Troposcatter transmission loss prediction based on particle swarm optimisation

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Abstract
Tropospheric scatter is a promising method for over-the-horizon propagation. Transmission loss caused by the three mainstream troposcatter mechanisms is analysed, namely turbulent incoherent scattering theory, coherent reflection by stable layers theory, and incoherent reflection by irregular layers theory. Then an experiment is conducted to explore the relationships among the three mechanisms. Based on this experiment, the troposcatter transmission loss prediction model is established in different climate zones by a particle swarm optimisation algorithm and experimental data from the global troposcatte database. The simulation shows that this model is more effective than the existing International Telecommunication Union-Radiocommunication Sector (ITU-R) P.617, P.452, and P.2001. Furthermore, by analysing the training parameters’ proportion of the new model in different climate zones, the specific composition of three troposcatter mechanisms can be obtained.

1 | INTRODUCTION
In the lowest portion of Earth's atmosphere, which is generally called the troposphere, there is a large degree of in-homogeneity. When radio waves pass through these inhomogeneous media, they are radiated by the inhomogeneity to achieve over-the-horizon (OTH) propagation in addition to being refracted [1,2]. This phenomenon is called tropospheric scattering (also known as troposcatter). There are three main applications of tropospheric scattering in communication: crossing obstacles communication, emergency communication, and the connection node of different communication means in the communication system. As early as 1937, Marconi proved through experiments that troposcatter is a new way of OTH propagation different from diffraction [3]. With the development of radar, high-power broadcasting, and television technology, more and more countries have discovered OTH propagation for ultrashort wave and microwave in experiments. Based on this, much research has been conducted on troposcatter propagation’s characteristics and mechanisms. In 1950, Booker and Gordon proposed in [4] that troposcatter propagation is caused by turbulent motion in the troposphere and formed the corresponding turbulent incoherent scattering theory. In 1952, an internal reflection mechanism based on the smooth spherical theory was introduced by Feinistien in [5]. In 1957, Friis developed the theory that OTH propagation is caused by a series of spring layers in the atmosphere [6]. In 1963, the coherent reflection by stable layers theory was proposed by Bullington in [7]. He divided the medium in the common volume into a series of layers according to height and believed that the receiver's field strength was the result of the superposition of each reflected component. Although many theoretical explanations for the troposcatter propagation mechanism have been proposed, there has not been a unified theoretical model until now [8].

Simultaneous with the study of troposcatter propagation mechanism is research on transmission loss prediction models. Transmission loss prediction is a critical step in analyzing and designing the link budget of a troposcatter communication system. In 1955, Norton et al. [9] proposed a new troposcatter transmission loss prediction method based on the Weisskopf–Villars theory. In 1967, the National Bureau of Standards developed a prediction model based on the Weissenkopf–Villas theory. In 1967, the National Bureau of Standards developed a prediction model based on the turbulent incoherent scattering theory [10]. In 1974, the International Radio Consultative Committee (CCIR) obtained a simplified transmission loss prediction model by analysing the symmetry circuit in [10] and finally formed the CCIR 238 report [11]. With the extensive implementation of
troposcatter experiments, it is Recommendations P.617 [12], P.452 [13], and P.2001 [14] issued by the International Telecommunication Union Radiocommunication Sector (ITU-R) that are currently widely used to predict troposcatter transmission loss. In ITU-R P.617, six climate zones are categorised, and time probability-based transmission loss prediction models in different climate zones are established. ITU-R P.425 is mainly used for the transmission loss prediction of ground links in the frequency band above 0.1 GHz. In ITU-R P.425, the models are combined, and a large-scale transmission loss prediction model suitable for 35–50 MHz with a link length of 1–1000 km is proposed. In 2016, [15] combines the three models in the ITU-R Recommendations above by genetic algorithm to establish a new empirical prediction model. Although these prediction models are well-established from different aspects, they are largely empirical formulas that cannot explain the statistical distribution of transmission loss from the scattering mechanism itself. However, with the development of optimisation algorithms, we can fit different troposcatter propagation models with many experimental data and analyse the specific troposcatter mechanisms from the fitted parameters. The particle swarm optimisation (PSO) algorithm is a representative optimisation algorithm [16]. Our primary motivation is to establish a troposcatter transmission loss prediction model from the troposcatter mechanism aspect. The purpose is to improve prediction accuracy and analyse the specific composition of the troposcatter mechanism.

The rest of this paper is organised as follows. In Section 2, we mainly analyse the three mainstream troposcatter mechanisms and give the corresponding transmission loss calculation formulas for each mechanism. In Section 3, to clarify the relationships among the three scattering mechanisms in transmission loss, we conduct an experiment on the field strength distribution of the tropospheric scattering signal. In Section 4, we first introduce the PSO algorithm and define the corresponding fitness function. The experimental link data from [17] is used to train the new transmission loss prediction models’ fitness parameters in different climate zones. The effectiveness of these models is simulated and verified. Moreover, by analysing each training parameter’s proportion in the new prediction model, the three mechanisms’ compositions in different climate zones are obtained. Section 5 is the conclusion.

2 | TROPOSCATTERING MECHANISM

Since the 1950s, many countries have researched tropospheric OTH propagation, mainly in the form of theoretical research [18,19,20]. Many studies have explained the characteristics of troposcatter propagation and clarified its propagation mechanism. Generally, there are three main theories: turbulent incoherent scattering theory [4], coherent reflection by stable layers theory [7], and incoherent reflection by irregular layers theory [6].

2.1 | Incoherent scattering by turbulence

Owing to turbulent motion in the troposphere, vortices of different scales appear. The continuous movement and variation of these vortices form inhomogeneity with a continually changing dielectric permittivity. Generally, the size of the physical inhomogeneity in the troposphere can be determined by \( \Lambda = \lambda/[2 \sin(\Theta/2)] \) [8], where \( \Lambda \) represents the size of the physical inhomogeneity and \( \Theta \) is the scattering angle. When radio waves are projected onto the turbulent inhomogeneity, the inhomogeneity is transformed into the source of secondary radiation that provide a scattering field strength component to the receiver. Through this, the OTH transmission is realized. The propagation process is shown in Figure 1.

We define \( P_{tr} \) to represent the receiving power. Then from [8], \( P_{tr} \) can be expressed as

\[
P_{tr} = P_t G_{10} G_{20} \left( \frac{\lambda}{4\pi} \right)^2 \int_0^{\frac{\pi}{2}} \int_0^{\frac{\pi}{2}} g_1 g_2 \sigma \, dV
\]

(1)

where \( P_t \) is the transmitting power, \( G_{10} \) and \( G_{20} \) represent the gains of the transmitting and receiving antennas, respectively, \( g_1 \) and \( g_2 \) are the directivity functions of the transmitting and receiving antennas, respectively, \( \sigma \) represents the scattering cross section, and \( r_1 \) and \( r_2 \) respectively indicate the distance from the transmitter and receiver to the common volume. To integrate (1), we transform the scattering volume element \( dV \) to

\[
dV = \frac{d_1 d_2}{\Theta_0} d\theta_1 d\theta_2 d\phi_2
\]

(2)

The transmitter and receiver antenna directivity functions \( g_1 \) and \( g_2 \) are selected with Gaussian patterns that can be expressed as

\[
g_i = \exp \left[ -a_i(\phi_i - \phi_{0i})^2 - b_i(\theta_i - \theta_{0i})^2 \right] (i = 1, 2)
\]

(3)

where

![Figure 1: Incoherent scattering by turbulence](image-url)
According to [4], \( \sigma \) can be expressed as

\[
\sigma = A_2 \lambda^m \Theta_0 e^{-m' \phi_0} \exp \left\{ -m' \phi_2^2 - 2c_1 \theta_1 - 2c_2 \theta_2 \right\}
\]

where

\[
m' = \frac{m}{2e \Theta_0^2}
\]

\[
c_i = \frac{m + \gamma \theta_0}{2e \Theta_0} s_i (i = 1, 2)
\]

\[
s_1 = \frac{1}{s_1} = \frac{d_2}{d_1}
\]

and \( d_1 \) and \( d_2 \) respectively represent the distance from T, R, to the scattering point's vertical projection. The meanings of the symbols in Equations (2)–(9) are explained in Table 1.

By substituting Equations (2)–(9) into Equation (1) the received power \( P_{tr} \) is

\[
P_{tr} = P_t G_{t0} G_{20} \left( \frac{\lambda}{4\pi} \right)^2 B \exp \left\{ -a_1 (\phi_1 - \phi_{10}) \right\}
\]

\[
\cdot \int_{-\infty}^{+\infty} \exp \left\{ -m' \phi_2 - a_2 (\phi_2 - \phi_{20})^2 \right\} d\phi_2
\]

\[
\cdot \int_{0}^{+\infty} \exp \left\{ -2c_1 \theta_1 - b_1 (\theta_1 - \theta_{10})^2 \right\} d\theta_1
\]

\[
\cdot \int_{0}^{+\infty} \exp \left\{ -2c_2 \theta_2 - b_2 (\theta_2 - \theta_{20})^2 \right\} d\theta_2
\]

where

\[
B = \frac{d_1 d_2 A_2 \lambda^m \Theta_0 e^{-m' \phi_0}}{(r_1 r_2)^2}
\]

and \( A_2 \) represents the structural parameter of the atmosphere, \( m \) is the negative power exponent of the scattering angle related to the tropospheric medium structure, \( n \) is the frequency index of the main basic transmission loss relative to free space, and \( \gamma \) represents the distribution index of the atmospheric uneven intensity with height. We do not consider the deflection loss of the antenna; that is, the azimuth angle of antennas is zero. By calculating the integral in Equation (10), we obtain

\[
P_{tr} = \frac{P_t G_{t0} G_{20} \left( \frac{\lambda}{4\pi} \right)^2 2\pi^{3/2} B}{\sqrt{b_1 b_2 (a_2 + 4m')}}
\]

\[
\cdot \exp \left\{ \frac{4c_1^2}{b_1} + \frac{4c_2^2}{b_2} \right\} \text{erfc} \left( \frac{2c_1}{\sqrt{b_1}} \right) \text{erfc} \left( \frac{2c_2}{\sqrt{b_2}} \right)
\]

Herein, the experimental data comes from the global tropospheric scattering databank [17] promulgated by the ITU in 1986. Since most transmission link loss in the databank is relative to free space, we also must consider the received power of radio waves propagating in free space, which is

\[
P_{free} = P_t G_{t0} G_{20} \left( \frac{\lambda}{4\pi d} \right)^2
\]

From Equations (12) and (13), we can obtain the expression of the received power relative to free space:

| Parameter | Meaning |
|-----------|---------|
| \( A_2, m, n, \gamma \) | Meteorological parameters |
| \( \Theta_0 \) | Minimum scattering angle |
| \( h_0 \) | Height above the straight line TR |
| \( d \) | Distance from transmitter to receiver |
| \( \Theta_{10}, \Theta_{20} \) | Elevation angles above straight line TR of horizon planes from T and R |
| \( \theta_1, \theta_2 \) | Elevation angles of T, R |
| \( \theta_{10}, \theta_{20} \) | Elevation angles of T, R main axis |
| \( \phi_{20}, \phi_{20} \) | Horizontal beam width of T, R |
| \( \phi_{20}, \phi_{20} \) | Vertical beam width of T, R |
| \( \Psi(x) \) | Complementary error function |
| \( \phi_{10}, \phi_{20} \) | Azimuth angle of T, R |
| \( \phi_{10}, \phi_{20} \) | Antenna main axis azimuth of T, R |
\[
\frac{P_{tr}}{P_{\text{free}}} = \frac{2\pi^{3/2}B}{\sqrt{b_1 b_2 (a_2 + 4m')}} \cdot \exp \left( \frac{4c_1^2}{b_1} + \frac{4c_2^2}{b_2} \right) \text{erfc} \left( \frac{2c_1}{\sqrt{b_1}} \right) \text{erfc} \left( \frac{2c_2}{\sqrt{b_2}} \right) \tag{14}
\]

where \(d_0\) represents the line-of-sight distance between the TR stations and can be expressed as

\[
d_0 = 4.12 \left( \sqrt{b_T} + \sqrt{b_R} \right) \tag{18}
\]

where \(b_T, b_R\) are the heights above ground, in m, of the transmitting and receiving antennas, respectively. Note further that \(\sigma^2(\Delta \varepsilon_r)\) in Equation (16) represents the variance of ground path dielectric permittivity and can be expressed as

\[
\sigma^2(\Delta \varepsilon_r) = \sigma^2 \left( N_r \times 10^{-6} + 1 \right)^2 - 1 \tag{19}
\]

where \(N_r\) is the average value of atmospheric refractivity at the Earth's surface, which can be found directly in the databank. The parameter \(b\) is

\[
b = \frac{8}{\Delta \varepsilon_r} \tag{20}
\]

where \(g\) is the acceleration of gravity in \(\text{km/s}^2\) at the transmitting station of the experimental link.

By taking the logarithm of Equation (16), the transmission loss caused by the stable layers’ coherent reflection is

\[
L_{st} = 10 \log \left( \frac{b \sigma^2(\Delta \varepsilon_r) \lambda}{8 \pi^2 \varphi_L^5} \right) + 20 \log \left( 1 - e^{-b \varphi_L d/4} \right) - \frac{5g \varphi_L d}{2 \Delta \varepsilon_r} \log e \tag{21}
\]

### 2.2 Coherent reflection by stable layers

This theory assumes that the medium in the common volume of the troposphere can be divided into a series of thin layers, as shown in Figure 2. In each layer, the dielectric permittivity value can be approximated as a constant. Moreover, these layers reflect the incident radio waves, and the coherent superposition of each reflected component at the receiver constitutes the receiving field strength.

Relative to free space, the received power coherently reflected by the stable layers can be expressed as

\[
\frac{P_{st}}{P_{\text{free}}} = \left[ \frac{b \sigma^2(\Delta \varepsilon_r) \lambda}{8 \pi^2 \varphi_L^5} e^{-b \varphi_L d/4} \right] \left[ 1 - e^{-b \varphi_L d/2} \right]^2 \tag{16}
\]

where \(\varphi_L\) is the glancing angle and can be calculated by

\[
\varphi_L = \frac{d - d_0}{8500} \tag{17}
\]

### 2.3 Incoherent reflection by irregular layers

A large number of observations have shown that there is also a spring layer formed by air convection and the intersection of cooling and heating air masses in the troposphere in addition to turbulent irregularities. In the spring layer, the gradient of the refractive index fluctuates wildly. Because these spring layers have different shapes and continuously change their positions and strengths with atmospheric movement, they are also called irregular layers, as shown in Figure 3.

The radio waves emitted from the transmitter are reflected by the irrelevant region of these irregular layers’ boundaries to conduct OTH propagation. The receiver’s field strength can be obtained by adding the reflection components of each irregular layer owing to the layer’s irrelevant nature. From [6] and (13), we obtain

\[
\frac{P_{ir}}{P_{\text{free}}} = \frac{4M'' \lambda}{3\Theta_0^2} \left[ \frac{\frac{d}{\Theta_0}}{\frac{d}{\Theta_0}} + \frac{\frac{d}{\Theta_0}}{\Theta_0} \right] \tag{22}
\]
where

\[
M' = \frac{0.75\Theta_{10}^5 \cdot \left(2 + \frac{a}{\sigma_{10}}\right)}{\lambda a f \cdot 10^{L_{\text{sky}}}} \tag{23}
\]

\[
q\left(\frac{a}{\Theta_{10}}\right) = 1 + \frac{1}{\frac{a}{\Theta_{10}}} - \frac{1}{8} \left(\frac{2 + \frac{a}{\sigma_{10}}}{1 + \frac{a}{\Theta_{10}}}\right)^2 \tag{24}
\]

and \(L_{\text{sky}}\) is the measured troposcatter propagation loss in the same area. Then the transmission loss caused by the irregular layers’ incoherent reflection is

\[
L_r = \log \frac{4 M' \lambda}{3 \Theta_{10}^4} + \log \frac{a}{\sigma_m} q\left(\frac{a}{\sigma_m}\right) \tag{25}
\]

3 | STATISTICAL PROPERTIES OF SCATTERING SIGNALS

The tropospheric scattering signals’ transmission loss prediction premise clarifies the relationships among the three aforementioned scattering mechanisms in the troposphere. First, we compare the transmission loss of the prediction models based on the three scattering mechanisms, respectively, with the losses obtained from the actual 34 troposcatter links in [17]. The simulation results are shown below.

The simulation results in Figure 4 show that the three scattering mechanisms do not exist alone in the troposphere but in two or more combinations. Any transmission loss model of a single scattering mechanism cannot accurately predict the actual link loss we have selected from [17]. Furthermore, we find that the transmission loss caused by stable layers is relatively stable when the transmission distance does not change significantly. The troposcatter channel is a typical multipath channel. When there is no signal propagating through the direct path except reflection, refraction, and scattering signals in the receiver, the multipath signal's field strength obeys the Rayleigh distribution. When the receiver also receives direct signals, the combined signals' field strength obeys the Rice distribution. Since troposcatter communication is usually applied as a means of OTH communication, there is no direct signal component in the receiver, so the troposcatter channel is often studied as a Rayleigh fading channel in most research. However, this hypothesis lacks relevant experimental verification.

In the existing troposcatter experiments, such as the global troposcatter database [17], most of the data given are the mean value of the long-term signal amplitude slow fading from which we cannot obtain the fast fading amplitude distribution of the received signal. Therefore, we conducted a 24 h experiment of the receiving troposcatter signal’s field strength variation to explore the signal's statistical characteristics. Moreover, the tropospheric scattering signal's fast fading period is generally within seconds to minutes, and the fading rate for the 2–5 GHz radiofrequency is 2-5 Hz. Therefore, the amount of data obtained in 24 h is sufficient to analyse the signal amplitude's statistical characteristics. Utilising related equipment, we established a scattering link between Xi'an, China (N 34°17'25", E 109°1'19") and Sanyuan, China (N 34°38'41", E 108°58'25") with a link length of 40 km. Due to the large undulations between the two points, there is no direct signal component between the transmitter and receiver. The receiving and transmitting antennas used in the experiment are both parabolic antennas. The height of the transmitting and receiving antennas from the ground is 6 m, and the elevation angle of the transmitting antenna is 4.8°. The output power is 50 dBm. In the experiment, we calibrated four frequency points M1, M2, M3, and M4, and they were 63 MHz, 67 MHz, 72.9 MHz, and 77 MHz, respectively. By analysing and drawing the field strength's frequency distribution histogram of the received scattering signal, the distribution probability curve can also be obtained by the fitting. Simultaneously, according to the collected signal field strength's sample data, the corresponding Rice distribution curve and Rayleigh distribution curve are.
extracted using the expectation-maximisation algorithm. We take the samples collected at 63 MHz, 67 MHz and the collection time in three periods: morning (8:00 AM–10:00 AM), noon (12:00 PM–2:00 PM), and evening (7:00 PM–9:00 PM) as an example, and the probability distribution is shown in Figure 5. The probability distributions of the frequency points M3 and M4 are similar to those of M1 and M2. For the sake of brevity, they are not shown in Figure 5.

It can be seen from Figure 5 that the troposcatter channel is a mixture of Rayleigh and Rice channels. Among the three troposcatter mechanisms, since the nonlinear distribution of dielectric constant with height is relatively stable, the coherent reflection component by stable layers is generally relatively constant in the short term. Due to the uncertainty of the turbulent motion and sharp change layer changes in the troposphere, the turbulent incoherent component and the incoherent reflection component by irregular layers change rapidly. Based on the above experimental results, we can assume that in troposcatter communication, the stable layer’s coherent reflection component assumes the role of the direct signal component in the multipath channel. Thus the field strength distribution of the received signal includes the form of the Rayleigh distribution. However, due to the randomness of the tropospheric atmosphere itself, the turbulent incoherent component and the incoherent reflection component by irregular layers dominate for a certain period, so the signal field strength distribution also includes the form of the Rice distribution. The experiment shows the contradictory relationship between the coherent reflection component by the stable layers and the other two components: the more violent the turbulent motion and the change of the sharp change layers are, the smaller the proportion of the coherent reflection component by the stable layer in the troposphere. Therefore, we define \( L \) to represent the transmission loss (relative to free space), and we conclude that the troposcatter transmission loss model based on the three mechanisms has the following form:

\[
L = x_1L_{tr} + x_2L_{ir} + (1 - x_1 - x_2)L_{st}
\] (26)

where \( x_1, x_2 \) respectively represent the weighting factors of \( L_{tr} \) and \( L_{ir} \). By analysing the experimental data in the databank, we define the value range of \( x_i \) as \([0,1]\).

4 | TROPOSCATTER TRANSMISSION LOSS PREDICTION MODEL BASED ON PSO

4.1 | Particle swarm optimisation algorithm

In Section 3, we determined the troposcatter transmission loss expression based on the relation of three scattering mechanisms. What we must do is find a set of \( x_1, x_2 \) values so that the predicted transmission loss error can be minimised between the result of (26) and the actual experimental value. In [13], Kennedy and Eberhart proposed the PSO algorithm. By simulating the search process of the bird group for food resources, the PSO algorithm can obtain the optimal solution of a specific problem. Because the PSO algorithm possesses fast convergence speed, concise parameter settings and is not limited by whether the objective function is continuous or differential, it has been widely used in function fitting. In this paper, we apply the PSO algorithm to fit the parameters in (26).

We regard a set of values of \( x_1, x_2 \) as a particle, and the number of its elements as the dimension of the particle. Then we can initialise \( N \) particles in the two-dimensional search space. We define the position of the \( i \)th particle:

\[
X_i = (x_{i1}, x_{i2})i = 1, K, N
\] (27)

and the corresponding fitness function is

\[
F(i) = \frac{1}{R} \sum_{r=1}^{R} \left| (x_{i1}L_{tr} + x_{i2}L_{ir} + (1 - x_{i1} - x_{i2})L_{st}) - L_{bey}\right|
\] (28)

where \( L_{bey} \) is the transmission loss median value of the \( r \)th troposcatter link of the experimental data we selected. In

![Figure 5](image-url) Distribution of received signal field strength in different time periods. (a) M1 frequency point and (b) M2 frequency point
addition, the iterative update of particle speed and position refers to the standard PSO algorithm. Through a certain number of iterations, the best position of particles is accessible for which the fitness value is optimal.

4.2 Prediction model

It is not easy to use a unified prediction expression owing to the strong randomness of the tropospheric atmosphere. In IUT-R P.617, according to climatic conditions, different troposcatter climate zones are divided as shown in Figure 6. In each climate zone, there is a corresponding prediction model that improves accuracy. Therefore, we locate the troposcatter databank experiments in different climate zones and establish their independent prediction models.

On the basis of the division of climate zones in [12], we obtain 54 scatter links belonging to zone 4, 44 scatter links in zone 5, and 275 scatter links in zone 6. Since the number of scattering links in other zones is too small to train the parameters $x_1, x_2$ in (26), we do not consider them in this paper. In addition, we make the following assumptions:

- Since antenna type and diameter are not recorded in the databank, we assume the antenna used in the experiment is a parabolic antenna.
- The ray of the antenna is in the centre of the beamwidth.
- The antenna’s deflection loss is not considered due to the lack of azimuth data in [17]. That is, we assume the azimuth angle of antennas is zero.

Based on the two assumptions, the antenna half-power beam width $\varphi$ can be approximated as [21,22] in rad:

$$\varphi = 1.2\lambda/D$$  \hspace{1cm} (29)

where we assume the value of $D$ is $\lambda/4$ [23,24,25]. Since only the measured data of the scattering angle $\Theta$ is provided in [17], we need to find the relationship between the other angles and $\Theta$. According to the geometric relationship in the three troposcatter propagation mechanisms, and we obtain

$$\Theta = \Theta_0 \exp\left\{\frac{2\theta_1}{\Theta_0}\right\}$$  \hspace{1cm} (30)

$$\theta_1 \approx 0.44\sqrt{\frac{\Theta_0 \psi_{e2}}{5 + 0.3h_0}}$$  \hspace{1cm} (31)

$$b_0 = \frac{d}{2} \tan \frac{\Theta_0}{2}$$  \hspace{1cm} (32)

From (30)–(32), we obtain the values of $\Theta_0$ by the geometric relationship, and we obtain all the angles needed in (16), (21), and (25).

In climate zone 4, we select 36 links’ data as training data; in climate zone 5, we select 28 links’ data as training data; and 215 links’ data are selected as training data in climate zone 6. Simultaneously, to verify the effectiveness of the prediction model, we select 15 additional links’ data in each climate zone as test data. After training, we obtain the fitting parameters of the three climate zones, as shown in Table 2:

Convert the form into (26):

$$L_4 = 0.7558L_{tr} + 0.0466L_{tr} + 0.1982L_{rt}$$  \hspace{1cm} (33)

$$L_5 = 0.7020L_{tr} + 0.2250L_{tr} + 0.0730L_{rt}$$  \hspace{1cm} (34)

$$L_6 = 0.3760L_{tr} + 0.3123L_{tr} + 0.3117L_{rt}$$  \hspace{1cm} (35)

Next, we need to verify the three prediction models obtained. We select the transmission loss empirical formulas in ITU-R P.617, P.2001, and P.452 as references to verify their effectiveness.

In P.617, the transmission loss empirical formula is

$$L'_{617} = A_2 + \log f + 10 \log d$$
$$+ 30 \log \Theta + L_N + L_c - G_t - G_r - Y(q)$$  \hspace{1cm} (36)

where $L_N$ represents the dependent loss in transmission, and $L_c$ is the aperture-to-medium coupling loss. They are respectively

$$L_t = 0.07 \exp[0.055(G_t + G_r)]$$  \hspace{1cm} (37)

$$L_N = 20 \log(5 + \gamma H) + 4.34\gamma b$$  \hspace{1cm} (38)

**Table 2** The fitting parameters

| Climate zone | 4    | 5    | 6    |
|--------------|------|------|------|
| $x_1$        | 0.7558 | 0.7020 | 0.3760 |
| $x_2$        | 0.0466 | 0.2250 | 0.3123 |

**FIGURE 6** Climate zones classified in International Telecommunication Union Radiocommunication P.617
Similarly, the transmission loss empirical formulas in ITU-R P.2001 and ITU-R P.452 are respectively

\[ L'_{2001} = A_2 + L_{\text{freq}} + L_{\text{dist}} + L_c - Y(q) \]  

(41)

\[ L_{\text{freq}} = 25 \log \left( \frac{f}{1000} \right) - 2.5 \left[ \log \left( \frac{f}{2000} \right) \right]^2 \]  

(42)

\[ L_{\text{dist}} = \max [10 \log d + 30 \log \Theta + L_N, 20 \log d + 0.573 \Theta + 20] \]  

(43)

\[ L'_{452} = 190 + L_f + 20 \log d + 0.573 \Theta - 0.15 N_0 + L_c + A_g - Y(q) \]  

(44)

\[ L_f = 25 \log(f) - 2.5 \left[ \log \left( \frac{f}{25} \right) \right]^2 \]  

(45)

Because what is considered in this paper is the average annual median loss of troposcatter, the conversion factor \( Y(q) \) is zero, and we ignore the loss of atmospheric absorption, \( A_g \). \( N_0 \) is the mean value of atmospheric refractive index at sea level, generally taking \( N_0 = 315 \). In addition, the free space basic transmission loss recommended in ITU-R P.525 is

\[ L_{\text{free}} = 32.4 + 20 \log f + 20 \log d \]  

(46)

In (16), (21), (25), the influence of antenna gain is not considered; therefore, we ignore the aperture-to-medium coupling loss \( L_c \). Based on this assumption, the transmission loss formulas relative to free space in three recommendations can be expressed as

\[ L_{417} = A_2 + \log f + 10 \log d + 30 \log \Theta + L_N - L_{\text{free}} \]  

(47)

\[ L_{2001} = A_2 + L_{\text{freq}} + L_{\text{dist}} - L_{\text{free}} \]  

(48)

\[ L_{452} = 190 + L_f + 20 \log d + 0.573 \Theta - 0.15 N_0 - L_{\text{free}} \]  

(49)

### 4.3 Simulation analysis

In the simulation, we use the 15 test links in each climate zone to calculate the errors between the actual loss and the four models’ prediction loss. The meteorological parameters \( m, n, A_2, \) and \( \gamma \) in each climate zone are defined in Table 3. Regarding the frequency and distance application range of the model, when training the PSO model, the smallest electromagnetic wave frequency is 55.8 MHz, and the largest is 9375 MHz; the shortest scattering link length is 10.3 km, and the longest is 1112.1 km. Therefore, the proposed PSO model’s theoretical effective frequency range is 55.8-9375 MHz, and the distance range is 10.3-1112.1 km.

The simulation results are shown in Figure 7.

The average calculation errors and root mean square errors for different climate zones are shown in Tables 4-6.

From Figure 7 and Tables 4-6, we find that the accuracy of the prediction model established by the PSO algorithm is closely related to the amount of training data. The more data involved in parameter training, the higher the prediction accuracy is. In climate zone 6, we utilise 215 effective links to train the PSO model, which is much more than the number of training links in climate zones 4 and 5. Thus, in climate zone 6, the model (35) is more accurate than the prediction model in P.617, P.2001, and P.452. In climate zones 4 and 5, the performance of the model (33) and (34) is close to the prediction model in P.452. In general, the simulation results prove the effectiveness of the PSO prediction based on the three scattering mechanisms derived in Section 2, and it also proves the feasibility of the conjecture of the relationships among the three tropospheric scattering mechanisms in Section 3. In addition, it should be noted that the above error calculations are all absolute values.

| TABLE 3 Meteorological parameters |
|-----------------------------------|
| Climate zone | 4 | 5 | 6 |
| \( M \) | 2.7 | 3 | 3 |
| \( N \) | 1.5 | 1 | 1 |
| \( A_2 \) (dB) | 38.50 | 29.73 | 33.20 |
| \( \gamma \) (km\(^{-1}\)) | 0.27 | 0.27 | 0.27 |

**FIGURE 7** Calculation errors of the four models. (a) Climate zone 4, (b) Climate zone 5 and (c) Climate zone 6
TABLE 4 The mean value and RMSE in climate zone 4

| Model | P617 | P2001 | P452 | PSO |
|-------|------|-------|------|-----|
| Mean  | 10.1437 | 11.7174 | 6.5578 | 8.1758 |
| RMSE  | 10.8108 | 13.1555 | 7.6784 | 10.6290 |

Abbreviation: RMSE, root mean square error.

TABLE 5 The mean value and RMSE in climate zone 5

| Errors relative to actual loss | Model | P617 | P2001 | P452 | PSO |
|-------------------------------|-------|------|-------|------|-----|
| Mean                          | 7.2748 | 12.3341 | 5.7563 | 6.8157 |
| RMSE                          | 10.1800 | 16.0474 | 7.5858 | 7.5554 |

Abbreviation: RMSE, root mean square error.

TABLE 6 The mean value and RMSE in climate zone 6

| Errors relative to actual loss | Model | P617 | P2001 | P452 | PSO |
|-------------------------------|-------|------|-------|------|-----|
| Mean                          | 6.3585 | 15.9803 | 6.1904 | 5.7820 |
| RMSE                          | 8.0825 | 20.1408 | 8.2832 | 7.8511 |

Abbreviation: RMSE, root mean square error.

TABLE 7 The proportion of three mechanisms in different climate zones

| Climate zone | 4 (%)  | 5 (%)  | 6 (%)  |
|--------------|--------|--------|--------|
| Turbulence   | 80.60  | 71.84  | 36.52  |
| Irregularities | 1.02  | 21.76  | 35.91  |
| Stable layers | 18.38 | 6.40   | 27.57  |

Through the values of $x_1, x_2$ in each model, we can analyse the proportion of the three troposscatter propagation mechanisms in different climate zones. We define the proportion of each propagation mechanism as its loss contribution rate, the expressions of which can be

$$P_{tr} = \frac{x_1 \overline{L}_{tr}}{\overline{L}} \times 100\% \quad (50)$$

$$P_{ir} = \frac{x_2 \overline{L}_{ir}}{\overline{L}} \times 100\% \quad (51)$$

$$P_{st} = \frac{(1 - x_1 - x_2) \overline{L}_{tr}}{\overline{L}} \times 100\% \quad (52)$$

where $\overline{L}$ represents the mean value of the transmission loss of the 15 links selected above for each climate zone. By calculation, the compositions of the three troposscatter mechanisms in different climate zones is given in Table 7.

And we use a curve to express the proportion variation with different climate zones.

From Figure 8, we find that all three troposscatter propagation mechanisms exist no matter the climate zone. Furthermore, this verifies the judgement that the three propagation mechanisms determine troposscatter transmission loss commonly, so when only one of the propagation mechanisms is used for loss prediction, the results are often inaccurate. Then we analyse climatic characteristics to explain why such a proportion variation occurs. From [26,27], we find that the monthly average value of $\Delta e_{tr}$ in climate zone 6 is greater than that in climate zones 4 and 5 at the same height, which means there is a larger $\sigma^2(\Delta e_{tr})$ in climate zone 6. Accordingly, the proportion of transmission loss caused by stable layers will have greater weight. On the other hand, the degree of the atmosphere's random movement can be judged by wind speed, and wind speed increases with latitude. Since most of our selected troposscatter links in climate zone 6 are located in the United States, the latitude is lower than that of climate zones 4 and 5. Therefore, compared with climate zone 6, the transmission loss caused by turbulence and irregular layers accounts for a larger proportion of loss in climate zones 4 and 5.

The Equations (33)–(35) are obtained from experimental data of transmission loss not exceeding 50% of total time. We can expand the prediction range to other time percentages by adding a conversion factor, $Y(q)$. Conversion factor $Y(q)$ for non-exceedance percentages $q$ other than 50% is

$$Y(q) = \begin{cases} 
0.035N_0 \exp(-b_0/h_b) \cdot (-\log(q/50))^{0.67} & q < 50 \\
-0.035N_0 \exp(-b_0/h_b) \cdot (-\log(100 - q)/50)^{0.67} & q > 50 
\end{cases}$$

(55)

where $h_b$ is the global average vertical height of 7.35 km.

![Figure 8](image-url)
5 | CONCLUSIONS

In this paper, we first derive the transmission loss formula caused by the three scattering mechanisms. Then we conduct an experiment to explore the field strength distribution of the troposcatter signal. The experimental results show that the coherent reflection component by stable layers in troposcatter propagation plays a role similar to the direct component in multipath propagation. Furthermore, this component decreases as (1) the incoherent reflection component by turbulence and (2) the reflection component by irregular layers increase. Finally, we establish a new prediction model of troposcatter transmission loss based on the PSO algorithm. This model is obtained by applying the PSO algorithm to optimise the combination of the three existing troposcatter mechanisms. The simulation results prove that in climate zones 4 and 5, the new prediction model is more accurate than the models in ITU-R P617, P2001 and approximates the accuracy of ITU-R P452. In climate zone 6, the new prediction model is more accurate than the three existing models. We also obtain the compositions of the three troposcatter mechanisms in different climate zones through the proportional analysis of different training parameters. The results demonstrate that the proportion of the coherent reflection by stable layers in climate zone 6 is higher than in climate zones 4 and 5. However, regardless of the climate zone, incoherent reflection by turbulence and incoherent reflection by irregular layers are the dominant components.

ACKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (Grant no. 61671468).

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest to this work.

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How to cite this article: Yuan D, Chen X. Troposcatter transmission loss prediction based on particle swarm optimisation. IET Microw. Antennas Propag. 2021;15:332–341. https://doi.org/10.1049/ima2.12052