ANTENNA MODELING AND CHARACTERIZATION OF A VLF AIRBORNE DUAL TRAILING WIRE ANTENNA SYSTEM

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Abstract

This paper describes the electrical characterization of the Very Low Frequency (VLF) dual trailing wire antenna systems associated with Navy aircraft used for communications to underwater Navy assets. The static wire geometry with the aircraft in orbit was obtained using a modified version of the program WIRE3, which models the mechanical parameters of the dual trailing wire antenna. The Numerical Electromagnetics Code (NEC) was used to model all electrical characteristics of the VLF dual trailing wire systems associated with the typical TACAMO aircraft. Antenna parameters such as current distribution, input impedance versus frequency, effective radiated power, and the effect of antenna wire conductivity were evaluated. It is demonstrated that the computer codes provide results which are consistent with measured values of static antenna electrical parameters.

I. Introduction

The Numerical Electromagnetics Code (NEC) was utilized to computer model the electrical characteristics of the VLF dual trailing wire transmitting antenna system, which consists of both a long and a short trailing wire [1]. A drogue is attached to the far end of the LTWA which causes the wire to be as vertical as possible. A drogue is also attached to the end of the STWA in order to provide stability. A measure, called verticality, is defined as the ratio of the projection of the wire on the Z-axis to the total length of the wire. Verticality is given in terms of a percentage, and the higher the number, the better for coupling into the earth-ionosphere waveguide for propagation. The wire shape geometries of the long trailing wire antenna (LTWA) and the short trailing wire antenna (STWA) were determined using the programs WIRE4NEC and STWANEC, respectively [2]. These are steady-state mechanical codes which provide piecewise wire segments for data input to NEC. The following antenna characteristics have been obtained for this system: current distribution, input impedance versus frequency, and efficiency. The computed antenna input impedance is compared to measured values for eight actual flights.

II. Static Characterization of the Dual Trailing Wire Antenna

A steady-state mathematical model, which computes the spatial configuration and tension along an orbiting LTWA, was originally developed at the Naval Air Development Center (NADC), Warminster, PA [3]. This model involved the numerical solution of a system of three coupled ordinary differential equations which describe the position of the LTWA with respect to a cylindrical coordinate system. The numerical technique used to evaluate this system of differential equations was later improved by others at NADC and the improved version of their code was given the name WIRE3 [4]. A corrected and modified version of the WIRE3 code was then created for use with NEC in the work reported here and was given the name WIRE4NEC. The WIRE4NEC code writes a file containing a set of NEC compatible geometry inputs.

A brief summary of input parameters necessary to run WIRE4NEC follows. All input parameters are contained in a data file called WIREIN.DAT:

Line 1	Number of runs to be executed (integer number)
Line 2	Run title (20 characters)
Line 3	True airspeed (kts), aircraft orbit radius (ft), aircraft altitude (ft), number of wire increments (integer number), step size (integer number), output flag (0 for trouble shooting, 1 for formatted output).
Line 4	Estimated separation between the aircraft and the drogue (ft), range of estimated separation (ft).
Line 5	Drogue weight (lbs), drogue diameter (ft), coefficient of drag of the drogue.
Line 6	Wire density (lbs/ft), wire diameter (ft), wire length (ft), coefficient of friction of the wire, coefficient of drag of the wire.
Lines 2-6	are repeated for multiple runs.

The WIRE4NEC program evaluates the wire model at five different separation cases between the aircraft and the drogue. The program will stop iterating at each separation case after 31 iterations or if the solution converges so that the antenna feed endpoint, known as LTWA distance, is within 100 feet of the aircraft. Generally, it requires the full number of iterations for the program to converge to a solution. In order to test the sensitivity of NEC to the endpoint of the LTWA, solutions less than 100 feet were accepted.

Several models were considered for the short trailing wire antenna (STWA). The first model treated the STWA as remaining in the plane of the flight path. Two cases for this assumption were analyzed: STWA tangential to the radius of the flight path, and the STWA along the circumference traced by the flight. Both models provided only marginal results. Next, the wire was allowed to drop at a constant angle with respect to horizontal, resulting in an improvement over the previous models. Finally, a code called STWANEC was developed which determines the steady-state geometry of the STWA for input to NEC. The STWANEC program numerically solves a system of coupled ordinary differential equations which represent the mechanical forces on the antenna. A fourth-order Runge-Kutta technique was used. A complete description of the mechanical model for the STWA is beyond the scope of this work [2].

III. NEC Modeling and Results

Determining the geometry of the Long Trailing Wire Antenna (LTWA) and the Short Trailing Wire Antenna (STWA) of the dual trailing wire system is done using the two aforementioned programs WIRE4NEC and STWANEC. Both of the programs utilize various flight data in order to predict the STWA and LTWA positions. Some of the parameters that are used in both programs include: true air speed, aircraft orbit radius, aircraft altitude, estimated separation between aircraft and drogue, and drogue weight. Based on all the parameters, the program determines the verticality of the wire and the separation of the predicted wire endpoint from the aircraft. In addition, the geometry inputs for use in NEC are produced. By merging the outputs from these two programs, the entire geometry of the two trailing wires is obtained.

Although using the outputs of WIRE4NEC and STWANEC yields the basic geometry of the long and short wires in a NEC format, the simple concatenation of the two files does not produce the final form of the model. Each section of the antenna must be analyzed in order to add the correct amount of segment length tapering near the feed point. It is also necessary to move the short wire so that it is connected to the endpoint of the long wire/feed section using the NEC "move" and "translate" input. After this movement, the short wire is rotated to make it tangential to the circumference of the flight path using the NEC "rotate" input.

To obtain accurate results from the model, the wire segment lengths near the feedpoint must be tapered. An algorithm has been developed to calculate the adjacent segment length ratios and the number of segments for both the long and short wires. The modeling approach is to choose very short segments near the critical feedpoint region and then to smoothly taper outward along the wires from this feedpoint. The process provides excellent detail at the feed point as well as throughout the entire antenna structure. Figure 1 shows the top view and Figure 2 shows a side view of the NEC wire segmentation used for the dual trailing wire antenna shown in Figure 3. The tapering algorithm and its implementations will now be described.

NEC has an option for tapering either the length or radius of adjacent segments on a straight wire. It requires as an optional input the ratio of the length of a segment to the length of the previous segment in the wire. It also requires the radius of the first segment and the last segment if stepped radius tapering is desired. For the work described in this paper only length tapering of the segments was required which will be discussed in the following.

In the method used in NEC, once given the end coordinates of the wire, the number of segments, N_S, and the adjacent ratio factor, R_Δ, one can calculate the length of the first segment, S_1, as:

$$S_1 = L(1-R_\Delta)/(1-R_\Delta^{N_s}) \tag{1}$$

where L is the total length of the straight wire. If the ratio factor equals 1, then

$$R_\Delta = 1. \tag{2}$$

which implies

$$S_1 = L / N_S \tag{3}$$

which is the normal case of the wire being divided up into a total of N_S equal length segments.

A more useful and desirable approach to this segment tapering problem is to choose the first segment length, L_1, and the last segment length, L_{N_s}, and with these parameters compute the number of segments, N_S, and the adjacent segment ratio factor, R_Δ, given the total length of wire, L. If the computed R_Δ is less than a factor of 2 or some other modeling guideline criterion, then this R_Δ can be used.

There have been some attempts at this problem [5] using an iterative solution of (1). This method is time consuming and unnecessary because there exists an exact analytical solution for this problem which will be described. The last segment, S_{N_s}, is

$$S_{N_s} = S_1 \, R_\Delta^{N_s-1} \tag{4}$$

This can be rewritten and solved for N_s as

$$N_s = \frac{\log(S_{N_s}/S_1)}{\log R_\Delta} + 1 \tag{5}$$

Since N_S is an integer, one must take the nearest integer of this expression when programming. Substituting (4) into (1), rearranging and solving for R_Δ gives

$$R_\Delta = \frac{(S_1 - L)}{(S_{N_s} - L)} \tag{6}$$

A FORTRAN program has been written incorporating the above equations and was used in the modeling discussed in this paper.

The final STWA geometry model was determined using the steady-state mechanical code called STWANEC discussed above. This model resulted in a curved drop for the STWA. Furthermore, the wire dropped such that it was tangential to the flight path circumference. The final form for the model can be seen in Figure 3 which plots the LTWA and STWA geometries from different aspect angles. Using this final form, excellent agreement was obtained with respect to the measured data. A comparison of the computed impedances using the simple arc and the final form versus the measured data is seen in Table 1 [6].

Figure 4 shows the calculated current distribution on the LTWA and STWA for the 22 kHz test case (title for this case is given as 08:0322:90 VAL). Both amplitude and phase of the current distribution are shown. Labels on the plot list the various aircraft parameters used in the calculation. Analysis of the results for the amplitude of the current distribution shows that the amplitude is peaking at 60 Amps. This peak occurs at an arc length of about 11,000 feet, which is about half of the distance from the drogue to the feed point.

Table 1. STWA Geometry Effects on Impedance

FREQUENCY (KHZ)	RUN TITLE	IMPEDANCE		
		MEASURED	NEC STWA ARC	NEC STWA MODEL
22	08:0322:90VAL	600-j350	712-j267	647-j399.8
WIRE DC RESISTANCE = 4.5 OHMS/1000 FT				

Figure 5 compares the NEC calculated current distribution for the 22 kHz test case with a pure sinusoidal current distribution. The calculated current distribution was normalized to a maximum value of 1 for comparison purposes. This figure demonstrates that the calculated current distribution is in general agreement with the classical sinusoidal current distribution approximation. However, there are some slight deviations at the feed point and towards the drogue end of the LTWA.

Table 2 is a comparison of measured versus calculated input impedance for the various runs. Figure 6 is a comparison of the measured and calculated input impedances over frequency. Both the real and imaginary parts of the impedance are displayed. The imaginary part is negative while the real part is positive.

The calculated impedance data agrees well with the measured data. The close agreement between the measured and calculated impedances provides further evidence that the NEC model is closely simulating the actual dual trailing wire antenna system.

Table 2. Measured Versus Calculated Input Impedance

FREQUENCY (KHZ)	RUN TITLE	LTWA DIST	LTWA VERT	STWA VERT	MEASURED IMPEDANCE	NEC IMPEDANCE
22	08:0322:90VAL	31.41	69.81	30.66	600-j350	647-j399.8
22	08:0322:90VAL	85.32	70.76	30.66	600-j350	654.8-j396.9
18	08:03182:90VAL	40.42	72.89	29.67	450-j525	642-j525
17	09:2417:90VAL	37.30	68.41	27.73	480-j525	665.3-j491
19	09:2419:90VAL	88.18	70.99	29.66	600-j490	665.4-j459.4
20	09:2420:90V(B24)	46.23	68.18	29.75	650-j490	674.6-j437.4
20	09:2420:90V(B24)	55.87	69.94	29.75	650-j490	690.4-j432.2
20	09:2420:90V(E48)09:2	19.11	69.98	30.28	550-j350	672.1-j433.1
20	420:90V(E48)	73.81	70.85	30.28	550-j350	679.6-j430.6
20	09:2420:90V(E48)	83.97	68.26	30.28	550-j350	657.9-j438.9
21	09:2421:90VAL	74.02	66.78	30.09	670-j480	649-j423.3

One of the options provided in the NEC code is the ability to model lossy wire antennas. NEC uses an exact expression for the skin effect resistance and internal reactance in ohms/meter. An approximation for the skin effect resistance which has been used at moderately low frequencies where the current is constant throughout the wire cross section is [7]:

$$R = \frac{1}{\pi r_0^2 \sigma}\left[1 + \frac{1}{48}\left(\frac{r_0}{\delta}\right)^4\right] \tag{7}$$

where

r_0 = radius of wire
σ = wire conductivity
δ = skin depth

At HF frequencies a better approximation can be given for both the real and imaginary parts of internal impedance of a round wire as:

$$Z_{HF} = \frac{R_s(1 + j)}{2\pi r_0} \tag{8}$$

where

$$R_s = \frac{1}{\sigma\delta} = \sqrt{\frac{\pi f \mu}{\sigma}} \tag{9}$$

and

f = frequency
μ = permeability

A more accurate expression for the internal impedance of a round wire is found from evaluating expressions of the total current in the wire and the magnetic field at the surface of the wire. The magnetic field can be obtained from the electric field via Maxwell's Equations:

$$\nabla \times \overline{E} = -j\omega\mu\overline{H} \tag{10}$$

Expressions can be derived for H_ϕ in terms of Bessel functions. The internal impedance per unit length can then be found from the ratio of the tangential component of the electric field at the surface of the wire divided by the total current in the wire:

$$Z_i = -\frac{T J_0(Tr_0)}{2\pi r_0 \sigma J_0'(Tr_0)} \tag{11}$$

where $T = j^{-1/2}\sqrt{\omega\mu\sigma}$

$= j^{-1/2}\sqrt{2}/\delta$

This complex internal impedance can be separated into real and imaginary parts using identities of Bessel functions resulting in Kelvin functions.

$$Z_i = \frac{jR_s}{\sqrt{2}\pi r_0}\left[\frac{Ber\ q + jBei\ q}{Ber'\ q + jBei'\ q}\right] \tag{12}$$

where $q = \dfrac{\sqrt{2}\, r_0}{\delta}$ and the following identities:

$$Ber\ \nu + jBei\ \nu = J_0\left(j^{-1/2}\nu\right) \tag{13a}$$

$$Ber'\ \nu + jBei'\ \nu = \frac{d}{d\nu}\left(Ber\ \nu + jBei\ \nu\right) = j^{-1/2} J_0'\left(j^{-1/2}\nu\right) \tag{13b}$$

NEC incorporates these exact expressions in the determination of wire conductivity skin effect.

Table 3 is a comparison of NEC calculated input impedance, loss resistance and efficiency for various antenna configurations. The first configuration listed is for a half-wave vertical dipole at an altitude of 20,500 feet over perfectly conducting ground. It is offset fed in the same manner corresponding to the STWA and LTWA of example 08:0322:90 VAL. The parameters are: LTWA = 19,500 feet, STWA = 2680 feet, frequency = 22kHz, and wire resistance = 4.5Ω/1000 ft. This case would correspond to an antenna with a verticality of 100% and offset fed. Shown also is the same vertical dipole offset fed assuming perfectly conducting wire, lossless case. The loss resistance can therefore be computed from the difference of the real part of the impedance for the two cases as well as an efficiency factor given by

$$\eta = \frac{R_{lossless}}{R_{lossy}} \tag{14}$$

Also shown are results for a center fed vertical halfwave dipole which is the same antenna as the offset case. The results are for over perfectly conducting ground and in free space for both lossy and perfectly conducting wire. The last result is the model for the dual trailing wire antenna system. The efficiency of the 22 kHz test case dual trailing wire antenna was found to be 47%, assuming a known wire DC resistance of 4.5 ohms/1000 feet. This suggests that nearly half of the power input to the antenna is being dissipated as heat.

IV. Conclusions

This paper has shown the application and validity of using the Numerical Electromagnetics Code for the modeling of the VLF aircraft dual trailing wire antenna system. A description was given of the approach of performing mechanical modeling of the steady-state shape geometry of the dual trailing wire antenna composed of the LTWA and STWA. Software has been written to convert these wire shapes into NEC geometry input data involving tapering of the wire segment lengths to achieve high accuracy. Figure 7 summarizes the procedures and various computer codes which have been used to obtain results in this work.

Comparisons have been made to actual experimental measurements of antenna feedpoint impedance with excellent agreement to computed results. Efficiencies have been calculated from various modeled results using exact formulations of wire conductivity effects.

These results are important in that the current distributions as computed can be input to an additional code, TWIRENEC, which computes VLF propagation in the earth-ionosphere waveguide [8]. Additionally, similar modeling can be performed with dynamic mechanical models of the wires to obtain the variations of all antenna characteristics (impedance, currents, and radiation fields) versus time, corresponding to the mechanical motions versus time.

Table 3. Efficiency of Wire Antenna (22 kHz)

ANTENNA CONFIGURATION	IMPEDANCE		LOSS RESISTANCE	EFF (%)
HALF-WAVE VERTICAL DIPOLE OVER GROUND (OFF-SET FEED)	1150-j85 (LOSSY)	724-j46 (LOSSLESS)	426	63%
HALF-WAVE VERTICAL DIPOLE OVER GROUND (CENTER FED)	157+j70.8 (LOSSY)	99.3+j50.5 (LOSSLESS)	57.7	63%
HALF-WAVE DIPOLE (FREE-SPACE) (CENTER FED)	133.7+j68.1 (LOSSY)	76.6+j47.2 (LOSSLESS)	57.1	57%
DUAL TRAILING WIRE	647-j399.8 (LOSSY)	303.8-j386.0 (LOSSLESS)	343.2	47%
WIRE DC RESISTANCE = 4.5 OHMS/1000 FT				

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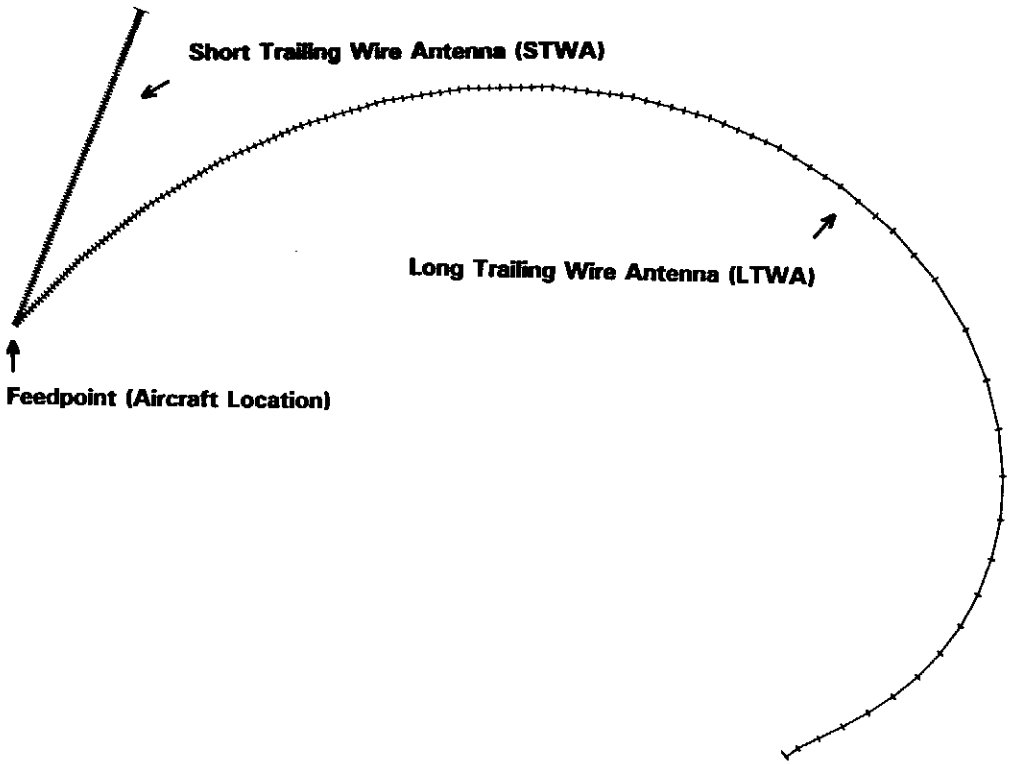

Figure 1. Top View Showing the NEC Wire Segmentation Geometry for the 22 kHz Test Case.

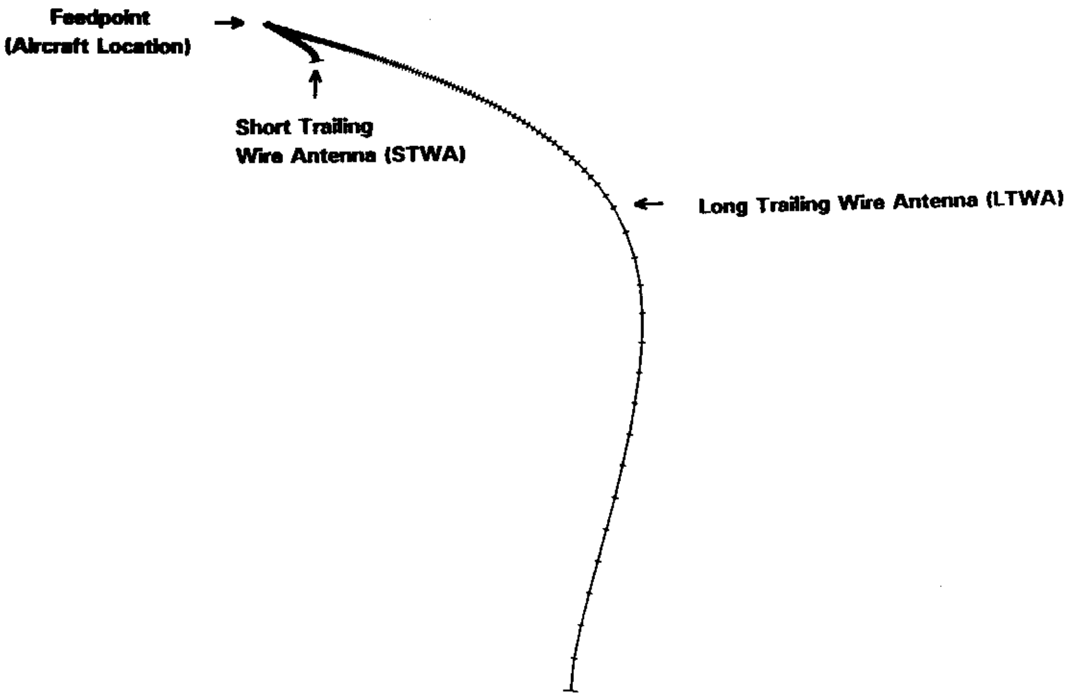

Figure 2. Side View Showing the NEC Wire Segmentation Geometry for the 22 kHz Test Case.

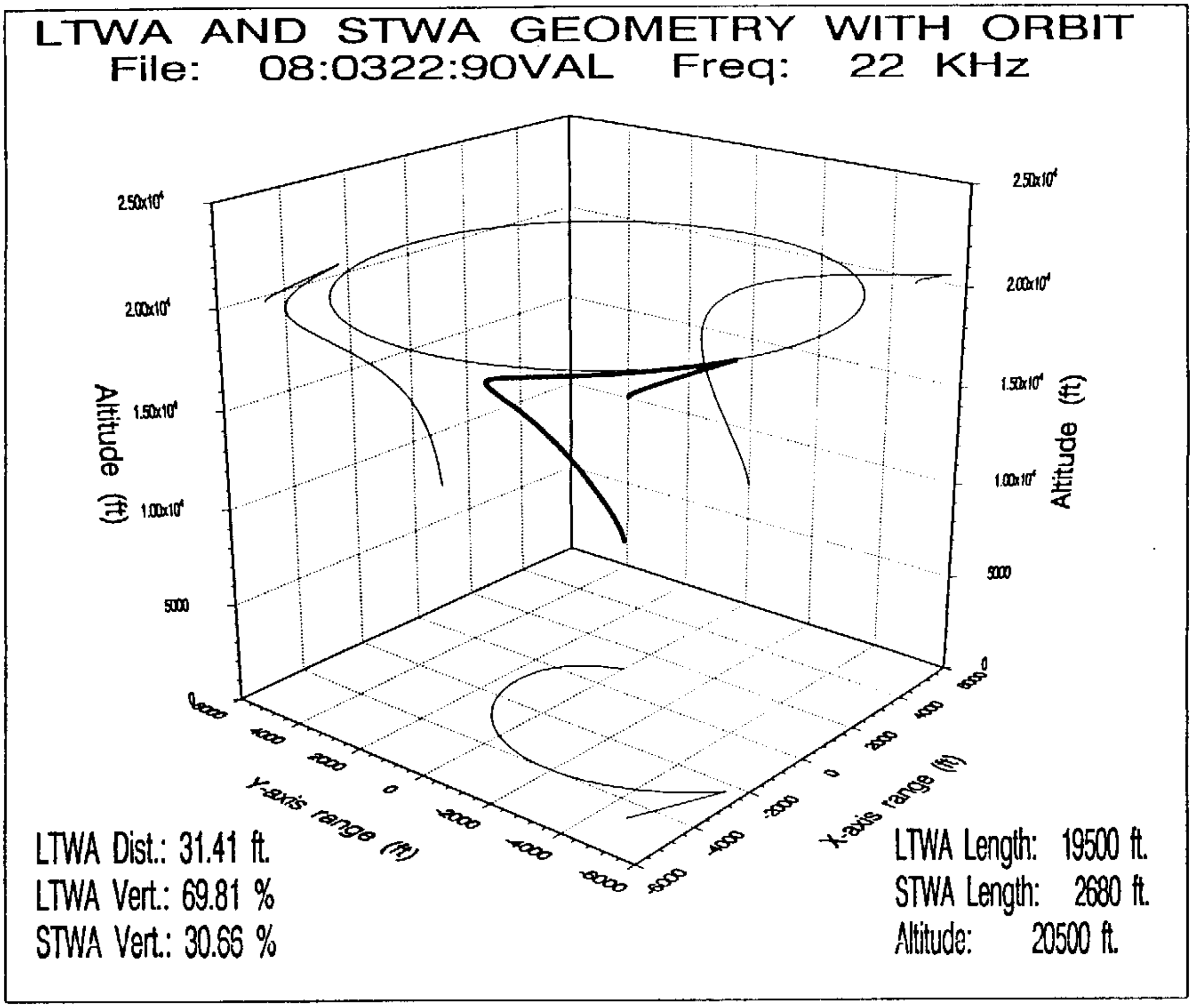

Figure 3. Steady-State Dual Trailing Wire Antenna Geometry for a 22 kHz Test Case.

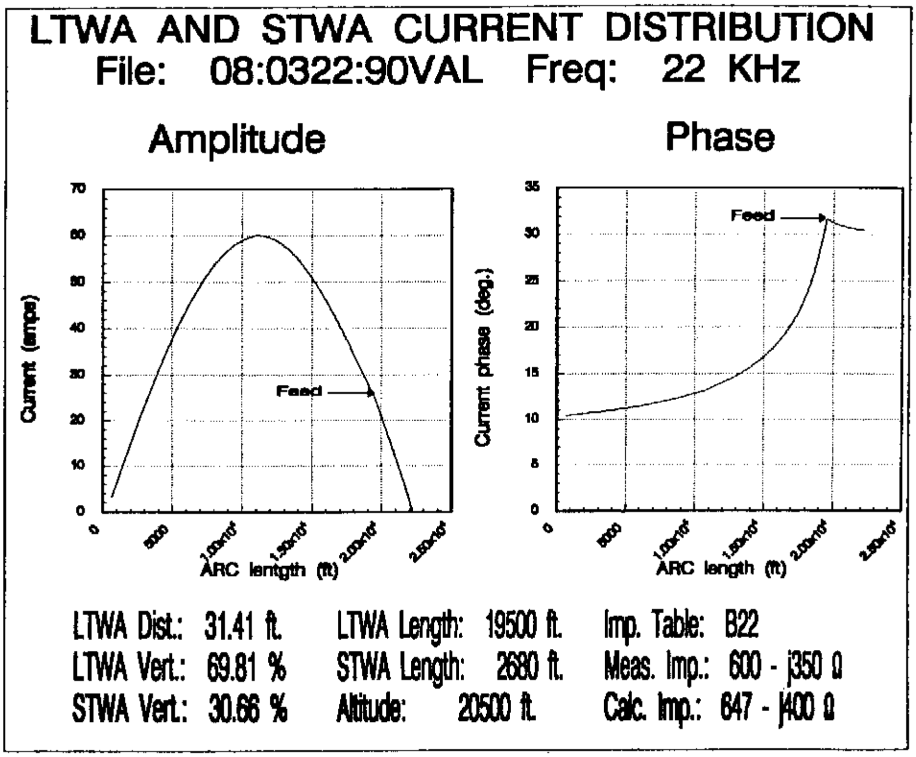

Figure 4. NEC Calculated Current Distribution Resulting From the 22 kHz Test Case of Figure 3.

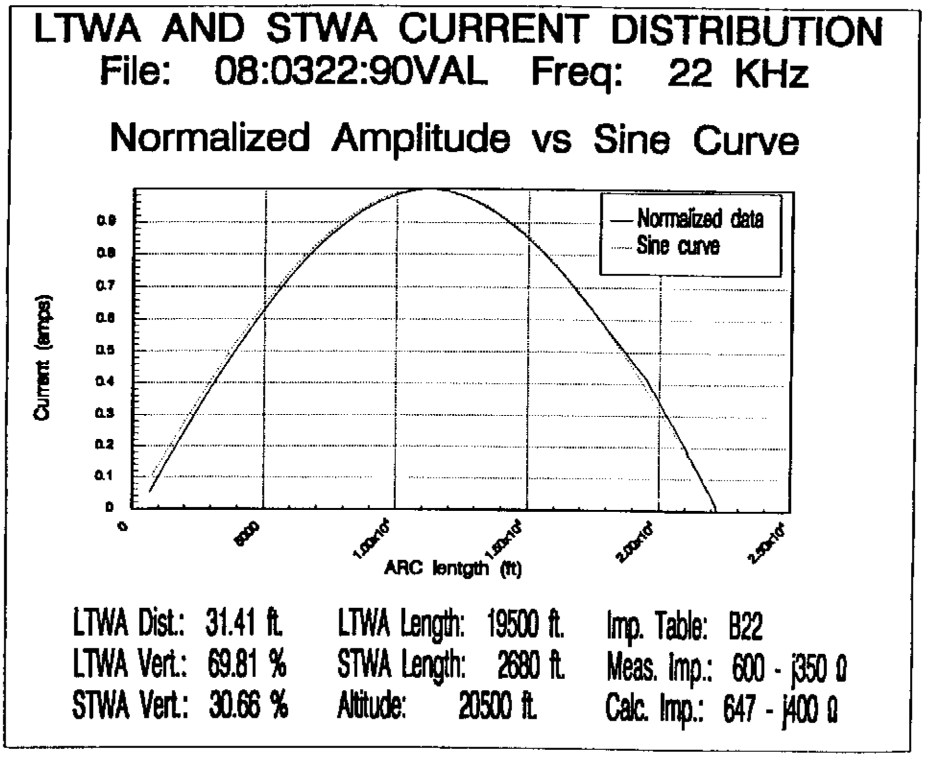

Figure 5. Normalized NEC Calculated Current Amplitude From Figure 4 Compared to a Sinusoidal Current Distribution.

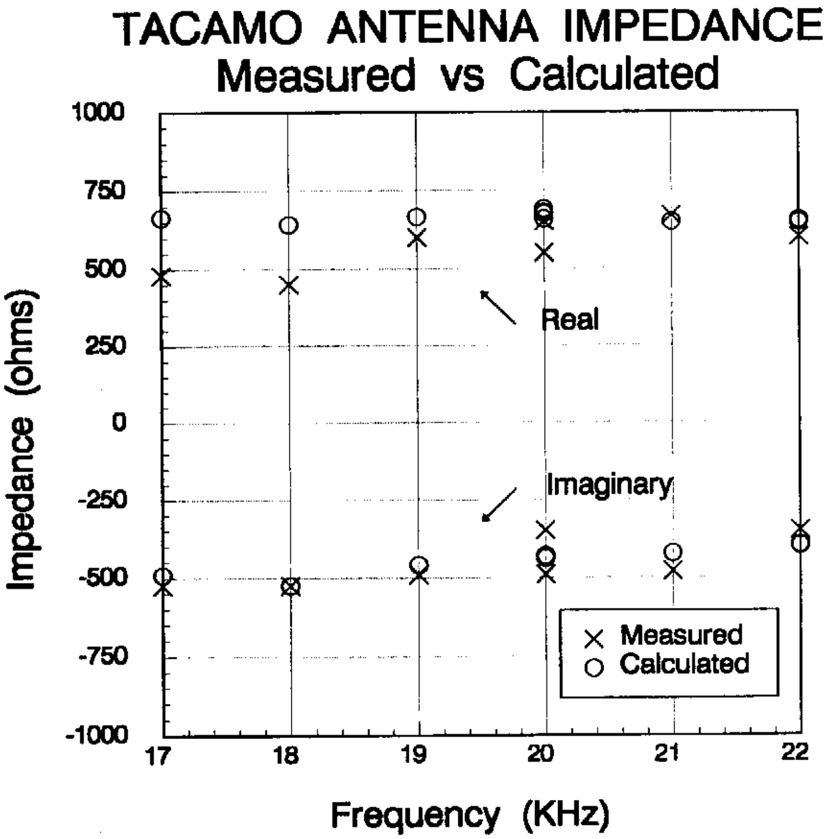

Figure 6. Measured Versus NEC Calculated Input Impedance (Real and Imaginary Parts) for the Validation Runs of Table 2.

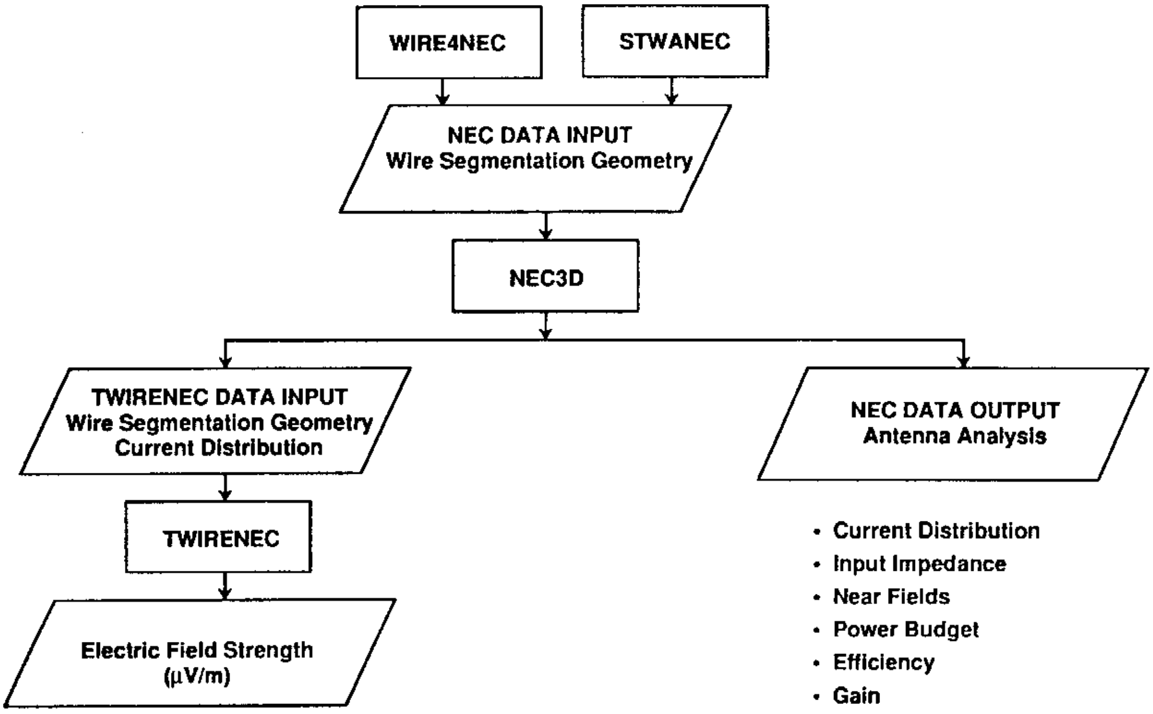

Figure 7. Flowchart showing the Interrelationship Between the Program Modules.