PILGRIMS' PROGRESS - LEARNING TO USE THE NUMERICAL ELECTROMAGNETICS CODE (NEC) TO CALCULATE MAGNETIC FIELD STRENGTH CLOSE TO A SOMMERFELD GROUND

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ABSTRACT

This paper gives the history and a description of work performed by the authors to identify some errors and solve some problems involved in the use of the Numerical Electromagnetics Code (NEC2 and NEC3, with the companion code SOMNEC) to calculate H-fields in the vicinity of a Sommerfeld ground, and describes some of the code errors and omissions that have been identified to date. The most significant discovery has been that a section of code has been omitted from the subroutine NHFLD in NEC2, which results in incorrect calculations by NEC2 of near H-field strengths close to a real ground. It must be noted that Macfarlane, Fleming, and Iskra, have access to NEC2 only, whilst Haack has access to both NEC2 and NEC3.

I. INTRODUCTION

In the study of electromagnetic compatibility (EMC) problems involving the interraction of conductors and electromagnetic waves close to a real ground, in particular at frequencies below 30 MHz, it will be very useful to have available a numerical electromagnetics computer code that can be used to accurately calculate both E- and H-fields. This will be particularly so for problems involving the near-field and the near far-field of wires and cables acting as inadvertent radiators or receivers of electromagnetic interference (EMI) near the Earth's surface.

For example, in the International Special Committee on Radio Interference (CISPR)[1] one of the Study Questions is concerned with radiation in vertical directions from industrial, scientific, and medical (ISM) radio-frequency apparatus. The purpose of that Study Question is to ensure that ISM emission limits that are set and verified for measurements made close to the ground will provide protection for safety-of-life services on aircraft in flight. At frequencies below 30 MHz, the CISPR measurement method for in situ measurement of radiation from ISM apparatus specifies the use of a loop antenna - that is, the H-field component is to be measured.

Early in 1989 Macfarlane contributed several papers to the CISPR showing that, for electrically small horizontal and vertical electric dipole sources at the surface of the Earth, ground-based measurements in the far-field in the frequency band 1.6065 - 2 MHz are a good guide to the maximum values of vertically polarized E-field strengths (and, by far-field inference, H-field strengths) that would be encountered by aircraft passing above the radiation sources. That frequency band can be used for vertically polarized non-directional beacons (NDB) in countries situated in the International Radio Consultative Committee's (CCIR) Region 3. The analyses used were based upon the methods given in [1] and [2], and were quite time consuming.

In June 1989, the CISPR asked for the analyses to be extended to cover the frequency range from 150 kHz to 30 MHz (or, preferably, from 10 kHz to 30 MHz), including considerations of magnetic loops as sources as well as electric dipoles. Moreover, the CISPR asked for the calculation of the H-field specifically. This entails more complicated calculations in the near-field for correlation with measured field strengths at the lower frequencies, because the CISPR measurement procedure requires that measurements be made with the CISPR measuring loop placed at a distance of 30 metres from the exterior wall of the building housing the ISM apparatus - which makes the measuring distance less than $\lambda/(2\pi)$ at the frequencies below 1.6 MHz.

The task appeared a daunting one.

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1 The CISPR is a committee of the International Electrotechnical Commission (IEC), and it aims to formulate internationally agreed recommendations for the control of EMI at frequencies above 10 kHz.

Up to this time, Macfarlane had expressed profound scepticism concerning the ability of computer codes to produce accurate results when tackling such problems. However, the pressing need to find a more general and less time consuming means of calculating the field strengths close to a real ground - combined with the evangelical enthusiasm of Fleming in extolling the virtues of the Numerical Electromagnetics Code (NEC2) [3] - overwhelmed Macfarlane's scepticism.

Early in August 1989, the pair decided to use NEC2 to calculate the near H-fields and E-fields generated by some very simple electrically small radiators in free space, to provide some initial confidence that NEC2 could perform the sort of task presented by the CISPR requirements.

If there were signs of success, they intended to extend the work by using NEC2 with the Sommerfeld interactions code SOMNEC to calculate the field patterns close to ground that would show whether or not CISPR-type ground-based measurements of H-field strengths can provide the required guidance to the values of the field strengths that will exist, at elevated angles, in the vicinity of such simple radiators at frequencies below 30 MHz.

The rest of this paper describes the work we have done to identify some errors and solve some problems that we have identified with the use of the NEC Method of Moments (MoM) code when it is used to calculate the electromagnetic fields associated with electrically small radiators over a Sommerfeld (i.e. real) ground.

Within the bounds of decency, we have attempted to provide a warts and all historical description of how the work developed and progressed.

II. IN THE BEGINNING - MODELLING IN FREE SPACE USING NEC2

Macfarlane and Fleming began with a model[2] of an electrically small radiator in free space. It consisted of a balanced dipole 3 metres in length, having a wire radius of 1 millimetre, and excited at a frequency of 2 MHz (λ = 150 metres). In a conventional rectangular coordinate system the dipole was located in the Z-X plane and placed parallel to the X-axis, centred on the Z-axis at a +z distance of 0.15 metres above the origin.

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2 For all our NEC models the following parameters were used:
a) the number of segments used ranged from 5 to 15 (differences in calculated results were insignificant);
b) for NEC2 calculations the extended thin wire kernel was used (a trial use of the standard thin wire kernel did not change the results), and for NEC3 calculations the standard thin wire kernel was used - in accordance with the NEC3 User's Guide instructions for use of the Sommerfeld integral ground option;
c) a voltage source (applied-E-field source) of 5 volts was used, applied to the centre segment of each dipole.

The H- and E-field strengths were calculated through one upper quadrant in the Z-X plane at points located at a radial distance of 30 metres from the origin of the coordinate system. The geometry is shown in Figure 1.

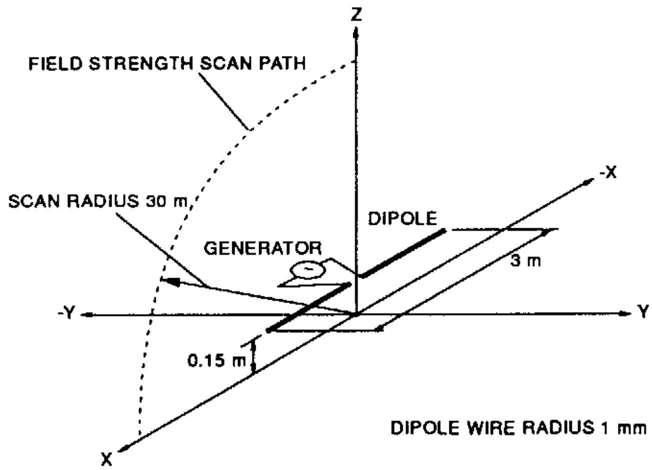

FIGURE 1. GEOMETRY FOR THE FIRST DIPOLE MODELLED USING NEC2S

Using NEC2 single precision (NEC2S) on a VAX 3600 computer, the calculated free space H- and E-field strengths both showed magnitude and phase fluctuations occurring over very short electrical distances ($< \lambda/250$). In the polar diagram of Figure 2 the full line curve shows the fluctuations of the calculated magnitude of the H-field strength[3] at low angles of elevation above the X-Y plane.

On the other hand, the H_y value calculated by NEC2S at 90° elevation is within 0.5% of the value calculated analytically for a small dipole having the same dipole moment (see §10.03 in [1]).

The question of the validity and origin, whether numerical or real, of the fluctuating values at small elevation angles involved Macfarlane and Fleming in several vigorous discussions.

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3 The H-field magnitudes given in this paper are the magnitudes of the H_y component of the field. The magnitudes are expressed in units of dBµV/m (dB relative to 1 µV/m), the magnitude of the equivalent far-field free space E-field. Such units for the H-field are used by the CISPR, and many field intensity measuring receivers that employ loop sensors are calibrated in equivalent units of dBµV/m. To convert dBµV/m to dBµA/m, subtract 51.5 dB ($20\log_{10}377$) from the E-field units.

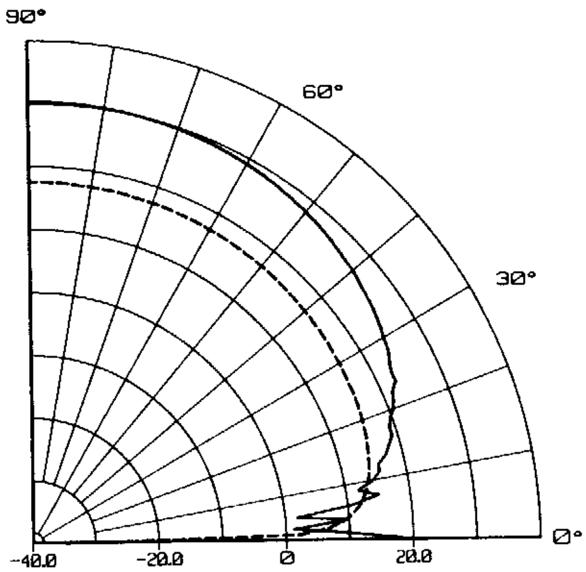

FIGURE 2. POLAR PLOTS OF THE H-FIELD STRENGTH CALCULATED BY NEC2S FOR THE HORIZONTAL DIPOLE MODEL IN FREE SPACE (FULL LINE) AND OVER GROUND (DASHED LINE) - THE GEOMETRY OF THE MODEL IS SHOWN IN FIGURE 1

III. MOVING ON - MODELLING WITH A SOMMERFELD GROUND

To help keep the peace several models were tried using NEC2S with SOMNEC to include the effect of a real ground at a frequency of 2 MHz. The ground was located in the horizontal X-Y plane. The calculated field strengths for a horizontal dipole proved the most interesting.

A 3 metre long dipole was oriented horizontally in the Z-X plane, at a height of 0.15 metres above the ground - this is the same geometry as is illustrated in Figure 1, with a real ground added in the X-Y plane. The dipole wire radius was 1 millimetre. A moist ground was assumed, and the values of conductivity $\sigma = 11 \times 10^{-3}$ S/m and relative permittivity $\varepsilon_r = 10$ were used.

The new field strength values were calculated along the same arc of radius 30 metres swinging round the origin from the positive Z axis down to the X axis (see Figure 1). The dashed curve in Figure 2 shows the H_y field strength values calculated for the horizontal dipole model. The values appeared more acceptable - they were, at least, free of the magnitude and phase fluctuations of the kind that were evident in the values calculated for the dipole in free space.

Fleming and Macfarlane were now faced with the puzzling fact that, for the electrically small dipole models they were using, in the simpler free space case NEC2S seemed to be suffering precision problems whereas in the presence of a real ground NEC2S/SOMNEC did not seem to be experiencing such problems.

Moreover, in the calculations involving a real ground the calculated values of E-field strength in the Z-X plane off the tip of the horizontal dipole model were relatively large at the surface of the ground, whilst the calculated values of H-field strength decreased dramatically as the ground was approached. In the polar diagram of Figure 2 the dashed curve labelled "dipole over ground" shows the marked decrease in magnitude of the calculated H-field at low angles of elevation for the horizontal dipole model.

The decrease in H-field strength predicted by NEC2S/SOMNEC close to ground sparked off another vigorous Macfarlane/Fleming discussion. Macfarlane insisted, without providing proof, that the near H-field close to ground should not decrease in the spectacular way that NEC2S/SOMNEC predicted.

IV. THE CARROT - MODELLING WITH NEC2D WILL CLARIFY THE SITUATION!!

In October 1989 the double precision version of the NEC2 code, NEC2D [4], became available to Macfarlane, Fleming, and Iskra. Iskra volunteered (unwisely, he was later to think) to install a working, compiled version of NEC2D with SOMNEC2D running on the VAX 3600 computer. The first step in the process was simple - compile the program and check its operation by running examples 1 through 4 as given in [5]. The result of this first test was less than encouraging.

A comparison of results for examples 1,2, and 3, showed that the compiled NEC2D code produced results which were identical with those given in [5].

For example 4, however, things were a little different. The input data describing the physical structure had been interpreted correctly by the program, but a comparison of the antenna input parameters, surface patch and wire currents, and radiation pattern, showed major discrepancies between results given in [5] and those obtained from the compiled NEC2D code. After much head scratching, it became clear that the difference between the output generated by the compiled code and results given in [5] was the result of a faulty section of code within NEC2D.

NEC2D was recompiled to produce a list of compiler warnings for comparison with the equivalent NEC2 listing. Emerging from the comparison was the existence of an additional warning associated with subroutine EKSCX indicating that the variable ERCGRK1 was never used.

A quick search within EKSCX exposed the culprit. It was a missing comma in line EK 6 such that the variable ERCGRK1 should have been written as ERC,GRK1. Having rectified this fault, NEC2D was recompiled and example 4 rerun. Again, the NEC2D result was in conflict with [5] indicating that the fix to EKSCX was not critical in this example. It seemed that there was yet another unresolved code violation. If there were further errors in the code, where would one look?

Example 4 was the first test example to include a structure composed of a mixture of wires and surfaces. Considering that the previous examples 1,2, and 3, dealt with wire models, and that the results obtained were consistent with [5], it was decided that a search should be undertaken of all subroutines that manipulated surface patch data in the hope that a comparison of Fortran specification statements would reveal the source of the error (as had occurred in EKSCX).

Not a pleasant task but one which did have its reward. The code error was tracked down to the subroutine PCINT in line PC 6 where the variables IIND1 and PGND should have been IND1 and IPGND respectively. This fix solved the problem with example 4.

Subsequent to the writing of most of this paper, the authors were informed that the code error found in line PC 6 of PCINT had been reported in [6]. The authors are unaware of any known report describing the error in line EK 6 of EKSCX.

NEC2D output for examples 5 through 10 showed almost complete agreement with [5]. There were, however, small differences between our NEC2D output and the results shown in [5] in examples 5 through 10 (occurring with real numbers having negative exponents of the order of 13 or greater) which we feel are directly attributable to problems of numerical precision inherent with the Fortran compiler resident on the VAX 3600 computer. We are further investigating this vexed question of numerical precision.

Having cleaned up the Telecom Research Labs' (TRL) copy of the NEC2D code in mid-October 1989, Iskra used NEC2D/SOMNEC2D to calculate field strength values near ground which, upon comparison, were found to be identical with those that had been obtained using NEC2S/SOMNEC. The investigation did not seem to be progressing. Macfarlane still refused to accept the calculated H-field strengths.

However, having regard for the possibility of even more serious precision problems with NEC2S, it was now decided that there would be a greater chance of successful progress if we used NEC2D for future work.

V. THE PROOF OF THE PUDDING - EXPERIMENTS VERSUS NEC2D/SOMNEC2D

In late November 1989, Macfarlane accepted Fleming's challenge to prove the actual existence near ground of a strong H_y field component near the end of a horizontal dipole radiating close to a real ground (Sommerfeld predicted that vertically polarized surface waves would be launched from the tips of horizontal dipoles operating close to the surface of the Earth [7]). Despite the fact that the weather was now becoming hot and humid, and the flies glue-footed and bothersome, Macfarlane began conducting a series of outdoor experimental measurements of the H-field strength radiated by an electrically short horizontal dipole near ground.

Initially, instrumentation limitations confined measurements to an upper frequency limit of 1.2 MHz, but later measurements were extended to include frequencies of 10 MHz and 20 MHz. All the measurements used a 3 metre horizontal dipole, with a wire radius of 1 millimetre, placed at a height of 0.15 metres above the ground. The measurements were performed as a vertical height scan in the plane of the dipole at a horizontal distance of 6 metres from the dipole centre. The geometry is depicted in Figure 3 - note that the ground is in the X-Y plane.

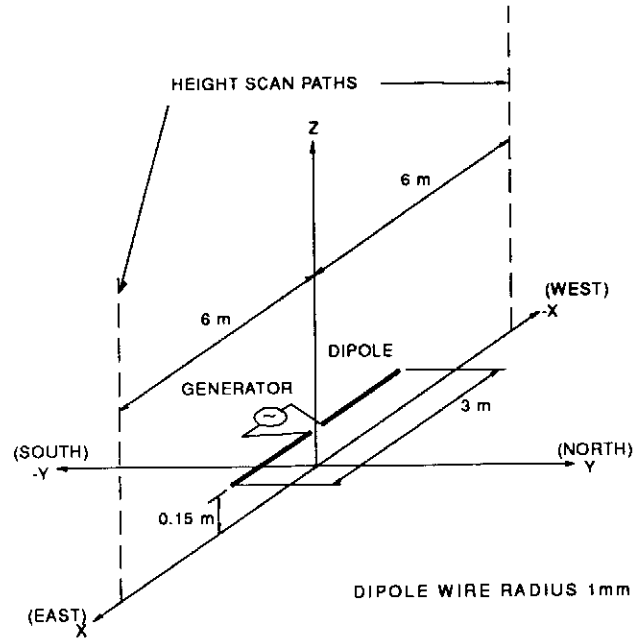

FIGURE 3. GEOMETRY OF THE EXPERIMENTAL MEASUREMENTS
AND OF THE MODEL USED IN THE NEC2D AND NEC3D CALCULATIONS

During the course of the experimental measurements, Iskra used NEC2D/SOMNEC2D to calculate the H-field strength values over the same height scan, at 1.2 MHz, 10 MHz, and 20 MHz, for comparison with the experimentally obtained values.

The experimental results were obtained in November/December 1989, and are reproduced in Sec. VI later in this paper. They strongly supported the existence of the Sommerfeld surface wave and indicated an erroneous calculation by NEC2 of the magnitude of the H-field strength near the surface of the ground. Fleming sent this news to Haack, and suggested that he might like to try the horizontal dipole model with NEC3.

In early December 1989 Macfarlane began preparing a paper that compared the experimental and NEC2-calculated H-field values, and which suggested that there was an incorrect calculation by NEC2 of the H-field strength close to a Sommerfeld ground.

In mid-December 1989, Fleming telephoned G. J. Burke at Lawrence Livermore National Laboratory (see [3]) to discuss possible causes of the erroneous calculations by NEC2 of H-field strengths close to the ground. Burke informed Fleming that a section of code had been omitted from the NHFLD subroutine in NEC2 and promptly sent to Fleming a copy of the missing section of code, by facsimile.

The additional section of code in NHFLD obtains the value of the H-field by using a six point finite-difference approximation of the curl of the E-field obtained in the Sommerfeld mode.

A listing of the NEC2D version of the NHFLD subroutine with the missing section of code restored is shown in Appendix A.

VI. TWO STEPS FORWARD - ONE STEP BACK

Goggle-eyed with anticipation, on the last working day before New Year's Eve 1989, Fleming ran a NEC2D/SOMNEC2D calculation that included the use of the heretofore missing section of code. Eureka! Fleming and Macfarlane metaphorically jumped out of the bath as the previously missing H-field strength near ground now appeared in the newly calculated results. New calculations were made at 1.2 MHz, 10 MHz, and 20 MHz, for comparison with the experimentally obtained H-field strength values.

Comparison of the new NEC2 H-field values with the experimentally measured values encouraged the belief that NEC2 was now calculating near H-field correctly, although precise agreement of the experimental values with the calculated ones was not obtained.

Macfarlane completed his paper [8], and included the results of the NEC2D/SOMNEC2D calculations using the previously missing section of code. Figures 4 to 7, comparing some of the measured H-field strengths with calculated values, are reproduced in this paper from [8], with permission.

Figures 4 and 5 show comparisons of the measured H-field strength values with the values predicted by the "deficient" NEC2D/SOMNEC2D, at the frequencies of 1.2 MHz and 10 MHz respectively.

Figures 6 and 7 show comparisons of the measured H-field strength values with the values predicted by the "restored" NEC2D/SOMNEC2D, also at the frequencies of 1.2 MHz and 10 MHz respectively.

A description of the experimental methods and some discussion of the remaining differences between the measured values and the values predicted by the "restored" code[4] are given in [8].

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4 Since this paper was first submitted to ACES Journal, another potential source of error in the finite-difference calculation of H-field has been identified. It is described in Appendix B.

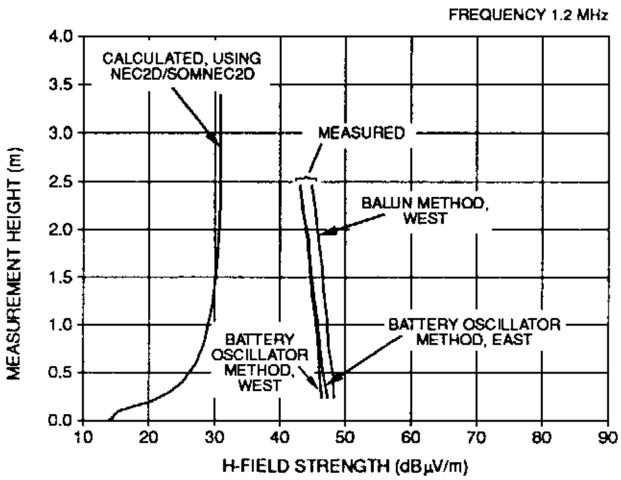

FIGURE 4. 1.2 MHz

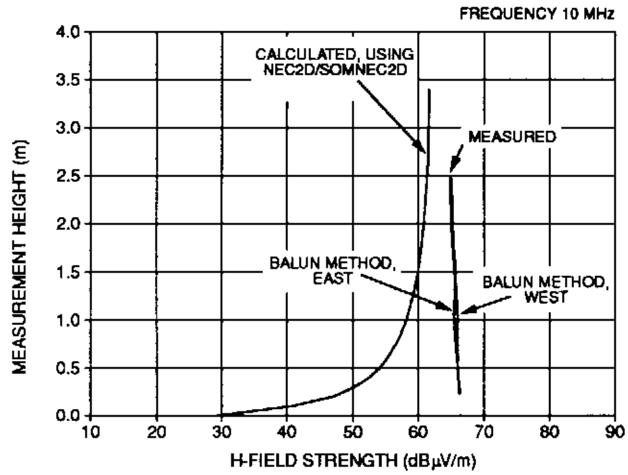

FIGURE 5. 10 MHz

COMPARISONS OF THE MEASURED H-FIELD STRENGTH VALUES WITH THOSE CALCULATED USING THE DEFICIENT NEC2D/SOMNEC2D CODE

(Reproduced from [8]*, with permission)*

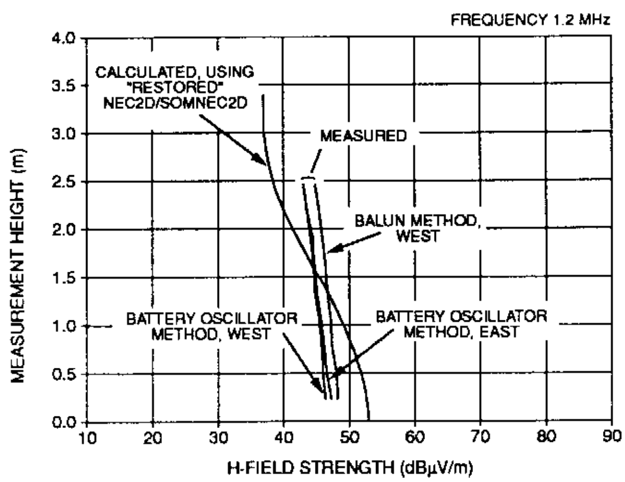

FIGURE 6. 1.2 MHz

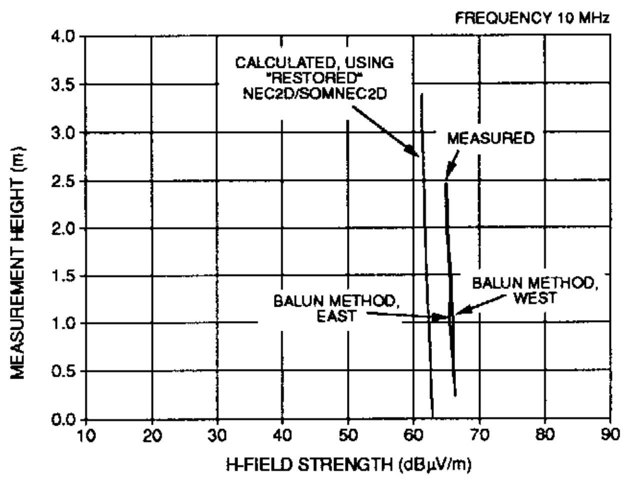

FIGURE 7. 10 MHz

COMPARISONS OF THE MEASURED H-FIELD STRENGTH VALUES WITH THOSE CALCULATED USING THE "RESTORED" NEC2D/SOMNEC2D CODE

(Reproduced from [8]*, with permission)*

Early in January 1990, Haack obtained results - using NEC3 double precision (NEC3D) on a VAX 8300 computer - which showed that NEC3 had problems calculating H-field strength near the ground, even though it supposedly used a near H-field routine similar to the one used by NEC2.

In particular, NEC3D calculated a very large increase in H-field strength at positions very close to ground as shown in Figures 8 and 9 (at heights less than $\lambda/1000$, the distance mentioned in a cautionary note contained in the NEC3 User's Guide), whereas the experimental measurements and NEC2D indicated that such an increase should not occur.

Moreover, Haack's results showed that when the NEC3D calculations were performed at a frequency of 10 MHz with the same horizontal 3 metre dipole, regular perturbations in the magnitude of the calculated H-field strength occurred at height intervals of approximately 7/8'ths of a metre ($\approx$ 0.03 λ) - this is shown in Figure 9. The comparable calculation performed at 10 MHz using NEC2D produced H-field strength values at points close to the ground that varied smoothly with height in a manner almost identical with the variation with height of the experimentally measured values (as shown in Figure 7).

A similar perturbation may be just beginning to manifest itself in the NEC3D calculations at 1.2 MHz - see the NEC3D curve plotted in Figure 8.

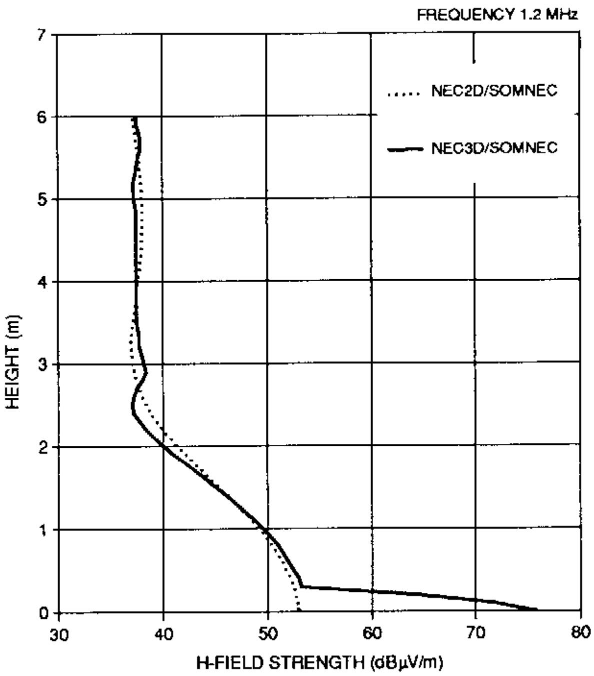

FIGURE 8. 1.2 MHz

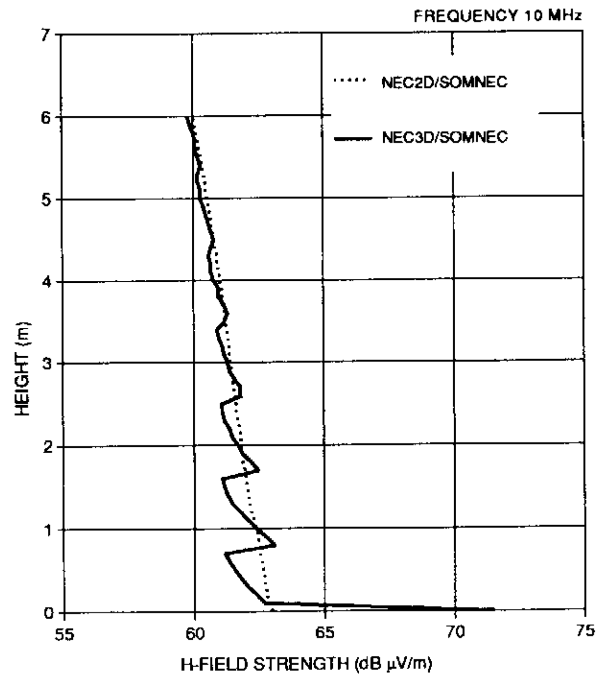

FIGURE 9. 10 MHz

COMPARISON OF THE H-FIELD STRENGTHS CALCULATED BY NEC3D AND BY THE "RESTORED" NEC2D - HORIZONTAL 3 METRE DIPOLE OVER A SOMMERFELD GROUND WITH CONSTANTS $\sigma = 11 \times 10^{-3}$ S/m AND $\varepsilon_r = 10$

In summary, it appeared from a comparison of the results from the NEC2D and NEC3D calculations that NEC2D - with the missing section of NHFLD code restored - was performing much better than NEC3D in the calculation of H-field strength in the vicinity of a Sommerfeld ground.

Discussion among us of possible reasons for the inaccurate calculation by NEC3 of near H-field very close to ground has been severely hampered by the restrictions on access to the NEC3 code (NEC3 is not available to the authors at TRL).

However, it is generally known from the open literature that NEC3 calculates electromagnetic field strengths above and below the air/ground interface, whilst NEC2 is confined to above-ground calculations and does not calculate the discontinuous E-field strengths across the interface. Both MoM codes calculate H-field strengths using a finite-difference approximation to the curl of the vector E-field.

More recent investigations by Fleming and Haack have studied what happens when the point at which the H-field is being calculated is so close to the interface that the $-\Delta z$ sampling increment goes below ground.

In the case of NEC3, the discontinuous normal component of the E-field at the interface that is correctly calculated by NEC3 produces large errors in the finite-difference curl calculation of the H-field strength very close to the interface.

On the other hand, NEC2 erroneously calculates a continuous normal component of E-field across the interface - thus yielding a smooth approximation for the curl and hence the H-field near the interface.

VII. CONCLUSIONS

We have identified some errors and omissions in the NEC2 code.

The most significant omission is of a section of code in the subroutine NHFLD in NEC2. The missing section of code is essential for the correct calculation of near H-field close to the surface of a Sommerfeld ground. The missing code for use with NEC2 has been supplied to us by G. J. Burke and a listing of the subroutine NHFLD suitable for use with NEC2D is included in Appendix A for the benefit of other NEC2 users.

It does seem that there may be many other NEC2 users who are unaware of the omission of the vital section of the near H-field code - possibly because interest in the H-field component seems to come a poor second to interest in the E-field component in many studies of electromagnetic fields for antenna, EMC, and bioelectromagnetic hazards, applications.

With the missing section of NHFLD code restored NEC2D seems to perform very well for the calculation of near H-field strengths near a Sommerfeld ground (but see also Appendix B), in the case of electrically small dipoles.

We have compared the performance of NEC3D with the performance of NEC2D (with the missing code restored) in the calculation of near H-fields close to a Sommerfeld ground and found that the NEC2D calculations more closely resembled the measured H-field strengths over a real ground.

Further investigations, involving a modified version of the finite-difference approximation for the curl of the E-field, are being made in order to correct the H-field calculation in NEC3D near the air/ground interface.

Work is also continuing to provide an explanation for the erroneous calculation by NEC3D of regular perturbations in the magnitude of the H-field strength at electrically small height intervals above a Sommerfeld ground, as is just manifest in Figure 8 and particularly evident in Figure 9.

VIII. ACKNOWLEDGEMENTS

We gratefully acknowledge very helpful and encouraging discussions with K. Lechmere, W. S. Davies, and K. H. Joyner, during the course of this work, and the invaluable technical assistance of B. C. Gilbert during the experimental measurements. We are also very grateful to G. J. Burke for supplying the missing NHFLD section of the NEC2 code and for giving his permission to reproduce the code here.

The permission of the Executive General Manager, Telecom Research Laboratories, to publish this paper is hereby acknowledged.

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APPENDIX A

LISTING OF THE "RESTORED" SUBROUTINE NHFLD FOR NEC2D

```
      SUBROUTINE NHFLD (XOB,YOB,ZOB,HX,HY,HZ)                          NH   1
C ************************************************
C     DOUBLE PRECISION 6/4/85
C
      IMPLICIT REAL*8(A-H,O-Z)
C ************************************************
C                                                                      NH   2
C     NHFLD COMPUTES THE NEAR FIELD AT SPECIFIED POINTS IN             NH   3
C     SPACE AFTER THE STRUCTURE CURRENTS HAVE BEEN COMPUTED.           NH   4
C                                                                      NH   5
      COMPLEX*16 HX,HY,HZ,CUR,ACX,BCX,CCX,EXK,EYK,EZK,EXS,EYS,         NH   6
     1EZS,EXC,EYC,EZC                                                  NH   7
C************************************************
      COMPLEX*16 ZRATI,ZRATI2,FRATI,T1,CON
      COMPLEX*16 EXPX,EXMX,EXPY,EXMY,EXPZ,EXMZ
      COMPLEX*16 EYPX,EYMX,EYPY,EYMY,EYPZ,EYMZ
      COMPLEX*16 EZPX,EZMX,EZPY,EZMY,EZPZ,EZMZ
      COMMON/GND/ZRATI,ZRATI2,FRATI,CL,CH,SCRWL,SCRWR,NRADL,
     1KSYMP,IFAR,IPERF,T1,T2
C************************************************
      COMMON /DATA/ LD,N1,N2,N,NP,M1,M2,M,MP,X(300),Y(300),            NH   8
     1Z(300),SI(300),BI(300),ALP(300),BET(300),ICON1(600),             NH   9
     2ICON2(300),ITAG(600),ICONX(300),WLAM,IPSYM                       NH  10
      COMMON /ANGL/ SALP(300)                                          NH  11
      COMMON /CRNT/ AIR(300),AII(300),BIR(300),BII(300),               NH  12
     1CIR(300),CII(300),CUR(900)                                       NH  13
      COMMON /DATAJ/ S,B,XJ,YJ,ZJ,CABJ,SABJ,SALPJ,EXK,EYK,EZK,         NH  14
     1EXS,EYS,EZS,EXC,EYC,EZC,RKH,IEXK,IND1,INDD1,IND2,INDD2,IPGND     NH  15
      DIMENSION CAB(1), SAB(1)                                         NH  16
      DIMENSION T1X(1), T1Y(1), T1Z(1), T2X(1), T2Y(1), T2Z(1),        NH  17
     1XS(1), YS(1), ZS(1)                                              NH  18
      EQUIVALENCE (T1X,SI), (T1Y,ALP), (T1Z,BET), (T2X,ICON1),         NH  19
     1(T2Y,ICON2), (T2Z,ITAG), (XS,X), (YS,Y), (ZS,Z)                  NH  20
      EQUIVALENCE (T1XJ,CABJ), (T1YJ,SABJ), (T1ZJ,SALPJ),              NH  21
     1(T2XJ,B), (T2YJ,IND1), (T2ZJ,IND2)                               NH  22
      EQUIVALENCE (CAB,ALP), (SAB,BET)                                 NH  23
C************************************************
       IF (IPERF.EQ.2) GO TO 6
C************************************************
      HX=(0.,0.)                                                       NH  24
      HY=(0.,0.)                                                       NH  25
      HZ=(0.,0.)                                                       NH  26
      AX=0.                                                            NH  27
```

```
      IF (N.EQ.0) GO TO 4
      DO 1 I=1,N
      XJ=XOB-X(I)
      YJ=YOB-Y(I)
      ZJ=ZOB-Z(I)
      ZP=CAB(I)*XJ+SAB(I)*YJ+SALP(I)*ZJ
      IF (ABS(ZP).GT.0.5001*SI(I)) GO TO 1
      ZP=XJ*XJ+YJ*YJ+ZJ*ZJ-ZP*ZP
      XJ=BI(I)
      IF (ZP.GT.0.9*XJ*XJ) GO TO 1
      AX=XJ
      GO TO 2
1     CONTINUE
2     DO 3 I=1,N
      S=SI(I)
      B=BI(I)
      XJ=X(I)
      YJ=Y(I)
      ZJ=Z(I)
      CABJ=CAB(I)
      SABJ=SAB(I)
      SALPJ=SALP(I)
      CALL HSFLD (XOB,YOB,ZOB,AX)
      ACX=DCMPLX(AIR(I),AII(I))
      BCX=DCMPLX(BIR(I),BII(I))
      CCX=DCMPLX(CIR(I),CII(I))
      HX=HX+EXK*ACX+EXS*BCX+EXC*CCX
      HY=HY+EYK*ACX+EYS*BCX+EYC*CCX
3     HZ=HZ+EZK*ACX+EZS*BCX+EZC*CCX
      IF (M.EQ.0) RETURN
4     JC=N
      JL=LD+1
      DO 5 I=1,M
      JL=JL-1
      S=BI(JL)
      XJ=X(JL)
      YJ=Y(JL)
      ZJ=Z(JL)
      T1XJ=T1X(JL)
      T1YJ=T1Y(JL)
      T1ZJ=T1Z(JL)
      T2XJ=T2X(JL)
      T2YJ=T2Y(JL)
      T2ZJ=T2Z(JL)
      CALL HINTG (XOB,YOB,ZOB)
      JC=JC+3
      ACX=T1XJ*CUR(JC-2)+T1YJ*CUR(JC-1)+T1ZJ*CUR(JC)
      BCX=T2XJ*CUR(JC-2)+T2YJ*CUR(JC-1)+T2ZJ*CUR(JC)
      HX=HX+ACX*EXK+BCX*EXS
      HY=HY+ACX*EYK+BCX*EYS
```

```
5     HZ=HZ+ACX*EZK+BCX*EZS                                              NH  78
      RETURN                                                             NH  79
C*************************************************
C
C     GET H BY FINITE DIFFERENCE OF E FOR SOMMERFELD GROUND
C     CON=j/(2*pi*eta)
C     DELT is the increment for getting central differences
C
C*************************************************
6     DELT=1.E-3
      CON=(0.,4.2246E-4)
      CALL NEFLD (XOB+DELT,YOB,ZOB,EXPX,EYPX,EZPX)
      CALL NEFLD (XOB-DELT,YOB,ZOB,EXMX,EYMX,EZMX)
      CALL NEFLD (XOB,YOB+DELT,ZOB,EXPY,EYPY,EZPY)
      CALL NEFLD (XOB,YOB-DELT,ZOB,EXMY,EYMY,EZMY)
      CALL NEFLD (XOB,YOB,ZOB+DELT,EXPZ,EYPZ,EZPZ)
      CALL NEFLD (XOB,YOB,ZOB-DELT,EXMZ,EYMZ,EZMZ)
      HX=CON*(EZPY-EZMY-EYPZ+EYMZ)/(2.*DELT)
      HY=CON*(EXPZ-EXMZ-EZPX+EZMX)/(2.*DELT)
      HZ=CON*(EYPX-EYMX-EXPY+EXMY)/(2.*DELT)
      RETURN
C*************************************************
      END                                                                NH  80
```

APPENDIX B

THAT'S ONE SMALL STEP.........!

After this "Pilgrims' Progress..." paper had been submitted to the ACES Journal, Macfarlane began using NEC2 to calculate the vertical radiation patterns of near H-fields over real grounds at very short electrical distances from small electric and magnetic dipole sources excited at frequencies down to 100 kHz. The H-field patterns that were calculated exhibited nulls that had no physical basis that he could think of.

After further pondering, Macfarlane surmised that the source of the error was the size of the spatial sampling interval, DELT, used in the finite-difference calculation of the curl of the E-field which gives the H-field in the "restored" NEC2 code. In the "restored" NHFLD subroutine the spatial sampling interval is normally fixed at $10^{-3}(\lambda)$, where λ is the free space wavelength at the frequency of interest. When calculations of the H-field strength are being made at a distance of 6 metres from the centre of a 3 metre long electric dipole at a frequency of 1.2 MHz (λ = 250 metres), it can be seen that $10^{-3}\lambda$ (0.25 metre) is a rather coarse sampling interval.

To enable testing of Macfarlane's surmise, Iskra modified NEC2D to allow the operator to either enter a new value of DELT for each set of near H-field calculations, or to use a default value of 1.E-3.

A reduction of the interval DELT to $10^{-4}(\lambda)$ (DELT = 1.E-4 in NHFLD) at 1.2 MHz produced the calculated H-field strength curve shown below in Figure 10, at 6 metres from the horizontal electric dipole, which matches the measured H-field much better than does the S-bend shown in Figure 6.

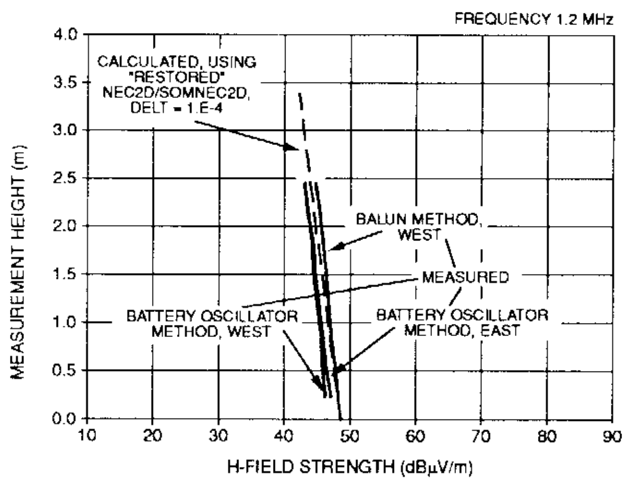

FIGURE 10. COMPARISON AT 1.2 MHz OF THE MEASURED H-FIELD STRENGTH VALUES WITH THOSE CALCULATED USING THE "RESTORED" NEC2D/SOMNEC2D CODE, AFTER SETTING THE SPATIAL SAMPLING INTERVAL, DELT, TO 1.E-4 IN THE NHFLD SUBROUTINE