

Volume Integral Equation Solution of Extinction Cross Section by Raindrops in the Range 0.6–100 GHz

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Abstract—The validity of the volume integral equation formulation (VIEF) is validated for the purpose of estimating the extinction cross section (ECS) of raindrops. The validations are performed against two well-established models. The validated volume integral equation model is employed to calculate extinction cross sections of raindrops specified by a modified Pruppacher and Pitter (MPP) model. Data are given for drops with mean radii between 0.25 to 3.5 mm in the frequency range 0.6 to 100 GHz. Our study has showed that results of the extinction cross section for vertical and horizontal polarizations can be used to predict rain attenuation in wireless communications.

Index Terms—Moment method, polarizations, rain attenuation, wireless communications.

I. INTRODUCTION

IN recent years, the demand for wireless communications has grown exponentially. With such a rapid growth, the most important problem for wireless communications is how to offer higher data rates and bandwidth-on-demand capacities. Since RF bandwidth is a limited resource, the solution to this problem is to increase operating frequencies. For higher operating frequencies in wireless communications, communication technology has become more and more sophisticated with the use of digital techniques. Moreover, frequencies above 5 GHz, especially in the microwave or millimeter-wave range, used for future terrestrial repeater systems or earth-satellite communication systems may cause some degradation to the performance of communication lines due to the hydrometeor attenuation (e.g., rain, hail, fog, snow, and ice crystals) [1], [2]. In this paper, we only consider attenuation (absorption and scattering) from rainfall since hail, fog, snow, and ice crystal are viewed as secondary affects in the studies of RF signal propagation.

The problem of rain attenuation has been studied for more than four decades [3]–[19]. These studies utilized different measurements for the attenuation produced by rain and a number of models have been developed. Experimental results were given by Medhurst [6], Yeo *et al.* [14], and Crane [18], respectively. In

most of the theoretical studies, a raindrop was usually considered as a sphere or an oblate spheroid for the computations of rain attenuation. In fact, raindrops are nonspherical in shape and have preferred axial orientation angles different from vertical direction [13]. Morrison and Cross [9] used the least-square fitting process of the boundary conditions and dealt with raindrop as a spheroidal object in order to calculate rain attenuation. Later, based on the spheroidal models, further developments have been achieved by many researchers [10]–[13].

A typical and accepted model for realistically describing raindrop shapes was developed by Pruppacher and Pitter [20], who solved a pressure balance equation on the surface of falling raindrops by numerical techniques and determined their shapes of raindrops for various sizes. To simplify the computation, Oguchi [21] used a cosine series function to replace Pruppacher and Pitter's nonlinear equation. Recently, Li *et al.* [22] used a different functional expression to further simplify the P-P (MPP) model for the calculation of rain attenuation. In this paper, the modified P-P model [22] will be adopted for the studies of extinction cross sections of raindrops in the frequency range from 0.6 to 100 GHz. Results of extinction cross sections obtained by the volume integral equation formulation (VIEF) implemented with the moment method [23] will be also presented.

II. MODIFIED P-P MODEL OF RAINDROPS

According to Oguchi's study [13], raindrops range in size from very small to fairly large. The smallest drops may be equivalent to those found in clouds. The largest drops do not exceed 4 mm in radius. Photographic measurements of raindrop shapes have shown that raindrops larger than about 1.0 mm in radius are of oblate spheroidal shape with a flattened base whose optical axes were orthogonal to reach other and lying on a horizontal plane to know the real axial ratio. For example, for drops with an equivolumetric sphere radius a_0 of 1.5 mm, the axial ratio a/b ranged from 0.6 to 1.2, where $2a$ is the height and $2b$ is the width of a drop, respectively [13]. Two straight lines A and B are the relations used in the calculations of scattering properties of oblate spheroidal raindrops [13]. The function forms of the lines A and B are $a/b = 1 - 0.1a_0$ and $a/b = 1 - (0.41/4.5)a_0$, respectively. Where the unit of a_0 is in millimeter. Based on Pruppacher and Pitter's nonlinear equation [20] and cosine series function, a newly modified P-P (MPP) model of raindrop

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proposed by Li *et al.* [22] has been obtained. In this new model, the surface of a raindrop in three-dimensional (3-D) spherical coordinates (r, θ, ϕ) is given by [16]

$$r = a(1 - v) \left(1 + \frac{v}{1 - v} \sin^2 \theta \right) \quad (1)$$

where

$$a = 1.11582a_0$$

and

$$\begin{aligned} v &= v_1 \\ &= -1.375447 \times 10^{-2} + 6.543960 \times 10^{-2}a, \\ &\quad 0 \leq \theta \leq \frac{\pi}{2}, \quad 0 \leq \phi \leq 2\pi \\ v &= v_2 \\ &= -7.239211 \times 10^{-2} + 1.827561 \times 10^{-1}a, \\ &\quad \frac{\pi}{2} \leq \theta \leq \pi, \quad 0 \leq \phi \leq 2\pi. \end{aligned}$$

The symbol a_0 denotes the raindrop mean radius introduced by Laws and Parsons [24] and Oguchi [21].

III. VIEF IMPLEMENTED WITH MOMENT METHOD

In this section, we will briefly describe the volume integral equation formulation (VIEF) [25]–[27] and its discretization into a linear system of equations using the moment method [23].

The volume integral equation formulation (VIEF) implemented with the moment method was developed to calculate the scattering and absorption by aerosol particles in previous works [25]–[27]. Based on Maxwell's equations and Van Bladel's analysis [28], we can obtain the following tensor integral equation [29]:

$$\left[1 + \frac{\tau(\bar{r})}{3j\bar{\omega}\varepsilon_0} \right] \bar{E}(\bar{r}) - PV \int_v \tau(\bar{r}') \bar{E}(\bar{r}') \cdot \bar{G}(\bar{r}, \bar{r}') dv = \bar{E}^i(\bar{r}) \quad (2)$$

where

$$\begin{aligned} \tau(\bar{r}) &= \sigma(\bar{r}) + j\bar{\omega}(\varepsilon(\bar{r}) - \varepsilon_0) \\ \bar{G}(\bar{r}, \bar{r}') &= -j\bar{\omega}\mu_0 \left[\bar{I} + \frac{\nabla\nabla}{k_0^2} \right] \psi(\bar{r}, \bar{r}') \\ \psi(\bar{r}, \bar{r}') &= \frac{\exp(-jk_0|\bar{r} - \bar{r}'|)}{4\pi|\bar{r} - \bar{r}'|} \\ k_0 &= \bar{\omega}(\mu_0\varepsilon_0)^{1/2} \\ \bar{I} &= \text{unit dyadic} \end{aligned}$$

The PV symbol is called the "principle value" of the integral, meaning that the integral is carried out by excluding a small volume surrounding the field point first and then letting this small volume approach zero. μ_0 and ε_0 are the permeability and permittivity of the free space. $\bar{r}$ and $\bar{r}'$ indicate the locations of the field and source points, respectively. σ and ε are the conductivity and the permittivity of the dielectric objects, respectively.

$\bar{\omega}$ represents angular frequency. $\bar{E}(\bar{r})$ is an unknown total electric field inside the dielectric object and needs to be determined. $\bar{E}^i(\bar{r})$ is a known incident electric field. To obtain a solution for the VIEF in (2), the object of interest is divided into N small mathematical cubical cells and constant electric field components were assumed in each. This process converts the integral equation into summation over the $3N$ components of the electric fields in the N cells.

In order to solve (2) numerically for electric fields, the moment method together with a point matching procedure are then applied to convert the $3N$ summation into $3N$ simultaneous equations in the $3N$ unknown field components in the N mathematical cells. The following matrix equation is then obtained:

$$\begin{bmatrix} G_{xx} & G_{xy} & G_{xz} \\ G_{yx} & G_{yy} & G_{yz} \\ G_{zx} & G_{zy} & G_{zz} \end{bmatrix} \begin{bmatrix} [E_x] \\ [E_y] \\ [E_z] \end{bmatrix} = - \begin{bmatrix} [E_x^i] \\ [E_y^i] \\ [E_z^i] \end{bmatrix} \quad (3)$$

where $[G_{X_p X_q}]$ is an $N \times N$ matrix, $p, q = 1, 2, 3$, and $x_1 = x$, $x_2 = y$, $x_3 = z$ in the rectangular coordinate system. The elements in $[G_{X_p X_q}]$ are defined by $G_{X_p X_q}^{mn}$, where $m, n = 1, 2, 3, \dots, N$.

$$\begin{aligned} G_{X_p X_q}^{mn} &= \frac{-j\bar{\omega}\mu_0 k_0 \tau(\bar{r}_n) \Delta V_n e^{-j\alpha_{mn}}}{4\pi\alpha_{mn}^3} \\ &\times \left[(\alpha_{mn}^2 - 1 - j\alpha_{mn}) \delta_{pq} + \frac{(x_p^m - x_p^n)(x_q^m - x_q^n)}{R_{mn}^2} \right. \\ &\quad \left. \times (3 - \alpha_{mn}^2 + 3j\alpha_{mn}) \right], \quad m \neq n \end{aligned} \quad (4)$$

$$\begin{aligned} G_{X_p X_q}^{mn} &= \delta_{pq} \left\{ \frac{-2j\bar{\omega}\mu_0 \tau(\bar{r}_n)}{3k_0^2} [e^{-jk_0 a_n} (1 + jk_0 a_n) - 1] \right. \\ &\quad \left. - \left[1 - \frac{\tau(\bar{r}_n)}{3j\bar{\omega}\varepsilon_0} \right] \right\}, \quad m = n \end{aligned} \quad (5)$$

where

$$\begin{aligned} \Delta V_n &= \text{volume of } n\text{th cell} = \int_{V_n} dv' \\ \alpha_{mn} &= k_0 R_{mn}, \quad R_{mn} = |\bar{r}_m - \bar{r}_n| \\ a_n &= \left(\frac{3\Delta V_n}{4\pi} \right)^{1/3}, \quad \delta_{pq} = \begin{cases} 1, & \text{if } p = q \\ 0, & \text{otherwise} \end{cases} \\ \begin{bmatrix} E_{x_p} \end{bmatrix} &= \begin{bmatrix} E_{x_p}(\bar{r}_1) \\ E_{x_p}(\bar{r}_2) \\ \vdots \\ E_{x_p}(\bar{r}_n) \end{bmatrix}, \quad \begin{bmatrix} E_{x_p}^i \end{bmatrix} = \begin{bmatrix} E_{x_p}^i(\bar{r}_1) \\ E_{x_p}^i(\bar{r}_2) \\ \vdots \\ E_{x_p}^i(\bar{r}_n) \end{bmatrix}. \end{aligned} \quad (6)$$

Once the internal fields are determined by solving the matrix equation, the total absorbed power in the dielectric objects can be calculated using the following equation:

$$P_{ab} = \int_v \frac{1}{2} \sigma |\bar{E}|^2 dv' \quad (7)$$

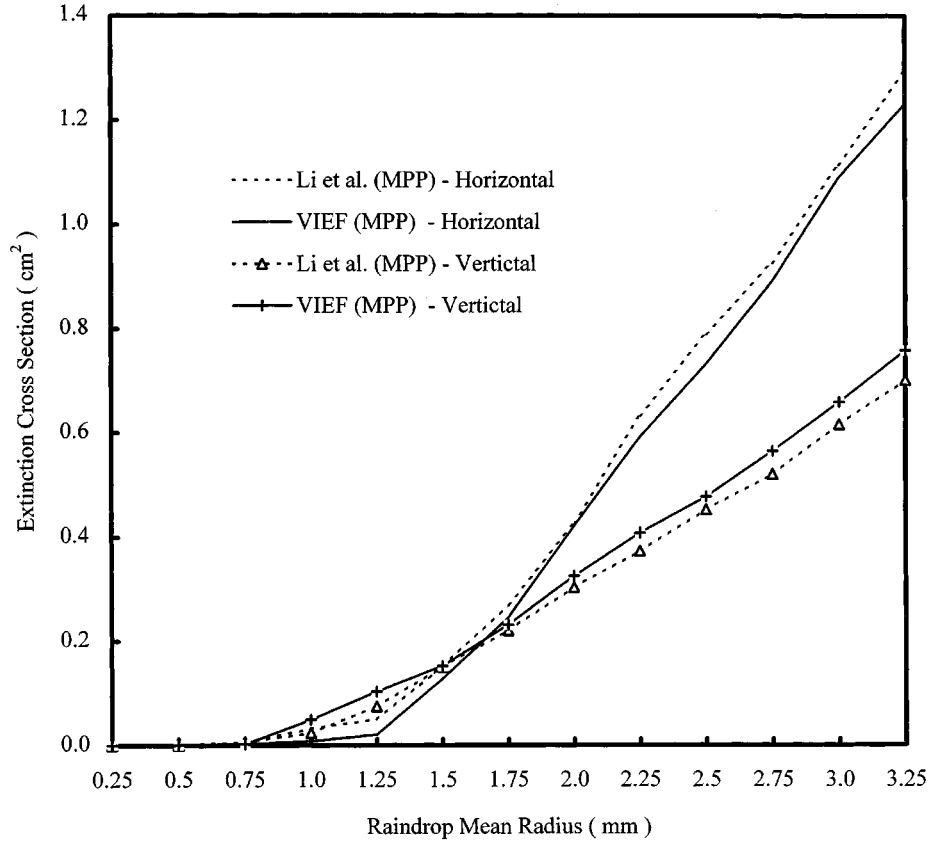


Fig. 1. Comparisons of extinction cross sections for horizontal and vertical polarization at 20 GHz. The refractive index of raindrops at $T = 20^\circ\text{C}$ is taken to be $N_r = 6.614 - j2.780$.

where σ is the conductivity of the dielectric objects. Similarly, the scattered power by the dielectric objects is given by

$$P_{sc} = \frac{1}{2} R_e \left[\int_s (\vec{E}^s(\vec{r}) \times \vec{H}^{s*}(\vec{r})) \cdot d\vec{s} \right] \quad (8)$$

where R_e represents the real part of the equation.

Finally, the absorption cross section Q_a and scattering cross section Q_s are defined by

$$Q_a = \frac{P_{ab}}{P_i}, \quad (\text{m}^2) \quad (9)$$

$$Q_s = \frac{P_{sc}}{P_i}, \quad (\text{m}^2) \quad (10)$$

where P_i is the incident power density (W/m^2).

The total (extinction) cross section is the sum of the scattering and absorption cross section

$$Q_t = Q_a + Q_s \quad (\text{m}^2). \quad (11)$$

IV. NUMERICAL RESULTS

To examine the accuracy of the VIEF procedure, we compare the obtained results of extinction cross sections with those obtained from Morrison and Cross [9], Warner and Hizal [10],

and Morgan [11] for spheroidal models and Li *et al.* for MPP models [16]. The dielectric properties of raindrops are usually expressed by the complex relative dielectric constant

$$\epsilon_r = \epsilon'_r - j\epsilon''_r \quad (12)$$

or by the complex refractive index

$$N_r = n' - jn'' \quad (13)$$

assuming the time harmonic factor is $\exp(j\omega t)$.

The real part of ϵ_r is the relative permittivity, while the imaginary part is the loss factor. At 20°C , we first take the refractive indices N_r of $(6.614 - j2.780)$, and $(5.581 - j2.848)$ for the simulation of extinction cross sections at frequencies of 20 and 30 GHz, respectively [30], [31]. The extinction cross sections for vertical and horizontal polarizations obtained by VIEF, Morrison and Cross [9], and Li *et al.* [16] are shown in Figs. 1 and 2. From Figs. 1 and 2, it is clear that the results of extinction cross sections obtained by the VIEF are quite close to those obtained by Li *et al.* for both horizontal and vertical polarizations. The reason is because the VIEF and Li *et al.* used the same MPP model. The results of extinction cross sections obtained by the VIEF and Li *et al.* are much higher than those obtained by Morrison and Cross for both horizontal and vertical polarizations, especially in the larger

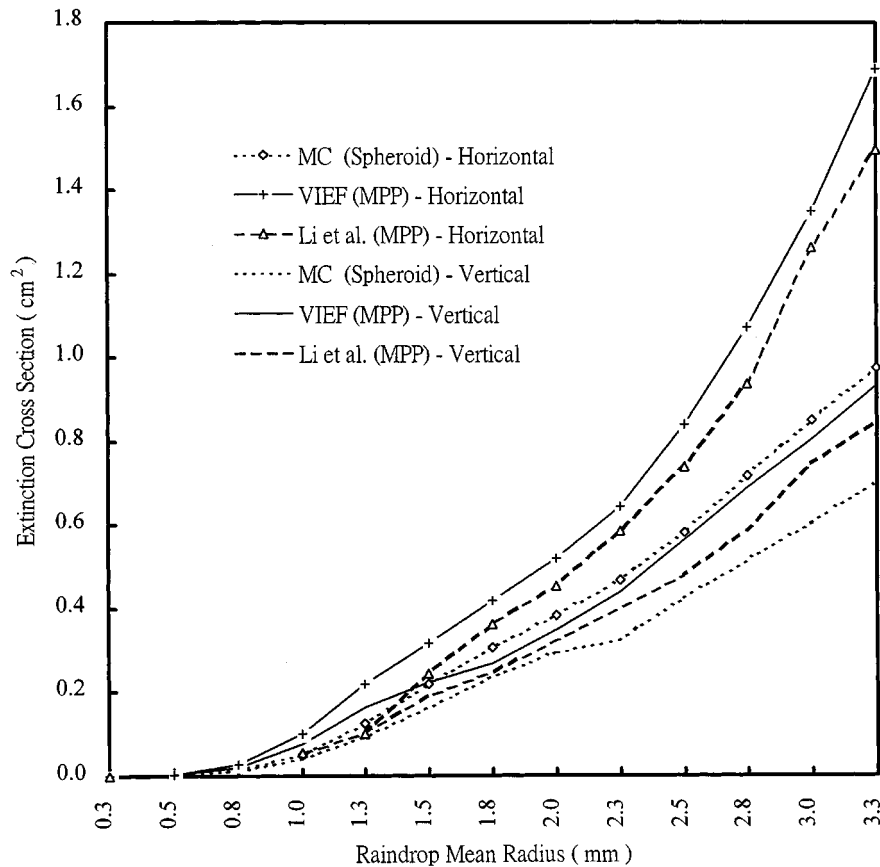


Fig. 2. Comparisons of extinction cross sections for horizontal and vertical polarizations at 30 GHz. The refractive index of raindrops at $T = 20^\circ\text{C}$ is taken to be $N_r = 5.581 - j2.848$.

raindrops. The main reason for larger relative errors between VIEFs and Morrison and Cross' results is because the second and higher order expansion terms of the Taylor series used by Morrison and Cross [9] to describe the spheroidal shapes have been neglected. A secondary check of the validity of the VIEF is made by comparing the results of extinction cross sections with those obtained by Warner and Hizal [10] and Morgan [11] for spheroidal models as shown in Table I. In this comparison, the mean radius is taken to be $a_0 = 2.38$ mm, the major semiaxis of the spheroid is taken to be $b = 2.9$ mm, the axial ratio of the spheroid is taken to be $a/b = 0.55$, and the refractive indices of raindrops at temperature $T = 10^\circ\text{C}$ are taken to be $N_r = 6.727 - j2.866$, $5.972 - j2.938$, $5.396 - j2.88$, and $4.954 - j2.789$ at respective frequencies of 15, 20, 25, and 30 GHz. From the comparison shown in Table I, it is clear that there is a good agreement among the VIEF, Varner and Hizal [10], and Morgan [11]. After checking the validity of the VIEF, we use the VIEF extensively to calculate the extinction cross sections of raindrops for MPP models in the frequency range from 0.6 to 100 GHz. Results of extinction cross sections for vertical and horizontal polarizations are shown in Figs. 3 and 4. Figs. 3 and 4 depict the variation of extinction cross sections with frequency for raindrops with a mean radius a_0 varying from 0.25 to 3.5 mm. The extinction cross-section values reach a relative maximum and then slowly increase as frequency continues to increase. It is also found that the extinction cross section decreases below 8 GHz and increases significantly with raindrop size. Results of extinction cross

TABLE I
COMPARISONS OF EXTINCTION CROSS SECTIONS WITH WARNER AND HIZAL [10] AND MORGAN [11] FOR SPHEROIDAL MODELS. THE MEAN RADIUS $a_0 = 2.38$ mm. THE SPHEROID HAS A MAJOR SEMIAXIS OF $b = 2.9$ mm, WITH AN AXIAL RATIO OF $a/b = 0.55$. THE REFRACTIVE INDICES OF RAINDROPS AT TEMPERATURE $T = 10^\circ\text{C}$ ARE $N_r = 6.727 - j2.866$, $5.972 - j2.938$, $5.396 - j2.888$, AND $4.954 - j2.789$ AT RESPECTIVE FREQUENCIES OF 15, 20, 25, AND 30 GHz. FEM, FINITE ELEMENT METHOD, PROPOSED BY MORGAN [11]; EBCM, EXTENDED BOUNDARY CONDITION METHOD, PROPOSED BY WARNER AND HIZAL [10]

Frequency (GHz)	Methods	Vertical Polarization (cm ²)	Horizontal Polarization (cm ²)
15	FEM	0.0795	0.6100
	EBCM	0.2346	0.6612
	VIEF	0.2265	0.6832
20	FEM	0.2620	0.6766
	EBCM	0.2953	0.6030
	VIEF	0.3257	0.6352
25	FEM	0.2919	0.6142
	EBCM	0.3022	0.5893
	VIEF	0.3282	0.6228
30	FEM	0.3043	0.5563
	EBCM	0.3238	0.5758
	VIEF	0.3541	0.6042

sections are available to provide predictions of rain attenuation in wireless communications.

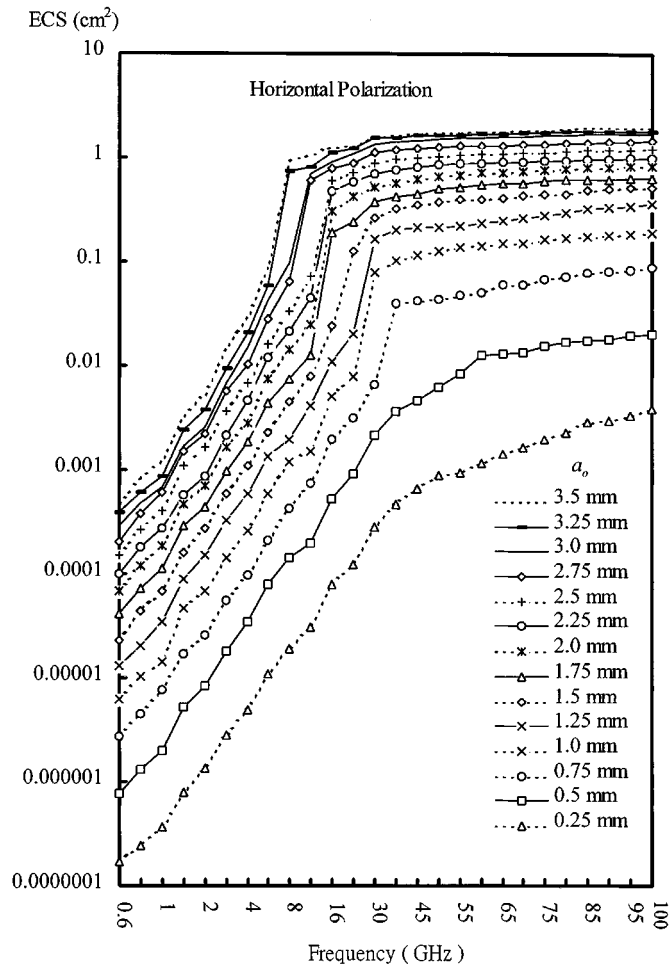


Fig. 3. Extinction cross sections (ECS) for horizontal polarization in the frequency range from 0.6 to 100 GHz. Results are obtained by the VIEF using MPP models with mean radius a_0 varying from 0.25 to 3.25 mm. The refractive indices of raindrops are taken at 20 °C from [31].

V. CONCLUSION

Although many researchers previously have investigated rain attenuation by raindrops, further investigation of scattering and absorption due to realistically distorted raindrops is still very important for wireless communications. When the raindrops are very small, it may be very easy and efficient to calculate the extinction cross sections using many analytical solutions based on the assumption of a spherical or spheroidal model. However, as the size of raindrops increases to over 1.0 mm in mean radius, the raindrops become distorted spheroidal shapes, and the exact analytical solution for the calculation of rain attenuation by these distorted spheroidal raindrops becomes impossible. Alternatively, the numerical method is one of the best choices to calculate rain attenuation for larger raindrops with distorted spheroidal shapes. In this paper, we used the numerical solution, volume integral equation formulation (VIEF), to calculate the scattering and absorption cross sections by raindrops. The validity of the VIEF was checked by comparing the obtained extinction cross section values with those obtained from Morisson and Cross, Warner and Hizal, and Morgan's solutions for spheroidal models and Li *et al.*'s solution for newly modified P-P models. After checking the validity and accuracy of the solution

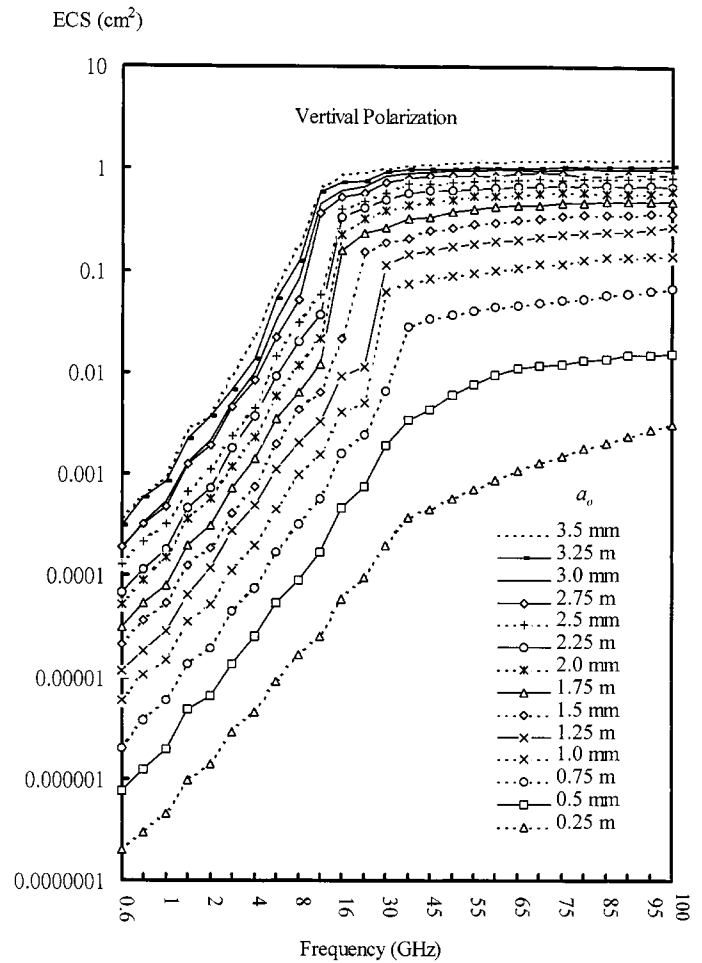


Fig. 4. Extinction cross sections (ECS) for vertical polarization in the frequency range from 0.6 to 100 GHz. Results are obtained by the VIEF using MPP models with mean radius a_0 varying from 0.25 to 3.5 mm. The refractive indices of raindrops are taken at 20 °C from [31].

procedure, we used the VIEF extensively to calculate the extinction cross sections by raindrops in the frequency range from 0.6 to 100 GHz. In our next paper [33], we will derive an empirical formula for rain attenuation based on extensive studies of extinction cross sections.

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