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XSPECT: A Set of PDP-12 Computer Programs for the Frequency Analysis of Power, Coherence, and Phase of Two Channels of EEG Data

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INTRODUCTION

XSPECT is a pair of programs written for the PDP -12 Computer. Program XS written in DIAL, [5], accepts 2048 digital data measurements for each of two EEG channels, written on one reel of LINCtape mounted on Unit 0. This input record may be created from analog voltages input to the AD12 analog-to-digital converter, using the two D.E.C. programs, ADTAPE and ADCON [9]. The output of programs XS is a three-block record written on the "intermediate output tape", mounted on Unit 1.

The second program of the set is $XS, written in FOCAL-12 under the DIAL-MS monitor System. It accepts a three-block intermediate record from the LINCtape mounted on Unit 1, and uses the ASR-33 Teletype to create a listing of two auto-power density spectra, plus the coherence and phase relationships between the two EEG data channels. Frequencies are written on the left edge of the paper, with each line of output representing a .5-Hz frequency interval.

Requirements:

Hardware: PDP-12 computer with the following minimum options:

1. 8K memory
2. AD12 analog-to-digital converter
3. KW12 clock
4. Two LINCtape units
5. ASR-33 Teletype

Software: to be recorded on a single reel of LINCtape, referred to as the "program tape"

1. DIAL-MS Monitor system, with FOCAL-12
2. D.E.C. Programs ADTAPE and ADCON, or equivalent
3. DIAL binary program XS, FOCAL-12 programs $XS and $TYPEXS and (optionally) FOCAL-12 programs #XS1 and $TYPEXS1
4. A one-block binary dummy file under the name $HOLD

Operating Procedure

A. Data Collection Phase

1. Provide two or more channels of EEG data as analog signals into the AD12A/D converter. Operate program ADTAPE so as to record at least 2048 digital data points from each channel. Refer to the analysis section, below, for a discussion of the sampling rate to be used. When as much data as desired has been recorded by ADTAPE, proceed to convert it by ADCON.

2. The above proeedure may be replaced by any other method to create LINCtape records with at least eight consecutive tape blocks of single precision integer data for each of the two EEG channels to be analyzed.

B. Analysis Phase

3. Mount the program tape on Unit 0 and call up the DIAL-MS monitor system. Call for it to load program XS from Unit 0. The binary program will generally be stored for automatic starting in LINC mode. If not, it may be manually entered at register 20 of Memory Bank 1, (absolute address 10020).

4. The first entry into program XS causes the execution of subroutine LOAD, which reads two tape blocks of utility programs from the DIAL-MS system at the top of the upper memory bank, absolute addresses 17000 through 17777. The program then enters subroutine INPUT, which by means of the standard QUANDA subroutine displays the following message on the oscilloscope:

INPUT FIRST CHANNEL
STARTING BLOCK ---

5. At this point, and not before, it is necessary to remove the program tape and mount the data tape which was prepared in accordance with either paragraph 1 or 2 above. Also mount a reel to hold the intermediate output on Unit 1, although it may have been mounted at any earlier time if convenient.

6. Now type the (octal) number of the first tape block of the eight consecutive tape blocks of the first channel of EEG data to be analyzed. Follow the usual QUANDA conventions, but be sure to include leading zeros.

7. As soon as the first set of data has been read from tape, a second message will appear:

INPUT SECOND CHANNEL
STARTING BLOCK ---

When the starting block of the second channel has been typed in, program XS will read it, perform its computations, and output a three-block record on Unit 1.

8. All of the computations, plus the time for input and output, generally take about 25 seconds, give or take 5 seconds. When they are completed, the program automatically returns to sub-routine INPUT and displays the first message, given at the end of paragraph 4 above. Since the data tape is already mounted, one may proceed to the next analysis by typing the starting blocks of two more sets of data, as in paragraphs 6 and 7.

9. Of course the user is free at any time to change data tapes, even to do coherence and phase comparisons between EEG channels recorded on different reels, assuming that the two recordings are properly synchronized. Program XS always writes its first intermediate output record in the three tape blocks beginning with Block 0. It automatically assigns the epoch number 0 to this record and writes it as described in the section on output format given below. The second analysis is automatically assigned epoch number 1 and is recorded on blocks 3, 4, and 5, etc. Thus, the results of 170 (decimal) analyses may be written on a single intermediate output tape. It is very important for the user to keep accurate notes as to what data has been analyzed in each intermediate output record. For this purpose the teletype output provides a good record of the block numbers which have been requested. It is hoped that a later version of program XS will cause the teletype to list the successive epoch numbers as well.

C. Output Phase

10. For typing the results of the foregoing analyses, remount the program tape on Unit 0, call up DIAL-MS, load FOCAL-12, and execute the two FOCAL commands

```
*L L,$XS,0
*GO
```

11. The FOCAL-12 program $XS begins with an ASK statement which calls for the following four parameters to be typed in, according to the usual FOCAL standards:

BLOCK: C1: C2: LINES: (carriage return)

The first parameter is the starting block of the next epoch to be output. It must be typed in decimal form, and is always either a zero or a number divisible by three, (cf. paragraph 9 above). The next two parameters are the calibration constants to be used with the two EEG channels. These are decimal numbers which represent microvolts per unit output from the A/D converter. The final parameter indicates the number of lines of output to be typed. The maximum number is 95, which gives a final spectral estimate of the powers and coherences lying in the half-Hz. frequency range centered at .5 Hz intervals, from .5 to .5 Hz. However, the user may call for less than 95 lines of output, if he is not interested in the higher frequencies and does not want to waste time on the teletype writing them out.

12. As shown by the illustrative example of the output in Appendix A, the XSPECT set of programs outputs five additional parameters besides the frequency-dependent data described in the introductory paragraph. These include the epoch number, as described in paragraph 9 above, plus the mean and variance of each of the two channels of the raw EEG data. These are computed by program XS independently of the subroutine FFT-R and they may be used in the course of making a partial check on the rest of the output.

13. Program $XS accepts the four input parameters described in paragraph 11, outputs the five extra parameters described at the end of the last paragraph, and the headings. It stores certain constants in the dummy file $HOLD, which must be previously indexed by the program tape that is still mounted on Unit 0. The $XS chains program $TYPEXS, which continues with the actual spectral output. When it has written the number of lines specified by the user, it then automatically overlays itself with $XS. Another direct FOCAL command will initiate the actions described in

*GO (carriage return)

paragraph 11 and folling. Any number of epochs may be output in succession, and in any order. However, if the program $TYPEXS is interrupted by the standard FOCAL-12 convention of typing (CONTROL key)-C, then it is necessary to re-load $XS, as described in paragraph 10.

<u>Operation of program XS</u>

List of major subroutines, in order of execution (cf, Memory Map, Appendix (A)

LOAD

INPUT, (calls QUANDA twice)

COMPUTE

RAWDTA (calls SQUARE, ADD, and FFT-R)

SWAP

RAWDRA, (see above)

SPECT, (calls SUMPR and executes output subroutine)

(Return to subroutine INPUT)

The organization of program XS has been largely determined by subroutine FFT-R. Rather than try to modify a standard, well-documented program, it was easier to locate the various subroutines of XS in such a way as not to require moving any part of FFT-R. The same is true of subroutine QUANDA. Both of these subroutines must be placed in memory bank 0, and they must also be called from there. Hence, the bulk of program XS is placed in memory bank 1, but there are two short routines located in Block 15 of the lower bank by which access is made to the major subroutines there. These are GETFFT and GETQA. Most of Block 0 has also been left available to store an interrupt routine, since an earlier version of this program allowed for the analog-to-digital conversion and spectral analysis of data in real time.

The function of subroutine LOAD, and some of the functions of INPUT have already been described in the Introduction. The first EEG channel that is specified for input is read into the holding area of memory bank 1. This area happens to have the same relative addresses, with respect to the memory bank in which it is located, as the working area used by FFT-R in the lower memory bank. Although this correspondence was intended to simplify the programming, the location of the holding area could easily be changed.

The second EEG channel is read into the working area in memory bank 0. At the completion of subroutine INPUT, entry is made to subroutine COMPUT, which serves mainly as a driver for the subsequent subroutines, as shown in the list at the beginning of this section. Before doing so, however, COMPUT stores the current epoch number in register 0 of the output buffer, (locations 11000 through 12377), and then increments it for use in the next analysis.

Subroutine RAWDTA, ("rawdata"), finds the mean and the mean squared value of the measurements located in the working area located in memory bank 0. The arithmetic details of this operation are described below. RAWDTA then calls FFT-R. This subroutine overlays the original data in the working area with the corresponding Fourier coefficients, as described in the DECUS documentation. It also produces a binary scaling factor, which is obtained by subroutine GETFFT and deposited by subroutine RAWDTA into the output buffer area.

Return is then made to COMPUT, which calls SWAP. All of the Fourier coefficients in the working area in memory bank 0 are transferred one by one into the holding area in memory bank 1, while the raw data from EEG channel 1 is transferred from the upper area down into the lower. Subroutine RAWDTA is called again, the same computations are made as with the other channel, and return is made to COMPUT. Subroutine SPECT now performs the bulk of the computations which are essentailly unique in program XS. The Fourier coefficients for the two separate EEG channels are combined and averaged in such a way as to produce estimates of power, coherence, and phase for a set of specified frequency intervals. The mathematical details are given in the next section. The computed spectra are stored in the output buffer, and transition is made to the output section of subroutine SPECT.

Since the transition is made without a JMP command, no user symbol has been assigned to the beginning of the output subroutine. This routine writes the output buffer, absolute addresses 11000 through 12377, in three blocks of the intermediate output tape mounted on Unit 1 Tape block numbers are updated, so that the results of previous analyses are not over-written. Control is then returned to subroutine INPUT, which re-initiates the operating cycle.

Mathematical discussion

A set of N observations, X_k, taken at equal intervals of time, where N is an even number, may be represented by the following fourier series:

$$1)\quad X_k = \sum_{j=N/2}^{N/2} S_j W^{-jk}$$

where we make the following conventional definitions

$$2)\quad 1^2 = -1; \quad W = \exp(-2(pi)i/N)$$

and where the complex coefficients S_j are given

$$3)\quad S_j = (1/N) \sum_{k=0}^{(N/2)-1} X_k W^{jk}$$

As explained in the documentation of the fast fourier transform, [7], the program makes use of the hermitian symmetry of the complex coefficients S_j, whose real and imaginary parts may be designated A_j and B_j, respectively. Each number pair, (A_j,B_j) represents one of the sinusoidal harmonics of the given series of observations, and the variance, (proportional to electrical power), at this frequency is equal to (1/2) $(A_j^2 + B_j^2)$. The power density spectrum is obtained by averaging the power contributed by several harmonics within successive frequency intervals.

In a typical application, an analog signal may be sampled 2048 times in a 16-second period. The fundamental frequency is then 1/16 of a Hz. Because of aliasing, or the fold-over effect, the highest observable frequency is 62.5 Hz. Within each .5-Hz. interval below this frequency there will be found 8 harmonic frequencies. Program XS is currently designed to sum the variances in successive groups of 8 sinusoids and record them on the intermediate output tape. This is done for each of the two input raw EEG channels separately. Over the same frequency intervals, the program also computes the real and imaginary parts of the average cross-product between corresponding coefficients S_j and S'_j, computed from the two channels. These are later used for computing the phase and coherence relations between the two channels. The coherence may be thought of as a squared correlation coefficient between two sets of 8 complex numbers. The user of this program is referred to the standard literature, such as Lee, [1], and Bendat and Pierson, [2].

Format of the intermediate ouput tape

Integer arithmetic is used through out program XS. It requires only a change of interpretation to adapt the results of the FFT subroutine to this format, as it is documented in terms of binary fractions, [7]. However, the computed spectra are written as 24-bit signed, double precision integers, with the low order word always preceding the high order word. The three 256-word blocks written for each analysis are organized in groups of 8 words. Each of these sets, except for the first one, generates one line of teletyped output. The first pair of words within one of these sets of eight numbers is the double precision representation of the auto-power of the channel first named as input to XS. The second pair is the power found in the second channel. The third pair is the real part of the cross-spectrum, and the final pair is the imaginary part. However, the first set of 8 words in the first block has special functions, as described in the following Table 1.

The three tape blocks written by a single pass of XS are enough to write out a maximum of 95 lines. However, the program could easily be modified to write out more tape blocks, and thus accommodate more lines. From the memory map, one can see that the output buffer occupies the three blocks just below the area in Field 1 that holds the Fourier coefficients for channel 1. However, by the time the first few words of the output buffer have been computed, the program has completed all operations that require the first few words of this holding area. Therefore the output buffer could be either moved upward or extended to overlay the holding area.

TABLE 1

Description of the first 20 (octal) words of an intermediate ouput tape record.

WORD	CONTENTS
000	Epoch number, automatically incremented by XS
001	Not used
002	Mean value of raw data on channel 2
003	Twice the mean squared raw data on channel 2
004	SCALE parameter from the FFT subroutine, channel 2
005	Mean value of raw data on channel 1
006	Twice the mean squared raw data on channel 1
007	SCALE parameter from the FFT subroutine, channel 1

The following 10 (octal) representative words pertain to the lowest frequency range:

010	LO order auto-spectrum, channel 1
011	HI order auto-spectrum,channel 1
012	LO order auto-spectrum, channel 2
013	HI order auto-spectrum, channel 2
014	LO real part of cross-spectrum
015	HI real part od cross-spectrum
016	LO imaginary part of cross-spectrum
017	HI imaginary part of cross-spectrum

Conclusion

At the time of this writing, the present set of programs has just been completed and is about to be placed into routine operation. A great deal of further development, diversification, and extension is expected in the months and years immediately ahead. As an example, a real-time version for on-line use has already been written but only partly debugged, as described in [3]. This and other versions on hand also provide for an arbitrary selection of frequency intervals which do not even have to be of the same length and may or may not be overlapping.

A special version of FOCAL program $XS, called $MEANXS, has been written to combine the intermediate outputs from four successive 16-second epochs so as to obtain spectra based upon longer time series. This has the advantage of providing greater sampling stability. It has also been used to compare the results obtained by the present system on the PDP-12 with corresponding results obtained with entirely different analog-to-digital equipment and computing facilities. However, the program was written mainly for checkout purposes so that it is simply written and is too slow for production use.

Potential users of any of the programs described in this report are invited to get in touch with the writer, either by letter or preferably by telephone.

REFERENCES

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5. Digital Equipment Corporation, PDP-12 LAP6-DIAL programmer's reference manual, DEC-12-SE2D,-D 1970.

6. Digital Equipment Corporation, FOCAL-12 programming manual, DEC-12-AJAA-D, 1970.

7. Rothman, James E., FFTS-R - a fast fourier transform routine for real valued functions, DECUS No. 8-143, August 12, 1968.

8. Digital Equipment Corporation, QUANDA, an interactive subroutine using the VR12 display, DEC-12-FISA-D.

9. Digital Equipment Corporation, ADTAPE and ADCON, DEC-12-UW2A-D, June, 1970.

Appendix A

Memory Map for Program XS and Subroutines

Memory Bank 0

Absolute	Adresses,	(Octal form)
FROM	TO	CONTENTS
Block 0:		
0000	0002	Not used
0003	0007	Used by FFT-E
0010	0017	Not used
0020	0107	Used by FFT-R
0110	0377	Not used
Blocks 1 and 2:		
0400	1377	Subroutine FFT-E, main portion
Blocks 3 and 4:		
1400	2377	Sine table, used by FFT-R
Blocks 5 through 14:		
2400	6377	Working area used by FFT-R
Block 15:		
6400	6401	Top of working area used by FFT-R
6402	6530	Subroutine GETQA
6531	6561	Not used
6572	6577	GETFFT
6600	6777	Not used
Blocks 16 and 17:		
7000	7777	QUANDA

Memory Bank 1

Block 20:		
10000	10017	Not used
10020	10022	Entry points for subroutines LOAD, INPUT, and COMPUTE, (L-mode)
10023	10124	Not used
10125	10177	Common area used by all sub routines
10200	10204	Subroutine LOAD
10205	10230	Subroutine INPUT
10231	10251	Subroutine COMPUT
10252	10363	Not used
10364	10373	Used by subroutine INPUT
10374	10377	Not used

Memory Bank 1 (Cont.)

Absolute From	Addresses To	(Octal form) Contents
Block 21:		
10400	10456	Subroutine RAWDTA
10457	10552	Arithmetic subroutines: SQUARE and ADD.
10553	10577	Not used
10600	10627	Subroutine SWAP
10630	10734	Subroutine SPECT
10735	10756	Output subroutine
10757	10777	Not used
Blocks 22 through 24:		
11000	12377	Output buffer
Blocks 25 through 34:		
12400	16377	Holding area
Block 35:		
16400	16546	Subroutine SUMPR
16547	16777	Not used
Blocks 36 and 37:		
17000	17777	DIAL-MS utility programs, for use by subroutine INPUT

ADDENDUM

1. After the main portion of this documentation was written, subroutine SQUARE was dismantled and included as an internal part of subroutine RAWDTA in such a way as to obtain an additional five bits of precision in the computed value for the sum of the squares of the raw data. The FOCAL-12 programs $XS and $TYPEXS were also slightly revised to obtain greater precision. All of the above revisions are included in the copies of the source programs distributed with this paper, even though not reflected in the memory map in Appendix A.

2. Instructions for assembly: For convenience, subroutine GETQA was assembled separately from and prior to the main program XS. Before GETQA is assembled, program QANDA must be chanied to it. Then, after program XS is assembled, the "Add Binary" command must be called twice, in order to add the machine code for GETQA and FFTE, (the latter being one of the aliases for FFT-R).

3. (Please refer to paragraph A-1 under <u>Operating Procedure</u> on page 2): In these programs it is assumed that each data channel is sampled 128 times per second, which corresponds to a sample interval of approximately 7812 micro-seconds, as required by program ADTAPE. Other sampling rates may be chosen, but require changing various constants in the programs. The author will be glad to help any one wishing to make

any such changes.

4. The results of a number of analyses may be combined to obtain statistically more reliable estimates of power and coherence. A pair of FOCAL-12 programs, $MEANXS and $MEANXS1, have been written to combine four epochs at a time. Thus, a set of four 16-second epochs will give results comparable to a since 64-second epoch. Some experimental studies are currently under way, (August, 1972), to determine just how accurgate the entire system is, by comparison with older programs that have been thoroughly checked out on an IBM 360/65 system. At present, it appears that the power and coherence estimates compare very well between the PDP-12 and the IBM systems, but there are some anamolies in the phase estimates.