FORTTRAN Program for Linear Predictive Spectral Analysis of Univariante Complex Data With Disjoint Equi-Sized Pieces

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12 December 1977

NUSC
NAVAL UNDERWATER SYSTEMS CENTER
Newport, Rhode Island • New London, Connecticut

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PREFACE

This research was conducted under NUSC Project No. A-752-05, "Applications of Statistical Communication Theory to Acoustical Signal Processing," Principal Investigator, Dr. A. H. Nuttall (Code 313), Navy Subproject and Task No. ZR-00-001, Program Manager, J. H. Probus (MAT 035), Naval Material Command.

REVIE WED AN D APPROVED: 12 December 1977

R. W. Hasse
Head: Special Projects Department

The author of this document is located at the New London Laboratory, Naval Underwater Systems Center, New London, Connecticut 06320.
A FORTRAN program for linear predictive spectral analysis of univariate complex data with disjoint equi-sized pieces is presented. This result has application to data taken with a device that periodically goes off-line, and to maximum entropy beamforming on a limited number of equi-spaced linear array elements.
FORTRAN PROGRAM FOR LINEAR PREDICTIVE SPECTRAL ANALYSIS OF UNIVARIATE COMPLEX DATA WITH DISJOINT EQUI-SIZED PIECES

INTRODUCTION

In reference 1, the theoretical basis for estimating spectra via linear predictive techniques from univariate complex data with bad data points was presented. Also, a program was given there for spectral analysis of real data with gaps. Later, in reference 2, a program for complex data with no bad data points was presented. However, neither program is capable of handling complex data with gaps. This present document remedies this situation for the case where the disjoint pieces of complex data each have the same number of points.

Complex data can arise when a real process is complex-demodulated to zero frequency and sampled at a low rate for purposes of ease of processing and computation. Alternatively, if a real process is subjected to Fourier transformation into the frequency domain, complex coefficients result. Both of these examples are of frequent occurrences in practical applications.

Data segments of equal length can occur, for example, when a recording device is periodically taken off-line (for calibration purposes, perhaps), or if large periodic bursts of noise occur. An important frequency-domain application occurs for an equi-spaced line array of limited extent. Then the number of elements in the array is the maximum size of each disjoint piece of frequency coefficients. If, for a particular time segment of array outputs, we look at the Fourier coefficients at one frequency, we can attempt linear prediction in space; averaging the prediction error over time then yields the extrapolation effect inherent in maximum entropy processing (see reference 3). This will result in the array appearing to have a longer length than its true length, and thereby yield improved angular resolution of plane-wave arrivals. This approach is analogous to the improved frequency resolution obtainable from limited time data.

The input parameters to the program are fully explained in the comment statements. For a single piece of data, the number of disjoint pieces, ND, can be set equal to 1. A sample run is presented after the program. For application to linear predictive beamforming, delete the statement

\[ X(I, J) = X(I, J) - \text{AVE} \]

in loop 3 of SUBROUTINE CXDISJ.
LINEAR PREDICTIVE SPECTRAL ANALYSIS FOR UNIVARIATE COMPLEX DATA WITH DISJOINT EQUI-SIZED PIECES

EQUATION REFERENCES ARE TO NUTTALL, NUSC TR 5303, 26 MARCH 1976

USER: CHANGE LINES 26 AND 40, AND REPLACE SUBROUTINE DATA

N = NUMBER OF COMPLEX DATA POINTS IN EACH PIECE; INTEGER INPUT
ND = NUMBER OF DISJOINT PIECES; INTEGER INPUT
X(1,1),...X(N+1),...,X(1,ND),...,X(N,ND) = COMPLEX INPUT DATA
ALTERED ON OUTPUT
PMAX = MAXIMUM ORDER OF FILTER; PMAX,LT,N; INTEGER INPUT
NF = SIZE OF FFT (MUST BE A POWER OF 2 TO USE MKFFT); INTEGER INPUT
AVE = COMPLEX SAMPLE MEAN OF INPUT DATA; OUTPUT
P0 = SAMPLE POWER OF INPUT DATA; OUTPUT
AIC = AKAIKE'S INFORMATION CRITERION; OUTPUT
PBEST = BEST ORDER OF FILTER; INTEGER OUTPUT
SPBEST = (EQ H-7)/NF FOR P=PBEST; OUTPUT
SPMAX = (EQ H-7)/NF FOR P=PMAX; OUTPUT
A(1),...,A(PBEST) = COMPLEX PREDICTIVE FILTER COEFFICIENTS =
A(1:PBEST),...,A(PBEST:PBEST); OUTPUT
RHO(1),...,RHO(PMAX) = COMPLEX NORMALIZED CORRELATIONS; OUTPUT
XX(1),...,XX(NF) = SCALED SPECTRUM, WHOSE SUM SAMPLE POWER; OUTPUT
COSI(1),...,COSI(NF/4+1) = QUARTER COSINE TABLE FOR FFT PURPOSES
Y(N,NL) IS A REQUIRED COMPLEX AUXILIARY ARRAY

PARAMETER N = 10, ND = 20, PMAX = 6, NF = 512, NF41=NF/4+1
INTEGER PBEST,P
REAL SPBEST,T1,T2
COMPLEX X(N,ND),Y(N,NL),A(PMAX),RHO(PMAX),AVE,G,T
DIMENSION XX(NF),YY(NF),COSI(NF/41),AIC(PMAX),AICO(2)
EQUIVALENCE (AIC(1),AICO(2))

PRINT OUT VALUES OF PARAMETERS
I=N
J=ND
K=PMAX
L=NF
PRINT 1. J,K,L
PRINT 2
2 FORMAT(/' COMPLEX INPUT DATA :',/N(13,17.E15))
DO 3 J=1,ND
3 FORMAT (14,E18,15.E15)
C COMPLEX INPUT DATA IN X(j,j),..,X(ND),..,XCN,ND)
CALL DATA
PRINT 2
2 FORMAT(/' COMPLEX INPUT DATA:')
DO 3 J=1,ND
3 FORMAT (' PIECE NUMBER',I3)
3 PRINT 4. (X(I,J), I=1,N)
4 FORMAT(4(E18,8.E15.R))
C EVALUATE FILTER COEFFICIENTS CALL CXDISJ
PRINT 5. AVE
5 FORMAT(/' COMPLEX MEAN OF INPUT DATA : ',E13.8,E13.R)
PRINT 6. P0
6 FORMAT(/' SAMPLE POWER OF INPUT DATA : ',E13.8)
PRINT 7
7 FORMAT(/' AKAIKE INFORMATION CRITERION :'/9X,'P',11X,'AIC(p)')
PRINT 8. (P,AIC(P), P=0,15)
8 FORMAT(I10,E20,8,E3.6,8)
PRINT 9, PBEST
9 FORMAT(/' PBEST ',T3)
PRINT 10
10 FORMAT(/' PARTIAL CORRELATION COEFFICIENTS :'/9X,'P',9X,'R E A (P;P)',7X,'I M A (P;P)')
PRINT 11. (P,Y(P,1), P=0,15)
11 FORMAT (It0,E20,8,E3.6,8)
IF(PBEST.EQ.0) GO TO 12
PRINT 13
13 FORMAT(/' PREDICTIVE FILTER COEFFICIENTS FOR PBEST :'/9X,'P',7X,'R E A (K;PBEST)',3X,'I M A (K;PBEST)')
PRINT 11. (P,A(P), P=PBEST)
12 PRINT 14
14 FORMAT(/' NORMALIZED CORRELATIONS:
      $7X,'DELAY',9X,'RE RH0',10X,'IM RH0')
P=0
T=(1.,0.)
PRINT 11: P, T
PRINT 11: (P,RHO(P), P=1, IA)
C EVALUATE SPECTRAL ESTIMATE
CALL SPECT
PRINT 15
15 FORMAT(/' POWER SPECTRUM, STARTING FROM ZERO FREQUENCY (BIN 1):')
PRINT 16: (XX(I), I=1, NF)
16 FORMAT(2X,10E13.8)
PRINT 17: SUM
17 FORMAT(/' SUM OF SPECTRUM VALUES =',E13.8)
PRINT 18: P0
18 FORMAT(' SAMPLE POWER OF INPUT =',E13.8)
C SUBROUTINE DATA
C THIS SUBROUTINE GENERATES COMPLEX DATA
DEFINE IRAND=I*5**15+((1-SIGN(1,I*5**15))/2)*34359738367
DEFINE RAND=FLOAT(I)/34359738367.
I=5281
G=(.65,.65)
DO 1 J=1, N
   T=(0.,0.)
   DO 2 K=1, 200  @ WILL DISCARD THESE INITIAL POINTS
      I=IRAND
      T1=RAND-.5
      I=IRAND
      T2=RAND-.5
      T=G*T+CMPLX(T1,T2)
   2   T=G*T+CMPLX(T1,T2)
   DO 3 K=1, N
      I=IRAND
      T1=RAND-.5
      I=IRAND
   3   CONTINUE
      T=G*T+CMPLX(T1,T2)
C SUBROUTINE CXDISJ
C THIS SUBROUTINE COMPUTES AIC, PBEST, ALL THE FILTER
C COEFFICIENTS, AND THE NORMALIZED CORRELATIONS
C DOUBLE PRECISION SAR, SAI, SB
I=N
K=PMAX
IA=N-1
IF(PMAX.GE.N) PRINT 1, K, I, IA
1 FORMAT(/' PMAX = ', I4, ' IS TOO LARGE FOR NUMBER OF DATA',
$' \cdot POINTS N = ', I5, '; SEARCH LIMITED TO P = ', I4)
IA=MIN(IA, PMAX)
FAC=4./(N*ND) & FAC=0. WOULD FORCE PBEST EQUAL TO IA
C COMPUTE SAMPLE MEAN
AVE=(0., 0.)
DO 2 J=1, NO
  DO 2 I=1, N
    AV E= AVE+X(I,J)
2 AVE=CMPLX(REAL(AVE)/(N*ND),AIMAG(AVE)/(N*ND))
C SUBTRACT SAMPLE MEAN AND COMPUTE SAMPLE POWER
PO=0.,
DO 3 J=1, ND
  DO 3 I=1, N
    X(I,J)=X(I,J)-AVE @ TO KEEP SAMPLE MEAN, DELETE THIS CARD
3 Y(I,J)=X(I,J)
PO=PO+REAL(X(I,J))*2+AIMAG(X(I,J))*2
PO=PO/(N*ND)
C BEGIN RECURSION
AIC(0)=LOG(P0)
AICMIN=AIC(0)
PBEST=0
C   CALCULATE CROSS-GAIN: EQ 155
     SAR=0.D0
     SAI=0.D0
     SB=0.D0
     L=P+1
     DO 5 J=1,N
     DO 5 I=L,N
     T1=REAL(X(I,J))
     T2=AIMAG(X(I,J))
     T3=REAL(Y(I-1,J))
     T4=AIMAG(Y(I-1,J))
     SAR=SAR+T1*T3+T2*T4
     SAI=SAI+T2*T3—T1*T4
     T1=2.*SAR/SB
     T2=2.*SAI/SB
     G=CMPLX(T1,T2)
   5   SB=SB+T1**2+T2**2+T3**2+T4**2

C   CALCULATE FILTER COEFFICIENTS: Eqs 160&148. STORE IN X(1,1)...X(P,1)
     X(P,1)=G
     IF(P.EQ.1) GO TO 6
     L=P/2
     DO 7 I=1,L
     T=X(I,1)*G*CONJG(X(P-I,1))
     X(P-I,1)X(P-I,1)=G*CONJG(X(I,1))
    7   X(I,1)=T
C   CALCULATE NORMALIZED CORRELATION: EQ 149
   6   T=X(P,1)
     IF(P.EQ.1) GO TO 8
     L=P-1
     DO 9 I=1,L
     T=T+X(I,1)*RHO(P-I)
    8   RHO(P)=T
     }
C CALCULATE AKAIKE'S INFORMATION CRITERION
T1=1.0-4.0*(SAR**2+SAI**2)/SB**2
SPMAX=SPMAX*T1
AIC(P)=LOG(SPMAX)+FAC*P
IF(AIC(P).GE.AICMIN) GO TO 10
AICMIN=AIC(P)
PBEST=P
SPBEST=SPMAX
DO 11 I=1,P
11 A(I)=X(I,1)
10 IF(P.EQ.IA) GO TO 12
C UPDATE FORWARD AND BACKWARD SEQUENCES; EQ 153
L=P+1
DO 13 J=1,ND
DO 13 I=L,-1
T=X(I,J)-G*Y(I-1,J)
Y(I,J)=Y(I-1,J)+CONJG(G)*X(I,J)
13 X(I,J)=T
4 Y(P,1)=G
12 Y(IA,1)=G
IF(PBEST.EQ.IA) GO TO 11
C COMPUTE EXTRAPOLATED NORMALIZED CORRELATION
C COEFFICIENTS FROM PBEST+1 TO PMAX; EQ 165
L=PBEST+1
DO 15 P=L,IA
A(P)=(0.,0.)
T=(0.,0.)
DO 16 I=1,PBEST
16 T=T+A(I)*RHO(P-I)
15 RHO(P)=T
14 RETURN
C
SUBROUTINE SPECT
C THIS SUBROUTINE COMPUTES THE POWER SPECTRUM FOR PBEST; IT IS SCALED
C SUCH THAT THE SUM OF VALUES COMPUTED SHOULD EQUAL THE SAMPLE POWER
XX(1)=1,
YY(1)=0.
IF(PBEST.EQ.0) GO TO 1
DO 2 I=1,PBEST
2 XX(I+1) = REAL(A(I))
YY(I+1) = AIMAG(A(I))
L = PBEST+2
DO 3 I = L,NF
3 XX(I) = 0.
YY(I) = 0.
CALL QTRCOS(COSI,NF)
L = LOG(NF)+.5
CALL MKLFFT(XX,YY,COSI,L,-1)
SUM=0.
DO 4 I=1,NF
4 XX(I)=SPBEST/(XX(I)**2+YY(I)**2)
SUM=SUM+XX(I)
RETURN
END

SUBROUTINE QTRCOS(C,N)
DIMENSION C(1)
N41=N/4+1
SCL=6.283185307/N
DO 1 I=1,N41
1 C(I)=COS((I-1)*SCL)
RETURN
END
SUBROUTINE MKLFFT(X,Y,CC,M,ISN)

DIMENSION X(1),Y(1),CC(1),L(12)

EQUIVALENCE (L12,L(1)),(L11,L(2)),(L10,L(3)),(L9,L(4)),(L8,L(5)),
1(L7,L(6)),(L6,L(7)),(L5,L(8)),(L4,L(9)),(L3,L(10)),(L2,L(11)),
2(L1,L(12))

K=2**M

ND4=N/4

LJ4P1=ND4+1

LJ4P2=ND4P1+1

SU2P2=ND4+ND4P2

DO 8 L0=1,M

LMX=2***(M—L0)

L1X=2*LMX

ISCL=N/LIX

DO 8 LM=1,*LM

IARG=(LM—1)*ISCL+1

IF(IARG.LE.ND4P2) GO TO 4

C=CC(ND2P2—IARG)

S=ISN*CC(IARG—ND4)

GO TO 6

4 C=CC(IARG)

S=ISN*CC(ND4P2—IARG)

DO 6 LI=LIX,N,LIX

J1=LI=LIX+LM

J2=J1+LM

T1=X(J1)*X(J2)

T2=Y(J1)*Y(J2)

X(J1)=X(J1)+X(J2)

Y(J1)=Y(J1)+Y(J2)

X(J2)=C*T1—S*T2

Y(J2)=C*T2+S*T1

CONTINUE

8 CONTINUE

CONTINUE
DO 40 J=1,12
L(J)=1
IF(J-M) 31,31,40
31 L(J)=2**(M+1-J)
40 CONTINUE
JN=1
DO 60 J1=1,L1
DO 60 J2=J1,L2,L1
DO 60 J3=J2,L3,L2
DO 60 J4=J3,L4,L3
DO 60 J5=J4,L5,L4
DO 60 J6=J5,L6,L5
DO 60 J7=J6,L7,L6
DO 60 J8=J7,L8,L7
DO 60 J9=J8,L9,L8
DO 60 J10=J9,L10,L9
DO 60 J11=J10,L11,L10
DO 60 JR=J11,L12,L11
IF(JN-JR) 51,51,52
51 R=X(JN)
X(JN)=X(JR)
X(JR)=R
FI=Y(JN)
Y(JN)=Y(JR)
Y(JR)=FI
52 JN=JN+1
60 CONTINUE
RETURN
END
COMPLEX MEAN OF INPUT DATA = (-.66319221-01, -.40282205-01)

SAMPLE POWER OF INPUT DATA = .12248106+01

AKAIKE INFORMATION CRITERION:

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PBEST = 1

PARTIAL CORRELATION COEFFICIENTS:

| P | RE A(P|P) | IM A(P|P) |
|---|--------|---------|
| 1 | .65607898+00 | .65910558+00 |
| 2 | .71265785-01 | .71918564-01 |
| 3 | .11103264-01 | .13693754-01 |
| 4 | .44373563-01 | -.26964517-01 |
| 5 | -.73896198-01 | -.97876096-01 |
| 6 | .20138093-03 | .80211493-01 |

PREDICTIVE FILTER COEFFICIENTS FOR PBEST:

| K | RE A(K|PBEST) | IM A(K|PBEST) |
|---|-------------|-------------|
| 1 | .65607898+00 | .65910558+00 |

NORMALIZED CORRELATIONS:

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**SUM OF SPECTRUM VALUES = 1.22480068+01**

**SAMPLE POWER OF INPUT = 1.22481010+01**
REFERENCES


## INITIAL DISTRIBUTION LIST

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