PROPAGATION OF VLF RADIATION IN THE EARTH-IONOSPHERE WAVEGUIDE EXCITED BY AN AIRBORNE DUAL TRAILING WIRE ANTENNA

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Abstract - Field strength variations produced by an orbiting aircraft dual trailing wire VLF transmitting antenna are investigated. The towplane is assumed to be executing a circular orbit at a constant altitude and speed. A steady-state mechanical model is adopted for determination of the shape of the dual trailing wire antenna. The exact current distribution on this antenna is calculated using the Numerical Electromagnetics Code (NEC) which is based on a method of moments solution of the Electric Field Integral Equation (EFIE). A propagation code developed at the Naval Ocean Systems Center (NOSC) called TWIRE has been modified to be used in conjunction with NEC. This modified version of TWIRE has been called TWIRENEC. The TWIRENEC code uses the current distribution information provided by NEC to determine the dipole moments for a segmented antenna. The wire segmentation geometry and corresponding dipole moments are then used to calculate the electric field strength as a function of distance and azimuth in the earth-ionosphere waveguide. The waveguide can be considered as either horizontally homogeneous or inhomogeneous. It is demonstrated that the periodic variations in field intensity resulting from an orbiting transmitter are a function of receiver position. These periodic variations can range from a small fraction of a dB to several dB depending upon the location of the receiver with respect to the transmitter. A point dipole approximation of the dual trailing wire antenna is suggested for use in the study of VLF radiation excited by an orbiting antenna in the presence of wind shear. The point dipole approximation is applied to estimate the field strength variations caused by a yo-yo oscillation of the transmitting antenna as it orbits. These yo-yo oscillations are characterized in terms of the change in verticality of the point dipole which occurs over one complete orbit.

I. INTRODUCTION

Kelly [1] investigates the VLF field strength variations resulting from an elevated and inclined point dipole transmitting antenna travelling in a circular orbit. This antenna is an idealization of a trailing wire antenna carried by an orbiting aircraft. The ionosphere is considered to be homogeneous and isotropic in the earth-ionosphere waveguide propagation model used for calculating VLF fields. An excellent discussion is presented on additional complications which would be introduced by an anisotropic ionosphere.

Pappert and Bickel [2] present theoretical expressions for the vertical (E_z) and horizontal (E_y) VLF electric fields excited by point dipoles of arbitrary orientation and elevation. Bickel et al. [3] and Bickel [4] apply these results to determine the VLF fields produced by an arbitrarily shaped wire composed of a series of point dipole radiators, each with the proper orientation, elevation and current moment. The field strength at any distance away from the antenna was found by taking the vector sum of the contributions from each point dipole. This extended source model was used to calculate the amplitude of vertical and horizontal field components for various configurations of an airborne VLF trailing wire antenna. Predicted values of the vertical field component E_z for daytime and nighttime propagation were generally found to be in good agreement with measurements. Pappert and Hitney [5] describe a propagation code called TWIRE which streamlines calculations of the type made by Bickel et al. [3] and Bickel [4]. One of the improvements incorporated into the TWIRE code is the ability to determine the current amplitude from an assumed current distribution and radiated power.

A modified version of the TWIRE code, called TWIRENEC, has been created by the authors. The major difference between the two codes is in the way the current distribution on the VLF antenna is determined. The TWIRE code makes the assumption that the current distribution on the antenna is sinusoidal and relates the current amplitude to an assumed radiated power. The TWIRENEC code uses the exact current distribution calculated by the Numerical Electromagnetics Code (NEC) [6]. This current distribution is calculated using an appropriate value of input power delivered to the antenna by the transmitter. This paper presents and discusses some VLF propagation results obtained using the new TWIRENEC code. In particular, this code is used to compute field strength variations caused by an orbiting aircraft which is trailing a VLF transmitting antenna.

II. THEORY

The TWIRENEC propagation code was developed for calculating VLF fields in the earth-ionosphere waveguide generated by antennas of arbitrary length, shape and elevation. A flowchart of the TWIRENEC computer program is shown in Figure 1. The original TWIRE subroutines COORD, RPOWER and FASTMC have been renamed COORD2, RPOWER2 and FASTMC2 to indicate that they were modified for use in TWIRENEC.

The subroutine COORD2 reads the wire segmentation geometry and the corresponding dipole moments from output files created by the NEC code. The wire segmentation geometry is then transformed from the towplane coordinate system to the propagation coordinate system. Figure 2 is an illustration of the propagation coordinate system. The direction of propagation is along the positive x axis which is at a bearing φ_a with respect to magnetic north. The towplane is assumed to be orbiting at an altitude $z = z_p$ with an orbital radius of $r_p = \sqrt{x_p^2 + y_p^2}$ and a constant velocity $\vec{V}$. The position of the towplane in its orbit with respect to the propagation axis may be described in terms of the angle ψ. One complete orbit of the towplane is characterized by a progression in the angle ψ from 0° to 360°.

The subroutine RPOWER2 calculates the time averaged radiated power from the wire segmentation geometry and dipole moments which are output from COORD2. The expression for radiated power used in this subroutine was derived by Pappert [7] assuming thin antennas of arbitrary elevation and orientation above perfectly conducting ground. This formulation is based upon segmentation of the wire antenna.

The mode sums for a horizontally inhomogeneous waveguide excited by an antenna which is composed of W segments are [5]

$$E_n^{(p)}(\mu V/m) = Q\sum_j \sum_m a_{jm}^{(p)} \left[\delta_{1n} \frac{S_j^{(p)}}{S_m^{(1)}} + (1 - \delta_{1n})\right] f_{nj}^{(p)}(z_r) \quad (1)$$

$$\cdot \exp\left[-ik(S_m^{(1)} x_2 + S_j^{(p)}(x - x_p))\right] F_{nm} \quad , p \neq 1$$

where

$$F_{nm} = \sum_{w=1}^{W} \frac{M_w \exp(ikS_m^{(1)}\bar{x}_w)}{\left[\sin\left(\frac{x - \bar{x}_w}{a}\right)\right]^{1/2}} \left[\lambda_{1nm}^{(1)} f_{1m}^{(1)}(\bar{z}_w)\cos\gamma_w \right. \quad (2)$$

$$\left. + \lambda_{2nm}^{(1)} f_{2m}^{(1)}(\bar{z}_w)\sin\gamma_w \sin\phi_w + \lambda_{3nm}^{(1)} f_{3m}^{(1)}(\bar{z}_w)\sin\gamma_w\cos\phi_w\right]$$

and

Q	=	$2.853 \times 10^{-3} f^{3/2}$
S_m	=	$\sin\theta_m$
f	=	frequency (kHz)
k	=	free space wave number
a	=	radius of the earth
z_r	=	receiver altitude
w	=	wire segment index
$(\bar{x}_w, \bar{z}_w)$	=	midpoint coordinates for the w^{th} segment
(γ_w, ϕ_w)	=	orientation angles for the w^{th} segment
M_w	=	dipole moment of the w^{th} segment (rms amp-meters)

p	=	waveguide slab number
j, m	=	mode indices
θ_m	=	modal eigenangle
$a_{jm}^{(p)}$	=	cumulative mode conversion coefficients
δ_{1n}	=	Kronecker delta function
E_n	=	electric field component at the receiver (n=1 implies E_z, n=2 implies E_y and n=3 implies E_x)
i	=	$\sqrt{-1}$
f_n	=	modal height gain (f_1 is height gain for E_z, f_2 is height gain for E_y and f_3 is height gain for E_x)
λ_n	=	excitation factor (λ_1 is the vertical dipole excitation factor, λ_2 is the broadside dipole excitation factor and λ_3 is the end-on dipole excitation factor)

The wave propagation is assumed to be in the *x-z* plane with the *x* coordinate as the range. The origin for the *x* coordinate is taken to be at the center of the towplane orbit projected onto the ground. The *z* coordinate has its origin on the ground and is directed positive towards the ionosphere. The midpoint of the w[th] dipole with current moment $\vec{M}_w$ is located at $(\bar{x}_w, \bar{y}_w, \bar{z}_w)$ with orientation ϕ_w and γ_w relative to the *x* and *z* axis, respectively. The $a_{jm}^{(p)}$ represent cumulative mode conversion coefficients for a slab mode conversion model in which x_n is the beginning of the n[th] slab and with the first slab described by the region $x < x_2$. The physical interpretation of the cumulative mode conversion coefficients are the accumulative conversion from a unit amplitude wave in mode *m* in the transmitter region to mode *j* in the p[th] slab. The electromagnetic field strength in the waveguide is calculated along a propagation path by making use of the subroutine FASTMC2. FASTMC2 is essentially a fast mode conversion propagation code developed by Ferguson and Snyder [8]. The subroutines PRESEG, MODEFNDR and SEGMWVGD are part of the Naval Ocean System Center's Long-Wave Propagation Capability (LWPC) program. The LWPC code is documented in Ferguson and Snyder [9] and in Ferguson et al. [10]. PRESEG is a driver program which sets up files that provide the necessary input and calls to the subroutines MODEFNDR [11] and SEGMWVGD [12]. Data files are set up by PRESEG as input for MODEFNDR which obtains starting mode solutions for a specific segment on the propagation path. The starting solutions determined by MODEFNDR are input to SEGMWVGD. The SEGMWVGD program then extrapolates these solutions as the waveguide parameters vary with distance from the transmitter. The resulting horizontally inhomogeneous waveguide parameters are then input into the FASTMC2 program to be used in the calculation of mode conversion coefficients and mode sums. The programs PRESEG, MODEFNDR and SEGMWVGD can be used to find the waveguide parameters for a horizontally homogeneous as well as a horizontally inhomogeneous waveguide. The mode sums for the fields in a horizontally homogeneous waveguide (p=1) excited by a W segmented antenna are

$$E_n^{(1)}(\mu V/m) = Q\sum_m f_{nm}^{(1)}(z_r)\exp\left[-ikS_m^{(1)}x\right]F_{nm} \tag{3}$$

A horizontally inhomogeneous waveguide model is more realistic than a model which is horizontally homogeneous. This is because a horizontally inhomogeneous model can take into account variations in the ground conductivity and ionosphere which may be present over a propagation path.

Bickel [4] and Pappert and Hitney [8] have shown that the trailing wire transmitting antenna can be approximated by a point dipole with the properly chosen current moment and orientation. In most cases the altitude and orientation of the point dipole can be chosen to correspond to the towline segment which contains the current maximum. The current on this point dipole is chosen so that it has a radiated power equivalent to that of the trailing wire antenna it is intended to replace. This is an important result because it implies that a considerable reduction in computation time can be achieved by replacing the complex structure of the trailing wire antenna with an appropriate point dipole.

One application where the point dipole approximation may be useful is in the study of propagation modes excited by a trailing wire which has periodic yo-yo oscillations. Yo-yo oscillations in the long trailing wire antenna frequently occur and have been verified by altitude measurements of a drogue located at the end of the wire [13]. In particular, oscillations in the drogue altitude of several thousands feet with a period equivalent to the orbital period have been observed. These yo-yo oscillations are believed to be the result of a variation in the wind velocity as a function of altitude, i.e. wind shear. The point dipole approximation suggests that a knowledge of the influence of yo-yo motion on the segment which contains the maximum current should be sufficient to characterize the transmitting antenna. Kelly [1] considers a model in which yo-yo produces a periodic variation in inclination of a point dipole antenna as it traverses a circle. The yo-yo motion is taken into account by allowing the inclination angle γ to oscillate about some average value γ_o as the antenna orbits. This periodic change in inclination can be represented by

$$\gamma = \gamma_o + \Delta\gamma\sin(\psi + \psi_o) \tag{4}$$

where ψ_o is an offset angle in the orbital period of the inclination. The variable $\Delta\gamma$ determines the amplitude of the yo-yo induced excursions in the inclination. When $\Delta\gamma = 0$ there are no oscillations in inclination which indicates that static conditions exist.

A reasonable assumption to make is that $0° < \gamma_o < 90°$ for the segment of the trailing wire antenna which has the current maximum. A typical value of γ_o would be 45°. It is physically realistic to assume that the change in inclination due to yo-yo must have the vertical and horizontal as the two limiting positions of the point dipole, hence $0° \leq \gamma \leq 90°$. In order to satisfy these conditions, $\Delta\gamma$ must be restricted to lie within the range given by

$$0^\circ \leq \Delta\gamma \leq \Delta\gamma_{max} = \min\,(\gamma_o\,,\, 90^\circ - \gamma_o) \tag{5}$$

At this point in the development it is convenient to introduce the concept of verticality. Verticality is defined to be the ratio of the vertical projection of the wire antenna to the total length of the antenna, in percent. For example, consider a point dipole antenna which is inclined at an angle γ_o from the vertical. The verticality V_0 of this antenna is then

$$V_0 = 100\cos\gamma_o \quad \% \tag{6}$$

The verticality would be about 70% for a point dipole inclined at an angle of 45° with respect to the vertical.

The minimum and maximum angle of inclination which result from yo-yo motion are

$$\gamma_{min} = \gamma_o - \Delta\gamma \tag{7}$$

$$\gamma_{max} = \gamma_o + \Delta\gamma \tag{8}$$

The corresponding minimum and maximum verticalities are

$$V_{min} = 100\cos\gamma_{max} \quad \% \tag{9}$$

$$V_{max} = 100\cos\gamma_{min} \quad \% \tag{10}$$

The change in verticality over one complete orbit is then

$$\Delta V = V_{max} - V_{min} \quad \% \tag{11}$$

Equations (7) - (11) can be used to derive an expression which relates the yo-yo oscillation amplitude $\Delta\gamma$ to the change in verticality ΔV. This relationship is

$$\Delta\gamma = \sin^{-1}\left[\frac{\Delta V(\%)}{200\sin\gamma_o}\right] \tag{12}$$

The bounds on ΔV can be obtained by substituting (12) into (5), which results in

$$0 \leq \Delta V \leq \Delta V_{max} = 200\sin\gamma_o\,\min\,(\sin\gamma_o\,,\,\cos\gamma_o) \tag{13}$$

III. RESULTS

Propagation characteristics of the 22 kHz dual trailing wire antenna shown in Figure 3 will be investigated in this section. Steady-state mechanical modeling codes, which are based on an analysis by Huang [14] and Narkis [15], were used to arrive at the geometry of this antenna. Projections of the antenna geometry onto the three principal planes along with the orbital path are displayed in this figure. Under steady state conditions, the antenna is assumed to maintain the same shape as it is being trailed by the orbiting towplane. The towplane trailing the antenna configuration shown in Figure 3 is orbiting counterclockwise. The length of the short and long trailing wires are 2680 feet and 19500 feet, respectively, which corresponds to an electrical length of one-half wavelength ($\lambda/2$). The altitude of the towplane is 20500 feet, the orbit radius is 6073 feet and its speed is 199 knots. The verticality of the short wire is 30.66% and the verticality of the long wire is 69.81%. The field strength variations produced by this antenna as it moves around in a circle are of particular interest. The current distribution along this antenna was determined using the NEC code and assuming a 200 kW input power with a DC wire resistance of 4.5 Ω/1000 feet. The presence of the aircraft was neglected in the modeling of the dual trailing wire antenna system.

An easterly propagation path ($\varphi_a = 90°$) over seawater is assumed in the analysis presented in this section. The values used for conductivity and relative permittivity of seawater were 4.64 S/m and 81, respectively. An exponential electron density profile of the form [16]

$$N(z) = 1.46x10^7 \exp[(\beta - 0.15)z - \beta h'] \; cm^{-3} \tag{14}$$

was adopted. The parameters of this model were chosen as β = 0.5 km^{-1} and $\mathbf{h}'$ = 87 km. This particular electron density profile has been shown to accurately predict nocturnal VLF propagation to the east [17]. The geomagnetic field strength was taken to be 0.5 Gauss with a dip angle of 50°.

Figure 4 shows curves of the vertical electric field component E_z at sea level expressed in dB above 1μV/m. The two curves shown in Figure 4 compare nocturnal easterly VLF propagation at 22 kHz for an orbiting towplane at positions which are 90° (solid curve) and 270° (dashed curve) with respect to the direction of propagation. A relatively large difference between the two signals is observed at a distance of 1.7 Mm, whereas a relatively small difference exists at 3.8 Mm. Figure 5 shows the orbital dependence of the E_z field component amplitude at a range of 1.7 Mm (diamonds) and 3.8 Mm (triangles) from the center of the towplane orbit. This demonstrates that it is possible to get a considerable variation in the signal level at the receiver caused by the orbiting of the towplane, in this case about 8 dB at 1.7 Mm. It is also possible, however, to select a suitable receiver location for which the variations in signal level due to orbiting are minimized (on the order of a few tenths of a dB at 3.8 Mm).

Figure 6 shows a plot of the electric field component E_z as a function of distance for an orbital position of 0° with respect to the direction of propagation (solid curve). The dashed curve represents a point dipole approximation to the dual trailing wire antenna. The point dipole was chosen to have the same altitude (4.976 km) and orientation (γ = 41.164°, ϕ = -36.695°) as the segment containing the current maximum. Equation (6) can be used to show that the verticality of this segment is around 75%. The point dipole current was determined by requiring that the point dipole have the same radiated power as the trailing wire antenna. The radiated power of the trailing wire antenna shown in Figure 3 was calculated as 96.28 kW.

It was found that the resultant radiation fields in the waveguide are relatively insensitive to the shape of the short trailing wire. This can be attributed to the fact that the current which exists on the short wire is small in comparison to the current on the long wire. Figure 6 demonstrates that reasonably accurate agreement can be obtained by replacing the entire trailing wire antenna by a point dipole.

The point dipole approximation can be utilized to greatly simplify the study of field strength variations caused by wind induced yo-yo oscillations in the trailing wire. For instance, suppose that it is desired to ascertain the influence of yo-yo motion on the field intensity of the dual trailing wire antenna shown in Figure 3. This can be accomplished by using the point dipole approximation of this antenna (see Figure 6) to represent the steady-state orientation for the point dipole yo-yo model described in the previous section. Table 1 lists the values of several parameters associated with this point dipole yo-yo model. The parameters are calculated based upon an assumed change in verticality of 10%, 15%, 20%, 25% and 30%.

TABLE 1. POINT DIPOLE YO-YO MODEL PARAMETERS

γ_o (°)	ΔV_{max} (%)	ΔV (%)	$\Delta\gamma_{max}$ (°)	$\Delta\gamma$ (°)	V_o (%)	V_{max} (%)	V_{min} (%)	γ_{max} (°)	γ_{min} (°)
41.164	86.650	10	41.164	4.357	75.283	80.065	70.065	45.521	36.807
41.164	86.650	15	41.164	6.543	75.283	82.292	67.292	47.707	34.621
41.164	86.650	20	41.164	8.739	75.283	84.409	64.409	49.903	32.425
41.164	86.650	25	41.164	10.947	75.283	86.413	61.413	52.111	30.217
41.164	86.650	30	41.164	13.173	75.283	88.302	58.302	54.337	27.991

Figure 7 contains plots of the vertical field strength as a function of distance for the steady-state case in which there would be a 0% change in verticality over one complete orbit of the towplane. The solid and dashed curves represent towplane angles of 90° and 270° in relation to the direction of propagation, respectively. The point dipole results of Figure 7 compare favorably with the dual trailing wire results shown in Figure 4. Since there is no change in verticality in this case (steady-state), the differences observed in the vertical electric field component are strictly a consequence of orbiting.

The yo-yo model of (4) with $\psi_0 = 0°$ can be used to show that a towplane angle of 90° with respect to the propagation direction corresponds to the point in the orbit where the verticality is the lowest. On the other hand, the verticality is highest when the towplane angle is 270°. The signal levels associated with the positions in the orbit for which the antenna attains the highest and the lowest verticality are compared in Figure 8 for $\Delta V = 15\%$ and in Figure 9 for $\Delta V = 30\%$. Figure 9 suggests that an orbital verticality change of 30% would produce a significant variation in the vertical field intensity over nearly the entire propagation path. Figure 10 shows the yo-yo dependence of E_z at 2.6 Mm which results from an antenna that undergoes a 0% (circles), 15% (triangles) and 30% (diamonds) change in verticality as it orbits. Figure 11 shows the corresponding yo-yo dependence of E_z at 2.9 Mm, a point which is 300 km distant from 2.6 Mm. Figure 10 suggests that a receiver located at 2.6 Mm would see very little variation in the vertical field intensity under steady-state conditions. However, yo-yo motion of the antenna characterized by a 15% and a 30% change in verticality would result in field intensity variations on the order of 1.9 dB and 3.7 dB, respectively. Figure 11 indicates that, in the absence of yo-yo, the receiver would see a variation in field intensity of about 4.8 dB. With the introduction of yo-yo, however, the magnitude of these field strength variations increase. A 9 dB variation in field strength results from an orbital verticality change of 30%. Figure 11 demonstrates that the steady-state orbital dependence of the field intensity can be considerably magnified by dynamic yo-yo motion.

IV. SUMMARY

The field strength variations associated with an orbiting aircraft which is trailing a VLF transmitting wire antenna have been investigated in this paper. A steady-state mechanical modeling code was used to determine the wire shape geometry of the orbiting VLF antenna. The mechanical modeling code provided piecewise wire segmentation for data input to NEC. This allowed the exact current distribution on the antenna to be calculated by NEC. Finally, the output NEC current distribution was used by the TWIRENEC VLF propagation code to compute the electric field strength as a function of distance, azimuth and altitude in the earth-ionosphere waveguide.

A detailed discussion of the TWIRENEC code was presented in Section 2 of this paper. The major advantage of this code is that, for a specified antenna input power, the exact current distribution on the wire is used in the calculation of the radiated power and associated mode sums. Propagation over paths in which the ionospheric or ground parameters significantly vary is modeled by considering the earth-ionosphere waveguide to be horizontally inhomogeneous. In this paper, the TWIRENEC code was used to model nocturnal easterly propagation over an all seawater path at a frequency of 22 kHz. Under these circumstances, a horizontally homogeneous waveguide model was sufficient to characterize the VLF propagation.

It was demonstrated that the entire segmented wire antenna can be approximated by a point dipole with an altitude and orientation chosen to correspond to the segment which contains the current maximum. A considerable reduction in TWIRENEC computation time was achieved by using the point dipole approximation of the trailing wire antenna. This paper combines the point dipole approximation with a yo-yo model in order to expedite the study of field strength variations caused by wind induced oscillations in the trailing wire. It was found that the steady-state orbital field strength variations tend to be localized, while the variations caused by yo-yo motion of the antenna are global in character. Results indicate that a magnification in the steady-state orbital dependence of the field intensity can be attributed to a yo-yo motion of the antenna.

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REFERENCES

[1] F. J. Kelly, "VLF field strength variations from an airborne trailing-wire antenna," *Radio Sci.*, *5* (5), 785-791, May 1970.

[2] R. A. Pappert and J. E. Bickel, "Vertical and horizontal VLF fields excited by dipoles of arbitrary orientation and elevation," *Radio Sci.*, *5*, 1445-1452, Dec. 1970.

[3] J. E. Bickel, D. G. Morfitt, I. J. Rothmuller and W. F. Moler, Propagation Analysis of Diversity for VLF Communication Systems, Naval Electronics Laboratory Center Technical Document No. 139, Sept. 1971.

[4] J. E. Bickel, Measurements of Vertical and Horizontal VLF Fields Excited by an Elevated, Arbitrarily Oriented Antenna, Naval Electronics Laboratory Center Technical Report No. 1833, July 1972.

[5] R. A. Pappert and L. R. Hitney, "TWIRE:" A Test Program for VLF Airborne Transmissions, Naval Ocean Systems Center Technical Document No. 1499, April 1989.

[6] G. J. Burke and A. J. Poggio, Numerical Electromagnetics Code (NEC) - Method of Moments, Naval Ocean Systems Center Technical Document No. 116, prepared by Lawrence Livermore Laboratory for the Naval Ocean Systems Center and Air Force Weapons Laboratory, July 1977.

[7] R. A. Pappert, "Radiation resistance of thin antennas of arbitrary elevation and configuration over perfectly conducting ground," *IEEE Trans. Antennas Propagat.*, *AP-35* (7), 863-866, July 1987.

[8] J. A. Ferguson and F. P. Snyder, Approximate VLF/LF Waveguide Mode Conversion Model: Computer Applications: FASTMC and BUMP, Naval Ocean Systems Center Technical Document No. 400, Nov. 1980.

[9] J. A. Ferguson and F. P. Snyder, Long-Wave Propagation Capability Program Description and User's Guide, Naval Ocean Systems Center Technical Document No. 1449, January 1989.

[10] J. A. Ferguson, F. P. Snyder, D. G. Morfitt and C. H. Shellman, Software Program: Long-Wave Propagation Capability and Documentation, Naval Ocean Systems Center Technical Document No. 1518, March 1989.

[11] C. H. Shellman, A New Version of MODESRCH Using Interpolated Values of the Magnetoionic Reflection Coefficients, Naval Ocean Systems Center Technical Report No. 1473, Oct. 1986.

[12] J. A. Ferguson and F. P. Snyder, The Segmented Waveguide Program for Long-Wavelength Propagation Calculations, Naval Ocean Systems Center Technical Document No. 1071, Dec. 1986.

[13] D. Nathans, TACAMO Dual Trailing Wire Antenna Input Impedance Measurements and Antenna Simulator Design, Naval Air Development Center Report No. 87040-40, Warminster, Pennsylvania, Dec. 1986.

[14] S. L. Huang, Mathematical Model for Long Cable Towed by Orbiting Aircraft, Naval Air Development Center Report No. NADC-AM-6849, Warminster, Pennsylvania, June 1969.

[15] Y. Narkis, "Approximate solution for the shape of flexible towing cables," *Journal of Aircraft*, *14* (9), 923-925, Sept. 1977.

[16] J. R. Wait and K. P. Spies, Characteristics of the Earth-Ionosphere Waveguide for VLF Radio Waves, National Bureau of Standards Technical Note No. 300, Gaithersburg, Maryland, 1964.

[17] R. A. Pappert and L. R. Hitney, "Empirical modeling of nighttime easterly and westerly VLF propagation in the earth-ionosphere waveguide," *Radio Sci. 23* (4), 599-611, July 1988.

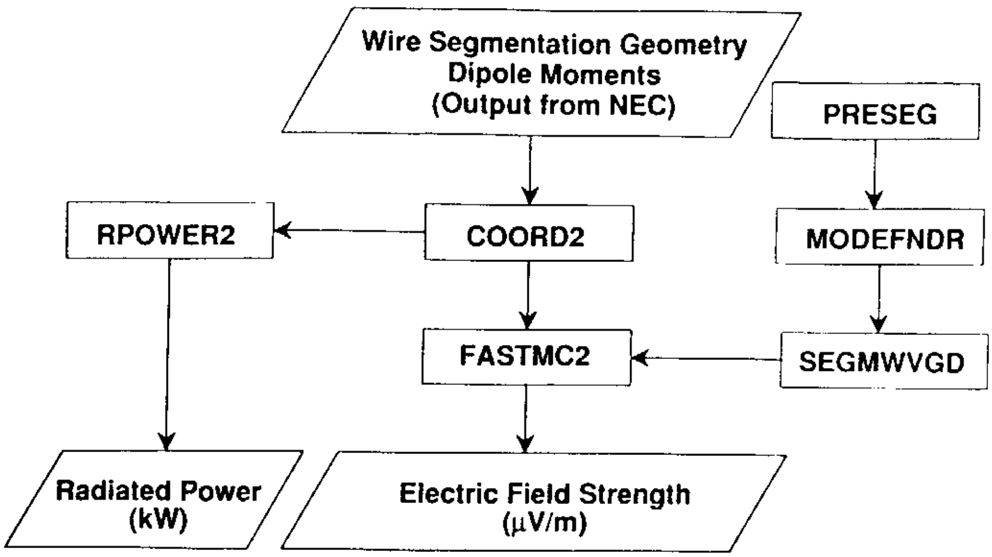

Figure 1. Flowchart of the TWIRENEC program.

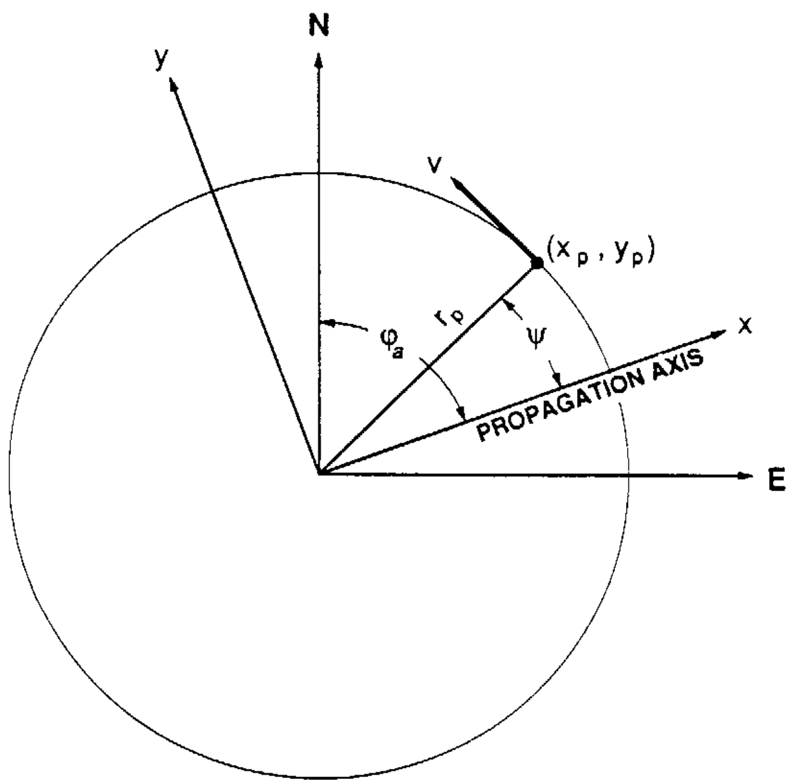

Figure 2. Propagation coordinate system.

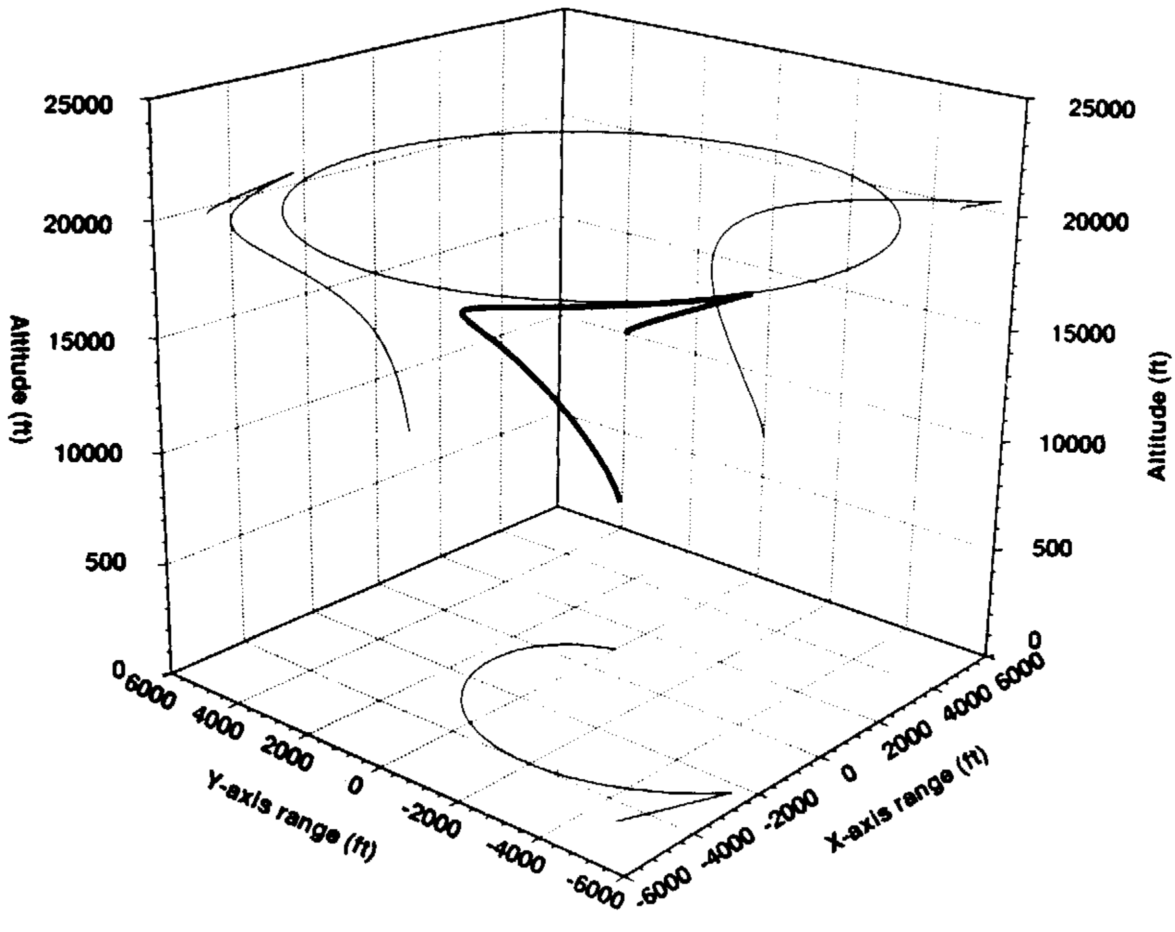

Figure 3. Dual trailing wire antenna steady-state geometry.

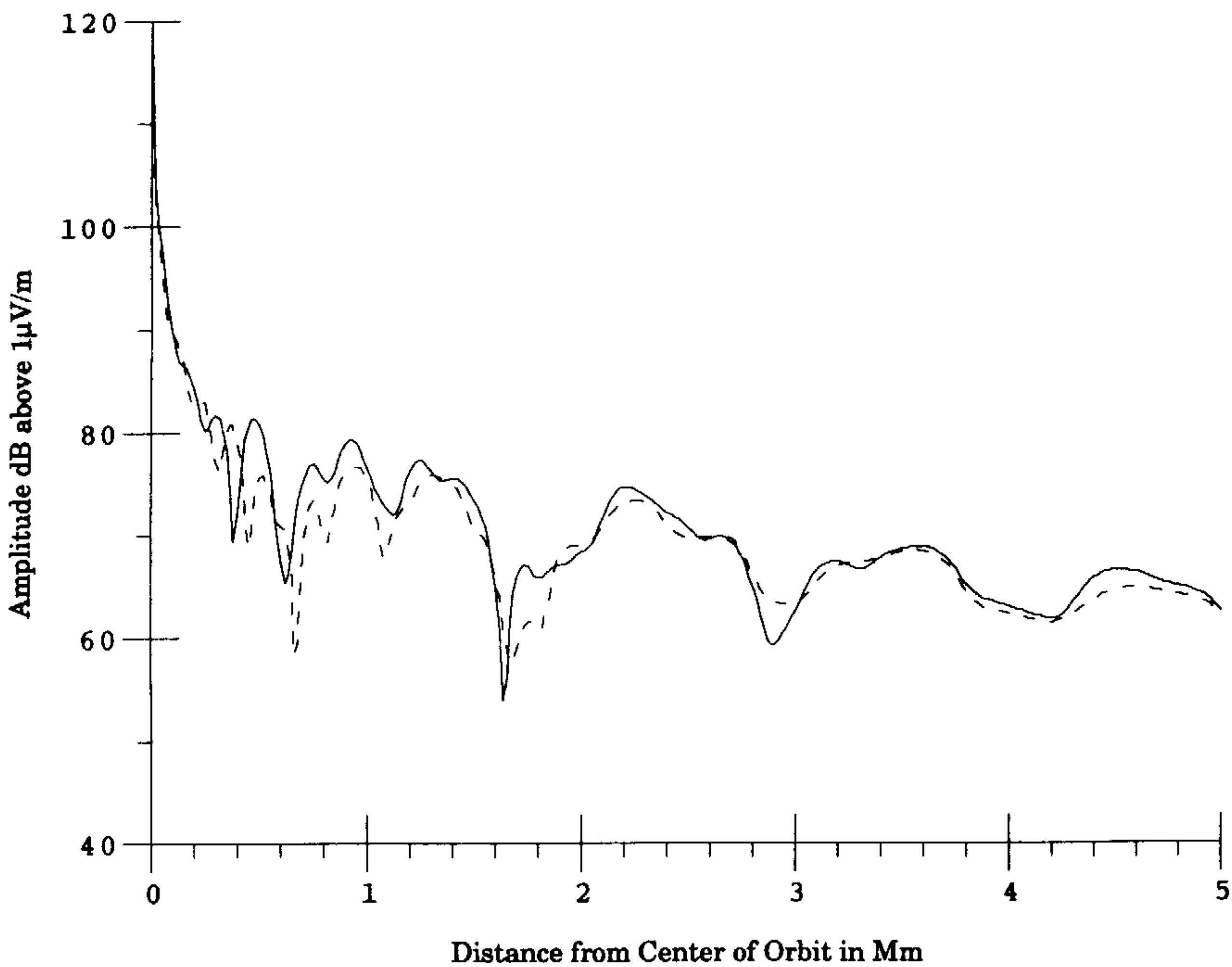

Figure 4. The vertical field strength E_z at sea level resulting from an orbiting towplane with $\psi = 90°$ (solid curve) and $\psi = 270°$ (dashed curve). Nocturnal easterly 22 kHz propagation from the dual trailing wire antenna.

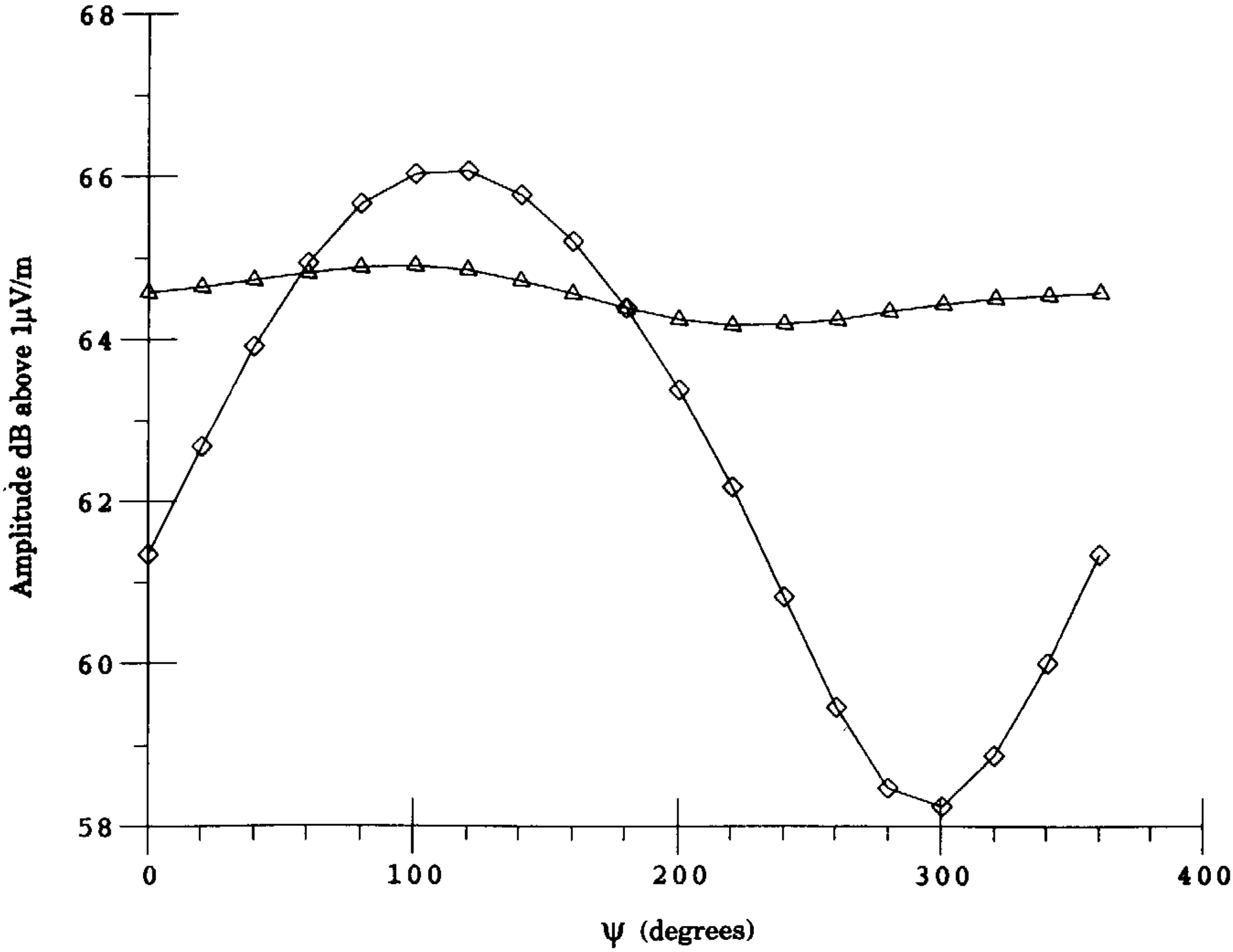

Figure 5. A comparison of the orbital dependence of the vertical field strength E_z at 1.7 Mm (diamonds) and at 3.8 Mm (triangles). Nocturnal easterly 22 kHz propagation from the dual trailing wire antenna.

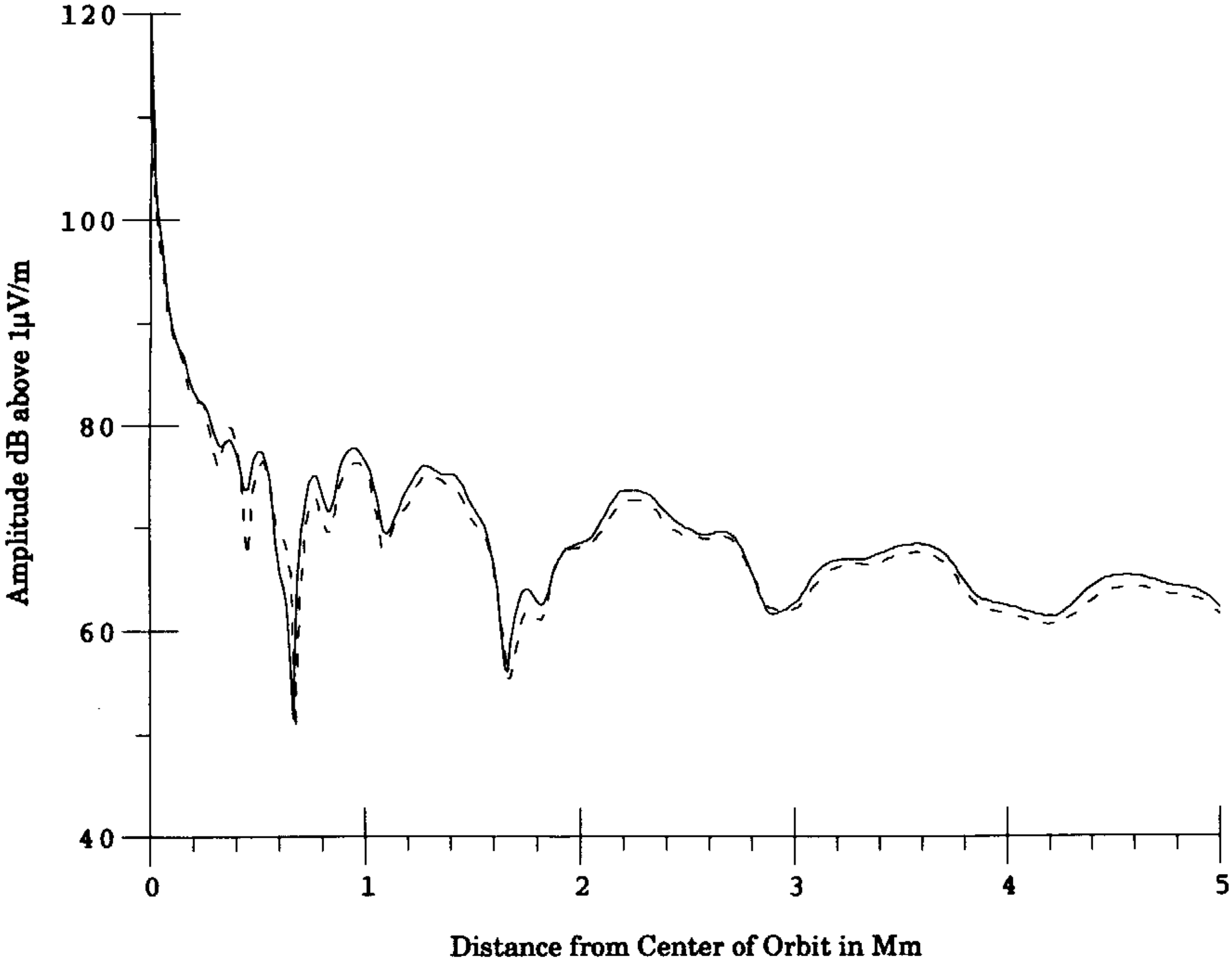

Figure 6. The vertical field strength E_z at sea level resulting from a dual trailing wire (solid curve) compared to a point dipole approximation (dashed curve). Nocturnal easterly 22 kHz propagation.

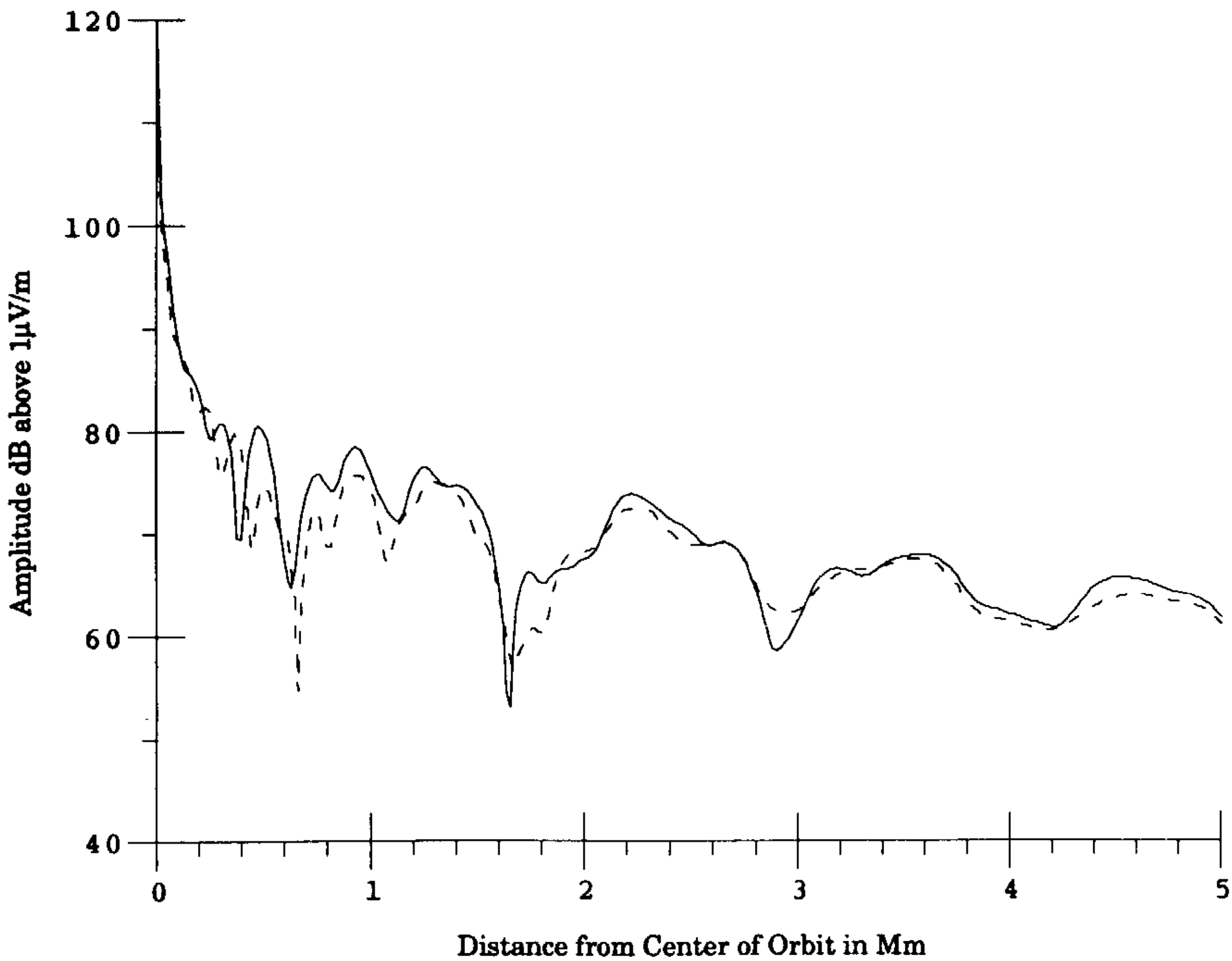

Figure 7. Vertical field strength E_z at sea level as a function of distance for the steady-state case ($\Delta V = 0\%$). The solid and the dashed curves correspond to $\psi = 90°$ and $\psi = 270°$, respectively. Nocturnal easterly 22 kHz propagation from a point dipole approximation of the dual trailing wire antenna.

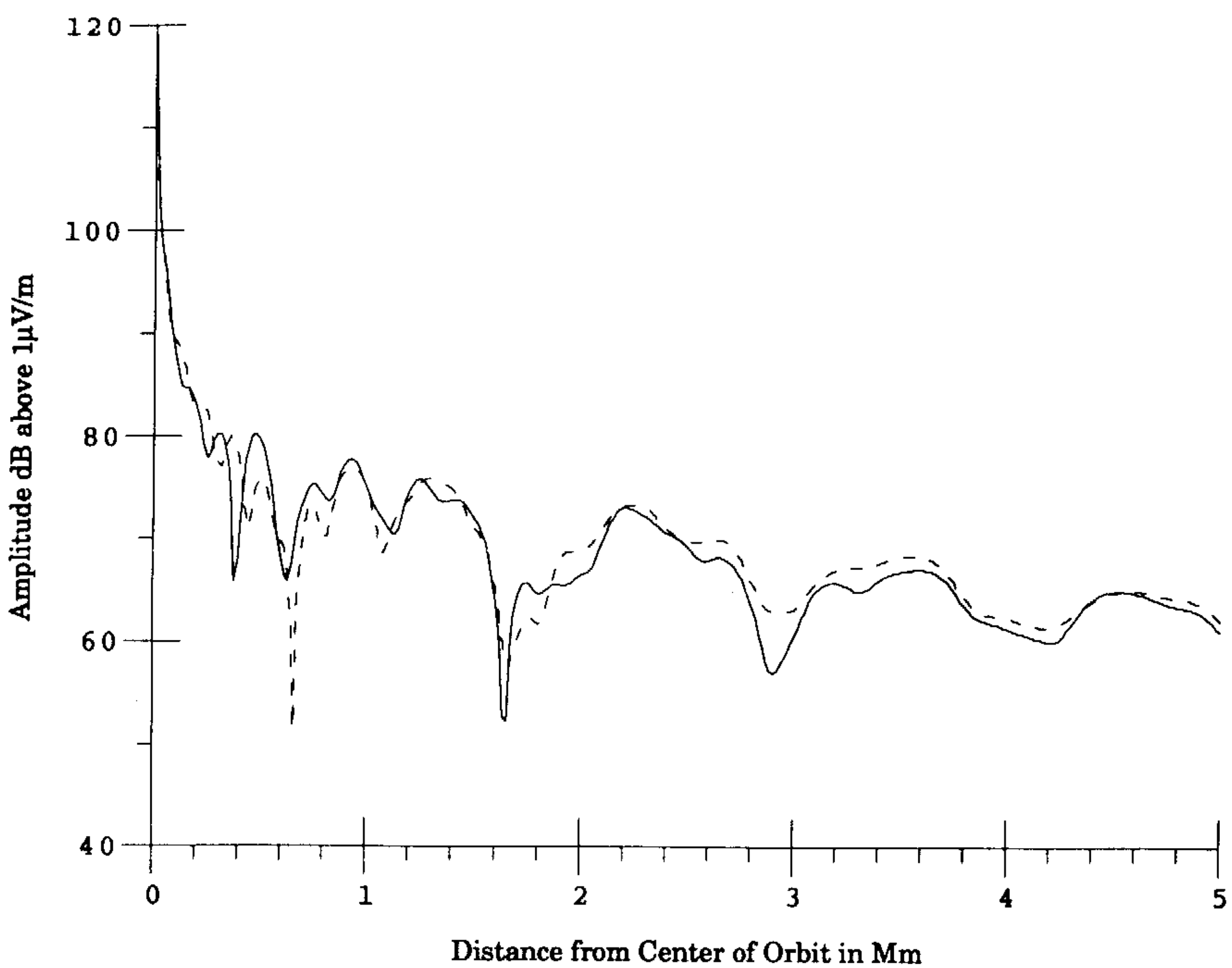

Figure 8. Vertical field strength E_z at sea level as a function of distance associated with $\Delta V = 15\%$. The solid and the dashed curves correspond to $\psi = 90°$ and $\psi = 270°$, respectively. Nocturnal easterly 22 kHz propagation from a point dipole approximation of the dual trailing wire antenna.

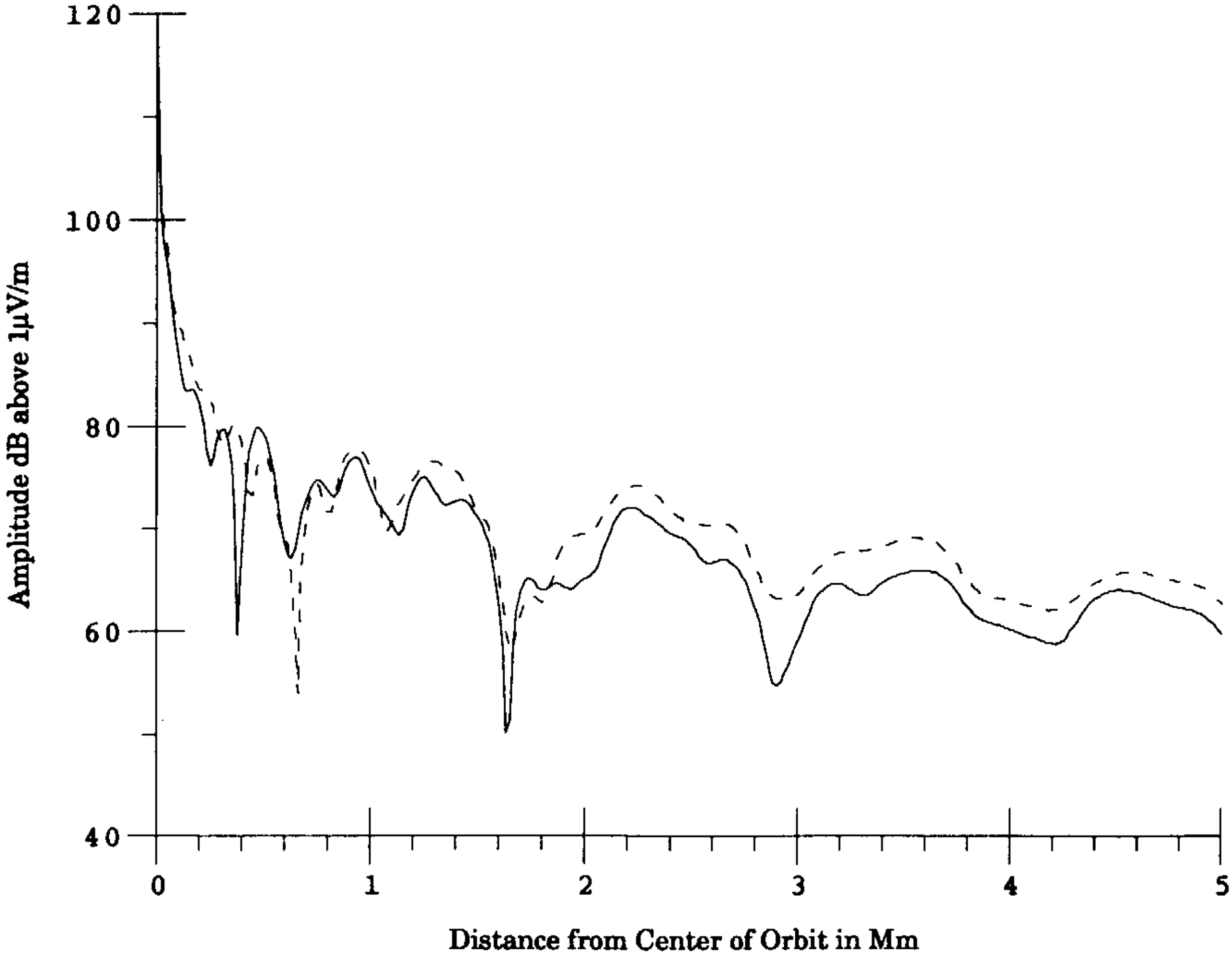

Figure 9. Vertical field strength E_z at sea level as a function of distance associated with $\Delta V = 30\%$. The solid and the dashed curves correspond to $\psi = 90°$ and $\psi = 270°$, respectively. Nocturnal easterly 22 kHz propagation from a point dipole approximation of the dual trailing wire antenna.

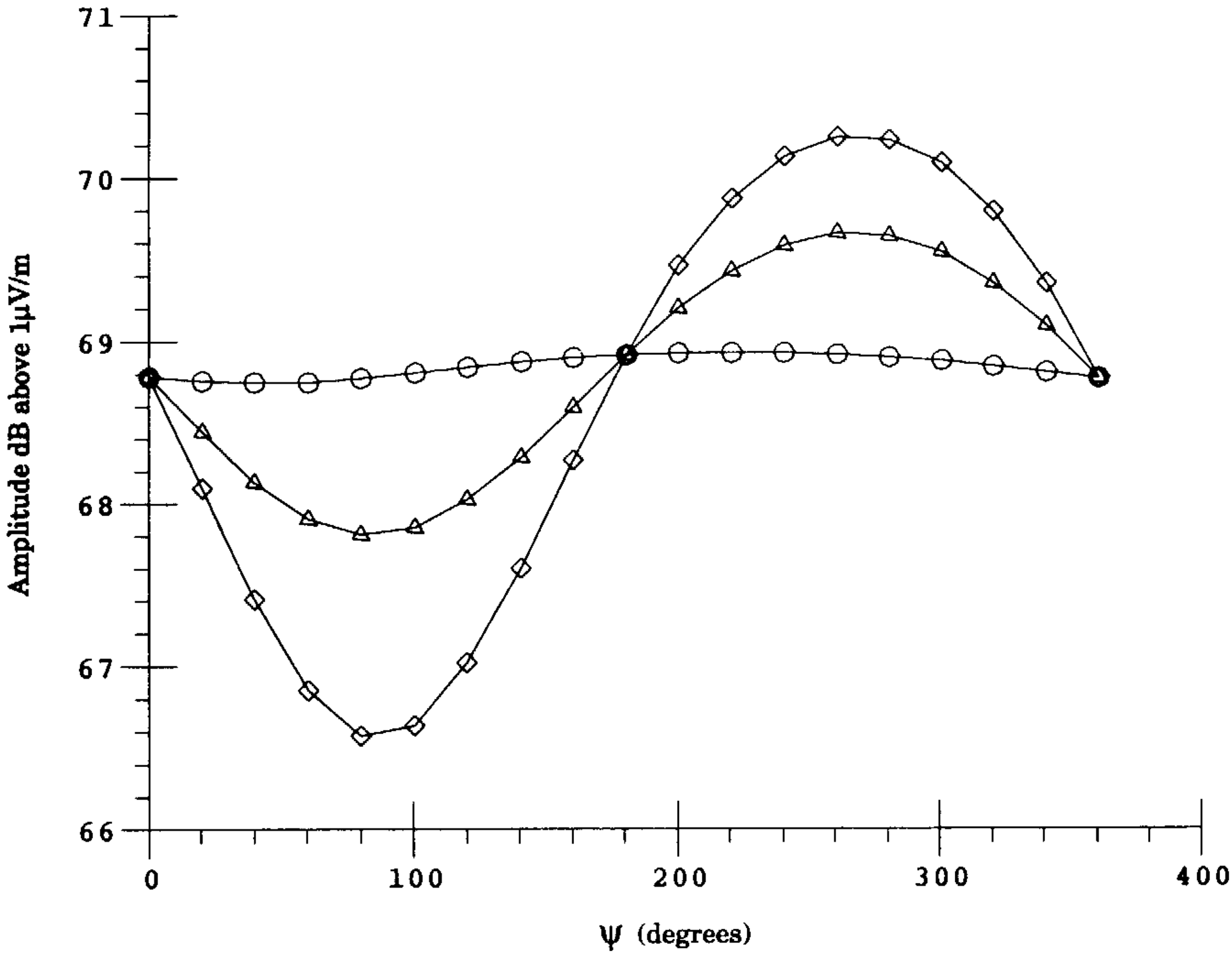

Figure 10. Yo-yo dependence of the vertical field strength E_z at 2.6 Mm. The circles correspond to $\Delta V = 0\%$, the triangles to $\Delta V = 15\%$ and the diamonds to $\Delta V = 30\%$. Nocturnal easterly 22 kHz propagation from a point dipole approximation of the dual trailing wire antenna.

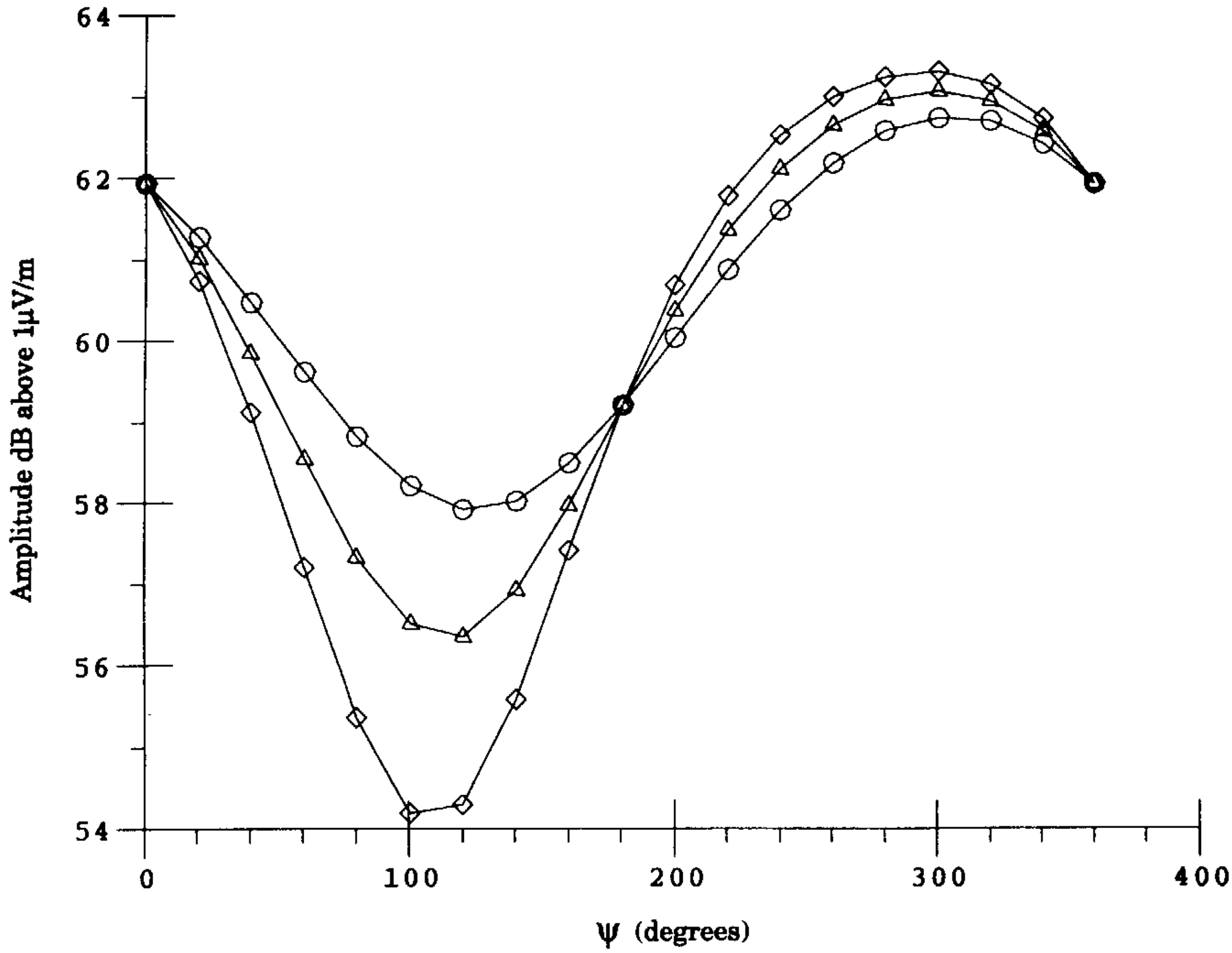

Figure 11. Yo-yo dependence of the vertical field strength E_z at 2.9 Mm. The circles correspond to $\Delta V = 0\%$, the triangles to $\Delta V = 15\%$ and the diamonds to $\Delta V = 30\%$. Nocturnal easterly 22 kHz propagation from a point dipole approximation of the dual trailing wire antenna.