HIGH FREQUENCY FFT ANALYSIS OF AN ELECTRICALLY LONG MONOPOLE ANTENNA

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ABSTRACT

In previous work the currents along a monopole, 20 meters long and operating at 299.8 MHz, placed over a perfectly conducting ground plane were analyzed using several modeling techniques and the Numerical Electromagnetics Code version two (NEC-2). An interesting topic to investigate is the presence of spurious modes of propagation along the monopole. Such modes of propagation are studied for each modeling technique, and conclusions are drawn accordingly. When the data are transformed into the k-space domain, using Fast Fourier Transforms (FFT), the spurious mode behavior along the monopole becomes clearly visible. This technique provides valuable information not yet documented.

INTRODUCTION

This work is a follow-on to previously published work, Reference [1]. In [1] three different modeling techniques, with NEC-2 [2, 3], were used to model a long monopole antenna placed over a perfectly conducting ground plane. The monopole antenna is 20 meters long, and has a radius of 1.5875 millimeters. Also, the monopole is operated at a frequency of 299.8 MHz, thus making the wavelength equal to one meter. The "EK" NEC command is used with the extended thin-wire kernel option, which guarantees accurate results for segment/radius ratio as low as 2. Since the shortest segment used in all the cases run is 0.01 meters (0.01λ), the smallest segment/radius ratio available exceeds 6, thus satisfying the extended thin-wire kernel condition for accurate results.

The three monopole antenna analysis techniques used are: Equal segmentation, entire grading, and partial grading. The purpose behind studying these techniques is to develop a new feasibility range for NEC to model extremely long (electrically) wire antennas as accurately as possible. Such long antennas are impossible to model with NEC by using the traditional techniques, and thus require special modeling techniques as the ones discussed here. These techniques take into consideration the memory limitation (16 MByte RAM for in-core solutions) of the DEC VAX 11/785 minicomputer used in the computational analysis of this effort.

In the equal segmentation technique the monopole, from source to end, was divided into 2000 equal segments of 0.01λ length each. In the entire grading technique, three cases were considered where the monopole segments were gradually increased from 0.01λ, at the source, to last segment lengths of approximately 0.25λ, 0.5λ, and 0.75λ, at the end, respectively. Finally, in the partial grading technique, and for every case studied, part of the monopole (starting with 0.01λ at the source) was segmented using the entire grading technique with a constant ratio RDEL = 1.1 (see Reference [1]), then equal segments of approximately the size of the last segment, from the entirely graded portion, were used to model the rest of the length of the monopole. For the cases studied, the equal segments had lengths of 0.25λ, 0.35λ, 0.45λ, 0.5λ, 0.55λ, 0.65λ, 0.75λ, 0.85λ, and 0.95λ.

As mentioned in [1], the use of very long segments (greater than 0.1λ) was not recommended by NEC-2. Also, segments very close to the source must be chosen to be even shorter (about 0.01λ). However, when electrically long antennas (20λ long in this case) are being analyzed, the use of short segments becomes almost impossible, due to the size of the interaction matrix in NEC-2 and computer memory limitations. Thus, the entire grading and partial grading techniques were implemented to study electrically long antennas. These techniques were compared with the equal segmentation technique to determine a new range of feasibility for NEC-2.

The conclusions presented in [1] were very informative. The "eye balling" technique (used to compare current versus distance data), the input impedance comparison, and the rms deviation analyses contributed to the resulting conclusions. Nonetheless, none of these analysis techniques gave any information about the presence and significance of spurious modes along the monopole antenna.

Spurious modes are defined as the appearance of eigenvalues of the static problem somewhere along the wavenumber axis of the resonance problem. In other words, additional peaks occurring in the approximation to a system behavior that do not exist in the actual behavior of the system itself. To observe such spurious modes, the k-space domain data for the monopole antenna are needed. Such data are the result of the Fast Fourier Transform (FFT) of the current versus distance data. The resulting transformed data have the units of "Ampere-meters" and "radians/meters" for the vertical and horizontal axes, respectively. The following section describes the approach used to fulfill this technique.

GENERAL FFT APPROACH

As mentioned earlier, the FFT technique determines the k-space domain data from the current along the monopole versus distance data. To apply the FFT technique, the current data must be re-evaluated at equally spaced distances. This is a restriction imposed on any data that needs to be Fourier transformed. Moreover, the number of data points (N_{dp}) to be transformed must be an integer power of 2. This is another basic restriction for finding the FFT of any available data set.

The number of current samples chosen in this effort, for all the cases studied, is

$$N_{dp} = 2^{11} = 2048 \text{ samples.}$$

This choice is made to guarantee that the undulations in the current distribution will be well described. Also, after a few tests were undertaken, this number of samples proved to be high enough to avoid aliasing. To check for over-sampling or under-sampling, the reference data set was re-sampled at 8192 and 512 points, respectively, yet the FFT data plots maintained the same shape as seen in the 2048 points case used in this paper. Hence, 2048 points were found to be adequate to represent the waveforms at hand.

Since the monopole antenna under study is 20 meters long, then the distance between samples (Δx) will be,

$$\Delta x = 20/N_{dp} = 9.76563\text{E-3 meters.}$$

This factor is needed due to its analogy to the sampling rate of discrete time domain data. Hence, the wavenumber sampling rate (Δk_x), in rad/meter, is given by,

$$\Delta k_x = 2\pi/(N_{dp} \cdot \Delta x) = 0.31416 \text{ radians/meter.}$$

Δk_x is analogous to the sampling rate of discrete frequency domain data, and is known as the wavenumber sampling rate. With all the necessary information available, the FFT routine can be applied to transform the current versus distance data, in [1], into the k-space domain.

The maximum wavenumber value ($k_{x,\ max}$) is given by,

$$k_{x,\ max} = 2\pi/\Delta x = 643.3982 \text{ radians/meter.}$$

Note that the k-space domain data will be plotted up to $k_{x,\ max}$ rather than to $k_{x,\ max}/2$, since the distance domain data are complex in nature, which means that the k_x-domain data will not necessarily be symmetric in nature (about the midpoint).

FFT OF MONOPOLE CURRENTS

A quick check on some of the cases reveals some valuable information. First, a Log-Log scale is necessary to clearly show the minima and maxima of each plot. Consequently, the point corresponding to $k_x = 0$ must be removed from the data before plotting the data, since $\text{Log}(0) \rightarrow -\infty$, which is impossible to show on a Log-scale. Hence, each plot will only show 2047 points instead of 2048 points. Even though both the magnitude and phase responses of the transformed data contain spurious mode information, only the magnitude of the FFT data will be considered in this analysis. The phase analysis is outside the intention of this effort.

The FFT of the reference case is shown in Fig. 1. Fig. 1 is the most accurate of all the results, and is assumed to be spurious mode free. Thus, any existing minimum and/or maximum in Fig. 1 is considered to correspond to the natural behavior of the current along the monopole. Hence, when Fig. 1 is observed carefully, it is obvious that the reference case has four visible extreme points, two minima and two maxima.

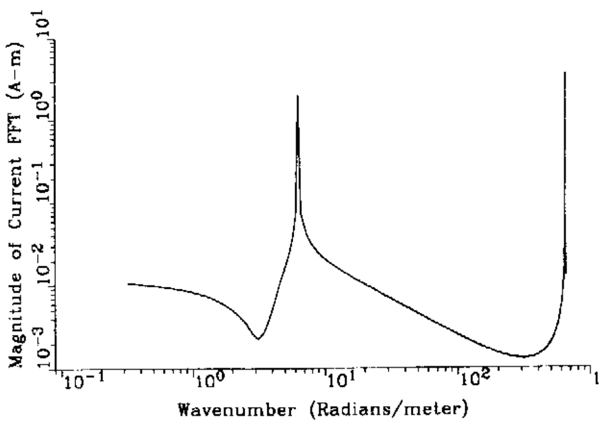

Fig. 1. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using 2000 Equal Segments of Length 0.01λ.

The minima and maxima in Fig. 1, and the sample number position where they exist, are shown in Table 1. The data in Table 1 will serve as a supplementary method used to compare results from other cases to those of the reference case. This is accomplished by comparing the sample value (SV) and the location of the corresponding sample number (SN) of the minima and maxima of the entire and partial grading techniques' cases to those of the reference case. The relative error method is used to compare the minima and maxima sample values (SV_{min1}, SV_{min2}, SV_{max1}, and SV_{max2}). The equation for relative error (RE) as determined in k-space is,

$$RE = \frac{(SV_{ref} - SV_{other})}{SV_{ref}} \cdot 100\%$$

For the entire grading technique, the FFT magnitude plots of the three cases studied (S_{NS} = Length of the last segment ≈ 0.25λ, 0.5λ, and 0.75λ) are shown in Figs. 2, 3, and 4, respectively. The minima and maxima information for these cases can be found in Table 1.

Comparing Fig. 2 to Fig. 1 it is seen that spurious modes are virtually nonexistent. Yet, there exists a minor oscillatory behavior close to the point where the second minimum in Fig. 2 takes place. The relative error analysis for the S_{NS} ≈ 0.25λ case shows that the only error of concern is that of the first minimum (RE_{min1} = 17.33%). Now, keeping in mind that NEC-2 documentation, [2, 3], states that an error of at least 5% is to be expected, the remaining portion of the relative error values for the S_{NS} ≈ 0.25λ case are well within the acceptable range.

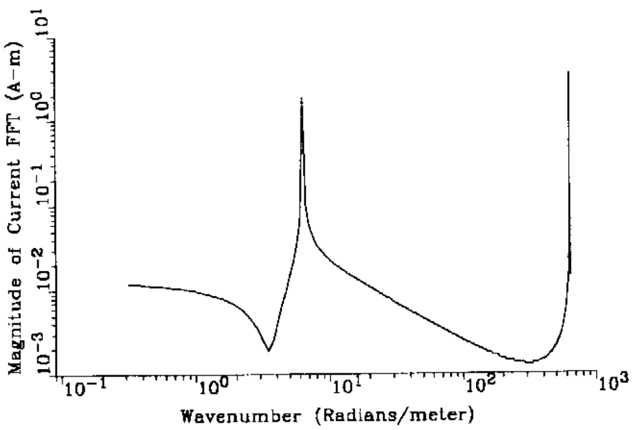

Fig. 2. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Entire Grading with S_{NS} ≈ 0.25λ.

Comparing Fig. 3 to Fig. 1 shows an oscillatory behavior just after the first maximum is observed. This behavior is more visible than that in Fig. 2, but is not significant enough to be considered as a spurious mode behavior. Yet, it is an indication that some form of instability in the solution does exist, mainly due to the use of some segments close to 0.5λ in length, which has been proven to violate the boundary conditions in NEC-2 [1]. Moreover, the first minimum dips far below that of Fig. 1. This can be clearly seen in the very large relative error value (RE_{min1} = 51.11%) corresponding to it in Table 1. Another value of some concern in Table 1 is that of RE_{max1} = 12%, since it represents a difference of 0.23 A-m, which is somewhat significant. Also, the negative sign in the value of RE_{max2} means that the SV_{max2} value for the S_{NS} ≈ 0.5λ case is larger than that of the reference case.

Fig. 4 shows many interesting results when compared to Fig. 1. First, it is noticed that the first minimum has almost totally disappeared. Second, the spurious mode behavior is clearly visible in the area preceding the first maximum. This behavior shows huge instability in the solution, and is definitely attributed to the extremely long segments ≈ 0.75λ used at the end of the antenna. The error analysis in Table 1 shows that RE_{min1} = -141.51% is tremendously large, and again amplifies the instability in that region. Nevertheless, when the rest of the error values are checked, it is noticed that the error values are extremely low and consequently might lead to very deceiving conclusions.

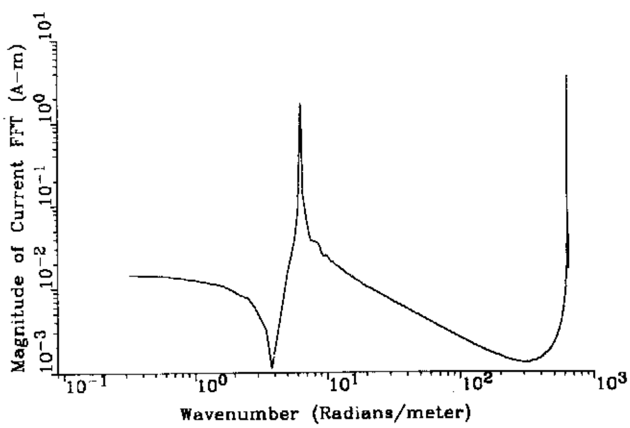

Fig. 3. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Entire Grading with S_{NS} ≈ 0.5λ.

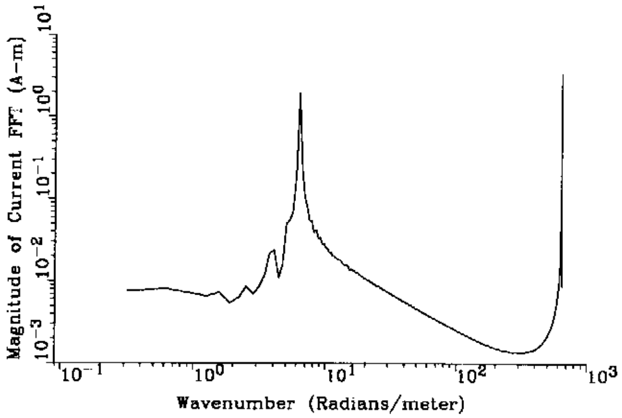

Fig. 4. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Entire Grading with $S_{NS} \approx 0.75\lambda$.

For the partial grading technique, the FFT magnitude plots of the nine cases studied ($S_{NS} \approx 0.25\lambda$, 0.35λ, 0.45λ, 0.5λ, 0.55λ, 0.65λ, 0.75λ, 0.85λ, and 0.95λ) are shown in Figs. 5, 6, 7, 8, 9, 10, 11, 12, and 13, respectively. The minima and maxima information for these cases can be found in Table 1.

Comparing Figs. 5 and 6 to Fig. 1 it is noted that insignificant spurious modes exist. The error analysis in Table 1 shows that the largest error for the $S_{NS} \approx 0.25\lambda$ and 0.35λ cases at the first minimum (RE_{min1} = -8.89% and 13.33%, respectively), which are still very acceptable values considering the size of the problem at hand.

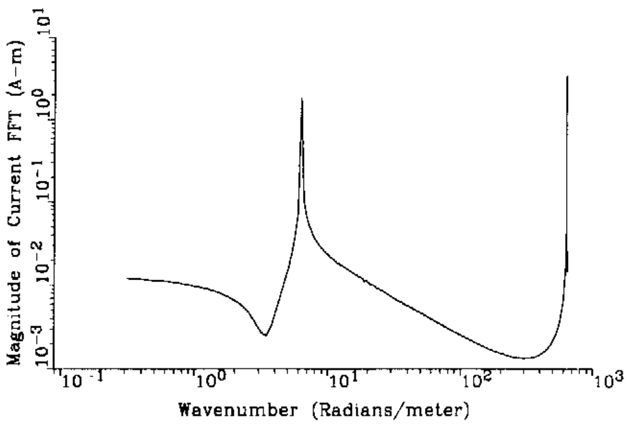

Fig. 5. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Partial Grading with RDEL ≈ 1.1 and $S_{NS} \approx 0.25\lambda$.

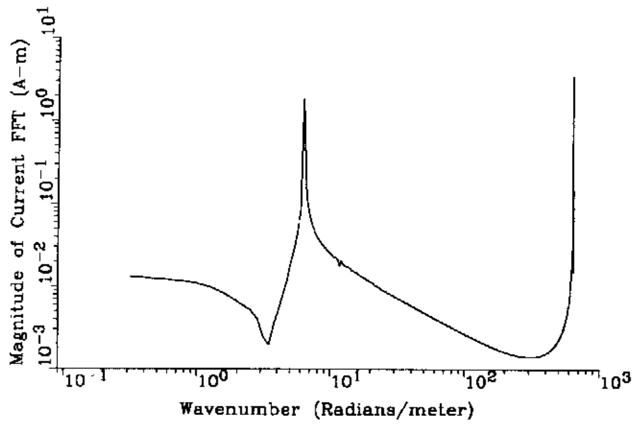

Fig. 6. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Partial Grading with RDEL ≈ 1.1 and $S_{NS} \approx 0.35\lambda$.

In Fig. 7 a minor spurious mode behavior is registered in the region directly following the first maximum. Moreover, from Table 1, the error analysis shows that larger errors are registered, especially at the second minimum and first maximum (RE_{min2} = -13.24% and RE_{max1} = 21.75%, respectively). These larger errors reflect the use of extremely long segments, and the use of the segment lengths that are close to the undesired 0.5λ value.

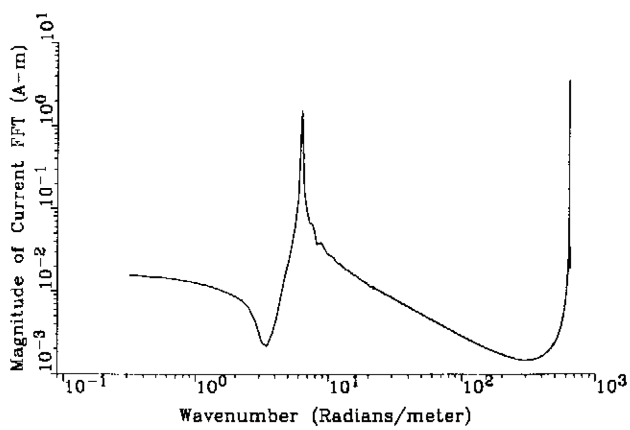

Fig. 7. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Partial Grading with RDEL ≈ 1.1 and $S_{NS} \approx 0.45\lambda$.

Comparing Fig. 8 to Fig. 1 it is noticed that very strongly visible spurious modes exist, and the first minimum value is almost nonexistent. Moreover, the results of Fig. 8 are approximately an order of magnitude higher than those of Fig. 1. This observation is seconded by the data in Table 1. The error analysis for this case shows that the smallest error occurs at the second maximum (RE_{max2} = -296.42%). This is a tremendously large value that clearly shows the violation of the boundary conditions in NEC-2.

Figs. 9, 10, 11, 12, and 13 all show strong spurious mode behavior, mainly in the region preceding the occurrence of the first maximum. Also, the spurious modes in Figs. 11, 12, and 13 are stronger than those of Figs. 9 and 10. Again, the error analysis in Table 1 shows that all the cases exhibit relatively high percentage errors, with the exception of the $S_{NS} \approx 0.65\lambda$ case where the errors remain moderately low. The $S_{NS} \approx 0.65\lambda$ is an exception without a clear reason to why are the errors so low. Nonetheless, the high errors in the other cases are a reflection of the very large segment sizes used in the equal segment portion of modeling the monopole antenna.

Finally, when the positions of the minima and maxima in Table 1 are compared, several observations are made. First, the positions of both maxima (SN_{max1} and SN_{max2}), in each entire and partial grading case, coincide with those of the reference case, respectively. Next, the positions of the first minimum (SN_{min1}), in each entire and partial grading case, varied slightly from that of the reference case, with the $S_{NS} \approx 0.5\lambda$ partial grading case being the furthest away. Last, the positions of the second minimum (SN_{min2}), in each entire and partial grading case, varies more significantly than the variation in the position of the first minimum. Again, the $S_{NS} \approx 0.5\lambda$ partial grading case possesses the largest shift.

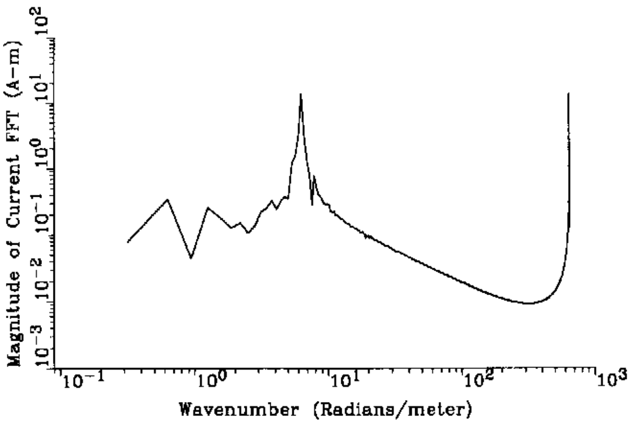

Fig. 8. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Partial Grading with RDEL ≈ 1.1 and $S_{NS} \approx 0.5\lambda$.

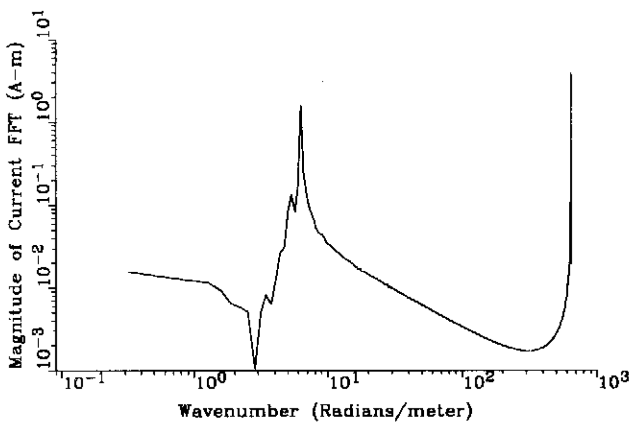

Fig. 9. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Partial Grading with RDEL ≈ 1.1 and $S_{NS} \approx 0.55\lambda$.

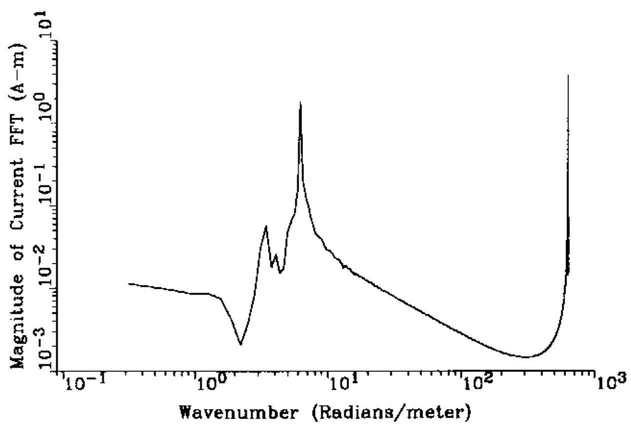

Fig. 10. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Partial Grading with RDEL ≈ 1.1 and $S_{NS} \approx 0.65\lambda$.

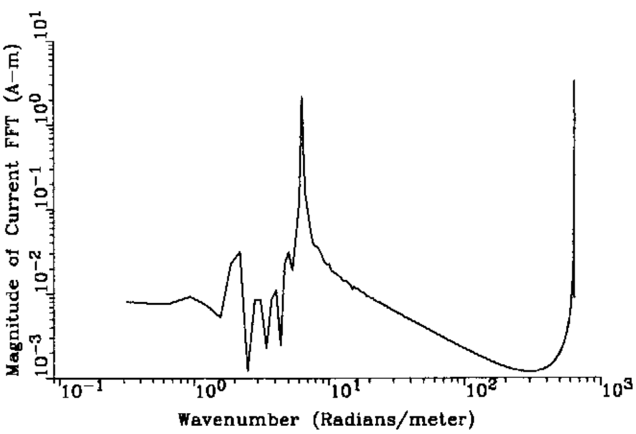

Fig. 11. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Partial Grading with RDEL ≈ 1.1 and $S_{NS} \approx 0.75\lambda$.

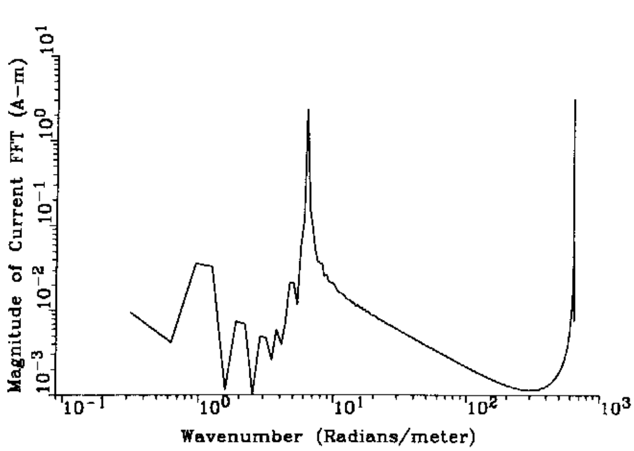

Fig. 12. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Partial Grading with RDEL ≈ 1.1 and S_{NS} ≈ 0.85λ.

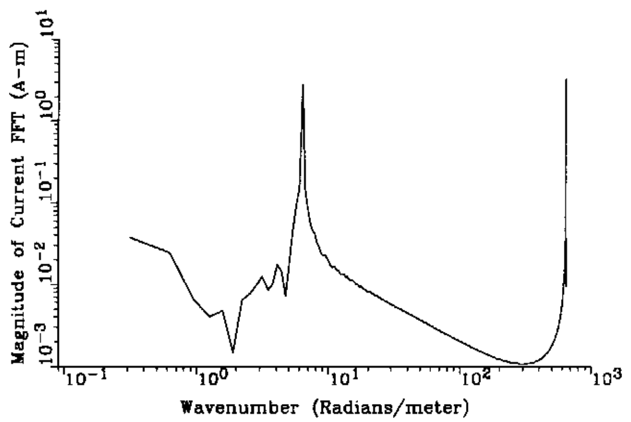

Fig. 13. Magnitude of Current FFT Versus Wavenumber Along a Monopole of Length 20λ Using Partial Grading with RDEL ≈ 1.1 and S_{NS} ≈ 0.95λ.

CONCLUSIONS

The FFT k-space analysis technique was used to further investigate the use of the entire and partial grading techniques as alternative methods of modeling the monopole antenna over a perfectly conducting ground plane studied in [1]. Again, the comparisons were made to the data from the equal segmentation technique, of 2000 equal segments of length 0.01λ each, serving as a reference. This form of analysis was mainly concerned with locating spurious modes, if any existed, and determining the main reason of their existence. When Figures 2 through 13 were compared to Fig. 1, it was noted that the use of extremely long segments (greater than 0.45λ) was the major reason for existence of spurious modes. Moreover, the conclusion arrived at in [1] stating that segments equal to 0.5λ, or even close to that value, should never be used was strongly backed in this analysis. This can be seen in Fig. 8 and the data in Table 1 corresponding to that figure, where even the monopole characteristic peaks were alarmingly larger than those evaluated using the equal segmentation technique (Fig. 1). The behavior in Fig. 8 was an ideal example of the presence of spurious modes, and the consequences suffered due to such presence. Hence, for the entire and partial grading techniques, it is recommended that longer segments (not exceeding 0.4λ) can be used to model extremely long (electrically) wire antennas while maintaining acceptable results.

Moreover, the data in Table 1 showed that the values and locations of the minima were, in most cases, far more affected than their maxima counterparts. This can be attributed to the fact that numerical solutions to problems of this magnitude cannot guarantee 100% accuracy. Hence, the addition (or subtraction) of a small error value to (from) an already small number changes its value tremendously. On the other hand, the addition (or subtraction) of a similar small error value to (from) a large number changes its value only slightly.

Finally, the conclusions presented in [1] were re-established using a different technique. More importantly, the presence of spurious modes resulting from the use of large segments, as well as ill chosen segment lengths (0.5λ, for example), was shown. This technique reflected a far more visible way to show discrepancies in data when different methods of solution are used. Also, the spurious modes show that when a system is poorly modeled, false system characteristics (such as additional peaks) show up, and consequently, lead to erroneous results.

ACKNOWLEDGMENTS

Special thanks go to Dr. Clayborne D. Taylor for reviewing this manuscript, and Dr. Nicolas H. Younan for his valuable input toward this effort.

REFERENCES

[1] S.N. Tabet, J.P. Donohoe, and C.D. Taylor, "Using Nonuniform Segment Lengths with NEC to Analyze Electrically Long Wire Antennas," *Applied Computational Electromagnetics Society Journal*, Vol. 5, No. 2, Winter 1990.

[2] G.J. Burke and A.J. Poggio, "Numerical Electromagnetics Code (NEC) - Method of Moments," Vol. 2, *Naval Ocean Systems Center*, Technical Report NOSC TD 116, January 1981.