Technical Report 1456
October 1991

User's Guide for the VTRPE (Variable Terrain Radio Parabolic Equation) Computer Model

Frank J. Ryan

NAVAL OCEAN SYSTEMS CENTER
San Diego, California 92152-5000

J. D. FONTANA, CAPT, USN
Commander

R. T. SHEARER
Technical Director

ADMINISTRATIVE INFORMATION

The computer code described in this report was developed through funding provided by the Joint Electronic Warfare Center (JEWC) under MIPR 90-0069, and by the Office of Naval Technology (ONT) under the ONT block program NO2C at the Naval Ocean Systems Center (NOSC).

Released by
M. F. Morrison, Head
Acoustic Branch

Under authority of
J. H. Richter, Head
Ocean and Atmospheric
Sciences Division

EXECUTIVE SUMMARY

This report is a user's guide to the VTRPE (variable terrain radio parabolic equation) computer model. It is designed to provide the reader with a summary of the physics and numerical methods used in the VTRPE model, along with detailed instructions on the model's use and operation.

The VTRPE computer program is a range-dependent, tropospheric microwave propagation model that is based upon the split-step Fourier parabolic wave equation algorithm. The nominal applicable frequency range of the model is VHF to K-band. The VTRPE program is able to make predictions for microwave propagation over both land and water. The VTRPE code is a full-wave propagation model that solves the electromagnetic wave equations for the complex electric and magnetic radiation fields. The model accounts for the effects of nonuniform atmospheric refractivity fields, variable surface terrain, and varying surface dielectric properties on microwave propagation.

Multiple refractivity vs. altitude profiles may be input, and the VTRPE code will internally compute a smooth, continuous rrefractivity field in range and altitude. The surface dielectric properties may be input directly into the model or computed internally using semi-empirical algorithms. For overland propagation, the terrain elevation profile is user selectable.

A wide variety of transmitter characteristics are encompassed, including

- horizontal and vertical polarization,
- variable mainlobe vertical beamwidth and tilt,
- arbitrary transmitter/receiver geometries, and
- analytic antenna radiation patterns.

The highly efficient split-step Fourier parabolic equation algorithm is used to calculate the antenna pattern propagation factor, which is a critical component of the radar transmission equation, that is used in the performance prediction and analysis of radar and communication systems. Optimized fast Fourier transform (FFT) algorithms are used in the code for high computational efficiency. The user has control over both the FFT size and horizontal range step size used in the calculation. Many model inputs have internal defaults, thus minimizing the amount of input data required for execution.

The code is highly portable, being written in ANSI-77 FORTRAN with MILSPEC-1753 FORTRAN language extensions. Modern software structures and modular program design are used throughout. The VTRPE program is currently configured to run under the UNIX operating system on SUN minicomputers and CONVEX supercomputers, and under MS-DOS on 80386/80486-based PC's.

CONTENTS

§1.0 INTRODUCTION

This report is designed to be a guide to the use and operation of the VTRPE (variable terrain radio parabolic equation) computer code. The VTRPE code is a microwave propagation model designed for use in range-dependent environments. It provides a full-wave solution (i.e., the electromagnetic wave equations are solved for the complex fields) to the problem of microwave propagation in a range-dependent environment having variable surface boundary conditions. The model is based upon the parabolic equation (PE) or paraxial approximation to the electromagnetic wave equation, and uses the split-step Fourier PE algorithm. The VTRPE model is an extension of the smooth surface RPE (radio parabolic equation) model developed by the author to predict microwave propagation in marine environments.[1] The major difference between the VTRPE and RPE codes is in the ability of the former to handle complicated finite conductivity boundary conditions and irregular surface terrain.

The primary use of the VTRPE program is to predict tropospheric microwave propagation in range-dependent environments. This information is used in the analysis and performance prediction of radar and communication systems operating in the microwave region of the spectrum. The frequency range of interest is VHF to K_u-band ($\sim$ 50 MHz - 18 GHz). At these frequencies, spatial variations in the tropospheric refractivity field and the earth's surface dielectric properties can have major effects on radar signal propagation. In fact, substantial differences may exist between radar propagation in range-dependent environments and the classic "standard atmosphere" that is typically assumed by radar system designers.

In practice, the actual performance of a radar in the atmosphere is often quite different from that predicted based upon free-space propagation conditions. Free-space ranges are often several orders of magnitude different from observed detection ranges in the atmosphere. The reason for this discrepancy is threefold:

1. The earth's surface is a finite conductor and scatters (reflects) incident energy in various directions, leading to complicated spatial interference patterns.
2. The curved earth casts a shadow giving rise to diffraction phenomena.
3. Inhomogeneities in the atmospheric index of refraction cause significant refraction or bending of radio wave energy.

The VTRPE model incorporates full-wave propagation physics to properly account for these "*anomalous*" *propagation effects*.

1.1 Antenna Patterns

In analyzing these various phenomena, it proves useful to separate those system parameters not influenced by the environment, for example the antenna radiating characteristics, from propagation effects that are environmentally influenced, such as ducting.

The radiating characteristics of an antenna are specified in terms of the antenna radiation pattern function $f(\theta, \phi)$, where (θ, ϕ) are the zenith and azimuthal angles, respectively, of a spherical coordinate system centered at the antenna, with polar axis pointed in the direction of maximum transmission. The antenna radiation pattern function is defined to be the ratio of electric (or magnetic) field strength, $\mathbf{E}(\theta, \phi)$, radiated in the direction (θ, ϕ) to the peak transmitted field strength, E_0 :

$$f(\theta, \phi) \equiv \frac{\mathbf{E}(\theta, \phi)}{E_0}. \tag{1}$$

The antenna pattern function f is related to the time-averaged Poynting vector S of the electromagnetic wave field by

$$S(\theta, \phi) = |f(\theta, \phi)|^2 S_0,$$

where S_0 is the energy flow per unit area corresponding to the peak field E_0. In general, the antenna radiation pattern function f is a complex valued quantity.

Closely related to the antenna pattern function is the antenna gain. The antenna gain G is expressed in terms of the antenna radiation pattern function f as

$$G = \frac{4\pi}{\int_{(4\pi)} |f(\theta, \phi)|^2 \, d\Omega}.$$

Note that the antenna radiation pattern function f and the corresponding antenna gain G are conventionally defined with respect to free-space propagation conditions, and therefore do not include any environmental effects.

1.2 Radar Transmission Equation

To systematically incorporate propagation effects and antenna characteristics in radar system performance calculations, the radar transmission equation is often employed. Following Kerr,[2] define the one-way generalized transmission equation, which relates the power received by an omnidirectional receiver at a point in space, $P_r(\mathbf{r})$, to the power emitted from a transmitting antenna, P_t, by

$$\frac{P_r(\mathbf{r})}{P_t} = G_t \left[\frac{F_t}{2k_0 R}\right]^2, \tag{2}$$

and the corresponding two-way generalized transmission equation for a monostatic radar (i.e., the transmitter and receiver are colocated):

$$\frac{P_r(\mathbf{r})}{P_t} = G_t G_r \frac{\sigma}{4\pi} \left[\frac{F_t F_r}{2k_0 R^2}\right]^2, \tag{3}$$

where

G_t = transmitting antenna power gain,

G_r = receiving antenna power gain,

k_0 = vacuum wavenumber = $\dfrac{2\pi}{\lambda}$,

σ = target radar cross section,

R = radar-to-target range,

F_r = pattern propagation factor for target-to-receiver path,

F_t = pattern propagation factor for transmitter-to-target path.

Environmental effects are included in the generalized transmission equation via the pattern propagation factor F. The pattern propagation factor accounts for the fact that (1) the receiver may not be in the mainlobe beam maximum of the vertical-plane antenna pattern, and (2) non-free-space wave propagation may occur.

The pattern propagation factor F is defined as the ratio of the field magnitude at a point in space, $\mathbf{E}(\mathbf{r})$, to the magnitude of the field at the same point but under free-space propagation conditions, $\mathbf{E}_0(\mathbf{r})$:

$$F = \left| \frac{\mathbf{E}(\mathbf{r})}{\mathbf{E}_0(\mathbf{r})} \right| . \tag{4}$$

This definition of the pattern propagation factor assumes that the transmitting antenna is aligned with its maximum response axis pointed directly at the observation point. The pattern propagation factor F is the component of the generalized transmission equation, Eq. (2) or Eq. (3), that includes antenna directivity and medium propagation effects. It is the fundamental quantity to be computed by the VTRPE model. The other parameters in the radar transmission equation are independent of the environment.

Because of the large dynamic ranges of the various terms in the radar transmission equation, it is customary to work in dB-space. Thus, define the dimensionless variables PF and PL by

$$PF = 20 \log |F|, \tag{5}$$

$$PL = 20 \log(2k_0 R) - 20 \log |F|. \tag{6}$$

The quantity PF is often called the propagation factor, while PL is denoted the path loss. The VTRPE code outputs either PF or PL values on a user specified range/altitude grid.

The remainder of this report is divided into sections which cover the VTRPE model physics and its operation. Section 2, on the VTRPE model physics, should be read before attempting to use the model. The VTRPE code inputs are described and sample input run streams are provided.

§2.0 Model Physics

This section briefly describes the physics and numerical methods used in the development of the VTRPE code, including the split-step Fourier PE (SSFPE) algorithm. Additional details and references may be found in a companion report by Ryan.[3] This section is designed to help the reader better understand the usage of various VTRPE model inputs that are covered in later sections.

First, the electromagnetic vector wave equations are derived from Maxwell's equations and then reduced to scalar Helmholtz form via an earth-flattening coordinate transformation. Second, the PE approximation to the reduced wave equation is derived and its solution via the SSFPE algorithm is discussed. Third, the calculation of the pattern propagation factor using free-space dipole fields is reviewed. Finally, various details of the SSFPE algorithm implementation, including starting fields and range step sizes, are covered.

2.1 Vector Wave Equation

To calculate the complex pattern propagation factor F, Eq. (4), requires knowledge of the macroscopic electric $\mathbf{E}$ and magnetic $\mathbf{H}$ radiation fields. These fields are solutions to vector wave equations that are derived from Maxwell's equations.

In a source-free region, the monochromatic Maxwell's equations (in rationalized mks units) which govern the propagation of electromagnetic waves are[4-6]

$$\begin{aligned} \nabla \times \mathbf{E}(\mathbf{r},\omega) &= +i\omega\mu_0\mathbf{H}(\mathbf{r},\omega), \\ \nabla \times \mathbf{H}(\mathbf{r},\omega) &= -i\omega\epsilon_0\varepsilon(\mathbf{r})\mathbf{E}(\mathbf{r},\omega), \\ \mu_0\nabla \cdot \mathbf{H}(\mathbf{r},\omega) &= 0, \\ \epsilon_0\nabla \cdot \varepsilon(\mathbf{r})\mathbf{E}(\mathbf{r},\omega) &= 0, \end{aligned} \tag{7}$$

where ω is the radian frequency ($\omega = 2\pi f$) and the implicit time-dependence $\exp(-i\omega t)$ has been suppressed. The medium electrical properties are specified via the free-space magnetic permeability μ_0 and the spatially varying, complex relative dielectric constant $\varepsilon(\mathbf{r})$. For microwave frequencies in nonionized media, the complex dielectric constant may be represented in the form

$$\varepsilon(\mathbf{r}) = \varepsilon_1(\mathbf{r}) + i\frac{\sigma(\mathbf{r})}{\omega\epsilon_0},$$

where ϵ_0 is the vacuum dielectric constant, σ is the medium conductivity, and ε_1 is the usual permittivity of the medium. A related parameter is the vacuum wave number $k_0 = \omega\sqrt{\mu_0\epsilon_0} \equiv \omega/c$, where c is the speed of light.

Using standard vector identities,[7] the first order Maxwell's equations (7) may be replaced by equivalent second order vector wave equations for either the electric or magnetic field. If the electric field $\mathbf{E}$ is eliminated from Eq. (7), then the magnetic intensity vector $\mathbf{H}(\mathbf{r})$ satisfies:

$$\nabla^2\mathbf{H}(\mathbf{r}) + \frac{\nabla\varepsilon(\mathbf{r})}{\varepsilon(\mathbf{r})} \times \nabla \times \mathbf{H}(\mathbf{r}) + k_0^2\varepsilon(\mathbf{r})\mathbf{H}(\mathbf{r}) = 0\,. \tag{8}$$

The electric field is then determined from the Maxwell curl relation

$$\mathbf{E}(\mathbf{r},\omega) = \frac{i}{\omega\epsilon_0\varepsilon(\mathbf{r})}\nabla\times\mathbf{H}(\mathbf{r},\omega).$$

In a similar fashion, if the magnetic field $\mathbf{H}$ is eliminated from Eq. (7), the electric field vector $\mathbf{E}(\mathbf{r})$ may be shown to satisfy:

$$\nabla^2\mathbf{E}(\mathbf{r}) + \nabla\left(\mathbf{E}(\mathbf{r})\cdot\frac{\nabla\varepsilon(\mathbf{r})}{\varepsilon(\mathbf{r})}\right) + k_0^2\varepsilon(\mathbf{r})\mathbf{E}(\mathbf{r}) = 0\,. \tag{9}$$

2.2 Scalar Wave Equation

The vector wave equations, Eq. (8) or (9), may be converted into simpler scalar wave equations if the transmitter emits radiation that is linearly polarized— i.e., the electric field vector has nonzero components lying either wholly within (vertical polarization) or perpendicular to (horizontal polarization) the meridian plane containing the source and observation point. This is the case for many types of radar systems.

Calculations are done in a spherical, earth-centered coordinate system (r,θ,ϕ), with respective unit vectors $(\hat{\epsilon}_r,\hat{\epsilon}_\theta,\hat{\epsilon}_\phi)$. In this coordinate system, one of the linearly polarized field components is in the azimuthal direction $\hat{\epsilon}_\phi$. For vertical polarization, the nonzero magnetic field component is $\mathbf{H}(\mathbf{r}) = H_\phi(\mathbf{r})\hat{\epsilon}_\phi$ which satisfies

$$\frac{\varepsilon}{r}\frac{\partial}{\partial r}\frac{1}{\varepsilon}\frac{\partial(rH_\phi)}{\partial r} + \frac{\varepsilon}{r^2\sin\theta}\frac{\partial}{\partial\theta}\frac{\sin\theta}{\varepsilon}\frac{\partial H_\phi}{\partial\theta} + \left[k_0^2\varepsilon - \frac{1}{r^2\sin^2\theta} - \frac{\cot\theta}{r^2\varepsilon}\frac{\partial\varepsilon}{\partial\theta}\right]H_\phi = 0.$$

For horizontal polarization, the nonzero electric field component is $\mathbf{E}(\mathbf{r}) = E_\phi(\mathbf{r})\hat{\epsilon}_\phi$ and satisfies

$$\frac{1}{r}\frac{\partial^2(rE_\phi(\mathbf{r}))}{\partial r^2} + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\sin\theta\frac{\partial E_\phi(\mathbf{r})}{\partial\theta} + \left[k_0^2\varepsilon(\mathbf{r}) - \frac{1}{r^2\sin^2\theta}\right]E_\phi(\mathbf{r}) = 0.$$

The above equations for H_ϕ or E_ϕ are then converted to the scalar Helmholtz form

$$\left[\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial z^2} + K^2(x,z)\right]w(x,z) = 0, \tag{10}$$

by means of an exact earth flattening transformation:[8]

$$x = a\theta,$$
$$z = a\ln(1 + h/a),$$

where a is the effective earth radius, and $h = r - a$ is the local altitude. A new dependent variable w is then defined by

$$\begin{aligned}\text{horizontal polarization:}\quad w_h &= \sqrt{r\sin\theta}\,E_\phi(\mathbf{r}),\\ &= e^{+z/(2a)}\sqrt{a\sin(x/a)}\,E_\phi(\mathbf{x}),\\ &\approx \sqrt{x}\,E_\phi(\mathbf{x}),\quad \text{if } x/a \ll 1 \text{ and } z/a \ll 1;\end{aligned} \tag{11}$$

and by

$$\text{vertical polarization:} \quad w_v = \frac{\sqrt{r \sin\theta}}{n} H_\phi(\mathbf{r}),$$
$$= \epsilon^{+3z/(2a)} \frac{\sqrt{a \sin(x/a)}}{m(x,z)} H_\phi(\mathbf{x}), \tag{12}$$
$$\approx \frac{\sqrt{x}}{m} H_\phi(\mathbf{x}), \quad \text{if } x/a \ll 1 \text{ and } z/a \ll 1.$$

A new "effective" wave number K is also defined by

$$\text{horizontal polarization:} \quad K_h^2 = k_0^2 m^2 - \frac{3\sec^2(x/a)}{4a^2}, \tag{13}$$

$$\text{vertical polarization:} \quad K_v^2 = k_0^2 m^2 - \frac{3\sec^2(x/a)}{4a^2} - \frac{\cot(x/a)}{am}\frac{\partial m}{\partial x}$$
$$- m\left(\frac{\partial^2 m^{-1}}{\partial x^2} - \frac{\partial^2 m^{-1}}{\partial z^2} - \frac{\partial m^{-1}}{a\partial z}\right), \tag{14}$$

where m is the modified index of refraction

$$m(x,z) \equiv n(\mathbf{r})\left(1 + \frac{h}{a}\right).$$

2.3 Boundary Conditions

Maxwell's equations are augmented with boundary conditions on the field components. These are (1) a Sommerfeld radiation-type boundary condition at infinity[9]

$$\lim_{r\to\infty} r\left(\frac{\partial A}{\partial r} - ik_0 A\right), \tag{15}$$

where A denotes H_ϕ or E_ϕ, and (2) continuity of the tangential electric and magnetic fields at the earth's surface $r = a$. Continuity of tangential field components is achieved by modeling the earth as a locally homogeneous dielectric with finite conductivity and specifying a surface boundary condition. This surface boundary condition is implemented via the Leontovich surface impedance boundary condition[10]

$$\left.\frac{\partial(rA)}{r\partial r}\right|_{r=a} = -ZA\bigg|_{r=a},$$

where the quantity Z is the local, flat-surface impedance defined by:

$$Z_h = ik_0\sqrt{\varepsilon_s - 1} \quad \text{for horizontal polarization,}$$
$$Z_v = \frac{ik_0}{\varepsilon_s}\sqrt{\varepsilon_s - 1} \quad \text{for vertical polarization.}$$

with ε_s the complex dielectric constant of the earth's surface.

The Leontovich impedance boundary condition in earth-flattened coordinates becomes

$$\left.\frac{\partial w_h(x,z)}{\partial z}\right|_{z=0} = -\left(\frac{1}{2a} + ik_0\sqrt{\varepsilon_s - 1}\right) w_h(x,0)$$

for horizontal polarization, and

$$\left.\frac{\partial w_v(x,z)}{\partial z}\right|_{z=0} = -\left(-\frac{1}{2a} + \frac{1}{m(x,0)}\left.\frac{\partial m(x,z)}{\partial z}\right|_{z=0} + ik_0\frac{\sqrt{\varepsilon_s - 1}}{\varepsilon_s}\right) w_v(x,0)$$

for vertical polarization.

2.4 Pattern Propagation Factor

If the transmitter emits only linearly polarized radiation, the pattern propagation factor F, Eq. (4), only involves the field component along $\hat{e}_o$:

$$F_h(\mathbf{r}) = \frac{|E_o(\mathbf{r})|}{|E_o^{fs}(\mathbf{r})|}, \quad \text{horizontal polarization}$$

$$F_v(\mathbf{r}) = \frac{|H_o(\mathbf{r})|}{|H_o^{fs}(\mathbf{r})|}, \quad \text{vertical polarization}$$

where E_o^{fs} and H_o^{fs} are the o-component of the free-space electric and magnetic fields respectively. To calculate the pattern propagation factor F, the free-space fields must first be specified. By convention, the pattern propagation factor is defined with respect to the free-space field of a unit-strength point dipole.

For horizontal polarization, the reference free-space electric field, E_{md}, is chosen to be that arising from a vertically oriented magnetic dipole (VMD). For vertical polarization, the reference magnetic field, H_{ed}, is that from a vertically oriented electric dipole (VED). For both the VED and VMD cases, the unit-strength point dipole is located at $\mathbf{r}_0 = (r_0, 0, 0)$ in a spherical earth-centered coordinate system (r, θ, ϕ) with the dipole moment oriented along the polar axis.

Employing the dyadic Green's function, the ϕ-components of the dipole fields are then given by[11]

$$H_{ed}(\mathbf{r}) = \frac{-\omega}{4\pi R} e^{ik_0 R} \sin\theta \left(\frac{r}{R}\right)\left(k_0 + \frac{i}{R}\right), \quad \text{VED} \tag{16}$$

$$E_{md}(\mathbf{r}) = \frac{\omega\mu_0}{4\pi R} e^{ik_0 R} \sin\theta \left(\frac{r}{R}\right)\left(k_0 + \frac{i}{R}\right), \quad \text{VMD} \tag{17}$$

where $R = |\mathbf{r} - \mathbf{r}_0| \equiv \sqrt{r^2 + r_0^2 - 2rr_0\cos\theta}$ is the radius vector between the dipole and the field observation point, and θ is the polar angle.

Employing Eq. (17) and (11), the propagation factor for horizontal polarization F_h is computed as

$$F_h(\mathbf{r}) \equiv \left| \frac{E_\phi(\mathbf{r})}{E_{md}(\mathbf{r})} \right| ,$$
$$= \frac{4\pi}{k_0 \omega \mu_0} \frac{|w_h(\mathbf{r})| R^2}{(r \sin\theta)^{\frac{3}{2}}} \left[1 + (k_0 R)^{-2} \right]^{-\frac{1}{2}} .$$

Similarly, using Eq. (16) and (12), the propagation factor for vertical polarization F_v is

$$F_v(\mathbf{r}) \equiv \left| \frac{H_\phi(\mathbf{r})}{H_{ed}(\mathbf{r})} \right| ,$$
$$= \frac{4\pi}{k_0 \omega} \frac{|n(\mathbf{r}) w_v(\mathbf{r})| R^2}{(r \sin\theta)^{\frac{3}{2}}} \left[1 + (k_0 R)^{-2} \right]^{-\frac{1}{2}} .$$

In earth-flattened coordinates, the propagation factor takes the following limiting form for altitudes and ranges typical of tropospheric propagation:

$$F_h(\mathbf{x}) \approx \frac{4\pi R^2}{k_0 \omega \mu_0} x^{-\frac{3}{2}} \frac{|w_h(\mathbf{x})|}{\sqrt{1 + (k_0 R)^{-2}}} ,$$
$$\to \frac{4\pi \sqrt{x}}{k_0 \omega \mu_0} \frac{|w_h(\mathbf{x})|}{\sqrt{1 + (k_0 x)^{-2}}} , \quad \text{if } (z - z_0)/x \ll 1$$
$$F_v(\mathbf{x}) \approx \frac{4\pi R^2}{k_0 \omega} x^{-\frac{3}{2}} \frac{|m(\mathbf{x}) w_v(\mathbf{x})|}{\sqrt{1 + (k_0 R)^{-2}}} ,$$
$$\to \frac{4\pi}{k_0 \omega} \frac{\sqrt{x} |m(\mathbf{x}) w_v(\mathbf{x})|}{\sqrt{1 + (k_0 x)^{-2}}} , \quad \text{if } (z - z_0)/x \ll 1 .$$

2.5 Split-Step PE

The propagation factor F requires the field ϕ-component, which is directly related to the solution w of the scalar wave equation (10). To calculate w, the elliptic Helmholtz equation is first approximated by a parabolic wave equation that in turn is solved via formal operator methods. Making the envelope transformation

$$w(\mathbf{x}) = e^{ik_0 x} v(\mathbf{x}) ,$$

with k_0 the reference wave number, the elliptic wave equation is replaced by the generalized one-way parabolic wave equation (GPE)

$$\frac{\partial v(\mathbf{x})}{\partial x} = iQ(\mathbf{x}) v(\mathbf{x}) . \tag{18}$$

The pseudodifferential GPE operator Q is defined by

$$Q(\mathbf{x}) = \sqrt{\partial^2/\partial z^2 + K^2(\mathbf{x})} - k_0.$$

Next, the "wide-angle" split-operator PE approximation to Q is made in terms of ordinary operators:[12]

$$\begin{aligned} Q(x,z) &\approx A(z) + B(x,z), \\ A(z) &= \sqrt{k_0^2 + \partial^2/\partial z^2} - k_0, \\ B(x,z) &= K(x,z) - k_0. \end{aligned}$$

Then a formal solution of Eq. (18) can be expressed in exponential operator form via the Magnus expansion[13]

$$\psi(x + \Delta_x, z) \approx e^{+i\Delta_x(A + \bar{B})}\, \psi(x,z),$$

where $\bar{B} = B(x + \frac{1}{2}\Delta_x, z)$.

The Trotter product formula[14] is then used to symmetrically factor the Magnus expansion into the product of simpler operators, U_A and U_B, where

$$\begin{aligned} U_A &= U_A(\Delta_x) = e^{+i\Delta_x A}, \\ U_B &= U_B(\Delta_x) = e^{+i\Delta_x \bar{B}}, \end{aligned}$$

to yield the split-step PE (SSPE) algorithm:

$$\begin{aligned} \psi(x + \Delta_x, z) &= U_A(\Delta_x/2)\, U_B(\Delta_x)\, U_A(\Delta_x/2)\, \psi(x,z), \\ &= e^{+i\Delta_x A/2}\, e^{+i\Delta_x \bar{B}}\, e^{+i\Delta_x A/2}\, \psi(x,z). \end{aligned} \tag{19}$$

The PE solution at range $x + \Delta_x$, $\psi(x + \Delta_x, z)$, is obtained from the known field at range x, $\psi(x,z)$, by means of the SSPE algorithm. Physically, the SSPE algorithm amounts to

(1) a half-step of free-space propagation, $U_A(\Delta_x/2)$,
(2) a phase correction, $U_B(\Delta_x)$, to account for refractive effects, and
(3) another half-step of free-space propagation, $U_A(\Delta_x/2)$.

2.6 Split-Step Fourier PE Algorithm

The presence of the differential operator $A(z)$ in the SSPE exponent, Eq. (19), is dealt with by transforming to a basis in which $A(z)$ is diagonal. One such basis is the Fourier basis. The z-space Fourier transform $\mathcal{F}$ is defined as

$$\Psi(x,p) = \mathcal{F}[\psi(x,z)] \equiv \int_{-\infty}^{\infty} \psi(x,z) e^{-ipz}\, dz,$$

with the corresponding inverse transform $\mathcal{F}^{-1}$ being defined by

$$\psi(x,z) = \mathcal{F}^{-1}[\Psi(x,p)] \equiv \frac{1}{2\pi}\int_{-\infty}^{\infty} \Psi(x,p)\epsilon^{+ipz}\,dp.$$

The transform variable p may be associated with a vertical wave number via $p = k_0 \sin\theta$, where θ is the propagation angle with respect to the horizontal.

The exponential operator $\epsilon^{+i\Delta_x A}$ is evaluated using Fourier transform methods as

$$\epsilon^{i\Delta_x A(z)}\psi(x,z) = \mathcal{F}^{-1}\left\{\epsilon^{-i\Delta_x\left(k_0 - \sqrt{k_0^2 - p^2}\right)}\mathcal{F}\left[\psi(x,z)\right]\right\}. \tag{20}$$

Employing Eq. (20) in Eq. (19) yields the split-step Fourier PE (SSFPE) algorithm:

$$\psi(x+\Delta_x, z) = \epsilon^{+i\Delta_x B}\,\mathcal{F}^{-1}\left\{\epsilon^{-i\Delta_x\left(k_0 - \sqrt{k_0^2 - p^2}\right)}\mathcal{F}\left[\psi(x,z)\right]\right\}. \tag{21}$$

Providing the initial starting field $\psi(0,z)$ is known, the SSFPE algorithm can efficiently advance the solution in range.

2.7 PE Starting Fields

The split-step PE method must be initialized with a starting field distribution $\psi(0,z)$. This is accomplished in the VTRPE model by using the duality of the z-space antenna aperture field distribution $A(z)$ and the corresponding p-space radiation pattern function $f(p)$.[15]

In free space, the antenna radiation pattern function $f(p)$ and the antenna aperture field distribution $A(z)$ are a Fourier transform pair:

$$\begin{aligned} f(p) &= \int_{-\infty}^{\infty} A(z)\epsilon^{-i(p-p_0)z}\,dz, \\ A(z) &= \frac{1}{2\pi}\int_{-\infty}^{\infty} f(p)\epsilon^{+i(z-z_0)p}\,dp, \end{aligned}$$

where the p-space parameters are defined by

$$\begin{aligned} p &= k_0 \sin\theta, \\ p_0 &= k_0 \sin\theta_0. \end{aligned} \tag{22}$$

In Eq. (22), θ is the elevation angle measured with respect to the horizontal ($\theta > 0$ is up) and θ_0 is the antenna mainlobe vertical pointing direction. The antenna pattern function $f(p)$ is used to construct even, $\Psi_e(0,p)$, and odd, $\Psi_o(0,p)$, symmetry p-space starting fields in the form

$$\Psi_e(0,p) = f(p)e^{-ipz_0} + f(-p)e^{+ipz_0}, \tag{23}$$

and

$$\Psi_o(0,p) = f(p)e^{-ipz_0} - f(-p)e^{+ipz_0}, \tag{24}$$

where the Fourier shift theorem has been used to properly account for a nonzero source altitude, z_0. Given the above even/odd symmetry p-space field, the corresponding even/odd symmetry z-space field is obtained by taking the inverse cosine or sine transform of Eq. (23) or Eq. (24), respectively:

$$\begin{aligned} \psi_e(0,z) &= \mathcal{F}_c^{-1}\left[\Psi_e(0,p)\right], \\ \psi_o(0,z) &= \mathcal{F}_s^{-1}\left[\Psi_o(0,p)\right]. \end{aligned} \tag{25}$$

In practice, the infinite Fourier transforms in Eq. (25) are replaced by finite discrete sine or cosine transforms over the finite interval $(0, Z_{\max})$.[16] These discrete transforms are in turn evaluated numerically using real-valued fast Fourier transform (FFT) methods.[17] Use of FFTs requires proper selection of the transform size N and the sampling interval $Z_{\max}$ to ensure satisfaction of the Nyquist theorem and thereby avoid aliasing problems.[18] If $p_{\max} \equiv k_0 \sin\theta_{\max}$ is the maximum vertical wave number in the FFT p-space transform grid, and N is the discrete cosine/sine transform size, then the relation between $Z_{\max}$ and $p_{\max}$ is given by

$$Z_{\max} p_{\max} = \pi N.$$

Equivalently, the specification of the FFT z-grid size, δ_z, and the corresponding p-grid size, δ_p, is provided by

$$\begin{aligned} \delta_z &= \pi / p_{\max}, \\ \delta_p &= \pi / Z_{\max}. \end{aligned} \tag{26}$$

Two constraints need to be placed on the FFT p-space grid to ensure accurate results using the SSFPE method. These constraints depend on the initial p-space field spectrum, and on the desired vertical resolution in z-space. First, the value of $p_{\max}$ must be sufficiently large to contain all significant energy in the starting field $\Psi(0,p)$. If θ_{SLL} is the elevation angle corresponding to a specified sidelobe level in the antenna radiation pattern (e.g., 50 dB down relative to the mainlobe peak) and $p_{SLL} = k_0 \sin\theta_{SLL}$, then an estimate for $p_{\max}$ is

$$p_{\max} \simeq p_{SLL} + |p_0|. \tag{27}$$

Typically, only sidelobes above a certain threshold are included in the VTRPE code to minimize the size of $p_{\max}$. Before transforming back from p-space to z-space, the initial field $\Psi(0,p)$ is low-pass filtered to remove energy above the Nyquist point $p_{\max}$ thereby avoiding FFT aliasing problems. Since $p_{\max}$ is related to the vertical spacing δ_z via

Eq. (26), a further constraint on its size is provided by the smallest vertical scale length l_v needed to resolve the refractivity field $N(z)$:

$$p_{\max} \geq \pi / l_v . \tag{28}$$

The maximum vertical wavenumber $p_{\max}$ is a function of the antenna pattern sidelobes, and the vertical tilt angle θ_0.

A second contraint is placed upon the p-space mesh size δ_p. To adequately resolve the surface image interference lobes in the starting field $\Psi(0, p)$, the p-space resolution δ_p must satisfy

$$\delta_p = \frac{\pi}{Z_{\max}} \lesssim \frac{\pi}{2z_0} .$$

This, in turn, constrains the minimum allowable size of $Z_{\max}$ to be

$$Z_{\max} \gtrsim 2z_0 .$$

2.8 Analytic Antenna Patterns

The SSFPE method is capable of modeling the radiation emitted by directional antennas—provided that the complex antenna radiation pattern $f(p)$ is known. Often this information is not available for specific radar systems, so simplified generic antenna patterns are used instead. These generic patterns display some of the features of real antennas while retaining fairly simple analytical forms. Each of the analytic antenna patterns is specified in terms of a normalized p-space steering parameter t defined by

$$t = \frac{\sin\theta - \sin\theta_0}{\sin(\frac{1}{2}\theta_{bw})} = \frac{p - p_0}{p_{\frac{1}{2}}},$$

where

$$p_{\frac{1}{2}} = k_0 \sin(\frac{1}{2}\theta_{bw}),$$

and θ_{bw} is the half-power beamwidth (HPBW). In addition to the HPBW, each antenna pattern has sidelobes specified at a certain power level relative to the mainlobe peak.

The following analytic antenna radiation patterns are useful approximations to real antenna radiation patterns and are implemented in the VTRPE model:

2.8.1 sin(x)/x

The uniformly illuminated aperture corresponds to a radiation pattern having the functional form

$$f(t) = \frac{\sin(at)}{at}, \quad a = 1.3916.$$

The scale parameter a is determined by solving the nonlinear equation

$$\sin a = \frac{a}{\sqrt{2}}.$$

This pattern has the narrowest mainlobe width, at the expense of high sidelobe levels.

2.8.2 Gaussian

The Gaussian antenna radiation pattern has the functional form

$$f(t) = e^{-a^2t^2}, \quad \text{where} \quad a^2 = \frac{\ln 2}{2}.$$

This pattern is the optimal compromise between sidelobe level and mainlobe beamwidth.

2.8.3 Compound

The compound radiation pattern is a one-parameter pattern that is a blend of the uniformly illuminated aperture and the cosine-squared aperture distribution, having the functional form

$$f(t) = \frac{2}{1+C_b}\frac{\sin(at)}{at}\left[C_b + \frac{1-C_b}{2}\frac{1}{1-(at/\pi)^2}\right], \quad 0 \le C_b \le 1.$$

The parameter a controls the mainlobe width and is determined by solving the nonlinear equation

$$\frac{\sin a}{a}\left[2C_b + \frac{1-C_b}{1-(a/\pi)^2}\right] = \frac{1+C_b}{\sqrt{2}}.$$

The uniform aperture corresponds to $C_b = 1$, while the cosine-squared aperture corresponds to $C_b = 0$. The cosine-squared aperture is often used as an approximation to the radiation pattern from a parabolic reflector antenna.

2.8.4 Hansen

Another single parameter pattern is obtained from the circular aperture distributions analyzed by Hansen.[19] This pattern has the functional form

$$f(t) = \frac{H}{i_1(H)}\begin{cases} \dfrac{i_1(\sqrt{x})}{\sqrt{x}}, & \text{for } x \ge 0 \\[2ex] \dfrac{j_1(\sqrt{|x|})}{\sqrt{|x|}}, & \text{for } x < 0. \end{cases}$$

where

$$x = H^2 - (at)^2,$$

and j_1 and i_1 are the first-order spherical and modified spherical Bessel functions respectively. The quantity a, which determines the 3-dB point in the pattern, is found by solving the transcendental equation

$$\frac{i_1(H)}{\sqrt{2}H} = \begin{cases} \dfrac{i_1(\sqrt{H^2-a^2})}{\sqrt{H^2-a^2}}, & \text{for } \dfrac{i_1(H)}{\sqrt{2}H} \ge \frac{1}{3} \\[2ex] \dfrac{j_1(\sqrt{a^2-H^2})}{\sqrt{a^2-H^2}}, & \text{for } \dfrac{i_1(H)}{\sqrt{2}H} < \frac{1}{3}. \end{cases}$$

The first sidelobe level, SLL, in the radiation pattern can be shown to have a value of

$$SLL = 30.84 + 20\log\left[\frac{3i_1(H)}{H}\right] \quad \text{dB}.$$

down from the peak, and is located at $p = p_{SLL}$

$$p_{SLL} - p_0 = \frac{p_{\frac{1}{2}}}{a}\sqrt{1 + (5.763/H)^2}.$$

The parameter H allows a trade-off between low sidelobe level and mainlobe beamwidth.

2.9 SSFPE Range Step Size

Each application of the SSFPE algorithm, Eq. (19), leads to a local truncation error in the solution v that is proportional to the cube of the PE range step Δ_x. Since many range steps are typically taken, these local errors can accumulate and produce unacceptable errors in the solution. To prevent this from happening, the VTRPE code performs a global error estimate based upon a detailed analysis of the local SSFPE errors. To bound the total global error in the solution v, the PE range step Δ_x is chosen so that

$$\Delta_x^2 \leq 24\epsilon_{rel}\frac{\|\delta^{(1)}v\|}{\|\delta^{(3)}v\|}.$$

where ϵ_{rel} is a specified error tolerance, and

$$\|\delta^{(1)}v\| = \frac{\Delta_x}{2k_0}\int_0^{Z_{\max}} v^*\left[\frac{\partial^2}{\partial z^2} - k_0^2 V\right] v\,dz\,.$$

$$\|\delta^{(3)}v\| = \frac{i\Delta_x^3}{48k_0}\left\{\int_0^{Z_{\max}}\left[k_0^2\left(\frac{\partial V}{\partial z}\right)^2|v|^2 + \frac{\partial^2 V}{\partial z^2}\left|\frac{\partial v}{\partial z}\right|^2 - \tfrac{1}{4}\frac{\partial^2 V}{\partial z^2}\frac{\partial^2|v|^2}{\partial z^2}\right]dz\right.$$
$$\left. + \tfrac{1}{4}\left.\frac{\partial^2 V}{\partial z^2}\right|_{z=0}\frac{\partial|v(x_0,0)|^2}{\partial z}\right\}.$$

Here $V(z) \equiv m^2(z) - 1$ is the "effective potential" related to the modified index of refraction m.

The SSFPE range step Δ_x is then set by

$$\Delta_x^2 = \frac{24\epsilon_{rel}\int_0^{Z_{\max}} v^*\left[\frac{\partial^2}{\partial z^2} - k_0^2 V\right] v\,dz}{\int_0^{Z_{\max}}\left[k_0^2\left(\frac{\partial V}{\partial z}\right)^2|v|^2 + \frac{\partial^2 V}{\partial z^2}\left|\frac{\partial v}{\partial z}\right|^2 - \frac{1}{4}\frac{\partial^2 V}{\partial z^2}\frac{\partial^2|v|^2}{\partial z^2}\right]dz + \frac{1}{4}\left.\frac{\partial^2 V}{\partial z^2}\frac{\partial|v|^2}{\partial z}\right|_{z=0}}.$$

As the VTRPE code advances the field, the local error budget is monitored and the range step-size Δ_x is dynamically adjusted to keep the local error below a preset threshold.

2.10 Reflectionless Absorber

The appropriate boundary condition to be satisfied as $z \to \infty$ by the PE field $v(x, z)$ is the Sommerfeld outgoing wave radiation condition, Eq. (15). Since the split-step Fourier algorithm employs finite Fourier transforms, the implementation of a radiation-type boundary condition is quite complicated. This follows from the fact that truncation of the infinite z-domain down to a finite interval in the Fourier transform leads to the introduction of spurious discrete standing wave solutions in the vertical. In effect, the terminal impedance at the end of the transform grid is not properly "matched" to the radiation boundary condition.

To circumvent this problem and attenuate the spurious standing wave solutions introduced by the finite Fourier transforms, a complex absorber potential $V_{abs}(z)$ is added to the split-step B operator:

$$B(x, z) \Rightarrow B(x, z) + \frac{ik_0}{2} V_{abs}(z).$$

The specific form chosen is

$$V_{abs}(z) = V_0 \,\mathrm{sech}^2[(z - Z_{\max})/w_0],$$

where the parameters $\{V_0, w_0\}$ are determined parametrically by minimizing transmission and reflection coefficients from the sponge region.[20] The actual "physical" propagation region in the VTRPE model thus extends to an altitude $z = H_{\max} < Z_{\max}$ to allow room for the absorber.

§3.0 USAGE

This section describes how to access and run the VTRPE code. It assumes that the VTRPE code has already been installed on either a DOS-based PC or UNIX-based system, and that the VTRPE executable is in the current working directory. Optionally, an environmental path variable may be set to the directory containing the VTRPE executable (this is the preferred method, since it allows sub-directory organization of data files).

3.1 Notation

The following notation conventions are used in this report.

3.1.1 Typographic Conventions

The following typographic conventions are used in later sections of this report to describe various input formats.

- { } Braces are used to group items together.
- ⟨⟩ An item within angle brackets (including the brackets) is a parameter which needs to be replaced by user-supplied text.
- [ ] Anything within square brackets is optional; the brackets are not part of the item.
- ... The ellipsis means that the previously defined pattern can be repeated several times. The ellipsis represents the position at which text or items have been omitted.
- `text` Input text to be entered, for example program names or input keywords, is shown in a monospaced `text` font.

3.1.2 Namelist Input

The VTRPE inputs are invoked via ASCII files in FORTRAN namelist format. This type of file consists of plain text records up to 80 characters in length (i.e.,"card images") and may be prepared using a text editor or word processor. If a word processor such as WordStar or WordPerfect is used, be sure to disable any "word wrap" or special output formatting options.

FORTRAN namelist input is a powerful, free-format type of input, consisting of ordered strings of "items" or symbolic variable names, and their associated "values." An item is a mnemonic name (e.g., `MEGAHZ` for the transmitter frequency in MHz) that is associated with a particular FORTRAN variable scalar, array name, or array element. Associated with each item in the namelist input stream is a value, that is a FORTRAN-type INTEGER, REAL, DOUBLE PRECISION, COMPLEX, LOGICAL, or CHARACTER constant that is appropriate for the associated item.

Different types of namelists are used to specify different categories of inputs to VTRPE.

Each namelist input field has the following general form:

$$
\begin{array}{ll}
\&ident & \\
\vdots & \text{namelist data fields} \\
\texttt{\&END} &
\end{array}
$$

The start of a namelist input stream is signaled by a unique identifier string of the form "&*ident*", where *ident* is the name of a particular namelist (e.g., **&RPE**), while the end of the input stream is signaled by the unique terminator string "**&END**". In between the initial and terminating identifier strings is the body of the namelist, consisting of free-format data fields. The following rules apply to the namelist identifier strings:

- The initial identifier string &*ident* must start in column two of the input record, be capitalized, contain no embedded blanks, and be contained within a single record.
- At least one blank space must separate the starting identifier string from the body of the namelist.
- The terminating identifier string is always **&END**.

Otherwise, white space (i.e., blanks) may appear anywhere in the list.

Each data field or input record in the namelist has the general format:

$$item_1 = value_1\,[< sep > [item_2] = value_2] \cdots$$

where *item* is the symbolic name of a scalar, array, array element, or character string; *value* is a FORTRAN-type INTEGER, REAL, DOUBLE PRECISION, COMPLEX, LOGICAL, or CHARACTER constant that is appropriate for the associated item; and $< sep >$ is a comma, tab, or space separator. The actual symbolic names and associated data types for various namelist items are covered later.

The following rules apply to namelist data field records:

- An item specified on the left side of the equal sign cannot contain spaces or tabs except within the parentheses of a subscript. Each item must be contained in a single record. The spelling and case of the item name is critical!
- CHARACTER string constants are enclosed in single quotes.
- COMPLEX constants are specified in the format $item = (real, imag)$ by enclosing the real and imaginary parts of the complex quantity in parenthesis, separated by a comma.
- A null value is specified by two consecutive commas, by an initial comma or by a trailing comma. A null value indicates that the corresponding namelist array element is unchanged. A null value can represent an entire complex element but cannot be used for only one part of a complex constant.
- Multiple items may appear on a single line.
- The equal sign in a value assignment can be delimited by spaces.

3.2 Program Invocation

To invoke the VTRPE model, simply enter **VTRPE** at the command line prompt:

> VTRPE

where ">" denotes the operating system command line prompt. After the model is loaded into memory, a logo will appear and the user will be prompted for the names of the input and output files to be used in the run. The content and format of the various input and output files are described in subsequent sections. Optionally, the run input and/or output filenames may be specified at program invocation via command line arguments that follow the program name:

> VTRPE *input_filespec* [,*print_filespec*] [,*plot_filespec*]

These run-time arguments consist of valid filenames (with an optional path) in the order indicated. Items inside the square brackets are optional. Each *filespec* denotes the name of a file to be processed, which can include a full or partial path specification. Not all filenames need be specified on the command line; those that are not will be prompted by the program.

VTRPE inputs are invoked via a formatted INPUT-file denoted by *input_filespec* . The contents and format of the INPUT-file are described later in this document. In addition to the INPUT-file, there are two optional output files: (1) the PRINT-file, denoted by *print_filespec*, which is an ASCII-formatted file containing diagnostic and/or debug output, and (2) the PLOT-file, denoted by *plot_filespec*, which may be either ASCII or binary and contains a compacted range–altitude matrix of loss values that may be postprocessed and input into a user specified plotting program. The file formats of the PRINT and PLOT files are covered later.

In addition to the above-mentioned files, the VTRPE code will automatically allocate temporary "scratch" files, which are deallocated upon successful run termination. If any errors have occurred during program execution, then a file having the same filename as *input_filespec* but with the extension ".err" will be created in the current working directory. Consult this *.err file for more details of any errors that may have occurred.

As the VTRPE program is run, many different input/output files are created, and it often proves beneficial to create separate subdirectories for different projects. Any valid filename may be used for the input/output filenames. However, to facilitate file management and prevent confusion, a uniform file-naming convention is strongly recommended for the input and output filenames. One possible choice is to use a unique, descriptive run filename and then vary the file extension depending upon the type of file. For example, the following default file extensions are suggested:

jobname.inp ⇒ INPUT-file

jobname.prt ⇒ PRINT-file

jobname.plt ⇒ PLOT-file

3.3 Input Files

Inputs to the VTRPE model are via ASCII formatted-type files in FORTRAN namelist format. Three types of namelist input streams are processed by VTRPE :

(1) RPE.

(2) SECTOR.
(3) GROUND.

The general layout of the VTRPE input stream is shown in figure 1.

```
&RPE
    :    transmitter characteristics and run-time options
&END
&SECTOR
    :    refractivity profile data sector 1
&END
&SECTOR
    :    refractivity profile data sector 2
&END
&SECTOR
    :    refractivity profile data sector N
&END
&GROUND
    :    surface elevation and dielectric properties (optional)
&END
```

Figure 1. VTRPE input stream.

The first namelist. RPE. contains information relating to the transmitter characteristics (e.g., frequency, beamwidth, or polarization) and general run-time parameters (e.g., output range stepsize). The RPE namelist should occur first in the input file. Section 4 describes the variables in the RPE namelist.

Following the RPE namelist are one or more SECTOR-type namelists which contain environmental refractivity profile data. For a range-independent run, only a single SECTOR-type namelist is required. For a range-dependent run, a separate SECTOR namelist is required for each distinct environmental refractivity profile. The refractivity profiles are grouped into data sectors that are to be arranged in monotonically increasing great circle range from the transmitter. Section 5 describes the variables in the SECTOR namelist.

Finally, if variable terrain or finite surface conductivity conditions are to be modeled, then the surface elevation profile and corresponding surface dielectric properties must be input via the GROUND-type namelist. In this case, the variable terrain control flag IVTPE must be set in the RPE namelist to flag the run as a variable terrain run. Various formats are available to input the surface dielectric properties and are discussed in section 6.

§4.0 General Inputs

This section describes the variables in the RPE namelist. These variables are used to set initial VTRPE run parameters that are not functions of the environment. These include

- transmitter height and antenna characteristics,
- specification of the model output altitude/range grid,
- range/altitude units flags,
- SSFPE range step size and FFT size, and
- type of VTRPE model output.

4.1 Output Range/Altitude Grid

The VTRPE code generates output (PF or PL) on a user specified range/altitude grid of N_r range points and N_z altitude points.

The vertical grid: $\{z_r(i), i = 1, 2, \ldots, N_z\}$, is constant with range and defined by the entries in the **ZR** input variable described below. At each output range, the VTRPE code interpolates the complex field from the equi-spaced FFT z-space grid: $\{z_i = i\delta_z, \quad i = 0, 1, \ldots, N\}$ to the user specified receiver grid $\{z_r\}$.

The $N_r \equiv$ **NRANGE** output range points, $\{r_i \quad i = 1, 2, \ldots, N_r\}$, correspond to the nearest VTRPE range step to the equi-spaced range grid $\{R_i\}$ defined by

$$R_i = R_0 + (i-1)\Delta_R, \quad i = 1, 2, \ldots, N_r,$$

where $R_0 \equiv$ **RFIRST** is the initial output range and $\Delta_R \equiv$ RNGINC is the output range increment. Note that the actual output ranges $\{r_i\}$ may not correspond to the user specified ranges $\{R_i\}$ due to the fact that the VTRPE code mau use a variable range step size. The user must specify at least two items in the triplet $\{R_0, N_r, \Delta_R\}$: the remaining component of the triplet is computed internally by the model.

For a range-independent run, (i.e., only one input refractivity profile, no terrain elevation variability, and simplified surface boundary conditions) the following RPE namelist variables are the minimum set needed to specify the run:

- transmitter antenna mainlobe vertical beamwidth.**BMWIDTH**
- transmitter frequency. **MEGAHZ**
- at least two of **NRANGE, RFIRST, RLAST**
- specification of the output range increment. **RNGINC**
- specification of the output altitudes. **ZR**
- specification of the transmitter height. **ZTRANS**

All other RPE namelist variables will take on their default values. To change a particular variable, merely specify it in the namelist input stream.

The list on the following pages describes the RPE namelist input variables. Mandatory input parameters are indicated, with all other input variables optional. If a nonmandatory input variable is not specified in the RPE namelist, then the internal default value will be used. Note that some input variables that normally are optional, become mandatory if certain options are specified.

4.2 RPE Namelist Variable Descriptions

ALPHA *Atmospheric volume attenuation* $\alpha_v(z)$

Total frequency dependent atmospheric volume microwave attenuation vs. altitude $\alpha_v(z)$. Arising, for example, from absorption by molecular gases, water vapor, or liquid water (rain). Stored as FORTRAN 2-D array ALPHA(j,i) that is input as ordered pairs: $\{z_i, \alpha_i\}$, $i < 50$, where ALPHA($1,i$) $= z_i$, ALPHA($2,i$) $= \alpha_i$, $i < 50$ where z_i is the ith altitude and $\alpha_i = \alpha(z_i)$ is the corresponding attenuation (dB/km) at the altitude z_i. The input attenuation values $\{z_i, \alpha_i\}$ must start at the surface and be ordered in terms of increasing altitude. The attenuation values should correspond to the actual run frequency as specified by MEGAHZ. The attenuation profile $\alpha(z)$ is modeled by piecewise constant layers, and is range-independent. The altitudes $\{z_i\}$ need not correspond to the input refractivity profile altitudes. If volume attenuation is desired, then also specify IVOLUME variable in addition.

UNITS: attenuation α_i in dB/km; altitude z_i in units as specified by IZUNIT variable

DEFAULT: ALPHA() = 0

BMWIDTH *Transmitter vertical beamwidth* θ_{BW}.

Free-space 1/2-power (i.e., angular width to 3-dB power points) transmitter vertical beamwidth. Used in conjunction with mainlobe tilt parameter BMELEV to compute the initial PE starting field. The particular type of antenna radiation pattern to be used in generating the starting field is specified by variable ISOURCE.

BMWIDTH < 180, use free-space pattern having specified 1/2-power beamwidth

BMWIDTH = 180, use omnidirectional point source pattern

RANGE: 0 < BMWIDTH ≤ 180

DEFAULT: *Note: mandatory input*

UNITS: deg

BMELEV *Transmitter vertical mainlobe beam tilt* θ_0

Transmitter free-space antenna pattern mainlobe vertical tilt angle (with respect to the horizontal).

BMELEV < 0, transmitter mainlobe is steered down

BMELEV = 0, transmitter mainlobe is steered horizontally

BMELEV > 0, transmitter mainlobe is steered up

RANGE: −90 < BMELEV < +90

DEFAULT: BMELEV = 0

UNITS: deg

CBEAM *Compound aperture parameter* C_b

Controls selection of the PE starter aperture field $A(z)$, which varies continuously from a uniform aperture ($C_b = 1$) to a cosine-squared type aperture ($C_b = 0$)

depending upon the value of C_b = CBEAM. The uniform aperture field (CBEAM = 1) corresponds to a $\sin(x)/x$ type radiation pattern, while the cosine-squared aperture field (CBEAM = 0) is a common approximation for parabolic reflector antennas. If CBEAM is specified, then the user must also specify ISOURCE = 1.

CBEAM = 0, cosine squared aperture field

0 < CBEAM < 1, compound type aperture field

CBEAM = 1, uniform aperture field

RANGE: 0 ≤ CBEAM ≤ 1

DEFAULT: 0

UNITS: none

DBPASS *PE wave number pass-band*

Controls the PE wave number (p-space) energy spectrum and starter field pass-band cutoffs. The initial PE fields vertical wave number power spectrum is low-pass filtered for levels > DBPASS down from spectrum peak. DBPASS is also used to low-pass filter (i.e., band limit) the PE field at each range step and controls variable range step size. May be used in lieu of $\theta_{\max}$ = THBMAX to limit maximum PE wave number $p_{\max}$. *WARNING: Do not specify this parameter unless sure of results.*

DBPASS = 0, truncate p-space PE field based upon value of THBMAX at $p_{\max} = k_0 \sin\theta_{\max}$

DBPASS > 0, truncate p-space field at specified sidelobe level

RANGE: DBPASS > 0

DEFAULT: DBPASS = 50

UNITS: dB

DRMAX *Maximum PE range step size*

Used in variable step size run to limit the maximum SSFPE range step size that will be used. Do not specify larger than RNGINC or missed output will result.

RANGE: 0 < DRMAX < RNGINC

DEFAULT: DRMAX = 1000

UNITS: m

DRMIN *Minimum PE range step size*

Used in variable step size run to limit the minimum PE range step that will be used.

RANGE: DRMIN > 0

DEFAULT: DRMIN = 75

UNITS: meters

EPSURF *Complex surface dielectric constant ε_s*

Complex effective surface dielectric constant at the transmitter ε_s ($\varepsilon_s = \varepsilon_1 + i\varepsilon_2$). If EPSURF = 0. then perfect conductor surface boundary conditions are used in the calculation: if nonzero. then finite conductivity surface boundary conditions are used. For range-dependent problems. the surface dielectric constant $\varepsilon_s(r)$ is input via the GROUND input stream. The complex input value ε_s is specified as an ordered pair: EPSURF = (ε_1, ε_2), where ε_1 is the surface permittivity. and ε_2 is the relative loss function (note that $\varepsilon_2 > 0$).

EPSURF = (0.,0.), flags perfect conductor surface

EPSURF ≠ (0.,0.), flags finite conductor surface

RANGE: $\varepsilon_1 \geq 1$, $\varepsilon_2 > 0$

DEFAULT: EPSURF = (0.,0.)

UNITS: none

FPLOT *PLOT-filename*

Character string. enclosed by apostrophes, for output PLOT-filename. If non-blank, then the specified filename is used for PLOT-filename: otherwise, prompt for filename OR use command-line argument.

DEFAULT: FPLOT = blank

UNITS: none

FPRINT *PRINT-filename*

Character string, enclosed by apostrophes, for output PRINT-filename. If non-blank, then the specified filename is used for PRINT-filename: otherwise. prompt for filename OR use command-line argument.

DEFAULT: FPRINT = blank

UNITS: none

HMAX *Maximum physical altitude $H_{\max}$*

Maximum physical region of SSFPE vertical grid: the transmitter altitude, z_0, and all output receiver altitudes, z_r, must be less than $H_{\max}$. The input refractivity profiles $N(z)$ must all extend to at least this altitude. In addition, $H_{\max}$ should exceed the height of the highest elevated refractivity profile duct (if any) along the propagation track.

HMAX = 0. compute $H_{\max}$ based upon the highest input refractivity profile point along propagation track

HMAX > 0. use as specified

DEFAULT: HMAX = 0

UNITS: m

HMIN *Minimum surface elevation* $H_{\min}$

Minimum altitude in SSFPE grid for variable terrain case: $H_{\min}$ must be $\leq$ minimum terrain elevation point along propagation track. All input profiles must start at or below this altitude.

DEFAULT: `HMIN` = 0

UNITS: meters relative to mean sea level

ICURVE *Earth curvature flag*

Earth-flattening transformation flag: controls whether the earth-flattening transform is to be used. If specified, then the refractive index profiles and transmitter/receiver heights are modified to account for an earth-flattened coordinate system.

`ICURVE` = 0, flags a spherical earth run: modify the refractivity profile, $N(z)$, and transmitter/receiver altitudes to account for earth curvature. If modified refractivity $M(z,r)$ is input, then ONLY correct the transmitter/receiver altitudes.

`ICURVE` = 1 flat-earth run: no earth-curvature corrections are applied to either the refractivity profile or the transmitter/receiver altitudes

RANGE: `ICURVE` = {0, 1}

DEFAULT: `ICURVE` = 0

UNITS: none

IDEBUG *Debug print flag*

Controls quantity and type of debug output from run; output is to file specified by `FPRINT` variable or to second filename on command line.

`IDEBUG` = −1, no PRINT-file output

`IDEBUG` = 0, no diagnostic debug

`IDEBUG` = 1, minimal debug output + tabular dB loss table

`IDEBUG` > 1, detailed debug output

DEFAULT: `IDEBUG` = 1

UNITS: none

IGRAPH *Screen graphics flag*

Controls the run-time screen graphics output. Plot layout is determined by variables in the PEGRAF-type namelist.

`IGRAPH` = 0, no run-time screen graphics

`IGRAPH` = 1, run-time screen graphics

DEFAULT: `IGRAPH` = 0

UNITS: none

ILOSS *PE output flag*

Controls type of VTRPE model output from the run. Output is dB-loss values on a range–altitude grid determined by the ZR-array and by the output ranges.

ILOSS = 1, output path loss $PL = 20\log(2k_0R/|F|)$

ILOSS = 2, output pattern propagation factor $PF = 20\log|F|$

DEFAULT: ILOSS = 1

UNITS: none

IPLOT *PLOT-file flag*

Controls format of the output PLOT-file specified by the FPLOT variable or by third filename on the command line. The PLOT-file contains dB values on range-altitude grid.

IPLOT = 0, no PLOT-file produced

IPLOT = 1, ASCII file; packed integer format

IPLOT = 2, EREPS compatible format

IPLOT = 3, binary output file

DEFAULT: IPLOT = 0

UNITS: none

IPOLAR *Transmitter polarization flag*

Flag specifying the transmitter field polarization.

IPOLAR = 0, horizontal polarization

IPOLAR = 1, vertical polarization

DEFAULT: IPOLAR = 0

UNITS: none

IRUNIT *Range units flag*

Flag specifying input range units; will apply to all refractivity profile and surface data unless reset.

IRUNIT = 0, ranges in kilometers

IRUNIT = 1, ranges in nautical miles

IRUNIT = 2, ranges in kiloyards

IRUNIT = 3, ranges in meters

DEFAULT: IRUNIT = 0

UNITS: none

ISOURCE *Transmitter antenna radiation pattern flag*

Specifies type of transmitter antenna radiation pattern used to initialize SSFPE field.

ISOURCE = 0, Gaussian antenna pattern

`ISOURCE` = 1, compound antenna pattern (must also specify the `CBEAM` parameter)

`ISOURCE` = 3, Kaiser-Bessel pattern

DEFAULT: `ISOURCE` = 0

UNITS: none

IVOLUME *Atmospheric attenuation flag*

Atmospheric volumetric absorption loss flag.

`IVOLUME` = 0, no volume absorption loss

`IVOLUME` = 1, add volume loss as specified in `ALPHA` array

DEFAULT: = 0

UNITS: none

IVTPE *Variable terrain flag*

Flag specifying variable surface boundary condition run. Used to specify either a variable terrain elevation or variable surface dielectric properties run.

`IVTPE` = 0, earth's surface modeled as smooth and flat

`IVTPE` = 1, surface dielectric properties and/or terrain elevation vary with range from transmitter: user MUST specify GROUND-type inputs.

DEFAULT: `IVTPE`= 0

UNITS: none

IZUNIT *Vertical units flag*

Controls all input vertical units for transmitter/receiver altitudes and refractivity profile altitudes.

`IZUNIT` = 0, all input altitudes in meters

`IZUNIT` = 1, all input altitudes in feet

DEFAULT: `IZUNIT` = 0

UNITS: none

MEGAHZ *Transmitter frequency*

Specifies VTRPE run frequency in mega-hertz.

DEFAULT: *Note: mandatory input*

UNITS: megahertz

NFFT *FFT exponent size N*

Controls the FFT size used in run: FFT size $N = 2^{\mathrm{NFFT}}$. The maximum FFT size allowed is dictated by the amount of available memory on the computer.

`NFFT` = 0, flags a variable FFT size run: program selects initial FFT transform size based on input values of `ZMAX`, `DBPASS` and wave number power spectrum: the FFT size is then dynamically adjusted as the run progresses to ensure no aliasing.

NFFT > 0, flags fixed FFT run: program runs at fixed, specified transform size. This option also disables all internal error checking. *CAUTION: if* NFFT *is too small, then PE output may be incorrect due to transform aliasing problems.*

RANGE: $7 \leq$ NFFT ≤ 12 PC version

RANGE: $7 \leq$ NFFT ≤ 16 UNIX version

DEFAULT: NFFT $= 0$

UNITS: none

NRANGE *Number of output ranges N_r*

Controls the number of range points N_r at which pathloss or propagation factor values will be written to output files. Used in lieu of RLAST to specify the number of output ranges.

NRANGE $= 0$, model computes number of output ranges N_r as

$$N_r = \max[1, (R_{\max} - R_0)/\Delta_R];$$

user must specify RFIRST,RLAST and RNGINC in this case

NRANGE > 0, specified number of output ranges, with last range being

$$R_{\max} = R_0 + (N_r - 1)\Delta_R$$

DEFAULT: NRANGE $= 0$

UNITS: none

PESTEP *PE range step size Δ_r*

PE algorithm range step size. *WARNING: Do not specify this parameter unless sure of results.*

PESTEP $= 0$, flags a variable step size run: PE range step Δ_r is computed based upon the local split-step truncation error estimates. The range step size will be dynamically adjusted within DRMIN $\leq \Delta_r \leq$ DRMAX to minimize the total error in the PE calculation

PESTEP > 0, run at fixed specified range step. *Warning — forcing the range step size disables all error checks*

DEFAULT: PESTEP $= 0$

UNITS: meters

RFIRST *First output range R_0*

Minimum range of PE model output: if $R_0 = 0$, then first output will be at PE range step r_i that is nearest to $\Delta_R \equiv$ RNGINC.

RFIRST $= 0$, first output range $R_0 =$ RNGINC

RFIRST > 0, first output range $R_0 =$ RFIRST

DEFAULT: RFIRST $= 0$

UNITS: units as specified by IRUNIT

RLAST *Last output range $R_{\max}$*

Used in lieu of $N_r \equiv$ **NRANGE** to specify the maximum range of PE output. The number of output range points N_r is then computed as

$$NR = (R_{\max} - R_0)/\Delta_R + 1\,.$$

RLAST $= 0$, then last output range computed by model as

$$R_{\max} = R_0 + (N_r - 1) * \Delta_R\,;$$

user must specify **NRANGE** parameter in this case

RLAST > 0, last output range $R_{\max} =$ RLAST

DEFAULT: RLAST $= 0$

UNITS: units as specified by IRUNIT

RNGINC *Output range increment Δ_R*

Range increment for model dB-loss output. Used in conjunction with $R_0 =$ RFIRST and $N_r =$ **NRANGE** inputs to determine the ranges at which loss will be output to the PLOT and PRINT files. The actual output range $\{r_i\}$ are the nearest SSFPE range step to the user specified equi-spaced range values $R_i = R_0 + (i-1)\Delta_R$, $i = 1, 2, \ldots, N_r$.

DEFAULT: *Note: mandatory input*

RANGE: RNGINC > 0

UNITS: units as specified by IRUNIT

TELEV *Transmitter terrain elevation h_0*

Terrain elevation (relative to mean sea level) at the transmitter:

DEFAULT: TELEV $= 0$

UNITS: units as specified by IZUNIT

THBMAX *Maximum PE vertical aperture $\theta_{\max}$*

Maximum PE vertical angular aperture 1/2-width: used ONLY for compound type aperture starter.

RANGE: $0 <$ THBMAX < 90

DEFAULT: none

UNITS: deg

TITLE *Run title*

Optional run title used to label output: quote-delimited character string

RANGE: string length ≤ 80 characters

DEFAULT: TITLE = NOSC Radio PE Model

UNITS: none

V0 *Sponge amplitude* V_0

SSFPE complex absorber amplitude. *WARNING: Do not specify this parameter unless sure of results.*

V0 = 0, absorber parameters computed by model

V0 > 0, specified absorber amplitude

RANGE: V0 ≥ 0

DEFAULT: = V0 = 0

UNITS: none

WV0 *Sponge scale length* w_0

Vertical length scale for complex "sponge" absorber. *WARNING: Do not specify this parameter unless sure of results.*

WV0 = 0, computed based upon frequency and transmitter properties

WV0 > 0, specified absorber scale length

RANGE: WV0 ≥ 0

DEFAULT:WV0 = 0

UNITS: meters

ZMAX *Max PE grid altitude* $Z_{\max}$

Maximum z-value in PE grid: $Z_{\max} = H_{\max}$ + absorber width. Used to set the vertical wave number mesh increment Δp via $\Delta p = \pi / Z_{\max}$. To avoid aliasing of Lloyd's mirror surface interference pattern, requires $Z_{\max} \geq 2z_0$, where z_0 is the transmitter altitude.

ZMAX = 0, set $Z_{\max}$ based upon run parameters

ZMAX > 0, use as specified

DEFAULT: = 0

UNITS: meters

ZR *Receiver altitudes*

Receiver (i.e., target) altitudes array ZR(): dB-loss values (either PL or PF) are interpolated, at each output range, from the internal high-density vertical PE mesh onto a vertical grid specified by the contents of the ZR-array. The entries in ZR() need not be equi-spaced, and are self-counting — the first non-positive entry terminates the input scan. Two options are available to specify the actual receiver altitudes:

(1) input a list of $N_z \leq 1000$ monotonically increasing receiver altitudes:

$$\text{ZR()} = z_1, z_2, \ldots, z_{N_z}$$

(2) specify the receiver altitudes by inputting via ZR up to five sets of ordered triplets having the form:

$$\text{ZR} = z_1, -N_1, d_1 \; [, z_2, -N_2, d_2 \cdots]$$

The lth triplet, $\{z_l, -N_l, d_l\}$, will then be expanded into N_l equi-spaced altitudes starting at $z = z_l$ with a vertical spacing of d_l. The sum of all the N_l's must be ≤ 1000.

RANGE: ZR(i) > 0, $i \leq 1000$

DEFAULT: *Note: mandatory input*

UNITS: input units as specified by IZUNIT flag

ZTRANS *Transmitter altitude* z_0

RANGE: ZTRANS > 0

DEFAULT: *Note: mandatory input*

UNITS: input units as specified by IZUNIT

Table 1 summarizes the variables in the RPE-type namelist and their defaults.

Table 1. RPE namelist variables.

Item	*Description*	*Type*[a]	*Units*	*Default*
ALPHA	Atmospheric attenuation array	R	dB/km	0.
BMWIDTH	Transmitter vertical beamwidth	R	deg	none
BMELEV	Transmitter vertical beam tilt	R	deg	0.
CBEAM	Compound aperture parameter	R		0.
DBPASS	p-space spectrum pass-band	R	dB	50.
DRMAX	Maximum PE range step size	R	m	1000.
DRMIN	Minimum PE range step size	R	m	75.
EPSURF	Surface dielectric constant	C		(0.,0.)
FPLOT	PLOT-filename	A		blank
FPRINT	PRINT-filename	A		blank
HMAX	Maximum physical altitude	R	m	0.
HMIN	Minimum surface elevation	R	m	0.
ICURVE	Earth curvature flag	I		0
IDEBUG	Debug print flag	I		1
IGRAPH	Screen graphics flag	I		0
ILOSS	PE output type flag	I		1
IPLOT	PLOT-file flag	I		0
IPOLAR	Transmitter polarization flag	I		0
IRUNIT	Range units flag	I		0
ISOURCE	Transmitter antenna type flag	I		0
IVOLUME	Atmospheric attenuation flag	I		0
IVTPE	Variable terrain flag	I		0
IZUNIT	Vertical units flag	I		0
MEGAHZ	Transmitter frequency	R	MHz	none
NFFT	FFT exponent size	I		0
NRANGE	Number of output ranges	I		0
PESTEP	PE range step size	R	m	0
RFIRST	First output range	R	IRUNIT[b]	0.
RLAST	Last output range	R	IRUNIT[b]	0.
RNGINC	Output range increment	R	IRUNIT[b]	none
TELEV	Terrain elevation at transmitter	R	IZUNIT[c]	0.
THBMAX	Maximum PE vertical aperture	R	deg	0.
TITLE	Run Title	A		'NOSC ... '
VO	Sponge amplitude	R		0.
WVO	Sponge scale length	R	m	0.
ZMAX	Max PE grid altitude	R	m	0.
ZR	Receiver altitudes array	R	IZUNIT[c]	none
ZTRANS	Transmitter altitude	R	IZUNIT[c]	none

[a] FORTRAN data type: A=character, C=complex, I=integer, R=real.

[b] Units set by IRUNIT.

[c] Units set by IZUNIT.

The SECTOR-type namelist variables contain the atmospheric refractivity profile data along the propagation track. For a range-independent (i.e., single refractivity profile) run, only one SECTOR-type namelist is required; for a range-dependent, multi-profile profile run, a separate SECTOR-type namelist is required for each input refractivity profile. Each refractivity profile input defines an environmental sector identified with a great circle range from the transmitter. For a multi-profile run, each SECTOR namelist must be ordered by increasing range from the transmitter.

5.1 Refractivity Profiles

The VTRPE model requires a specification of the atmospheric radio refractivity field as a function of altitude z and range r. The refractivity field is defined by one or more vertical profiles of refractivity vs. altitude at various ranges from the transmitter. Each refractivity profile is input as ordered pairs $\{z_i, P_i \equiv P(z_i)\}$, where z_i is the ith profile altitude and P_i is the corresponding refractivity value. The refractivity profile $P(z)$ is modeled by layers within which the profile is assumed to be piecewise linear with altitude.

The refractivity profile may be specified either in terms of refractivity (N-units) or in terms of refractive modulus (M-units). Each refractivity profile that is input must extend from the minimum physical altitude $H_{\rm min}$ (as specified by the HMIN variable in the RPE namelist), to the maximum physical altitude $H_{\rm max}$ (as specified by the HMAX variable in the RPE namelist). Linear extrapolation is then used to extend the profile from $H_{\rm max}$ to the upper boundary of the PE grid, $Z_{\rm max}$. In addition, the profiles should extend to a sufficiently high altitude to encompass any ducts that may be present. The last layer in the input profile must contain a positive vertical gradient. All profiles should be specified to an altitude beyond which simple linear extrapolation is appropriate.

Optionally, the refractivity profile data may be stored in separate files in an EREPS compatible format, and the filenames specified in the SECTOR namelist.

5.2 Profile Range Interpolation

For a multiple profile run, the input profiles are combined to form a continuous refractivity field in range and altitude. This is accomplished by means of a bi-variate surface fitting algorithm that uses the input pairs $\{z_i, P_i\}$ to construct a smooth surface.

Range interpolation between profiles is controlled by specifying the points on adjacent profiles (vertices) which define quadrilateral surface interpolation regions. If no surface interpolation is desired, then simply connect the first and last points in each profile. Note that for range-dependent input, ALL profiles must be extended to a common maximum altitude.

5.3 SECTOR Namelist Variable Description

The SECTOR namelist variables are defined below:

CONNECT *Profile vertex connection altitudes array*

Array of refractivity profile vertex connection altitudes in adjacent profiles that are used to define the quadrilateral regions (tesselation) used for profile range/altitude interpolation. Used ONLY for range-dependent data inputs, and for the second and successive data sectors. The `CONNECT`-array data are input as ordered pairs of profile vertices: $\{z_1(i), z_2(i)\}$, $i = 1, 2, \cdots,$ `NPAIR`, where $z_1(i)$ is the altitude of the ith vertex connection in the previous profile, and $z_2(i)$ is the altitude of the ith vertex connection in the current profile. The points chosen for vertex connection pairs should typically be local extrema (i.e., local maxima or minima) in the profile.

DEFAULT: none

UNITS: units as specified by `IZUNIT`

IPTYPE *Profile data type flag*

Specifies type of atmospheric refractivity profile data that are input via the `PROFILE` array.

`IPTYPE` = 1, contents of `PROFILE` are refractivity $N(z)$ in N-units

`IPTYPE` = 2, contents of `PROFILE` are modified refractivity $M(z)$ in M-units

`IPTYPE` = 3, contents of `PROFILE` are normalized modified refractivity, $M(z) - M_0$, (M-units) where M_0 is the reference modified refractivity as specified by the `MZERO` parameter

DEFAULT: `IPTYPE` = 3

UNITS: none

IRUNIT *Profile range units flag*

Specifies input range units of the refractivity profile data; overrides value of `IRUNIT` set in `RPE`-type namelist.

`IRUNIT` = 0, profile ranges in kilometers

`IRUNIT` = 1, profile ranges in nautical miles

`IRUNIT` = 2, profile ranges in kiloyards

`IRUNIT` = 3, profile ranges in meters

DEFAULT: set in RPE namelist

UNITS: none

IZUNIT *Profile altitude units flag*

Specifies input altitude units in refractivity profile; overrides `IZUNIT` value set in `RPE`-type namelist.

`IZUNIT` = 0, input heights in meters

`IZUNIT` = 1, input heights in feet

DEFAULT: set in `RPE` namelist

UNITS: none

MZERO *Reference modified refractivity M_0*

Reference value for modified refractivity: MUST be input when IPTYPE=3. Normally set to the surface modified refractivity value.

DEFAULT: MZERO = 0

UNITS: M-units

NPAIR *Number of CONNECT points*

Number of vertex altitude pairs specified in the CONNECT array: ONLY used for range-dependent profile inputs. Should not be specified for the first environmental sector!

RANGE: NPAIR ≥ 2

DEFAULT: none

UNITS: none

NVP *Number of profile points N_p*

Number of points in the input profile array PROFILE: MUST be specified for multiple-profile inputs in lieu of self-counting.

NVP = 0, self-counting input: the number of profile input points determined by the model based upon last non-zero entry in PROFILE(). The self-counting option may only used for single profile runs. For multiple profile runs, each profile input must specify NVP.

NVP > 0, number of data pairs input via PROFILE-array

DEFAULT: NVP = 0

UNITS: none

PFILE *Profile filename*

Optional name of datafile containing input refractivity profile data: used in lieu of inputting the profile via PROFILE namelist variable. Quote-delimited character string containing a valid filename with optional path.

PFILE = blank, profile input via PROFILE-array

PFILE = 'filename', read profile from indicated file in EREPS format

DEFAULT: PFILE = blank

PRANGE *Profile range*

Profile great circle range relative to the transmitter: used only for multiple-profile input. Mandatory input for a multiple-profile run: PRANGE=0 for 1st profile

DEFAULT: none

UNITS: as specified by IRUNIT variable

PROFID *Profile ID*

Optional profile ID character string: quote-delimited character string (maximum 80 characters).

DEFAULT: PROFID = ' '

UNITS: none

PROFILE *Profile array* $P(z)$

Refractivity profile data array: input consists of ordered pairs $\{z_i, P_i\}, 1 \leq i < 50$, where z_i is the ith profile altitude relative to mean sea level and P_i is the corresponding refractivity in units as specified by the IPTYPE variable. The vertical units are specified by the IZUNIT variable. The first profile point MUST be at or below the minimum terrain elevation $z = H_{\min}$ ($H_{\min} \equiv$ HMIN is set in the RPE namelist) along the propagation track for a variable-terrain run, or at the surface ($z = 0$) for a smooth-surface run. The last point in the profile array should extend to a sufficiently high altitude to encompass any ducts present in the profile, or in any event be greater than $z =$ HMAX.

DEFAULT: none

UNITS: altitude units by IZUNIT, refractivity units by IPTYPE

Table 2 summarizes the variables in the SECTOR-type namelist.

Table-2: SECTOR Namelist Variables

Item	*Description*	*Type*[a]	*Units*	*Default*
CONNECT	Profile vertex connection array	R	IZUNIT[b]	0.
IPTYPE	Profile data type flag	I		3
IRUNIT	Profile range units flag	I		RPE
IZUNIT	Profile altitude units flag	I		RPE
MZERO	Reference modified refractivity	R	M-units	0
NPAIR	Number of CONNECT points	I		none
NVP	Number of profile points	I		0
PFILE	Optional profile filename	A		blank
PRANGE	Profile range	R	IRUNIT[c]	0.
PROFID	Profile ID	A		blank
PROFILE	Refractivity profile array	R	IZUNIT[b] IPTYPE[d]	none

[a]FORTRAN data type: A=character, C=complex, I=integer, R=real.
[b]Units set by IZUNIT.
[c]Vertical units set by IRUNIT.
[d]Profile units set by IPTYPE.

§6.0 Surface Inputs

Surface environmental inputs are specified in the GROUND namelist input. It contains information specifying the terrain elevation and/or the surface dielectric properties along the propagation track. This information is used by the VTRPE model if a variable terrain run is specified by means of the **IVTPE** parameter in the RPE namelist. If the earth's surface is not flat or if finite conductivity surface boundary conditions are desired, then GROUND-type input data must be supplied. This includes the terrain elevation vs. range profile and specification of the complex surface dielectric constant.

6.1 Terrain Elevation Data

For propagation over variable terrain, the user must specify the terrain elevation vs. range profile $h(r)$. The surface-elevation profile may be specified in one of two ways:

- the terrain elevation profile $h(r)$ is input as ordered pairs $\{r_i, h_i)\}$ where r_i is the ith range and $h_i \equiv h(r_i)$ is the corresponding terrain elevation relative to mean sea level. Piecewise linear interpolation is used to construct a continuous (with range) profile $h(r)$.
- by specification of the parameters of an analytical "bump" surface-elevation model. The specific analytic form used is a Lorentzian function with specified peak and FWHM (full-width at half maximum).

6.2 Surface Dielectric Data

The complex surface dielectric constant is defined to be piecewise constant with range and may be specified in two general ways.

First, if the actual complex dielectric constant is known, then it is input directly into the VTRPE model. This is accomplished by specifying the surface permittivity ε_1 (i.e., the real part of the complex dielectric constant) and either the imaginary part of the dielectric constant, ε_2, or the loss tangent, δ, where $\tan\delta = \varepsilon_2/\varepsilon_1$. This is the prefered approach, provided the user has sufficient knowledge about the dielectric properties of the surface.

Alternatively, if knowledge of the complex surface dielectric is not available, then the VTRPE model will compute surface dielectric constant data internally using semiempirical models. These models of the dielectric data are based upon environmental surface properties such as temperature and salinity that are commonly available. The particular semiempirical model used depends upon whether the surface is land or ocean.

6.2.1 Sea Water Model

If the surface is the ocean, then a semiempirical model is used that is parameterized by frequency, sea surface temperature and sea surface salinity.

For a good conductor like sea water, the frequency-dependent dielectric constant is modeled by the Debye expression[21]

$$\varepsilon(\omega) = \varepsilon_{ir} + \frac{\varepsilon_0 - \varepsilon_{ir}}{1 - i\omega\tau} + \frac{i\sigma}{\omega\epsilon_0}.$$

where $\varepsilon_{ir} = 4.9$ is the far-infrared value of the pure-water dielectric constant, ε_0 is the static dielectric constant of sea water (i.e., the zero frequency limit), τ is the relaxation time, and σ is the ionic conductivity. For sea water, ε_0, σ, and τ are all functions of the temeperature (T) and salinity (s) of the water.

Klein and Swift[22] have analysed L-band experimental data to derive the following empirical formulas which are used internally by the VTRPE model:

$$\varepsilon_0 = \left(87.134 - 0.1949T - 0.01276T^2 + 2.491 \times 10^{-4}T^3\right) a(T, s),$$

where

$$a(T, s) = 1.0 + 1.613 \times 10^{-5}sT - 3.656 \times 10^{-3}s + 3.21 \times 10^{-5}s^2 - 4.232 \times 10^{-7}s^3,$$

$$\tau = \left(1.768 \times 10^{-11} - 6.086 \times 10^{-13}T + 1.104 \times 10^{-14}T^2 - 8.111 \times 10^{-17}T^3\right) b(T, s),$$

where

$$b(T, s) = 1.0 + 2.282 \times 10^{-5}sT - 7.638 \times 10^{-4}s - 7.760 \times 10^{-6}s^2 + 1.105 \times 10^{-8}s^3,$$

and

$$\sigma = \sigma(25, s)e^{-\beta\Delta}, \quad \Delta = 25 - T,$$

with

$$\beta \equiv \beta(\Delta, s) = 2.033 \times 10^{-2} + 1.266 \times 10^{-4}\Delta + 2.464 \times 10^{-6}\Delta^2 - s\left[1.849 \times 10^{-5} - 2.551 \times 10^{-7}\Delta(1.0 - 0.1\Delta)\right],$$

and

$$\sigma(25, s) = s\left(0.182521 - 1.46192 \times 10^{-3}s + 2.09324 \times 10^{-5}s^2 - 1.28205 \times 10^{-7}s^3\right).$$

In the above formulas, T is the water temeperature in °C, and s is the salinity in psu.

6.2.2 Soil Model

For propagation over ground, a wet soil model developed by Hallikainen *et al* is used.[23] This model treats the ground as a mixture of soil particles, air voids, and liquid water. The water contained in the soil is divided into two fractions: (1) bound water, and (2) free water. Based on experimental measurements between 1.4 and 18 GHz, the dielectric data at each frequency are fit by polynomial regression to an expression of the form

$$\varepsilon = a_0 + a_1S + a_2C + (b_0 + b_1S + b_2C)m_v + (c_0 + c_1S + c_2C)m_v^2,$$

where S is the percentage of sand in the soil, C is the percentage of clay and m_v is the soil volumetric moisture content.

6.3 GROUND Input Data Stream

The user may input surface terrain and dielectric data in one of six ways:

(1) by direct input of the complex surface dielectric constant $\varepsilon_s = \varepsilon_1 + i\varepsilon_2$;
(2) by input of the sea surface temperature and salinity (marine only); an internal computation of the complex sea water dielectric constant ε is done using semiempirical models;
(3) by input of the surface soil type and moisture content; an internal computation of the complex soil dielectric constant via semiempirical formulas;
(4) by input of the surface permittivity ε_1 and conductivity σ;
(5) by input of the surface permittivity ε_1 and loss tangent $\tan\delta = \varepsilon_2/\varepsilon_1$; or
(6) by the analytical bump model.

The actual format of GROUND-type inputs is a pseudo namelist format. The input file run stream is scanned for the starting control string, `&GROUND`, and the terminating control string, "`&END`". Each control string must be on a separate input record, start in column two or later, and have no embedded blanks. The actual surface data are found between these two control strings as a series of individual data records, one for each range, preceded by a header record. The input format of the header record and data records is standard FORTRAN list-directed input. If default inputs are assumed, then commas should be used to specify the default inputs. All header and data records should be terminated with a slash (/). The GROUND input data stream is organized as follows:

`&GROUND`	⇐ starting control string
header record	
data record 1	
data record 2	⇐ input data records
...	
...	
`&END`	⇐ terminating control string

6.3.1 Header Record Format

The header input data record has the format:

```
IGTYPE, IZUNIT, IRUNIT
```

The first item in the header record is the data type flag `IGTYPE`. This determines the type of input data records which follow. Each input data record must have the same format. Depending upon the specification of the `IGTYPE` flag, the following types of input data records are allowed:

(1) `IGTYPE`=0: range, surface elevation, and complex surface dielectric constant are input;
(2) `IGTYPE`=1: range, surface elevation, surface permittivity, and surface conductivity are input;

(3) IGTYPE=2: range, surface elevation, surface permittivity, and the surface loss-tangent are input;
(4) IGTYPE=3: range, sea surface temperature, and salinity are input (water only)
(5) IGTYPE=4: peak range, peak height, peak width, and surface dielectric constant are input (bump model);
(6) IGTYPE=5: range, surface elevation, and the soil clay/sand/moisture content are input (semiempirical soil dielectric model);

IRUNIT = input range units flag (same as RPE namelist)

IZUNIT = input z-units flag (same as RPE namelist)

6.3.2 Data Record Format

Each input data record consists of a range value r_i followed by a list of parameters $\{param_i\}$ that specify the surface properties and a trailing slash:

$$range, param_1 [, param_2, parm_3, \ldots] /$$

The format is FORTRAN list-directed input, terminated by a slash (/).

The actual order and contents of the items in the data record depend upon the IGTYPE flag in the header record. The first item in the data record is always the range. Following the range item are one or more items in the order specified in the following list as determined by the IGTYPE flag:

IGTYPE = 0	$r_i, h_i, \varepsilon_1, \varepsilon_2$;
IGTYPE = 1	$r_i, h_i, \varepsilon_1, \sigma$;
IGTYPE = 2	$r_i, h_i, \varepsilon_1, \tan\delta$;
IGTYPE = 3	r_i, T, s ;
IGTYPE = 4	r_i, peak-height, peak-width, $\varepsilon_1, \varepsilon_2$;
IGTYPE = 5	r_i, h_i, C, S, m_v .

The input variables have the following meaning:

$C =$	soil clay textural component by weight (%)
$\sigma =$	surface conductivity (Siemens/meter)
$h_i =$	surface elevation relative to mean sea level
$\varepsilon_2 =$	imaginary part of dielectric constant
$\tan\delta =$	dielectric loss tangent $= \varepsilon_2/\varepsilon_1$
$m_v =$	soil volumetric moisture content $\left(\mathrm{cm}^3/\mathrm{cm}^3\right)$
$\varepsilon_1 =$	relative dielectric permittivity
$s =$	surface salinity (psu)
$S =$	soil sand textural component by weight (%)
$T =$	surface temperature (centigrade)

§7.0 OUTPUT FILES

There are three possible output files from the VTRPE model:

(1) An ASCII formatted-type file containing a diagnostic listing controlled by the RPE namelist input variable **IDEBUG**.

(2) An optional ASCII-type plot file controlled by the RPE namelist input variable IPLOT. This plot output file is intended to be input to a suitable plotting program and contains tabular values of path loss (PL) or propagation factor (PF) on a range/altitude matrix as specified by inputs in the RPE namelist. (See the description at the end of this section.)

(3) An optional BINARY-type file containing path loss or propagation factor on a range/altitude matrix.

7.1 Plot Output File: ASCII Format

The plot output file is an ASCII-type file consisting of a header block followed by columnar values of range and dB loss values (i.e., PL or PF). The header block is comprised of the following records formed by five FORTRAN formatted-type records which may be read using list directed INPUT/OUTPUT as and is shown in figure 2.

logical record 1	run_title
logical record 2	program version
logical record 3	input_filespec
logical record 4	integer run parameters
logical record 5	real run parameters
logical record 6	refractivity profile data
logical record 7	receiver altitudes

Figure 2. Output file header.

The header block is comprised of the following records formed by five FORTRAN formatted-type records which may be read using list directed INPUT/OUTPUT as:

record 1: *run_title*:
quote delimited FORTRAN character string containing the title of the run ($\leq$ 80 characters).

record 2: *version_id date_time_group data_format*
three quote delimited FORTRAN character strings in the order indicated where

- *version_id* is the VTRPE program version identification.
- *date_time_group* is the date and time of the run.
- *data_format* is the FORTRAN format of subsequent data.

record 3 *input_filespec*
full name of file containing run inputs.

record 4 $N\ item_1\ item_2 \cdots item_N$
integer parameters.where N is the total number of items which follow (currently, $N = 14$) and

$item_1$ = input range units flag IRUNIT
$item_2$ = input altitude units flag IZUNIT
$item_3$ = number of receiver altitudes N_z
$item_4$ = number of output ranges N_r
$item_5$ = number of points in first refractivity profile, N_p
$item_6$ = profile data type flag IPTYPE
$item_7$ = transmitter antenna type flag ISOURCE
$item_8$ = transmitter polarization flag IPOLAR
$item_9$ = type of absorber
$item_{10}$ = type of dB-loss output flag ILOSS
$item_{11}$ = FFT exponent size used NFFT
$item_{12}$ = scale factor for loss values ISCALE
$item_{13}$ = number of "triplets" in receiver altitudes array
$item_{14}$ = number of items in floating point record, N_{float}

record 5 $item_1\, item_2 \cdots item_N$

floating point parameter values, where

$item_1$ = transmitter altitude (m)
$item_2$ = transmitter frequency (Hz)
$item_3$ = first output range (km)
$item_4$ = last output range (km)
$item_5$ = output range increment (km)
$item_6$ = transmitter vertical mainlobe tilt (deg)
$item_7$ = transmitter vertical beamwidth (deg)
$item_8$ = initial PE range step (m)
$item_9$ = maximum altitude in PE grid (m), Z_{max}
$item_{10}$ = complex absorber amplitude, V_0
$item_{11}$ = complex absorber scale length, w_0
$item_{12}$ = FFT p-space pass-band limit, DBPASS

Following the floating point parameters record, are one or more records which contain N_p profile data pairs corresponding to the first input refractivity profile. Each profile data record contains up to five pairs of altitude, z_i, and corresponding refractivity, P_i, $\{z_1\, P_1\; z_2\, P_2 \cdots\}$, starting at the surface. The type of refractivity data is indicated by $item_6$ of the integer parameters record.

Following the profile data logical record, is the receiver altitudes logical record consisting of one or more physical records containing the N_z receiver altitudes. This concludes the header block.

After the header block, there are NR logical range records, each of which contain NZ scaled (by scale factor ISCALE) integer dB-loss values. Each logical range record comprises one or more physical records and has the format:

$$range \quad item_1\, item_2 \cdots item_{NZ}$$

where

$range$ = floating point range in units specified by `IRUNIT`

$item_i$ = integer scaled dB-loss value corresponding to ith receiver altitude

The actual FORTRAN format used to write the range data record is contained in the CHARACTER string *data_format* contained in logical record 2 of the header.

7.2 Plot Output File: EREPS Format

If `IPLOT=2` is specified in the RPE namelist, then the output plot file will be in a format that may be input into the EREPS model. Consult the EREPS documentation for the exact format.

7.3 Plot Output File: Binary Format

If `IPLOT=3` is specified in the RPE namelist, then the output plot file will be a FORTRAN binary-type file. The file will consist of N_r logical records, each having the form

$$range_i \; dB_1 \; dB_2 \; \ldots \; dB_{N_z}$$

where $range_i$ is the PE output range, and the $\{dB_i\}$ are the model output db-loss values.

§8.0 Examples

The following examples of VTRPE input run streams illustrate various options previously described.

8.1 Test Case 1: Evaporation Duct

Test case 1 is a range-independent, 28-meter evaporation-duct profile, with smooth surface boundary conditions. The title of the run is `TEST case 1: 28m Evap Duct`. A 400 MHz (`MEGAHZ=400`) transmitter is located at a height of 25 meters (`ZTRANS=25`) above the ocean surface. The transmitter has a Gaussian-type beam pattern (`ISOURCE=0`) with a vertical beamwidth of 2.5 degrees (`BMWIDTH=2.5`) and is steered horizontally (`BMELEV=0`). There are 10 receivers (i.e., targets) equispaced at 0.5-meter intervals starting at 1 meter (`ZR=1.0, -10., .5`). The maximum physical altitude in the calculation is 309.5 meters (`HMAX=309.5`). Output will consist of dB values of path loss (`ILOSS=1`) starting at the origin (`RFIRST=0`), spaced at 0.25 km (`RNGINC=.25`) increments (or the closest actual PE step) out to a maximum range of 50 km (`RLAST=50`). No plot-file will be produced (`IPLOT=0`). The refractivity profile is input in scaled modified refractivity format (IPTYPE=3), with a reference modified refractivity value of 309.5 M-units (`MZERO=309.5`). The profile consists of 23 height/refractivity pairs, with the vertical units being meters.

The following lines show the input file corresponding to this test case. Note that the namelist identifier strings `&RPE` and `&SECTOR` MUST start in column 2.

```
 &RPE
  TITLE= 'TEST case 1:  28m Evap Duct',
  IPLOT= 0,
  ISOURCE= 0,
  ILOSS= 1,
  IDEBUG=1,
  MEGAHZ= 400.0,
  ZTRANS= 25.0,
  ZR= 1.0, -10.0, .5,
  BMWIDTH= 2.5, BMELEV= 0.0,
  RFIRST= 0., RNGINC= 0.25, RLAST= 50.0,
  HMAX = 309.5,
 &END
 &SECTOR     IPTYPE= 3, MZERO= 339.0,
  PROFILE=
   0.0,     0.0,      0.2,   -12.83,     0.316, -14.24,    0.501, -15.67,
   0.794, -17.08,     1.259, -18.46,     1.995, -19.81,    3.162, -21.1,
   5.012, -22.31,     7.943, -23.38,    12.589, -24.24,   19.953, -24.76,
```

```
 28.0,    -24.84,   39.811, -24.48,   50.119, -23.91,  63.096, -23.01,
 79.433, -21.69,  100.0,    -19.84,  125.893, -17.32, 158.489, -13.97,
199.526,  -9.56,  209.526,   -8.38,  309.526,   3.42,
&END
```

8.2 Test Case 2: Guadalupe Island

Test case 2 is an example of a range-dependent run over water. The environmental data correspond to the Gaudalupe Island experiment conducted off the coast of Southern California in 1948. The experiment consisted of a beacon-equipped airplane flying a "saw tooth" profile away from receivers mounted on a bluff overlooking the ocean. Using reciprocity, the received field patterns may be computed by reversing the position of the receiver and source.

The transmitter properties are thus:

(1) frequency of 200 MHz;

(2) Gaussian-type antenna pattern having a 2 degree vertical beamwidth and steered up 2 degrees;

(3) elevation of 150 meters.

The range units are nautical miles, with path loss PL output every 2 nmi. Ten equispaced receiver altitudes are specified, spaced 20 meters apart starting at 10 meters. Five refractivity profiles are input, spaced from 0 to 200 nmi from the transmitter. The profile altitude units are in feet, with refractivity in N-units being specified. The first profile has 28 points, starting at the sea surface and extending to 3500 feet. Range interpolation is defined between the first profile at range = 0 nmi and the second profile at range = 80 nmi by the specification of 7 vertex connection pairs that determine the quadrilateral bivariate surface interpolation regions. The tessellation is defined as:

(1) between $z = 0$ on profile 1 and $z = 0$ on profile 2

(2) between $z = 500$ on profile 1 and $z = 500$ on profile 2

(3) between $z = 500$ on profile 1 and $z = 700$ on profile 2

(4) between $z = 800$ on profile 1 and $z = 1050$ on profile 2

(5) between $z = 1500$ on profile 1 and $z = 1500$ on profile 2

(6) between $z = 1600$ on profile 1 and $z = 1600$ on profile 2

(7) between $z = 3500$ on profile 1 and $z = 3500$ on profile 2

```
&RPE
  TITLE= 'Guadalupe Island Experiment',
  MEGAHZ= 200.,
  BMELEV= 2.,
  BMWIDTH= 2.,
  ZR= 10., -10., 20.,
  ZTRANS= 150.,
```

```
  ZMAX=1500.,
  IDEBUG=1,
  IPLOT=2,
  ILOSS= 1,
  NRANGE=100,
  RNGINC= 2.,
  IRUNIT = 1,
  RFIRST= 0.,
&END
&SECTOR
   PROFID='Guadalupe Is Exp:  Modified profile #1',    PRANGE=0.,
   IPTYPE=1, IRUNIT=1, IZUNIT=1, NVP= 28,
   PROFILE=
    0., 336.,   200., 335.,   300., 334.,   400., 334.,   500., 332.,
  550., 329.,   600., 326.,   650., 314.,   700., 302.,   800., 285.,
  850., 284.,   900., 282.,  1000., 279.,  1200., 276.,  1300., 276.,
 1400., 276.,  1500., 275.,  1600., 273.,  1800., 272.,  2000., 272.,
 2200., 271.,  2400., 269.,  2600., 267.,  2800., 266.,  3000., 266.,
 3200., 266.,  3400., 264.,  3500., 263.,
&END
&SECTOR
  PROFID='Guadalupe Is Exp:  profile #2',   PRANGE=80.,   NVP=28,
  PROFILE=
   0., 337.,   200., 335.,   400., 333.,   500., 332.,  700., 330.,
 800., 324.,   900., 309.,   950., 304.,  1000., 296.,  1050., 293.,
1100., 291.,  1200., 290.,  1300., 287.,  1400., 286.,  1500., 282.,
1550., 275.,  1600., 273.,  1700., 273.,  1800., 272.,  2000., 272.,
2200., 271.,  2400., 269.,  2600., 267.,  2800., 266.,  3000., 266.,
3200., 266.,  3400., 264.,  3500., 263.,
NPAIR=7,
CONNECT=    0.,   0.,
          500., 500.,
          500., 700.,
          800., 1050.,
         1500., 1500.,
         1600., 1600.,
         3500., 3500.
&END
&SECTOR
```

```
  PROFID='Guadalupe Is Exp:  profile #3',   PRANGE=120., NVP=28,
  PROFILE=
    0., 334.,    200., 334.,   300., 333.,   400., 333.,   600., 331.,
  700., 330.,    800., 328.,  1000., 327.,  1100., 327.,  1200., 326.,
 1250., 319.,   1300., 312.,  1400., 295.,  1450., 291.,  1500., 286.,
 1550., 284.,   1600., 283.,  1800., 281.,  1900., 276.,  2000., 271.,
 2100., 270.,   2200., 269.,  2400., 269.,  2600., 269.,  2800., 266.,
 3000., 265.,   3300., 263.,  3500., 263.,
NPAIR=7,
CONNECT=    0.,    0.,
          700., 700.,
          700., 1200.,
         1050., 1500.,
         1500., 1800.,
         2000., 2000.,
         3500., 3500.
&END
&SECTOR                  PROFID='Guadalupe Is Exp:  profile #4',
  PRANGE=160.,   NVP=24,
  PROFILE=
   0., 333.,     50., 332.,   300., 330.,   400., 329.,   600., 327.,
 800., 325.,   1000., 324.,  1150., 323.,  1200., 320.,  1400., 305.,
1500., 297.,   1600., 292.,  1650., 289.,  1700., 287.,  1800., 282.,
2000., 273.,   2200., 267.,  2400., 271.,  2500., 273.,  2600., 272.,
2800., 267.,   3000., 265.,  3300., 265.,  3500., 261.,
NPAIR=6,
CONNECT=    0., 0.,   1000., 1000., 1200., 1150.,  1500., 1600.,
       2000., 2000.,  3500., 3500.
&END
&SECTOR   PROFID='Guadalupe Is Exp:  profile #5',
  PRANGE=200.,  NVP=24,
  PROFILE=
   0., 331.,    200., 329.,   300., 327.,   400., 327.,   600., 324.,
 800., 321.,   1000., 320.,  1200., 318.,  1400., 315.,  1600., 307.,
1700., 299.,   1750., 301.,  1850., 290.,  2000., 280.,  2200., 274.,
2400., 270.,   2500., 273.,  2600., 274.,  2700., 278.,  2800., 265.,
2900., 261.,   3100., 264.,  3300., 263.,  3500., 262.,
 NPAIR=8,
 CONNECT=  0.      0.,    1000.  1000.,    1200.  1600.,  1600.  2000.,
```

```
        2000.  2000.,  2200.  2200.,   2400.  2400.,  3500.  3500.
&END
```

8.3 Test Case 3: N. Persian Gulf

This test case is a range dependent, variable terrain run between 0.5 and 200 km. The frequency is 520 MHz, with the transmitter located at 60 meters and 1 receiver at 10 meters altitude. There are three refractivity profiles specified, and the surface properties are specified in the IGTYPE=0 format.

```
&RPE
  TITLE= 'N. Persian Gulf Test',
  MEGAHZ= 520.,
  NFFT=0,
  BMELEV= 0.,  BMWIDTH= 1.6,
  ZR= 10.,
  ZTRANS= 60.,
  DRMAX = 500.,
  DRMIN = 75.,
  PESTEP=0.,
  HMAX=1000.,
  IDEBUG=2,
  IPLOT=0,
  ILOSS= 1,
  RFIRST=.5, RNGINC=.5, RLAST=200.
  IVTPE=1,
&END
&SECTOR
  PROFID='16m Evap Duct:  profile #1',
  PRANGE=0.,    IPTYPE=3,   MZERO=339.,   NVP= 22,
  PROFILE=
   0.,     0.,      0.1, -12.995,    0.25, -14.839,    0.50, -16.161,
   1.0, -17.485,    2.0, -18.746,    4.0, -19.882,     6.0, -20.443,
   8.0, -20.768,   12.,  -21.08,    14.0, -21.138,    16.0, -21.155,
  18.0, -21.140,   20.0, -21.101,   25.0, -20.923,    50.,  -19.184,
 100.,  -14.320, 125.0, -11.64,    150.0,  -8.88,    200.0,  -3.206,
1000.0,  93.57,  1500., 155.26
&END
```

```
&SECTOR
  PROFID='Profile #2',
  PRANGE=100.,    IPTYPE=2,    MZERO=0.,    NVP= 12,
  PROFILE=
    0.,     376.0,
   50.,     363.0,
  100.,     339.0,
  125.,     325.0,
  150.,     315.0,
  200.,     320.,
  250.,     321.,
  300.,     319.,
  350.,     318.,
  380.,     325.,
  500.,     339.,
 1500.,     475.,
  NPAIR=3,
  CONNECT=
    0.,   0.,
   16., 150
  1500., 1500.
&END
&SECTOR
  PROFID='Profile #3',
  PRANGE=140.,
  IPTYPE=2,
  MZERO=0.,
  NVP= 9,
  PROFILE=
    0.,     275.0,
  150.,     315.0,
  200.,     320.,
  250.,     321.,
  300.,     319.,
  350.,     318.,
  380.,     325.,
  500.,     339.,
 1500.,     475.,
  CONNECT=
```

```
   0.,    0.,
  150., 150.,
 1500., 1500.
&END
&GROUND
 0, 0, 0
 0.,      0.,      70.,     50.  /
 98.,     0.,      70.,     50.  /
100.,     0.,      70.,     50.  /
101.,     1.,      70.,     50.  /
124.2     1.5,     70.,     50.  /
126.0,    2.0,     24.,     32.  /
129.8,    60.,     10.,     1.6 /
132.6,    100.,     3.,     .02 /
136.6     200.,     3.,     .02 /
138.2,    160.,     3.,     .02 /
142.6,    100.,     3.,     .02 /
157.4,    100.,     3.,     .02 /
158.6,    200.,     3.,     .02 /
159.4,    300.,     3.,     .02 /
160.4,    400.,     3.,     .02 /
161.8,    150.,     3.,     .02 /
162.2,    325.,     3.,     .02 /
177.4,    400.,     3.,     .02 /
191.0,    400.,     3.,     .02 /
197.0,    500.,     3.,     .02 /
201.,     600.,     3.,     .02 /
202.,     500.,     3.,     .02 /
212.6,    600.,     3.,     .02 /
250.6,    600.,     3.,     .02 /
&END
```

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	October 1991	Final: May 90 — Sep 91

4. TITLE AND SUBTITLE

USER'S GUIDE FOR THE VTRPE (VARIABLE TERRAIN RADIO PARABOLIC EQUATION) COMPUTER MODEL

5. FUNDING NUMBERS

0602435N CDB6
OMAF MP03

6. AUTHOR(S)

Frank J. Ryan

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Ocean Systems Center
San Diego, CA 92152–5000

8. PERFORMING ORGANIZATION REPORT NUMBER

TR 1456

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Technology
Arlington, VA 22217–5000

Joint Electronic Warfare Center
Kelley AFB
San Antonio, TX 78243

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

This report is a user's guide to the VTRPE (variable terrain radio parabolic equation) computer model. It is designed to provide the reader with a summary of the physics and numerical methods used in the VTRPE model, along with detailed instructions on the model's use and operation.

The VTRPE computer program is a range-dependent, tropospheric microwave propagation model that is based upon the split-step Fourier parabolic wave equation algorithm. The nominal applicable frequency range of the model is VHF to K-band. The VTRPE program is able to make predictions for microwave propagation over both land and water. The VTRPE code is a full-wave propagation model that solves the electromagnetic wave equations for the complex electric and magnetic radiation fields. The model accounts for the effects of nonuniform atmospheric refractivity fields, variable surface terrain, and varying surface dielectric properties on microwave propagation.

The code is written in ANSI–77 FORTRAN with MILSPEC–1753 FORTRAN language extensions. The VTRPE program is currently configured to run under the UNIX operating system on SUN minicomputers and CONVEX supercomputers, and under MS–DOS on 80386/80486-based PC's.

14. SUBJECT TERMS

microwave propagation
numerical wave propagation

15. NUMBER OF PAGES

60

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAME AS REPORT

21a. NAME OF RESPONSIBLE INDIVIDUAL	21b. TELEPHONE *(include Area Code)*	21c. OFFICE SYMBOL
Frank J. Ryan	(619) 553-3099	Code 541

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