A Radix 2 FFT Program for the HPC

National Semiconductor
Application Note 487
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April 1987

INTRODUCTION

This report describes the implementation of a radix-2, Decimation-in-time FFT algorithm on the HPC. The program, as presently set up can do FFTs of length 2, 4, 8, 16, 32, 64, 128 and 256. The program can be easily modified to work with higher FFT lengths by increasing the Twiddle Factor table.

FFT FUNDAMENTALS

If x(n), $n = 0, 1, \ldots, N-1$ are N samples of a time domain signal, its Discrete Fourier Transform (DFT) is defined as

$$X(k) = \sum_{n=0}^{n=N-1} x(n)\, W^{nk}, \quad k = 0, 1, \ldots, N-1$$

where $W = e^{-j2\pi/N}$

The straight evaluation of the above equation requires on the order of N^2 complex multiplies. The FFT is nothing but a fast algorithm to compute the DFT that uses only on the order of N log(N) complex multiplies. Many different FFT algorithms exist (please see references 1, 2 and 3). The algorithm implemented for the HPC is the most common type of FFT — a radix-2, Decimation-in-time algorithm. This class of algorithms requires that the number of input samples, N, be a power of 2. This is usually not a problem, since the input data can be zero padded to achieve this. The development of this algorithm is described in references 1 and 2; the discussion here is brief and based on reference 1.

Separating the DFT summation above into the even-numbered points and odd-numbered points of x(n), we can rewrite the above sum as:

$$X(k) = \sum_{n\ \text{even}} x(n)\, W^{nk} + \sum_{n\ \text{odd}} x(n)\, W^{nk}$$

Using $n = 2r$ for n even and $n = 2r + 1$ for n odd, we can further rewrite the above as:

$$X(k) = \sum_{r=0}^{N/2-1} x(2r)\, W^{2rk} + W^{k} \sum_{r=0}^{N/2-1} x(2r+1)\, W^{2rk}$$

If G(k) is the N/2 point DFT of x(2r) and H(k) is the N/2 point DFT of x(2r+1), the above equation can be written as:

$$X(k) = G(k) + W^{k} H(k)$$

This equation shows that a N point DFT can be written as the sum of two N/2 point DFTs. The N/2 point DFTs can be computed as the sum two N/4 point DFTs and so on until we are left with two point DFTs. The two point DFTs can be trivially evaluated by direct computation.

Figure 1, taken from reference 1, shows the decomposition for the case $N = 8$. With reference to this figure, we can note the following points.

1. If N is the number of points in the original sequence, where $N = 2^L$, then there are L stages in the DFT decomposition.
2. The basic computation unit is the so-called Butterfly, shown in *Figure 2*. Each stage involves the computation of N/2 butterflies.
3. The results from the computation in one stage are fed to the next stage after multiplication by some power of W. These powers of W are the so-called Twiddle Factors. Note that each power of W is really a complex number that can be represented by its real and imaginary parts. The real part of W^k is $\cos(2\pi k/N)$ and the imaginary part is $-\sin(2\pi k/N)$.
4. The number of distinct Twiddle Factors used in the first stage is 1, in the second stage is 2 etc., until the L^{th} stage that involves $2^{L-1} = N/2$ twiddle factors. Each twiddle factor in the first stage is involved in N/2 Butterflies, in the second stage with N/4 butterflies etc., until in the L^{th} stage each twiddle factor is involved with $N/(2^L) = 1$ butterfly.
5. The input data sequence needs to be suitably scrambled if the output sequence is to be in the proper order. This scrambling is easily accomplished by using the so-called Bit-Reverse counter as outlined in reference 2.
6. The outputs from each stage can be stored back again in the same storage area as the input sequence. This gives the algorithm the in-place property. Thus the final DFT results overwrite the initial data.

THE INVERSE FFT

If X(k) $k = 0, 1, \ldots, N-1$ is the DFT of a sequence, then its inverse DFT, x(n), is defined as follows:

$$x(n) = \left(\frac{1}{N}\right) \sum_{k=0}^{k=N-1} X(k)\, W^{-nk} \quad n = 0, 1, \ldots, N-1.$$

Thus the Inverse FFT is the same as the forward FFT except for the following: 1. Negative powers of W are used instead of positive powers; and 2. The final sequence is scaled by 1/N. The basic FFT program can therefore be used to compute the inverse FFT with these two changes. This is the approach used in the HPC implementation.

TWIDDLE FACTOR TABLE

The brief description of the FFT in the previous section shows that the algorithm needs to use the Twiddle Factors W^k in the computation. The twiddle factors can either be computed as required, they can be computed using a recursive relation, or they can be obtained by looking up in a table (Ref. 2). The approach used in the HPC implementation is to construct a table containing the needed twiddle factors. This table is stored in ROM and values needed are looked up from this table. The length of the table needed is determined by the maximum FFT length that you want to use. The HPC FFT implementation is presently limited to a maximum length of 256. This requires that the twiddle factors W^0, W^1, ... W^{255} be available, where

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$W = e^{-j2\pi/256}$. Since $e^{jx} = \cos(x) + j\sin(x)$, the values stored in this table are cos(0), sin(0), cos($2\pi/256$), sin($2\pi/256$) etc., up to cos($2\pi \times 255/256$), sin ($2\pi \times 255/256$). The table used in the implementation is organized as follows:

.WORD cos(0) $\times 2^{14}$
.WORD sin(0) $\times 2^{14}$
.WORD cos($2\pi/256$) $\times 2^{14}$
.WORD sin($2\pi/256$) $\times 2^{14}$
.
.
.
.WORD cos($2\pi 255/256$) $\times 2^{14}$
.WORD sin($2\pi 255/256$) $\times 2^{14}$

This table is available in the file TWDTBL.MAC and occupies 1024 bytes of storage.

DATA STORAGE

The data to be transformed, x(0), . . . , x(N−1) are also regarded as complex numbers with a real and an imaginary part. Let xr(i) be the real part of x(i) and xi(i) the imaginary part of x(i). Then the data needs to be stored as follows:

.WORD xr(0)
.WORD xi(0)
.WORD xr(1)
.WORD xi(1)
.
.
.
.WORD xr(N−1)
.WORD xi(N−1)

The length of this storage area obviously depends on the number of data points to be transformed. Note that the FFT program itself does not use any base page user RAM. Also, only 8 words of stack are needed. Thus the base page user RAM can be used to store the data to be transformed. Since 192 bytes are available in this area, transforms of up to 32 point in length can be in the single chip mode with no external RAM.

USING THE FFT PROGRAM

The FFT program along with test data to test the program is provided in the files FFT.MAC, TSTDAT.MAC and TWDTBL.MAC. TSTDAT.MAC contains the test data, and the output from the FFT routines. TWDTBL.MAC contains the Twiddle Factors. The FFT computation involves the use of 4 different subroutines: FFT, IFFT, BRNCNTR and SMULT. FFT does the forward FFT calculation, IFFT the Inverse FFT calculation, BRNCNTR implements the bit reversed counter, and SMULT does signed multiplication.

Two global symbols need to be defined by the user to use the FFT routines. The first, called TWSTAD should be set to the address of the start of the twiddle factor table. The second, called DTSTAD, should be set to the address of the start of the data area to be transformed. For details on the organization of these storage areas, see the preceding sections.

The actual number of data points to be transformed needs to be passed to the FFT routines. This is done as follows.

Two symbols that refer to words of on-chip RAM have been defined. The first is NUMB = W(01C0) and the second is L1 = W(01C2). Before calling the FFT routine, the user should load NUMB with N, the number of data points to be transformed, and L1 with L, $N = 2^L$.

To do a forward FFT, call FFT; to do an inverse FFT, call IFFT. In both cases, the output of the transform overwrites the input data.

INCREASING THE MAXIMUM TRANSFORM LENGTH

The maximum transform length for the FFT program is primarily limited by the size of the Twiddle Factor table. To increase the transform length, the following needs to be done.

1. Increase the Twiddle Factor table. Thus, if the maximum transform length required is 1024, the table needs to store the cosine and sine of the angles

   $0, 2\pi/1024, 2\pi \times 2/1024, \ldots, 2\pi \times 1023/1024$

2. Change the global symbol LMAX such that the maximum transform length is 2^{LMAX}.

FFT/IFFT TEST PROGRAM

The data in the file TSTDAT.MAC can be used to test the FFT program. The data and its transform value is from reference 3. The program in reference 3 is for a Floating point FORTRAN FFT program. Since the HPC FFT program is a fixed point one, the input data needs to be suitably scaled. The scale factor chosen is 2^{10}. The file TSTDAT.MAC contains the scaled input data, and the expected transform. The input data is stored in memory words 200/27E and the expected transform is stored in memory words 280/2FE. To run the test program, do the following.

Set up the MOLE Development System with Blocks 0, 13, 14 and 15 mapped ON. Download the program to the MOLE. Set up a Breakpoint at F410. Run the program starting at F400. When the program is breakpointed, list memory words 200/27F and compare them with memory words 280/2FE.

Note that any difference between the expected DFT values and the DFT values actually computed is due to the fixed point computations in the FFT program.

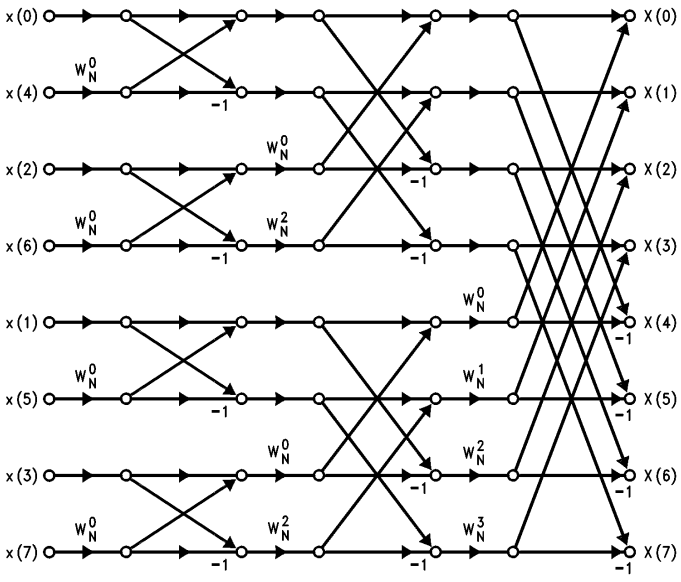

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FIGURE 1. FFT Flow Graph for N = 8 Points

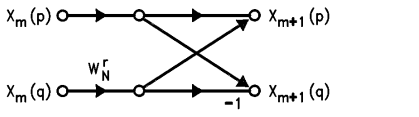

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FIGURE 2. The Butterfly—The Basic Computation Unit in the FFT

REFERENCES

1. A.V. Oppenheim and R.W. Schafer, *Digital Signal Processing*, Prentice-Hall, New Jersey, 1975.
2. L.R. Rabiner and B. Gold, *Theory and Applications of Digital Signal Processing*, Prentice-Hall, New Jersey, 1975.
3. IEEE ASSP Society Digital Signal Processing Committee, *Programs for Digital Signal Processing*, IEEE Press, New York, 1979.

The code listed in this App Note is available on Dial-A-Helper.

Dial-A-Helper is a service provided by the Microcontroller Applications Group. The Dial-A-Helper system provides access to an automated information storage and retrieval system that may be accessed over standard dial-up telephone lines 24 hours a day. The system capabilities include a MESSAGE SECTION (electronic mail) for communicating to and from the Microcontroller Applications Group and a FILE SECTION mode that can be used to search out and retrieve application data about NSC Microcontrollers. The minimum system requirement is a dumb terminal, 300 or 1200 baud modem, and a telephone.

With a communications package and a PC, the code detailed in this App Note can be down loaded from the FILE SECTION to disk for later use. The Dial-A-Helper telephone lines are:

Modem (408) 739-1162
Voice (408) 721-5582

For Additional Information, Please Contact Factory

APPENDIX A

Listing of FFT Program Code

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  1                     ;
  2                     ; THIS PROGRAM IMPLEMENTS A RADIX-2, DECIMATION IN TIME FFT ALGORITHM.
  3                     ;
  4                     ;
  5      0008                           LMAX = 08               ; MAXIMUM FFT LENGTH IS 2^LMAX.
  6                                                            ;
  7      F000                           TWSTAD = 0F000          ; TWIDDLE FACTOR TABLE START
  8                                                            ; ADDRESS.
  9      0200                           DTSTAD = 0200           ; DATA STORAGE AREA START
 10                                                            ; ADDRESS.
 11                     ;
 12      01C0                           NUMB = W(01C0)          ; NUMBER OF DATA POINTS TO BE
 13                                                            ; TRANSFORMED.
 14      01C2                           L1 = W(01C2)            ; NUMB IS 2^L1.
 15      01C4                           LSHIFT = W(01C4)        ; LSHIFT = LMAX - L1. IT IS A SHIFT
 16                                                            ; FACTOR NEEDED TO COMPUTE THE
 17                                                            ; ADDRESS REQUIRED FOR TWIDDLE
 18                                                            ; FACTOR LOCKUP.
 19      01C6                           NBFLY = W(01C6)         ; NUMBER OF BUTTERFLIES PER
 20                                                            ; TWIDDLE FACTOR PER STAGE.
 21      01C8                           ISTEP = W(01C8)         ; IF X(1) AND X(J) ARE INVOLVED
 22                                                            ; IN A BUTTERFLY, THEN J=I+ISTEP.
 23                                                            ; IT IS ALSO THE NUMBER OF TWIDDLE
 24                                                            ; FACTORS IN A STAGE.
 25      01CA                           ILEAP = W(01CA)         ; IF X(I) IS THE FIRST DATA VALUE
 26                                                            ; FOR THE FIRST BUTTERFLY FOR A
 27                                                            ; GIVEN TWIDDLE FACTOR, THEN THE
 28                                                            ; SUBSEQUENT BUTTERFLIES FOR THAT
 29                                                            ; TWIDDLE FACTOR HAVE AS THE FIRST
 30                                                            ; DATA VALUE X(I+N*ILEAP).
 31      01CC                           WESTEP = W(01CC)        ; TWIDDLE FACTOR EXPONENT STEP.
 32                                                            ; THE TWIDDLE FACTORS FOR A GIVEN
 33                                                            ; STAGE ARE W^(I*WESTEP).
 34      01CE                           NSTG = W(01CE)          ; FFT STAGE BEING EVALUATED.
 35                                                            ;
 36      01D0                           ISTART = W(01D0)        ; INDEX OF THE FIRST DATA VALUE
 37                                                            ; FOR THE FIRST BUTTERFLY FOR A
 38                                                            ; GIVEN TWIDDLE FACTOR.
 39      01D2                           WEXP = W(01D2)          ; EXPONENT VALUE FOR A GIVEN
 40                                                            ; TWIDDLE FACTOR.
 41      01D4                           NTWD = W(01D4)          ; TWIDDLE FACTOR BEING EVALUATED.
 42                                                            ;
 43      01D6                           COSTH = W(01D6)         ; COSINE PART OF TWIDDLE FACTOR.
 44                                                            ;
 45      01D8                           SINTH = W(01D8)         ; SINE PART OF TWIDDLE FACTOR.
 46                                                            ;
 47      01DA                           M1 = W(01DA)            ; INDEX OF FIRST DATA VALUE FOR
 48                                                            ; A BUTTERFLY.
 49      01DC                           NBCNT = W(01DC)         ; BUTTERFLY BEING EVALUATED.
 50                                                            ;
 51      01DE                           R1ADDR = W(01DE)        ; ADDRESS OF REAL PART OF FIRST
```

```
 52                                                     ; DATA VALUE INVOLVED IN A BUTTERFLY.
 53      01E0                           R2ADDR = W(01E0) ; ADDRESS OF REAL PART OF SECOND
 54                                                     ; DATA VALUE INVOLVED IN A BUTTERFLY.
 55      01E2                           XR1 = W(01E2)    ; REAL PART OF FIRST DATA VALUE
 56                                                     ; INVOLVED IN A BUTTERFLY.
 57      01E4                           XI1= W(01E4)     ; IMAGINARY PART OF ABOVE.
 58                                                     ;
 59      01E6                           XR2 = W(01E6)    ; REAL PART OF SECOND DATA VALUE
 60                                                     ; INVOLVED IN A BUTTERFLY.
 61      01E8                           XI2 = W(01E8)    ; IMAGINARY PART OF ABOVE.
 62                                                     ;
 63      01EA                           TEMPR = W(01EA)  ; TEMPORARY STORAGE USED IN
 64                                                     ; A BUTTERFLY.
 65      01EC                           TEMPI = W(01EC)  ; SAME AS ABOVE.
 66                                                     ;
 67      01EE                           MTEMP = W(01EE)  ; TEMPORARY STORAGE USED IN SMULT.
 68                      ;
 69                                     .INCLD TSTDAT.MAC
 70                                     .INCLD TWDTBL.MAC
 71                      ;
 72                      ;
 73      F400                           . = 0F400
 74                      TSTFFT:
 75 F400 B701F0C4                       LD SP, 01F0
 76 F404 832001C0AB                     LD NUMB, 020     ; 32 POINT FFT.
 77 F409 830501C2AB                     LD L1, 05        ; 32 = 2**5.
 78 F40E 3049                           JSR FFT          ; COMPUTE FFT.
 79 F410 40                             NOP
 80 F411 31C4                           JSR IFFT
 81 F413 40                             NOP
 82 F414 61                             JP .-1
 83                      ;
 84                      ;
 85                      ; THIS SUBROUTINE IMPLEMENTS A BIT REVERSED COUNTER AS NEEDED FOR
 86                      ; DATA SHUFFLING IN THE FFT ROUTINE. THE ALGORITHM IS BASED ON
 87                      ; THE DESCRIPTION IN:
 88                      ;       RABINER AND GOLD,
 89                      ; THEORY AND APPLICATIONS OF DIGITAL SIGNAL PROCESSING,
 90                      ;       PRENTICE-HALL, 1975.
 91                      ;
 92                      ; ON INPUT, X CONTAINS THE PREVIOUS BIT REVERSED COUNTER VALUE.
 93                      ; THE NEXT BIT REVERSED OUTPUT IS RETURNED IN X.
 94                      ; A IS LOST, B AND K ARE PRESERVED.
 95                      ;
 96                                     .LOCAL
 97                      BRCNTR:
 98 F415 B601C0A8                       LD A, NUMB       ; GET NUMBER OF DATA SAMPLES
 99                                                     ; TO BE TRANSFORMED.
100 F419 C7                            SHR A            ; DIVIDE BY 2.
101      $REPEAT:
102 F41A 96CEFD                        IFGT A, X        ; IS BIT BEING TESTED A 0 ?
```

```
103 F41D 47                         JP $FOUND               ; YES, SO STOP CHECKING.
104                                                         ; GET HERE MEANS BIT BEING
105                                                         ; CHECKED IS 1.
106 F41E 02                         SET C
107 F41F A0C8CEE8                   SUBC X, A               ; ZERO OUT THE BIT.
108 F423 C7                         SHR A                   ; UPDATE BIT LOCATOR.
109 F424 6A                         JP $REPEAT
110                     $FOUND:
111 F425 A0C8CEF8                   ADD X, A
112 F429 3C                         RET
113                                 .LOCAL
114                     ;
115                     ;
116                     ;
117                     ; THIS SUBROUTINE MULTIPLIES TWO 16-BIT 2'S COMPLEMENT INTEGERS AND RETURNS
118                     ; THE UPPER HALF OF THE RESULT. THE MULTIPLICAND IS IN A, AND THE MULTIPLIER
119                     ; IN W(B). THE RESULT IS RETURNED IN A. ONE TEMPORARY WORD OF STORAGE,
120                     ; ADDRESSED AS MTEMP IS USED.
121                     ;
122                     SMULT:
123 F42A 830001EEAB                 LD MTEMP, 0             ; CLEAR TEMPORARY STORAGE.
124 F42F A9CC                       INC B                   ; B NOW POINTS TO UPPER BYTE
125                                                         ; OF MULTIPLIER.
126 F431 17                         IF M(B).7               ; IS IT NEGATIVE ?
127 F432 B601EEAB                   ST A, MTEMP             ; THEN SAVE MULTIPLICAND IN MTEMP.
128 F436 AACC                       DECSZ B                 ; B INTO WORD POINTER.
129 F438 40                         NOP
130 F439 B601EEAE                   X A, MTEMP              ; SWAP A AND MTEMP.
131 F430 B601EF17                   IF M(($MTEMP)+1).7      ; IS MULTIPLICAND NEGATIVE ?
132 F441 F8                         ADD A, W(B)             ; THEN ACCUMULATE MULTIPLIER.
133 F442 B601EEAE                   X A, MTEMP
134 F446 FE                         MULT A, W(B)            ; UNSIGNED MULTIPLY.
135 F447 AECE                       X A, X                  ; UPPER HALF IN A.
136 F449 02                         SET C
137 F44A B601EEEB                   SUBC A, MTEMP
138 F44E E7                         SHL A
139 F44F 96CF17                     IF H(X).7
140 F452 04                         INC A
141 F453 E7                         SHL A
142 F454 96CF16                     IF H(X).6
143 F457 04                         INC A
144 F458 3C                         RET
145                     ;
146                     ;
147                     ;
148                     ; THIS SUBROUTINE IMPLEMENTS THE FIXED POINT RADIX-2 DECIMATION-IN-TIME
149                     ; FFT ALGORITHM. THE DATA IS INITIALLY PUT IN THE BIT REVERSED ORDER, AND
150                     ; THEN THE FFT IS COMPUTED. FOR THE THEORY BEHIND THE ALGORITHM, CONSULT:
151                     ;
152                     ;       1. OPPENHEIM AND SCHAFER, DIGITAL SIGNAL PROCESSING,
153                             PRENTICE-HALL.
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154                     ;
155                     ;       2. RABINER AND GOLD, THEORY AND APPLICATIONS OF DIGITAL SIGNAL
156                     ;               PROCESSING, PRENTICE-HALL, 1975.
157                     ;
158                     ; THE ALGORITHM USED CLOSELY FOLLOWS THE FORTRAN PROGRAM FOREA IN
159                     ;
160                     ;       3. PROGRAMS FOR DIGITAL SIGNAL PROCESSING, IEEE.
161                     ;
162                     ;
163                     FFT:
164                     ;
165                     ; FIRST PUT THE DATA IN BIT REVERSED ORDER.
166                     ;
167 F459 00                             CLR A
168 F45A ABCC                          ST A, B                 ; SET UP NORMAL COUNTER.
169 F45C ABCE                          ST A, X                 ; SET UP BIT REVERSED COUNTER.
170 F45E A401C0CAAB                    LD K, NUMB              ; K HAS NUMBER OF DATA POINTS.
171                     REVLP:
172 F463 A0CCCEFD                      IFGT X, B               ; IS BIT REV CNTR → NORM CNTR ?
173 F467 42                            JP SWAP                 ; YES, SO SWAP DATA.
174 F468 9421                          JMP COUNT               ; NO SO INCREMENT COUNT.
175                     SWAP:
176 F46A AFCC                          PUSH B
177 F46C AFCE                          PUSH X
178 F46E A8CC                          LD A, B                 ; INDEX VALUE I IS IN A.
179 F470 E7                            SHL A
180 F471 E7                            SHL A
181 F472 B80200                        ADD A, DTSTAD           ; GET ADDR. OF XR(I).
182 F475 ABCC                          ST A, B                 ; SAVE IT IN B.
183 F477 A8CE                          LD A, X                 ; INDEX VALUE J IS IN A.
184 F479 E7                            SHL A
185 F47A E7                            SHL A
186 F47B B80200                        ADD A, DISTAD           ; GET ADDR. OF XR(J).
187 F47E ABCE                          ST A, X                 ; SAVE IT IN X.
188 F480 E4                            LD A, W(B)              ; A ← XR(I).
189 F481 F1                            X A, W(X+)              ; A ← XR(J), XR(J) ← XR(I).
190 F482 E1                            XS A, W(B+)             ; A ← XR(I), XR(I) ← XR(J).
191 F483 40                            NOP
192 F484 E4                            LD A, W(B)              ; A ← XI(I).
193 F485 F5                            X A, W(X)               ; A ← XI(J), XI(J) ← XI(I).
194 F486 E6                            ST A, W(B)              ; XI(I) ← XI(J).
195 F487 3FCE                          POP X
196 F489 3FCC                          POP B
197                     ;
198                     COUNT:
199                     ;
200 F48B AACA                          DECSZ K                 ; DONE ?
201 F48D 41                            JP UPIT                 ; NO GO DO SOME MORE.
202 F48E 46                            JP DOFFT
203                     UPIT:
204 F48F 347A                          JSR BRCNTR              ; COUNT UP ON BIT REV CNTR.
```

```
205 F491 A9CC                       INC B                   ; COUNT UP ON NORMAL CNTR.
206 F493 9530                       JMP REVLP
207                 DOFFT:
208                 ;
209                 ; DATA IS NOW STORED IN THE BIT REVERSED ORDER. COMPUTE THE FFT.
210                 ;
211 F495 9008                       LD A, LMAX              ; A HAS MAX FFT EXPONENT.
212 F497 04                        INC A
213 F498 04                        INC A
214 F499 02                        SET C
215 F49A B601C2EB                  SUBC A, L1              ; COMPUTE LSHIFT.
216 F49E B601C4AB                  ST A, LSHIFT
217 F4A2 B601C0A8                  LD A, NUMB
218 F4A6 C7                        SHR A
219 F4A7 B601C6AB                  ST A, NBFLY             ; INITIALIZE NBFLY.
220 F4AB B601CCAB                  ST A, WESTEP            ; INITIALIZE WESTEP.
221 F4AF 830101C8AB                LD ISTEP, 01            ; INITIALIZE ISTEP.
222 F4B4 830201CAAB                LD ILEAP, 02            ; INITIALIZE ILEAP.
223                 ;
224                 ; SET UP L1 STAGES OF BUTTERFLIES.
225                 ;
226 F4B9 B601C2AB                  LD A, L1
227 F4BD B601CEAB                  ST A, NSTG              ; LOOP L1 TIMES.
228                 LOOP1:
229                 ;
230 F4C1 00                        CLR A
231 F4C2 B601D0AB                  ST A, ISTART            ; INITIALIZE ISTART FOR EACH STAGE.
232 F4C6 B601D2AB                  ST A, WEXP              ; INITIALIZE WEXP.
233                 ;
234                 ; SET UP ISTEP LOOPS OF TWIDDLE FACTORS.
235                 ;
236 F4CA B601C8A8                  LD A, ISTEP
237 F4CE B601D4AB                  ST A, NTWD              ; LOOP ISTEP TIMES.
238                 LOOP2:
239                 ;
240                 ; LOOK UP THE TWIDDLE FACTOR.
241                 ;
242 F4D2 A401C4CAAB                LD K, LSHIFT            ; SHIFT LEFT LSHIFT TIMES.
243 F4D7 B601D2A8                  LD A, WEXP
244                 GADLP:
245 F4DB E7                        SHL A
246 F4DC AACA                      DECSZ K                 ; DONE SHIFTING ?
247 F4DE 63                        JP GADLP                ; NO SO DO MORE.
248 F4DF B8F000                    ADD A, TWSTAD           ; ADD STARTING ADDR OF TWIDDLE
249                                                        ; FACTOR TABLE.
250 F4E2 ABCE                      ST A, X                 ; TWIDDLE FACTOR ADDR IN X.
251 F4E4 F0                        LD A, W(X+)             ; GET COS(THETA).
252 F4E5 B601D6AB                  ST A, COSTH
253 F4E9 F4                        LD A, W(X)              ; GET SIN(THETA).
254 F4EA 01                        COMP A
255 F4EB 04                        INC A                   ; MAKE IT NEGATIVE.
```

```
256 F4EC B601D8AB                       ST A, SINTH
257                     ;
258 F4F0 A501D001DAAB                   LD M1, ISTART           ; INITIALIZE M1.
259                     ;
260                     ; SET UP NBFLY BUTTERFLIES FOR THIS TWIDDLE FACTOR.
261                     ;
262 F4F6 A501C601DCAB                   LD NBCNT, NBFLY         ; LOOP NBFLY TIMES.
263                     L00P3:
264 F4FC B601DAAB                      LD A, M1                ; GET INDEX OF X(I).
265 F500 E7                            SHL A
266 F501 E7                            SHL A
267 F502 B80200                        ADD A, DTSTAD           ; ADDR. OD XR(I).
268 F505 B601DEAB                      ST A, R1ADDR
269 F509 ABCE                          ST A, X
270 F50B F0                            LD A, W(X+)             ; A ← XR(I).
271 F50C B601E2AB                      ST A, XR1               ; STORE IN XR1.
272 F510 F4                            LD A, W(X)              ; A ← XI(I).
273 F511 B601E4AB                      ST A, XI1               ; STORE IN XI1.
274 F515 B601DAA8                      LD A, M1
275 F519 B601C8F8                      ADD A, ISTEP            ; GET INDEX OF X(J).
276 F51D E7                            SHL A
277 F51E E7                            SHL A
278 F51F B80200                        ADD A, DISTAD           ; ADDR. OF XR(J).
279 F522 B601E0AB                      ST A, R2ADDR
280 F526 ABCE                          ST A, X
281 F528 F0                            LD A, W(X+)             ; A ← XR(J).
282 F529 B601E6AB                      ST A, XR2               ; STORE IN XR2.
283 F520 F4                            LD A, W(X)              ; A ← XI(J).
284 F52E B601E8AB                      ST A, XI2               ; STORE IN XI2.
285                     ;
286 F532 B201E6                        LD B, #XR2              ; B ← ADDR(XR2).
287 F535 B601D6A8                      LD A, COSTH             ; A ← COS(THETA).
288 F539 350F                          JSR SMULT               ; COMPUTE XR(J)*COS(THETA).
289 F53B B601EAAB                      ST A, TEMPR             ; SAVE IN TEMPR.
290 F53F B601D8A8                      LD A, SINTH             ; A ← SIN(THETA).
291 F543 3519                          JSR SMULT               ; COMPUTE XR(J)*SIN(THETA).
292 F545 B601ECAB                      ST A, TEMPI             ; SAVE IN TEMPI.
293 F549 B201E8                        LD B, #XI2              ; B ← ADDR(XI2).
294 F54C B601D8A8                      LD A, SINTH             ; A ← SIN(THETA).
295 F550 3526                          JSR SMULT               ; COMPUTE XI(J)*SIN(THETA).
296 F552 01                            COMP A
297 F553 04                            INC A
298 F554 B601EAF8                      ADD A, TEMPR            ; COMPUTE XR(J)*COS(THETA)−
299                                                            ; XI(J)*SIN(THETA).
300 F558 B601EAAB                      ST A, TEMPR
301 F55C B601D6A8                      LD A, COSIN             ; A ← COS(THETA).
302 F560 3536                          JSR SMULT               ; COMPUTE XI(J)*COS(THETA).
303 F562 B601ECF8                      ADD A, TEMPI            ; COMPUTE XR(J)*SIN(THETA)+
304                                                            ; XI(J)*COS(THETA).
305 F566 B601ECAB                      ST A, TEMPI
306                     ;
```

```
307                     ;
308 F56A A401DECEAB                    LD X, R1ADDR            ; X ← ADDR(XR(I)).
309 F56F A401E0CCAB                    LD B, R2ADDR            ; B ← ADDR(XR(J)).
310 F574 F0                            LD A, W(X+)             ; A ← XR(I).
311 F575 02                            SET C
312 F576 B601EAEB                      SUBC A, TEMPR           ; A ← XR(I) - TEMPR.
313 F57A E1                            XS A, W(B+)
314 F57B 40                            NOP
315 F57C F2                            LD A, W(X-)             ; A ← XI(I).
316 F57D 02                            SET C
317 F57E B601ECEB                      SUBC A, TEMPI           ; A ←XI(J) - TEMPI.
318 F582 E6                            ST A, W(B)
319 F583 F4                            LD A, W(X)              ; A ← XR(I).
320 F584 B601EAF8                      ADD A, TEMPR            ; A ← XR(I) + TEMPR.
321 F588 F1                            X A, W(X+)
322 F589 F4                            LD A, W(X)              ; A ← XI(I).
323 F58A B601ECF8                      ADD A, TEMPI            ; A ← XI(I) + TEMPI.
324 F58E F6                            ST A, W(X)
325                     ;
326 F58F A501CA01DAF8                  ADD M1, ILEAP           ; UPDATE M1 FOR NEXT LOOP.
327                     ;
328 F595 B601DCAA                      DECSZ NBCNT             ; DONE WITH ALL BUTTERFLIES
329                                                             ; FOR THIS TWIDDLE FACTOR ?
330 F599 959D                          JMP LOOP3               ; NO, SO GO DO SOME MORE.
331                     ;
332                     ;
333 F59B B601D0A9                      INC ISTART              ; SET UP STARTING INDEX FOR
334                                                             ; NEXT TWIDDLE FACTOR.
335 F59F A501CC01D2F8                  ADD WEXP, WESTEP        ; UPDATE TWIDDLE FACTOR
336                                                             ; EXPONENT VALUE.
337                     ;
338 F5A5 B601D4AA                      DECSZ NTWD              ; DONE WITH ALL TWIDDLES
339                                                             ; FOR THIS STAGE ?
340 F5A9 95D7                          JMP LOOP2               ; NO, SO GO DO SOME MORE.
341                     ;
342                     ;
343 F5AB B601CAA8                      LD A, ILEAP
344 F5AF E7                            SHL A
345 F5B0 B601CAAB                      ST A, ILEAP             ; UPDATE ILEAP FOR NEXT STAGE.
346 F5B4 B601C8A8                      LD A, ISTEP
347 F5B8 E7                            SHL A
348 F5B9 B601C8AB                      ST A, ISTEP             ; UPDATE ISTEP FOR NEXT STAGE.
349 F58D B601C6A8                      LD A, NBFLY
350 F5C1 C7                            SHR A
351 F5C2 B601C6AB                      ST A, NBFLY             ; UPDATE NBFLY FOR NEXT STAGE.
352 F5C6 B601CCA8                      LD A, WESTEP
353 F5CA C7                            SHR A
354 F5CB B601CCAB                      ST A, WESTEP            ; UPDATE WESTEP FOR NEXT STAGE.
355                     ;
356 F5CF B601CEAA                      DECSZ NSTG              ; DONE WITH ALL STAGES ?
357 F5D3 B4FEEB        +               JMP LOOP1               ; NO SO GO DO SOME MORE.
```

```
358                     ;
359 F5D6 3C                        RET                     ; ALL OVER.
360                     ;
361                     ; THE CODE BELOW IS FOR THE INVERSE FFT. THE ONLY DIFFERENCE IS THAT
362                     ; THE TWIDDLE FACTORS ARE USED A LITTLE DIFFERENTLY, AND A FINAL SCALING BY
363                     ; 1/NUMB IS DONE.
364                     IFFT:
365                     ;
366                     ; FIRST PUT THE DATA IN BIT REVERSED ORDER.
367                     ;
368 F5D7 00                         CLR A
369 F5D8 ABCC                      ST A, B                 ; SET UP NORMAL COUNTER.
370 F5DA ABCE                      ST A, X                 ; SET UP BIT REVERSED COUNTER.
371 F5DC A401C0CAAB                LD K, NUMB              ; K HAS NUMBER OF DATA POINTS.
372                     IREVLP:
373 F5E1 A0CCCEFD                  IFGT X, B               ; IS BIT REV CNTR → NORM CNTR ?
374 F5E5 42                        JP ISWAP                ; YES, SO SWAP DATA.
375 F5E6 9421                      JMP ICOUNT              ; NO SO INCREMENT COUNT.
376                     ISWAP:
377 F5E8 AFCC                      PUSH B
378 F5EA AFCE                      PUSH X
379 F5EC A8CC                      LD A, B                 ; INDEX VALUE I IS IN A.
380 F5EE E7                        SHL A
381 F5EF E7                        SHL A
382 F5F0 B80200                    ADD A, DTSTAD           ; GET ADDR. OF XR(I).
383 F5F3 ABCC                      ST A, B                 ; SAVE IT IN B.
384 F5F5 A8CE                      LD A, X                 ; INDEX VALUE J IS IN A.
385 F5F7 E7                        SHL A
386 F5F8 E7                        SHL A
387 F5F9 B80200                    ADD A, DTSTAD           ; GET ADDR. OF XR(J).
388 F5FC ABCE                      ST A, X                 ; SAVE IT IN X.
389 F5FE E4                        LD A, W(B)              ; A ← XR(I).
390 F5FF F1                        X A, W(X+)              ; A ← XR(J), XR(J) ← XR(I).
391 F600 E1                        XS A, W(B+)             ; A ← XR(I), XR(I) ← XR(J).
392 F601 40                        NOP
393 F602 E4                        LD A, W(B)              ; A ← XI(I).
394 F603 F5                        X A, W(X)               ; A ← XI(J), XI(J) ← XI(I).
395 F604 E6                        ST A, W(B)              ; XI(I) ← XI(J).
396 F605 3FCE                      POP X
397 F607 3FCC                      POP B
398                     ;
399                     ICOUNT:
400                     ;
401 F609 AACA                      DECSZ K                 ; DONE ?
402 F60B 41                        JP IUPIT                ; NO GO DO SOME MORE.
403 F60C 46                        JP DOIFFT
404                     IUPIT:
405 F60D 35F8                      JSR BRCNTR              ; COUNT UP ON BIT REV CNTR.
406 F60F A9CC                      INC B                   ; COUNT UP ON NORMAL CNTR.
407 F611 9530                      JMP IREVLP
408                     DOIFFT:
```

```
409                     ;
410                     ; DATA IS NOW STORED IN THE BIT REVERSED ORDER. COMPUTE THE FFT.
411                     ;
412 F613 9008                          LD A, LMAX              ; A HAS MAX FFT EXPONENT.
413 F615 04                            INC A
414 F616 04                            INC A
415 F617 02                            SET C
416 F618 B601C2EB                      SUBC A, L1              ; COMPUTE LSHIFT.
417 F61C B601C4AB                      ST A, LSHIFT
418 F620 B601C0A8                      LD A, NUMB
419 F624 C7                            SHR A
420 F625 B601C6AB                      ST A, NBFLY             ; INITIALIZE NBFLY.
421 F629 B601CCAB                      ST A, WESTEP            ; INITIALIZE WESTEP.
422 F62D 830101C8AB                    LD ISTEP, 01            ; INITIALIZE ISTEP.
423 F632 830201CAAB                    LD ILEAP, 02            ; INITIALIZE ILEAP.
424                     ;
425                     ; SET UP L1 STAGES OF BUTTERFLIES.
426                     ;
427 F637 B601C2AB                      LD A, L1
428 F63B B601CEAB                      ST A, NSTG              ; LOOP L1 TIMES.
429                     ILOOP1:
430                     ;
431 F63F 00                            CLR A
432 F640 B601D0AB                      ST A, ISTART            ; INITIALIZE ISTART FOR EACH STAGE.
433 F644 B601D2AB                      ST A, WEXP              ; INITIALIZE WEXP.
434                     ;
435                     ; SET UP ISTEP LOOPS OF TWIDDLE FACTORS.
436                     ;
437 F648 B601C8A8                      LD A, ISTEP
438 F64C B601D4AB                      ST A, NTWD              ; LOOP ISTEP TIMES.
439                     ILOOP2:
440                     ;
441                     ; LOOK UP THE TWIDDLE FACTOR.
442                     ;
443 F650 A401C4CAAB                    LD K, LSHIFT            ; SHIFT LEFT LSHIFT TIMES.
444 F655 B601D2AB                      LD A, WEXP
445                     IGADLP:
446 F659 E7                            SHL A
447 F65A AACA                          DECSZ K                 ; DONE SHIFTING ?
448 F65C 63                            JP IGADLP               ; NO DO SOME MORE.
449 F65D B8F000                        ADD A, TWSTAD           ; ADD STARTING ADDR OF TWIDDLE
450                                                            ; FACTOR TABLE.
451 F660 ABCE                          ST A, X                 ; TWIDDLE FACTOR ADDR IN X.
452 F662 F0                            LD A, W(X+)             ; GET COS(THETA).
453 F663 B601D6AB                      ST A, COSTH
454 F667 F4                            LD A, W(X)              ; GET SIN(THETA).
455 F668 B601D8AB                      ST A, SINTH
456                     ;
457 F66C A501D001DAAB                  LD M1, ISTART           ; INITIALIZE M1.
458                     ;
459                     ; SET UP NBFLY BUTTERFLIES FOR THIS TWIDDLE FACTOR.
```

```
460                     ;
461 F672 A501C601DCAB                  LD NBCNT, NBFLY         ; LOOP NBFLY TIMES.
462                     ILOOP3:
463 F678 B601DAA8                      LD A, M1                ; GET INDEX OF X(I).
464 F67C E7                            SHL A
465 F67D E7                            SHL A
466 F67E B80200                        ADD A, DTSTAD           ; ADDR. OD XR(I).
467 F681 B601DEA8                      ST A, R1ADDR
468 F685 ABCE                          ST A, X
469 F687 F0                            LD A, W(X+)             ; A ← XR(I).
470 F688 B601E2AB                      ST A, XR1               ; STORE IN XR1.
471 F68C F4                            LD A, W(X)              ; A ← XI(I).
472 F68D B601E4AB                      ST A, XI1               ; STORE IN XI1.
473 F691 B601DAA8                      LD A, M1
474 F695 B601C8F8                      ADD A, ISTEP            ; GET INDEX OF X(J).
475 F699 E7                            SHL A
476 F69A E7                            SHL A
477 F69B B80200                        ADD A, DTSTAD           ; ADDR. OF XR(J).
478 F69E B601E0AB                      ST A, R2ADDR
479 F6A2 ABCE                          ST A, X
480 F6A4 F0                            LD A, W(X+)             ; A ← XR(J).
481 F6A5 B601E6AB                      ST A, XR2               ; STORE IN XR2.
482 F6A9 F4                            LD A, W(X)              ; A ← XI(J).
483 F6AA B601E8AB                      ST A, XI2               ; STORE IN XI2.
484                     ;
485 F6A8 B201E6                        LD B, #XR2              ; B ← ADDR(XR2).
486 F6B1 B601D6A8                      LD A, COSTH             ; A ← COS(THETA).
487 F6B5 368B                          JSR SMULT               ; COMPUTE XR(J)*COS(THETA).
488 F6B7 B601EAAB                      ST A, TEMPR             ; SAVE IN TEMPR.
489 F6BB B601D8A8                      LD A, SINTH             ; A ← SIN(THETA).
490 F6BF 3695                          JSR SMULT               ; COMPUTE XR(J)*SIN(THETA).
491 F6C1 B601ECAB                      ST A, TEMPI             ; SAVE IN TEMPI.
492 F6C5 B201E8                        LD B, #XI2              ; B ← ADDR(XI2).
493 F6C8 B601D8A8                      LD A, SINTH             ; A ← SIN(THETA).
494 F6CC 36A2                          JSR SMULT               ; COMPUTE XI(J)*SIN(THETA).
495 F6CE 01                            COMP A
496 F6CF 04                            INC A
497 F6D0 B601EAF8                      ADD A, TEMPR            ; COMPUTE XR(J)*COS(THETA) -
498                                                            ; XI(J)*SIN(THETA).
499 F6D4 B601EAAB                      ST A, TEMPR
500 F6D8 B601D6A8                      LD A, COSTH             ; A ← COS(THETA).
501 F6DC 36B2                          JSR SMULT               ; COMPUTE XI(J)*COS(THETA).
502 F6DE B601ECF8                      ADD A, TEMPI            ; COMPUTE XR(J)*SIN(THETA) +
503                                                            ; XI(J)*COS(THETA).
504 F6E2 B601ECAB                      ST A, TEMPI
505                     ;
506                     ;
507 F6E6 A401DECEAB                    LD X, R1ADDR            ; X ← ADDR(XR(I)).
508 F6EB A401E0CCAB                    LD B, R2ADDR            ; B ← ADDR(XR(J)).
509 F6F0 F0                            LD A, W(X+)             ; A ← XR(I).
510 F6F1 02                            SET C
```

```
511 F6F2 B601EAEB                       SUBC A, TEMPR           ; A ← XR(I) - TEMPR.
512 F6F6 E1                             XS A, W(B+)
513 F6F7 40                             NOP
514 F6F8 F2                             LD A, W(X-)             ; A ← XI(I).
515 F6F9 02                             SET C
516 F6FA B601ECEB                       SUBC A, TEMPI           ; A ← XI(J) - TEMPI.
517 F6FE E6                             ST A, W(B)
518 F6FF F4                             LD A, W(X)              ; A ← XR(I).
519 F700 B601EAF8                       ADD A, TEMPR            ; A ← XR(I) + TEMPR.
520 F704 F1                             X A, W(X+)
521 F705 F4                             LD A, W(X)              ; A ← XI(I).
522 F706 B601ECF8                       ADD A, TEMPI            ; A ← XI(I) + TEMPI.
523 F70A F6                             ST A, W(X)
524                     ;
525 F70B A501CA01DAF8                   ADD M1, ILEAP           ; UPDATE M1 FOR NEXT LOOP.
526                     ;
527 F711 B601DCAA                       DECSZ NBCNT             ; DONE WITH ALL BUTTERFLIES
528                                                             ; FOR THIS TWIDDLE FACTOR ?
529 F715 959D                           JMP IL00P3              ; NO, SO GO DO SOME MORE.
530                     ;
531                     ;
532 F717 B601D0A9                       INC ISTART              ; SET UP STARTING INDEX FOR
533                                                             ; NEXT TWIDDLE FACTOR.
534 F71B A501CC01D2F8                   ADD WEXP, WESTEP        ; UPDATE TWIDDLE FACTOR
535                                                             ; EXPONENT VALUE.
536                     ;
537 F721 B601D4AA                       DECSZ NTWD              ; DONE WITH ALL TWIDDLES
538                                                             ; FOR THIS STAGE ?
539 F725 95D5                           JMP IL00P2              ; NO, SO GO DO SOME MORE.
540                     ;
541                     ;
542 F727 B601CAA8                       LD A, ILEAP
543 F72B E7                             SHL A
544 F72C B601CAAB                       ST A, ILEAP             ; UPDATE ILEAP FOR NEXT STAGE.
545 F730 B601C8A8                       LD A, ISTEP
546 F734 E7                             SHL A
547 F735 B601C8AB                       ST A, ISTEP             ; UPDATE ISTEP FOR NEXT STAGE.
548 F739 B601C6A8                       LD A, NBFLY
549 F73D C7                             SHR A
550 F73E B601C6AB                       ST A, NBFLY             ; UPDATE NBFLY FOR NEXT STAGE.
551 F742 B601CCA8                       LD A, WESTEP
552 F746 C7                             SHR A
553 F747 B601CCAB                       ST A, WESTEP            ; UPDATE WESTEP FOR NEXT STAGE.
554                     ;
555 F748 B601CEAA                       DECSZ NSTG              ; DONE WITH ALL STAGES ?
556 F74F B4FEED       +                 JMP IL00P1              ; NO SO GO DO SOME MORE.
557                     ;
558                     ;
559                     ; DO THE FINAL SCALING OF THE DATA BY 1/NUMB.
560                     ;
561 F752 B04000                         LD A, 04000             ; A ← 1.0
```

```
562 F755 A401C2CAAB                 LD K, L1                ; K ← L1.
563                      SCALLP:
564 F75A C7                         SHR A                   ; DIVIDE BY 2.
565 F75B AACA                       DECSZ K
566 F75D 63                         JP SCALLP
567                                                         ;
568                                                         ; GET HERE MEANS A IS 1/(2^L1).
569 F75E B601EAAB                   ST A, TEMPR             ; SAVE IT IN TEMPR.
570 F762 A501C001DCAB               LD NBCNT, NUMB          ; LOOP COUNTER.
571 F768 B20200                     LD B, DTSTAD            ; B ← ADDR(XR(0)).
572                      SCALIT:
573 F76B B601EAA8                   LD A, TEMPR
574 F76F 3745                       JSR SMULT               ; A ← XR(I)*(1/NUMB).
575 F771 E1                         XS A, W(B+)             ; XR(I) ← XR(I)*(1/NUMB).
576 F772 40                         NOP
577 F773 B601EAA8                   LD A, TEMPR             ; A ← 1/NUMB.
578 F777 374D                       JSR SMULT               ; A ← XI(I)*(1/NUMB).
579 F779 E1                         XS A, W(B+)             ; XI(I) ← XI(I)*(1/NUMB).
580 F77A 40                         NOP
581 F77B B601DCAA                   DECSZ NBCNT             ; DONE ?
582 F77F 74                         JP SCALIT               ; NO DO SOME MORE.
583 F780 3C                         RET                     ; ALL OVER.
584                      ;
585 FFFE 00F4                       .END TSTFFT
```


SYMBOL TABLE

A	00C8 W	B	00CC W	BRCNTR	F415	COSTN	01D6 W
COUNT	F48B	DOFFT	F495	DOIFFT	F613	DTSTAD	0200
FFT	F459	GADLP	F40B	ICOUNT	F609	IFFT	F507
IGADLP	F659	ILEAP	01CA W	ILOOP1	F63F	ILOOP2	F650
ILOOP3	F678	IREVLP	F5E1	ISTART	01D0 W	ISTEP	01C8 W
ISWAP	F5E8	IUPIT	F600	K	00CA W	L1	01C2 W
LMAX	0008	LOOP1	F4C1	LOOP2	F4D2	LOOP3	F4FC
LSHIFT	01C4 W	M1	01DA W	MTEMP	01EE W	NBCNT	01DC W
NBFLY	01C6 W	NSTG	01CE W	NTWD	01D4 W	NUMB	01C0 W
PC	00C6 W	R1ADDR	01DE W	R2ADDR	01E0 W	REVLP	F463
SCALIT	F76B	SCALLP	F75A	SINTH	01D8 W	SMULT	F42A
SP	00C4 W	SWAP	F46A	TEMPI	01EC W	TEMPR	01EA W
TSTFFT	F400	TWSTAD	F000	UPIT	F48F	WESTEP	01CC W
WEXP	01D2 W	X	00CE W	XI1	01E4 W	XI2	01E8 W
XR1	01E2 W	XR2	01E6 W	$FOUND	F425	$REPEA	F41A

```
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MACRO TABLE



   NO WARNING LINES

   NO ERROR LINES

 2307  ROM BYTES USED

SOURCE CHECKSUM = E9FC
OBJECT CHECKSUM = 28FC

INPUT   FILE C:FFT.MAC
LISTING FILE C:FFT.PRN
OBJECT  FILE C:FFT.LM
```

APPENDIX B

Twiddle Factor Table

```
;
; TWIDDLE FACTOR TABLE FOR USE IN THE FFT ROUTINES.
;
; TABLE SET FOR MAX FFT LENGTH OF 256.
;
; TABLE STARTS AT F000 AND OCCUPIES 1024 BYTES OF STORAGE.
;
                . = 0F000
                .WORD 16384, 0
                .WORD 16379, 402
                .WORD 16364, 804
                .WORD 16340, 1205
                .WORD 16305, 1606
                .WORD 16261, 2006
                .WORD 16207, 2404
                .WORD 16143, 2801
                .WORD 16069, 3196
                .WORD 15986, 3590
                .WORD 15893, 3981
                .WORD 15791, 4370
                .WORD 15679, 4756
                .WORD 15557, 5139
                .WORD 15426, 5520
                .WORD 15286, 5897
                .WORD 15137, 6270
                .WORD 14978, 6639
                .WORD 14811, 7005
                .WORD 14635, 7366
                .WORD 14449, 7723
                .WORD 14256, 8076
                .WORD 14053, 8423
                .WORD 13842, 8765
                .WORD 13623, 9102
                .WORD 13395, 9434
                .WORD 13160, 9760
                .WORD 12916, 10080
                .WORD 12665, 10394
                .WORD 12406, 10702
                .WORD 12140, 11003
                .WORD 11866, 11297
                .WORD 11585, 11585
                .WORD 11297, 11866
                .WORD 11003, 12140
                .WORD 10702, 12406
                .WORD 10394, 12665
                .WORD 10080, 12916
                .WORD 9760, 13160
                .WORD 9434, 13395
                .WORD 9102, 13623
                .WORD 8765, 13842
                .WORD 8423, 14053
                .WORD 8076, 14256
                .WORD 7723, 14449
                .WORD 7366, 14635
                .WORD 7005, 14811
                .WORD 6639, 14978
                .WORD 6270, 15137
                .WORD 5897, 15286
                .WORD 5520, 15426
                .WORD 5139, 15557
                .WORD 4756, 15679
                .WORD 4370, 15791
                .WORD 3981, 15893
                .WORD 3590, 15986
                .WORD 3196, 16069
                .WORD 2801, 16143
                .WORD 2404, 16207
                .WORD 2006, 16261
                .WORD 1606, 16305
                .WORD 1205, 16340
                .WORD 804, 16364
                .WORD 402, 16379
                .WORD 0, 16384
                .WORD -402, 16379
                .WORD -804, 16364
                .WORD -1205, 16340
                .WORD -1606, 16305
                .WORD -2006, 16261
                .WORD -2404, 16207
                .WORD -2801, 16143
                .WORD -3196, 16069
                .WORD -3590, 15986
                .WORD -3981, 15893
                .WORD -4370, 15791
                .WORD -4756, 15679
                .WORD -5139, 15557
                .WORD -5520, 15426
                .WORD -5897, 15286
                .WORD -6270, 15137
                .WORD -6639, 14978
                .WORD -7005, 14811
                .WORD -7366, 14635
                .WORD -7723, 14449
                .WORD -8076, 14256
                .WORD -8423, 14053
                .WORD -8765, 13842
                .WORD -9102, 13623
                .WORD -9434, 13395
                .WORD -9760, 13160
                .WORD -10080, 12916
                .WORD -10394, 12665
                .WORD -10702, 12406
                .WORD -11003, 12140
                .WORD -11297, 11866
                .WORD -11585, 11585
                .WORD -11866, 11297
                .WORD -12140, 11003
                .WORD -12406, 10702
                .WORD -12665, 10394
                .WORD -12916, 10080
```

```
.WORD -13160, 9760
.WORD -13395, 9434
.WORD -13623, 9102
.WORD -13842, 8765
.WORD -14053, 8423
.WORD -14256, 8076
.WORD -14449, 7723
.WORD -14635, 7366
.WORD -14811, 7005
.WORD -14978, 6639
.WORD -15137, 6270
.WORD -15286, 5897
.WORD -15426, 5520
.WORD -15557, 5139
.WORD -15679, 4756
.WORD -15791, 4370
.WORD -15893, 3981
.WORD -15986, 3590
.WORD -16069, 3196
.WORD -16143, 2801
.WORD -16207, 2404
.WORD -16261, 2006
.WORD -16305, 1606
.WORD -16340, 1205
.WORD -16364, 804
.WORD -16379, 402
.WORD -16384, 0


.WORD -16379, -402
.WORD -16364, -804
.WORD -16340, -1205
.WORD -16305, -1606
.WORD -16261, -2006
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.WORD 15893, -3981
.WORD 15986, -3590
.WORD 16069, -3196
.WORD 16143, -2801
.WORD 16207, -2404
.WORD 16261, -2006
.WORD 16305, -1606
.WORD 16340, -1205
.WORD 16364, -804
.WORD 16379, -402

.END
```

APPENDIX C

Test Data and Expected Results

```
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  1                     ;
  2                     ;
  3                     ; TEST DATA FOR FFT ROUTINES.
  4                     ; OBTAINED FROM : PROGRAMS FOR DIGITAL SIGNAL PROCESSING, IEEE PRESS,
  5                     ; CHAPTER 1 BY GOLD.
  6                     ;
  7                     ;
  8      0200                           . = 0200
  9 0200 0004                           .WORD 1024, 0
    0202 0000
 10 0204 9A03                           .WORD 922, 307
    0206 3301
 11 0208 E102                           .WORD 737, 553
    020A 2902
 12 020C F201                           .WORD 498, 719
    020E CF02
 13 0210 E800                           .WORD 232, 796
    0212 1C03
 14 0214 E2FF                           .WORD -30, 786
    0216 1203
 15 0218 F9FE                           .WORD -263, 699
    021A BB02
 16 021C 42FE                           .WORD -446, 550
    021E 2602
 17 0220 C9FD                           .WORD -567, 361
    0222 6901
 18 0224 96FD                           .WORD -618, 155
    0226 9800
 19 0228 A5FD                           .WORD -603, -46
    022A D2FF
 20 022C EFFD                           .WORD -529, -222
    022E 22FF
 21 0230 67FE                           .WORD -409, -359
    0232 99FE
 22 0234 FBFE                           .WORD -261, -446
    0236 42FE
 23 0238 9BFF                           .WORD -101, -479
    023A 21FE
 24 023C 3500                           .WORD 53, -462
    023E 32FE
 25 0240 BA00                           .WORD 186, -400
    0242 70FE
 26 0244 1F01                           .WORD 287, -304
    0246 D0FE
 27 0248 5E01                           .WORD 350, -187
    024A 45FF
 28 024C 7301                           .WORD 371, -64
    024E C0FF
 29 0250 6101                           .WORD 353, 54
    0252 3600
 30 0254 2001                           .WORD 301, 154
```

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   0256 9A00
31 0258 E100                        .WORD 225, 229
   025A E500
32 025C 8600                        .WORD 134, 274
   025E 1201
33 0260 2600                        .WORD 38, 287
   0262 1F01
34 0264 CCFF                        .WORD -52, 269
   0266 0D01
35 0268 81FF                        .WORD -127, 227
   026A E300
36 026C 49FF                        .WORD -183, 166
   026E A600
37 0270 2AFF                        .WORD -214, 95
   0272 5F00
38 0274 23FF                        .WORD -221, 21
   0276 1500
39 0278 33FF                        .WORD -205, -48
   027A DDFF
40 027C 55FF                        .WORD -171, -104
   027E 98FF
41                      ;
42                      ; THESE ARE THE EXPECTED DFT RESULTS.
43                      ;
44 0280 C702                        .WORD 711, 3584
   0282 000E
45 0284 2B0B                        .WORD 2859, 8244
   0286 3420
46 0288 9D25                        .WORD 9629, -9354
   028A 76DB
47 028C 7707                        .WORD 1911, -3926
   028E AAF0
48 0290 8704                        .WORD 1159, -2288
   0292 10F7
49 0294 9F03                        .WORD 927, -1571
   0296 DDF9
50 0298 3303                        .WORD 819, -1167
   029A 71FB
51 029C F502                        .WORD 757, -903
   029E 79FC
52 02A0 CE02                        .WORD 718, -715
   02A2 35FD
53 02A4 B202                        .WORD 690, -572
   02A6 C4FD
54 02A8 9D02                        .WORD 669, -457
   02AA 37FE
55 02AC 8C02                        .WORD 652, -361
   02AE 97FE
56 02B0 7F02                        .WORD 639, -279
   02B2 E9FE
57 02B4 7302                        .WORD 627, -205
```

```
   0286 33FF
 58 02B8 6902                          .WORD 617, -139
   02BA 75FF
 59 02BC 6002                          .WORD 608, -77
   02BE B3FF
 60 02C0 5802                          .WORD 600, -18
   02C2 EEFF
 61 02C4 5102                          .WORD 593, 39
   02C6 2700
 62 02C8 4A02                          .WORD 586, 95
   02CA 5F00
 63 02CC 4302                          .WORD 579, 152
   02CE 9800
 64 02D0 3C02                          .WORD 572, 210
   02D2 0200
 65 02D4 3502                          .WORD 565, 271
   02D6 0F01
 66 02D8 2E02                          .WORD 558, 336
   02DA 5001
 67 02DC 2702                          .WORD 551, 408
   02DE 9801
 68 02E0 2002                          .WORD 544, 488
   02E2 EB01
 69 02E4 1802                          .WORD 536, 581
   02E6 4502
 70 02E8 1002                          .WORD 528, 691
   02EA B302
 71 02EC 0702                          .WORD 519, 827
   02EE 3B03
 72 02F0 FE01                          .WORD 510, 1004
   02F2 EC03
 73 02F4 F701                          .WORD 503, 1248
   02F6 E004
 74 02F8 F701                          .WORD 503, 1615
   02FA 4F06
 75 02FC 1202                          .WORD 530, 2241
   02FE C108
 76                    ;
 77                    ;
 78                    ; TEST DATA FOR FFT ROUTINES.
 79                    ; OBTAINED FROM :
 80                    ;
 81                    ;
 82 0300 0004                          .WORD 1024, 0
   0302 0000
 83 0304 9A03                          .WORD 922, 307
   0306 3301
 84 0308 E102                          .WORD 737, 553
   030A 2902
 85 030C F201                          .WORD 498, 719
   030E CF02
```

```
 86 0310 E800                       .WORD 232, 796
    0312 1C03
 87 0314 E2FF                       .WORD -30, 786
    0316 1203
 88 0318 F9FE                       .WORD -263, 699
    031A BB02
 89 031C 42FE                       .WORD -446, 550
    031E 2602
 90 0320 C9FD                       .WORD -567, 361
    0322 6901
 91 0324 96FD                       .WORD -618, 155
    0326 9B00
 92 0328 A5FD                       .WORD -603, -46
    032A D2FF
 93 032C EFFD                       .WORD -529, -222
    032E 22FF
 94 0330 67FE                       .WORD -409, -359
    0332 99FE
 95 0334 FBFE                       .WORD -261, -446
    0336 42FE
 96 0338 9BFF                       .WORD -101, -479
    033A 21FE
 97 033C 3500                       .WORD 53, -462
    033E 32FE
 98 0340 BA00                       .WORD 186, -400
    0342 70FE
 99 0344 1F01                       .WORD 287, -304
    0346 D0FE
100 0348 5E01                       .WORD 350, -187
    034A 45FF
101 034C 7301                       .WORD 371, -64
    034E C0FF
102 0350 6101                       .WORD 353, 54
    0352 3600
103 0354 2D01                       .WORD 301, 154
    0356 9A00
104 0358 E100                       .WORD 225, 229
    035A E500
105 035C 8600                       .WORD 134, 274
    035E 1201
106 0360 2600                       .WORD 38, 287
    0362 1F01
107 0364 CCFF                       .WORD -52, 269
    0366 0D01
108 0368 81FF                       .WORD -127, 227
    036A E300
109 036C 49FF                       .WORD -183, 166
    036E A600
110 0370 2AFF                       .WORD -214, 95
    0372 5F00
111 0374 23FF                       .WORD -221, 21
```

```
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    0376 1500
112 0378 33FF                          .WORD -205, -48
    037A D0FF
113 037C 55FF                          .WORD -171, -104
    037E 98FF
114                     ;
115                                    .END
                                         @
ERROR, OPERAND MUST BE SINGLE VALID SYMBOL NAME



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SYMBOL TABLE


A      00C8 W       B      00CC W       K      00CA W       PC     00C6 W
SP     00C4 W       X      00CE W
```

```
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MACRO TABLE



   NO WARNING LINES

    1 ERROR LINES

  384  ROM BYTES USED

SOURCE CHECKSUM = 7A03
OBJECT CHECKSUM = 0705

INPUT   FILE C:TSTDAT.MAC
LISTING FILE C:TSTDAT.PRN
```

Lit. # 100487

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2. A critical component is any component of a life support device or system whose failure to perform can be reasonably expected to cause the failure of the life support device or system, or to affect its safety or effectiveness.

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