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Technical Memorandum

# RECAT - REDUNDANT CHANNEL ALIGNMENT TECHNIQUE

Date: 22 July 1986

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14. ABSTRACT

**A problem in the analog-to-digital, (A/D), conversion of broadband tape recorded data occurs when the desired number of simultaneous data channels exceeds the number of available A/D converter channels. A technique for overcoming this difficulty has been developed using two common data channels between multiple passes over the same section of data. RECAT, or Redundant Channel Alignment Technique, is used to align data taken on one pass with data from any other pass. The accuracy of this alignment is a function of the digital sampling rate used, and for highly accurate alignments a sampling rate several times the Nyquist rate is often required.**

15. SUBJECT TERMS

**RECAT; Redundant Channel Alignment Technique; analog-to-digital; A/D; Broadband Bearing Time Processing**

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# PREFACE

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## INTRODUCTION

A problem in the analog-to-digital, (A/D), conversion of broadband tape recorded data occurs when the desired number of simultaneous data channels exceeds the number of available A/D converter channels. A technique for overcoming this difficulty has been developed using two common data channels between multiple passes over the same section of data. RECAT, or Redundant Channel Alignment Technique, is used to align data taken on one pass with data from any other pass. The accuracy of this alignment is a function of the digital sampling rate used, and for highly accurate alignments a sampling rate several times the Nyquist rate is often required.

## DESCRIPTION OF RECAT

### Obtaining the Digitial Data

Assume we are given an analog tape with M data channels, and N A/D converter channels, where $M > N$ and $N > 3$. The data of interest begins on all channels at time $t_o$, with highest frequency $f_o$. The sampling rate of the A/D converters is $f_s$, where $f_s > 2f_o$. The first set of N data channels are A/D converted at sample rate $f_s$. This set of channels is referred to as the Pass 1 data. To form the second pass data set, N-2 new data channels are connected to the A/D converter, along with 2 channels from the first pass of the data. These 2 channels are referred to as the redundant data channels and are used to align data taken on different passes. In digitizing the second pass of data, it is important to begin sampling prior to to, and continue beyond the stop time of the Pass 1 data. This process is repeated until all the data channels have been sampled. The total number of passes required, J, is

$$J = (M-2)/(N-2) \qquad \text{(Equation 1)}$$

and the total number of channels digitized, including the redundant channels is simply J*N.

### Aligning Separate Passes

The central idea behind RECAT is to align the two common channels acquired on each pass of the data with the data obtained on Pass 1. The common data channels of Pass 1 are referred to as the reference channels. The common data channels from other passes are termed the redundant channels.

To calculate the sample value in a redundant channel that corresponds to the first sample in the reference channel the mean square difference between the first K samples in reference channels, x(t), and the first K samples in the redundant channel, y(t), is computed, or

$$E = \frac{1}{K} \sum_{k=1}^{K} (x(k) - y(k))^2 \qquad \text{(Equation 2)}$$

This mean-square difference is stored and the difference between the samples 1 to K+1 in the reference channel and samples 2 to K+2 in the redundant channel are computed. If this second mean square value is greater than the first, the shift index, 2 in this case, and the value of the second difference are stored. This process is continued over some range of sample shifts in redundant channel, and the shift index corresponding to the minimum difference, K1, is associated with time delay between the first and second pass data. The process is repeated for the second reference-redundant channel pair to form the shift index of minimum difference, K2.

For K1 = K2, both reference-redundant channel pairs have a minimum mean square difference at the same sample shift, and the Pass 2 data is best aligned with the Pass 1 data by shifting the Pass 2 data by K1 samples. Since the accuracy of the alignment is only good to $1/f_s$, the sampling rate used may exceed that required for the data bandwidth. After aligning, the data may be subsampled to some new sampling frequency, with the channel alignment accuracy still given by the reciprocal of the original sampling frequency.

If K1 ≠ K2, the alignment procedure is refined. The size of the number of samples used to compute the mean square difference between reference and redundant channels, K, is increased by half its original value. RECAT is then retried and two new values of K1 and K2 computed. If the shift differences are still not equal, K is increased until it equals the length of the reference array. If K1 ≠ K2, the Pass 1 and 2 data cannot be aligned, and RECAT has failed.

## Computer Implementation

RECAT has been implemented in FORTRAN on the Code 333 VAX computer. Appendix A contains a listing of the FORTRAN source code for RECAT, and the VMS command procedure RECAT.COM, required for logical name assignments. The generic subroutine READ (X,LU,N) is supplied by the user to read the digital data.

# EXAMPLES

## Test Data Description

Acoustic data in the 0 - 500 Hz band were low pass filtered at 1100 Hz, and digitized at 10,000 Hz to provide a test data set. A time code reader was used to start the collection of digital data, with the Pass 2 data starting roughly 2 seconds before the start of the Pass 1 data. Figure 1 is a diagram of the equipment used to obtain the test data, and shows the relationships between the four data channels used in each example.

## Test Case No. 1 - Simple RECAT Test

Figure 2 is a plot of the mean square error, in dB, as a function of sample shift for the first pair of reference - redundant channels, using 100 differences or K = 100, to form the mean-square-error. The average error is between -1 and -2 dB, with a sharp dip of roughly -20 dB at a sample index of 18744. This delay corresponds roughly the two second delay expected between the Pass 1 and Pass 2 data. Other local minima of -10 to -12 dB are observed, but there is little ambiguity in the location of the global minimum error. Figure 3 is a similar plot for the second RECAT channel pair. While the average error level is slightly different, a sharp dip at sample 18744 indicates a successful RECAT alignment. Figure 4 is an enlargment of Figure 3 about the minimum error, and shows the sharpness of the error null. The data may now be subsampled by a factor of 4, or digitally low-pass filtered to 500 Hz and subsampled by a factor of 10, with the time alignment error between passes less than $\pm 10^{-4}$ sec.

## Test Case No. 2 - Aliased Data

The same data used in the previous test were subsampled by a factor of 8 for a RECAT test with K = 100. The effective data sampling rate is 10000 / 8, or 1250 Hz, aliasing the data between 675 and 1100 Hz. Figure 5 is a plot of the mean square error versus sample shift for the first RECAT channel pair. The minimum erro occurs at sample 2343, or 18744 / 8, as expected. Figure 6 is the error plot for the second RECAT channel pair, and also has a minimum at sample shift 2343. The accuracy of the RECAT alignment has been reduced to 0.8 ms by the subsampling, but as expected, the presence of aliasing does not effect the alignment technique.

## Test Case No. 3 - Effect of Comparison Array Size

In the previous examples, the number of differences used to compute the mean square error for a given sample index, K, was fixed at 100. The error is normalized by K, to give a measure of differences between channels that is independent of the number of samples used to form the mean square error. Figure 7 is an error plot for the data used in Test Case No. 1, with K = 1000. The error minimum still occurs at sample 18744, but the variance of the average error has been reduced, and the region about the minimum appears similar to a band-limited correlation. The ratio of the average mean square error to the minimum error is further reduced for K = 5000, as shown by Figure 8.

## Test Case No. 4 - A Comparison with Correlation Processing

A comparison between RECAT and correlation processing was performed using low-pass filtered tape noise only. For this example the sampling rate was 2500 Hz, and the delay between Pass 1 and Pass 2 data was roughly 1 second. Figure 9 is the RECAT error plot, and shows the minimum error, at sample 2997, obscured by nearby local error minimums. A comparison array size of K = 100 was used.

To produce the crosscorrelation between the reference and redundant channel data, 4906 samples of each were correlated, via the FFT method (8192 point FFT with zero padding). Figure 10 is the envelope of the crosscorrelation with the peak representing the true delay between channels marked by the dashed line. Since the correlation is not circular, but convolved with a rectangular data window, the envelope should be corrected for this window by

$$CC'(NSHIFT) = CC(NSHIFT) * NSHIFT / (NFFT - NSHIFT)$$

where NFFT is the FFT size and NSHIFT is the sample delay. The result is shown in Figure 11. Note that the correct peak has been enhanced by the window correction, but the true delay between channels is still not clearly observable.

## COMMENTS

This section briefly discusses a number issues that arise from using RECAT. A description of the problems and potential solutions is provided.

### False Alignments

Figure 9, with several closely spaced local minima, indicates the possiblilty of false alignments arising from RECAT. While in general, RECAT has proved to be reasonably robust, as examplified in Figures 2-8, strong narrowband components, or other data features may cause RECAT not to produce an unambiguious minimum error delay. The dominant causes of potential false alignment are discussed below;

A) Incorrect search. If the true delay between channels is not included in the range of time delays used for the RECAT search, it is possible that the two reference-redundant channel pairs will still have minimum errors at the same delay. This condition is often evidenced by very large comparison array sizes and small differences between the minimum error and surrounding errors, similar to the plot shown in Figure 9. One possible solution is to simply increase the range of samples searched by RECAT. Either a change in the location of the error minimum, or a large, 2-5 dB, change in the difference between the global minimum and surrounding local minima is a clue that the alignment may not be correct. A second remedy is to use three redundant channels instead of two. This provides three alignment pairs for RECAT, and reduces the chance of false alignment.

B) Time delays or equipment changes between reference and redundant channel acquisition. Differences between playback equipment can cause difficulties in obtaining a RECAT alignment. Switching low-pass filters between the reference and other passes has been shown to be troublesome with low SNR data. Similarly, all analog equipment is subject to thermal drift. Acquiring reference data just after amplifiers and filters have been turned on can cause difficulties, as well as with reference and redundant data digitized over a period of days. In the experience of the author, thermal drift over several days has not been a significant problem, but several days have been spent in frustration using data from an amplifier that required 20 minutes to reach equilibrium.

### Forward and Reverse Alignment

RECAT is also useful in concatenating data records, provided there is some overlap between the end of the first record and the start of the second. A version of RECAT, called ENDALIGN is available to calclulate the shift index in the redundant channel that corresponds to the last data point in the reference channel. If both versions are used to overcome A/D and digital storage limitations, experience has shown that the forward alignment, RECAT, before the backward alignment, ENDALIGN, is preferable to avoid gaps in second data set, Pass 2 record.

### Beamformer Considerations

If RECAT is used on hydrophone element data, intended for later beamforming, the effect of small time delays between channels is to degrade the beamformer performance. For uniformly distributed phase errors, this error is a function of sampling frequency, and is less than 0.1 dB for $f_s > 10\ f_o$ [1]. However, since RECAT alignments affect data channels in each pass identically, the phase errors are not random, but step functions, and may result in beam steering errors. By converting data in each pass from arbitrarily selected elements, these phase errors may be reduced to random equivalent.

### Data Bandwidth

For data with strong narrowband components some pre-processing can help RECAT align correctly. Clearly, for noise free sinusoids, RECAT will find a minimum error at each wave period. By notch filtering the narrowband components prior to RECAT with a digital filter, background and tape noise may be used for the alignment. Once RECAT has found the minimum error, this delay is applied to unfiltered data. Note that the entire data set need not be pre-filtered, only enough data to include the range of channel delays and the size of the comparison array.

## CONCLUSIONS

At present, RECAT has been used on three different broadband acoustic sets. The technique has been used to align both across many data channels and to concatenate data records. Thus, it can be used to overcome analog and digital hardware limitations. The principal assumption used in developing RECAT is that the user can digitally sample the data fast enough, typically 4-20 times the Nyquist rate, to achieve the required alignment accuracy. For more critical alignments, the usefulness of RECAT diminshes, as the cost of acquiring and processing extra data offsets additional hardware investments.

# REFERENCES

[1] Handbook of Array Design Technology, Volume 1, prepared by Applied Hydro-Acoustics Research Inc., for Naval Electronics Systems Command, Code 20, 1976, UNCLASSIFIED.

# APPENDIX A - LISTING OF RECAT PROGRAMS

```
C     RECAT.FOR
C     REDUNDANT CHANNEL ALIGNMENT TECHNIQUE
C     REAL REF1(10000),REF2(10000),COMP1(100000)
C     REAL COMP2(100000)
C     READ REFERENCE INPUT FILES
      WRITE (6,2)
2     FORMAT (' '/'  ** RECAT ** - READING 1ST REFERENCE FILE')
      CALL READ (REF1,9,ILEN1)
      WRITE (6,4)
4     FORMAT (' ',' ** RECAT ** - READING 2ND REFERENCE FILE')
      CALL READ (REF2,10,ILEN2)
C     CHECK REF FILE LENGTHS
      IF (ILEN1.NE.ILEN2) WRITE (6,10) ILEN1,ILEN2
10    FORMAT (' ','ERROR IN REFERENCE FILE LENGTHS'/      >' FILE 1 = ',I6,'
      FILE 2 = ',I6)
      IF (ILEN1.NE.ILEN2) GO TO 999
      NLEN=ILEN1
C     READ REDUNDANT INPUT FILES
      WRITE (6,12)
12    FORMAT (' ',' ** RECAT ** - READING 1ST REDUNDANT FILE')
      CALL READ (COMP1,11,ILEN1)
      WRITE (6,14)
14    FORMAT (' ',' ** RECAT ** - READING 2ND REDUNDANT FILE'/)
      CALL READ  (COMP2,12,ILEN2)
C     CHECK COMP FILE LENGTHS
      IF (ILEN1.NE.ILEN2) WRITE (6,20) ILEN1,ILEN2   20 FORMAT (' ','ERROR IN
      REDUNDANT FILE LENGTHS'/
      >' FILE 1 = ',I6,'  FILE 2 = ',I6)
      IF (ILEN1.NE.ILEN2) GO TO 999
      MLEN=ILEN1
C     READ IN ALIGNMENT
C     PARAMETERS
      READ (13,*) NOFF
      READ (13,*) NCOMP
      READ (13,*) NMAX
C     CORRECT NAMX FOR NOFF
      NMAX=NMAX-NOFF
C     WRITE (6,100)
100   FORMAT (' ',' ** BEGIN CHANNEL ALIGNMENT **')
C     CALL RECAT (REF1,COMP1,REF2,COMP2,NLEN,MLEN,
      > NCOMP,NSHIFT,NMAX,NOFF)
C     999
      STOP
      END
```

```
C     SUBROUTINE RECAT (X1,X2,Y1,Y2,N,M,NCOMP,NSHIFT,NMAX,NOFF)
C
C     NCOMP = NUMBER OF SAMPLES USED IN REFERENCE ARRAY
C             TO COMPUTE SHIFT INDEX
C     NMAX  = MAXIMUM NUMBER OF SAMPLES TO SHIFT FOR X2,Y2
C     X1    = PASS 1 CHAN 1 N SAMPLES
C     X2    = PASS 2 CHAN 1 M SAMPLES
C     Y1    = PASS 1 CHAN 2 N SAMPLES
C     Y2    = PASS 2 CHAN 2 M SAMPLES
C
C     REAL X1(N),Y1(N),X2(M),Y2(M)
      INTEGER N1(10000),N2(10000),NTST(10000)
C     START OF NCOMP LOOP
      ILOOP=1
C     SET ERROR FLAG
      IFLAG=0
C     COMPUTE N1 AND N2
10    CALL SHIFT (X1,N,X2,M,NCOMP,N1T,NMAX,SNRX,NOFF)
      CALL SHIFT (Y1,N,Y2,M,NCOMP,N2T,NMAX,SNRY,NOFF)
      N1(ILOOP)=N1T
      N2(ILOOP)=N2T
C     CHECK N1 AND N2
      IF (N1(ILOOP).NE.NMAX.AND.N2(ILOOP).NE.NMAX) GO TO 15
      WRITE (6,12)
12    FORMAT (' ','** ERROR IN RECAT - ALIGNMENT NOT CORRECT **')
      RETURN
C
15    NTST(ILOOP)=IABS(N1(ILOOP)-N2(ILOOP))
      IF (NTST(ILOOP)) 100,100,20
C     ERROR LOOP
20    WRITE (6,22) ILOOP,N1(ILOOP),N2(ILOOP),NTST(ILOOP)
22    FORMAT (' ','PASS',I4,'  INFORMATION'/
      >' OFFSET OF FILE 1 =',I8/
      >' OFFSET OF FILE 2 =',I8/
      >' DIFFERENCE BETWEEN OFFSETS =',I8/)
C     CHECK IF NTST=1
      IF (NTST(ILOOP).NE.1)  GO TO 40
      WRITE (6,30)
30    FORMAT (' ','ONE SAMPLE DIFFERENCE BETWEEN CHANNELS'/
       >' USE LESSER VALUE AS SHIFT INDEX (1)  OR TRY LARGER ARRAY
       >(0)')
      READ (5,5) ICONT
5     FORMAT (I1)
      IF (ICONT.EQ.1) GO TO 100
C     CHECK IN NTST(I)>NTST(I-1)
40    IF (IFLAG.EQ.1.AND.NTST(ILOOP).GT.NTST(ILOOP-1)) GO TO 60
      IF (NTST(ILOOP).GT.NTST(ILOOP-1)) IFLAG=1
C     CALC NEW REF ARRAY SIZE
      NCOMP=NCOMP+NCOMP/2
      IF (NCOMP.LT.((M-N)/2)) GO TO 90
```

```
C   REFERENCE ARRAY TOO LARGE
    WRITE (6,80) NCOMP
80  FORMAT (' ',' ** RECAT ** FATAL ERROR -'/
     >'                 SHIFT INDEX TOO LARGE =',I8)
    RETURN
C   SHIFT DIFFERENCE GETTING WORSE
C   FOR LARGER REFERENCE ARRAY
C   SIZE -- STOP
60  WRITE (6,70)
70  FORMAT (' ',' ** RECAT ** FATAL ERROR -'/
     >'                 SHIFT DIFFERENCES BETWEEN REDUNDANT CHANNELS'/
     >'                 INCREASING WITH INCREASING REFERENCE ARRAY'/
     >'                 LENGTH -- CHANGE SETUP AND RE-TRY'//
     >'  INPUT NEW COMPARISON ARRAY SIZE'/)
    ACCEPT *,NCOMP
C   INDEX I AND TRY AGAIN
C   BY GOING TO 10
90  WRITE (6,95) NCOMP
95  FORMAT (' ',' ** RECAT ** COMPARISON ARRAY SIZE SET TO ',I6)
    ILOOP=ILOOP+1
    GO TO 10
C   SUCCESSFUL ALIGMENT
100 CONTINUE
    SNRX=10.0*ALOG10(SNRX)
    SNRY=10.0*ALOG10(SNRY)
    WRITE (6,110) N1(ILOOP),SNRX,SNRY,ILOOP,NCOMP
110 FORMAT (' ',' ** RECAT SUCCESS ** '//
     >' SHIFT INDEX = ',I7//
     >' CHAN 1 SNR = ',F10.3,' DB'/
     >' CHAN 2 SNR = ',F10.3,' DB'//
     >'       ALIGNMENT TOOK ',I6,' PASSES'/
     >'         FOR REFERENCE FILE SIZE = ',I7)
C   END
    RETURN
    END
C
    SUBROUTINE SHIFT (X1,N,X2,M,NCOMP,NSHIFT,NMAX,SNR,NOFF)
C
C   RECAT SUBROUTINE
C   USED TO COMPUTE SHIFT INDEX CORRESPONDING TO MINIMUM
C   MEAN OF ABSOLUTE DIFFERENCE FIRST NCOMP SAMPLES
C   IN X1 AND ANY NCOMP SAMPLES IN X2
C
C   NSHIFT=0  ==> FATAL ERROR IN SHIFT ROUTINE
C
    REAL X1(N),X2(M)
    REAL REF(10000),COMP(10000),ERROR(10000),TEMP,SUM
    REAL XT(10000),YT(100000)
C
C   CHECK FILE LENGTHS
    IF (M.GE.N) GO TO 20
    NSHIFT=0
    WRITE (6,10)
10  FORMAT (' ',' ** SHIFT **  ERROR IN FILE LENGTHS')
    STOP
```

```
20  CONTINUE
C   SET UP REFERENCE
    DO 30 I=1,NCOMP
    REF(I)=X1(I)
30  CONTINUE
C   CALC NUMBER OF SHIFTS
    IF (NMAX.EQ.0) NMAX=2*(M-N)
    DO 100 J=1,NMAX
C   SET UP COMPARISON ARRAY

40  DO 50 I=1,NCOMP
    IOFFSET=I+J+NOFF-1
    COMP(I)=X2(IOFFSET)
50  CONTINUE
C   CALCULATE ERROR
    SUM=0.0
    DO 60 I=1,NCOMP
    TEMP=ABS(REF(I)-COMP(I))**2
    SUM=SUM+TEMP
60  CONTINUE
    ERROR(J)=SUM/FLOAT(NCOMP)
C   FIND MIN ERROR
C   NSHIFT = J OF
C   MIN ERROR
    IF (J.EQ.1) ERRMIN=ERROR(J)
    IF (ERROR(J).GT.ERRMIN) GO TO 100
    ERRMIN=ERROR(J)
    NSHIFT=J+NOFF-1
    PRINT *,ERRMIN,NSHIFT
100 CONTINUE
C   FLAG IF J=NMAX
    IF (ERRMIN.EQ.ERROR(NMAX)) WRITE (6,105) NSHIFT
105 FORMAT (' ',' ** SHIFT WARNING **'/
     >'     MINIMUM ERROR OCCURED AT MAXIMUM SHIFT SAMPLE'/
     >'     NSHIFT SET TO NMAX'/
     >' NSHIFT = ',I6/)
C   COMPUTE MS ERROR/SIGNAL
C   POWER RATIO
    SUM=0.0
    DO 110 I=1,NCOMP
    TEMP=REF(I)**2
    SUM=SUM+TEMP
110 CONTINUE
    SNR=ERRMIN*FLOAT(NCOMP)/SUM
C   PLOT ERROR VERSUS SHIFT
C   IF DESIRED
    WRITE (6,200)
200 FORMAT (' ','PLOT ERROR VERSUS SAMPLE SHIFT  NO=0  YES=1')
    READ (5,210) IFPLOT
210 FORMAT (I1)
    IF (IFPLOT.NE.1) GO TO 999
    DO 220 I=1,NMAX
    XT(I)=FLOAT(I)+NOFF-1
    YT(I)=10.0*ALOG10(ERROR(I))
```

```
220 CONTINUE
    CALL APLOT (XT,YT,NMAX,'SAMPLE INDEX','MS ERROR IN DB',
     >' SHIFT ERROR VERSUS SAMPLE')
C
 999     RETURN
    END
```

```
$! RECAT.COM
$ IF P1.EQS."" THEN WRITE SYS$OUTPUT "
"
$ IF P1.EQS."" THEN WRITE SYS$OUTPUT "
    ** RECAT ** "
$ IF P1.EQS."" THEN WRITE SYS$OUTPUT -
"   REDUNDANT CHANNEL ALIGNMENT TECHNIQUE"
$ IF P1.EQS."" THEN WRITE SYS$OUTPUT "
"
$ IF P1.EQS."" THEN INQUIRE P1 " 1ST REFERENCE FILE NAME"
$ IF P2.EQS."" THEN INQUIRE P2 " 2ND REFERENCE FILE NAME"
$ IF P3.EQS."" THEN INQUIRE P3 " 1ST REDUNDANT FILE NAME"
$ IF P4.EQS."" THEN INQUIRE P4 " 2ND REDUNDANT FILE NAME"
$ IF P5.EQS."" THEN INQUIRE P5 " INITIAL SAMPLE OFFSET"
$ IF P6.EQS."" THEN INQUIRE P6 " SAMPLES IN COMPARISON ARRAY"
$ IF P7.EQS."" THEN INQUIRE P7 " MAXIMUM SAMPLES OF SHIFT ALLOWED"
$!
$ NOFF=F$INTEGER(P5)
$ NCOMP=F$INTEGER(P6)
$ NMAX=F$INTEGER(P7)
$!
$ ASSIGN/USERMODE 'INPUTDIR''P1'.'DATATYPE' FOR009
$ ASSIGN/USERMODE 'INPUTDIR''P2'.'DATATYPE' FOR010
$ ASSIGN/USERMODE 'INPUTDIR''P3'.'DATATYPE' FOR011
$ ASSIGN/USERMODE 'INPUTDIR''P4'.'DATATYPE' FOR012
$!
$ ASSIGN/USERMODE INPUTS.TMP FOR013
$ OPEN/WRITE INPUTS INPUTS.TMP
$ WRITE INPUTS 'NOFF'
$ WRITE INPUTS 'NCOMP'
$ WRITE INPUTS 'NMAX'
$ CLOSE INPUTS
$!
$ ASSI/USERMODE SYS$COMMAND FOR005
$ ASSI/USERMODE SYS$COMMAND FOR$ACCEPT
$!
$ RUN 'PROCESSDIR'RECAT
$!
$ DELETE INPUTS.TMP;*
$!
$ EXIT
```

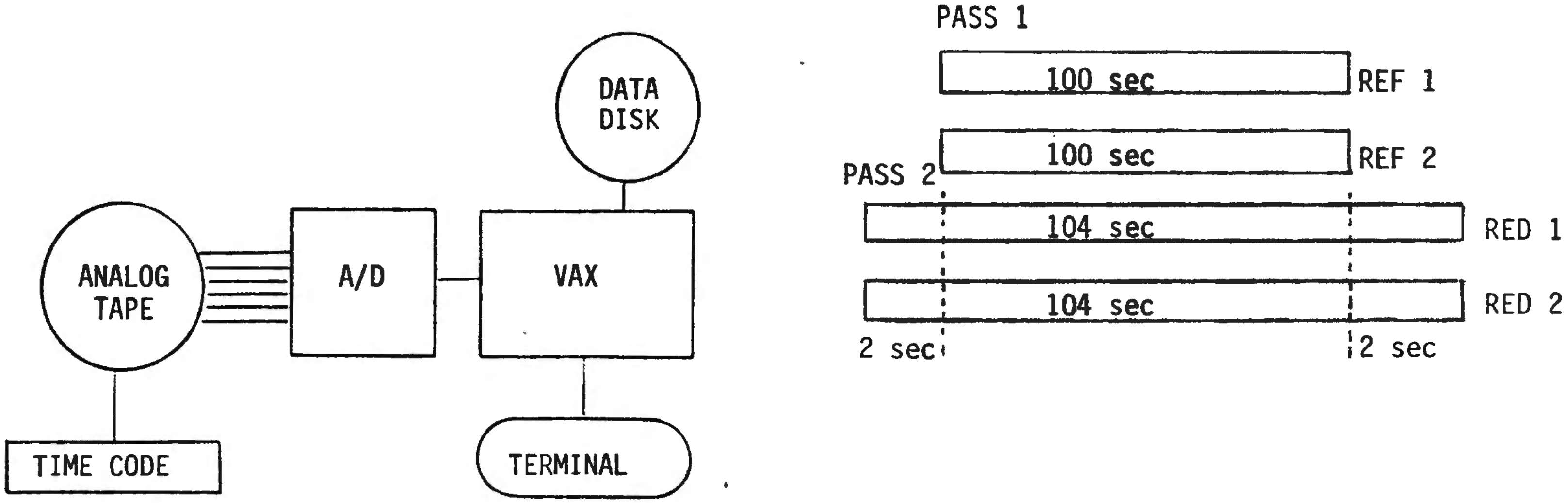


FIGURE 1 - Data Collection Equipment and Relationship of Pass 1 and Pass 2 Data files.

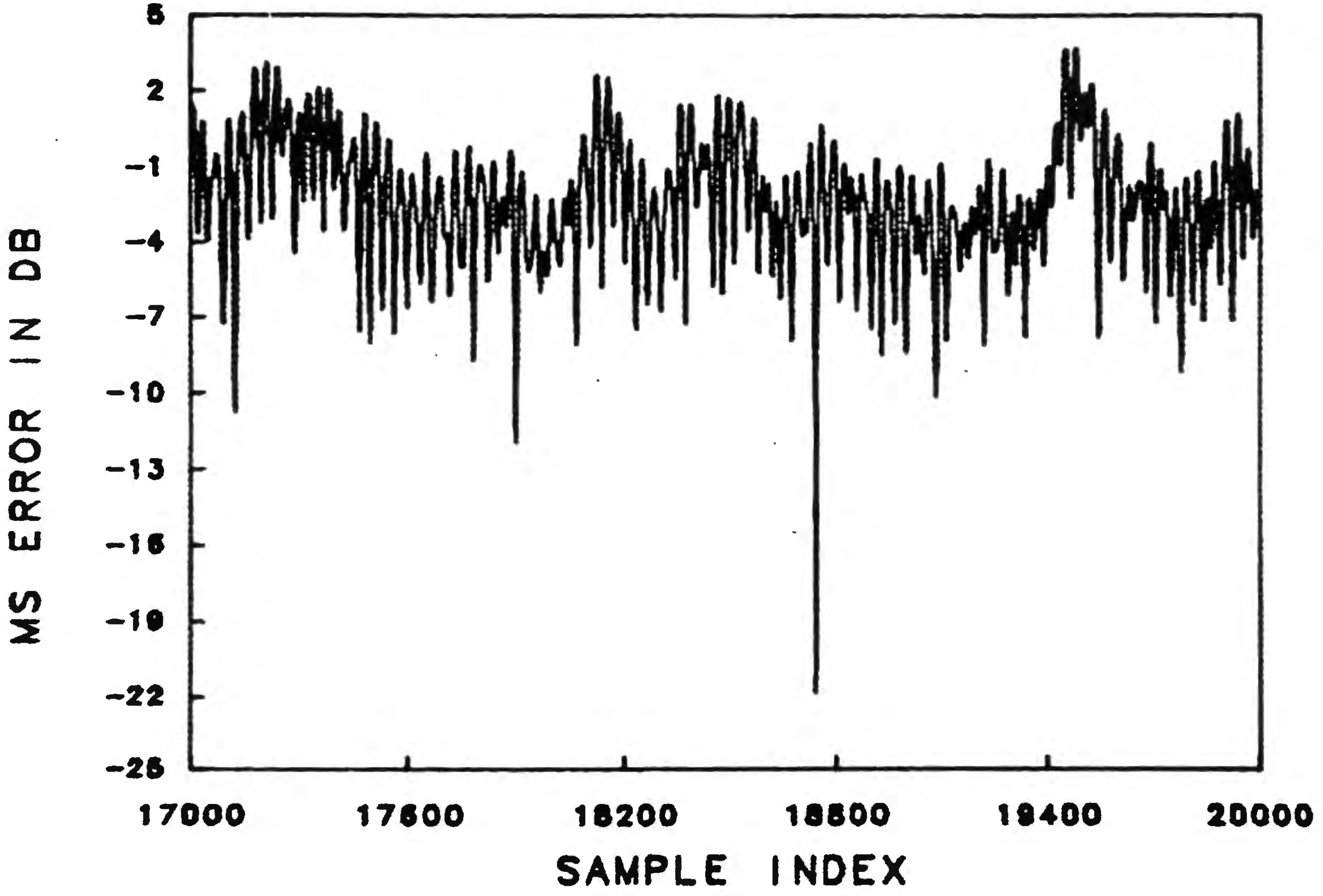


FIGURE 2 - Mean Square Difference versus Sample Shift for First Reference/Redundant Channel Pair in Test Case #1.

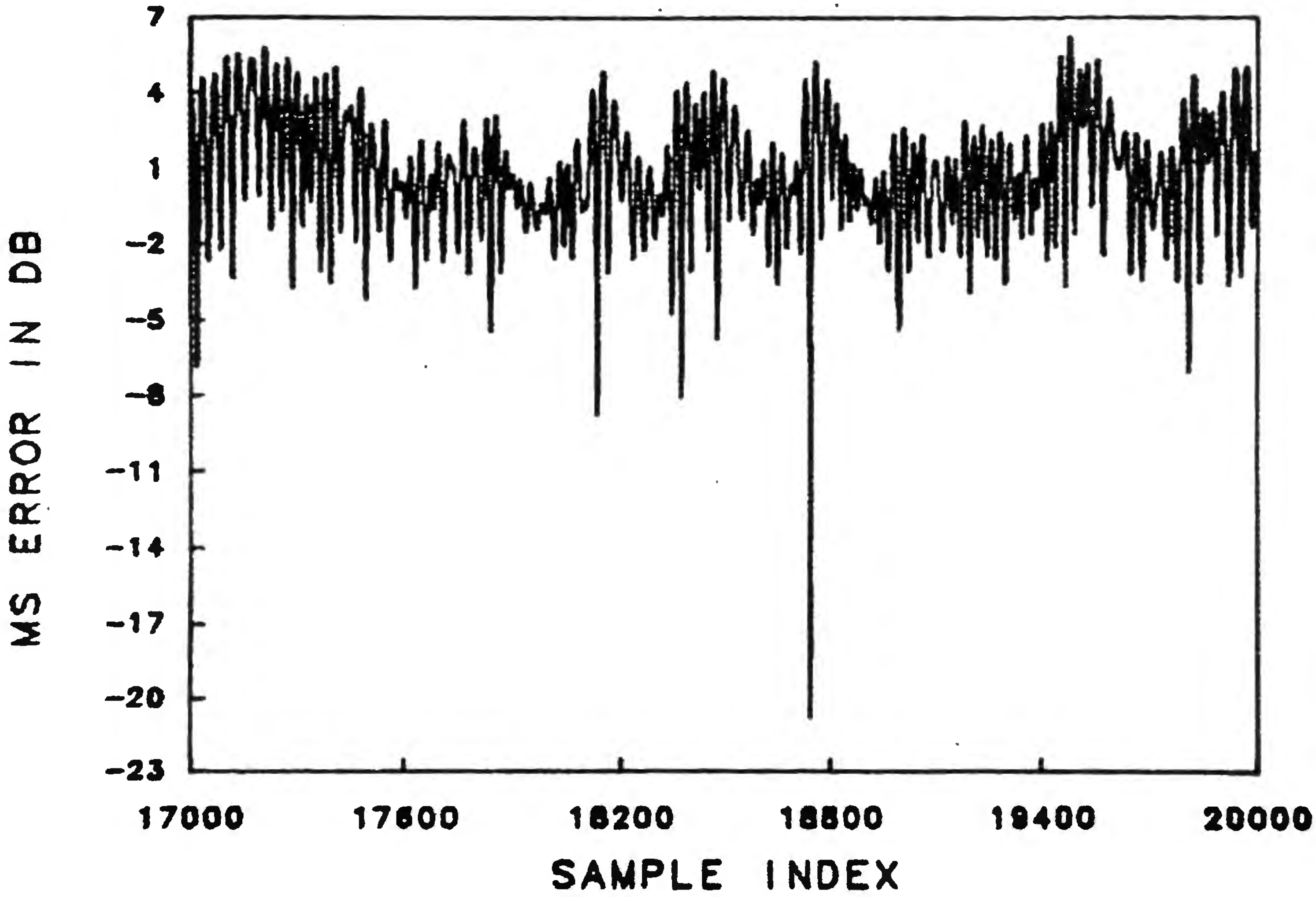


FIGURE 3 - Mean Square Difference versus Sample Shift for Second Reference/Redundant Channel Pair in Test Case #1.

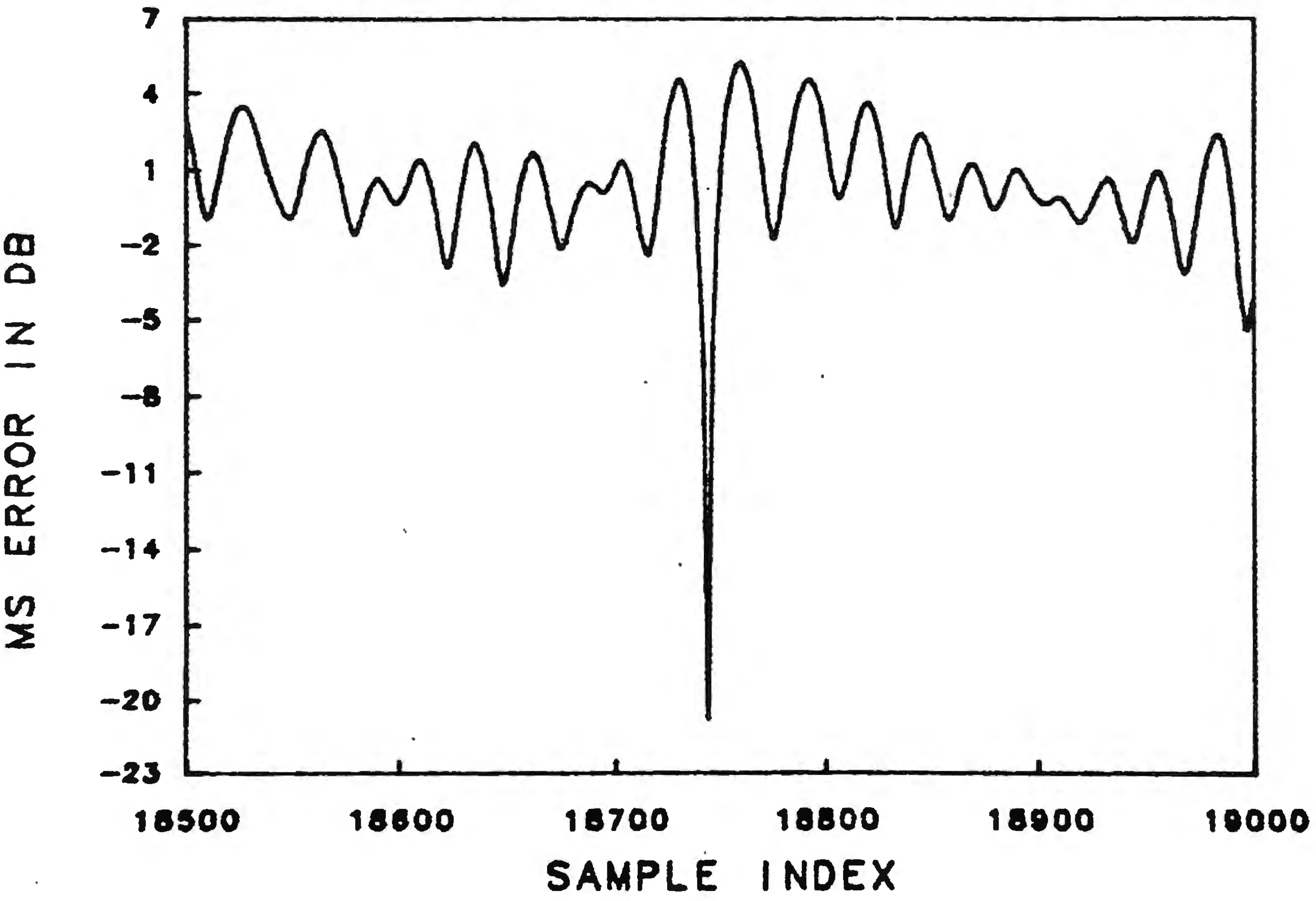


FIGURE 4 - Mean Square Difference versus Sample Shift for Second Reference/Redundant Channel Pair in Test Case #1. Plot is Expanded to Show Region Near the Minimum Difference.

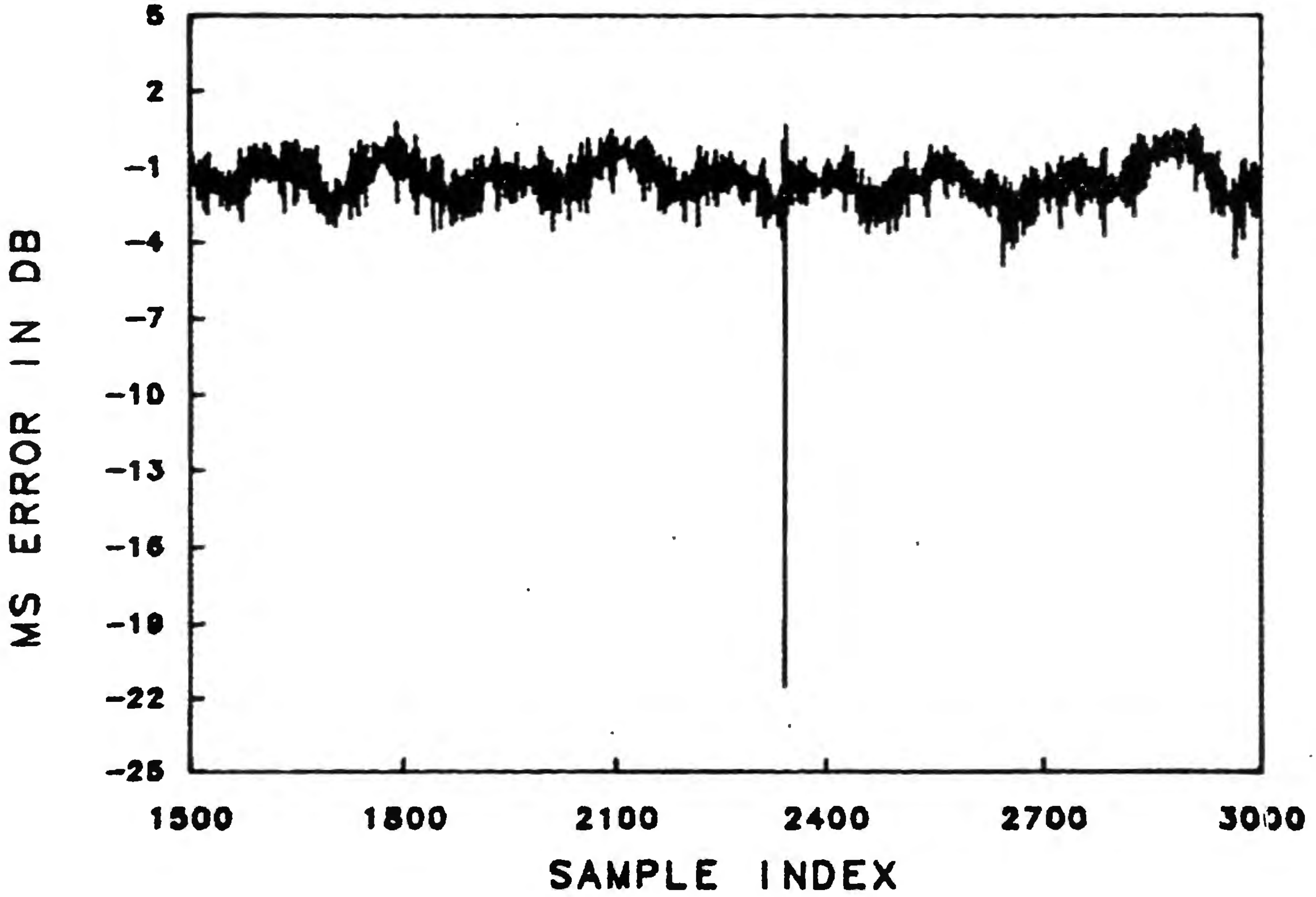


FIGURE 5 - Mean Square Difference versus Sample Shift for First Reference/Redundant Channel Pair in Test Case #2.

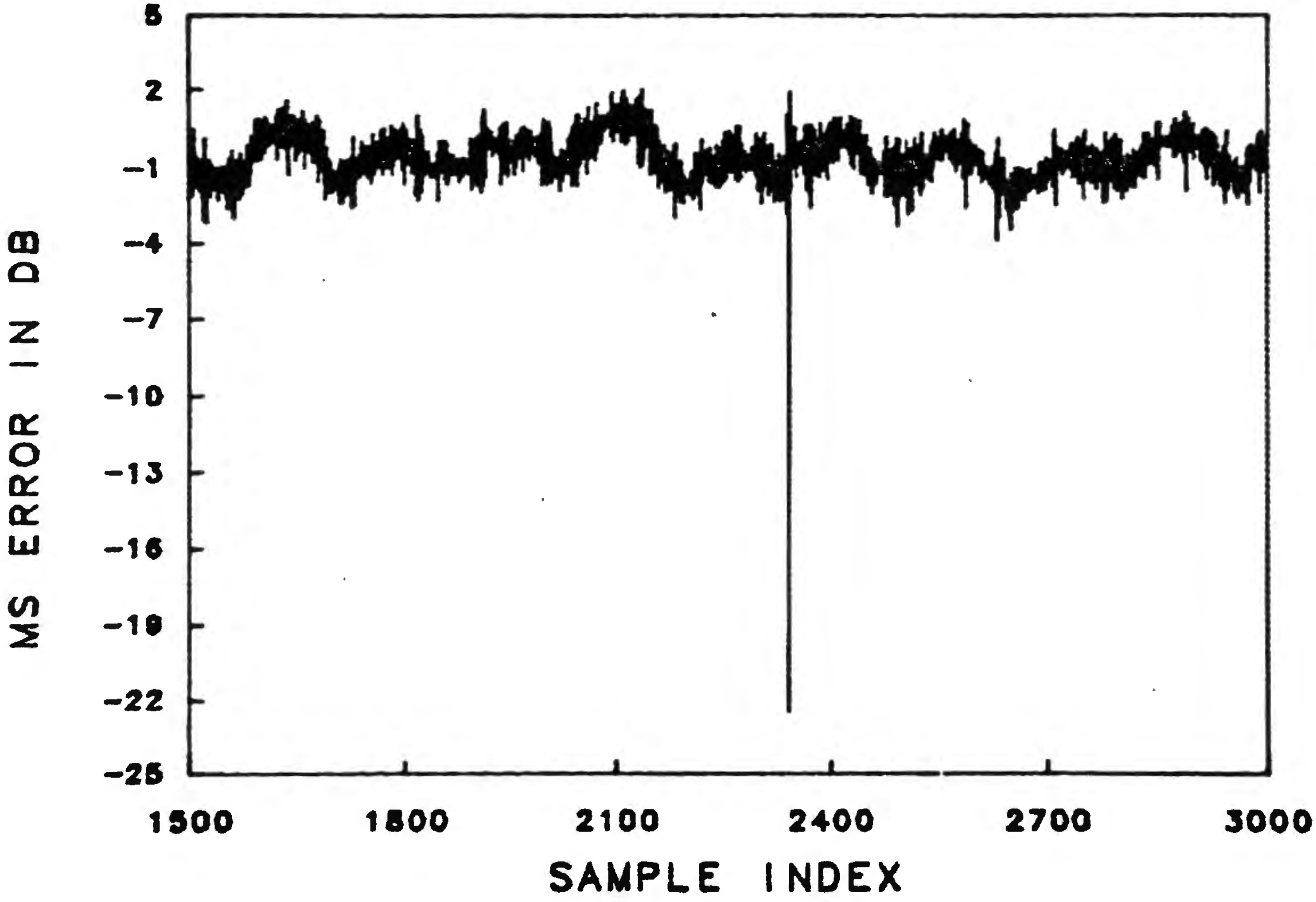


FIGURE 6 - Mean Square Difference versus Sample Shift for Second Reference/Redundant Channel Pair in Test Case #2.

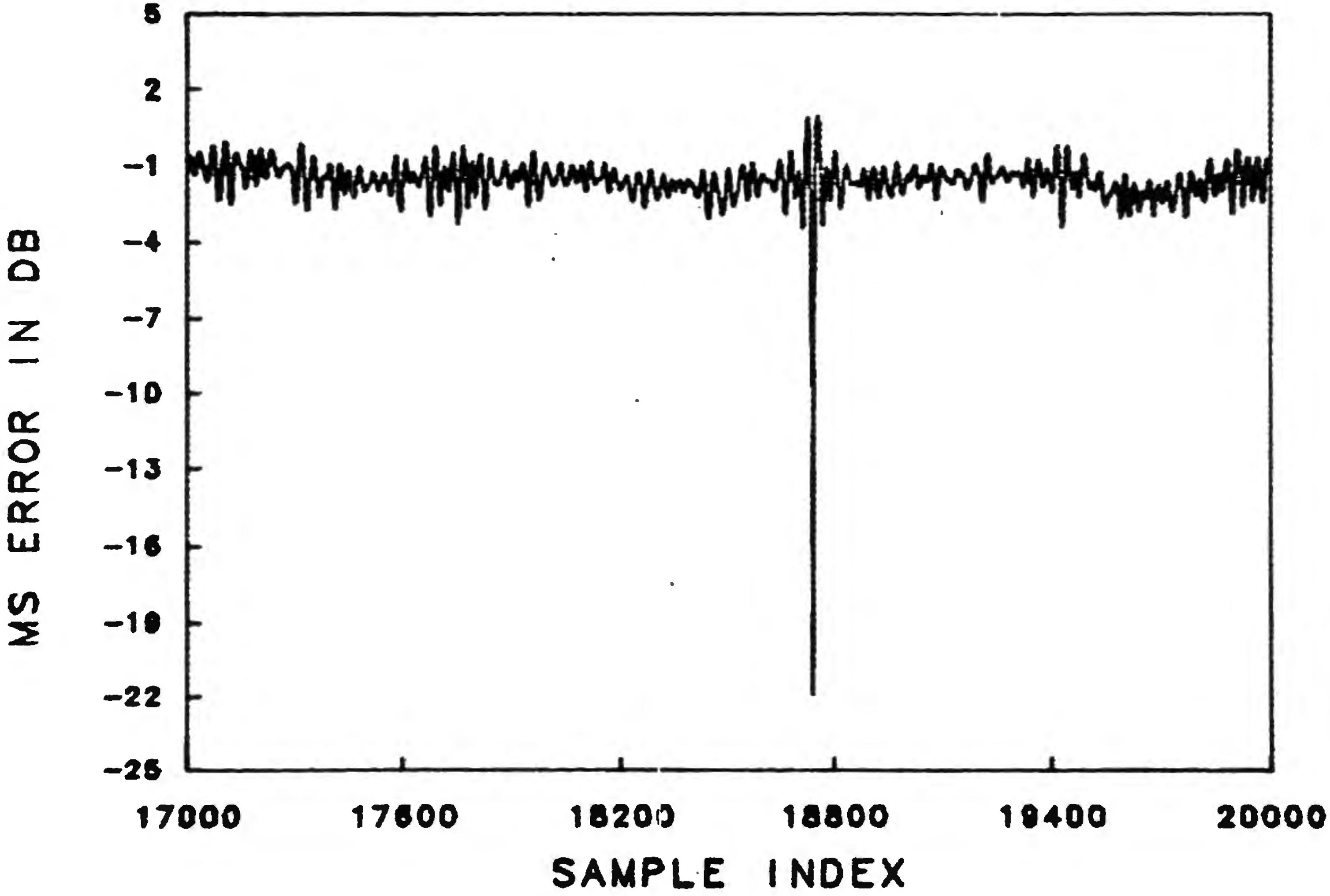


FIGURE 7 - Mean Square Difference versus Sample Shift for Reference/Redundant Channel Pair used in Test Case #3, K=1000.

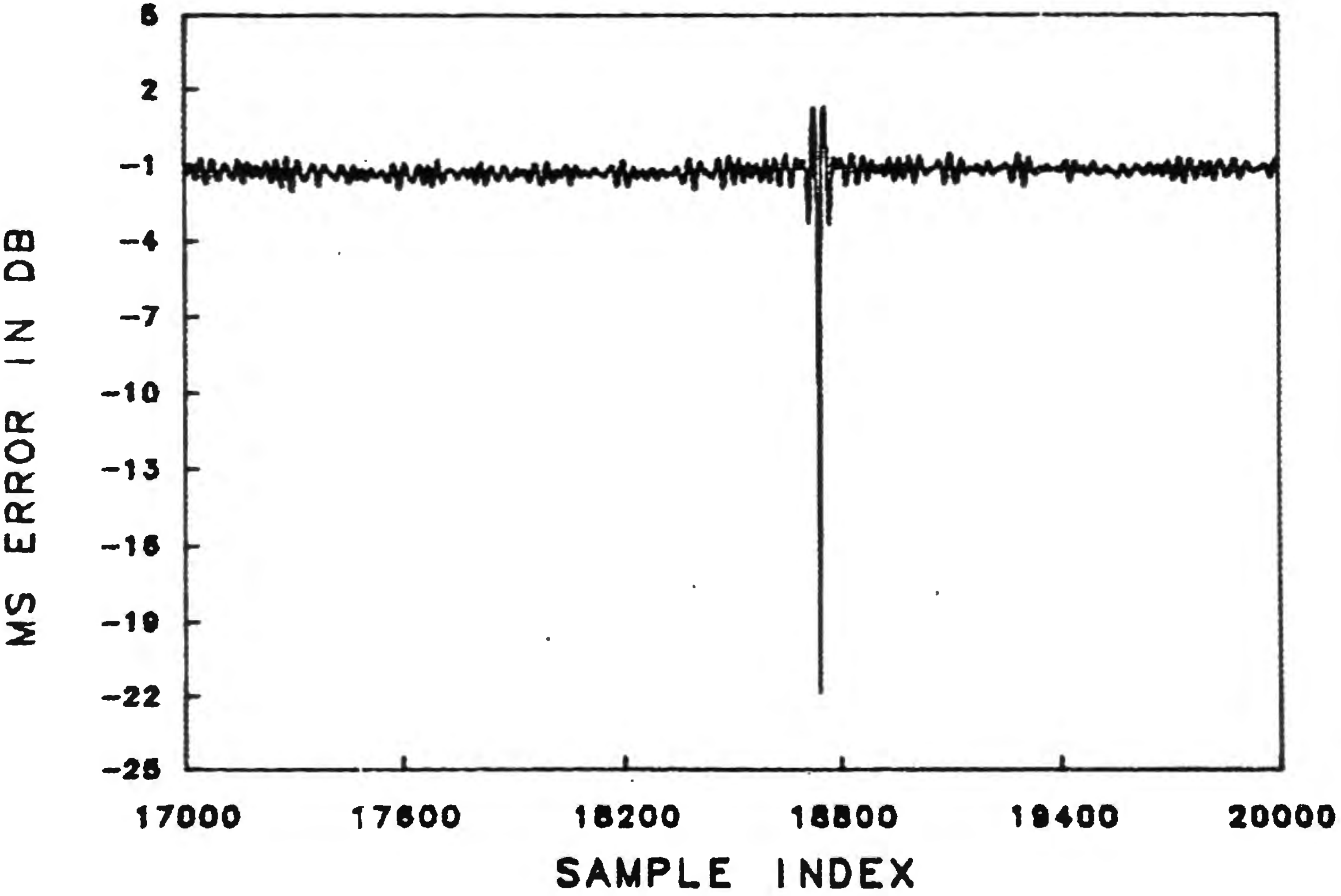


FIGURE 8 - Mean Square Difference versus Sample Shift for Reference/Redundant Channel Pair used in Test Case #3, K=5000.

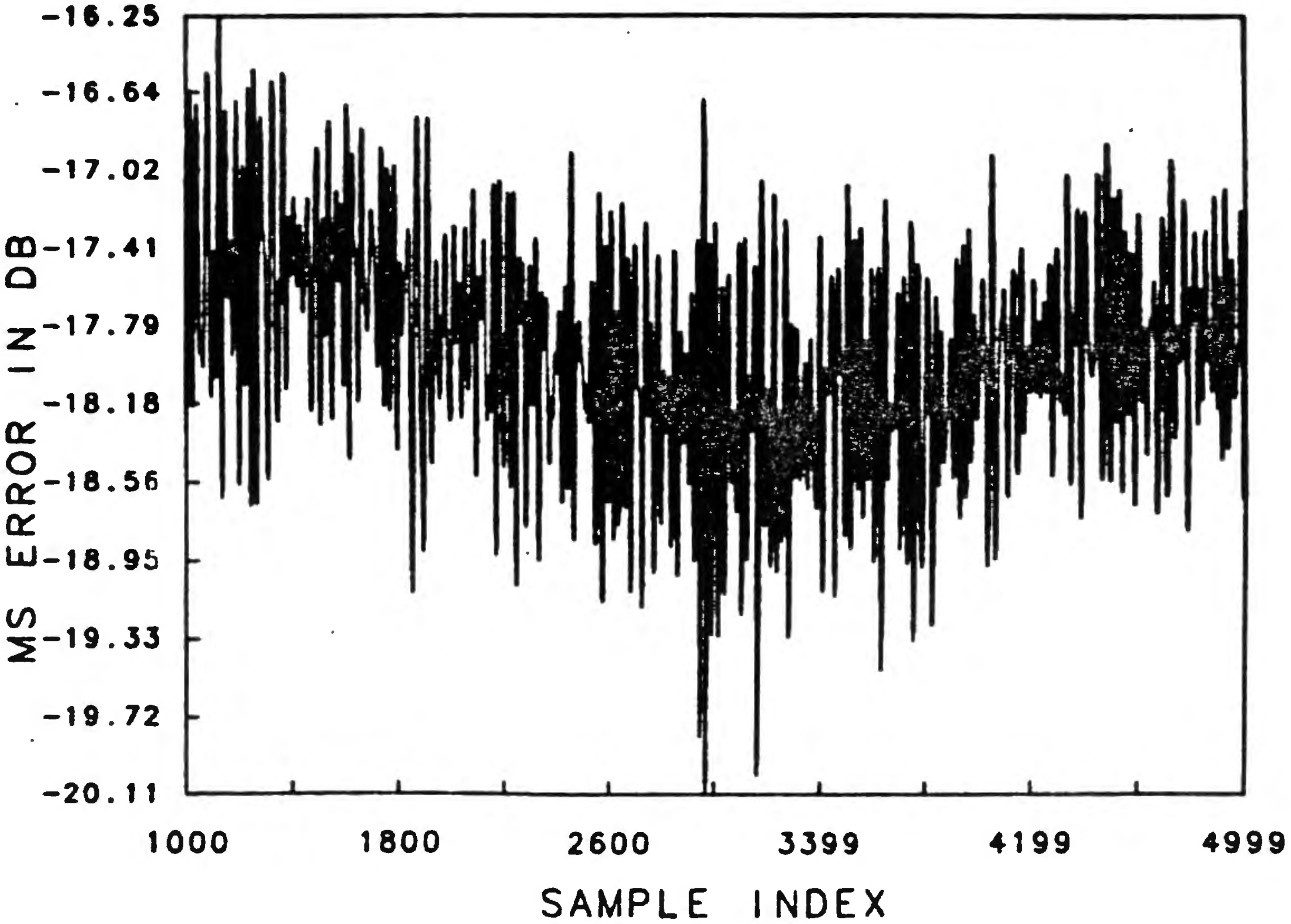


FIGURE 9 - Mean Square Difference versus Sample Shift for Reference/Redundant Channel Pair used in Test Case #4. Note Obscured Minimum Difference Peak.

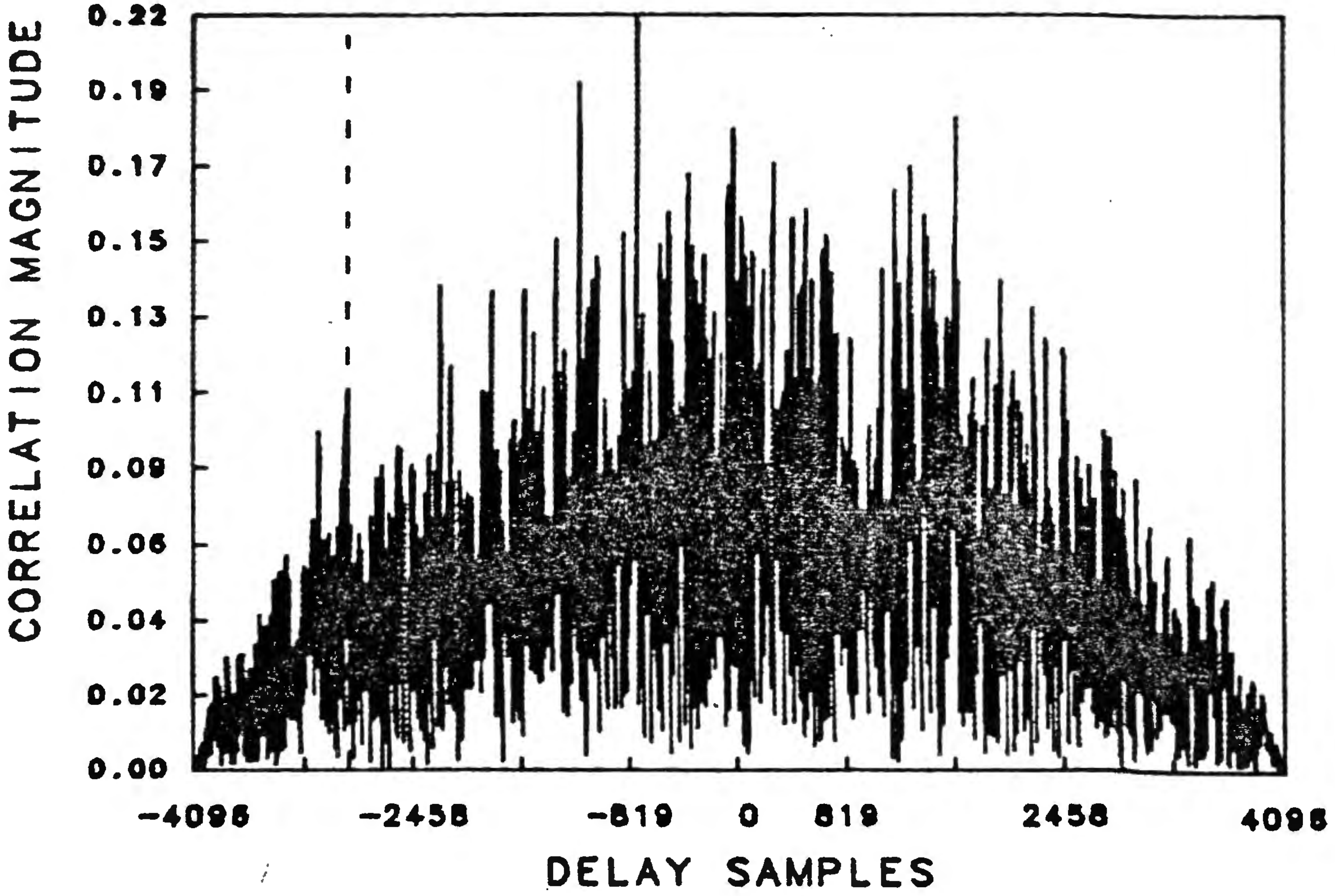
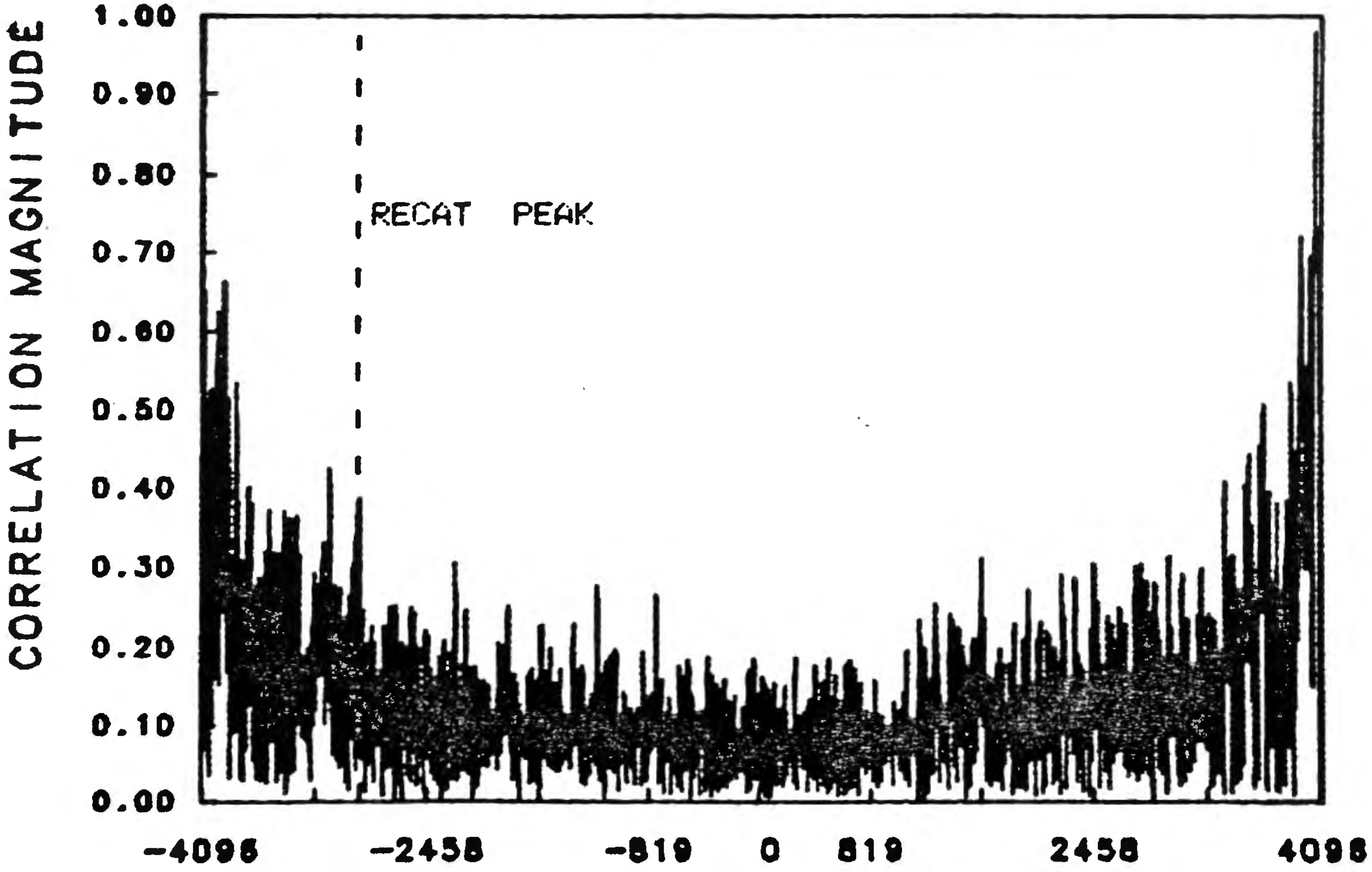


FIGURE 10 - Envelope of the Crosscorrelation between Reference and Redundant Channel Pair for Test Case #4. Dashed line Indicates Location of Minimum Error Determined using RECAT.



DELAY SAMPLES

FIGURE 11 - Envelope of Crosscorrelation Weighted by the Inverse of the Sample Shift. Dashed Line Indicates Location of Minimum Error Calculated using RECAT.

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Walter S. Hauck III
TM No. 861118
22 July 86

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