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July 1981

Numerical Deconvolution to Obtain Cloud Signatures from Scattered Light Pulses

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TO: Recipients of HDL-CR-81-100-1

Please show the following corrections in subject report.

Page 8, paragraph 2, line 9

[$C(x_i)$ = 0.15 m] should read $C(x_i$ = 0.15 m)

Page 8, paragraph 2, line 11

$C(x)$ should read $C(x_i)$

Page 9, line 3

$C(x_{100})$ = 15 m should read $C(x_{100}$ = 15 m)

FOR THE COMMANDER:

NELDA H. McNEIL
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REPORT DOCUMENTATION PAGE

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The optical return pulse resulting from light reflected from a cloud is given by a convolution of the transmitted pulse with the system range response and the cloud signature. To calculate the cloud signature when everything else is known requires a deconvolution. Since this deconvolution enhances noise, it is very difficult to get better resolution in the cloud signature than the 1 to 2 m that is immediately available by dividing

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20. ABSTRACT (Cont'd)

the return pulse by the range response. (This relatively good resolution is available in this way because the transmitted pulse is fairly short, being about 6 ns FWHM.) It is shown that modestly improved resolution is possible if the signal to noise ratio in the return pulse is greater than about 100 to 1.

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FIGURES (Cont'd)

1. PROBLEM

Optical pulses that result from the reflection of GaAs laser pulses from water clouds have been measured. The amplitude of the return pulse as a function of time, $V(t)$, depends on the transmitted laser pulse, $P(t)$; the overall system sensitivity as a function of distance (range response) $R(x)$; and the optical properties of the cloud. For the present purpose, the properties of the cloud along the pencil beam path of the optical probe can be described by a single function, $C(x)$, the cloud signature.[1,2] Light arriving at the detector at time t must have been transmitted at an earlier time, $t - \tau$ $(\tau > 0)$. τ is the time that it takes light at speed c to travel from the transmitter to the point of reflection (distance = x) and then back to the detector, which is near the transmitter. Therefore,

$$\tau = 2x/c \quad . \tag{1}$$

All pairs of τ and x such that τ 0 and equation (1) holds will contribute to the return at time t, with the contribution weighted according to the system range response at the distance x and the cloud signature at that location. Therefore, the total return is given by the convolution

$$V(t) = K \int_0^\infty P(t - \tau)R(x)C(x)\, d\tau \quad , \quad x = c\tau/2 \quad , \tag{2}$$

where K is for normalization.

The purpose of this study is to investigate a method for finding $C(x)$ given $V(t)$, $P(t)$, and $R(x)$. $P(t)$ and $R(x)$ are constant functions of the system. $V(t)$ has been measured for a large number of pulses.

One method for solving for $C(x)$ in equation (2) is as follows.[2] Using the notation of McGuire,[2] let

$$h(t) = K \cdot C(ct/2) \cdot R(ct/2) \quad . \tag{3}$$

Now, to consider equation (2) numerically, let

$$t = n \cdot \Delta t \quad , \qquad \tau = i \cdot \Delta t \quad .$$

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[1] *H. H. Burroughs, Computation of Cloud Backscatter Power as a Function of Time for an Active Optical Radar (U), Naval Weapons Center NWC TP 5090 (April 1971). (CONFIDENTIAL)*

[2] *Dennis McGuire and Michael Conner, The Deconvolution of Aerosol Backscattered Optical Pulses to Obtain System-Independent Aerosol Signatures, Harry Diamond Laboratories HDL-TR-1944 (June 1981).*

The integral then becomes a sum:

$$V(n\cdot\Delta t) = \Delta t \sum_{i=1}^{n} P((n - i)\Delta t)\cdot h(i\Delta t) \quad . \tag{4}$$

The upper limit equals n because P = 0 for $t \leq 0$. Thinking of V and h as vectors, the notation becomes

$$\vec{V} = \Delta t \cdot P\vec{h} \quad , \tag{5}$$

where

$$P = \begin{pmatrix} P(\Delta t) & 0 & 0 & \cdots & 0 \\ P(2\Delta t) & P(\Delta t) & 0 & \cdots & 0 \\ P(3\Delta t) & P(2\Delta t) & P(\Delta t) & \cdots & 0 \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & & \cdot \\ P(n\Delta t) & P((n-1)\Delta t) & \cdots & & P(\Delta t) \end{pmatrix} .$$

The problem of solving for C(x) (by here solving for h) then becomes one of matrix inversion. The solution to equation (5) is

$$\vec{h} = (1/\Delta t)P^{-1}\vec{V} \quad . \tag{6}$$

Equation (6) does not give satisfactory results[2] if V contains noise. This failure is probably because the form of P(t) causes some large elements to appear in P^{-1}, giving too much significance to some small variation in V due to noise. It is not surprising that there is some difficulty related to dealing with P^{-1}. This difficulty is because the determinant of P is $[P(\Delta t)]^n$, which is very small since $P(\Delta t)$ is the first nonzero point of the transmitted pulse. One might easily expect this problem from another point of view; namely, since the convolution of C (eq. 2) will smooth out small bumps in C, the deconvolution of V using the same equation will badly exaggerate small bumps (noise).

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[2] *Dennis McGuire and Michael Conner, The Deconvolution of Aerosol Backscattered Optical Pulses to Obtain System-Independent Aerosol Signatures, Harry Diamond Laboratories HDL-TR-1944 (June 1981).*

A way to avoid all such difficulty is to make the approximation that $P(t) = A \cdot \delta(t - t_o)$, where A is a normalization constant and t_o is the center of the transmitted pulse. Then equation (2) immediately yields

$$C\left[\frac{c\left(t - t_o\right)}{2}\right] = \frac{V(t)}{K \cdot A \cdot R\left[\frac{c(t - t_o)}{2}\right]} \quad . \tag{7}$$

This discards all information about the shape of the transmitted pulse, thus reducing the resolution in C(x) to about 1 to 2 m since the transmitted pulse has a full width at half maximum (FWHM) of about 6 ns.

2. DESCRIPTION OF METHOD

In this investigation, equation (7) is used as a first approximation to C(x). Since one desires a cloud signature with better than the 1- to 2-m resolution achieved by using equation (7), some effort is then made to modify C(x) to find a more accurate cloud signature. In this discussion, a more accurate (or "better") cloud signature refers to a signature with a smaller error, where error is defined as follows: Insert the cloud signature currently being considered into equation (2) to calculate the return pulse (V_c, subscript c for calculated) that would result from that signature. Compare that with the measured return pulse (V_m) defining

$$\text{error} = \int \left[V_m(t) - V_c(t)\right]^2 dt \quad . \tag{8}$$

Various functions (as discussed later) are tried for C(x), and the C(x) that gives the smallest error is recorded as the extracted cloud signature.

Now, equation (6) immediately gives the cloud signature with error = 0, but that signature is noise dominated nonsense.[2] Here, then, one is not seeking the absolute minimum in the error (which would be zero), but rather one seeks a relative minimum in error by varying C(x) in some gentle way about the δ (delta) extracted (eq. 7) first guess.

The following measures are available to prevent the cloud signature from becoming wildly bumpy:

a. Restrict how far the successive estimates of C(x) can vary from the original δ extracted C(x).

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[2] *Dennis McGuire and Michael Conner, The Deconvolution of Aerosol Backscattered Optical Pulses to Obtain System-Independent Aerosol Signatures, Harry Diamond Laboratories HDL-TR-1944 (June 1981).*

b. Subject the return pulse, $V_m(t)$, to a low-pass filter.

c. Subject the final answer for C(x) to a low-pass filter.

The severity of each of these restrictions is easily varied. It was hoped that with these restrictions a relative minimum in the error could be found associated with some reasonable cloud signature that would have the same gross properties as the delta extracted signature, but with sharper features. Before sample calculations were carried out, it was not clear whether restrictions and filtering (measures a to c) adequate to smooth out the noise would simultaneously doom resolution to worse than 1- to 2-m resolution of the delta function case. If filtering alone (b and c) can successfully suppress the noise in a given data bank while still allowing improved resolution (this would depend chiefly on the signal to noise ratio for that data), then one may consider using equation (6) after all, with the appropriate filtering of V(t) and C(x). On the other hand, if the a priori assumption that the desired cloud signature closely resembles the delta extracted signature is essential, then the method described below may be useful.

In the present method, the calculations are done by computer. The cloud signature, C(x), is in digitized form with 100 values for C. These values are at 0.15-m intervals in distance (x), covering a total of 15 m. The first estimate of C(x) is provided by the delta function method; that is, equation (7) is used for 100 values of t (corresponding to 100 values of x with $x = ct/2$). The various values of C(x) are then varied in an effort to find a C(x) with a smaller error (as defined above). The variation of C proceeds as follows: For a chosen initial value of Q ($Q > 1$), begin with the first point [$C(x_i) = 0.15$ m] and consider the following five possibilities:

a. Leave C(x) unaltered.

b. Multiply $C(x_i)$ by Q.

c. Divide $C(x_i)$ by Q.

d. Multiply $C(x_i)$ by Q and decrease the next value, $C(x_{i+1})$, by the amount by which $C(x_i)$ increased.

e. Divide $C(x_i)$ by Q and increase $C(x_{i+1})$ by the amount by which $C(x_i)$ decreased.

(Choices d and e are motivated by the consideration that they leave the integrated return less changed; since the original guess had approximately the correct total energy, these possibilities are probably desirable.) One then takes whichever of the five resulting cloud signatures that has the lowest associated error and considers it to be the current (or "new and improved") cloud signature. This variational method is then repeated for the next point and successive points through $C(x_{100}) = 15$ m. This constitutes one pass. If after any pass the error is smaller than it was at the beginning of the pass, it is deemed worthwhile to make another pass by using a smaller value of Q,

$$Q_{new} = (nQ + 1)/(n + 1) \ , \ n > 0 \ ,$$

to achieve finer variations in C(x). The flow chart and coding for the computer program that carries out this procedure are shown in appendices A and B, respectively. The values for n and the initial Q can be specified as desired for each computer run. The particular values of Q_1 ($= Q_{initial}$) and n that were used to generate the examples in this report are given in appendix C. The cloud signature is constrained to vary only within a certain region because no value of C could be multiplied or divided by more than approximately $Q_1 \cdot Q_2 \cdot Q_3 \cdot \ldots \cdot Q_\infty$, and this product has a finite value depending on Q_1 ($= Q_{initial}$) and n (see app D).

In this way, C(x) varies until some relative minimum in the error is found. When a pass is executed (one Q, all 100 points) with no decrease in the error, the process is stopped and the cloud signature is recorded.

3. RESULTS

The characteristics of the signature found by this method depend critically on the signal to noise ratio of the return signal, V(t), as the following examples show.

3.1 Case I

An idealized cloud with the backscatter coefficient proportional to the extinction coefficient[3] and extinction coefficient profile as shown in figure 1 results in the cloud signature shown in figure 2. Here one assumes[1,2]

$$C(x) = \mu(x) e^{-2\int_0^x \sigma(s)\, ds} \ .$$

[1]*H. H. Burroughs, Computation of Cloud Backscatter Power as a Function of Time for an Active Optical Radar (U), Naval Weapons Center NWC TP 5090 (April 1971). (CONFIDENTIAL)*

[2]*Dennis McGuire and Michael Conner, The Deconvolution of Aerosol Backscattered Optical Pulses to Obtain System-Independent Aerosol Signatures, Harry Diamond Laboratories HDL-TR-1944 (June 1981).*

[3]*D. Deirmendjian, Electromagnetic Scattering on Spherical Polydispersions, American Elsevier, New York (1969). The ratio of backscatter coefficient to extinction coefficient depends on the wavelength of the radiation and the aerosol particle size distribution. If the latter is a locally homogeneous property of the cloud, μ/σ (backscatter/extinction coefficients) will be constant.*

The return pulse (calculated by a straightforward convolution, eq 2) that would result from such a cloud was subjected to the present signature extraction algorithm. The algorithm includes filtering out high frequency bumps in the return pulse and signature. The resulting extracted signature (fig. 3) is relatively close to the actual signature and provides better resolution of the sharp peak than the delta function extracted signature (fig. 4).

Noise in the return signal becomes exaggerated on deconvolution. This exaggeration means that the signature extraction becomes less reliable as the signal to noise ratio decreases. To demonstrate this effect, the return pulse from the idealized cloud has been corrupted with noise and the signature extraction has been attempted again. The results for a signal to noise ratio of about 100 to 1 are shown in figures 5 and 6 and for a signal to noise ratio of about 40 to 1 are shown in figures 7 and 8. For a signal to noise ratio of 100 to 1, the initial rise and sharp peak are just slightly more accurate than the delta function was, but a large amount of noise has shown up in the exponentially decaying tail. For a signal to noise ratio of about 40 (fig. 6), the situation is worse.

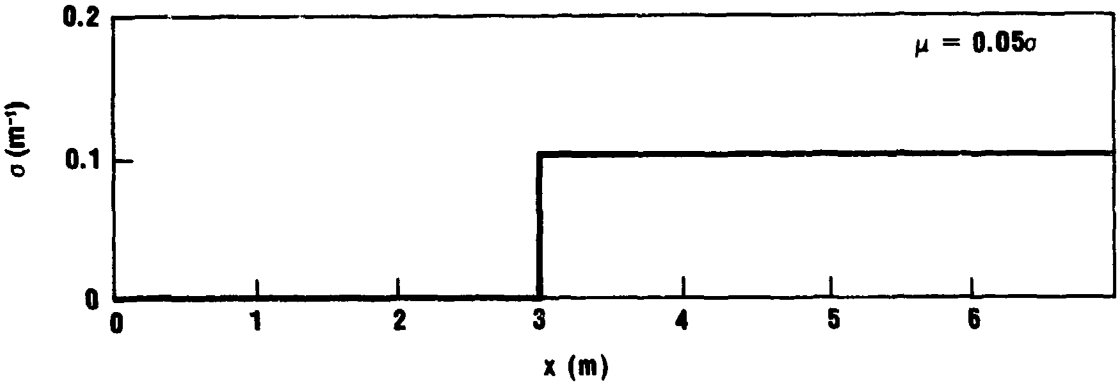

Figure 1. Case I: extinction coefficient.

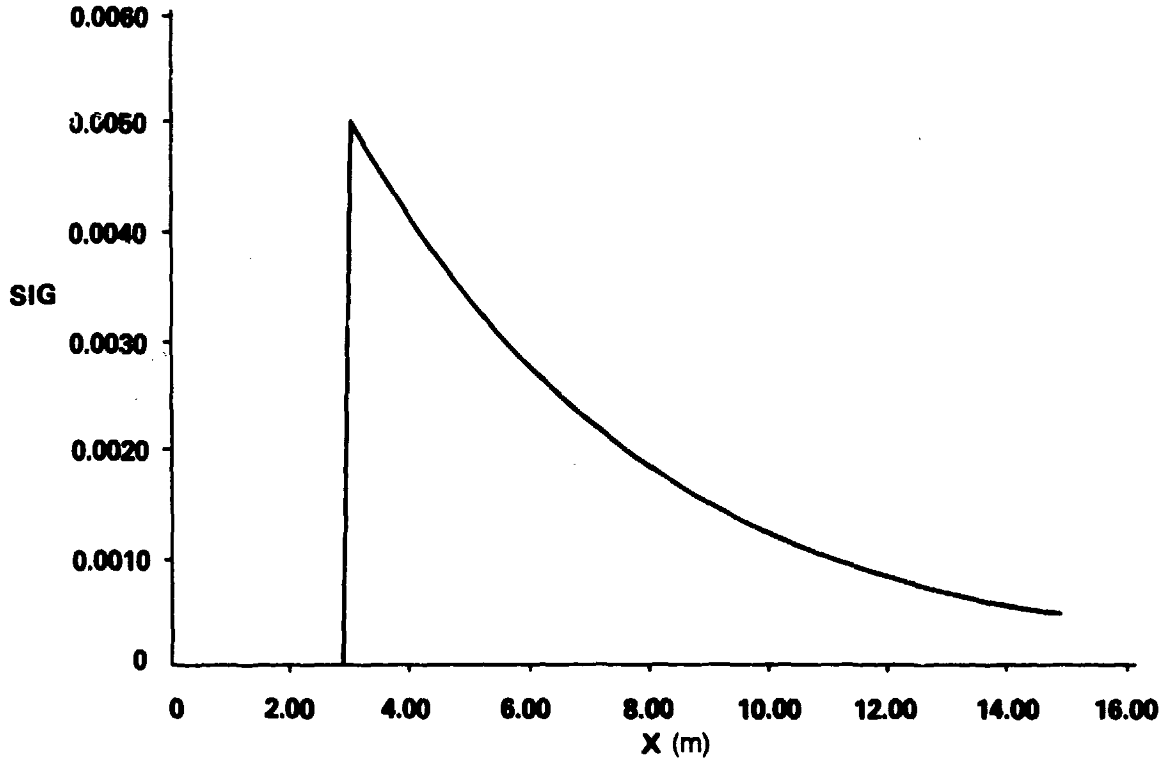

Figure 2. Case I: cloud signature.

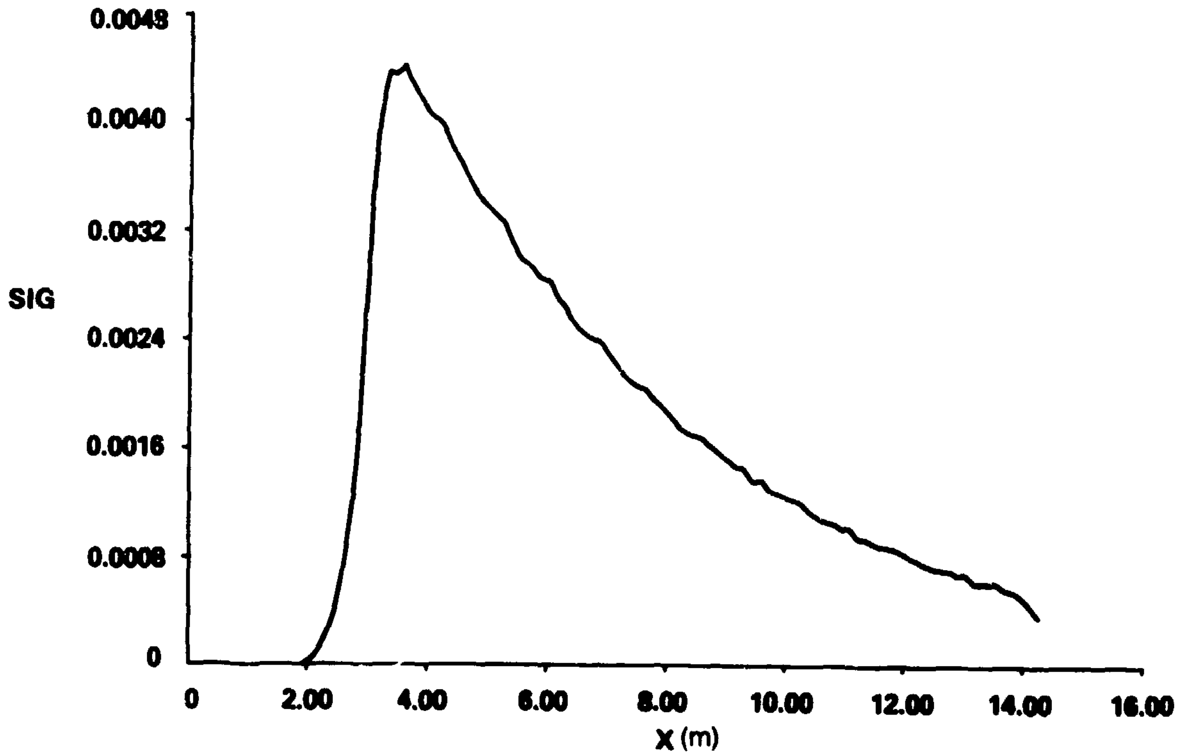

Figure 3. Case I: extracted cloud signature (noiseless return pulse).

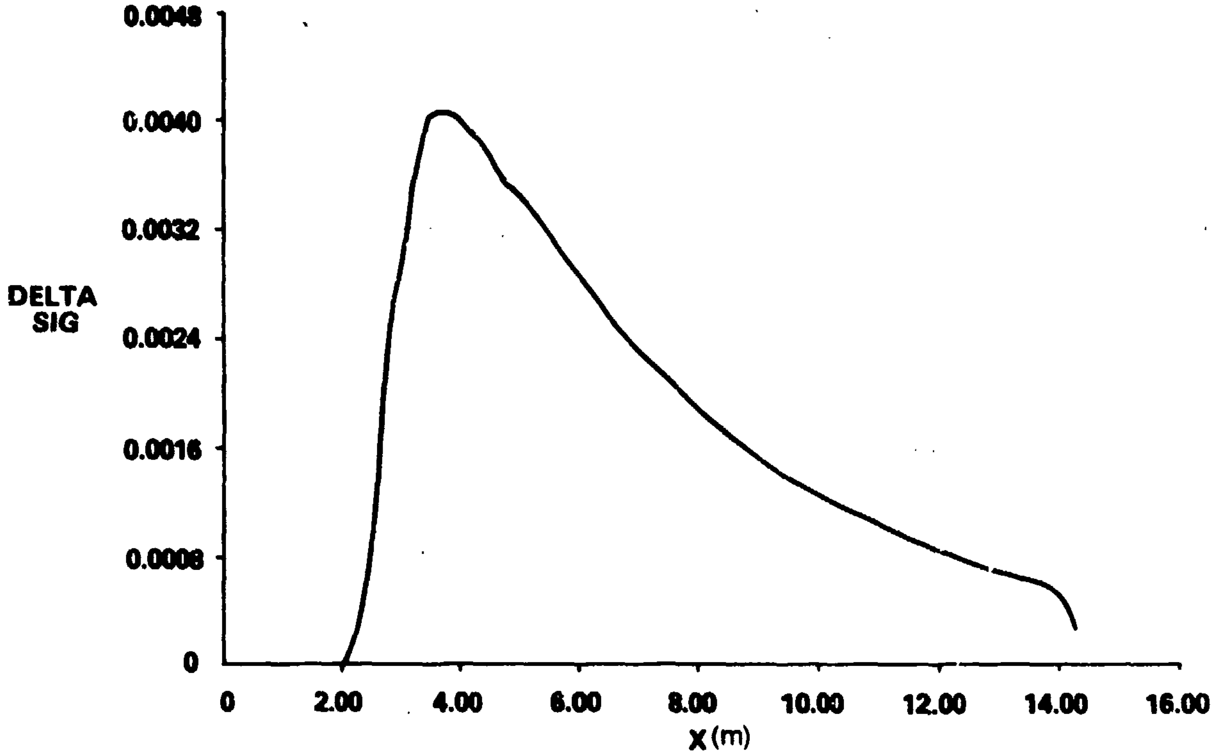

Figure 4. Case I: delta extracted cloud signature (noiseless return pulse).

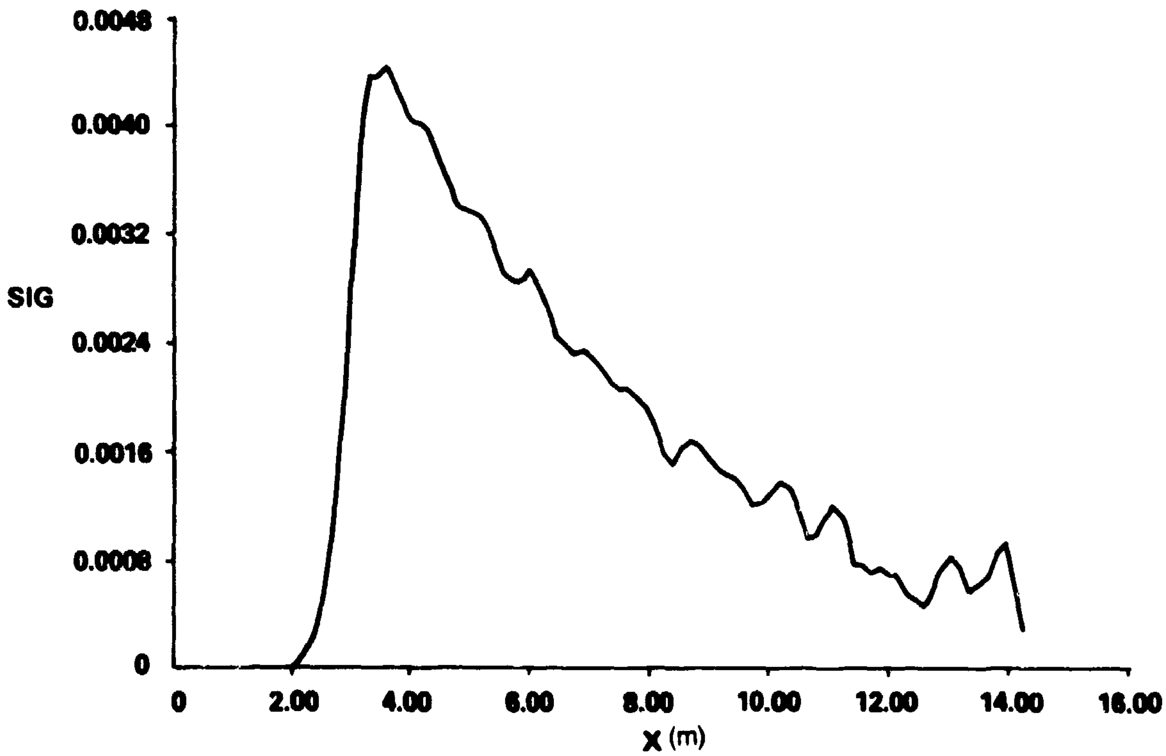

Figure 5. Case I: extracted cloud signature (return pulse signal to noise ratio ~ 100).

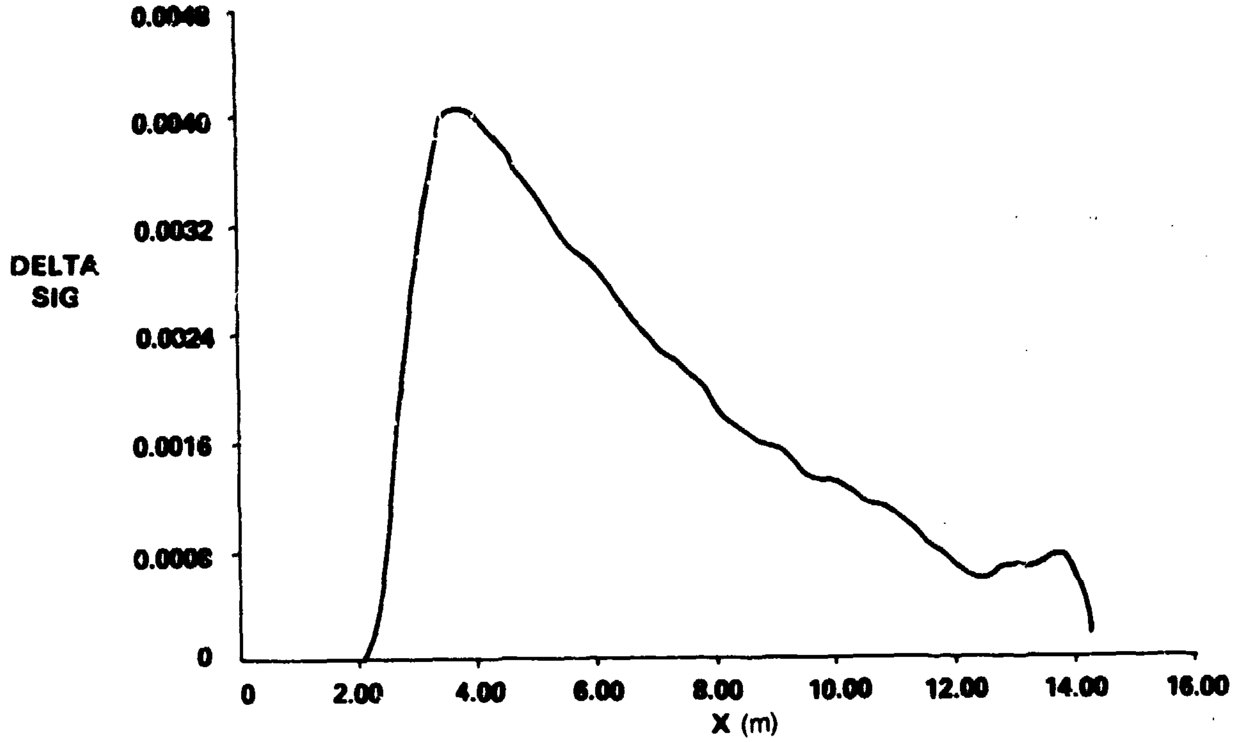

Figure 6. Case I: delta extracted cloud signature (return pulse signal to noise ratio ~ 100).

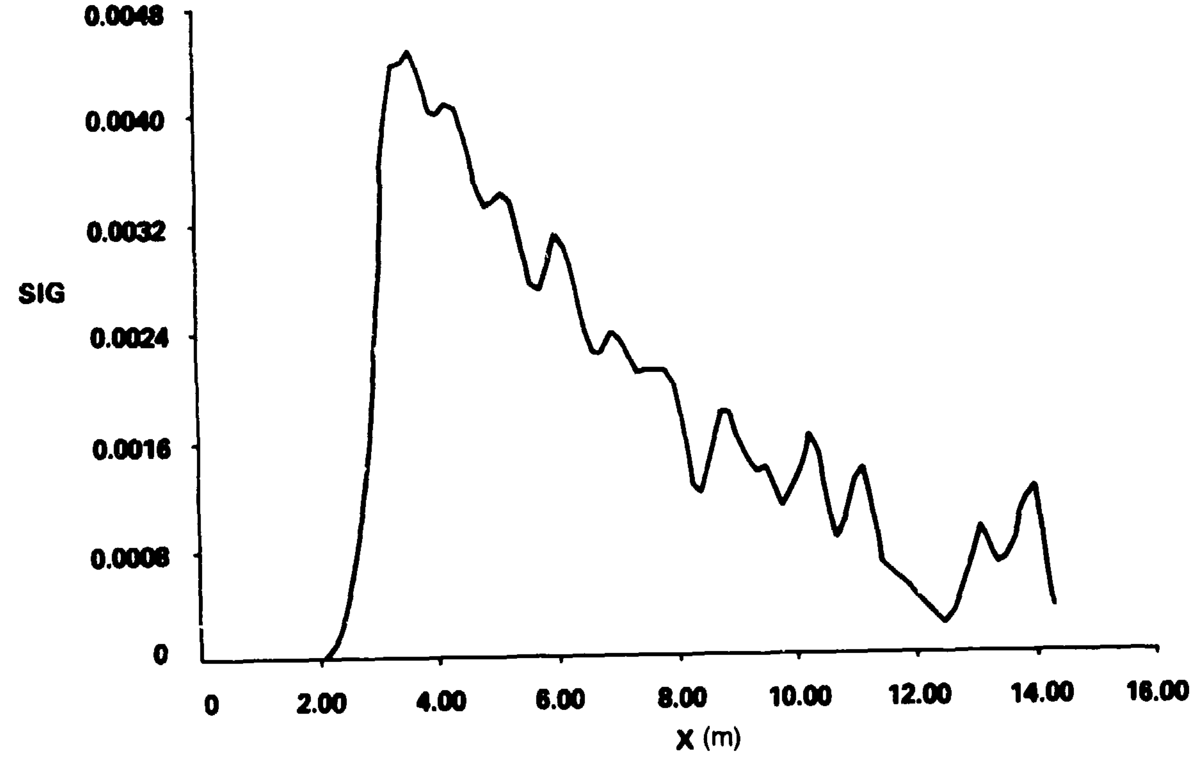

Figure 7. Case I: extracted cloud signature (return pulse signal to noise ratio ~ 40).

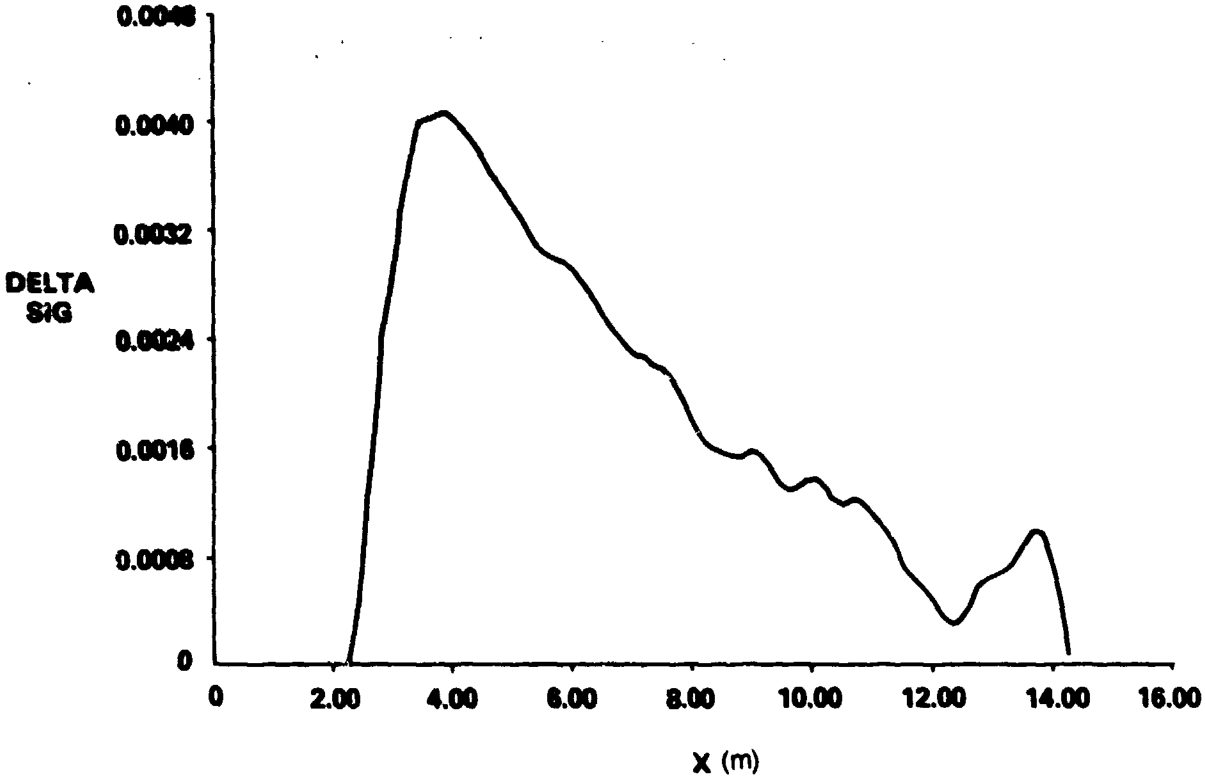

Figure 8. Case I: delta extracted cloud signature (return pulse signal to noise ratio ~ 40).

3.2 Case II

Figures 9 to 16 follow the same format as figures 1 to 8, but for a different idealized cloud, case II. Here the improvement is less substantial because the case II cloud has a softer edge, so the delta extracted signature is closer to the correct signature.

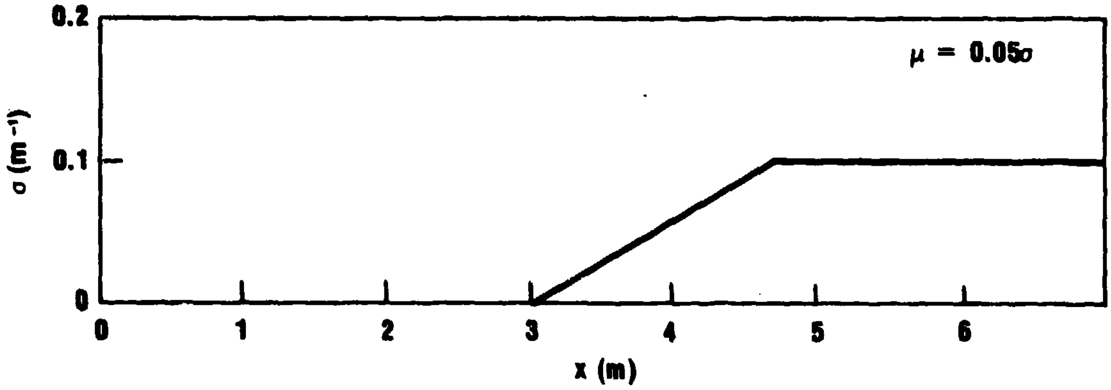

Figure 9. Case II: extinction coefficient.

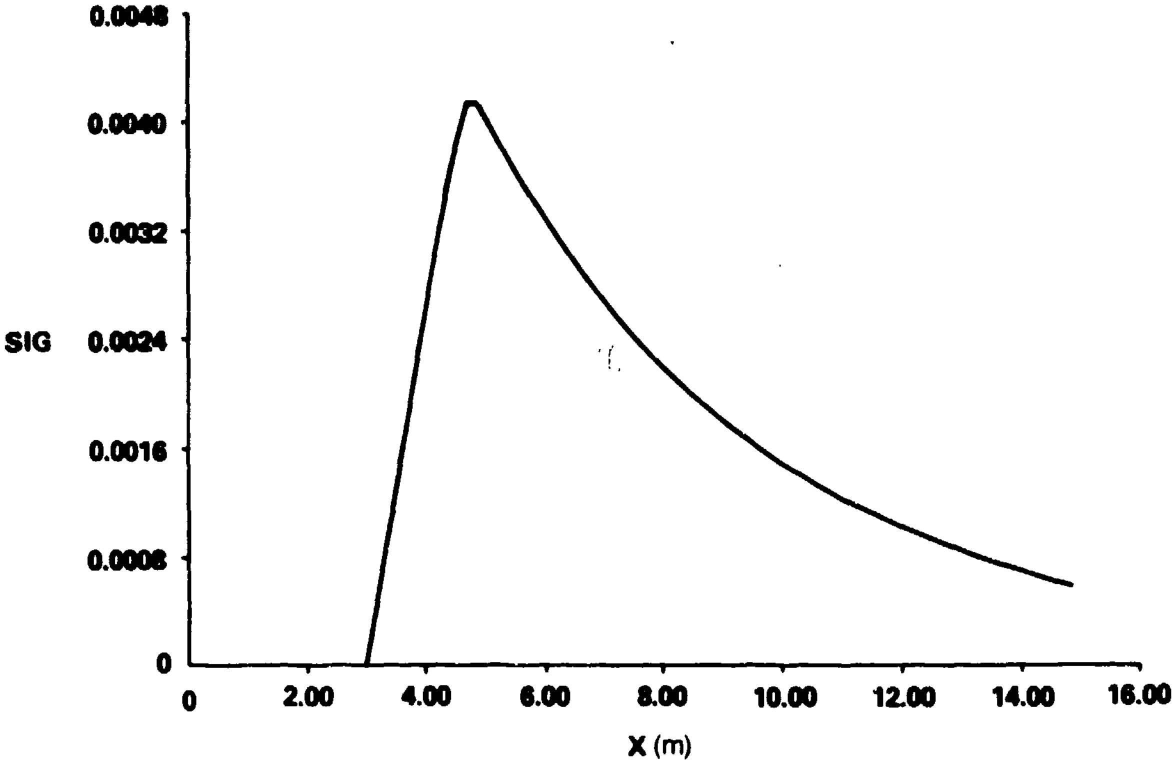

Figure 10. Case II: cloud signature.

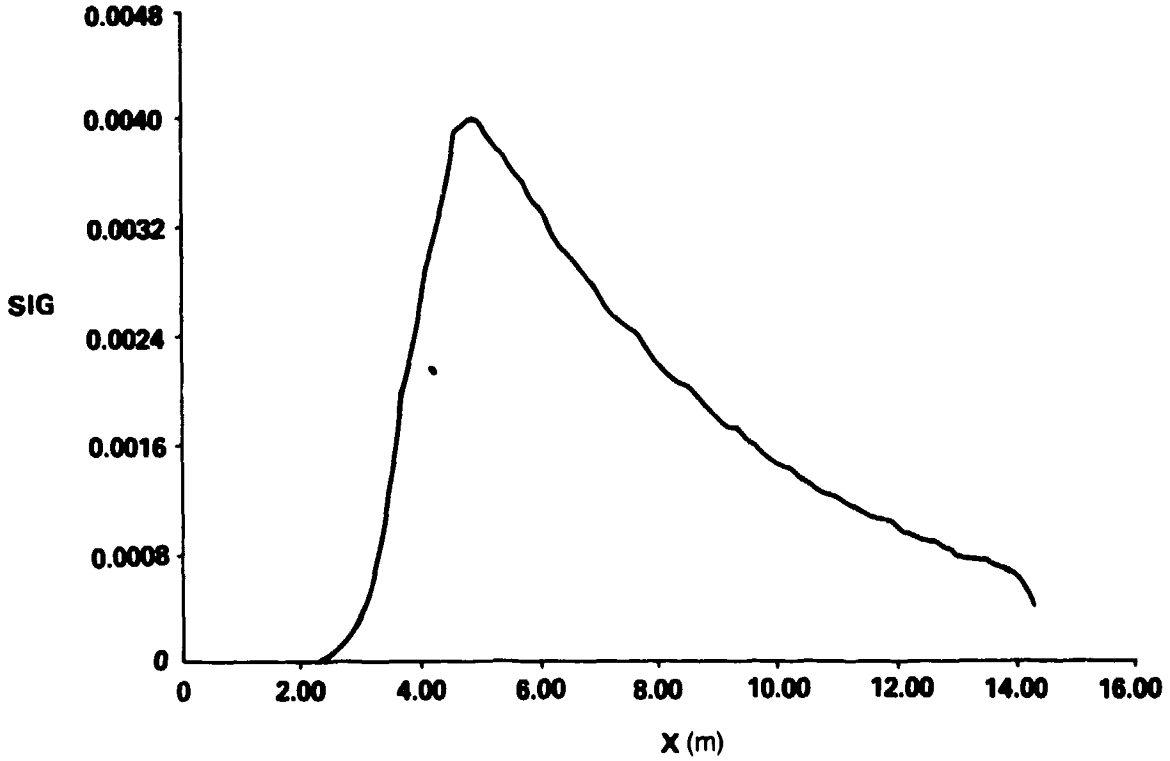

Figure 11. Case II: extracted cloud signature (noiseless return pulse).

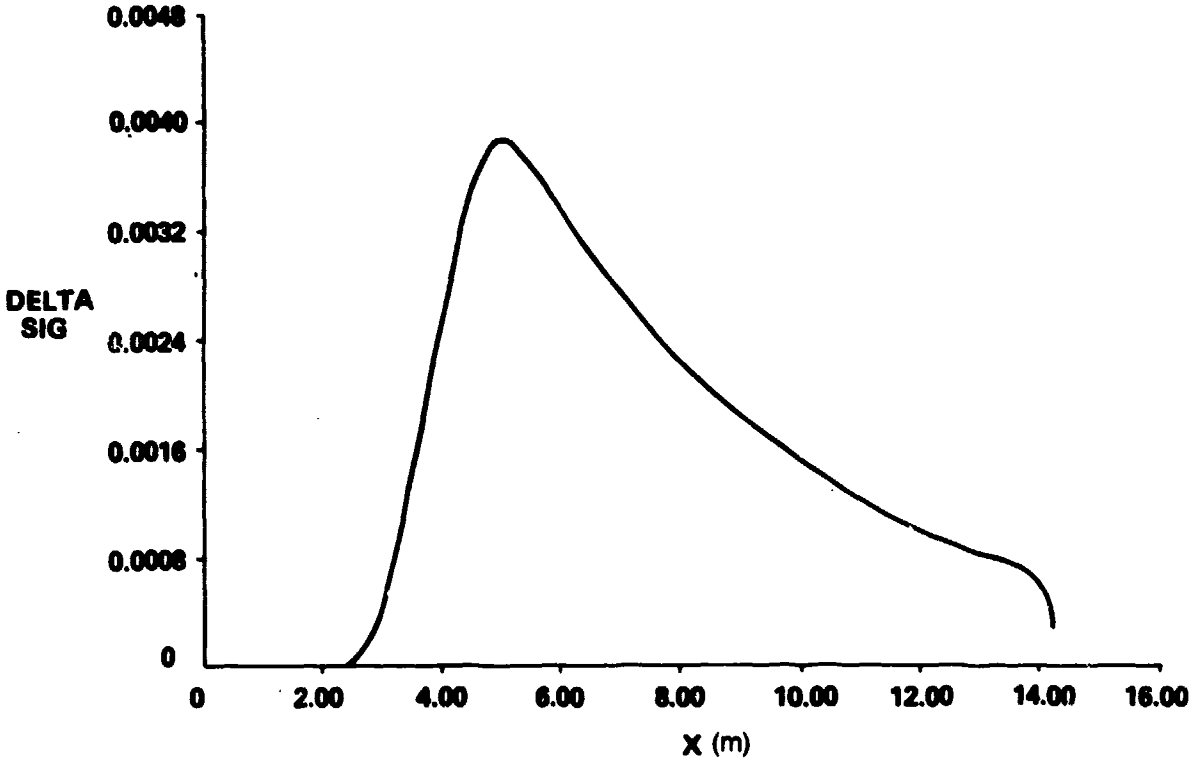

Figure 12. Case II: delta extracted cloud signature (noiseless return pulse).

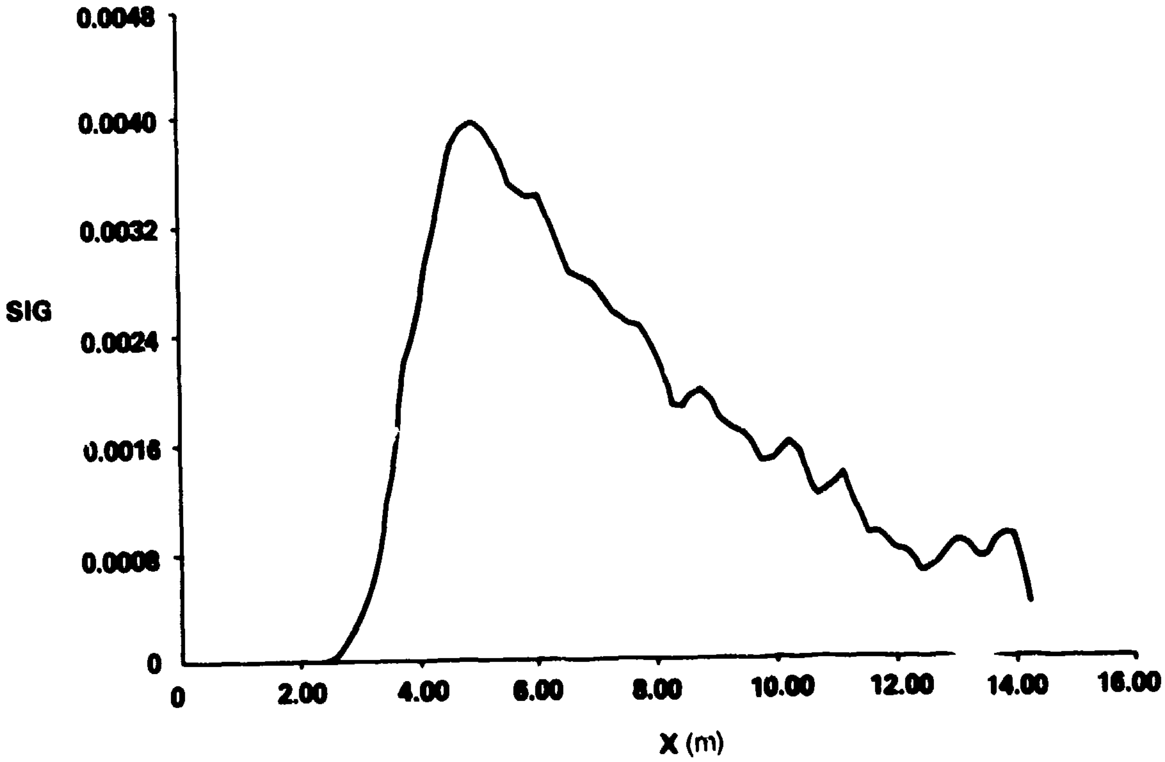

Figure 13. Case II: extracted cloud signature (return pulse signal to noise ratio ~ 100).

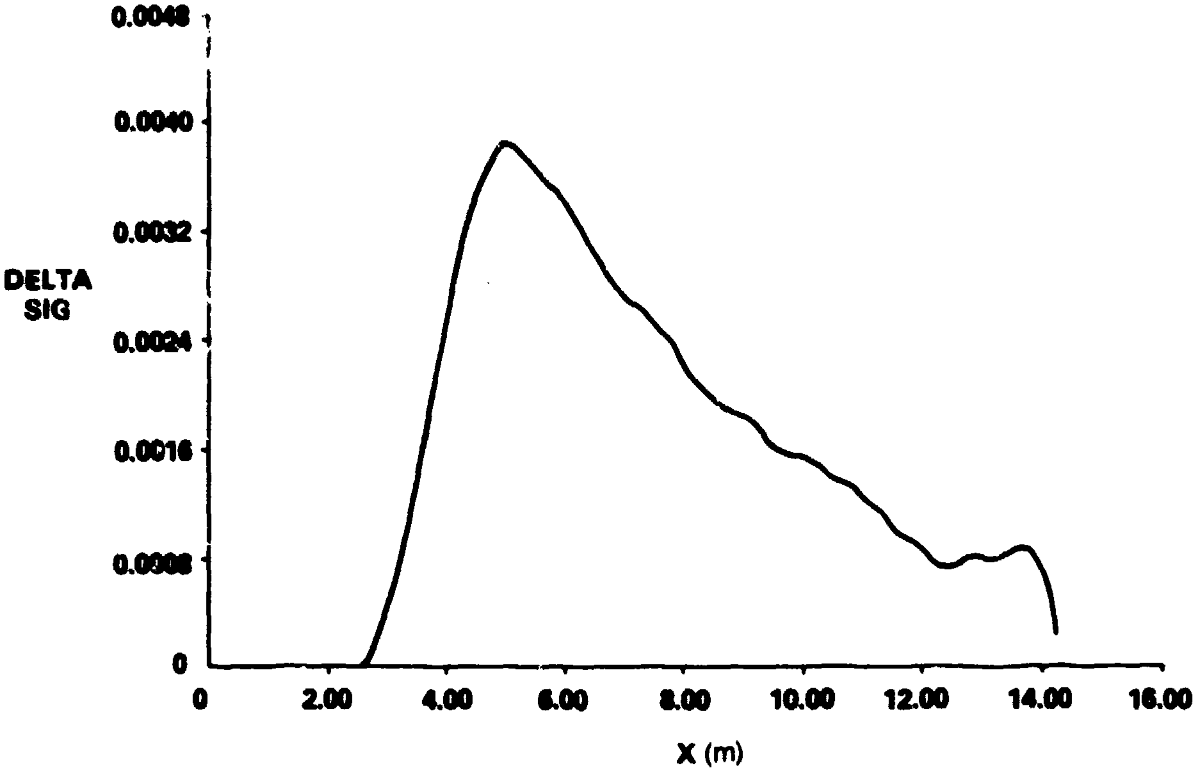

Figure 14. Case II: delta extracted cloud signature (return pulse signal to noise ratio ~ 100).

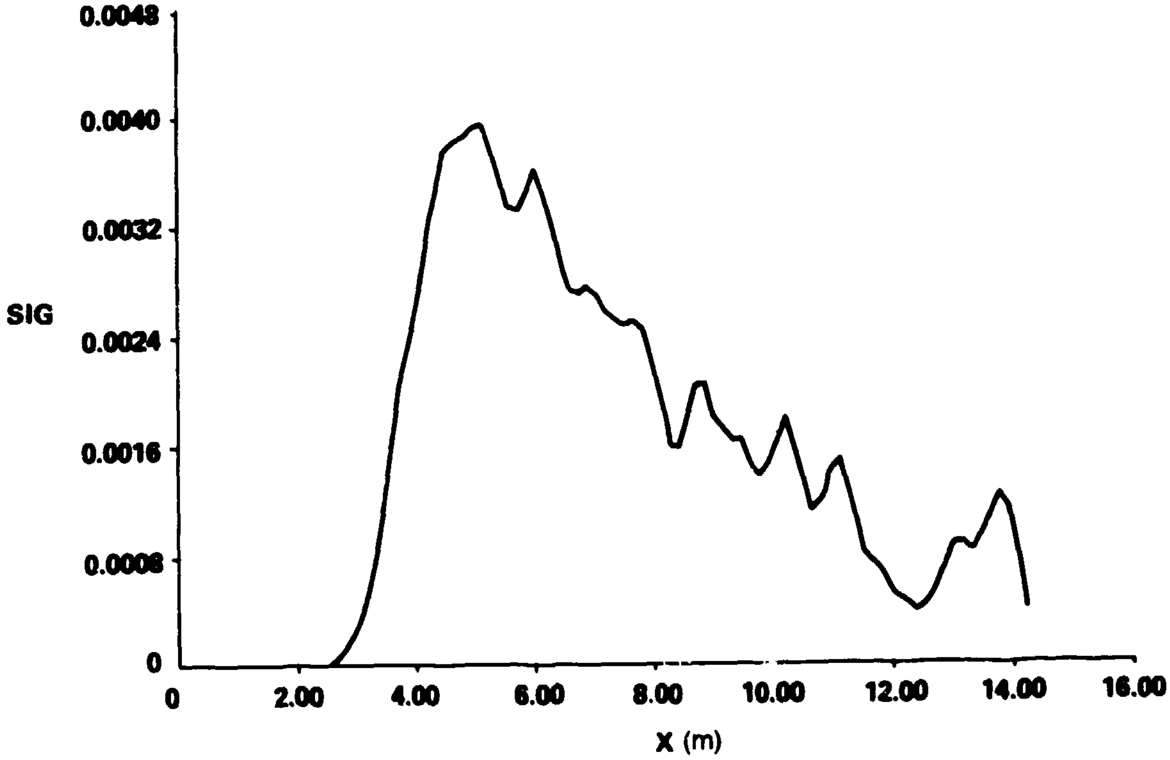

Figure 15. Case II: extracted cloud signature (return pulse signal to noise ratio ~ 40).

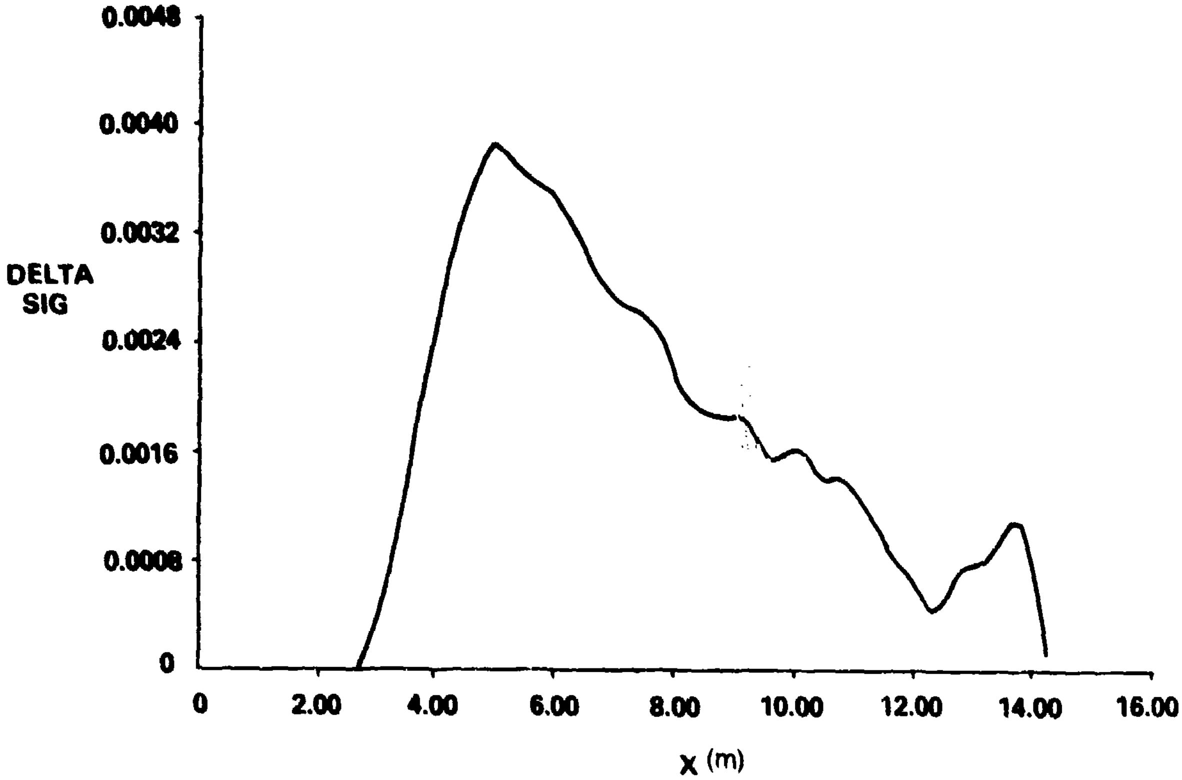

Figure 16. Case II: delta extracted cloud signature (return pulse signal to noise ratio ~ 40).

4. CONCLUSIONS

If the data have a signal to noise ratio of about 100 to 1 or better, it is possible to achieve slightly better resolution in the cloud signature than the resolution that would be available from equation (7), dividing by the range response (delta function extraction). The extent of the improvement in the resolution depends on the signal to noise ratio. There is no evidence that restriction a (sect. 2) (limiting how far estimates of the cloud signature can vary from the delta function estimate) is essential to the reasonable behavior of the cloud signature. Low-pass filtering of the return pulse or resulting cloud signature probably is necessary. This necessity indicates that, with a signal to noise ratio greater than 100 to 1 and adequate filtering, perhaps equation (6) should be reconsidered as a method for solving this problem. It may be worthwhile to consider using a hybrid method by which equation (6) could be used to treat that portion of the return where the signal is high, while settling for the delta extracted signature where the signal is lower.

It was considered desirable to analyze a select portion of the measured data by using the present method. Because of a computer malfunction, this analysis has not been done. It is suggested that for each return pulse two estimates of the cloud signature be recorded, one using the algorithm discussed in this report and, for comparison, one using the delta function extraction. Unlike the test cases shown in the figures, the real data provide no answer key and, hence, it may not be clear which signature is more accurate. However, it may prove instructive to generate graphs of the two estimates for various pulses and to note the similarities and differences in the two.

Interestingly, McGuire[2] predicts that the signal to noise ratio should decrease by a factor of about 0.14 on deconvolution, with filtering of the return pulse as was done in the test cases. This compares the signal to noise ratio of the filtered return with that of the cloud signature. In the present study, the signal to noise ratio in the unfiltered return signal is compared with that of the cloud signature. Also, the cloud signature was smoothed here. For these two reasons, one expects the apparent increase in noise to be less than that predicted by McGuire.[2] The two test cases here show an increase in noise (compared with signal) on deconvolution by a factor of about three, roughly consistent with this expectation.

ACKNOWLEDGEMENTS

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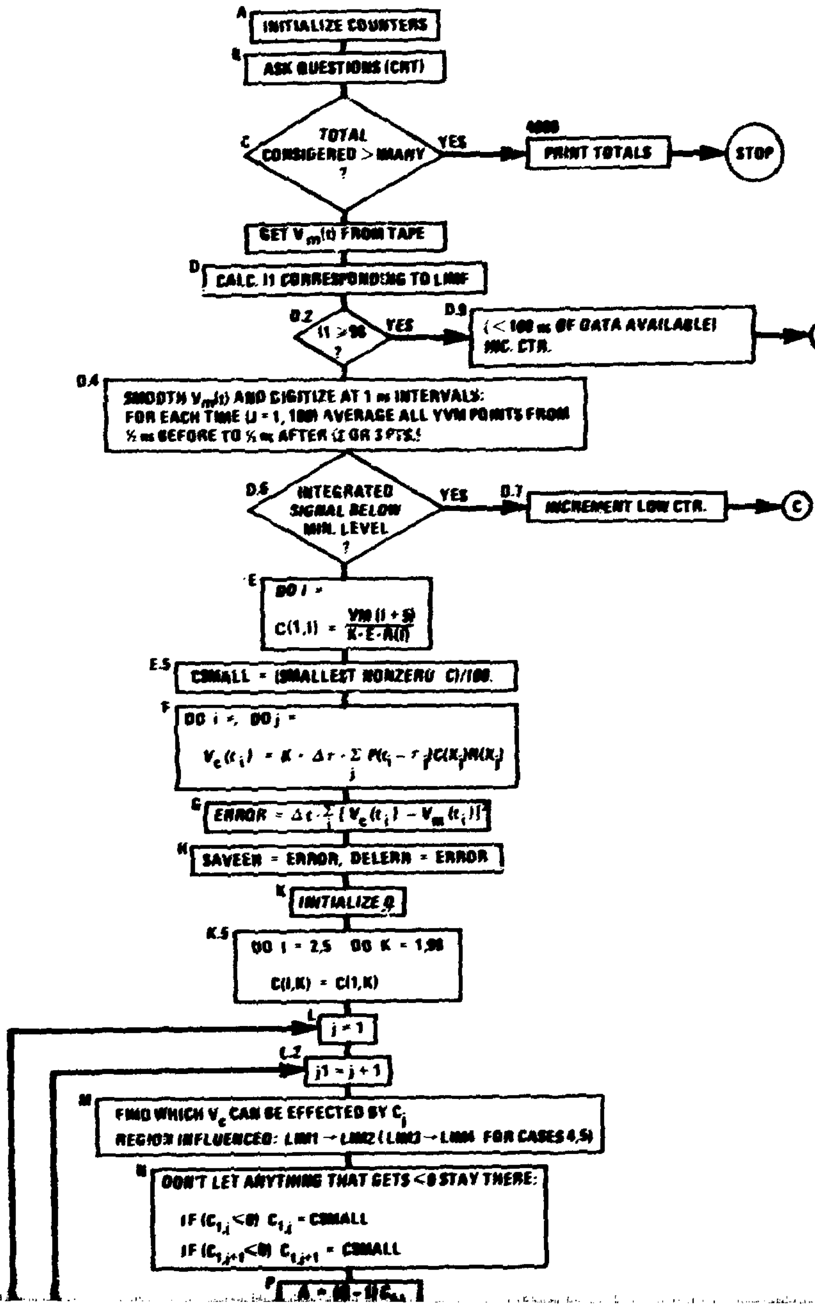
[2] *Dennis McGuire and Michael Conner, The Deconvolution of Aerosol Backscattered Optical Pulses to Obtain System-Independent Aerosol Signatures, Harry Diamond Laboratories HDL-TR-1944 (June 1981).*

APPENDIX A.--FLOW CHART OF COMPUTER PROGRAM FOR CLOUD SIGNATURE EXTRACTION

A computer program was developed to deconvolve an optical return pulse in such a way as to minimize the affect of return signal noise. The flow chart for this computer program follows (fig. A-1).



IN COMPUTER:

$V(I) = V(t_i)$, $C(I) = C(X_i)$, $R(I) = R(X_i)$

WHERE

$t_i = i$ ms $\quad X_i = \frac{ct_i}{2} = 0.15\,i$ meters

ADJUST:

$A = (Q - 1)C_j$

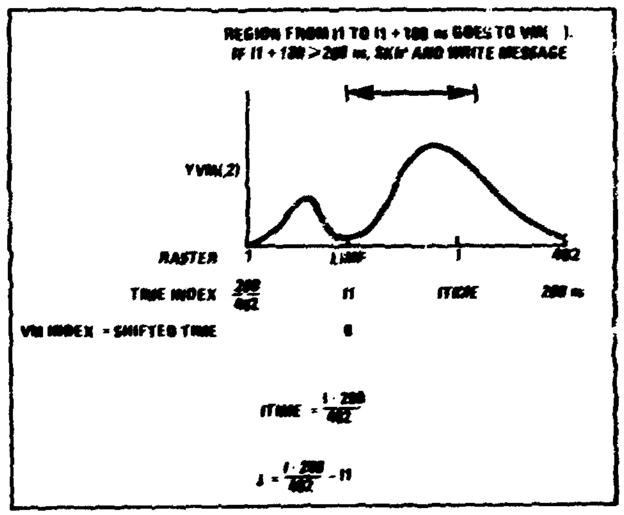
M = 1: NO CHANGE (I.E., PREVIOUS RESULT)

2: $C_j = C_j + A$

3: $C_j = C_j - A$

4: $C_j = C_j + A$, $C_{j+1} = C_{j+1} - A$

5: $C_j = C_j - A$, $C_{j+1} = C_{j+1} + A$



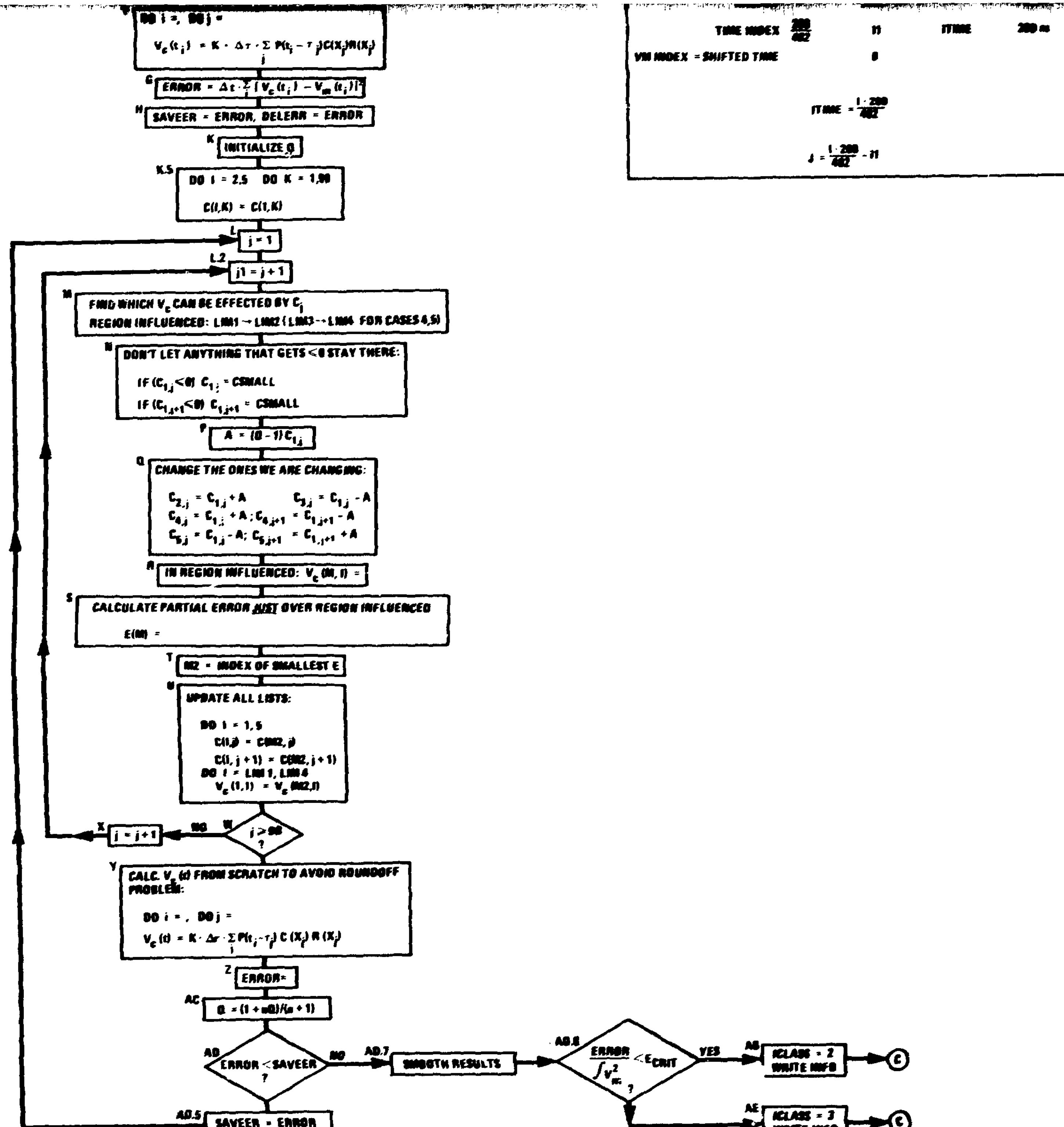


Figure A-1. Flow chart of computer program for cloud signature extraction.

APPENDIX B.--COMPUTER CODE FOR CLOUD SIGNATURE EXTRACTION

A computer program was developed to deconvolve an optical return pulse in such a way as to minimize the effect of return signal noise. A FORTRAN listing of this program follows.

APPENDIX B

```
$BATCH
C
C
C
C       VERSION: AUGUST 20, 1980
C       C L O U D   S I G N A T U R E   E X T R A C T I O N
C
C
C
C
C
C******************************
C
C       ASK JIM GRIFFIN IF CALL
C       FOR 'GETFR' HAS CHANGED.
C
C******************************
C
C     WARNING:
C       THIS PROGRAM ASSUMES P=0 FOR T GE 13 NS (TO SAVE CPU TIME).  IF THIS
C       PROGRAM IS USED WITH A TRANSMITTER PULSE THAT EXCEEDES 13 NS, THE SUM
C       LIMITS NEED TO BE MODIFIED.
C
C
C    SOME VARIABLES:
C       VM(I):  (INPUT)  MEASURED RETURN PULSE AT EACH NSEC (SHOULD BE SMOOTHED
C                          OVER ABOUT 1 OR 2 NSEC)
C       R(I):  RANGE RESPONSE.  X=I*.15 M  (=C*T/2)
C       P(I):  TRANSMITTER PULSE (EACH NSEC)
C       C(M,I):  CLOUD SIGNATURE (VARIATION M)  X=I*.15 M
C                CLOUD SIGNATURE PRINTED IS FOR I=11 TO 98.
C       VC(M,I):  RETURN PULSE AT EACH NSEC THAT WOULD RESULT FROM THIS SIGNATURE.
C                   (VARIATION M)
C                COMPARE IT WITH VM(I) TO SEE HOW WELL WE DID.
C          VARIATION M:
C             A=(Q-1.)*C(J)
C               M=1:  NO CHANGE (I.E. PREVIOUS RESULT)
C                 2:  C(J)=C(J)+A
C                 3:  C(J)=C(J)-A
C                 4:  C(J)=C(J)+A, C(J+1)=C(J+1)-A
C                 5:  C(J)=C(J)-A, C(J+1)=C(J+1)+A
C
        COMMON /BR/TRASH(20),LIMN,LIMF
        COMMON /FRAME/YVM(482,4),IFRAM1,IFRAM2
        COMMON /UNITS/LUOUT
        INTEGER*2 NAM1(9)
        DIMENSION VC(5,100),VM(100),C(5,99),R(99),P(12),E(5),
       CTMATRX(100),RASTER(482),CSHIFT(85),
       CXSHIFT(85),CTEMP(85),VCPLOT(100),YPASS(482)
        EQUIVALENCE (YVM(1,2),YPASS(1))
        DATA P/0.44,3.60,4.96,5.68,5.86,5.50,4.58,3.20,1.70,0.68,0.27,0.10
       C/
        DATA R/1.,4.,10.,15.,24.,30.,31.,32.,33.,35.,55.,80.,105.,140.,
       C175.,210.,250.,300.,350.,430.,480.,520.,550.,585.,605.,615.,
       C622.,625.,618.,612.,608.,595.,579.,565.,550.,535.,520.,505.,
       C485.,470.,455.,443.,431.,418.,402.,390.,377.,362.,350.,338.,
       C325.,313.,306.,298.,288.,280.,273.,263.,255.,245.,238.,230.,
```

```
     C225.,216.,210.,204.,198.,191.,187.,182.,177.,173.,171.,166.,
     C161.,157.,152.,147.,142.,140.,137.,132.,128.,125.,120.,117.,
     C113.,111.,108.,104.,101.,99.,98.,96.,95.,90.,88.,86.,84./
C
C    ********************************************************************
      CALL SETPDG
      CALL INITG(1.5,.8)
C
C     NOT NORMALIZED NOW
      FKKKK=1.
C
      IOUTDV=2
      INDV=1
C   OUTPUT DEVICE 8:
      LUOUT=8
C    ********************************************************************
C
C     FLOW CHART BOX A
C
      LOWCTR=0
      ICTR1=0
      ICTR2=0
      ICTR3=0
      ITOTCT=0
      DO 120 I=1,100
         FI=I
         TMATRX(I)=FI
  120 CONTINUE
      DO 125 I=1,25
         K=I+10
         FK=K
         XSHIFT(I)=FK*.15
  125 CONTINUE
      DO 130 I=1,482
         FI=I
         RASTER(I)=FI
  130 CONTINUE
C
C     FLOW CHART BOX B
C
      WRITE(IOUTDV,90113)
      READ(INDV,90103)SIGMIN
      WRITE(IOUTDV,90115)
      WRITE(IOUTDV,90502)
      READ(INDV,90505)FMANY
      IMANY=FMANY
      WRITE(IOUTDV,90101)
      READ(INDV,90103)ECRIT
      WRITE(IOUTDV,90105)
      WRITE(IOUTDV,90502)
      READ(INDV,90505)Q1
      WRITE(IOUTDV,90107)
      WRITE(IOUTDV,90502)
      READ(INDV,90505)FN
      WRITE(IOUTDV,90221)
      WRITE(IOUTDV,90502)
      READ(INDV,90505)ETIMEI
```

APPENDIX B

```
      WRITE(IOUTDV,99203)
      WRITE(IOUTDV,99502)
      READ(INDV,99505)ETIMEO
      WRITE(IOUTDV,99205)
      WRITE(IOUTDV,99502)
      READ(INDV,99505)PLOTFL
      IPLOTF=PLOTFL+.01
      WRITE(IOUTDV,99100)
      READ(INDV,99500)(NAM1(I),I=1,8)
      CALL OPENW(LUOUT,NAM1,3,0,0,IST)
      DELLT=1.E-9
C
C     FLOW CHART BOX C
C
  300 ITOTCT=ITOTCT+1
      IF(ITOTCT.GT.IMANY)GO TO 4000
      CALL GETFR(ISTAT,ITEMP,128.,1,0,86,86)
      IF(ITEMP.GT.0.AND.ITEMP.LE.18)GO TO 4900
      IF(ISTAT.NE.0)GO TO 5000
  305 IF(IPLOTF.EQ.1)CALL SUBPLT(RASTER,482,'RASTER',6,
     CYPASS,'RAW PULSE',9,IFRAM1)
C     MAKE PULSE RIGHT SIDE UP!
C
      DO 310 I=1,482
        YUM(I,2)=255.-YUM(I,2)
  310 CONTINUE
C
C     FLOW CHART BOX D
C
      FLIMF=LIMF
      FI1=FLIMF*200./482.
      FI1=FI1+.5
      I1=FI1
C
C     FLOW CHART BOX D.2
C
      IF(I1.GE.98)GO TO 400
C
C     FLOW CHART BOX D.4
C
      FI1=I1
C   BELOW:
C     J IS VM INDEX = SHIFTED TIME IN NSEC.
C      K IS RASTER INDEX
C
      DO 457 J=1,100
          FJ=J
          TEMP1=FJ-2.*ETIMEI
          TEMP2=FJ+2.*ETIMEI
          FLIM1=(TEMP1+FI1)*482./200.
          FLIM2=(TEMP2+FI1)*482./200.
          LIM1=FLIM1
          LIM2=FLIM2
          IF(LIM1.LT.LIMF)LIM1=LIMF
          IF(LIM2.GT.482)LIM2=482
          SUM=0.
          FNORM=0.

          TEMP4=FJ+FI1
          DO 445 K=LIM1,LIM2
              FK=K
              TEMP3=ABS((TEMP4-FK*200./482.)/ETIMEI)
              TEMP7=EXP(-TEMP3)
              SUM=SUM+YUM(K,2)*TEMP7
              FNORM=FNORM+TEMP7
  445     CONTINUE
          VM(J)=SUM/FNORM
  457 CONTINUE
C
```

```
C
C         FLOW CHART BOX D.6
C
C     JIM GRIFFIN SUGGESTS AVOIDING THE LAST 14 RASTER
C     POINTS  TO ESTABLISH BASELINE.
C   FIND BASELINE:
          TEMP=0.
          DO 468 I=448,467
              TEMP=TEMP+YVM(I,2)
      468 CONTINUE
          BASE=TEMP/20.
C     SUBTRACT BASELINE
          DO 464 I=1,100
          VM(I)=VM(I)-BASE
          IF(VM(I).LT.0.)VM(I)=0.
      464 CONTINUE
          SUM=0.
          DO 465 I=1,100
              SUM=SUM+VM(I)
      465 CONTINUE
          IF(SUM.GE.SIGMIN)GO TO 500
C
C         FLOW CHART BOX D.7
C
          LOWCTR=LOWCTR+1
          GO TO 300
C         FLOW CHART BOX E
C
      500 DO 520 I=1,95
          J=I+5
          C(1,I)=VM(J)/(FKKKK*3.657E-8*R(I))
      520 CONTINUE
          DO 530 I=96,99
C         LACKING ANY BETTER INFORMATION, TRY, FOR INITIAL VALUES:
          C(1,I)=C(1,95)
      530 CONTINUE
C
C
C**********
C**********
C**********     JIM GRIFFIN:
C**********     HERE, WRITE TWO COPIES OF THE FRAME CODE
C**********     (IFRAM1, IFRAM2) ON THE OUTPUT TAPE.
C**********     ALSO, WRITE TO TAPE:  C(1,I), I=11,95
C**********     (THIS IS THE CLOUD SIGNATURE OBTAINED
C**********     BY DIVIDING BY THE RANGE RESPONSE.)
C**********
C**********
C
C
C
C         FLOW CHART BOX E.5
C
          DO 552 I=1,98
          IF(C(1,I).NE.0.)GO TO 553
      552 CONTINUE
      553 TEMP=C(1,I)
```

APPENDIX B

```
      DO 500 I=1,99
      IF(C(1,I).NE.0..AND.C(1,I).LT.TEMP)TEMP=C(1,I)
  500 CONTINUE
      CSMALL=TEMP/100.
C
C     FLOW CHART BOX F
C
      VC(1,1)=0.
      DO 630 I=2,100
      VC(1,I)=0.
      ITEMP=I-12
      IF(ITEMP.LT.1)ITEMP=1
      LIM2=I-1
      DO 620 J=ITEMP,LIM2
      M=I-J
      VC(1,I)=VC(1,I)+P(M)*C(1,J)*R(J)
  620 CONTINUE
      VC(1,I)=FKKKK*DELLT*VC(1,I)
  630 CONTINUE
C
C     FLOW CHART BOX G
C
      SUM=0.
      DO 730 I=1,100
      TEMP2=VC(1,I)-VM(I)
      SUM=SUM+TEMP2*TEMP2
  730 CONTINUE
      ERROR=DELLT*SUM
C
```

```
C       FLOW CHART BOX H
C
        SAVEER=ERROR
        DELERR=ERROR
C
        IF(IPLOTF.NE.1)GO TO 850
        DO 840 I=1,85
           K=I+10
           CTEMP(I)=C(1,K)
  840   CONTINUE
        CALL SUBPLT(XSHIFT,85,'X',1,CTEMP,'DELTA SIG',9,IFRAM1)
  850   CONTINUE
C
C       FLOW CHART BOX K
C
        Q=Q1
C
C       FLOW CHART BOX K.5
C
        DO 1155 I=2,5
           DO 1155 K=1,99
              C(I,K)=C(1,K)
 1155   CONTINUE
C
C       FLOW CHART BOX L
C
 1200   J=1
C
C       FLOW CHART BOX L.2
C
 1220   J1=J+1
C
C       FLOW CHART BOX M
C
        LIM1=J+1
        LIM2=J+12
        LIM3=J+2
        LIM4=J+13
        IF(LIM2.GT.100)LIM2=100
        IF(LIM4.GT.100)LIM4=100
C
C       FLOW CHART BOX N
C
        IF(C(1,J).LE.0.)C(1,J)=CSMALL
        IF(C(1,J1).LE.0.)C(1,J1)=CSMALL
C
C       FLOW CHART BOX P
C
        A=(Q-1.)*C(1,J)
C
C       FLOW CHART BOX Q
C
        C(2,J)=C(1,J)+A
        C(3,J)=C(1,J)-A
        C(4,J)=C(1,J)+A
        C(4,J1)=C(1,J1)-A
        C(5,J)=C(1,J)-A
```

APPENDIX B

```
      C(5,J1)=C(1,J1)+A
C
C     FLOW CHART BOX R
C
      DO 1820 M=2,3
         DO 1815 I=LIM1,LIM2
            N=I-J
            UC(M,I)=UC(1,I)+FKKKK*DELLT*P(N)*R(J)*(C(M,J)-C(1,J))
 1815    CONTINUE
         UC(M,LIM4)=UC(1,LIM4)
 1820 CONTINUE
      DO 1840 M=4,5
      UC(M,LIM1)=UC(1,LIM1)+FKKKK*DELLT*P(1)*R(J)*(C(M,J)-C(1,J))
         DO 1835 I=LIM3,LIM2
            N=I-J
            N1=I-J1
            UC(M,I)=UC(1,I)+FKKKK*DELLT
     C*(P(N)*R(J)*(C(M,J)-C(1,J))+P(N1)*R(J1)*(C(M,J1)-C(1,J1)))
 1835    CONTINUE
      UC(M,LIM4)=UC(1,LIM4)+FKKKK*DELLT*P(12)*R(J1)*(C(M,J1)-C(1,J1))
 1840 CONTINUE
C
C     FLOW CHART BOX S
C
      DO 1940 M=1,5
         SUM=0.
         DO 1935 I=LIM1,LIM4
            TEMP2=UC(M,I)-UM(I)
            SUM=SUM+TEMP2*TEMP2
 1935    CONTINUE
         E(M)=DELLT*SUM
 1940 CONTINUE
C
C     FLOW CHART BOX T
C
      L=2
      M2=1
 2010 DO 2020 I=L,5
         IF(E(I).LT.E(M2))GO TO 2025
 2020 CONTINUE
      GO TO 2030
 2025 M2=I
      L=I+1
      IF(L.GT.5)GO TO 2030
      GO TO 2010
 2030 CONTINUE
C
C     FLOW CHART BOX U
C
      DO 2120 I=1,5
         C(I,J)=C(M2,J)
         C(I,J1)=C(M2,J1)
 2120 CONTINUE
      DO 2130 I=LIM1,LIM4
         UC(1,I)=UC(M2,I)
 2130 CONTINUE
C
```

```
C        FLOW CHART BOX W
C
  2200 IF(J.GE.50)GO TO 2500
C
C        FLOW CHART BOX X
C
         J=J+1
         GO TO 1820
C
C        FLOW CHART BOX Y
C
  2500 UC(1,1)=0.
         DO 2530 I=2,100
         UC(1,I)=0.
         ITEMP=I-12
         IF(ITEMP.LT.1)ITEMP=1
         LIMIT=I-1
         DO 2520 J=ITEMP,LIMIT
         M=I-J
         UC(1,I)=UC(1,I)+P(M)*C(1,J)*R(J)
  2520 CONTINUE
         UC(1,I)=FKKKK*DELLT*UC(1,I)
  2530 CONTINUE
C
C        FLOW CHART BOX Z
C
         SUM=0.
         DO 2580 I=1,100
         TEMP2=UC(1,I)-UM(I)
         SUM=SUM+TEMP2*TEMP2
  2580 CONTINUE
         ERROR=DELLT*SUM
         GO TO 2900
C
C        FLOW CHART BOX AB
C
  2800 ICLASS=2
         ICTR2=ICTR2+1
         GO TO 3100
C
C
C        FLOW CHART BOX AC
C
  2900 Q=(1.+FN*Q)/(FN+1.)
C
C        FLOW CHART BOX AD
C
         IF(ERROR.GE.SAVEER)GO TO 3070
C
C        FLOW CHART BOX AD.5
C
         SAVEER=ERROR
         GO TO 1800
C
C        FLOW CHART BOX AD.7
C
  3070 DO 3075 I=1,50
```

APPENDIX B

```
         YUM(I,4)=C(1,I)
 3072 CONTINUE
C
C     BELOW:
C
C        I=UMINDEX=SHIFTED TIME
C
      DO 3074 I=11,95
         FI=I
         TEMP1=FI-2.*ETIMEO
         TEMP2=FI+2.*ETIMEO
         LIM1=TEMP1
         IF(LIM1.LT.1)LIM1=1
         LIM2=TEMP2
         IF(LIM2.GT.99)LIM2=99
         C(1,I)=0.
      FNORM=0.
         DO 3076 K=LIM1,LIM2
            FK=K
            TEMP=ABS((FI-FK)/ETIMEO)
            C(1,I)=C(1,I)+YUM(K,4)*EXP(-TEMP)
            FNORM=FNORM+EXP(-TEMP)
 3076    CONTINUE
         C(1,I)=C(1,I)/FNORM
 3074 CONTINUE
C
C     FLOW CHART BOX AD.2
C
      SUM=0.
      DO 3085 I=1,100
         SUM=SUM+UM(I)*UM(I)
 3085 CONTINUE
      ERRORA=ERROR/SUM
      DELERA=DELERR/SUM
      IF(ERRORA.LT.ECRIT)GO TO 2000
C
C     FLOW CHART BOX AE
C
      ICLASS=3
      ICTR3=ICTR3+1
 3100 CONTINUE
      IF(IPLOTF.NE.1)GO TO 3200
      DO 3103 I=1,85
         J=I+10
         CSHIFT(I)=C(1,J)
 3103 CONTINUE
      CALL SUBPLT(XSHIFT,85,'(',1,CSHIFT,'SIG',3,IFR
AM1)
 3105 CONTINUE
      DO 3107 I=1,100
         UCPLOT(I)=UC(1,I)
 3107 CONTINUE
      CALL SUBPLT(TMATRX,100,'MSEC',4,UCPLOT,'CALC.
RETURN',12,IFRAM1)
 3110 CONTINUE
      CALL SUBPLT(TMATRX,100,'MSEC',
     C4,UM,'MEAS. RETURN',12,IFRAM1)
```

```
 3200 CONTINUE
C
C
C**********
C**********
C**********    JIM GRIFFIN:
C**********    HERE, WRITE TO TAPE:  C(1,I), I=11,25
C**********    (THIS IS THE MODIFIED VERSION OF THE
C**********    CLOUD SIGNATURE.)
C**********
C**********
C
C
      GO TO 300
C
C     END OF PROGRAM SUMMARY
C
C
 4000 CALL SCREEN
      WRITE(IOUTDV,90301)IMANY
      WRITE(IOUTDV,90303)LOWCTR
      WRITE(IOUTDV,90304)ICTR1
      WRITE(IOUTDV,90305)ICTR2
      WRITE(IOUTDV,90307)ICTR3
C
C
C**********
C**********
C**********    INSERT A CALL FFMM HERE.
C**********
C**********
C
C
C
      STOP
  490 ICTR1=ICTR1+1
      GO TO 300
 4990 WRITE(IOUTDV,90550)ITEMP
      STOP
C
C     IF WE GET A BAD FRAME:
C
 5000 WRITE(IOUTDV,90551)ISTAT
C
C
C**********
C**********
C**********    INSERT A CALL FFMM HERE.
C**********
C**********
C
C
C
C
      STOP
C
C
```

APPENDIX B

```
                                                                  000    00END
      90101 FORMAT(' ENTER CRITICAL ERROR.')
      90103 FORMAT(E15.3)
      90105 FORMAT(' ENTER INITIAL VALUE FOR Q.')
      90107 FORMAT(' ENTER N (WEIGHT FACTOR FOR Q DECREASE).')
      90108 FORMAT(' ENTER OUTPUT TAPE DEVICE.')
      90113 FORMAT(' ENTER INTEGRATED PULSE HEIGHT BELOW WHICH ',
           C'SIGNAL SHOULD NOT BE PROCESSED.')
      90115 FORMAT(' ENTER NUMBER OF PULSES TO BE PROCESSED.')
      90221 FORMAT(' FOR FILTERING OF RETURN PULSE, ENTER '
           C,'1/E TIME (IN NSEC):'/'DO NOT USE ZERO'/
           C'SHOULD USE AT LEAST .5 NSEC SO YOU AVG.'/
           C'OVER MORE THAN ONE RASTER POINT.')
      90223 FORMAT(' FOR FILTERING OF CLOUD SIGNATURE, ENTER '
           C,'1/E DISTANCE (IN UNITS OF .15 METERS):'/'DO NOT USE ZERO')
      90225 FORMAT(' ENTER 1. FOR PLOTS.')
      90301 FORMAT(1X,I8,' RETURN PULSES WERE EXAMINED.')
      90303 FORMAT(1X,I8,' OF THESE PULSES WERE BELOW THRESHOLD.')
      90304 FORMAT(1X,I8,' OF THESE PULSES HAS LESS THAN 100 NSEC'/
           C'OF USEABLE RETURN.')
      90305 FORMAT(1X,I8,' CLOUD SIGNATURES WERE SUCCESSFULLY EXTRACTED.')
      90307 FORMAT(1X,I8,' CASES FAILED.')
      90502 FORMAT(' USE DECIMAL POINT')
      90505 FORMAT(F12.3)
      90509 FORMAT(9A2)
      90550 FORMAT(' ASSIGNMENT ERROR',I8,'FROM GETFR')
      90551 FORMAT(' IF CODE = 136, FILE MARKER FOUND.'/
           C' ANY OTHER CODE MEANS TAPE ERROR.'/
           C' CODE = ',I10)
            END
            SUBROUTINE SUBPLT(PASS1,IPASS2,IPASS3,IPASS4,
           CPASS5,IPASS6,IPASS7,IFRAME)
            DIMENSION PASS1(1),IPASS3(4),IPASS6(4),PASS5(1)
      C
      C   VARIABLES PASSED:
      C
      C      1:  X ARRAY NAME
      C      2:  # POINTS
      C      3:  'X LABEL'
      C      4:  # CHARACTERS IN LABEL
      C      5:  Y ARRAY NAME
      C      6:  'Y LABEL'
      C      7:  # CHARACTERS IN LABEL
      C      IFRAME:  FRAME CODE
            CALL SCREEN
            WRITE(1,905)IFRAME
            CALL SCALE(PASS1,IPASS2,8.,1,0)
            CALL SCALE(PASS5,IPASS2,6.,1,1)
            CALL ENTGRA
            CALL XAXIS(IPASS3,IPASS4,8.)
            CALL YAXIS(IPASS6,IPASS7,6.)
            CALL DATAQ(PASS1,PASS5,IPASS2,1,1)
            CALL EXITGR
            READ(1,903)IFAKE
            RETURN
        903 FORMAT(I1)
        905 FORMAT(25X,'FRAME',I8)
            END
```

APPENDIX C.--VALUES OF PARAMETERS USED IN POINT WEIGHTING ALGORITHM

The return pulse was filtered by replacing each digitized value, $V(t_i)$, by a weighted average of the points in its neighborhood. The weight factor decreases exponentially as t moves away from t_i. The time (in nanoseconds) by which the weight factor has decreased to 1/e is called t_o. The filtering of the cloud signature is similar, except that the units for x_o are 0.15 m (corresponding to 1 ns).

The filtering values and the values for Q_l and n used to generate the figures in the main body of this report were these:

Case I

t_o = 1.3 (= 1.3 ns),

x_o = 1.3 (= 0.195 m),

Q_l = 1.2,

n = 2.

Case II

t_o = 1.3 (= 1.3 ns),

x_o = 1.3 (= 0.195 m),

Q_l = 1.1,

n = 2.

APPENDIX D.--CLOUD SIGNATURE RESTRICTIONS PRODUCED BY PARAMETERS USED IN POINT WEIGHTING ALGORITHM

As discussed in the main body of this report, the extent of variation of the cloud signature depends on the product of the Q_i's. The author has not been able to write this product in terms of Q_1 and n in closed form, but some discussion and numerical results are given below.

Note: $1 < Q < 2$, $n > 0$, $0 < Z < 1$, $0 < \alpha < 1$.

Find

$$\prod_{i=1}^{\infty} Q_i = Q_1 \cdot Q_2 \cdot Q_3 \cdot Q_4 \cdot \cdot \cdot \cdot \quad , \tag{D-1}$$

where

$$Q_{i+1} = \frac{1 + nQ_i}{n + 1} \quad . \tag{D-2}$$

Let

$$Z_i = Q_i - 1 \quad . \tag{D-3}$$

Then from equation (D-2) it follows that

$$Z_{i+1} = \frac{n}{n + 1} \left(Z_i \right) = \alpha Z_i \quad , \tag{D-4}$$

$$\alpha \equiv \frac{n}{n + 1} \quad . \tag{D-5}$$

Using equation (D-4) repeatedly shows that

$$Z_i = \alpha^{i-1} Z_1 \tag{D-6}$$

Back to the task at hand,

$$\prod_{i=1}^{\infty} Q_i = \prod_{i=1}^{\infty} \left(Z_i + 1 \right) \quad , \tag{D-7}$$

$$\ln \left(\prod Q_i \right) = \ln \left[\prod \left(Z_i + 1 \right) \right] = \sum \ln \left(Z_i + 1 \right) \quad , \tag{D-8}$$

$$\ln \left(\prod Q_i \right) = \ln \left(1 + Z_1 \right) + \ln \left(1 + \alpha Z_1 \right) + \ln \left(1 + \alpha^2 Z_1 \right) + \ln \left(1 + \alpha^3 Z_1 \right) + \cdot \cdot \cdot \cdot \tag{D-9}$$

Using

$$\ln (1 + x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \frac{x^5}{5} \cdot \cdot \cdot \quad \text{for } x^2 < 1 \text{ and } x = 1$$

in each term in equation (D-9) yields

APPENDIX D

$$\ln\left(\prod Q_i\right) = \left[z_1 - \frac{z_1^2}{2} + \frac{z_1^3}{3} - \frac{z_1^4}{4} + \frac{z_1^5}{5} \cdots\right]$$

$$+ \left[\alpha z_1 - \frac{(\alpha z_1)^2}{2} + \frac{(\alpha z_1)^3}{3} - \frac{(\alpha z_1)^4}{4} + \frac{(\alpha z_1)^5}{5} \cdots\right]$$

$$+ \left[\alpha^2 z_1 - \frac{(\alpha^2 z_1)^2}{2} + \frac{(\alpha^2 z_1)^3}{3} - \frac{(\alpha^2 z_1)^4}{4} + \frac{(\alpha^2 z_1)^5}{5} \cdots\right]$$

$$+ \left[\alpha^3 z_1 - \frac{(\alpha^3 z_1)^2}{2} + \frac{(\alpha^3 z_1)^3}{3} - \frac{(\alpha^3 z_1)^4}{4} + \frac{(\alpha^3 z_1)^5}{5} \cdots\right]$$

$$+ \cdots \qquad \text{(D-10)}$$

Collecting like powers of Z,

$$\ln\left(\prod Q_i\right) = z_1 \left[1 + \alpha + \alpha^2 + \alpha^3 + \cdots\right]$$

$$- \frac{z_1^2}{2}\left[1 + \alpha^2 + \alpha^4 + \alpha^6 + \cdots\right]$$

$$+ \frac{z_1^3}{3}\left[1 + \alpha^3 + \alpha^6 + \alpha^9 + \cdots\right] \qquad \text{(D-11)}$$

$$- \frac{z_1^4}{4}\left[1 + \alpha^4 + \alpha^8 + \alpha^{12} + \cdots\right]$$

$$+ \cdots$$

Summing the algebraic series in each square bracket yields

$$\ln\left(\prod Q_1\right) = z_1\left[\frac{1}{1-\alpha}\right] - \frac{z_1^2}{2}\left[\frac{1}{1-\alpha^2}\right] + \frac{z_1^3}{3}\left[\frac{1}{1-\alpha^3}\right] \qquad \text{(D-12)}$$

$$- \frac{z_1^4}{4}\left[\frac{1}{1-\alpha^4}\right] + \cdots$$

These terms get very small very fast. The sum therefore can be approximated by the first few terms. The exponential of the sum then gives

$$\prod_{i=1}^{\infty} Q_i \quad .$$

Table D-1 was generated by computer. Using the first five terms of equation (D-12) gives the same results as the first 100 terms of equation (D-1) to the accuracy shown here.

TABLE D-1. NUMERICAL RESULTS FOR PRODUCT $\prod_{i=1}^{\infty} Q_i$

n	Q_1						
	1.4	1.3	1.2	1.1	1.05	1.02	1.01
0.5	1.70	1.50	1.32	1.16	1.08	1.03	1.02
1	2.04	1.73	1.46	1.21	1.10	1.04	1.02
2	2.95	2.29	1.76	1.34	1.16	1.06	1.03
3	4.25	3.04	2.14	1.48	1.22	1.08	1.04
4	6.13	4.02	2.58	1.63	1.28	1.10	1.05
5	8.84	5.32	3.13	1.79	1.34	1.13	1.06
10	55.1	21.6	8.12	2.92	1.72	1.24	1.12

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