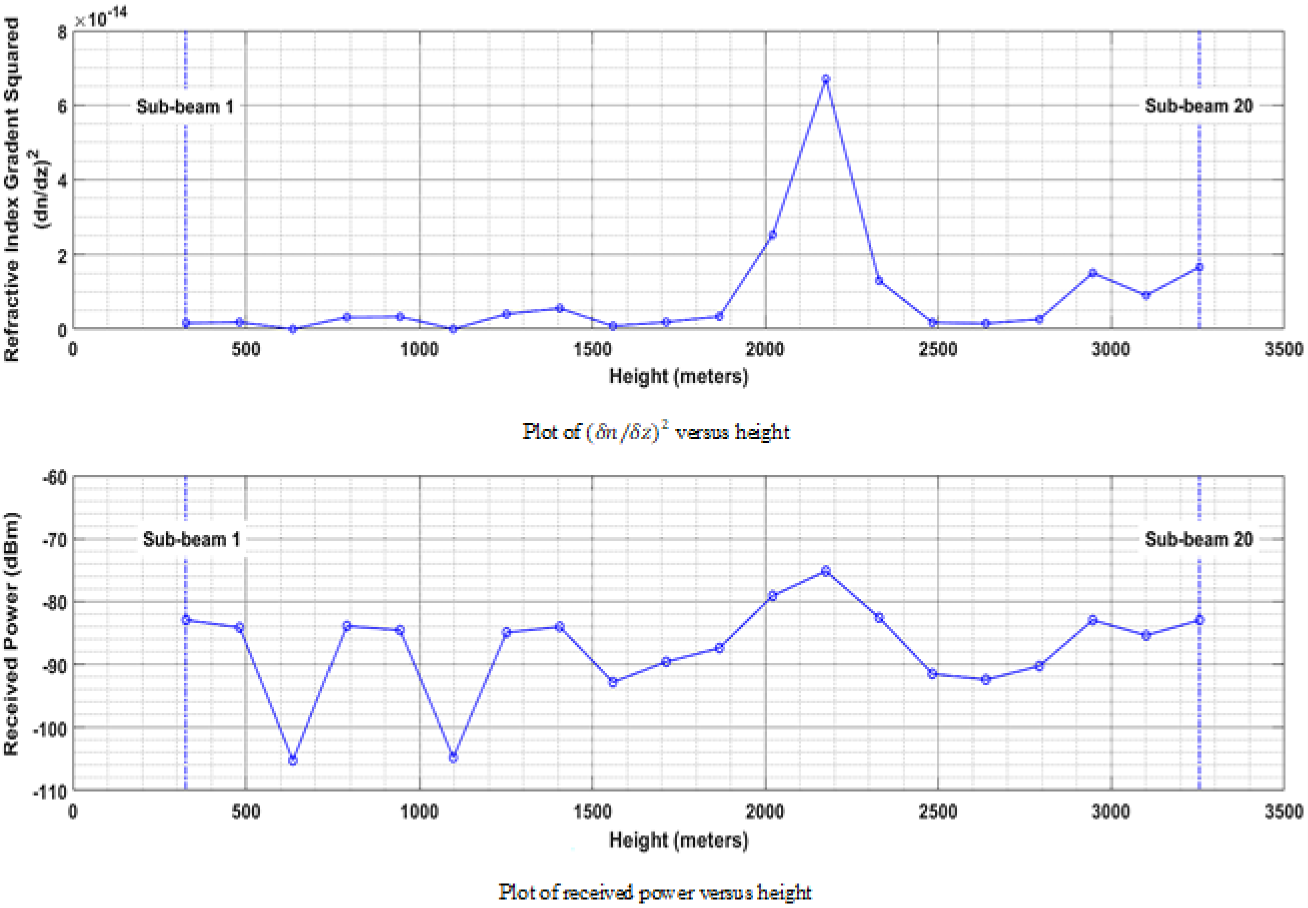


Figure. 7 Variation of square of refractive index and received power with heights of common volume formed by different sub-beams

CDF plot in ITU model at 50% time and corresponding dip in its PDF plot at 221.7 dB is due to different formula for calculation of C for p ≥ 50 and p < 50 in (19). RMS error between transmission loss CDFs of ITU model and modified model shown in fig. 6(a) is 9.77. Whereas, RMS error between transmission loss CDFs of ITU model and Dinc's model is much higher at 24.83. Average yearly transmission loss for ITU model, modified model and Dinc's model, obtained from fig. 6(a) at 50% time and fig. 6(b) at maximum probability points, are 221.7 dB, 212.4 dB and 196.8 dB, in that order. It can be seen that RMS error and difference of mean transmission loss from ITU model is much higher for Dinc's model as compared to modified model. As seen from both fig. 6(a) and 6(b), minimum transmission loss for ITU model and modified model are almost same while maximum transmission loss for ITU model is higher than the other two models. Again, the difference of maximum transmission loss from ITU model is higher for Dinc's model. Variance of transmission loss for ITU-R P.2001 model, modified model and Dinc's model, as calculated from their transmission loss data sets, are 78.43, 47.35 and 26.17, respectively. Hence, it can be seen that yearly distribution of transmission obtained from modified model is much closer to the yearly transmission loss distribution of ITU model as compared to Dinc' ray-based model. Thus, widely used ITU-R P.2001 model is in much better agreement with modified model as compared to Dinc's model.

ITU model still has higher average and maximum transmission loss than modified model. This is because value of M and expression for Y_{90}, used in ITU model for each zone, are averages obtained from experimental observations made over several years and over various links belonging to that zone. Also, the ITU model is designed to calculate maximum possible transmission loss for different percentages of time, to ascertain the time in a year for which a given link will be able to provide the required services.

Validation of modified ray-based channel model on the second aspect is done by considering 20 transmit and receive sub-beams. First 10 sub-beams belong to default transmit and receive antenna beams (antenna beams just clearing their respective horizons), while next 10 sub-beams lie above the default antenna beams. This helps in determining propagation conditions at heights above the common volume formed by default beams. $(\delta n/\delta z)^2$ and received power were calculated for each set of corresponding transmit and receive sub-beams using IMD data for different tropospheric heights at 05:30 a.m. on 12 Nov 2006. Fig. 7 shows the plots of $(\delta n/\delta z)^2$ and received power for different sub-beam sets against average heights of common volumes formed by these sub-beam sets. It can be seen from fig. 7(b) that received powers for sub-beam set no. 12 and 13 are much higher than other sub-beams. As seen from (32), ψ, R_t and R_r increase with sub-beam height, which leads to increased losses. However, as seen from fig.

7(a), value of $(\delta n/\delta z)^2$ in the common volume formed by sub-beam set no. 12 and 13 is considerably high, which results in high received power for these sub-beam sets in spite of increased losses. Hence, 2020 m and 2175 m are the most favourable heights at 05:30 a.m. on 12 Nov 2006.Transmit and receive antenna beams at this particular time and day should be steered such that their common volume includes these heights.

Favourable heights at 05:30 a.m. on all days of year 2006 were determined using modified model. It was found that favourable heights were often different on different days and changed significantly with seasons. Hence, it can be seen that modified model, using meteorological data from IMD, can be used to determine the favourable heights for different times of a day in different seasons, over a period of several years. An analysis of these favourable heights can be used to decide the height to which the antenna beams should be steered on a particular time and day of the year, besides limiting the steering range. Thus, modified model can be used for employing beam steering on tropospheric communication links.

VII. CONCLUSION

Major difficulty in deploying beam steering on tropo communication links has been the large sized heavy antennas which cannot be physical steered However, recent work aimed at development of tropo systems in C band [24] and Ku band [25] will replace the erstwhile large sized tropo antennas (operating in S band) with small sized antenna of diameter 10 meters or less. Phased array antennas will replace passive antennas in future, for employing beam forming [26,27] and possibly beam steering.

Refractive index and its gradient can be obtained from recordings of meteorological parameters being done worldwide. Based on our discussions and data obtained from Indian Metrological Department (IMD), it was found that radiosonde recordings of atmospheric pressure, temperature and dew point temperature are made from more than 40 different IMD observatories in Indian subcontinent. Advanced techniques and sensors are being developed for meteorological observations, with satellite-based sensors being used lately. These satellite-based sensors are capable of gathering atmospheric data at different tropospheric heights for any location, almost continuously in time, with high height resolution. These high resolution and accurate meteorological databases can be used to determine the diurnal and seasonal variations in atmospheric refractivity (and its gradient) at any point of interest. Beam steering in tropo systems will become a practical reality in near future and modified ray-based channel model, presented in this paper, can be effectively used for the same.

Beam steering is essential for performance enhancement of tropospheric communication links making them capable of fulfilling modern warfare requirements. Steering mechanism should comprise of coarse beam steering based on prior information of favourable heights followed by a finer beam steering using real time monitoring of received signal. Various channel models developed since discovery of troposcatter phenomenon have been discussed in this paper for their suitability for employing beam steering. Dinc's model, owing to its ray-based approach and use of real-world data of atmospheric parameters, provides an effective and practical method for employing beam steering. A modified ray-based channel model has been presented in this paper which is a more realistic tropospheric channel model as compared to Dinc's model. Modified model has been shown to be in better agreement with well-known ITU-R P.2001 model. It has also been established that modified model is capable to identify favourable tropospheric heights and hence, is suitable for employing beam steering.

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***Article Received:** 25 July 2023 **Revised:** 12 September 2023 **Accepted:** 30 September 2023*

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