UNITED STATES DEPARTMENT OF INTERIOR

GEOLOGICAL SURVEY

A Fortran IV Program for Analytic Continuation of VLF Electromagnetic Data

by

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This report is preliminary and has not been reviewed for conformity with USGS standards.

Introduction

The purpose of program VLFDRV and subroutines TRUNC, VLFCON, and VLFPLT is to analytically continue VLF survey profiles either upward or downward. This means that data taken at one level over an electrical anomaly can be used to simulate what the data would look like at another (higher or lower) level. The upward continuation is accurate and stable. The downward continuation is unstable under conditions which will be discussed later.

The present programs consist of a main program, VLFDRV, and three subroutines, TRUNC (with entry point VLFCON), VLFPLT, and FFT. TRUNC-VLFCON is a general subroutine which continues any complex potential field profile (assumed to be taken on a line perpendicular to the structural strike) upward or downward. VLFDRV is a somewhat specialized routine designed to read data from a disk file, interpolate into regular spacing, and control TRUNC-VLFCON and VLFPLT. VLFPLT is a plot routine for a Tektronix 4010 on the USGS DEC 1070 computer in Denver. FFT is a Fast Fourier Transform routine which might be replaced by any other FFT program.

The theory for this continuation is given by Roy (1968).

Input

The main program VLFDRV handles the input data. This routine could be replaced by another which would accept data in any format desired.

The input to VLFDRV is in two forms: from the timeshare keyboard and from ASCII disk files. The actual profile data are read from disk. Sample disk files are printed in Appendix B (p. 16). The first line in each file gives the number of observations. Subsequent lines contain one observation each, giving the x-coordinate in arbitrary sampling units from the center of the structure, and two real constants representing the real and imaginary parts of the observed VLF signal, which is a Cartesian component of the electromagnetic field. The data are in the DEC-10 list-directed input format.

The program starts by asking for the name of the file containing the profile data. The user types the name and a carriage return (cr). The data are read from disk. Values are derived at each range of an integral number of sampling intervals by linear interpolation between the observations. The observation at greatest range is continued as an extrapolation to the end of the array. VLFDRV assumes the input data to be the positive half of an even function. Simple modifications will provide for odd or non-symmetric input.

The program asks the user to type a continuation height (units are sampling intervals). Positive numbers are upward continuation, negative downward. The continuation is performed.

The program asks for a value for the variable LOOP. If LOOP = 0, the program stops. If LOOP = 1, another height (relative to the latest height) can be entered for another continuation. If LOOP = 2, a new request for a data file is made.

Output

The only output is in plot form (figs. 1-7), presently set up for plotting on a Tektronix 4010 terminal. The original data profile and the profiles at the various continued heights are plotted. The solid line is the real part of the component being continued. The dashed line is the imaginary part.

The user can easily replace VLFPLT with a routine which prints or types the data, or writes them on disk.

Downward continuation stability

The process of downward continuation is unstable due to the accentuation of relatively inaccurate high-frequency spectral values. To partially compensate for this problem, the high-frequency part of the spectrum is truncated.

The example in Appendix B shows the range of stability for downward continuation. The continued profile loses stability about halfway down to the level of the anomalous conductor from the height of observation. Loss of stability is normally characterized by high-frequency ripple in the profile (fig. 4). Truncation of high spectral frequencies results in a systematic amplitude-reduction for sharply defined features (compare figs. 3 and 4).

References

Roy, A., 1968, Continuation of Electromagnetic Fields-I: Geophysics, v. 33, no. 5, p. 834-837.

Appendix A

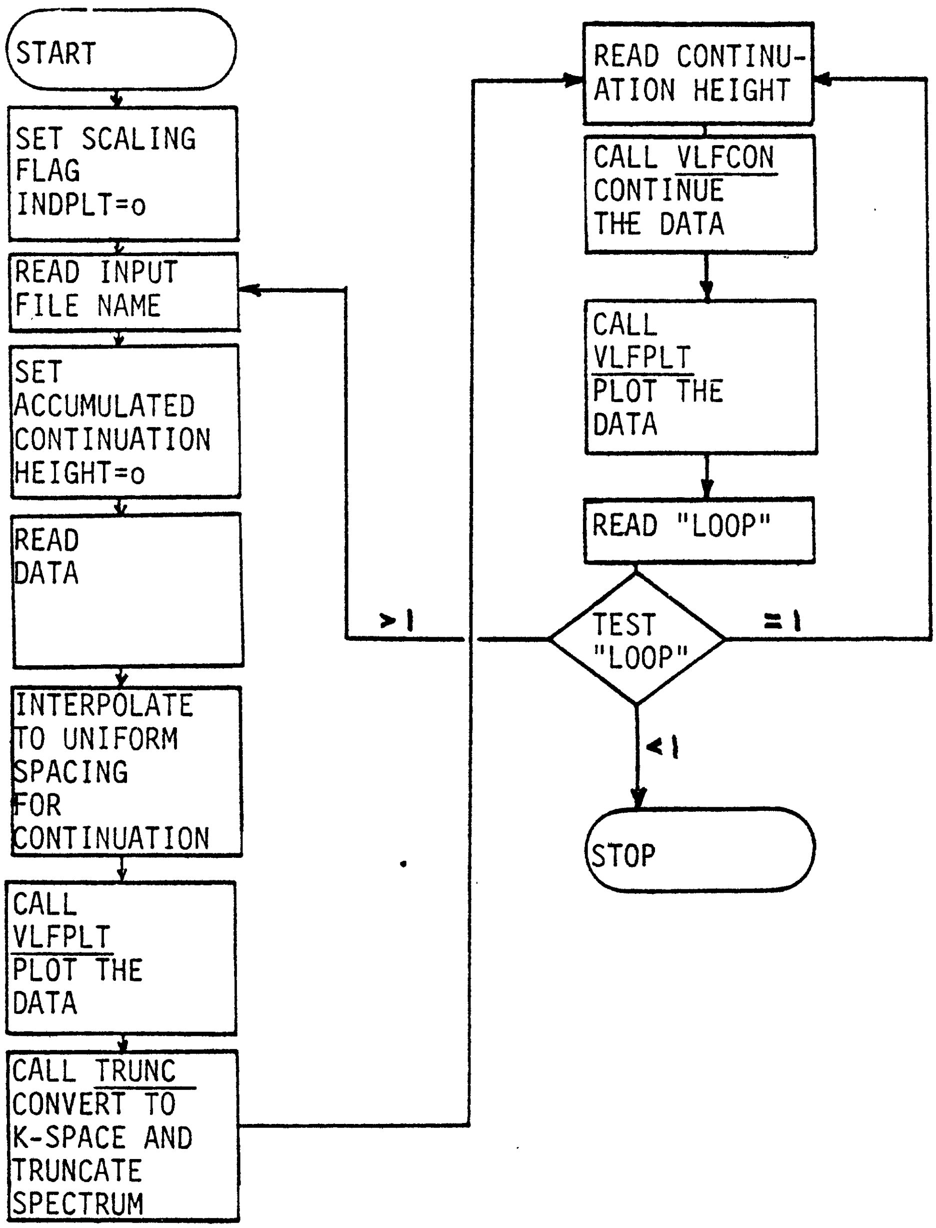
Flow diagrams and listings for main program VLFDRV and subroutines TRUNC and VLFPLT.

Listing for subroutine FFT.

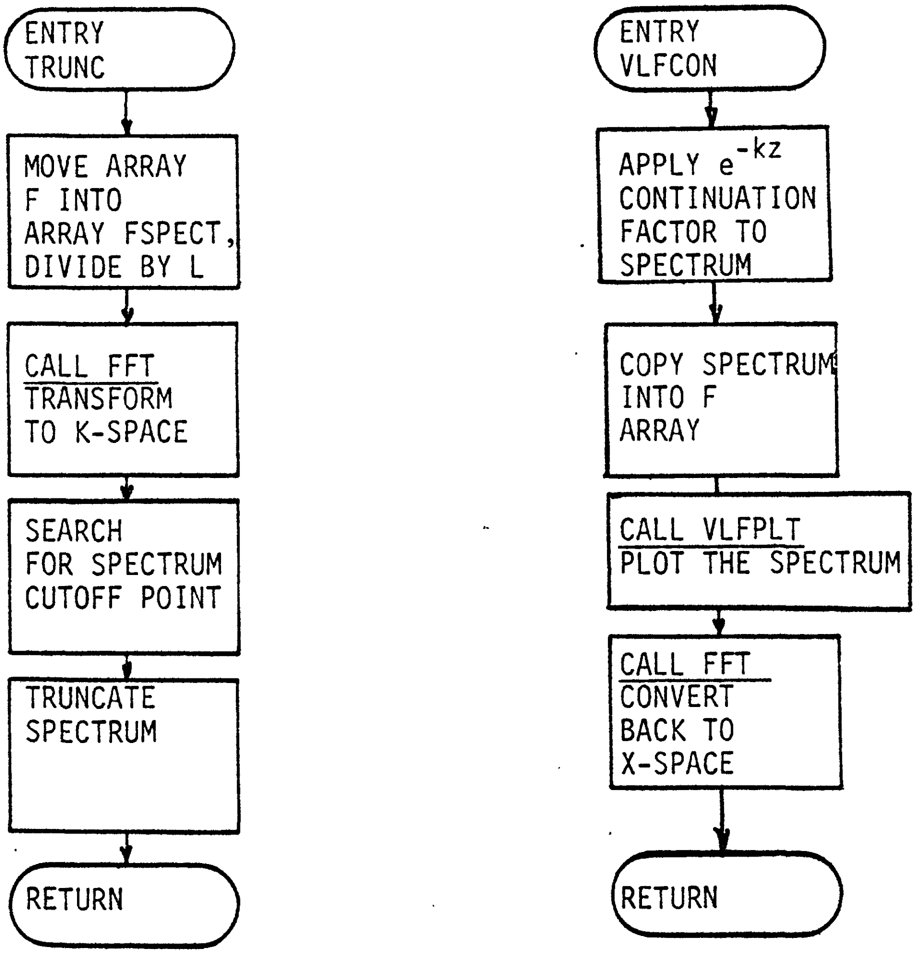
The main program VLFDRV is in a file by itself, VLFDRV.FOR.

The subroutines TRUNC (with entry VLFCON) and VLFPLT are in file VLFCON.FOR. Subroutine FFT is in FFT.FOR.

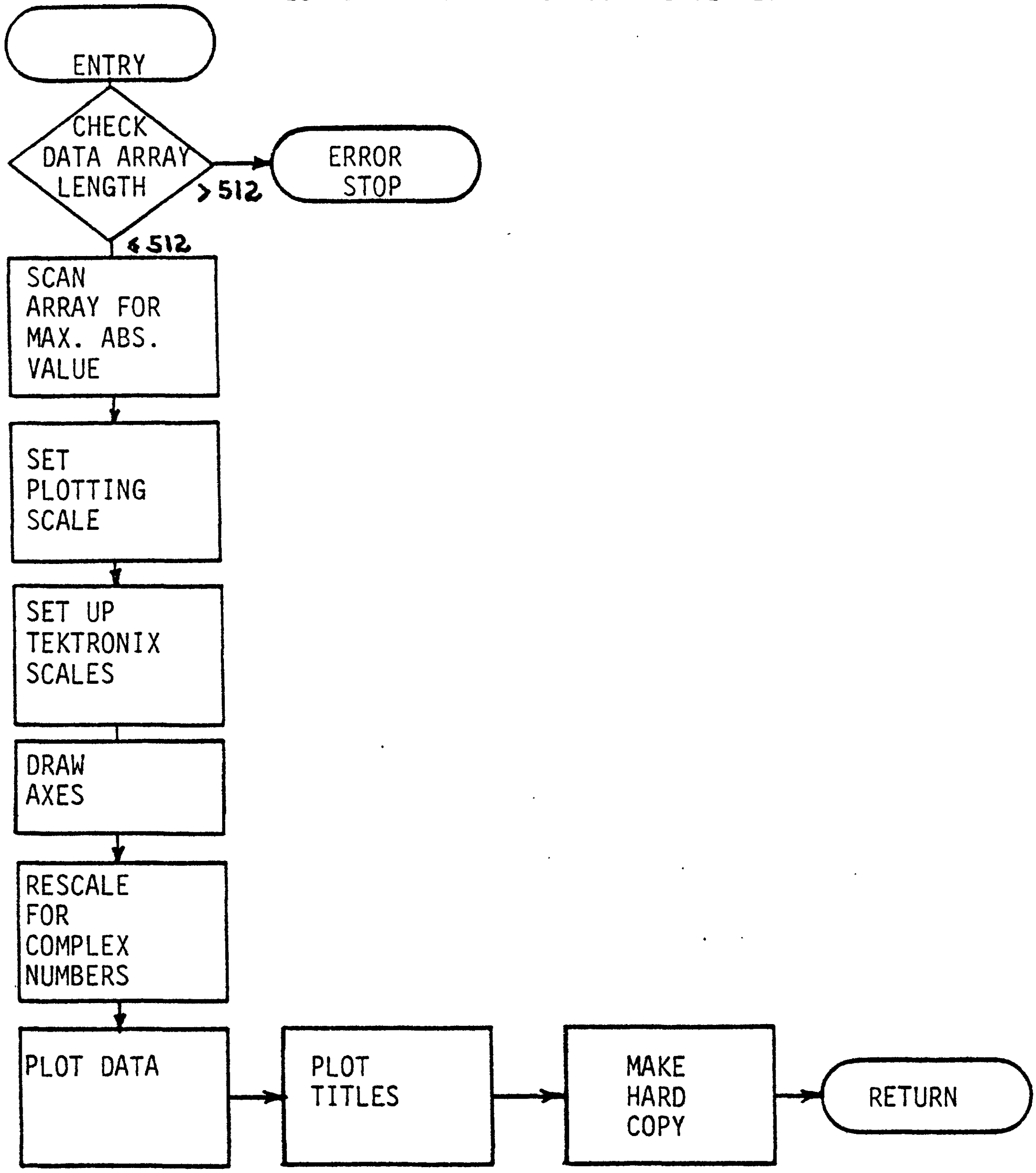
FLOW DIAGRAM FOR MAIN PROGRAM VLFDRV



FLOW DIAGRAM FOR SUBROUTINE VLFCON



FLOW DIAGRAM FOR SUBROUTINE VLFPLT



```
C      VLFDRV
C      VLFDRIVER
C      READS MODEL DATA FOR CONTINUATION OF VLF DATA
       COMPLEX F(256),FSPECT(256),A,B,FILE,FIN(22),T
       REAL FINPUT(2,22),IN(22)
       EQUIVALENCE(FIN,FINPUT)

C      READ INPUT FILE NAME
   20  TYPE 102
  102  FORMAT(' ENTER INPUT FILE NAME')
       ACCEPT 100,FILE
  100  FORMAT(2A5)

C      SET ACCUMULATED CONTINUATION HEIGHT TO ZERO
       ZACC=0.

C      OPEN INPUT FILE
       OPEN(UNIT=9,DEVICE='DSK',ACCESS='SEQIN',MODE='ASCII',
      ,      FILE=FILE)

C      READ NUMBER OF INPUT POINTS
       READ(9,*)NIN
C      READ INPUT DATA
       DO 1 I=1,NIN
    1  READ(9,*)IN(I),(FINPUT(J,I),J=1,2)

C      CLOSE INPUT FILE
       CLOSE(UNIT=9)

C      INTERPOLATE INPUT ARRAY INTO DATA ARRAY
       N=NIN-1
       DO 2 I=1,N
       AIST=IN(I)
       IST=AIST
       IND=IN(I+1)
       A=FIN(I)
       B=(FIN(I+1)-A)/(IN(I+1)-AIST)
       DO 2 INT=IST,IND
       T=A+B*(INT-AIST)
       F(129+INT)=T
    2  F(129-INT)=T
       IST=IN(NIN)+1
C      EXTRAPOLATE TO ARRAY END USING LAST VALUE
       DO 3 INT=IST,127
       F(129+INT)=T
    3  F(129-INT)=T
       F(1)=T

C      PLOT THE DATA
       CALL VLFPLT(F,256,ZACC,FILE)

C      DO SPECTRAL TRUNCATION FOR DOWNWARD STABILITY
       CALL TRUNC(F,FSPECT,256)

C      READ AMOUNT TO UPWARD CONTINUE IT
   10  TYPE 103
  103  FORMAT(' ENTER CONTINUATION HEIGHT')
       ACCEPT *,Z

C      KEEP TRACK OF ACCUMULATED HEIGHT
```

```
      ZACC=ZACC+Z

C     UPWARD OR DOWNWARD CONTINUE THE PROFILE
      CALL VLFCON(Z,ZACC,FILE)

C     PLOT IT
      CALL VLFPLT(F,256,ZACC,FILE)

C     ASK ABOUT LOOPING
      TYPE 101
  101 FORMAT(' TYPE 1 FOR ANOTHER CONTINUATION, 0 TO STOP,',
     ,      ' 2 FOR NEW SOURCE FILE')
      ACCEPT *,LOOP
      IF(LOOP-1)30,10,20
   30 STOP

      END
```

```
C      USING LAPLACE'S EQUATION.
C      Z IS IN UNITS OF THE SAMPLING INTERVAL OF F.

C      APPLY VERTICAL CONTINUATION FACTOR EXP(-K*Z) TO SPECTRUM
       FACTOR=1.
C      2.*PI/L IS K-INTERVAL
       FACTO=EXP(-2.*3.141593/L*Z)
       FSPECT(1)=FACTOR*FSPECT(1)
       M=L/2
       N=L+2
       DO 10 I=2,M
       FACTOR=FACTOR*FACTO
C      POSITIVE PART OF SPECTRUM
       FSPECT(I)=FSPECT(I)*FACTOR
C      NEGATIVE PART OF SPECTRUM
    10 FSPECT(N-I)=FSPECT(N-I)*FACTOR
       FACTOR=FACTOR*FACTO
       FSPECT(M+1)=FSPECT(M+1)*FACTOR

C      MOVE TO PROFILE ARRAY AND TRANSFORM BACK TO X-SPACE
       DO 7 I=1,L
     7 F(I)=FSPECT(I)
C      TRANSFORM BACK TO DISTANCE SPACE
       CALL FFT(F,L,-1.)

       END



       SUBROUTINE VLFPLT(F,L,ZACC,NAME)
C      PLOTS VLF DATA
C      ARGUMENTS -
C        F    - COMPLEX DATA FOR PLOT
C        L    - LENGTH OF ARRAY F
C        ZACC - ACCUMULATED CONTINUATION HEIGHT
C        NAME - SOURCE FILE NAME

       COMPLEX NAME
       REAL F(2,L),X(512),XP(4),YP(4),DXP(2),DYP(3),TITLE(10)

C      CHECK ARRAY LENGTH
       IF(L.GT.512)STOP ' ARRAY LENGTH TOO LARGE IN VLFPLT'

C      DETERMINE VERTICAL SCALE
       FMIN=F(1,1)
       FMAX=FMIN
       DO 1 I=1,2
       DO 1 J=1,L
       FT=F(I,J)
       FMIN=AMIN1(FMIN,FT)
     1 FMAX=AMAX1(FMAX,FT)
       A=AMAX1(ABS(FMAX),ABS(FMIN))
       LOG=ALOG10(A)
       IF(A.LT.1.)LOG=LOG-1
       B=10**LOG
       FSCALE=2.*B; IF(FSCALE.GT.A)GO TO 2
       FSCALE=5.*B; IF(FSCALE.GT.A)GO TO 2
       FSCALE=10.*B

C      SET UP PLOT PARAMETERS FOR TEKTRONIX
```

```
    2 CALL PLTSET(1,XMAX,YMAX,2)
      DXP(1)=0.; DXP(2)=L
      DYP(1)=-FSCALE; DYP(2)=FSCALE
      XP(1)=14.; YP(1)=9.
      XP(2)=1.; YP(2)=1.
      XP(3)=3.; YP(3)=3.
      XP(4)=XMAX; YP(4)=YMAX
      CALL SCALE(DXP,DYP,XP,YP,4,IERROR)
      IF(IERROR.NE.0)STOP ' SCALE ERROR '

C     DRAW SCALES
      CALL XAXIS(DXP,DYP,XP,(DXP(2)-DXP(1))/10.,1,.25,'(F6.1)',6)
      CALL YAXIS(DYP,DXP,YP,(DYP(2)-DYP(1))/10.,1,.25,'(1PE8.1)',8)
      CALL NEATLN

C     RESCALE FOR COMPLEX PLOTTING
      DYP(3)=DYP(2)
      YP(2)=3.
      CALL SCALE(DXP,DYP,XP,YP,3,ICODE)

C     PLOT DATA
      DO 3 I=1,L
    3 X(I)=I
      CALL LINE(X,F,L,0,0)
      CALL LINE(X,F(2,1),L,0,1)

C     LABEL THE PLOT
      ENCODE(50,100,TITLE)NAME
  100 FORMAT('SOURCE FILE: ',2A5)
      CALL CHAR(3.,.7,TITLE,23,3,.25,0.,0.,0.)
      ENCODE(50,101,TITLE)ZACC
  101 FORMAT('TOTAL CONTINUATION HEIGHT:',F6.2)
      CALL CHAR(9.,.7,TITLE,32,3,.25,0.,0.,0.)
      CALL CHAR(9.,1.4,'RANGE ->',8,3,.3,0.,0.,0.)
      CALL CHAR(.4,5.,'FIELD STRENGTH ->',17,3,.3,3.141593/2.,0.,0.)
      OPEN(UNIT=10,MODE='ASCII',DEVICE='PLOT')
      WRITE(10,102)
  102 FORMAT('^G^[^W')
      CALL ENDPLT(0)

      END
```

```
      SUBROUTINE FFT(F,N,S)
      COMPLEX F(0/1),W,WP,X,Y
      INTEGER GRSIZE,HRSIZE,GROUP

C     ---------- BIT REVERSAL ----------
  100 J=N/2; K=J
      DO 101 I=1,N-2
      IF(I<J)102,103
  102 X=F(I)
      F(I)=F(J)
      F(J)=X

C     BIT-REVERSE COUNTER UPDATE
  103 L=K
  106 IF(J>=L)104,101
  104 J=J-L; L=L/2; GO TO 106
  101 J=J+L

C     ------- SET UP FOR TRANSFORMATION ------
      W=(-1.,0.)
      GRSIZE=2; HRSIZE=1

C     LOOP FOR EACH GROUP

C     USE OUTPUT FROM PREVIOUS TRANSFORMS
    1 DO 2 GROUP=0,N-1,GRSIZE

C     SCAN HALF THE GROUP
C     SET THE W-POWERS
      WP=(1.,0.)
      DO 2 I=GROUP,GROUP+HRSIZE-1
      J=I+HRSIZE
      X=F(I);  Y=F(J)*WP
      F(I)=X+Y;  F(J)=X-Y
    2 WP=WP*W

C     CHANGE W
      W=CSQRT(W); IF(AIMAG(W)*S<0)W=-W

C     CHANGE GROUP SIZE
    5 HRSIZE=GRSIZE
      GRSIZE=GRSIZE*2

C     IF DONE, RETURN,  OTHERWISE, DO NEXT GROUP-SIZE.
      IF(GRSIZE>N)RETURN
      GO TO 1


      END
```

Appendix B

Printout of sample input data files. File name gives height above conductor at which data were recorded.

Examples of continuation of scale-model data. Continuation height is relative to observation height of data read from source file. Height and range units are arbitrary, but must be the same (they are cm. for the scale-model examples). Field strength is also in arbitrary units. The data for continuation must be real and imaginary parts of one constant-direction component of the electromagnetic field. The real part is plotted by a solid line, the imaginary part by a dashed line.

22 FILE VLFHX,0 MODEL DATA, HEIGHT 0,0

0	2,898	-,307
1	2,441	-,285
2	1,779	-,211
3	1,374	-,146
4	1,165	-,104
5	1,045	-,074
6	,992	-,058
7	,938	-,042
8	,923	-,032
10	,892	-,012
12	,886	-,007
15	,877	,001
20	,901	,008
25	,918	,014
30	,934	,015
35	,947	,017
40	,958	,017
45	,966	,016
50	,975	,014
60	,985	,010
70	,991	,006
80	,994	,002

20 FILE VLFHX,5 MODEL DATA, HEIGHT 5,0

0	1,387	-,107
1	1,375	-,101
2	1,340	-,098
3	1,296	-,091
4	1,244	-,080
5	1,198	-,073
6	1,151	-,062
8	1,073	-,045
10	1,022	-,034
12	,990	-,024
15	,962	-,013
20	,947	-,003
25	,947	,007
30	,954	,011
35	,961	,012
40	,968	,012
45	,973	,010
50	,980	,008
60	,987	,010
70	,992	,006

19 FILE VLFHX.10 MODEL DATA, HEIGHT 10.0

0	1.172	-.060
1	1.171	-.058
2	1.164	-.056
3	1.154	-.054
4	1.143	-.052
5	1.127	-.050
6	1.112	-.047
7	1.096	-.041
8	1.080	-.039
10	1.053	-.032
12	1.029	-.024
15	1.004	-.018
20	.98	-.006
25	.971	.000
30	.970	.005
35	.976	.006
50	.982	.008
60	.987	.006
80	.996	.001

18 FILE VLFHX,15 MODEL DATA, HEIGHT 15,0

0	1,092	-,037
1	1,092	-,037
2	1,089	-,037
3	1,087	-,037
4	1,082	-,037
5	1,077	-,035
7	1,066	-,031
10	1,046	-,026
12	1,032	-,021
15	1,016	-,020
20	,996	-,012
25	,985	-,006
30	,980	-,003
35	,979	,001
40	,982	,001
50	,986	,003
60	,989	,001
80	,996	,001

```
14      FILE VLFHX.20      MODEL DATA, HEIGHT 20.0
0  1.059 -.029
2  1.059 -.026
5  1.053 -.025
8  1.045 -.024
10  1.038 -.020
15  1.020 -.014
20  1.006 -.011
25  .997 -.005
30  .993 -.003
35  .989 .000
40  .989 .000
50  .990 .001
70  .992 .003
80  .996 .003
```

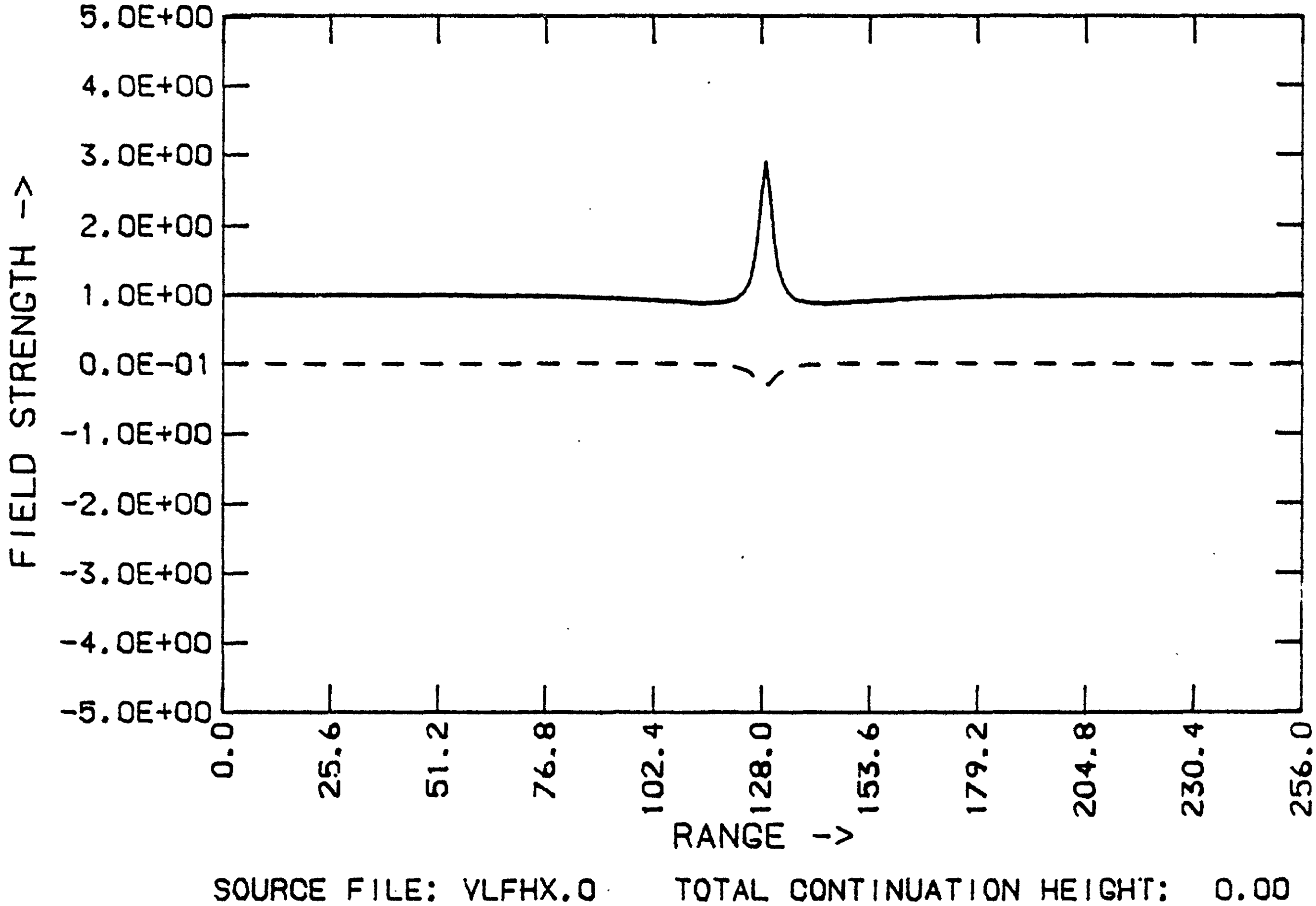


Figure 1 - Measured data, height above conductor = o.
For explanation of range and field strength units, see p. 16.

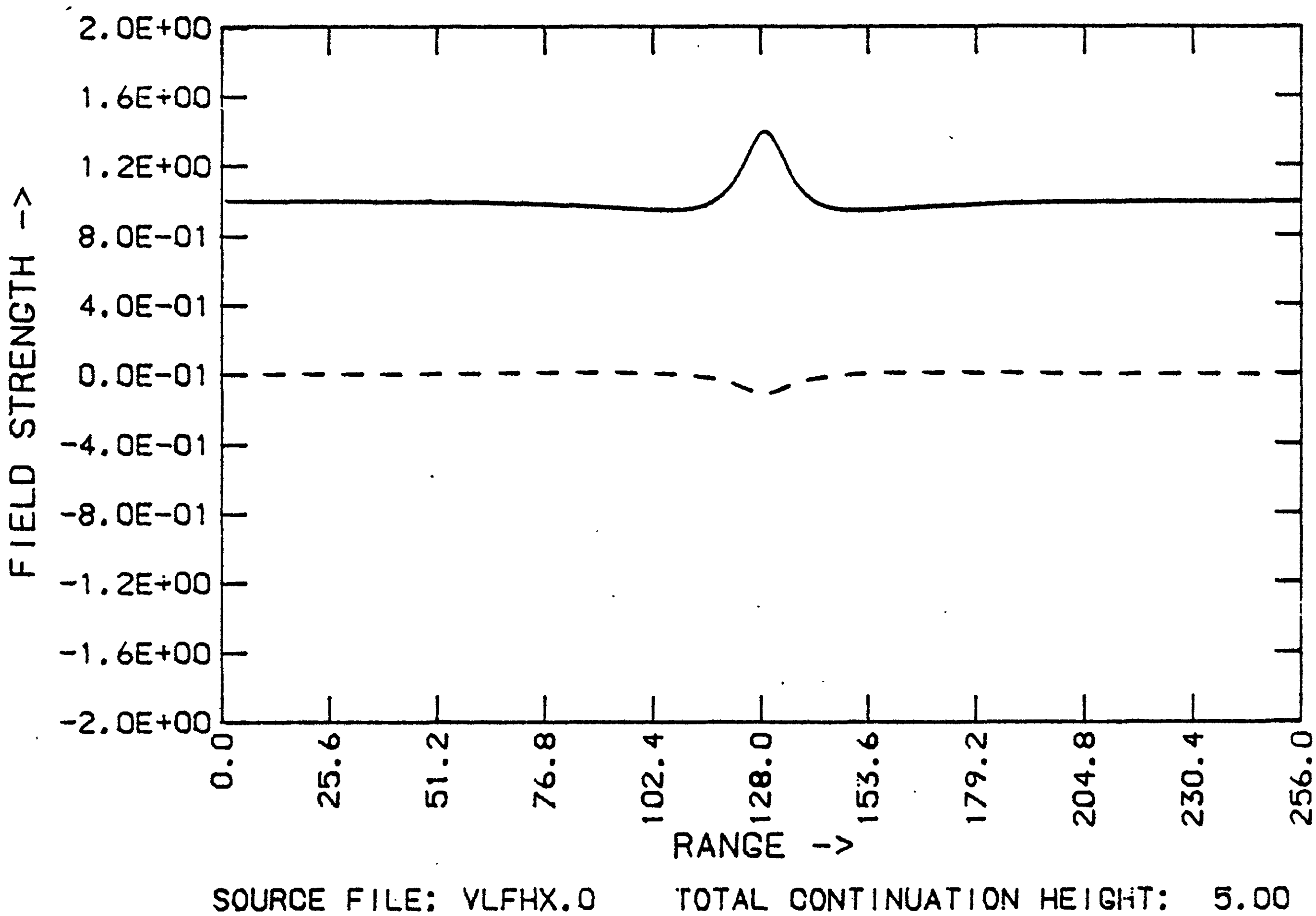


Figure 2 - The data of Fig. 1, upward continued 5 cm.
For explanation of range and field strength units,
see p. 16.

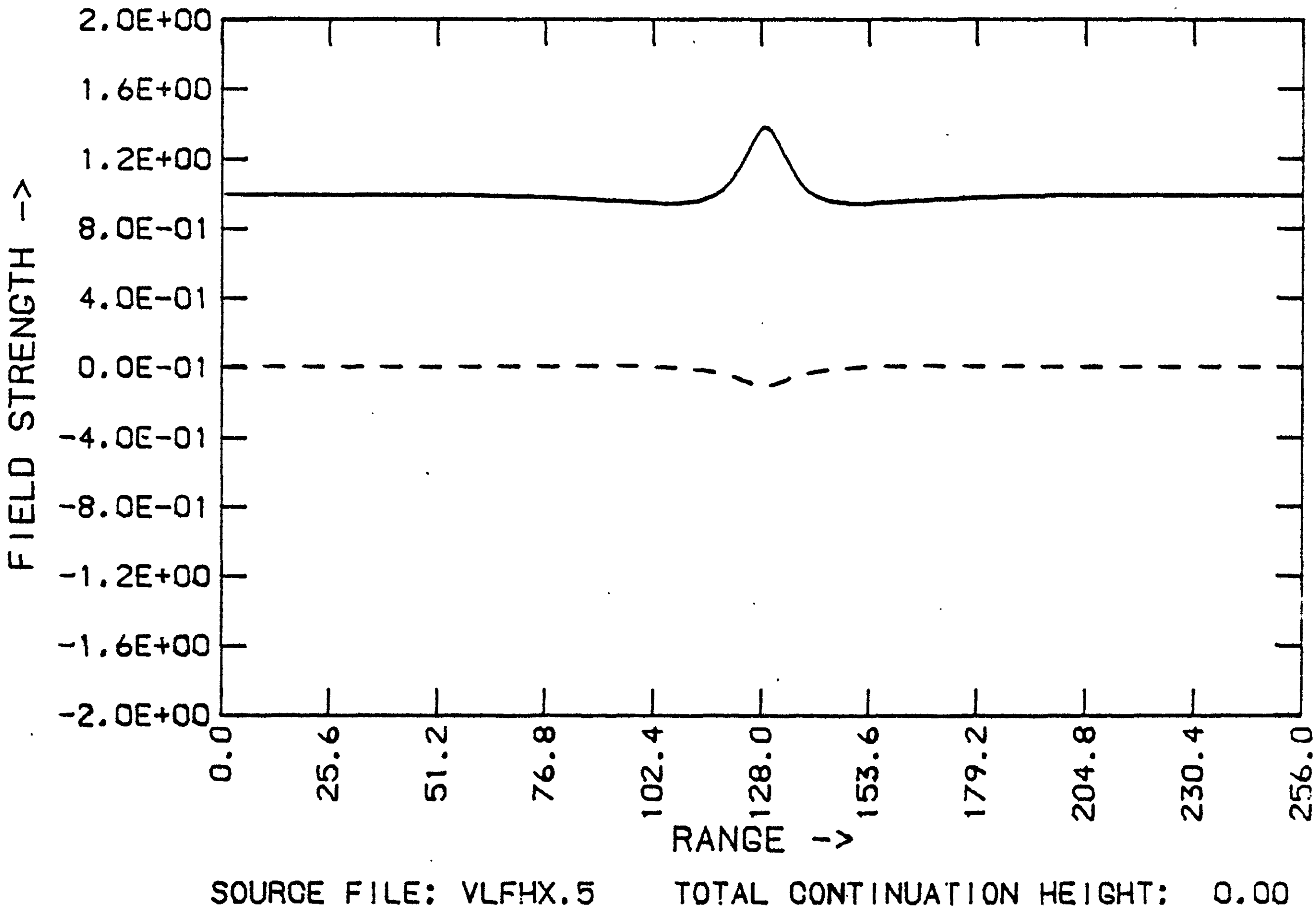


Figure 3 - Measured data, height above conductor = 5 cm. Compare with upward continued data of Fig. 2 and downward continued data of Fig. 4. For explanation of range and field strength units, see p. 16.

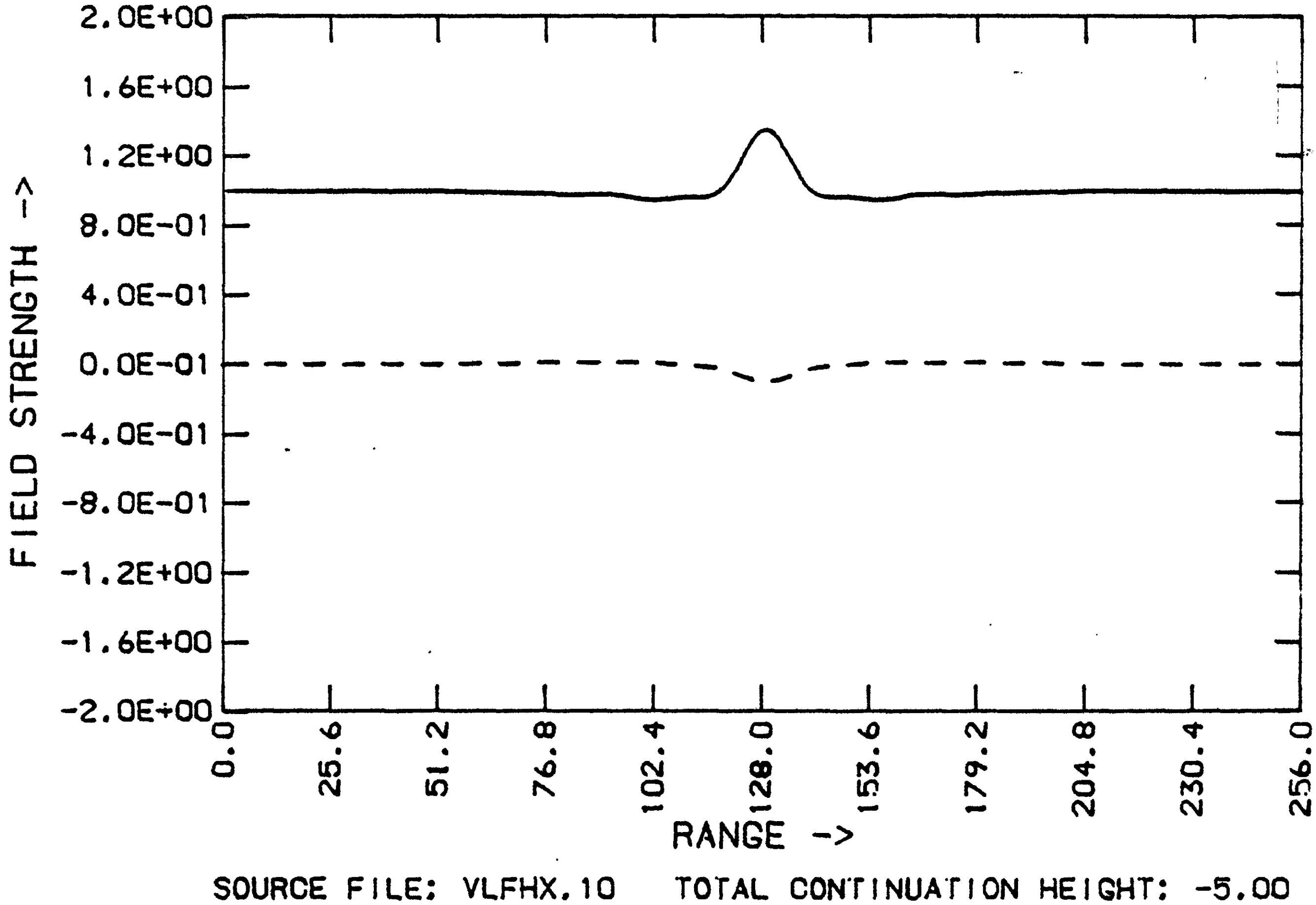


Figure 4 - Measurements at 10 cm. height. Compare with Fig. 3. For explanation of range and and field strength units, see p. 16.

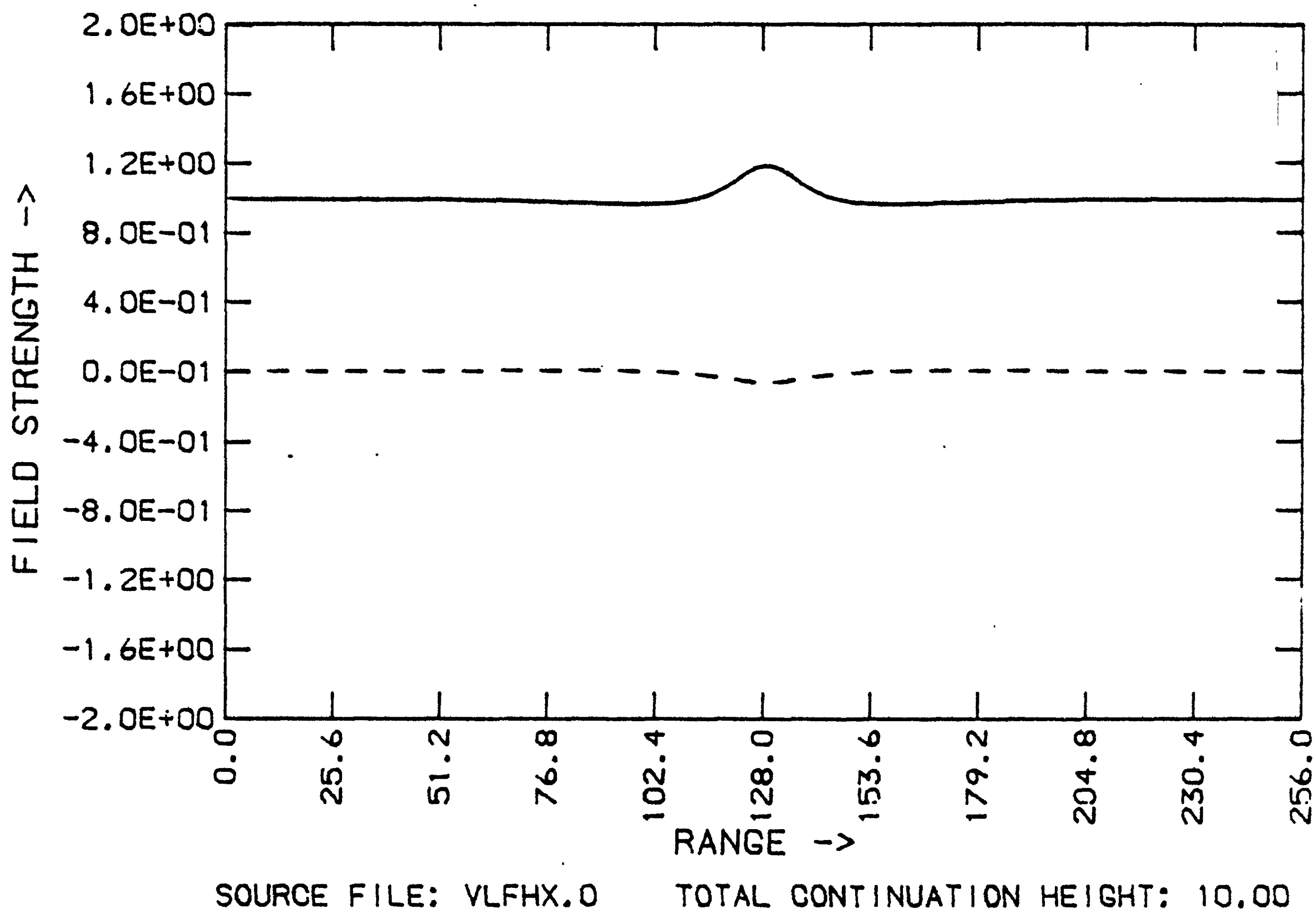


Figure 5 - The data of Fig. 1, upward continued to 10 cm. height. Compare with Fig. 6. For explanation of range and field strength units, see p. 16.

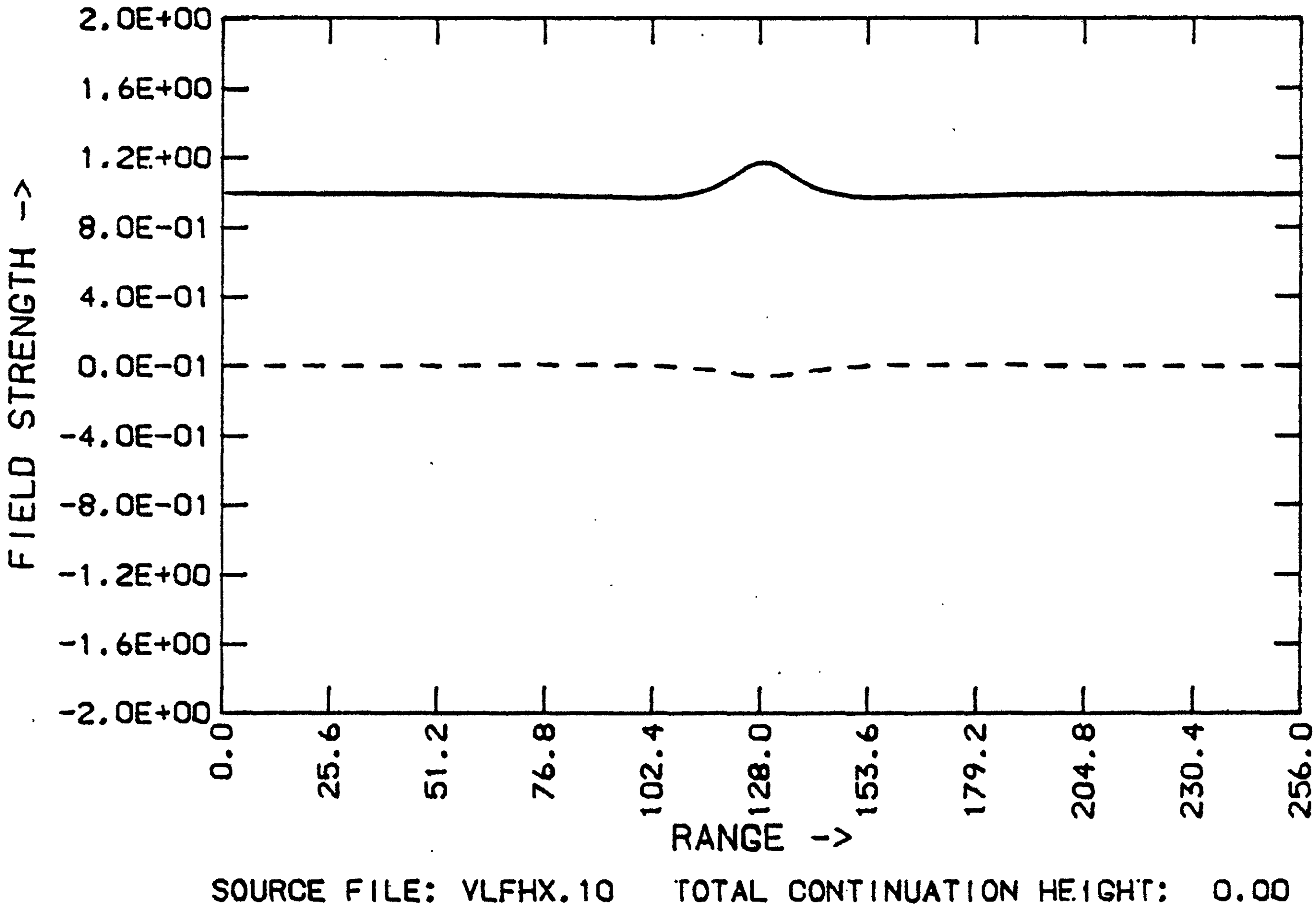


Figure 6 - Measured data, height above conductor = 10 cm.
For explanation of range and field strength units, see p. 16.

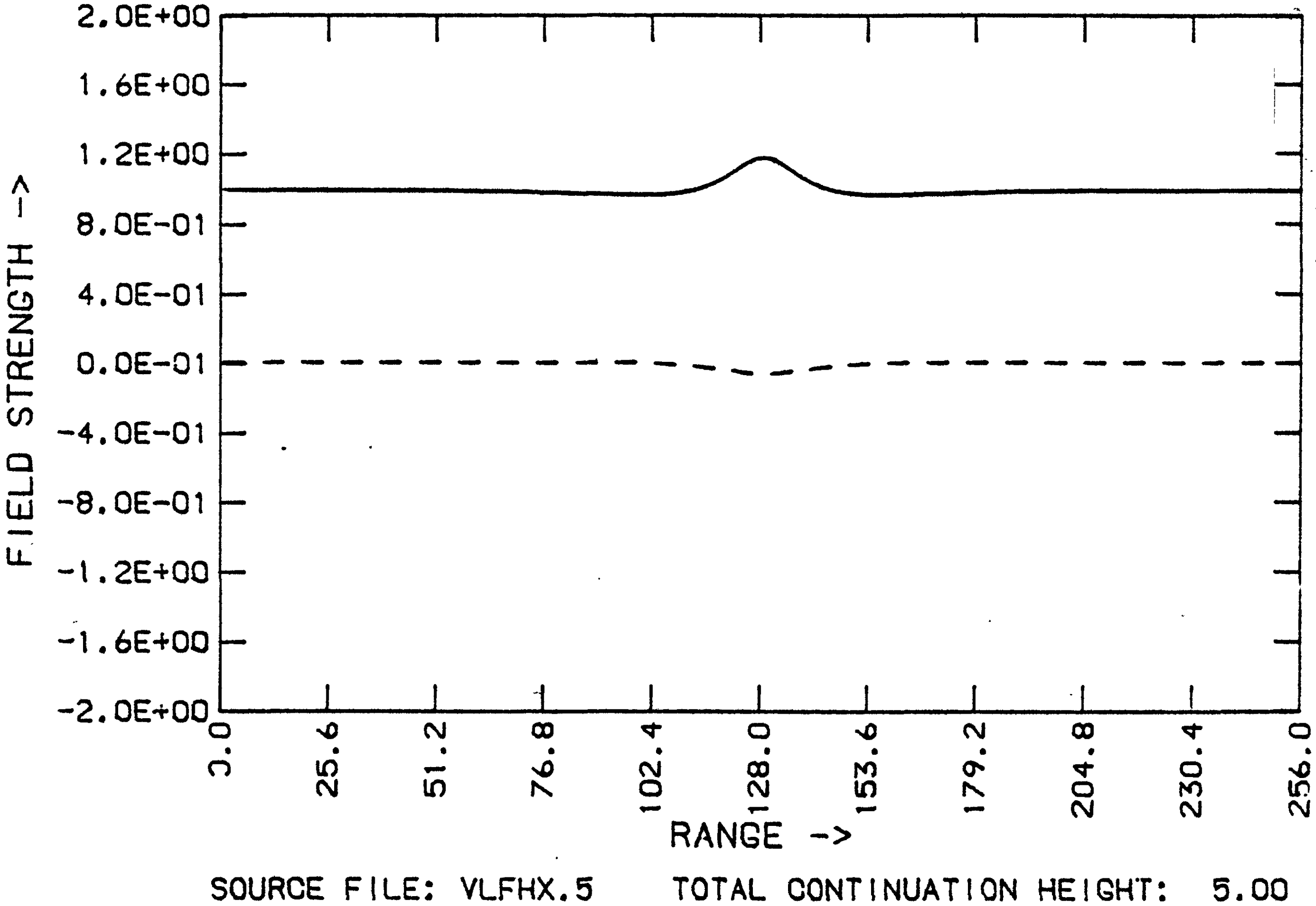


Figure 7 - The data of Fig. 3, upward continued to 10 cm. height. Compare with Fig. 6. For explanation of range and field strength units, see p. 16.