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SIGNAL AVERAGING TECHNIQUE FOR COMPUTATION OF SOME GEOLOGIC LAYER PARAMETERS USING LOW QUALITY SEISMIC REFRACTION DATA

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ABSTRACT

A simple method is described for computation of some geologic layer parameters using low quality seismic refraction data. Based on the basic time-distance equations of refraction seismology, the signal averaging technique achieves improvement in signal-to-noise ratio (SNR) by steering the seismic arrivals from the same subsurface refractor for coherency, sums them up and obtains their average called the beam. Automatic determination of apparent layer velocities is achieved by using a range of trial velocities to steer the signals and determine the velocity which maximizes the beam energy.

A computer program written to perform the signal-averaging was tested on noise-free synthetic data and noisy synthetic data consisting of a simple wavelet to which was added random noise of varying amplitudes. The tests with the noise-free data showed high performance of the technique with relative percentage error ranges of 0.67-4.20, 0.01-3.00, 1.25-3.33 and 0.00-0.20 in velocities, intercept times, layer thicknesses and dips respectively. On the other hand, the test with the noisy data showed that for data with SNR varying between 2.65 and 0.05, the errors in the velocities and intercept times varied between 1 to 6% and 5 to 24% respectively. These results have shown effectiveness of the signal averaging technique in analyzing low quality seismic refraction data.

KEYWORDS: Layer Parameters, Refraction Data, Signal-Averaging, Steering, Beam Energy

INTRODUCTION

Seismic refraction data, if correctly interpreted, can yield valuable information regarding depth and dip of geologic interfaces, fault, lithology, etc. A data set may be wrongly interpreted as a result of wrong choices of first arrival times caused by low signal to noise ratio (SNR). The deterioration in data quality may be due to noise caused by backscattering from near-surface inhomogeneities, source-generated noise, wind noise, noise from fixed machinery, instrument noise, etc (Anderson and McMechan, 1988; Telford et al., 1990). The impact of this unwanted signal on near-surface geophysical data acquired in foundation study, groundwater prospecting, mineral prospecting and similar investigations using seismic refraction method, requires adequate attention as have been done in the oil and gas sector by Brittan et al.(2008); Crider et al.(2008); and Halliday et al.(2008).

This paper presents a processing technique that computes the layer parameters automatically, even in the presence of high level noise. The signal averaging technique involves steering of seismic refraction arrivals by assuming some values for the apparent layer velocities. For each velocity assumed, a beam is formed and its energy computed. In the process of forming the beam, the technique achieves improvement in the SNR resulting in computations of more accurate values for the layer parameters.

Theory

Ojo and Meru (1983) represents each discrete amplitude of seismic data as

$g_{ij} = s_j + n_{ij}$, $i = 1,2,\ldots\ldots M$ and $j = 1,2,\ldots.., N$

where $g_{ij} = j-th$ sample of the data at the $i-th$ geophone

$s_j = j-th$ sample of the signal

$n_{ij} = j-th$ sample of noise at the $i-th$ geophone

$M =$ number of geophones receiving signals from a refractor

$N =$ number of discrete amplitudes per data.

The equation for the beam is then given by

$$B_j = \frac{1}{M}\sum g_{ij}$$

$$\text{or} \quad B_j = s_j + \frac{1}{M}\sum_{i=1}^{M} n_{ij} . \qquad (1)$$

If the noise is adequately random, the second term of equation (1) is approximately zero; that is, $B_j \cong s_j$. The beam energy, defined as sum of its squared amplitudes (Robinson, 1980) is given by $E_B = \sum_{j=1}^{N} B_j^2$.

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The process of signal averaging is based on the time-distance relations of seismic refraction method in which the time-distance (T-X) expression for horizontal three-layer case has been given by Kearey et al (2002) as

$$T = \frac{x}{V_3} + \frac{2z_1\sqrt{V_3^2 - V_1^2}}{V_1V_3} + \frac{2z_2\sqrt{V_3^2 - V_2^2}}{V_2V_3},$$

where V_1,V_2, and V_3 are velocities of the first, second and third layers respectively, while z_1 and z_2 are thicknesses of the first two layers. Hence, for n-th number of horizontal geologic layers, the travel time T_n is given by

$$T_n = \frac{x}{V_n} + \sum_{k=1}^{n-1} \frac{2z_k\sqrt{V_n^2 - V_k^2}}{V_kV_n}. \qquad (2)$$

If the geologic interface dips at an angle α, then the T-X equation (Telford et al, 1990) in equation (2), shooting up dip and shooting down dip, becomes

$$T_u = \frac{x}{V_1}\sin(i_c - \alpha) + \sum_{k=1}^{n-1} 2h_{uk}\frac{\sqrt{V_n^2 - V_k^2}}{V_kV_n} \qquad (3)$$

and

$$T_d = \frac{x}{V_1}\sin(i_c + \alpha) + \sum_{k=1}^{n-1} 2h_{dk}\frac{\sqrt{V_n^2 - V_k^2}}{V_kV_n}. \qquad (4)$$

where h_u and h_d are perpendicular distances from the shot to the interface, while i_c is the critical angle of incidence at the interface between any two layers.

The slope of the straight line graph of either equation (3) or (4) is $\frac{\sin(i_c - \alpha)}{V} = \frac{1}{V_u}$ or $\frac{\sin(i_c + \alpha)}{V} = \frac{1}{V_d}$, while the last term on the right hand side (RHS) of those equations represent intercept times T_i for each segment of the T-X plot (Dobrin and Savit, 1980). Therefore equations (3) and (4) can be re-expressed respectively as

$$T_u = \frac{x}{V_u} + T_{iu} \quad \text{and} \quad T_d = \frac{x}{V_d} + T_{di}. \qquad (5)$$

where V_u and V_d are the corresponding apparent velocities of the layers.

Equation (5) can be generalized as

$$T_i = T - \frac{x}{V_a}, \qquad (6)$$

where T_i, T and V_a denote intercept time, travel time and apparent velocity respectively.

Implementation

The second term to the RHS of equation (6), called steering delay, was used in applying delays to each of the seismic traces (Fig. 1a) to obtain the coherent arrangement of the traces (Fig. 1b). To achieve this, appropriate value of the steering delay computed for individual trace is subtracted from the travel time, T, of the corresponding trace. With the signal perfectly coherent along the refraction branch and the steering delays correctly determined, the energy of the beam is equal to the energy of the individual traces. This condition thus suggested a procedure for the application of the signal averaging technique. First of all, a rough estimate of the refractor velocity was determined from the T-X plot. A range of trial velocities centred at the first estimate was then used in applying appropriate steering to travel times. For each trial velocity used, a beam was

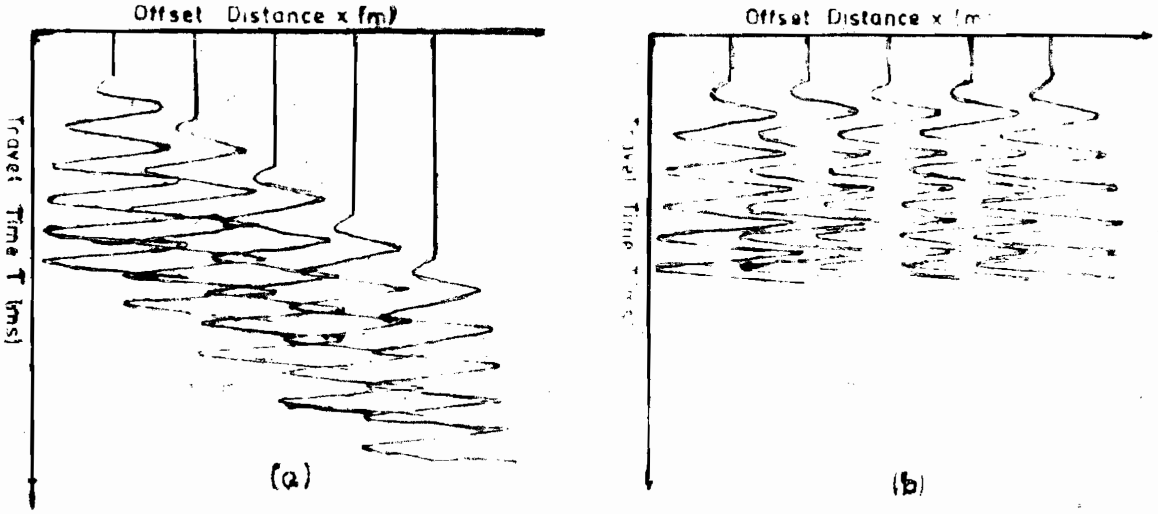

Fig. 1: (a) A typical example of the synthetic section generated
(b) The synthetic section after application of the steering delay

obtained and the beam energy computed. The velocity which corresponded to the maximum beam energy was therefore taken as apparent velocity of the subsurface refractor. Also for every i-th trace steered, a value was obtained for T_i. This value could differ from any other value obtained for another trace by an optimum value of ±0.9ms resulting from rounding up of the figure to a whole number. The values of the T_i corresponding to the segment of the refractor branch were therefore averaged to obtain an accurate intercept time for that segment.

To investigate the performance and feasibility of the signal averaging technique in analyzing seismic refraction data, tests were carried out with the aid of some synthetic data primarily to determine the effectiveness of velocity and intercept time selecting procedure and the accuracy of the automatically computed layer thicknesses and dips using sets of noise-free and noisy synthetic data.

(i) Analysis with noise-free synthetic data

The synthetic data was generated by assuming some layer models (both horizontal and dipping) with assumed layer velocities, thicknesses and dips (where necessary). Travel times for the models were then computed at a set of suitable geophone distances using ray theory (Telford et al, 1990). A set of synthetic sections (see Fig. 1a) were then generated by convolving a 61ms wavelet with the spike sequence corresponding to the travel times using a sampling interval of 1ms. The three models used here were horizontal and dipping two-layer cases and horizontal three layer case. The signal averaging computer program was used to re-compute the values of these model parameters to evaluate its performance. Table 1 shows the results obtained in one of the three models.

Table 1: Performance Test of the Technique on Dipping Two Layer Case

Parameter	Model value of parameter	Calculated value of parameter	Relative % error
Apparent velocity and intercept time			
(2nd layer forward profile):	1499.5ms^{-1},30.9ms	1450.0 ms^{-1},30.0ms	3.3, 3.0
2nd layer reverse profile):	3036.6 ms^{-1},57.9ms	2910.0 ms^{-1},57.0ms	4.2, 1.6
Actual second layer velocity	2000.0 ms^{-1}	1927.8 ms^{-1}	3.6
thick ness of first layer			
(up-dip):	15.0m	14.8m	1.3
(down-dip):	8.0m	7.8m	2.5
Dip	5.0^{0}	4.9^{0}	2.0

Table 2 Performance Test of the Technique on Horizontal Three Layer Case

Parameter	Model value of parameter	Calculated value of parameter	Relative % error
Apparent velocity and intercept time of the second layer			
(forward profile):	1500.00ms^{-1},30.20ms	1490.00 ms^{-1},30.00ms	0.67, 0.01
(reverse profile):	1500.00ms^{-1},30.20ms	1490.00 ms^{-1},30.00ms	0.67, 0.01
Actual second layer velocity	1500.00 ms^{-1}	1490.00 ms^{-1}	0.67
Apparent velocity and intercept time of the third layer			
(forward profile):	3500.00ms^{-1}, 57.70ms	3530.00 ms^{-1}, 58.00ms	0.86, 0.52
(reverse profile):	3500.00ms^{-1}, 57.70ms	3530.00 ms^{-1}, 58.00ms	0.86, 0.52
Actual third layer velocity	3500.00 ms^{-1}	3530.00 ms^{-1}	0.86
Thickness of the first layer	8.00m	7.90m	1.25
Thickness of the second layer	15.00m	14.50m	3.33

(ii) Analysis with noisy synthetic data

A simple two-layer model was used. Assuming first layer thickness of 3m, first and second layer velocities were chosen as 500ms^{-1} and 1000ms^{-1} respectively.

A random number routine (Merchant, 1979) that could generate random numbers between 0 and 1 was used to superimpose various levels of noise on the data. The routine was modified to generate both positive and negative random numbers of any desired amplitudes. The performance of the method was tested quantitatively by computing the layer parameters while various levels of noise were added to the data (see Table 3).

Table 3: Performance Test of the Technique on Noisy Synthetic Data

Parameter	SNR	2.67	0.68	0.17	0.05
	Model value of parameter	Computed values of the parameters with the varying SNR			
Second layer velocity (ms^{-1})	1000.00	1010.00	1030.00	1040.00	1060.00
Relative error(%)	-	1.00	3.00	4.00	6.00
Intercept time(ms)	10.00	10.50	10.80	11.00	12.40
Relative error(%)	-	5.00	8.00	10.00	24.00
Thickness of top layer	3.00	3.02	3.09	3.14	3.52
Relative error(%)	-	0.67	3.00	4.70	17.33

DISCUSSION, RECOMMENDATIONS AND CONCLUSION

Analysis with the noiseless synthetic data showed high performance of the technique with relative percentage error ranges of 0.67 - 4.20, 0.01 - 3.00, 1.25 – 3.33 and 0.00 – 0.20 in the velocities, intercept times, layer thicknesses and dips respectively. The deviations in values of the parameters computed from those of the starting model, as the noise level increased or as the SNR decreased, was then considered a measure of the accuracy of the technique. Using these deviations, the relative percentage errors in each of the computed parameters was determined (see Table 3). The table shows higher errors in the computed parameters with decreasing SNR.

The results obtained shows that the signal averaging technique can be reliably used in interpreting noisy seismic refraction data acquired for the near-surface geophysical studies but with the following limitations:

(i) inability of the technique to cancel out coherent noise

(ii) It makes use of ranges of trial velocities from manual T-X plots.

Further studies are thereby recommended on how the signal averaging technique can be used to automatically determine the group of seismic traces that should belong to the same refractor by examining some characteristics of the individual traces. It is also recommended that other noise adaptive methods (Telford et al, 1990) be used in an area known for high level of coherent noise.

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APPENDIX

PROGRAME ARRAY

```
C   IMPUT:
C             NCH       NO OF TRACES TO BE USED
C             NPT       NO OF POINTS USED TO FORM BEAM
C             NTRACE    NO OF POINTS DIGITIZED
C             DT        DIGITIZING INTERVAL
C            VSTRT      INITIAL TRIAL VELOCITY
C            VSTOP      FINAL TRIAL VELOCITY
C            DV         VELOCITY INCREMENT FO ANALYSIS
C            X(I)       DISTANCE OF I-TH TRACE FROM SHOT POINT
C           TSTRT(I)    TIME OF FIRST NON ZERO AMPLITUDE ON I-TH TRACE
C            CHA(I)     DIGITIZED VALUES FOR I-TH TRACE
C   OUTPUT:
C               STEERING VELOCITY AND CORRESPONDING BEAM ENERGY
     DIMENSION TIT(20), X(12), TSTRT(12), CHA(12,200)
     OPEN (UNIT = 6, FILE='OUT2')
C
C   READ IN DATA COMMON TO BOTH FORWARD AND REVERSE PROFILES
C
    WRITE(*,*) 'PROVIDE THE 1ST LAYER VELOCITY.'
    WRITE(*,*)
    READ(*,*)VI
C
C    PRINT INPUT CONTROL DATA
C
     CALL VAIT(NCH,NPT,NTRACE,DT,VSTRT,VSTOP.DV.X,TIT,TSTRT,VF2,TF2)
     WRITE(6,10)(TIT(I),I=1,20)
     WRITE(6,15)NCH,NPT,NTRACE
     WRITE(6,20)DT,VSTRT,VSTOP.DV
     WRITE(6,25)
     DO 105 I=1,NCH
105  WRITE(6,30)I,X(I),TSTRT(I)
     WRITE(6;32)VF2,TF2
    CALL VAIT(NCH,NPT,NTRACE.DT,VSTRT,VSTOP,DV,X,TIT,TSTRT,VR2,TR2)
     WRITE(6,10)(TIT(I),I=1,20)
     WRITE(6,15)NCH,NPT,NTRACE
     WRITE(6,20)DT,VSTRT,VSTOP,DV
     WRITE(6,25)
     DO 106 I=1,NCH
106  WRITE(6,30)I,X(I),TSTRT(I)
     WRITE(6,34)VR2,TR2
C
     IF(VR2-VF2)114,116,118
C
114  VU2=VF2
      VD2=VR2
```

```
      TU2=TF2
      TD2=TR2
      GO TO 102
116   VH=VF2
      TH=TF2
      GO TO 102
118   VU2=V2
       VD2=VF2
       TU2=TR2
       TD2=TF2
 102   CONTINUE
C
C      COMPUTE ACTUAL LAYER VELOCITY(2), DEPTH(S) OF THE 1ST
INTERFACE
C       AND ANY LIKELY DIP OF THE LAYER(DIP1)
C
        XT=110.0
        PIE=3.141592654
        VUA=V1/VU2
        VDA=V1/VD2
C
      C12=ASIN(VUA)+ASIN(VDA)*0.5
C
      V2=V1/SIN(C12)
      H1U=(V1*TU2)/((2.0*COSC12))*1000.0
      HD1=(V1*TD2)/((2.0*COS(C12))*1000.0)
C
      ARG=(H1U-H1D)/XT
C
      DIP1=ATAN(ARG)
      DIP1D=(DIP1*180.0)/PIE
C
      CALL VAIT(NCH.NPT.NTRACE,DT,VSTRT,VSTOP.DV.X.TIT.TSTRT.VF3.TF3)
      WRITE(6,10)(TIT(I),I=1.20)
      WRITE(6.15)NCH.NPT.NTRACE
      WRITE(6.20)DT.VSTRT.VSTOP.DV
      WRITE(6.25)
      DO 107 I=1,NCH
107   WRITE(6,30)I.X(I).TSTRT(I)
      WRITE(6.44)VF3.TF3
     CALL VAIT(NCH.NPT.NTRACE.DT,VSTRT.VSTOP.DV.X.TIT.TSTRT.VR3.TR3)
      WRITE(6.10)(TIT(I),I=1,20)
      WRITE(6.15)NCH.NPT,NTRACE
      WRITE(6.20)DT.VSTRT,VSTOP.DV
      WRITE(6,25)
      DO 108 I=1.NCH
```

```
108   WRITE(6,30)I,X(I),TSTRT(I)
      WRITE(6,46)VR3,TR3
C
           IF(VR3-VF3)224,226,228
C
224   VU3=VF3
       VD3=VR3
       TU3=TF3
       TD3=TR3
       GO TO 202
226    VH3=VF3
      TH3=TF3
      GO TO 202
228    VU3=VR3
        VD3=VF3
        TU3=TR3
        TD3=TF3
 202  CONTINUE
 C
        VUB=V1/VU3
         VDB=V1/VD3
C
       C13D=ASIN(VUB)+DIP1
       C13U=ASIN(VDB)-DIP1
C
       VRA=V2/V1
       VSU=VRA*SIN(C13U)
       VSD=VRA*SIN(C13D)
        C23=0.5*(ASIN(VSU)+ASIN(VSD))
C
        DIP2=(0.5*((ASIN(VSU)-ASIN(VSD)+(2.0*DIP1)))
        DIP2D=(DIP2*180.0)/PIE
C
       HEU=(H1U*COS(C13U)+COS(C13D))/V1
       H2U=(V2*TU3*0.001)-HEU))/((2.0*COS(C23))
       HED=(HID*(COS(C13U)+COSC13D))/V1
       H2D=(V2*((TD3*0.001)-HED))/(2.0*COS(C23))
C
       V3=V2/SIN(C23)
C
        WRITE(6,48)V1
        WRITE(6,50)V2,V3
        WRITE(6,52)H1U,H2U
        WRITE(6,54)H1D,H2D
        WRITE(6,56)DIP1D,DIP2D
C
```

```
C   WHERE V1,V2,V3 ARE VELOCITIES OF 1ST, 2ND, AND 3RD LAYERS
RESPECTIVELY
C    H1U AND H2U ARE DEPTHS OF 1ST AND 2ND INTERFACES SHOOTING UPDIP
C    HID AND H2D ARE DEPTHS OF 1ST AND 2ND INTERFACES SHOOTING
DOWNDIP
C    AND DIP1D AND DIP2D ARE DIPS OF 2ND AND 3RD LAYERS.
C
          STOP
10        FORMAT(1X,20A4/)
15        FORMAT(1X,'NO OF TRACES=',15,3X,'NO OF POINTS/BEAM=', 15,3X,'N
    10 OF POINTS IN TRACE='15)
20        FORMAT(1X,'SAMPL.INT.=',F5.1,3X,'VSTRT,VSTOP=',2FB.1,3X,'VEL
      1 INCREMENT=',F5.1)
25        FORMAT(16X,'CHANNEL      DISTANCE      START        TIME')
30        FORMAT(16X,15,9X,F5.1,9X,F5.1)
32        FORMAT(14X,'2ND LAYER (F.PROF)VEL=',F6.1,1X,'TM INTER.=',F6.2///)
34        FORMAT(14X,'2ND LAYER (R.PROF)VEL=',F6.1,1X,'TM INTER.=',F6.2///)
44        FORMAT(14X,'3RD LAYER (F.PROF)VEL=',F6.1,5X,'TM INTER.=',F6.2///)
46        FORMAT(14X,'3D LAYER (R.PROF)VEL=',F6.1,5X,'TM INTER.=',F6.2///)
48        FORMAT(27X,'V1=',F5.1/)
50        FORMAT(20X,'V2=',F6.1,5X,'V3=',F6.1)
52        FORMAT(20X,'H1U=',F5.2,5X,'H2U=',F5.2/)
54        FORMAT(20X,'H1D=',F5.2,5X,'H2D=',F5.2/)
56        FORMAT(20X,'DIP1D  ',F5.2,5X,'DIP2D=',F5.2/)
          END

CALL VAIT(NCH,NPT,NTRACE,DT,VSTRT,VSTOP,DV,X,TIT,TSTRT,VM,T1)
 DIMENSION TIT(20), X(12), TSTRT(12), CHA(12,200),CHT(12,200),BEAM(200)
 OPEN (UNIT = 5, FILE='I.DAT')
C
C    READ IN INPUT DATA
C
       READ(5,1)(TIT(I),I=1,NCH)
       READ(5,2)NCH,NPT,NTACE
       READ(5,3)DT,VSTRT,VSTOP,DV
C
       DO 100 I=1,NCH
       READ(5,4)X(I),TSTRT(I)
100  CONTINUE
C
C     ZERO ALL CHANNELS
C
        V=VSTRT
        DO 112 I=1,NCH
        DO 11O J=1, NPT
110     CHA(I,J)=0.0
112     CONTINUE
```

```
C
C     DREAD IN AND APPLY STEERING DELAYS TO DIGITIZED TRACES
C
      BEAMX=0.0
121   SIT=0.0
      DO 125 I=1,NCH
      DO 125 J=1,NPT
125   CHT(I,J)=0.0
      DO 126 J=1,NPT
126   BEAM(J)=0.0
C
      DO 120 I=1,NCH
      NSTRT=IFIX((TSTRT(I)/DT)+0.5)
      NEND=NSTRT+NTRACE-1
      IF(V.GT.VSTRT) GO TO 128
      READ(5,5)(CHA(I,J),J=NSTRT,NEND)
128   TCOR=(X(I)/V)*1000.0
      ICOR=IFIX((TCOR/DT)+0.5)
      DO 130 J=NSTRT,NPT
      K=J-ICOR
      CHT(I,K)=CHA(I,J)
130   CONTINUE
120   CONTINUE
C
      DO 140 I=1,NCH
      DO 140 J=1,NPT
      BEAM(J)=BEAM(J)+CHT(I,J)
140   CONTINUE
      BEAMP=0.0
      D0 150 J=1,NPT
      BEAM(J)=BEAM(J)/FLOAT(NCH)
150   BEAMP=BEAMP+(BEAM(J)*BEAM(J))
C
      IF(BEAMX.GT.BEAMP)GO TO 155
      BEMAX=BEAMP
      VM=V
C
      MM=0
152   MM=MM+1
      DO 153 J=MM,NPT
      TNE=0.0
      TPO=0.0
      IF(ABS(BEAM(J)).GT.0.0)GO TO 200
153   CONTINUE
C
200   INTER=J
      NEND+INTER+5
```

```
C
210   INEG=INTER+1
      DO 220 K=INEG,INEND
      IF(BEAM(K).EQ.0.0.OR.BEAM(K).GT.0.0)GO TO 152
220   CONTINUE
      TNE=FLOAT(INTER)
      GO TO 500
C
250   INPOS=INTER+1
      DO 270 KK=INPOS,INEND
      IF(BEAM(KK).EQ.0.0.OR.BEAM(KK).LT.0.0)GO TO 152
270   CONTINUE
      TPO=FLOAT(INTER)
500   TI=TNE+TPO
C
155   V=V+DV
      IF(VSTOP-V)160,121.121
160   CONTINUE
C
1     FORMAT(20A4)
2     FORMAT(315)
3     FORMAT(F5.1.1X.F6.1,1X,F6.1.1X.F5.1)
4     FORMAT(F5.1,1X.F5.1)
5     FORMAT(10F8.1)
C
      RETURN
      END
```