Implementation of Fast Fourier Transform Algorithms with the TMS32020

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Implementation of Fast Fourier Transform Algorithms with the TMS32020

Abstract

Fast Fourier Transforms (FFT), containing a class of computationally efficient algorithms implementing the Discrete Fourier Transforms (DFT), are widely used in DSP applications. In this report on FFT, the development of the FFT from the continuous Fourier Transform and DFT is first presented. Issues regarding the implementation of the FFT with the TMS32020 processor are then discussed, such as scaling, special FFT structures, and system memory and I/O considerations. The report also includes the TMS32020 code for 256-point and 1024-point FFT algorithms.

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INTRODUCTION

The Fourier transform converts information from the time domain into the frequency domain. It is an important analytical tool in such diverse fields as acoustics, optics, seismology, telecommunications, speech, signal processing, and image processing. In discrete-time systems, the Discrete Fourier Transform (DFT) is the counterpart of the continuous-time Fourier transform. Since the DFT is computation-intensive, it had relatively few applications, even with modern computers. The Fast Fourier Transform (FFT) is the generic name for a class of computationally efficient algorithms that implement the DFT and are widely used in the field of Digital Signal Processing (DSP).

Recent advances in VLSI hardware, such as the Texas Instruments TMS320 family of digital signal processors, have further enhanced the popularity of the FFT. This application report describes the implementation of FFT algorithms using the TMS32020 processor, which has features particularly suited to digital signal processing. This report begins with a discussion of the development of the DFT algorithm, leading to the derivation of the FFT algorithm. Special attention is given to various FFT implementation aspects, such as scaling. Although this report refers to radix-2 and radix-4 FFT only, the implementation techniques described are applicable to all FFT algorithms in general.[1-3] Specific examples of FFT implementations on the TMS32010 processor are contained in the book by Burrus and Parks.[4] To expedite TMS32020 FFT code development, two macro libraries are included in the appendices for both the direct and indirect memory addressing modes. TMS32020 source code examples are also given for a 256-point (both radix-2 and radix-4) and a 1024-point complex FFT, along with some system memory considerations for implementing large FFTs. The FFT source code can be found in Appendices A through G.

DEVELOPMENT OF THE DFT ALGORITHM

The Discrete Fourier Transform (DFT) is the discrete-time version of the continuous-time Fourier transform. The continuous-time Fourier transform or frequency spectrum of an analog signal x(t) is

$$X(w) = \int_{-\infty}^{\infty} x(t)e^{-jwt}dt \tag{1}$$

where, in general, both x(t) and X(w) are complex functions of the continuous-time variable t and the frequency variable w, respectively. The continuous-time signal x(t) is converted to a discrete-time signal x(nT) by sampling it every T seconds. When there is no ambiguity, the sampling period T notation is dropped and the discrete signal is represented by x(n). The Fourier transform of the discrete signal is given by

$$X(w) = \sum_{n=-\infty}^{\infty} x(n)e^{-jwn} \tag{2}$$

where w represents normalized frequency and takes on values between 0 and 2π. X(w) is periodic with period 2π and, as a result, it is sufficient to consider its values only between 0 and 2π.[2] The periodicity of X(w) is a direct result of the sampled nature of x(n). In general, sampling in the time domain is associated with periodicity in the frequency domain and, conversely, sampling in the frequency domain is associated with periodicity in the time domain. This property is a basic result in Fourier theory, and forms the foundation of the DFT.

Assume that a signal x(n) consists of N samples. Since no restriction is imposed on what happens outside the interval of N points, it is convenient to assume that the signal is periodically repeated. Under this assumption, and because of the above correspondence of sampling and periodicity, the Fourier transform becomes discrete with the distance between successive samples equal to the fundamental frequency of the signal in the time domain. This distance is $2\pi/N$ in normalized frequency units. The result is the DFT, given by

$$X(k) = \sum_{n=0}^{N-1} x(n)\, W_N^{nk} \qquad k = 0,1,\ldots,N-1 \tag{3}$$

where $W_N = e^{-j2\pi/N}$, and W_N is known as the phase or twiddle factor. Equation (3) is generally referred to as an N-point DFT. Because the number of complex multiplications and additions required is approximately N^2 for large N, the total number of arithmetic operations required for a given N increases rapidly with the value of N. In fact, the excessively large amount of computations required to compute the DFT directly when N is large has directly prompted alternative methods for computing the DFT efficiently. Most of these methods make use of the inherent symmetry and periodicity of the above twiddle factor, as shown in Figure 1 for the case where N = 8.

Figure 1 shows that the following symmetry and periodicity relationships are true:

$$\text{Symmetry Property:} \quad W_N^k = -W_N^{k+(N/2)} \tag{4}$$

$$\text{Periodicity Property:} \quad W_N^k = W_N^{N+k} \tag{5}$$

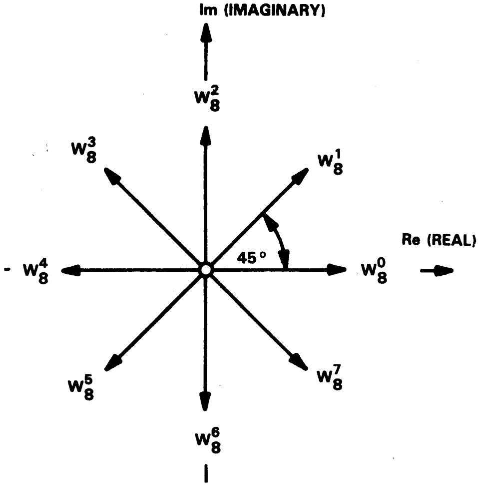


Figure 1. Symmetry and Periodicity of the Twiddle Factor for N = 8

In the next section, these relationships are utilized in the derivation of the radix-2 FFT algorithm.

DERIVATION OF THE FFT ALGORITHM

A more efficient method of computing the DFT that significantly reduces the number of required arithmetic operations is the so-called decimation-in-time (DIT) FFT algorithm.[2] With the FFT, N is a factorable number that allows the overall N-point DFT to be decomposed into successively smaller and smaller transforms. The size of the smallest transform thus derived is known as the radix of the FFT algorithm. Thus, for a radix-2 FFT algorithm, the smallest transform or "butterfly" (basic computational unit) used is the 2-point DFT. Generally, for an N-point FFT, there are N resultant frequency samples corresponding to N time samples of the input signal x(n). For a radix-2 FFT, N is a power of 2.

The number of arithmetic operations can be reduced initially by decomposing the N-point DFT into two N/2-point DFTs. This means that the input time sequence x(n) is decomposed into two N/2-point subsequences (hence the name, decimation-in-time), which consist of its even-numbered and odd-numbered samples with time indices expressed mathematically as 2n and 2n + 1, respectively. Substituting these time indices into the original DFT equation gives

$$X(k) = \sum_{n=0}^{N/2-1} x(2n)\, W_N^{2nk} + \sum_{n=0}^{N/2-1} x(2n+1)\, W_N^{(2n+1)k} \tag{6}$$

$$= \sum_{n=0}^{N/2-1} x(2n)\, W_N^{2nk} + W_N^{k} \sum_{n=0}^{N/2-1} x(2n+1)\, W_N^{2nk}$$

Since

$$W_N^2 = [e^{-j(2\pi/N)}]^2 = [e^{-j\pi/(N/2)}]^2 = W_{N/2}$$

equation (6) can be written as

$$X(k) = \sum_{n=0}^{N/2-1} x(2n)\, W_{N/2}^{nk}$$

$$+ W_N^{k} \sum_{n=0}^{N/2-1} x(2n+1)\, W_{N/2}^{nk} \tag{7}$$

$$= Y(k) + W_N^{k}\, Z(k) \qquad k = 0,1,\ldots,N-1$$

where Y(k) is the first summation term and Z(k) is the second summation term.

Y(k) and Z(k) are further seen to be the N/2-point DFTs of the even-numbered and odd-numbered time samples, respectively. In this case, the number of complex multiplications and additions is approximately $N+2(N/2)^2$ because, according to (7), the N-point DFT is split in two N/2-point DFTs, which are then combined by N complex multiplications and additions. Thus, by splitting the original N-point DFT into two N/2-point DFTs, the total number of arithmetic operations has been reduced. This reduction is illustrated in Figure 2.

Implicit in the above derivation is the periodicity of X(k), Y(k), and Z(k). X(k) is periodic in k with a period N, while Y(k) and Z(k) are both periodic in k with a period N/2. Consequently, despite the fact that the index k ranges over N values from 0 to $N-1$ for X(k), both Y(k) and Z(k) must be computed for k between 0 and $(N/2)-1$ only. The periodicity of Y(k) and Z(k) is also assumed in Figure 2.

Although (7) can be used to evaluate X(k) for $0 \leq k \leq N-1$, further reduction in the amount of computation is possible when the symmetry property (4) and periodicity (5) of the twiddle factor are utilized to compute X(k) separately over the following ranges:

1st Half of Frequency Spectrum: $0 \leq k \leq (N/2)-1$

2nd Half of Frequency Spectrum: $(N/2) \leq k \leq (N-1)$

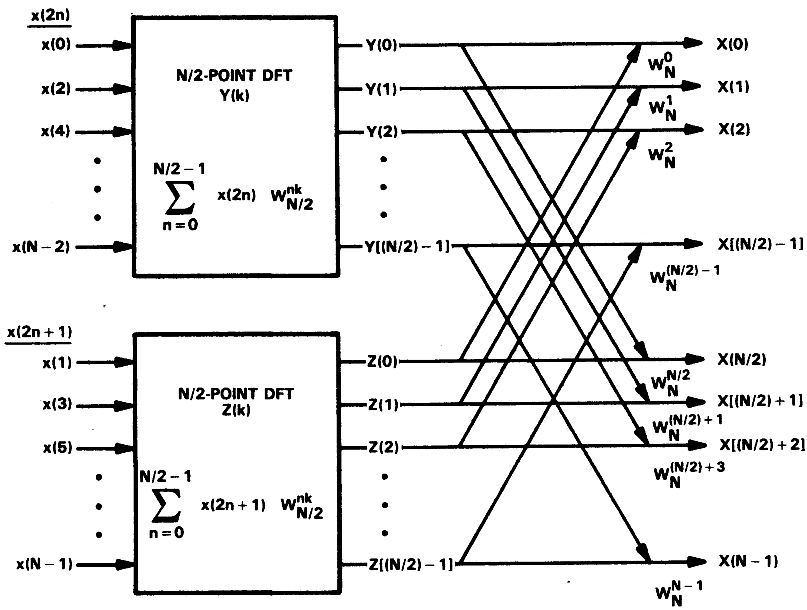


Figure 2. First DIT Decomposition of an N-Point DFT

Equation (7), for $N/2 \leq k \leq N-1$, can be rewritten as

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

$$+ W_N^{k+N/2} \sum_{n=0}^{N/2-1} x(2n+1)\, W_{N/2}^{n(k+N/2)} \tag{8}$$

where $0 \leq k \leq (N/2)-1$

Since

$$W_{N/2}^{n(k+N/2)} = W_{N/2}^{n(N/2)}\, W_{N/2}^{nk} = e^{-j2\pi n}\; W_{N/2}^{nk} = W_{N/2}^{nk}$$

and

$$W_N^{k+N/2} = W_N^k\; e^{-j\pi} = -W_N^k$$

equation (8) can be rewritten as

$$X(k+N/2) = \sum_{n=0}^{N/2-1} x(2n)\, W_{N/2}^{nk} - W_N^k \sum_{n=0}^{N/2-1} x(2n+1)\, W_{N/2}^{nk} = Y(k) - W_N^k\, Z(k) \quad k = 0,1,\ldots,(N/2)-1 \tag{9}$$

Therefore, (7) can be used to compute the first half of the frequency spectrum $X(k)$ for the index range $0 \leq k \leq (N/2)-1$, while equation (9) can be used to compute the second half of the frequency spectrum $X(k+N/2)$.

Figure 3 depicts the situation when the symmetry property of the twiddle factor is used to compute $X(k)$. The above decimation process and symmetry exploitation can reduce the DFT computation tremendously. By further decimating the odd-numbered and even-numbered time samples in a similar fashion, four N/4-point DFTs can be obtained, resulting in a further reduction in the DFT computation. Consequently, to arrive at the final radix-2 DIT FFT algorithm, this decimation process is repetitively carried out until eventually the N-point DFT can be evaluated as a collection of 2-point DFTs or butterflies.

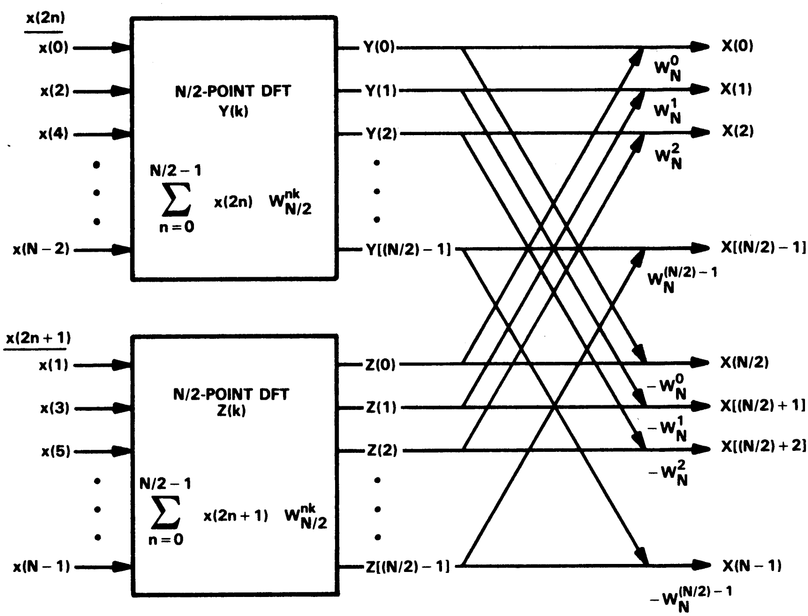


Figure 3. Decomposition of a DFT Using the Symmetry Property

RADIX-2 DECIMATION-IN-TIME (DIT) FFT BUTTERFLY

In the radix-2 DIT FFT algorithm, the time decimation process passes through a total of M stages where $N = 2^M$ with N/2 2-point FFTs or butterflies per stage, giving a total of $(N/2)\log_2 N$ butterflies per N-point FFT.

For the case of an 8-point DFT implemented using the radix-2 DIT FFT algorithm discussed in the previous pages, the input samples are processed through three stages. Four butterflies are required per stage, giving a total of twelve butterflies in the radix-2 implementation. Each butterfly is a 2-point DFT of the form depicted in Figure 4. P and Q are the inputs to the radix-2 DIT FFT butterfly. In general, the inputs to each butterfly are complex as is also the twiddle factor.

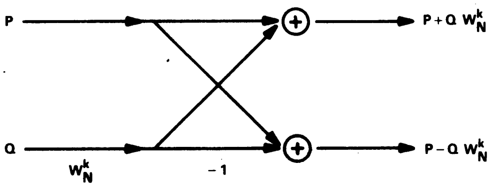


Figure 4. A Radix-2 DIT FFT Butterfly Flowgraph

As shown in Figure 4, the outputs P′ and Q′ of the radix-2 butterfly are given by

$$P' = P + Q\,W_N^k$$

$$Q' = P - Q\,W_N^k \tag{10}$$

While Figure 4 actually uses signal flowgraph nomenclature, another commonly used symbol for a radix-2 butterfly is shown in Figure 5.

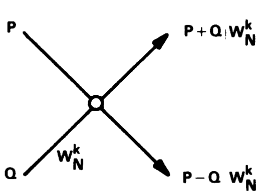


Figure 5. A Simplified Radix-2, DIT FFT Butterfly Symbol

For an explanation of the various notational conventions in use, the reader is referred to reference [3]. Both the flowgraph nomenclature and the butterfly symbol are used interchangeably in this report.

Implementation of the FFT Butterfly with Scaling

In the computation of the FFT, scaling of the intermediate results becomes necessary to prevent overflows. The TMS32020 processor has features optimized for digital signal processing and a number of on-chip shifters for scaling. In particular, the input scaling shifter, the 32-bit double-precision ALU and accumulator, and its output shifters are used extensively for scaling.

To see why scaling is necessary, observe that from the general equation of an N-point DFT (3), application of Parseval's theorem gives

$$\sum_{n=0}^{N-1} x^2(n) = \frac{1}{N} \sum_{k=0}^{N-1} |X(k)|^2 \tag{11}$$

or

$$N \left[\frac{1}{N} \sum_{n=0}^{N-1} x^2(n) \right] = \left[\frac{1}{N} \sum_{k=0}^{N-1} |X(k)|^2 \right] \tag{12}$$

i.e., the mean-squared value of X(k) is N times that of input x(n). Consequently, in computing the DFT of the input sequence x(n), overflows may occur when fixed-point arithmetic is employed without appropriate scaling. To see how overflows can actually occur in FFT computations, consider the general radix-2 butterfly in the mth stage of an N-point DIT FFT as shown in Figure 6.

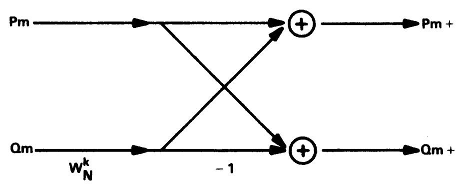


Figure 6. Signal Flowgraph of a Butterfly at the mth Stage

From Figure 6, the final form of the FFT can be written as

$$Pm+1 = Pm + W_N^k\,Qm$$

$$Qm+1 = Pm - W_N^k\,Qm \tag{13}$$

where Pm and Qm are the inputs, and Pm + 1 and Qm + 1 are the outputs of the mth stage of the N-point FFT, respectively. In general, Pm, Qm, Pm + 1, and Qm + 1 are complex as is the twiddle factor. The twiddle factor can be expressed as

$$W_N^k = e^{-j(2\pi/N)k} = \cos(X) - j\sin(X) \tag{14}$$

where $X = (2\pi/N)k$ and $j = \sqrt{-1}$.

The inputs Pm and Qm can be expressed in terms of their real and imaginary parts by

$$\begin{aligned} Pm &= PR + j\,PI \\ Qm &= QR + j\,QI \end{aligned} \tag{15}$$

By substituting the values from (14) and (15), equation (13) becomes

$$\begin{aligned} Pm+1 &= PR + j\,PI + (QR\cos(X) + QI\sin(X) \\ &\quad + j\,(QI\cos(X) - QR\sin(X)) \\ &= (PR + QR\cos(X) + QI\sin(X)) \\ &\quad + j\,(PI + QI\cos(X) - QR\sin(X)) \\ Qm+1 &= PR + j\,PI - (QR\cos(X) + QI\sin(X)) \\ &\quad - j\,(QI\cos(X) - QR\sin(X)) \\ &= (PR - QR\cos(X) - QI\sin(X)) \\ &\quad + j\,(PI - QI\cos(X) + QR\sin(X)) \end{aligned} \tag{16}$$

Although the inputs of each butterfly stage have real and imaginary parts with magnitudes less than one, the real and imaginary parts of the outputs from (15) can have a maximum magnitude of

$$1 + 1\sin(45) + 1\cos(45) = 2.414213562$$

To avoid the possibility of overflow, each stage of the FFT is scaled down by a factor of 2. In this way, if an FFT consists of M stages, the output is scaled down by $2^M = N$, where N is the length of the FFT. Even with scaling, overflow is possible because of the maximum magnitude value for complex input data. This possibility is avoided by scaling down the input signal by a factor of 1.207106781, and then scaling up the output of the last FFT stage by the same factor. This additional scaling is not implemented in the code of the appendices, because the input signal is assumed real (i.e., the imaginary part is zero), and the above maximum value cannot be attained. The maximum value for a real input is 2.

Using (15), the TMS32020 butterfly code is given in Figure 7. It is assumed that all input and output data values are in Q15 format; i.e., they are expressed in two's-complement fractional arithmetic with the binary point immediately to the right of the sign bit (15 bits after the binary point). This code incorporates one stage of scaling (i.e., scaling by two) for the implementation of the general radix-2 DIT FFT butterfly with the 16-bit sine and cosine values of the twiddle factor also stored in Q15 format. Note that in performing fractional multiplications, the product of two 16-bit Q15 fractions is a 32-bit double-precision fraction in Q30 format with two sign bits. This result is illustrated in Figure 8, where S stands for sign bit.

The code for a general radix-2 DIT FFT is given in Figure 7. In the comment section, ACC, P-REGISTER, and T-REGISTER represent the on-chip 32-bit accumulator, 32-bit product register, and 16-bit temporary register of the TMS32020 processor, respectively. For more information about the TMS32020 processor and its architecture, see the TMS32020 User's Guide.[5]

The first block in the butterfly code of Figure 7 (starting with the label INIT) is for general system initialization. The second block of code (starting with the label BTRFLY) takes advantage of the double sign bits to provide a "free" divide-by-2 scaling in calculating the term (1/2)(QR COS(X) + QI SIN(X)), which is the scaled real part of the product of the twiddle factor and Qm. In addition, since the current contents of memory location QR are no longer required for subsequent calculations, QR is also used as a temporary storage for this term.

The third block of code calculates the term (1/2) (QI COS(X) − QR SIN(X)), which is the scaled imaginary part of the product of the twiddle factor and Qm. By completing this calculation, QI is also freed as a temporary storage for this term.

The fourth block of code calculates the real parts of Pm + 1 and Qm + 1 and provides the divide-by-2-per-stage scaling function to avoid signal overflows. To perform this function, the input binary scaling shifter of the TMS32020 is used.

```
*************************************************************************
* TMS32020 CODE FOR A GENERAL RADIX-2 DIT FFT BUTTERFLY                 *
*************************************************************************
*
* EQUATES FOR THE REAL AND IMAGINARY PARTS OF Xm(P) AND Xm(Q).
* THE LOCATIONS PR, PI, QR, AND QI ARE USED BOTH FOR THE INPUT
* AND THE OUTPUT DATA.
*
PR      EQU     0           Re(Pm) STORED IN LOCATION 0 IN DATA MEMORY
PI      EQU     1           Im(Pm) STORED IN LOCATION 1 IN DATA MEMORY
QR      EQU     2           Re(Qm) STORED IN LOCATION 2 IN DATA MEMORY
QI      EQU     3           Im(Qm) STORED IN LOCATION 3 IN DATA MEMORY
*
* EQUATES FOR THE REAL AND IMAGINARY PARTS OF THE TWIDDLE FACTOR.
*
COSX    EQU     4           COS(X) STORED IN LOCATION 4 IN DATA MEMORY
SINX    EQU     5           SIN(X) STORED IN LOCATION 5 IN DATA MEMORY
*
* INITIALIZE SYSTEM.
*
        AORG    >20
INIT    SPM     0           NO SHIFT AT OUTPUTS OF P-REGISTER
        SSXM                SELECT SIGN-EXTENSION MODE
        ROVM                RESET OVERFLOW MODE
        LDPK    4           CHOOSE DATA PAGE 4
*
* CALCULATE (QR COS(X) + QI SIN(X)); STORE RESULT IN QR.
*
BTRFLY  LT      QR          LOAD T-REGISTER WITH QR
        MPY     COSX        P-REGISTER = (1/2) QR COSX
        LTP     QI          ACC= (1/2) QR COSX ; LOAD T-REGISTER WITH QI
        MPY     SINX        P-REGISTER = (1/2) QI SINX
        APAC                ACC= (1/2)(QR COSX+QI SINX)
        MPY     COSX        P-REGISTER = (1/2) QI COSX
        LT      QR          LOAD T-REGISTER WITH QR
        SACH    QR          QR = (1/2)(QR COSX+QI SINX)
*
* CALCULATE (QI COS(X) - QR SIN(X)); STORE RESULT IN QI.
*
        PAC                 ACC= (1/2) QI COSX
        MPY     SINX        P-REGISTER = (1/2) QR SINX
        SPAC                ACC= (1/2)(QI COSX - QR SINX)
        SACH    QI          QI = (1/2)(QI COSX - QR SINX)
*
* CALCULATE Re(Pm+1) AND Re(Qm+1); STORE RESULTS IN PR AND QR.
*
        LAC     PR,14       ACC= (1/4)PR
        ADD     QR,15       ACC= (1/4)(PR + QR COSX + QI SINX)
        SACH    PR,1        PR = (1/2)(PR + QR COSX + QI SINX)
        SUBH    QR          ACC= (1/4)(PR - QR COSX - QI SINX)
        SACH    QR,1        QR = (1/2)(PR - QR COSX - QI SINX)
*
```

Figure 7. TMS32020 code for a General Radix-2 DIT FFT Butterfly

```
* CALCULATE Im[Pm+1] AND Im[Qm+1]; STORE RESULTS IN PI AND QI.
*
        LAC     PI,14      ACC= (1/4)PI
        ADD     QI,15      ACC= (1/4)(PI + QI COSX - QR SINX)
        SACH    PI,1       PI = (1/2)(PI + QI COSX - QR SINX)
        SUBH    QI         ACC= (1/4)(PI - QI COSX + QR SINX)
        SACH    QI,1       QI = (1/2)(PI - QI COSX + QR SINX)
*
```

Figure 7. TMS32020 Code for a General Radix-2 DIT FFT Butterfly (concluded)

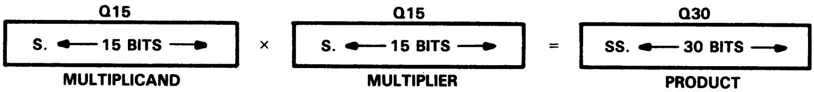


Figure 8. Multiplication of Two Q15 Numbers

Initially, the contents of PR are scaled down by a factor of 4 (equivalent to a 14-bit left-shift). Note that the shift or scaling function is being performed while the contents of PR are being loaded into the 32-bit accumulator. Since the TMS32020 has a 32-bit double-length accumulator, no accuracy is lost in this binary scaling process. To generate the final result of Re(Pm + 1), the contents of QR must be added to the contents of the accumulator with a 1-bit right-shift (equivalent to a 15-bit left-shift). This means adding (1/4)(QR COS(X) + QI SIN(X)) to (1/4)PR, which is the current value held in the accumulator. The upper-half of the accumulator is then stored in PR with a 1-bit left-shift to yield the term (1/2)(PR + QR COS(X) + QI SIN(X)), which is precisely Re(Pm + 1) scaled down by 2. This shift or scaling function is being performed while the contents of the upper half of the accumulator are loaded into PR. At this point, the accumulator still has a value equal to (1/4)(PR + QR COS(X) + QI SIN(X)). Hence, to obtain the final result of Re(Qm + 1), the unscaled contents of QR must be subtracted from the accumulator. The upper-half of the accumulator is again stored in QR with a 1-bit left-shift to yield the term (1/2)(PR + QR COS(X) + QI SIN(X)), which is precisely Re(Qm + 1) scaled down by 2.

In a similar fashion, the fifth block of code calculates the imaginary parts of Pm + 1 and Qm + 1. Note that all the scaling functions performed so far have come "free" with the architecture of the TMS32020.[5]

In summary, the data values are scaled down by right-shifting the 16-bit words as they are loaded into the 32-bit accumulator. In this way, full precision is still maintained in all calculations. The right-shifts are implemented by a corresponding number of left-shifts into the upper half of the accumulator. On the other hand, if the accumulator had been single precision or 16 bits wide, all scaling operations would have resulted in a loss of accuracy.

In-Place FFT Computations

In the butterfly implementation, the set of input registers in data memory (PR, PI, QR, and QI) for the two complex inputs Pm and Qm are used for holding the two complex outputs Pm + 1 and Qm + 1, respectively. When the same set of input registers is used as output registers for holding the FFT results, the FFT computation is said to be performed in-place. Therefore, FFTs implemented on the TMS32020 using the general butterfly routine are performed in-place.

As a general rule, an in-place FFT computation means that a total of 2N memory locations are required for an N-point FFT since the inputs to the FFT can be complex. On the other hand, a total of up to 4N memory locations is required for not-in-place computations.

Another attractive feature of the butterfly routine is that temporary or scratch-pad registers are not needed for intermediate results or calculations. Where coefficient quantization and other finite wordlength effects are not critical, 13-bit sine and cosine values can be used instead of 16-bit values addressed by the MPY instruction. In this way, the registers COSX and SINX for the twiddle factors can be dispensed with altogether. For this purpose, the MPYK instruction, which has a 13-bit signed constant embedded in its opcode, can be employed instead of the MPY instruction in the butterfly code. In Appendix A, two FFT macros (NORM1 and NORM2) illustrate the use of the MPY and MPYK instructions, respectively. Appendices A and B contain macro libraries that perform the same tasks, but in Appendix A they use direct addressing while in Appendix B they use indirect addressing.

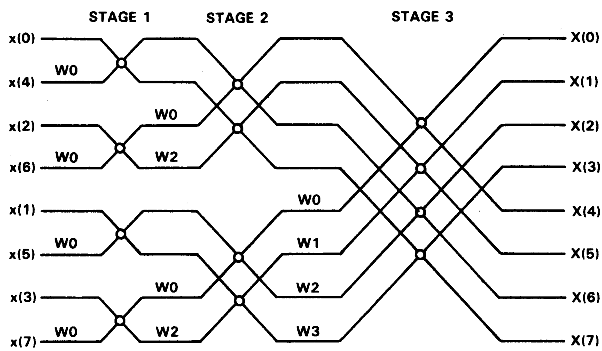
Bit-Reversal/Data Scrambling

As shown in Figure 9, the input time samples x(n) are not in order, i.e., they are scrambled. Such data scrambling or bit reversal is a direct result of the radix-2 FFT derivation. On closer inspection, it is seen that the index of each input sample is actually bit-reversed, as shown in Table 1.

Therefore, the input data sequence must be prescrambled prior to executing the FFT in order to produce in-order outputs. To perform bit reversal on the 8-point FFT, shown in Figure 9, the pairs of input samples, [x(1) and x(4)] and [x(3) and x(6)], must be swapped. On the other hand, Figure 10 has in-order input samples by rearranging the ordering of all the butterflies. However, the outputs are now bit-reversed.

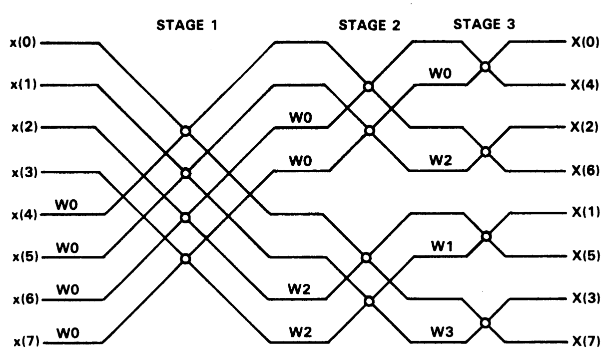
Table 1. Bit-Reversal Algorithm for an 8-Point Radix-2 DIT FFT

INDEX	BIT PATTERN	BIT-REVERSED PATTERN	BIT-REVERSED INDEX
0	000	000	0
1	001	100	4
2	010	010	2
3	011	110	6
4	100	001	1
5	101	101	5
6	110	011	3
7	111	111	7



LEGEND FOR TWIDDLE FACTOR: $W0 = W_8^0$ $W1 = W_8^1$ $W2 = W_8^2$ $W3 = W_8^3$

Figure 9. An In-Place DIT FFT with In-Order Outputs and Bit-reversed Inputs



LEGEND FOR TWIDDLE FACTOR: $W0 = W_8^0$ $W1 = W_8^1$ $W2 = W_8^2$ $W3 = W_8^3$

Figure 10. An In-Place DIT FFT with In-Order Inputs but Bit-Reversed Outputs

In general, bit reversal or data scrambling must be performed either at the input stage on the time samples (Figure 9) or at the output stage on the frequency samples (Figure 10). Bit reversal can be performed in-place. Such a process generally requires the use of one temporary data memory location.

Because of its double-precision accumulator and its versatile instruction set, the TMS32020 processor can perform in-place bit reversal or data scrambling without the use of a temporary data memory location. For example, the TMS32020 code for swapping input data locations x(1) and x(4) is given in Figure 11.

Although bit-reversal can be regarded as a separate task performed either at the input or output stage of an FFT implementation, some FFT algorithms exist with bit reversal as an integral part.[5] Such algorithms are said to be in-place and in-order, and they tend to have higher execution speeds than that of the FFT and bit-reversal algorithms executed separately.

A Numerical Example: 8-Point DIT FFT

To illustrate the concept of the FFT, a numerical example of an 8-point, decimation-in-time FFT is presented. The input signal is a square pulse with four samples equal to 0.5 and four samples equal to zero, as shown in Figure 12(a). The broken line in Figure 12 represents the envelope of the plotted signal. Figure 12(b) plots the magnitude of the computed FFT, where the number next to each sample indicates its magnitude. The choice of the amplitude for this example is arbitrary, but it is restricted to be less than 1 since it assumed that the numbers handled by the processor are in Q15 format.

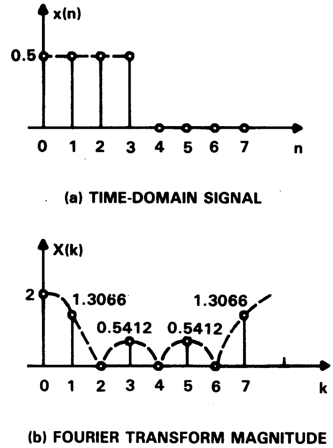


Figure 12. Time-Domain Signal and the Magnitude of Its FFT

The FFT of this time signal is computed by an 8-point DIT FFT as shown in Figure 13. On the left side, the samples x(n) of the time signal are arranged in their normal order. On the right side, the computed samples X(k) of the FFT are in bit-reversed order. Since the computation produces complex numbers, all the numerical values are presented as (R, I), where R is the real part and I is the imaginary part of the complex number. Figure 13 shows also the numerical values computed in the intermediate stages.

```
**********************************************************************
* TMS32020 CODE FOR THE BIT REVERSAL OF x(1) AND x(4)                *
**********************************************************************
*
BITREV ZALH   RX1      LOAD REAL PART OF x(1) IN UPPER ACCUMULATOR
       ADDS   RX4      LOAD REAL PART OF x(4) IN LOWER ACCUMULATOR
       SACL   RX1      STORE REAL PART OF x(4) IN REAL PART OF x(1)
       SACH   RX4      STORE REAL PART OF x(1) IN REAL PART OF x(4)
       ZALH   IX1      LOAD IMAG PART OF x(1) IN UPPER ACCUMULATOR
       ADDS   IX4      LOAD IMAG PART OF x(4) IN LOWER ACCUMULATOR
       SACL   IX1      STORE IMAG PART OF x(4) IN IMAG PART OF x(1)
       SACH   IX4      STORE IMAG PART OF x(1) IN IMAG PART OF x(4)
```

Figure 11. TMS32020 Code for the Bit Reversal of x(1) and x(4)

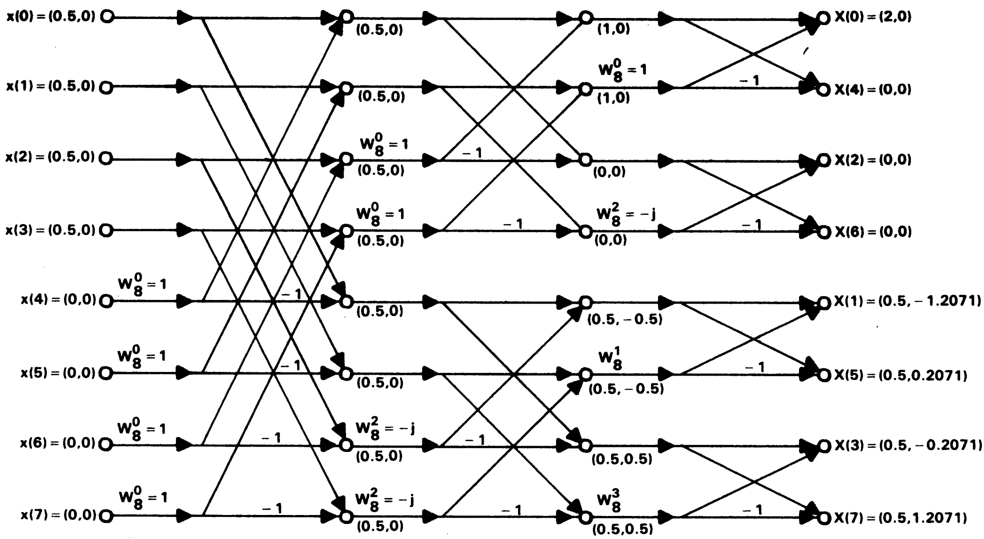


Figure 13. Numerical Example of an 8-Point DIT FFT without Scaling

Table 2 shows the values of the twiddle factor W_8^i for i = 0,1,...,7. Of these factors, only the first four are used in the FFT. The other four are related to them through the symmetry property (see equation (4)).

Table 2. Numerical Values of W_8^i, where i = 0, 1, ..., 7

TWIDDLE FACTOR	VALUE
W_8^0	1
$W_8^1 = e^{-\pi/4}$	0.7071 − j 0.7071
$W_8^2 = e^{-\pi/2}$	−j
$W_8^3 = e^{-3\pi/4}$	−0.7071 − j 0.7071
$W_8^4 = e^{-\pi} = -W_8^0$	−1
$W_8^5 = e^{-5\pi/4} = -W_8^1$	−0.7071 + j 0.7071
$W_8^6 = e^{-3\pi/2} = -W_8^2$	j
$W_8^7 = e^{-7\pi/4} = -W_8^3$	0.7071 + j 0.7071

Figure 13 has demonstrated the need for scaling. Without scaling, the intermediate results can attain values greater than or equal to 1. This would cause overflows in an implementation that uses Q15 numbers. Therefore, scaling is applied as mentioned earlier. Figure 14 shows exactly the same example, but now every stage is scaled by 1/2. No overflows occur with this implementation. The final output is the same as in Figure 13 but scaled by 1/8.

Special Butterflies

Although any N-point FFT (where N is a power of 2) can be directly implemented with the general butterfly only, special butterflies are normally used in order to increase the FFT execution speed.

Special butterflies can be coded by taking advantage of certain sine and cosine values of the twiddle factor. For instance, when the angle X takes on values such as 0, 90, 180, and 270 degrees, butterflies require much less code. Other special butterflies can also be coded for angles such as 45, 135, 225, and 315 degrees. Examples of these special butterflies can be found in nine macros located in Appendix A.

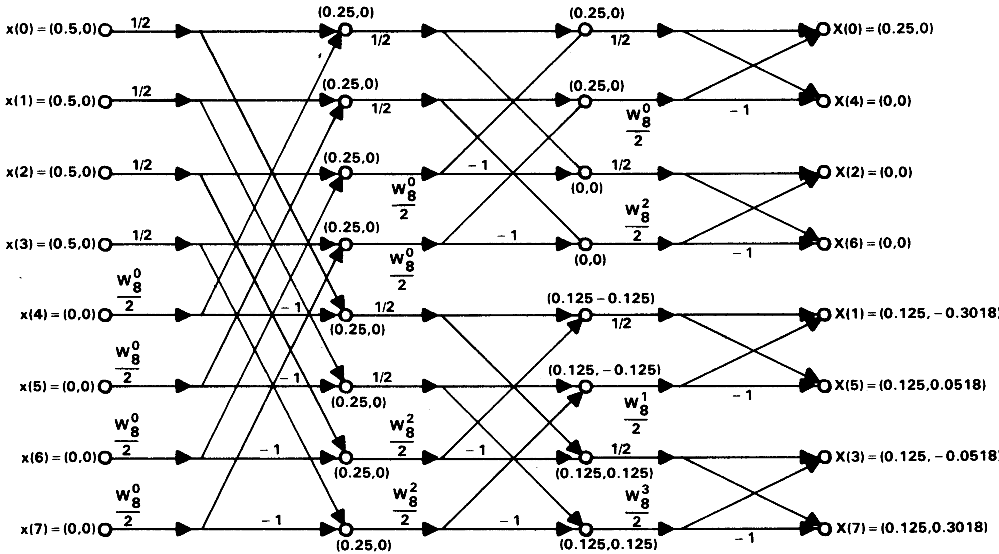


Figure 14. Numerical Example of an 8-Point DIT FFT with Scaling

An interesting point to be noted is that the first two stages of an N-point radix-2 FFT can be performed simultaneously with a special radix-4 butterfly to enhance execution speed. This special radix-4 butterfly is depicted in Figure 15 with the corresponding code (MACRO 9) listed in Appendix A.

The special radix-4 butterfly actually consists of four separate radix-2 butterflies. The radix-4 butterfly is further seen to be a 4-point DFT.

Together with the general butterfly, these special butterflies greatly improve the execution speed of an FFT algorithm. An example of the use of such butterflies for an 8-point DIT FFT is given in Figure 16. Since the FFT implementation is, in general, highly modular, the code in Figure 16 has been structured into a number of macro calls, including a macro for bit reversal.

During assembly time, the TMS32020 Macro Assembler fully expands these macros into in-line code.[5] The first two stages of the 8-point DIT FFT are implemented by the special radix-4 DIT FFT macro COMBO. The last stage consists of the special radix-2 DIT FFT macros ZERO, PIBY4, PIBY2, and PI3BY4. These macros can be found in Appendix A. The difference from the general radix-2 DIT butterfly is that the angle X of the twiddle factor takes on the values 0, 45, 90, and 135, respectively.

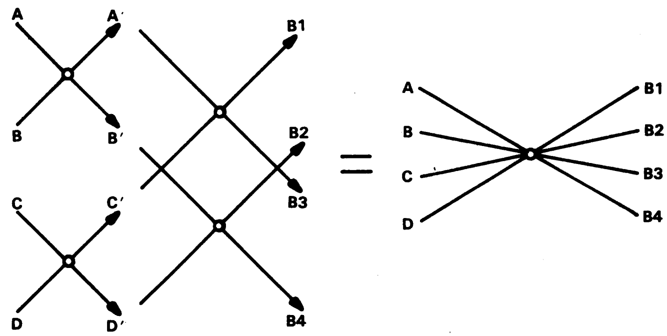


Figure 15. The Equivalence of Four Radix-2 Butterflies to one Radix-4 Butterfly

```
**********************************************************************
*                    AN 8-POINT DIT FFT                              *
**********************************************************************
*
XOR     EQU     00
XOI     EQU     01
X1R     EQU     02
X1I     EQU     03
X2R     EQU     04
X2I     EQU     05
X3R     EQU     06
X3I     EQU     07
X4R     EQU     08
X4I     EQU     09
X5R     EQU     10
X5I     EQU     11
X6R     EQU     12
X6I     EQU     13
X7R     EQU     14
X7I     EQU     15
W       EQU     16
        AORG    >20
WTABLE DATA     >5A82     VALUE FOR SIN(45) OR COS(45)
```

Figure 16. TMS32020 Code for an 8-Point DIT FFT Implementation

```
*
* INITIALIZE SYSTEM
*
INIT    SPM    0         NO SHIFT AT OUTPUTS OF PR
        SSXM             SELECT SIGN-EXTENSION MODE
        ROVM             RESET OVERFLOW MODE
        LDPK   4         CHOOSE DATA PAGE 4
        LALK   WTABLE    GET TWIDDLE FACTOR ADDRESS
        TBLR   W         STORE SIN(45) OR COS(45) IN W
*
* MACRO FOR INPUT BIT REVERSAL
*
BITREV $MACRO PR,PI,QR,QI
        ZALH   :PR:
        ADDS   :QR:
        SACL   :PR:
        SACH   :QR:
        ZALH   :
        ADDS   :QI:
        SACL   :
        SACH   :QI:
        $END
*
* FFT CODE WITH BIT-REVERSED INPUT SAMPLES
*
FFT8PT BITREV 2,3,8,9
        BITREV 6,7,12,13
*
* FIRST & SECOND STAGES COMBINED WITH DIVIDE-BY-4 INTERSTAGE SCALING
*
        COMBO  X0R,X0I,X1R,X1I,X2R,X2I,X3R,X3I
        COMBO  X4R,X4I,X5R,X5I,X6R,X6I,X7R,X7I
*
* THIRD STAGE WITH DIVIDE-BY-2 INTERSTAGE SCALING
*
        ZERO   X0R,X0I,X4R,X4I
        PIBY4  X1R,X1I,X5R,X5I,W
        PIBY2  X2R,X2I,X6R,X6I
        PI3BY4 X3R,X3I,X7R,X7I,W
```

Figure 16. TMS32020 Code for an 8-Point DIT FFT Implementation (concluded)

RADIX-4 DECIMATION-IN-FREQUENCY (DIF) FFT

The implementation described thus far is that of a radix-2 FFT using Decimation In Time (DIT). The decimation-in-time FFT is calculated by breaking the input sequence x(n) into smaller and smaller sequences and computing their FFTs. In an alternate approach, the output sequence X(k), which represents the Fourier transform of x(n), can be broken down into smaller subsequences that are computed from x(n). This method is called Decimation In Frequency (DIF). Computationally, there is no real difference between the two approaches. DIF is introduced here for two reasons: (1) to give the reader a broader understanding of the different methods used for the computation of the FFT, and (2) to allow a comparison of this implementation with the FORTRAN programs provided in the book by Burrus and Parks.[4] The programs from that book were the basis for the development of the radix-4 FFT code on the TMS32020.

In a radix-4 FFT, each butterfly has four inputs and four outputs instead of two as in the case of radix-2 FFT. As shown in the following equations, this is advantageous because the twiddle factor W has special values when the exponent corresponds to multiples of $\pi/2$. The end result is that the computational load of the FFT is reduced, and the radix-4 FFT is computed faster than the radix-2 FFT.

To introduce the radix-4 DIF FFT, equation (3) is broken into four summations. These four summations correspond to the four components in radix-4. The choice of having N/4 consecutive samples of x(n) in each sum is dictated by the choice of Decimation In Frequency (DIF).

$$
\begin{aligned}
X(k) &= \sum_{n=0}^{N-1} x(n)\, W_N^{nk} = \sum_{n=0}^{(N/4)-1} x(n)\, W_N^{nk} \\
&+ \sum_{n=N/4}^{(N/2)-1} x(n)\, W_N^{nk} + \sum_{n=N/2}^{(3N/4)-1} x(n)\, W_N^{nk} \\
&+ \sum_{n=3N/4}^{N-1} x(n)\, W_N^{nk} = \sum_{n=0}^{(N/4)-1} x(n)\, W_N^{nk} \\
&+ W_N^{Nk/4} \sum_{n=0}^{(N/4)-1} x(n+N/4)\, W_N^{nk} \\
&+ W_N^{Nk/2} \sum_{n=0}^{(N/4)-1} x(n+N/2)\, W_N^{nk} \\
&+ W_N^{3Nk/4} \sum_{n=0}^{(N/4)-1} x(n+3N/4)\, W_N^{nk}
\end{aligned}
\tag{17}
$$

$$k = 0,1,\ldots,N-1$$

From the definition of the twiddle factor, it can be shown that

$$W_N^{Nk/4} = (-j)^k,\ W_N^{Nk/2} = (-1)^k, \text{ and } W_N^{3Nk/4} = (j)^k$$

where j is the square root of -1. With this substitution, (17) can be rewritten as

$$
\begin{aligned}
X(k) = \sum_{n=0}^{(N/4)-1} &[x(n)+(-j)^k\, x(n+N/4) \\
&+(-1)^k\, x(n+N/2)+(j)^k\, x(n+3N/4)]\, W_N^{nk}
\end{aligned}
\tag{18}
$$

Equation (18) is not yet an FFT of length N/4, because the twiddle factor depends on N and not on N/4. To make it an N/4-point FFT, the sequence X(k) is broken into four sequences (decimation in frequency) for the cases where $k = 4r,\ 4r+1,\ 4r+2$, and $4r+3$.

Introducing this segmentation, and remembering that

$$W_N^{4nr} = W_{N/4}^{nr}$$

the following four equations (19) are derived from (18)

$$
\begin{aligned}
X(4r) &= \sum_{n=0}^{(N/4)-1} [x(n) + x(n+N/4) \\
&\quad + x\,(n+N/2) + x(n+3N/4)]\, W_N^0\, W_{N/4}^{nr} \\
X(4r+1) &= \sum_{n=0}^{(N/4)-1} [x(n) - j\, x(n+N/4) \\
&\quad - x(n+N/2) + j\, x(n+3N/4)]\, W_N^n\, W_{N/4}^{nr} \\
X(4r+2) &= \sum_{n=0}^{(N/4)-1} [x(n) - x(n+N/4) \\
&\quad + x(n+N/2) - x(n+3N/4)]\, W_N^{2n}\, W_{N/4}^{nr} \\
X(4r+3) &= \sum_{n=0}^{(N/4)-1} [x(n) + j\, x(n+N/4) \\
&\quad - x(n+N/2) - j\, x(n+3N/4)]\, W_N^{3n}\, W_{N/4}^{nr}
\end{aligned}
\tag{19}
$$

Each one of these equations is now an N/4-point FFT that can be computed by repeating the above procedure until N=4. Note that the factors W_N^0, W_N^n, W_N^{2n}, and W_N^{3n} are considered part of the signal. In general, an N-point FFT (where N is a power of 4) can be reduced to the computation of four N/4-point FFTs by transforming the input signal x(n) into an intermediate signal y(n), as suggested by (19). Figure 17 shows the corresponding radix-4 DIF butterfly, which generates one term for each sum in (19).

For simplicity, the notation of Figure 18 is often used instead of that of Figure 17 for the butterfly of radix-4 DIF FFT.

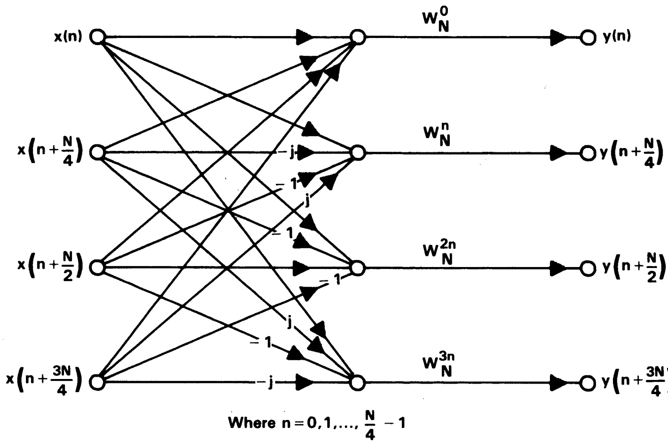


Figure 17. Radix-4 DIF Butterfly

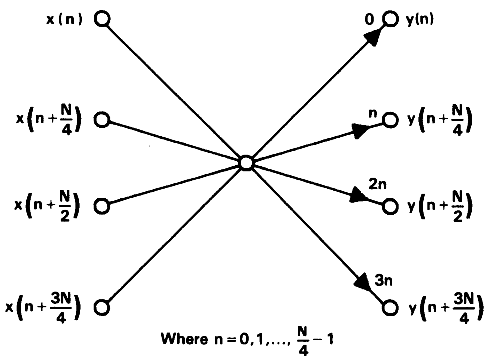


Figure 18. Alternate Form of the Radix-4 DIF Butterfly

Figure 19 shows an example of a 64-point, radix-4 DIF FFT.

Note that the inputs are normally ordered while the outputs are presented in a digit-reversed order. The principle of digit reversal is the same as in radix-2 FFT, but now the digits are 0, 1, 2, and 3 (quaternary system) instead of 0 and 1 (binary system). The code for digit reversal is the same as that shown in Figure 11. For example, the datapoint occupying location 132 (quaternary number corresponding to decimal 30) exchanges positions with the datapoint at location 231 (corresponding to the decimal 45).

Another important point of the radix-4 algorithm regards scaling. Since each stage of the radix-4 algorithm corresponds to two stages of the radix-2 algorithm, equivalent results are obtained by dividing the output of each stage of the radix-4 algorithm by 4.

Appendix E contains the implementation of a 256-point, radix-4 DIF FFT on the TMS32020. This implementation follows the one described in FORTRAN code in the book by Burrus and Parks.[4]

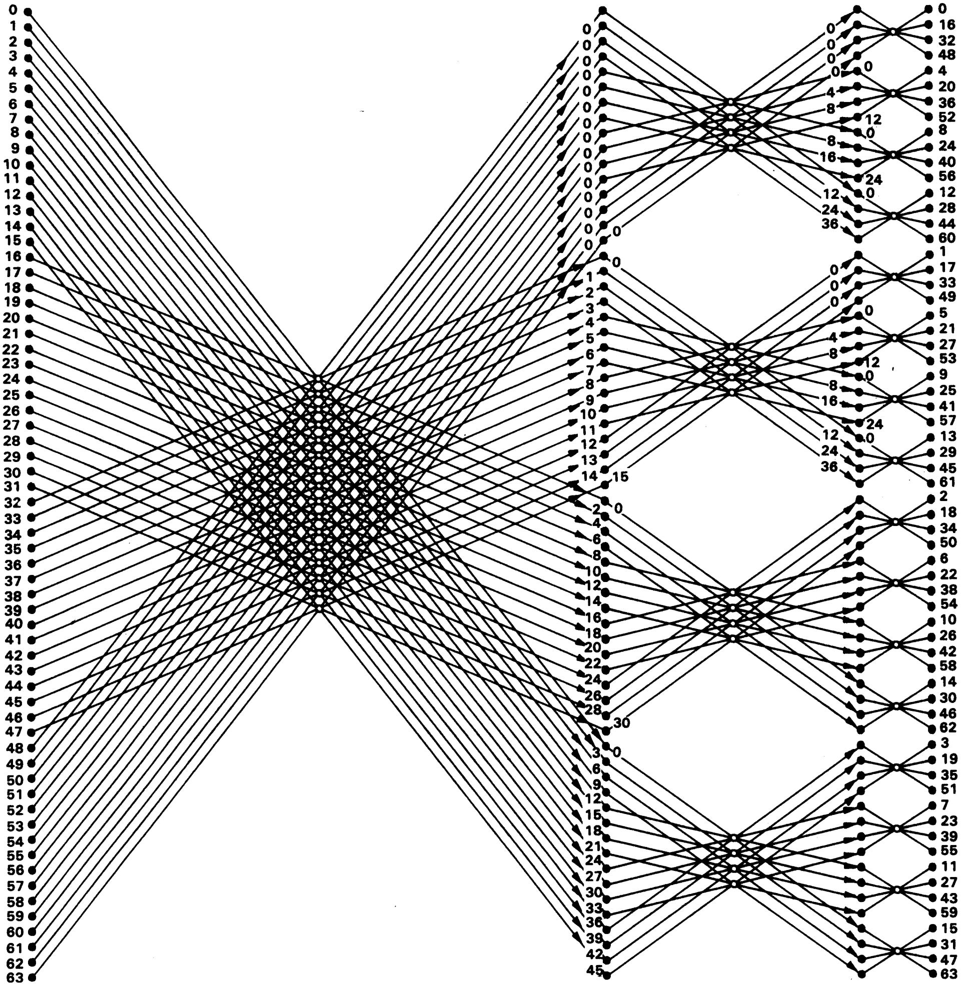


Figure 19. A 64-Point, Radix-4 DIF FFT

SYSTEM MEMORY AND I/O CONSIDERATIONS

Unlike non-realtime FFT applications where data samples to be transformed are assumed to already be in data memory, realtime FFT applications demand careful considerations of data input/output and system memory utilization.

The TMS32020 has 544 words of on-chip data RAM, organized into two 256-word blocks (B0 and B1) and one 32-word block (B2) that can be used as scratch-pad locations.[5] In non-realtime applications, this memory configuration allows a 256-point complex FFT to be easily performed (see Appendix C). However, for realtime FFT applications, input/output data buffering is generally required.

For small transform sizes, up to 128-point complex (or 256-point real) FFTs, the double-buffering technique, shown in Figure 20, can be used for realtime applications without the need of any external data memory. The on-chip RAM blocks B0 and B1 are organized into Buffer A and Buffer B, respectively.

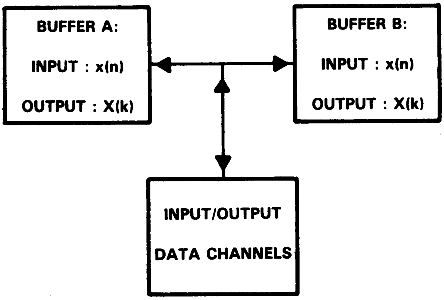


Figure 20. Input/Output Double-Buffering

Consider a 128-point complex FFT. Realtime input data to be transformed can be grouped into "frames" of 256 words (128 complex inputs) read into either Buffer A or Buffer B, depending on which one is not currently being used by the FFT program. The idea is to use the two on-chip RAM blocks B0 and B1 alternatively as I/O and transform buffers.

Assuming that the frame of data in Buffer A, the current transform buffer, is being transformed in-place, a software flag is then set to indicate that Buffer B can now be used as the current I/O buffer. This means that while time-domain data is read into Buffer B, the current I/O buffer, previous transformed data in Buffer B must be transferred out at the same time to make room for the incoming data. This can be acomplished efficiently if the I/O transfers are sequential and organized in a back-to-back manner (i.e., an output operation followed by an input operation).

Resetting the flag indicates that the roles of Buffer A and Buffer B are now reversed. In this case, Buffer B now has a full frame of input data ready to be transformed while Buffer A has a full frame of transformed data (spectral samples) ready to be transferred out to make room for more incoming time-domain data. The setting of the software flag is often implemented as an I/O device service routine (DSR) or as an interrupt handler in the case of interrupt-driven I/O.

Although this double-buffering technique is also applicable to larger transforms with the use of external memory, the actual memory required can be optimized if the transform time for an N-point FFT is shorter than the time to assemble a frame of N complex input data samples. For this purpose, the circular-buffer technique, shown in Figure 21, can be used.

Instead of a double-buffer size of 2N, a circular-buffer size of $N+M < 2N$ can be used where $M < N$ and M depends on the system input data rate in general. For example, M is chosen to be no less than 8T for an 8-kHz input sampling frequency and an N-point complex FFT with a transform time of T ms.

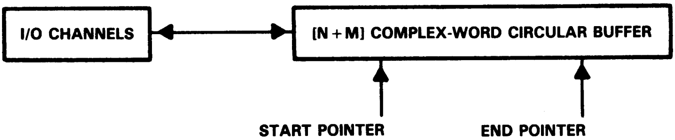


Figure 21. Input/Output Circular-Buffering for Large FFTs

A set of pointers is used to manage the data in the circular buffer. The start pointer is set at the beginning of the current frame, whereas the end pointer always indicates the current input data position in the circular buffer. Both pointers "wrap around" at the end of the circular buffer.

When a complete frame of input data has been collected, the set of pointer values is passed to the FFT program to transform the frame of data. For the next frame of input data, the start pointer points to the location immediately following the last location of the previous frame. As before, the end pointer for the current frame tracks the location of the next input data, and the whole process is repeated.

To decrease execution time, a large N-point FFT can be divided into smaller 256-point complex FFTs and executed 256 complex points at a time utilizing the on-chip RAM, as shown in Figure 22. Note that the system is still collecting incoming time-domain data samples and storing them in the external circular buffer while the FFT program is executing with internal data RAM. When 256 complex points have been processed, the FFT program returns them to the external buffer while fetching the next set of 256 samples for execution.

This scheme takes advantage of the fact that off-chip data accesses take two cycles each while on-chip data accesses take one cycle each. Certain instructions (e.g., SACL and SACH) even take three cycles to execute when operating on external RAM. To speed execution, off-chip data blocks can be efficiently moved into on-chip data memory via the BLKD (block move from data memory to data memory) instruction, which executes in a single cycle when used in the repeat mode with the repeat counter having a maximum count of 256.

IMPLEMENTING LARGE FFT'S

Figure 23 shows the memory configurations and transfers for a 1024-point complex FFT computed as four 256-point complex FFTs. A kernel 256-point complex FFT can operate on a group of 256 complex points at one time using on-chip RAM. Data transfers between on-chip and off-chip RAM are efficiently performed via the RPTK and BLKD instructions.

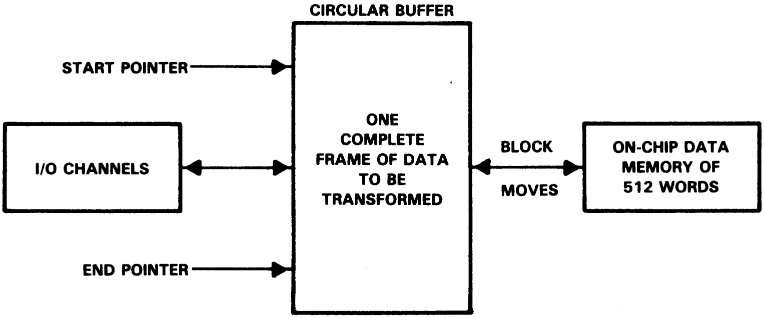


Figure 22. Use of On-Chip Memory to Speed FFT Execution

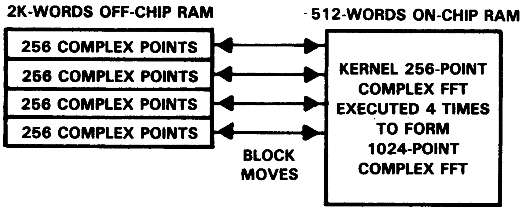


Figure 23. Execution of a 1024-Point Complex FFT with On-Chip RAM

Figure 24 shows a more detailed block diagram of a 1024-point radix-2 complex FFT. It can be seen that 512 butterflies must be performed at each stage. The first eight stages have a total of 4096 butterflies computed by four 256-point FFTs. The 256-point FFT in Appendix C is used as a subroutine for this purpose. Appendix D contains a listing for the 1024-point complex FFT performed with the help of on-chip RAM. However, due to the size of the 1024-point FFT program, the user may find it necessary to subdivide the code into smaller sections prior to assembly.

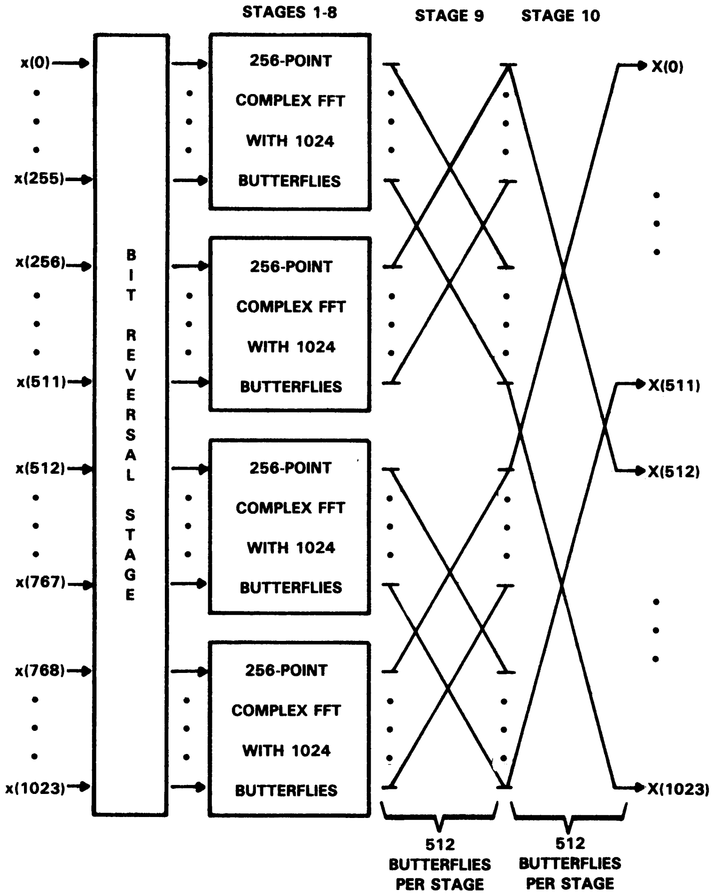


Figure 24. A 1024-Point Complex FFT Using a 256-Point Kernel for Stages 1-8

HIGHER-RADIX FFT'S

The same decomposition principle as for radix-2 FFT algorithms applies to higher radices as well. Table 3 shows the computation requirements[7] for a 4096-point FFT using various radices that are a power of two.

The main benefit of using higher-radix algorithms is the reduced amount of arithmetic operations required for the FFT computation. Beyond the use of radix-8 algorithms, however, the point of diminishing returns rapidly approaches. Memory addressing, data scaling, and program control become more and more complicated. On the other hand, a suitable combination of the radix-2, radix-4, and radix-8 algorithms becomes a flexible and efficient "mixed-radix" algorithm for most FFT applications. Reference [4] contains some useful FORTRAN routines for higher-radix FFT algorithms.

REAL TRANSFORMS VIA COMPLEX FFT'S

In practice, many signals are real functions of time, whereas the FFT algorithm has been derived for complex signals. This means that for real inputs, the imaginary parts of the complex entries are simply set to zero. This results in a certain amount of redundancy. To utilize the bandwidth of the FFT algorithm more effectively, one can use the fact that the frequency spectrum of a real signal is a hermitian function (i.e., the real part is an even function while the imaginary part is an odd function).[11] For example, two N-point real FFTs can be computed simultaneously with a single N-point complex FFT.[8,9,10] On the other hand, a single N-point complex FFT can also be utilized effectively to perform a 2N-point real FFT.[10] Such algorithms substantially reduce the amount of computation required for real FFTs.

Other efficient algorithms exist that further utilize the properties of real signals. In particular, the FFTs of four N-point real symmetric (even) and antisymmetric (odd) sequences can be computed with just one N-point complex FFT.[2] Alternatively, the same N-point complex FFT can be used to compute the FFTs of four N-point real symmetric (even) sequences simultaneously.[2]

INVERSE FFT

The inverse FFT is given by the equation

$$x(n) = (1/N) \sum_{k=0}^{N-1} X(k)\, W_N^{-nk} \qquad n=0,1,\ldots,N-1 \qquad (20)$$

where X(k) is the Fourier transform of the time-domain signal x(n). Note that (20) is essentially the same equation as (1), which represents the "forward" FFT, with two important differences: the scaling factor is (1/N), and the exponent of the twiddle factor is the negative of the one in equation (1). Because of the similarity between (20) and (1), the implementation of the inverse FFT is very straightforward. The code can be derived from that given in the appendices by applying the following modifications.

If the forward FFT is implemented with scaling, the resulting values in the frequency domain are (1/N)X(k) and not X(k). Hence, for the inverse FFT, no scaling must be applied in order to get back the original signal. On the other hand, if the forward FFT has not been scaled, the inverse FFT must be scaled. This scaling can be performed all at one point as suggested by (20), or at every stage as described earlier in the forward FFT.

The negative exponent of the twiddle factors implies that the values of sin(X) will have the opposite sign from that in the forward FFT. Therefore, one way to implement the inverse FFT is to have an additional table with the negatives of sin(X). Another method is possible if the complex conjugate of (20) is considered.

$$\overset{*}{x}(n) = (1/N) \sum_{k=0}^{N-1} \overset{*}{X}(k)\, W_N^{nk} \qquad n=0,1,\ldots,N-1 \qquad (21)$$

In (21), the asterisk indicates complex conjugate. In this form, there is no need to have an additional table for sin(X). Instead, the inverse FFT is implemented by applying the forward FFT on the complex conjugate of X(k) (with appropriate scaling). The complex conjugate of the resulting time signal is the desired result. Note that if x(n) is real, this last step is not necessary since, in this case, $\overset{*}{x}(n) = x(n)$.

Table 3. Computational Requirements for Higher-Radix FFT Algorithms

ALGORITHM	NUMBER OF REAL MULTIPLICATIONS	NUMBER OF REAL ADDITIONS
RADIX-2 $(N=2^{12})$	81,924	139,266
RADIX-4 $(N=4^{6})$	57,348	126,978
RADIX-8 $(N=8^{4})$	49,156	126,978
RADIX-16 $(N=16^{3})$	48,132	125,442

Table 4. FFT Performance for a TMS32020 Implementation

FFT			EXECUTION		
ALGORITHM	SIZE	TYPE	CYCLES	CLOCK	TIME
RADIX-2	128-Pt	Looped	21,879	5 MHz	4.375 ms
RADIX-2	256-Pt	Looped	42,416	5 MHz	8.483 ms
RADIX-2	256-Pt	Straight-Line	22,595	5 MHz	4.519 ms
RADIX-2	1024-Pt	Straight-Line	159,099	5 MHz	31.8198 ms
RADIX-4	256-Pt	Straight-Line	15,551	5 MHz	3.1102 ms

FFT PERFORMANCE TIMING

Table 4 provides the FFT timing performance for the TMS32020 code in the appendices. The source code examples included in Appendices C through G are not optimized for any specific application since they have been designed to emphasize clarity rather than code optimization. The key feature of these codes is that they do not require any scratch-pad (temporary) memory locations. Consequently, these codes should be useful in memory-critical applications. For time-critical applications, the codes can be optimized for better execution time. Higher execution speed is achieved by using straightline instead of looped code. The tradeoff for this optimization is the larger program memory requirements of the straightline code.

DESCRIPTION OF THE APPENDICES

At the end of this report, there are five appendices with TMS32020 code implementing several FFTs. The contents of the appendices are the following:

Appendix A: N-point, radix-2, DIT FFT (9 macros)
Appendix B: N-pŏint, radix-2, DIT FFT using indirect addressing (7 macros)
Appendix C: 256-point, radix-2 DIT FFT
Appendix D: 1024-point, radix-2 DIT FFT
Appendix E: 256-point, radix-4 DIF FFT
Appendix F: 128-point, radix-2 DIF FFT (looped code)
Appendix G: 256-point, radix-2 DIF FFT (looped code)

SUMMARY

The purpose of this report has been to develop an understanding of the underlying principles in FFT implementations with the TMS32020 processor. The book by Burrus and Parks[4] contains examples of FFT implementations on the TMS32010 processor, the first member of the TMS320 family.

This report has discussed the development of the DFT algorithm, leading to the derivation of the FFT algorithm. The implementation of the radix-2 DIT FFT algorithm was covered in detail, and the radix-4 DIF FFT algorithm was also explained. Special attention was given to various FFT implementation aspects, such as scaling, system memory, and input/outpput considerations.

The TMS32020 digital signal processor offers many advantages for the implementation of FFT algorithms. Its 200-ns cycle time and special features, such as the single-cycle multiplication, allow high execution speed. The 544 16-bit words of on-chip memory permit the implementation of a 256-point complex FFT without access to external memory, thus further reducing execution time. Furthermore, special instructions, such as RPTK and BLKD, allow the quick transfer of data from external to internal memory, so that portions of large FFTs can be implemented with the on-chip RAM. Due to the flexibility of the TMS32020, the designer can trade-off program memory with execution speed.

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APPENDIX A
FFT MACRO LIBRARY (DIRECT ADDRESSING)

APPENDIX A

```
*************************************************************
*                                                           *
*  THIS TMS32020 FFT MACRO LIBRARY CONTAINS A TOTAL OF 9    *
*  MACROS FOR IMPLEMENTING A GENERAL RADIX-2 DIT N-POINT    *
*  FFT.  ALL DIT BUTTERFLIES ARE IMPLEMENTED WITH DYNAMIC   *
*  SCALING TO AVOID ARITHMETIC OVERFLOWS. TWO'S-COMPLEMENT  *
*  FIXED-POINT FRACTIONAL ARITHMETIC IS USED THROUGHOUT.    *
*  WHILE THESE MACROS ARE NOT NECESSARILY OPTIMIZED FOR     *
*  SPEED, THEY ARE SO STRUCTURED THAT NO INTERMEDIATE OR    *
*  TEMPORARY REGISTERS ARE REQUIRED FOR THEIR EXECUTION.    *
*  CONSEQUENTLY, THESE MACROS ARE PARTICULARLY USEFUL IN    *
*  APPLICATIONS WHERE MEMORY SPACE PROVES TO BE CRITICAL.   *
*  IN ADDITION,  ALL FFT COMPUTATIONS ARE PERFORMED         *
*  IN-PLACE AND THE REAL AND IMAGINARY PARTS OF ALL COMPLEX*
*  INPUTS ARE ASSUMED TO BE IN CONSECUTIVE DATA MEMORY      *
*  LOCATIONS.                                               *
*                                                           *
*                                                           *
*************************************************************
*                                                           *
*************************************************************
*                                                           *
*                                          K                *
*          P .                    . P = P + Q*W             *
*              `                 '         N                *
*                `             '                            *
*                  `         '                              *
*                    `     '                                *
*                       O                                   *
*                     '    `                                *
*                   '        `                              *
*                 ' K          `                            *
*               '  W             `         K                *
*          Q .     N              . Q = P - Q*W             *
*                                          N                *
*                                                           *
*                                                           *
*    NOTATION FOR IN-PLACE RADIX-2 DIT FFT BUTTERFLY        *
*                                                           *
*************************************************************
*                                                           *
*************************************************************
*                                                           *
*                                                         M *
* IN A RADIX-2 N-POINT FFT, THERE ARE M PASSES WHERE N =2   *
* WITH [N/2] 2-POINT BUTTERFLIES PER PASS, GIVING A TOTAL   *
* OF [N/2]LOG N BUTTERFLIES PER FFT.                        *
*            2                                              *
*                                                           *
*************************************************************
```

```
*************************************************************
*                                                           *
*        MACRO 1: W =1, k=0.                                *
*                  N                                        *
*                                                           *
*        P=(PR+jPI)      P+Q=(PR+QR)+j(PI+QI)               *
*                     \ /                                   *
*                     / \                                   *
*        Q=(QR+jQI)      P-Q=(PR-QR)+j(PI-QI)               *
*                                                           *
*                                                           *
*            -j(2(pi)/N)k                                   *
*        W =e            =COS[(2(pi)/N)k]-jSIN[(2(pi)/N)k]  *
*         N                                                 *
*                      =WR+jWI                              *
*                                                           *
*                      =1                                   *
*                                                           *
*                                                           *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE   *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR      *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A    *
*  TOTAL OF 10 INSTRUCTIONS IS USED.  EXECUTION             *
*  TIME IS EQUAL TO 10 MACHINE CYCLES.                      *
*                                                           *
*************************************************************
ZERO     $MACRO     PR,PI,QR,QI
*
*        CALCULATE Re[P+Q] AND Re[P-Q]
*
         LAC        :PR:,15     ACC := (1/2)(PR)
         ADD        :QR:,15     ACC := (1/2)(PR+QR)
         SACH       :PR:        PR  := (1/2)(PR+QR)
         SUBH       :QR:        ACC := (1/2)(PR+QR)-(QR)
         SACH       :QR:        QR  := (1/2)(PR-QR)
*
*        CALCULATE Im[P+Q] AND Im[P-Q]
*
         LAC        :PI:,15     ACC := (1/2)(PI)
         ADD        :QI:,15     ACC := (1/2)(PI+QI)
         SACH       :PI:        PI  := (1/2)(PI+QI)
         SUBH       :QI:        ACC := (1/2)(PI+QI)-(QI)
         SACH       :QI:        QI  := (1/2)(PI-QI)
         $END
*
```

```
*************************************************************
*                                                           *
*       MACRO 2: W =-1, k=N/2.                              *
*                 N                                         *
*                                                           *
*       P=(PR+jPI)     P-Q=(PR-QR)+j(PI-QI)                 *
*                  \ /                                      *
*                  / \                                      *
*       Q=(QR+jQI)     P+Q=(PR+QR)+j(PI+QI)                 *
*                                                           *
*                                                           *
*           -j(2(pi)/N)k                                    *
*       W =e              =COS[(2(pi)/N)k]-jSIN[(2(pi)/N)k] *
*        N                                                  *
*                     =WR+jWI                               *
*                                                           *
*                     =-1                                   *
*                                                           *
*                                                           *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE   *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR      *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A    *
*  TOTAL OF 10 INSTRUCTIONS IS USED.  EXECUTION             *
*  TIME IS EQUAL TO 10 MACHINE CYCLES.                      *
*                                                           *
*************************************************************
PI      $MACRO    PR,PI,QR,QI
*
*       CALCULATE Re[P+Q] AND Re[P-Q]
*
        LAC       :PR:,15   ACC := (1/2)(PR)
        SUB       :QR:,15   ACC := (1/2)(PR-QR)
        SACH      :PR:      PR  := (1/2)(PR-QR)
        ADDH      :QR:      ACC := (1/2)(PR-QR)+(QR)
        SACH      :QR:      QR  := (1/2)(PR+QR)
*
*       CALCULATE Im[P+Q] AND Im[P-Q]
*
        LAC       :PI:,15   ACC := (1/2)(PI)
        SUB       :QI:,15   ACC := (1/2)(PI-QI)
        SACH      :PI:      PI  := (1/2)(PI-QI)
        ADDH      :QI:      ACC := (1/2)(PI-QI)+(QI)
        SACH      :QI:      QI  := (1/2)(PI+QI)
        $END
 *
```

```
*************************************************************
*                                                           *
*       MACRO 3: W =-j, k=N/4.                              *
*                 N                                         *
*                                                           *
*       P=(PR+jPI)     P-jQ=(PR+QI)+j(PI-QR)                *
*                  \ /                                      *
*                  / \                                      *
*       Q=(QR+jQI)     P+jQ=(PR-QI)+j(PI+QR)                *
*                                                           *
*                                                           *
*           -j(2(pi)/N)k                                    *
*       W =e              =COS[(2(pi)/N)k]-jSIN[(2(pi)/N)k] *
*        N                                                  *
*                     =WR+jWI                               *
*                                                           *
*                     =-j                                   *
*                                                           *
*                                                           *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE   *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR      *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A    *
*  TOTAL OF 11 INSTRUCTIONS IS USED.  EXECUTION             *
*  TIME IS EQUAL TO 11 MACHINE CYCLES.                      *
*                                                           *
*  WARNING: THIS MACRO REQUIRES THE INPUT SAMPLES QR AND    *
*           QI TO BE IN CONSECUTIVE DATA MEMORY LOCATIONS   *
*           OF ASCENDING ORDER. THE FOLLOWING STEPS ARE     *
*           USED TO IMPLEMENT THIS MACRO:                   *
*                                                           *
*          (1) [PI-QR] -----> [PI]                          *
*          (2) [PI+QR] -----> [QR]                          *
*          (3) [PR+QI] -----> [PR]                          *
*          (4) [PR-QI] -----> [ACC]                         *
*          (5) [QR]    -----> [QI]                          *
*          (6) [ACC]   -----> [QR]                          *
*                                                           *
*************************************************************
PIBY2   $MACRO    PR,PI,QR,QI
*
*       CALCULATE Re[P+jQ] AND Re[P-jQ]
*
        LAC       :PI:,15   ACC := (1/2)(PI)
        SUB       :QR:,15   ACC := (1/2)(PI-QR)
        SACH      :PI:      PI  := (1/2)(PI-QR)
        ADDH      :QR:      ACC := (1/2)(PI-QR)+(QR)
        SACH      :QR:      QR  := (1/2)(PI+QR)
*
*       CALCULATE Im[P+jQ] AND Im[P-jQ]
*
        LAC       :PR:,15   ACC := (1/2)(PR)
        ADD       :QI:,15   ACC := (1/2)(PR+QI)
```

```
        SACH     :PR:      PR  := (1/2)(PR+QI)
        SUBH     :QI:      ACC := (1/2)(PR+QI)-(QI)
        DMOV     :QR:      QR  -> QI
        SACH     :QR:      QR  := (1/2)(PR-QI)
        $END
*


************************************************************
*                                                          *
*       MACRO 4: W =j, k=3N/4.                             *
*                  N                                       *
*                                                          *
*       P=(PR+jPI)     P+jQ=(PR-QI)+j(PI+QR)               *
*                  \ /                                     *
*                  / \                                     *
*       Q=(QR+jQI)     P-jQ=(PR+QI)+j(PI-QR)               *
*                                                          *
*                                                          *
*           -j(2(pi)/N)k                                   *
*       W =e             =COS[(2(pi)/N)k]-jSIN[(2(pi)/N)k] *
*        N                                                 *
*                      =WR+jWI                             *
*                                                          *
*                      =j                                  *
*                                                          *
*                                                          *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE  *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR     *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A   *
*  TOTAL OF 10 INSTRUCTIONS ARE USED SUCH  THAT EXECUTION  *
*  TIME IS EQUAL TO 10 MACHINE CYCLES.                     *
*                                                          *
*  WARNING: THIS MACRO REQUIRES THE INPUT SAMPLES QR AND   *
*           QI TO BE IN CONSECUTIVE DATA MEMORY LOCATIONS  *
*           ASCENDING ORDER. THE FOLLOWING STEPS ARE USED  *
*           TO IMPLEMENT THIS MACRO:                       *
*                                                          *
*           (1) [PI-QR] -----> [PI]                        *
*           (2) [PI+QR] -----> [QR]                        *
*           (3) [PR+QI] -----> [PR]                        *
*           (4) [PR-QI] -----> [ACC]                       *
*           (5) [QR]    -----> [QI]                        *
*           (6) [ACC]   -----> [QR]                        *
*                                                          *
************************************************************
PI3BY2  $MACRO    PR,PI,QR,QI
*
*       CALCULATE Re[P+jQ] AND Re[P-jQ]
*
        LAC      :PI:,15   ACC := (1/2)(PI)
        ADD      :QR:,15   ACC := (1/2)(PI+QR)
        SACH     :PI:      PI  := (1/2)(PI+QR)
        SUBH     :QR:      ACC := (1/2)(PI+QR)-(QR)
        SACH     :QR:      QR  := (1/2)(PI-QR)
*
```

```
*       CALCULATE Im[P+jQ] AND Im[P-jQ]
*
        LAC      :PR:,15   ACC := (1/2)(PR)
        SUB      :QI:,15   ACC := (1/2)(PR-QI)
        SACH     :PR:      PR  := (1/2)(PR-QI)
        ADDH     :QI:      ACC := (1/2)(PR-QI)+(QI)
        DMOV     :QR:      QR  -> QI
        SACH     :QR:      QR  := (1/2)(PR+QI)
        $END
*


************************************************************
*                                                          *
*       MACRO 5:     k=N/8.                                *
*                                                          *
*       P=(PR+jPI)   P+Q*W=(PR+Re[Q*W])+j(PI+Im[Q*W])      *
*                  \ /                                     *
*                  / \                                     *
*       Q=(QR+jQI)   P-Q*W=(PR-Re[Q*W])+j(PI-Im[Q*W])      *
*                                                          *
*           -j(2(pi)/N)k                                   *
*       W =e             =COS((pi)/4)-jSIN((pi)/4)=WR+jWI  *
*        N                                                 *
*                                                          *
*       LET          W=|COS((pi)/4)|=|SIN((pi)/4)|         *
*                                                          *
*       THEN     [Q*W]=(QR+QI)*W+j(QI-QR)*W                *
*                                                          *
*              Re[Q*W]=(QI+QR)*W                           *
*                                                          *
*              Im[Q*W]=(QI-QR)*W                           *
*                                                          *
*                                                          *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE  *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR     *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A   *
*  TOTAL OF 20 INSTRUCTIONS ARE USED SUCH  THAT EXECUTION  *
*  TIME IS EQUAL TO 20 MACHINE CYCLES.   THIS MACRO        *
*  REQUIRES W TO BE THE ABSOLUTE VALUE (MAGNITUDE)  OF     *
*  COS((pi)/4) AND SIN((pi)/4).  THE SIGNS OF THESE TRIG   *
*  FUNCTIONS HAVE BEEN TAKEN CARE OF IN THE CODE.          *
*                                                          *
************************************************************
PIBY4   $MACRO    PR,PI,QR,QI,W
*
        LT       :W:       T-REGISTER :=W=COS(PI/4)=SIN(PI/4)
        LAC      :QI:,14   ACC := (1/4)(QI)
        SUB      :QR:,14   ACC := (1/4)(QI-QR)
        SACH     :QI:,1    QI  := (1/2)(QI-QR)
        ADD      :QR:,15   ACC := (1/4)(QI+QR)
        SACH     :QR:,1    QR  := (1/2)(QI+QR)
        LAC      :PR:,14   ACC := (1/4)(PR)
        MPY      :QR:      P-REGISTER := (1/4)(QI+QR)*W
        APAC               ACC := (1/4)[PR+(QI+QR)*W]
        SACH     :PR:,1    PR  := (1/2)[PR+(QI+QR)*W]
```

```
        SPAC                    ACC := (1/4)(PR)
        SPAC                    ACC := (1/4)[PR-(QI+QR)*W]
        SACH      :QR:,1        QR  := (1/2)[PR-(QI+QR)*W]
        LAC       :PI:,14       ACC := (1/4)(PI)
        MPY       :QI:          P-REGISTER := (1/4)(QI-QR)*W
        APAC                    ACC := (1/4)[PI+(QI-QR)*W]
        SACH      :PI:,1        PI  := (1/2)[PI+(QI-QR)*W]
        SPAC                    ACC := (1/4)(PI)
        SPAC                    ACC := (1/4)[PI-(QI-QR)*W]
        SACH      :QI:,1        QI  := (1/2)[PI-(QI-QR)*W]
        $END
*
```

```
***********************************************************
*                                                         *
*       MACRO 6:     k=3N/8.                              *
*                                                         *
*       P=(XR+jXI)   X+Q*W=(XR+Re[Q*W])+j(XI-Im[Q*W])     *
*                  \ /                                    *
*                  / \                                    *
*       Q=(QR+jQI)   X-Q*W=(XR-Re[Q*W])+j(XI+Im[Q*W])     *
*                                                         *
*           -j(2(pi)/N)k                                  *
*       W =e               =COS(3(pi)/4)-jSIN(3(pi)/4)    *
*        N                                                *
*                        =WR+jWI                          *
*                                                         *
*       LET          W=|COS(3(pi)/4)|=|SIN(3(pi)/4)|      *
*                                                         *
*       THEN      [Q*W]=(QI-QR)*W-j(QI+QR)*W              *
*                                                         *
*              RE[Q*W]=(QI-QR)*W                          *
*                                                         *
*              IM[Q*W]=(QI+QR)*W                          *
*                                                         *
*                                                         *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR    *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A  *
*  TOTAL OF 20 INSTRUCTIONS ARE USED SUCH  THAT EXECUTION *
*  TIME IS EQUAL TO 20 MACHINE CYCLES.   THIS MACRO       *
*  REQUIRES W TO BE THE ABSOLUTE VALUE (MAGNITUDE)  OF    *
*  COS(3(pi)/4) AND SIN(3(pi)/4).  THE SIGNS OF THESE TRIG *
*  FUNCTIONS HAVE BEEN TAKEN CARE OF IN THE CODE.         *
*                                                         *
***********************************************************
PI3BY4    $MACRO     PR,PI,QR,QI,W
*
        LT        :W:           T-REGISTER :=W=COS(PI/4)=SIN(PI/4)
        LAC       :QI:,14       ACC := (1/4)(QI)
        SUB       :QR:,14       ACC := (1/4)(QI-QR)
        SACH      :QI:,1        QI  := (1/2)(QI-QR)
        ADD       :QR:,15       ACC := (1/4)(QI+QR)
```

```
        SACH      :QR:,1        QR  := (1/2)(QI+QR)
        LAC       :PR:,14       ACC := (1/4)(PR)
        MPY       :QI:          P-REGISTER := (1/4)(QI-QR)*W
        APAC                    ACC := (1/4)[PR+(QI-QR)*W]
        SACH      :PR:,1        PR  := (1/2)[PR+(QI-QR)*W]
        SPAC                    ACC := (1/4)(PR)
        SPAC                    ACC := (1/4)[PR-(QI-QR)*W]
        MPY       :QR:          P-REGISTER := (1/4)(QI+QR)*W
        SACH      :QR:,1        QR  := (1/2)[PR-(QI-QR)*W]
        LAC       :PI:,14       ACC := (1/4)(PI)
        SPAC                    ACC := (1/4)[PI-(QI+QR)*W]
        SACH      :PI:,1        PI  := (1/2)[PI-(QI+QR)*W]
        APAC                    ACC := (1/4)(PI)
        APAC                    ACC := (1/4)[PI+(QI+QR)*W]
        SACH      :QI:,1        QI  := (1/2)[PI+(QI+QR)*W]
        $END
*
```

```
***********************************************************
*                                                         *
*       MACRO 7:  A GENERAL RADIX-2 DIT FFT 'BUTTERFLY'   *
*                                                         *
*       P=(PR+jPI)   P+Q*W=(PR+Re[Q*W])+j(PI-Im[Q*W])     *
*                  \ /                                    *
*                  / \                                    *
*       Q=(QR+jQI)   P-Q*W=(PR-Re[Q*W])+j(PI+Im[Q*W])     *
*                                                         *
*           -j(2(pi)/N)k                                  *  *
*       W =e               =COS(O)-jSIN(O)                *
*        N                                                *
*                          =WR+jWI                        *
*                                                         *
*                                                         *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR    *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A  *
*  TOTAL OF 23 INSTRUCTIONS ARE USED SUCH  THAT EXECUTION *
*  TIME IS EQUAL TO 23 MACHINE CYCLES.   THIS MACRO       *
*  REQUIRES W TO BE THE ABSOLUTE VALUE (MAGNITUDE)  OF    *
*  COS(O) AND SIN(O).  THE SIGNS OF THESE TRIG FUNCTIONS  *
*  HAVE BEEN TAKEN CARE OF IN THE CODE.                   *
*                                                         *
***********************************************************
NORM1   $MACRO          PR,PI,QR,QI,WR,WI
*
*       CALCULATE QR*WR + QI*WI AND STORE RESULT IN QI
*
        LT   :QI:        T-REGISTER := QI
        MPYK :WI:        P-REGISTER := (1/16)(QI*WI)
        LTP  :QR:        ACC := (1/16)(QI*WI); LOAD T WITH QR
        MPYK :WR:        P-REGISTER := (1/16)(QR*WR)
        APAC             ACC := (1/16)(QR*WR+QI*WI)
        SFR              ACC := (1/32)(QR*WR+QI*WI)
        SACH :QR:,4      QR  := (1/2)(QR*WR+QI*WI)
```

```
*
*       CALCULATE QI*WR - QR*WI AND STORE RESULT IN QR
*
        MPYK -:WI:      P-REGISTER := (1/16)(-QR*WI)
        LTP  :QI:       ACC := (1/16)(-QR*WI); T-REGISTER := QI
        MPYK :WR:       P-REGISTER := (1/16)(QI*WR)
        APAC            ACC := (1/16)(QI*WR-QR*WI)
        SFR             ACC := (1/32)(QI*WR-QR*WI)
        SACH :QI:,4     QI  := (1/2)(QI*WR-QR*WI)
*
*       CALCULATE Re[P+jQ] & Re[P-jQ] STORE RESULTS in PR & QR
*
        LAC  :PR:,14    ACC := (1/4)PR
        ADD  :QR:,15    ACC := (1/4)[PR+(QR*WR+QI*WI)]
        SACH :PR:,1     PR  := (1/2)[PR+(QR*WR+QI*WI)]
        SUBH :QR:       ACC := (1/4)[PR-(QR*WR+QI*WI)]
        SACH :QR:,1     QR  := (1/2)[PR-(QR*WR+QI*WI)]
*
*       CALCULATE Im[P+jQ] & Im[P-jQ] STORE RESULTS in PI & QI
*
        LAC  :PI:,14    ACC := (1/4)PI
        ADD  :QI:,15    ACC := (1/4)[PI+(QI*WR-QR*WI)]
        SACH :PI:,1     PR  := (1/2)[PI+(QI*WR-QR*WI)]
        SUBH :QI:       ACC := (1/4)[PI-(QI*WR-QR*WI)]
        SACH :QI:,1     QI  := (1/2)[PI-(QI*WR-QR*WI)]
        $END


**************************************************************
*                                                            *
*       MACRO 8:  A GENERAL RADIX-2 DIT FFT 'BUTTERFLY'      *
*                                                            *
*       P=(PR+jPI)   P+Q*W=(PR+Re[Q*W])+j(PI-Im[Q*W])        *
*                 \ /                                        *
*                 / \                                        *
*       Q=(QR+jQI)   P-Q*W=(PR-Re[Q*W])+j(PI+Im[Q*W])        *
*                                                            *
*           -j(2(pi)/N)k                                     *
*       W =e           =COS(O)-jSIN(O)                       *
*        N                                                   *
*                      =WR+jWI                               *
*                                                            *
*                                                            *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE    *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR       *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A     *
*  TOTAL OF 22 INSTRUCTIONS ARE USED SUCH  THAT EXECUTION    *
*  TIME IS EQUAL TO 22 MACHINE CYCLES.   THIS MACRO          *
*  REQUIRES W TO BE THE ABSOLUTE VALUE (MAGNITUDE)  OF       *
*  COS(O) AND SIN(O).  THE SIGNS OF THESE TRIG FUNCTIONS     *
*  HAVE BEEN TAKEN CARE OF IN THE CODE.                      *
*                                                            *
**************************************************************
NORM2   $MACRO          PR,PI,QR,QI,WR,WI
*
*       CALCULATE QR*WR + QI*WI AND STORE RESULT IN QR
*
        LT   :QR:       T-REGISTER := QR
        MPY  :WR:       P-REGISTER := (1/2)(QR*WR)
        LTP  :QI:       ACC := (1/2)(QR*WR); T-REGISTER := QI
```

```
        MPY  :WI:       P-REGISTER := (1/2)(QI*WI)
        APAC            ACC := (1/2)(QR*WR+QI*WI)
        MPY  :WR:       P-REGISTER := (1/2)(QI*WR)
        LT   :QR:       LOAD T-REGISTER WITH QR
        SACH :QR:       QR  := (1/2)(QR*WR+QI*WI)
*
*       CALCULATE QI*WR - QR*WI AND STORE RESULT IN QI
*
        PAC             ACC= (1/2)(QI*WR)
        MPY  :WI:       P-REGISTER := (1/2)(QR*WI)
        SPAC            ACC= (1/2)(QI*WR-QR*WI)
        SACH :QI:       QI = (1/2)(QI*WR-QR*WI)
*
*       CALCULATE Re[Pm+1] & Re[Qm+1] STORE RESULTS in PR & QR
*
        LAC  :PR:,14    ACC= (1/4)PR
        ADD  :QR:,15    ACC= (1/4)[PR+(QR*WR+QI*WI)]
        SACH :PR:,1     PR = (1/2)[PR+(QR*WR+QI*WI)]
        SUBH :QR:       ACC= (1/4)[PR-(QR*WR+QI*WI)]
        SACH :QR:,1     QR = (1/2)[PR-(QR*WR+QI*WI)]
*
*       CALCULATE Im[Pm+1] & Im[Qm+1] STORE RESULTS in PI & QI
*
        LAC  :PI:,14    ACC= (1/4)PI
        ADD  :QI:,15    ACC= (1/4)[PI+(QI*WR-QR*WI)]
        SACH :PI:,1     PI = (1/2)[PI+(QI*WRRQR*WI)]
        SUBH :QI:       ACC= (1/4)[PI-(QI*WR-QR*WI)]
        SACH :QI:,1     QI = (1/2)[PI-(QI*WR-QR*WI)]
        $END


**************************************************************
*                                                            *
*       MACRO 9:                                             *
*                                                            *
*                     A     A'        B1                     *
*                      \ /   \      /                        *
*                      / \    \ /   B2                       *
*                     B     B'\ / \ /                        *
*                     C     C'/ \ / \                        *
*                      \ /    / \   B3                       *
*                      / \   /    \                          *
*                     D     D'        B4                     *
*                                                            *
*                                                            *
*       A = R1+jI1                                           *
*                                                            *
*       B = R2+jI2                                           *
*                                                            *
*       C = R3+jI3                                           *
*                                                            *
*       D = R4+jI4                                           *
*                                                            *
*       A' = (R1+R2) + j(I1+I2)                              *
*                                                            *
*       B' = (R1-R2) + j(I1-I2)                              *
*                                                            *
*       C' = (R3+R4) + j(R3+R4)                              *
*                                                            *
```

```
*        D' = (R3-R4) + j(R3-R4)                              *
*                                                             *
*        B1 = A'+C'                                           *
*                                                             *
*        B2 = B'-jD'                                          *
*                                                             *
*        B3 = A'-C'                                           *
*                                                             *
*        B4 = B'+jD'                                          *
*                                                             *
*        REAL(B1) = ((R1+R2) + (R3+R4)) /2                    *
*        IMAG(B1) = ((I1+I2) + (I3+I4)) /2                    *
*                                                             *
*        REAL(B2) = ((R1-R2) + (I3-I4)) /2                    *
*        IMAG(B2) = ((I1-I2) - (R3-R4)) /2                    *
*                                                             *
*        REAL(B3) = ((R1+R2) - (R3+R4)) /2                    *
*        IMAG(B3) = ((I1+I2) - (I3+I4)) /2                    *
*                                                             *
*        REAL(B4) = ((R1-R2) - (I3-I4)) /2                    *
*        IMAG(B4) = ((I1-I2) + (R3-R4)) /2                    *
*                                                             *
*                                                             *
* THE FIRST TWO STAGES OF A RADIX-2 N-POINT DIT FFT CAN BE    *
* IMPLEMENTED WITH A SPECIAL RADIX-4 BUTTERFLY WHICH HAS A    *
* UNITY TWIDDLE FACTOR USED TO SPEED UP THE EXECUTION TIME    *
* OF THE FFT WITH THE ABOVE EQUATIONS.  WHEN USING THESE      *
* EQUATIONS, ALL INPUT VALUES MUST BE WITHIN THE RANGE        *
* -1 <= X < 1.0. TOTAL NUMBER OF INTRUCTIONS IS 37.           *
* EXECUTION TIME IS EQUIVALENT TO 39 MACHINE CYCLES.          *
*                                                             *
***************************************************************


***************************************************************
*                                                             *
*  THE FOLLOWING STEPS ARE USED TO IMPLEMENT THE SPECIAL      *
*  RADIX-4 MACRO 'COMBO' FOR THE FIRST TWO STAGES OF AN       *
*  N-POINT RADIX-2 DIT FFT.                                   *
*                                                             *
*  STEP 1         STEP 2               STEP 3                 *
*  ------         ------               ------                 *
*                                                             *
*  R1 R1          (R1+R2)/1            [(R1+R2)+(R3+R4)]/2    *
*  I1 I1          (I1+I2)/1            [(I1+I2)+(I3+I4)]/2    *
*                                                             *
*  R2 R2          [(R1-R2)+(I3-I4)]/2  [(R1-R2)+(I3-I4)]/2    *
*  I2 I2          [(I1-I2)-(R3-R4)]/2  [(I1-I2)-(R3-R4)]/2    *
*                                                             *
*  R3 (R3+R4)/1   (R3+R4)/1            [(R1+R2)-(R3+R4)]/2    *
*  I3 (I3+I4)/1   (I3+I4)/1            [(I1+I2)-(I3+I4)]/2    *
*                                                             *
*  R4 (R3-R4)/1   [(R1-R2)-(I3-I4)]/2  [(R1-R2)-(I3-I4)]/2    *
*  I4 (I3-I4)/1   R4--->I4:=(R3-R4)/1                         *
*                 [(I1-I2)+(R3-R4)]/2  [(I1-I2)+(R3-R4)]/2    *
*                                                             *
***************************************************************
COMBO    $MACRO     R1,I1,R2,I2,R3,I3,R4,I4
*
*        CALCULATE PARTIAL TERMS FOR R3,R4,I3 AND I4
*
         LAC        :R3:,14   ACC := (1/4)(R3)
         ADD        :R4:,14   ACC := (1/4)(R3+R4)
         SACH       :R3:,1    R3  := (1/2)(R3+R4)
         SUB        :R4:,15   ACC := (1/4)(R3+R4)-(1/2)(R4)
         SACH       :R4:,1    R4  := (1/2)(R3-R4)
         LAC        :I3:,14   ACC := (1/4)(I3)
         ADD        :I4:,14   ACC := (1/4)(I3+I4)
         SACH       :I3:,1    I3  := (1/2)(I3+I4)
         SUB        :I4:,15   ACC := (1/4)(I3+I4)-(1/2)(I4)
         SACH       :I4:,1    I4  := (1/2)(I3-I4)
*
*        CALCULATE PARTIAL TERMS FOR R2,R4,I2 AND I4
*
         LAC        :R1:,14   ACC := (1/4)(R1)
         ADD        :R2:,14   ACC := (1/4)(R1+R2)
         SACH       :R1:,1    R1  := (1/2)(R1+R2)
         SUB        :R2:,15   ACC := (1/4)(R1+R2)-(1/2)(R2)
         ADD        :I4:,15   ACC := (1/4)[(R1-R2)+(I3-I4)]
         SACH       :R2:      R2  := (1/4)[(R1-R2)+(I3-I4)]
         SUBH       :I4:      ACC := (1/4)[(R1-R2)-(I3-I4)]
         DMOV       :R4:      I4  := R4 = (1/2)(R3-R4)
         SACH       :R4:      R4  := (1/4)[(R1-R2)-(I3-I4)]
         LAC        :I1:,14   ACC := (1/4)(I1)
         ADD        :I2:,14   ACC := (1/4)(I1+I2)
         SACH       :I1:,1    I1  := (1/2)(I1+I2)
         SUB        :I2:,15   ACC := (1/4)(I1+I2)-(1/2)(I2)
         SUB        :I4:,15   ACC := (1/4)[(I1-I2)-(R3-R4)]
         SACH       :I2:      I2  := (1/4)[(I1-I2)-(R3-R4)]
         ADDH       :I4:      ACC := (1/4)[(I1-I2)+(R3-R4)]
         SACH       :I4:      I4  := (1/4)[(I1-I2)+(R3-R4)]
*
*        CALCULATE PARTIAL TERMS FOR R1,R3,I1 AND I3
*

         LAC        :R1:,15   ACC := (1/4)(R1+R2).
         ADD        :R3:,15   ACC := (1/4)[(R1+R2)+(R3+R4)]
         SACH       :R1:      R1  := (1/4)[(R1+R2)+(R3+R4)]
         SUBH       :R3:      ACC := (1/4)[(R1+R2)-(R3+R4)]
         SACH       :R3:      R3  := (1/4)[(R1+R2)-(R3+R4)]
         LAC        :I1:,15   ACC := (1/4)(I1+I2)
         ADD        :I3:,15   ACC := (1/4)[(I1+I2)+(I3+I4)]
         SACH       :I1:      I1  := (1/4)[(I1+I2)+(I3+I4)]
         SUBH       :I3:      ACC := (1/4)[(I1+I2)-(I3+I4)]
         SACH       :I3:      I3  := (1/4)[(I1+I2)-(I3+I4)]
         $END
```

APPENDIX B
FFT MACRO LIBRARY (INDIRECT ADDRESSING)

A P P E N D I X B

```
*************************************************************
*                                                           *
*  THIS TMS32020 FFT MACRO LIBRARY CONTAINS A TOTAL OF 7    *
*  MACROS FOR IMPLEMENTING A GENERAL RADIX-2 DIT N-POINT    *
*  FFT USING INDIRECT ADDRESS FORMAT OF THE TMS32020.  ALL  *
*  DIT BUTTERFLIES ARE IMPLEMENTED WITH DYNAMIC SCALING TO  *
*  AVOID ARITHMETIC OVERFLOWS.  2'S COMPLEMENT FIXED-POINT  *
*  FRACTIONAL ARITHMETIC IS USED THROUGHOUT.  WHILE THESE   *
*  MACROS ARE NOT NECESSARILY OPTIMISED FOR SPEED, THEY     *
*  ARE SO STRUCTURED THAT NO INTERMEDIATE OR TEMPORARY      *
*  REGISTERS ARE REQUIRED FOR THEIR EXECUTION.  HENCE,      *
*  THESE MACROS ARE PARTICULARLY USEFUL IN APPLICATIONS     *
*  WHERE MEMORY SPACE PROVES TO BE CRITICAL.  IN ADDITION,  *
*  ALL FFT COMPUTATIONS ARE DONE IN PLACE AND THE REAL AND  *
*  IMAGINARY PARTS OF ALL COMPLEX INPUTS ARE ASSUMED TO BE  *
*  IN CONSECUTIVE DATA MEMORY LOCATIONS.                    *
*                                                           *
*************************************************************
*                                                           *
*************************************************************
*                                                           *
*                                         K                 *
*          P .                  . P = P + Q*W               *
*             \               '           N                 *
*               \           '                               *
*                 \       '                                 *
*                   \   '                                   *
*                     O                                     *
*                   '   \                                   *
*                 '       \                                 *
*               ' K         \                               *
*             ' W             \           K                 *
*          Q .  N               . Q = P - Q*W               *
*                                         N                 *
*                                                           *
*                                                           *
*         NOTATION FOR RADIX-2 DIT FFT BUTTERFLY            *
*                                                           *
*************************************************************
*                                                           *
*************************************************************
*                                                           *
*                                                         M *
* IN A RADIX-2 N-POINT FFT THERE ARE M PASSES WHERE N = 2   *
* WITH [N/2] 2-POINT BUTTERFLIES PER PASS, GIVING A TOTAL   *
* OF [N/2]LOG N BUTTERFLIES PER FFT.                        *
*            2                                              *
*                                                           *
*************************************************************
```

```
*       MACRO 1: W=1, k=0.                                  *
*                                                           *
*       P=(PR+jPI)     P+Q=(PR+QR)+j(PI+QI)                 *
*                 \ /                                       *
*                 / \                                       *
*       Q=(QR+jQI)     P-Q=(PR-QR)+j(PI-QI)                 *
*                                                           *
*          -j(2(pi)/N)k                                     *
*       W=e             =COS[(2(pi)/N)k]-jSIN[(2(pi)/N)k]   *
*                                                           *
*                    =WR+jWI =1                             *
*                                                           *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE   *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR      *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A    *
*  TOTAL OF 12 INSTRUCTIONS ARE USED SUCH THAT EXECUTION    *
*  TIME IS EQUAL TO 14 MACHINE CYCLES.                      *
*                                                           *
*  MACRO ENTRY CONDITION: ARP MUST POINT AT AR1             *
*  MACRO EXIT CONDITION : ARP MUST POINT AT AR1             *
*                                                           *
*  MEMORY ADDRESS BIAS  : BIAS FOR DATA MEMORY PAGE 4       *
*                                                           *
*************************************************************
ZEROI    $MACRO   PR,QR,BIAS
*
*       INITIALISE AUXILIARY REGISTERS
*
        LRLK     AR1,:PR:+:BIAS:   AR1 POINTS TO PR
        LRLK     AR2,:QR:+:BIAS:   AR2 POINTS TO QR
*
*       CALCULATE Re[P+Q] AND Re[P-Q]
*
        LAC      *,15,AR2     ACC := (1/2)(PR)
        ADD      *,15,AR1     ACC := (1/2)(PR+QR)
        SACH     *+,0,AR2     PR  := (1/2)(PR+QR)
        SUBH     *            ACC := (1/2)(PR+QR)-(QR)
        SACH     *+,0,AR1     QR  := (1/2)(PR-QR)
*
*       CALCULATE Im[P+Q] AND Im[P-Q]
*
        LAC      *,15,AR2     ACC := (1/2)(PI)
        ADD      *,15,AR1     ACC := (1/2)(PI+QI)
        SACH     *-,0,AR2     PI  := (1/2)(PI+QI)
        SUBH     *            ACC := (1/2)(PI+QI)-(QI)
        SACH     *-,0,AR1     QI  := (1/2)(PI-QI)
        $END
```

```
************************************************************
*                                                          *
*       MACRO 2: W=-j, k=N/4.                              *
*                                                          *
*       P=(PR+jPI)      P-jQ=(PR+QI)+j(PI-QR)              *
*                    \ /                                   *
*                    / \                                   *
*       Q=(QR+jQI)      P+jQ=(PR-QI)+j(PI+QR)              *
*                                                          *
*          -j(2(pi)/N)k                                    *
*       W=e               =COS[(2(pi)/N)k]-jSIN[(2(pi)/N)k] *
*                                                          *
*                      =WR+jWI =-j                         *
*                                                          *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE  *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR     *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A   *
*  TOTAL OF 13 INSTRUCTIONS ARE USED SUCH THAT EXECUTION   *
*  TIME IS EQUAL TO 15 MACHINE CYCLES.                     *
*                                                          *
*  WARNING: THIS MACRO REQUIRES THE INPUT SAMPLES QR AND   *
*           QI TO BE IN CONSECUTIVE DATA MEMORY LOCATIONS  *
*           ASCENDING ORDER. THE FOLLOWING STEPS ARE USED  *
*           TO IMPLEMENT THIS MACRO:                       *
*                                                          *
*          (1) [PI-QR] -----> [PI]                         *
*          (2) [PI+QR] -----> [QR]                         *
*          (3) [PR+QI] -----> [PR]                         *
*          (4) [PR-QI] -----> [ACC]                        *
*          (5) [QR]    -----> [QI]                         *
*          (6) [ACC]   -----> [QR]                         *
*                                                          *
*  MACRO ENTRY CONDITION: ARP MUST POINT AT AR1            *
*  MACRO EXIT CONDITION : ARP MUST POINT AT AR1            *
*                                                          *
*  MEMORY ADDRESS BIAS  : BIAS FOR DATA MEMORY PAGE 4      *
*                                                          *
************************************************************
PBY2I    $MACRO   PR,QR,BIAS
*
*       INITIALISE AUXILIARY REGISTERS
*
        LRLK     AR1,:PR:+:BIAS:+1  AR1 POINTS TO PI
        LRLK     AR2,:QR:+:BIAS:    AR2 POINTS TO QR
*
*       CALCULATE Re[P+jQ] AND Re[P-jQ]
*
        LAC      *,15,AR2    ACC := (1/2)(PI)
        SUB      *,15,AR1    ACC := (1/2)(PI-QR)
        SACH     *-,0,AR2    PI  := (1/2)(PI-QR)
        ADDH     *           ACC := (1/2)(PI-QR)+(QR)
        SACH     *+,0,AR1    QR  := (1/2)(PI+QR)
*
*       CALCULATE Im[P+jQ] AND Im[P-jQ]
*
        LAC      *,15,AR2    ACC := (1/2)(PR)
        ADD      *,15,AR1    ACC := (1/2)(PR+QI)
        SACH     *,0,AR2     PR  := (1/2)(PR+QI)
```

```
        SUBH     *-          ACC := (1/2)(PR+QI)-(QI)
        DMOV     *           QR  -> QI
        SACH     *,0,AR1     QR  := (1/2)(PR-QI)
        $END

************************************************************
*                                                          *
*       MACRO 3:     k=N/8.                                *
*                                                          *
*       P=(PR+jPI)   P+Q*W=(PR+Re[Q*W])+j(PI+Im[Q*W])      *
*                  \ /                                     *
*                  / \                                     *
*       Q=(QR+jQI)   P-Q*W=(PR-Re[Q*W])+j(PI-Im[Q*W])      *
*                                                          *
*           -j(2(pi)/N)k                                   *
*       W =e              =COS((pi)/4)-jSIN((pi)/4)=WR+jWI *
*        N                                                 *
*                        =WR+jWI                           *
*                                                          *
*       LET            W=|COS((pi)/4)|=|SIN((pi)/4)|       *
*                                                          *
*       THEN     [Q*W]=(QR+QI)*W+j(QI-QR)*W                *
*              Re[Q*W]=(QI+QR)*W                           *
*              Im[Q*W]=(QI-QR)*W                           *
*                                                          *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE  *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR     *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A   *
*  TOTAL OF 22 INSTRUCTIONS ARE USED SUCH THAT EXECUTION   *
*  TIME IS EQUAL TO 24 MACHINE CYCLES. THIS MACRO REQUIRES *
*  W TO BE THE ABSOLUTE VALUE (MAGNITUDE) OF COS( /4) AND  *
*  SIN( /4).  THE SIGNS OF THESE TRIG FUNCTIONS HAVE BEEN  *
*  TAKEN CARE OF IN THE CODE.                              *
*                                                          *
*  MACRO ENTRY CONDITION: ARP MUST POINT AT AR1            *
*  MACRO EXIT CONDITION : ARP MUST POINT AT AR1            *
*                                                          *
*  MEMORY ADDRESS BIAS  : BIAS FOR DATA MEMORY PAGE 4      *
*                                                          *
************************************************************
PBY4I    $MACRO   PR,QR,BIAS
*
        LRLK     AR1,:QR:+:BIAS:+1  AR1 POINTS TO QI
        LRLK     AR2,:PR:+:BIAS:    AR2 POINTS TO PR
*
        LAC      *-,14       ACC := (1/4)(QI)
        SUB      *+,14       ACC := (1/4)(QI-QR)
        SACH     *-,1        QI  := (1/2)(QI-QR)
        ADD      *,15        ACC := (1/4)(QI+QR)
        SACH     *,1,AR2     QR  := (1/2)(QI+QR)
        LAC      *,14,AR0    ACC := (1/4)(PR)
        LT       *,AR1       T   :=W=COS(PI/4)=SIN(PI/4)
        MPY      *,AR2       P   := (1/4)(QI+QR)*W
        APAC                 ACC := (1/4)[PR+(QI+QR)*W]
        SACH     *+,1,AR1    PR  := (1/2)[PR+(QI+QR)*W]
        SPAC                 ACC := (1/4)(PR)
        SPAC                 ACC := (1/4)[PR-(QI+QR)*W]
        SACH     *+,1,AR2    QR  := (1/2)[PR-(QI+QR)*W]
        LAC      *,14,AR1    ACC := (1/4)(PI)
```

```
        MPY      *,AR2        P   := (1/4)(QI-QR)*W
        APAC                  ACC := (1/4)[PI+(QI-QR)*W]
        SACH     *-,1,AR1     PI  := (1/2)[PI+(QI-QR)*W]
        SPAC                  ACC := (1/4)(PI)
        SPAC                  ACC := (1/4)[PI-(QI-QR)*W]
        SACH     *-,1,AR1     QI  := (1/2)[PI-(QI-QR)*W]
        $END


*************************************************************
*                                                           *
*       MACRO 4:     k=3N/8.                                *
*                                                           *
*       P=(PR+jPI)   P+Q*W=(PR+Re[Q*W])+j(PI+Im[Q*W])       *
*                 \ /                                       *
*                 / \                                       *
*       Q=(QR+jQI)   P-Q*W=(PR-Re[Q*W])+j(PI+Im[Q*W])       *
*                                                           *
*           -j(2(pi)/N)k                                    *
*       W =e             =COS(3(pi)/4)-jSIN(3(pi)/4)        *
*        N                                                  *
*                      =WR+jWI                              *
*                                                           *
*       LET          W=|COS(3(pi)/4)|=|SIN(3(pi)/4)|        *
*                                                           *
*       THEN      [Q*W]=(QI-QR)*W-j(QI+QR)*W                *
*               RE[Q*W]=(QI-QR)*W                           *
*               IM[Q*W]=(QI+QR)*W                           *
*                                                           *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE   *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR      *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A    *
*  TOTAL OF 22 INSTRUCTIONS ARE USED SUCH THAT EXECUTION    *
*  TIME IS EQUAL TO 24 MACHINE CYCLES. THIS MACRO REQUIRES  *
*  W TO BE THE ABSOLUTE VALUE (MAGNITUDE) OF COS(3 /4) AND  *
*  SIN(3 /4).  THE SIGNS OF THESE TRIG FUNCTIONS HAVE BEEN  *
*  TAKEN CARE OF IN THE CODE.                               *
*                                                           *
*  MACRO ENTRY CONDITION: ARP MUST POINT AT AR1             *
*  MACRO EXIT CONDITION : ARP MUST POINT AT AR1             *
*                                                           *
*  MEMORY ADDRESS BIAS  : BIAS FOR DATA MEMORY PAGE 4       *
*                                                           *
*************************************************************
P3BY4I  $MACRO   PR,QR,BIAS
*
        LRLK     AR1,:QR:+:BIAS:+1  AR1 POINTS TO QI
        LRLK     AR2,:PR:+:BIAS:    AR2 POINTS TO PR
*
        LAC      *-,14        ACC := (1/4)(QI)
        SUB      *+,14        ACC := (1/4)(QI-QR)
        SACH     *-,1         QI  := (1/2)(QI-QR)
        ADD      *,15         ACC := (1/4)(QI+QR)
        SACH     *+,1,AR2     QR  := (1/2)(QI+QR)
        LAC      *,14,AR0     ACC := (1/4)(PR)
        LT       *,AR1        T   :=W=COS( /4)=SIN( /4)
        MPY      *-,AR2       P   := (1/4)(QI-QR)*W
        APAC                  ACC := (1/4)[PR+(QI-QR)*W]
        SACH     *+,1,AR1     PR  := (1/2)[PR+(QI-QR)*W]
```

```
        SPAC                  ACC := (1/4)(PR)
        SPAC                  ACC := (1/4)[PR-(QI-QR)*W]
        MPY      *            P   := (1/4)(QI+QR)*W
        SACH     *+,1,AR2     QR  := (1/2)[PR-(QI-QR)*W]
        LAC      *,14         ACC := (1/4)(PI)
        SPAC                  ACC := (1/4)[PI-(QI+QR)*W]
        SACH     *-,1,AR1     PI  := (1/2)[PI-(QI+QR)*W]
        APAC                  ACC := (1/4)(PI)
        APAC                  ACC := (1/4)[PI+(QI+QR)*W]
        SACH     *-,1,AR1     QI  := (1/2)[PI+(QI+QR)*W]
        $END


*************************************************************
*                                                           *
*       MACRO 5:                                            *
*                                                           *
*                   A      A'        B1                     *
*                    \ /    \       /                       *
*                    / \      \ /    B2                     *
*                   B      B'\ / \ /                        *
*                   C      C'/ \ / \                        *
*                    \ /      / \    B3                     *
*                    / \    /       \                       *
*                   D      D'        B4                     *
*                                                           *
*       A = R1+jI1                                          *
*                                                           *
*       B = R2+jI2                                          *
*                                                           *
*       C = R3+jI3                                          *
*                                                           *
*       D = R4+jI4                                          *
*                                                           *
*       A' = (R1+R2) + j(I1+I2)                             *
*                                                           *
*       B' = (R1-R2) + j(I1-I2)                             *
*                                                           *
*       C' = (R3+R4) + j(R3+R4)                             *
*                                                           *
*       D' = (R3-R4) + j(R3-R4)                             *
*                                                           *
*       B1 = A'+C'                                          *
*                                                           *
*       B2 = B'-jD'                                         *
*                                                           *
*       B3 = A'-C'                                          *
*                                                           *
*       B4 = B'+jD'                                         *
*                                                           *
*       REAL(B1) = ((R1+R2) + (R3+R4)) /2                   *
*       IMAG(B1) = ((I1+I2) + (I3+I4)) /2                   *
*                                                           *
*       REAL(B2) = ((R1-R2) + (I3-I4)) /2                   *
*       IMAG(B2) = ((I1-I2) - (R3-R4)) /2                   *
*                                                           *
*       REAL(B3) = ((R1+R2) - (R3+R4)) /2                   *
*       IMAG(B3) = ((I1+I2) - (I3+I4)) /2                   *
*                                                           *
```

```
*       REAL(B4) = ((R1-R2) - (I3-I4)) /2                      *
*       IMAG(B4) = ((I1-I2) + (R3-R4)) /2                      *
*                                                              *
*                                                              *
* THE FIRST TWO STAGES OF A RADIX-2 N-POINT DIT FFT CAN BE *
* IMPLEMENTED WITH A SPECIAL RADIX-4 BUTTERFLY WHICH HAS A *
* UNITY TWIDDLE FACTOR USED TO SPEED UP THE EXECUTION TIME *
* OF THE FFT WITH THE ABOVE EQUATIONS. WHEN USING THESE    *
* EQUATIONS, ALL INPUT VALUES MUST BE WITHIN THE RANGE     *
* -1 <= X < 1.0.  TOTAL NUMBER OF INTRUCTIONS IS 39.       *
* EXECUTION TIME IS EQUIVALENT TO 41 MACHINE CYCLES.       *
*                                                              *
************************************************************


************************************************************
*  THE FOLLOWING STEPS ARE USED TO IMPLEMENT THE SPECIAL   *
*  RADIX-4 MACRO 'COMBO' FOR THE FIRST TWO STAGES OF AN    *
*  N-POINT RADIX-2 DIT FFT.                                *
*                                                          *
*  STEP 1        STEP 2              STEP 3                *
*  ------        ------              ------                *
*                                                          *
*  R1 R1         (R1+R2)/1           [(R1+R2)+(R3+R4)]/2  *
*  I1 I1         (I1+I2)/1           [(I1+I2)+(I3+I4)]/2  *
*                                                          *
*  R2 R2         [(R1-R2)+(I3-I4)]/2  [(R1-R2)+(I3-I4)]/2  *
*  I2 I2         [(I1-I2)-(R3-R4)]/2  [(I1-I2)-(R3-R4)]/2  *
*                                                          *
*  R3 (R3+R4)/1  (R3+R4)/1           [(R1+R2)-(R3+R4)]/2  *
*  I3 (I3+I4)/1  (I3+I4)/1           [(I1+I2)-(I3+I4)]/2  *
*                                                          *
*  R4 (R3-R4)/1  [(R1-R2)-(I3-I4)]/2  [(R1-R2)-(I3-I4)]/2  *
*  I4 (I3-I4)/1  R4--->I4:=(R3-R4)/1                       *
*                [(I1-I2)+(R3-R4)]/2  [(I1-I2)+(R3-R4)]/2  *
*                                                          *
*   IN THE FOLLOWING CODE, ALL IMAGINARY TERMS (I'S) ARE   *
*   ASSUMED TO IN LOCATIONS CONSECUTIVE TO THOSE OF THE    *
*   REAL TERMS (R'S).  THEREFORE, THE ADDRESS OF EACH      *
*   IMAGINARY TERM (I) IS REPRESENTED AS (R+1).            *
*                                                          *
************************************************************
COMBOI    $MACRO    R1,R2,R3,R4,BIAS
*
*         CALCULATE PARTIAL TERMS FOR R3,R4,I3 AND I4
*
          LAC       :R3:-:BIAS:,14      ACC  := (1/4)(R3)
          ADD       :R4:-:BIAS:,14      ACC  := (1/4)(R3+R4)
          SACH      :R3:-:BIAS:,1       R3   := (1/2)(R3+R4)
          SUB       :R4:-:BIAS:,15      ACC  := (1/4)(R3+R4)-(1/2)(R4)
          SACH      :R4:-:BIAS:,1       R4   := (1/2)(R3-R4)
          LAC       :R3:+1-:BIAS:,14    ACC  := (1/4)(I3)
          ADD       :R4:+1-:BIAS:,14    ACC  := (1/4)(I3+I4)
          SACH      :R3:+1-:BIAS:,1     I3   := (1/2)(I3+I4)
          SUB       :R4:+1-:BIAS:,15    ACC  := (1/4)(I3+I4)-(1/2)(I4)
          SACH      :R4:+1-:BIAS:,1     I4   := (1/2)(I3-I4)
*
*         CALCULATE PARTIAL TERMS FOR R2,R4,I2 AND I4
*
          LAC       :R1:-:BIAS:,14      ACC  := (1/4)(R1)
          ADD       :R2:-:BIAS:,14      ACC  := (1/4)(R1+R2)
          SACH      :R1:-:BIAS:,1       R1   := (1/2)(R1+R2)
          SUB       :R2:-:BIAS:,15      ACC  := (1/4)(R1+R2)-(1/2)(R2)
          ADD       :R4:+1-:BIAS:,15    ACC  := (1/4)[(R1-R2)+(I3-I4)]
          SACH      :R2:-:BIAS:         R2   := (1/4)[(R1-R2)+(I3-I4)]
          SUBH      :R4:+1-:BIAS:       ACC  := (1/4)[(R1-R2)-(I3-I4)]
          DMOV      :R4:-:BIAS:         I4   := R4 = (1/2)(R3-R4)
          SACH      :R4:-:BIAS:         R4   := (1/4)[(R1-R2)-(I3-I4)]
          LAC       :R1:+1-:BIAS:,14    ACC  := (1/4)(I1)
          ADD       :R2:+1-:BIAS:,14    ACC  := (1/4)(I1+I2)
          SACH      :R1:+1-:BIAS:,1     I1   := (1/2)(I1+I2)
          SUB       :R2:+1-:BIAS:,15    ACC  := (1/4)(I1+I2)-(1/2)(I2)
          SUB       :R4:+1-:BIAS:,15    ACC  := (1/4)[(I1-I2)-(R3-R4)]
          SACH      :R2:+1-:BIAS:       I2   := (1/4)[(I1-I2)-(R3-R4)]
          ADDH      :R4:+1-:BIAS:       ACC  := (1/4)[(I1-I2)+(R3-R4)]
          SACH      :R4:+1-:BIAS:       I4   := (1/4)[(I1-I2)+(R3-R4)]

*
*         CALCULATE PARTIAL TERMS FOR R1,R3,I1 AND I3
*
          LAC       :R1:-:BIAS:,15      ACC  := (1/4)(R1+R2).
          ADD       :R3:-:BIAS:,15      ACC  := (1/4)[(R1+R2)+(R3+R4)]
          SACH      :R1:-:BIAS:         R1   := (1/4)[(R1+R2)+(R3+R4)]
          SUBH      :R3:-:BIAS:         ACC  := (1/4)[(R1+R2)-(R3+R4)]
          SACH      :R3:-:BIAS:         R3   := (1/4)[(R1+R2)-(R3+R4)]
          LAC       :R1:+1-:BIAS:,15    ACC  := (1/4)(I1+I2)
          ADD       :R3:+1-:BIAS:,15    ACC  := (1/4)[(I1+I2)+(I3+I4)]
          SACH      :R1:+1-:BIAS:       I1   := (1/4)[(I1+I2)+(I3+I4)]
          SUBH      :R3:+1-:BIAS:       ACC  := (1/4)[(I1+I2)-(I3+I4)]
          SACH      :R3:+1-:BIAS:       I3   := (1/4)[(I1+I2)-(I3+I4)]
          $END

************************************************************
*                                                          *
*  MACRO 6:  A GENERAL RADIX-2 DIT FFT 'BUTTERFLY'         *
*                                                          *
*       P=(PR+jQI)   P+Q*W=(PR+Re[Q*W])+j(PI+Im[Q*W])      *
*                 \ /                                      *
*                 / \                                      *
*       Q=(QR+jQI)   P-Q*W=(PR-Re[Q*W])+j(PI+Im[Q*W])      *
*                                                          *
*           -j(2(pi)/N)k                                   *
*       W =e             =COS(O)-jSIN(O)                   *
*        N                                                 *
*                      =WR+jWI                             *
*                                                          *
*  ALL OUTPUT SAMPLES ARE SCALED DOWN BY 2 TO ACCOMMODATE  *
*  A 1-BIT OVERFLOW.  HOWEVER, NO OVERFLOWS WILL OCCUR     *
*  FOR FRACTIONAL INPUTS OF THE FORM X : -1 <= X < 1.  A   *
*  TOTAL OF 25 INSTRUCTIONS ARE USED SUCH  THAT EXECUTION  *
*  TIME IS EQUAL TO 27 MACHINE CYCLES.   THIS MACRO        *
*  REQUIRES W TO BE THE ABSOLUTE VALUE (MAGNITUDE)  OF     *
*  COS(O) AND SIN(O).  THE SIGNS OF THESE TRIG FUNCTIONS   *
*  HAVE BEEN TAKEN CARE OF IN THE CODE.                    *
```

```
*                                                           *
*  MACRO ENTRY CONDITION: ARP MUST POINT AT AR1             *
*  MACRO EXIT CONDITION : ARP MUST POINT AT AR1             *
*                                                           *
*  MEMORY ADDRESS BIAS  : BIAS FOR DATA MEMORY PAGE 4       *
*                                                           *
*************************************************************
BTRFLI  $MACRO    PR,QR,WR,WI,BIAS
*
*       INITIALISE AUXILIARY REGISTERS
*
        LRLK      AR1,:QR:+:BIAS:+1  AR1 POINTS TO QI
        LRLK      AR2,:PR:+:BIAS:    AR2 POINTS TO PR
*
*       CALCULATE QR*WR + QI*WI AND STORE RESULT IN QI
*
        LT        *-          T-REGISTER := QI
        MPYK      :WI:        P-REGISTER := (1/16)(QI*WI)
        LTP       *           ACC := (1/16)(QI*WI); T-REGISTER=QR
        MPYK      :WR:        P-REGISTER := (1/16)(QR*WR)
        APAC                  ACC := (1/16)(QR*WR+QI*WI)
        SFR                   ACC := (1/32)(QR*WR+QI*WI)
        SACH      *+,4        QR  := (1/2)(QR*WR+QI*WI)



*
*       CALCULATE QI*WR - QR*WI AND STORE RESULT IN QR
*
        MPYK      -:WI:       P-REGISTER := (1/16)(-QR*WI)
        LTP       *           ACC := (1/16)(-QR*WI); T-REGISTER=QI
        MPYK      :WR:        P-REGISTER := (1/16)(QI*WR)
        APAC                  ACC := (1/16)(QI*WR-QR*WI)
        SFR                   ACC := (1/32)(QI*WR-QR*WI)
        SACH      *-,4,AR2    QI  := (1/2)(QI*WR-QR*WI)
*
*       CALCULATE Re[P+jQ] & Re[P-jQ] STORE RESULTS in PR & QR
*
        LAC       *,14,AR1    ACC := (1/4)PR
        ADD       *,15,AR2    ACC := (1/4)[PR+(QR*WR+QI*WI)]
        SACH      *+,1,AR1    PR  := (1/2)[PR+(QR*WR+QI*WI)]
        SUBH      *           ACC := (1/4)[PR-(QR*WR+QI*WI)]
        SACH      *+,1,AR2    QR  := (1/2)[PR-(QR*WR+QI*WI)]
*
*       CALCULATE Im[P+jQ] & Im[P-jQ] STORE RESULTS in PI & QI
*
        LAC       *,14,AR1    ACC := (1/4)PI
        ADD       *,15,AR2    ACC := (1/4)[PI+(QI*WR-QR*WI)]
        SACH      *-,1,AR1    PI  := (1/2)[PI+(QI*WR-QR*WI)]
        SUBH      *           ACC := (1/4)[PI-(QI*WR-QR*WI)]
        SACH      *-,1,AR1    QI  := (1/2)[PI-(QI*WR-QR*WI)]
        $END

*************************************************************
*                                                           *
*       MACRO 7:  RADIX-2 INPUT BIT REVERSAL                *
*                                                           *
*       ENTRY CONDITION: ARP MUST POINT AT AR1              *
*                                                           *
*       EXIT  CONDITION: ARP MUST POINT AT AR1              *
*                                                           *
*       A TOTAL OF 10 INSTRUCTIONS ARE USED SUCH THAT       *
*       EXECUTION TIME IS EQUAL TO 12 MACHINE CYCLES.       *
*                                                           *
*************************************************************
*
BITRVI  $MACRO    PR,QR,BIAS
*
*       INITIALISE AUXILIARY REGISTERS
*
        LRLK      AR1,:PR:+:BIAS:  AR1 POINTS TO PR
        LRLK      AR2,:QR:+:BIAS:  AR2 POINTS TO QR
*
        ZALH      *,AR2
        ADDS      *,AR1
        SACL      *+,0,AR2
        SACH      *+,0,AR1
        ZALH      *,AR2
        ADDS      *,AR1
        SACL      *-,0,AR2
        SACH      *-,0,AR1
        $END
```

APPENDIX C
A 256-POINT, RADIX-2 DIT FFT IMPLEMENTATION

A P P E N D I X   C

```
        IDT       'FFT256'
*************************************************************
*                                                           *
*  A 256-POINT RADIX-2 DIT COMPLEX FFT FOR THE TMS32020     *
*  ---------------------------------------------------     *
*                                                           *
*  THE FOLLOWING FILE RAD2FFT.MAC CONSISTS OF ALL THE       *
*  MACROS LISTED IN APPENDIX  B                             *
*                                                           *
*************************************************************
*
        COPY      RAD2FFT.MAC
*
*************************************************************
*                                                           *
*  DATA MEMORY MAP FOR PAGES 4, 5, 6 AND 7 (BLOCKS B0,B1)   *
*                                                           *
*************************************************************
*
        DORG     0
*
*       DATA MEMORY PAGE 4 (STARTING ADDRESS 512 OR >200)
*
X000    DATA     0,0
X001    DATA     0,0
X002    DATA     0,0
X003    DATA     0,0
X004    DATA     0,0
X005    DATA     0,0
X006    DATA     0,0
X007    DATA     0,0
X008    DATA     0,0
X009    DATA     0,0
X010    DATA     0,0
X011    DATA     0,0
X012    DATA     0,0
X013    DATA     0,0
X014    DATA     0,0
X015    DATA     0,0
X016    DATA     0,0
X017    DATA     0,0
X018    DATA     0,0
X019    DATA     0,0
X020    DATA     0,0
X021    DATA     0,0
X022    DATA     0,0
X023    DATA     0,0
X024    DATA     0,0
X025    DATA     0,0
X026    DATA     0,0
X027    DATA     0,0
X028    DATA     0,0
X029    DATA     0,0
X030    DATA     0,0
X031    DATA     0,0
X032    DATA     0,0
X033    DATA     0,0
X034    DATA     0,0
X035    DATA     0,0
X036    DATA     0,0
X037    DATA     0,0
X038    DATA     0,0
X039    DATA     0,0
X040    DATA     0,0
X041    DATA     0,0
X042    DATA     0,0
X043    DATA     0,0
X044    DATA     0,0
X045    DATA     0,0
X046    DATA     0,0
X047    DATA     0,0
X048    DATA     0,0
X049    DATA     0,0
X050    DATA     0,0
X051    DATA     0,0
X052    DATA     0,0
X053    DATA     0,0
X054    DATA     0,0
X055    DATA     0,0
X056    DATA     0,0
X057    DATA     0,0
X058    DATA     0,0
X059    DATA     0,0
X060    DATA     0,0
X061    DATA     0,0
X062    DATA     0,0
X063    DATA     0,0
*
*       DATA MEMORY PAGE 5 (STARTING ADDRESS 640 OR >280)
*
X064    DATA     0,0
X065    DATA     0,0
X066    DATA     0,0
X067    DATA     0,0
X068    DATA     0,0
X069    DATA     0,0
X070    DATA     0,0
X071    DATA     0,0
X072    DATA     0,0
X073    DATA     0,0
X074    DATA     0,0
X075    DATA     0,0
X076    DATA     0,0
X077    DATA     0,0
X078    DATA     0,0
X079    DATA     0,0
X080    DATA     0,0
X081    DATA     0,0
X082    DATA     0,0
X083    DATA     0,0
X084    DATA     0,0
X085    DATA     0,0
X086    DATA     0,0
X087    DATA     0,0
X088    DATA     0,0
X089    DATA     0,0
X090    DATA     0,0
```

```
X091     DATA    0,0
X092     DATA    0,0
X093     DATA    0,0
X094     DATA    0,0
X095     DATA    0,0
X096     DATA    0,0
X097     DATA    0,0
X098     DATA    0,0
X099     DATA    0,0
X100     DATA    0,0
X101     DATA    0,0
X102     DATA    0,0
X103     DATA    0,0
X104     DATA    0,0
X105     DATA    0,0
X106     DATA    0,0
X107     DATA    0,0
X108     DATA    0,0
X109     DATA    0,0
X110     DATA    0,0
X111     DATA    0,0
X112     DATA    0,0
X113     DATA    0,0
X114     DATA    0,0
X115     DATA    0,0
X116     DATA    0,0
X117     DATA    0,0
X118     DATA    0,0
X119     DATA    0,0
X120     DATA    0,0
X121     DATA    0,0
X122     DATA    0,0
X123     DATA    0,0
X124     DATA    0,0
X125     DATA    0,0
X126     DATA    0,0
X127     DATA    0,0
*
*        DATA MEMORY PAGE 6 (STARTING ADDRESS 768 OR >300)
*
X128     DATA    0,0
X129     DATA    0,0
X130     DATA    0,0
X131     DATA    0,0
X132     DATA    0,0
X133     DATA    0,0
X134     DATA    0,0
X135     DATA    0,0
X136     DATA    0,0
X137     DATA    0,0
X138     DATA    0,0
X139     DATA    0,0
X140     DATA    0,0
X141     DATA    0,0
X142     DATA    0,0
X143     DATA    0,0
X144     DATA    0,0
X145     DATA    0,0
X146     DATA    0,0
X147     DATA    0,0
X148     DATA    0,0
X149     DATA    0,0
X150     DATA    0,0
X151     DATA    0,0
X152     DATA    0,0
X153     DATA    0,0
X154     DATA    0,0
X155     DATA    0,0
X156     DATA    0,0
X157     DATA    0,0
X158     DATA    0,0
X159     DATA    0,0
X160     DATA    0,0
X161     DATA    0,0
X162     DATA    0,0
X163     DATA    0,0
X164     DATA    0,0
X165     DATA    0,0
X166     DATA    0,0
X167     DATA    0,0
X168     DATA    0,0
X169     DATA    0,0
X170     DATA    0,0
X171     DATA    0,0
X172     DATA    0,0
X173     DATA    0,0
X174     DATA    0,0
X175     DATA    0,0
X176     DATA    0,0
X177     DATA    0,0
X178     DATA    0,0
X179     DATA    0,0
X180     DATA    0,0
X181     DATA    0,0
X182     DATA    0,0
X183     DATA    0,0
X184     DATA    0,0
X185     DATA    0,0
X186     DATA    0,0
X187     DATA    0,0
X188     DATA    0,0
X189     DATA    0,0
X190     DATA    0,0
X191     DATA    0,0
*
*        DATA MEMORY PAGE 7 (STARTING ADDRESS 896 OR >380)
*
X192     DATA    0,0
X193     DATA    0,0
X194     DATA    0,0
X195     DATA    0,0
X196     DATA    0,0
X197     DATA    0,0
X198     DATA    0,0
X199     DATA    0,0
X200     DATA    0,0
X201     DATA    0,0
X202     DATA    0,0
X203     DATA    0,0
X204     DATA    0,0
```

```
X205      DATA     0,0
X206      DATA     0,0
X207      DATA     0,0
X208      DATA     0,0
X209      DATA     0,0
X210      DATA     0,0
X211      DATA     0,0
X212      DATA     0,0
X213      DATA     0,0
X214      DATA     0,0
X215      DATA     0,0
X216      DATA     0,0
X217      DATA     0,0
X218      DATA     0,0
X219      DATA     0,0
X220      DATA     0,0
X221      DATA     0,0
X222      DATA     0,0
X223      DATA     0,0
X224      DATA     0,0
X225      DATA     0,0
X226      DATA     0,0
X227      DATA     0,0
X228      DATA     0,0
X229      DATA     0,0
X230      DATA     0,0
X231      DATA     0,0
X232      DATA     0,0
X233      DATA     0,0
X234      DATA     0,0
X235      DATA     0,0
X236      DATA     0,0
X237      DATA     0,0
X238      DATA     0,0
X239      DATA     0,0
X240      DATA     0,0
X241      DATA     0,0
X242      DATA     0,0
X243      DATA     0,0
X244      DATA     0,0
X245      DATA     0,0
X246      DATA     0,0
X247      DATA     0,0
X248      DATA     0,0
X249      DATA     0,0
X250      DATA     0,0
X251      DATA     0,0
X252      DATA     0,0
X253      DATA     0,0
X254      DATA     0,0
X255      DATA     0,0
*
************************************************************
*                                                          *
*   DATA LOCATION IN BLOCK B2 FOR W=COS(45) OR SIN(45)     *
*                                                          *
************************************************************
*
          DORG     96
W         DATA     0
*
************************************************************
*                                                          *
*   13-BIT TWIDDLE FACTORS FOR 256-POINT COMPLEX FFT       *
*                                                          *
************************************************************
*
C000      EQU      4095
C001      EQU      4094
C002      EQU      4091
C003      EQU      4085
C004      EQU      4076
C005      EQU      4065
C006      EQU      4052
C007      EQU      4036
C008      EQU      4017
C009      EQU      3996
C010      EQU      3973
C011      EQU      3948
C012      EQU      3920
C013      EQU      3889
C014      EQU      3857
C015      EQU      3822
C016      EQU      3784
C017      EQU      3745
C018      EQU      3703
C019      EQU      3659
C020      EQU      3612
C021      EQU      3564
C022      EQU      3513
C023      EQU      3461
C024      EQU      3406
C025      EQU      3349
C026      EQU      3290
C027      EQU      3229
C028      EQU      3166
C029      EQU      3102
C030      EQU      3035
C031      EQU      2967
C032      EQU      2896
C033      EQU      2824
C034      EQU      2751
C035      EQU      2675
C036      EQU      2598
C037      EQU      2520
C038      EQU      2440
C039      EQU      2359
C040      EQU      2276
C041      EQU      2191
C042      EQU      2106
C043      EQU      2019
C044      EQU      1931
C045      EQU      1842
C046      EQU      1751
C047      EQU      1660
C048      EQU      1567
C049      EQU      1474
C050      EQU      1380
C051      EQU      1285
C052      EQU      1189
```

```
C053     EQU     1092
C054     EQU     995
C055     EQU     897
C056     EQU     799
C057     EQU     700
C058     EQU     601
C059     EQU     501
C060     EQU     401
C061     EQU     301
C062     EQU     201
C063     EQU     101
C064     EQU     0
C065     EQU     -101
C066     EQU     -201
C067     EQU     -301
C068     EQU     -401
C069     EQU     -501
C070     EQU     -601
C071     EQU     -700
C072     EQU     -799
C073     EQU     -897
C074     EQU     -995
C075     EQU     -1092
C076     EQU     -1189
C077     EQU     -1285
C078     EQU     -1380
C079     EQU     -1474
C080     EQU     -1567
C081     EQU     -1660
C082     EQU     -1751
C083     EQU     -1842
C084     EQU     -1931
C085     EQU     -2019
C086     EQU     -2106
C087     EQU     -2191
C088     EQU     -2276
C089     EQU     -2359
C090     EQU     -2440
C091     EQU     -2520
C092     EQU     -2598
C093     EQU     -2675
C094     EQU     -2751
C095     EQU     -2824
C096     EQU     -2896
C097     EQU     -2967
C098     EQU     -3035
C099     EQU     -3102
C100     EQU     -3166
C101     EQU     -3229
C102     EQU     -3290
C103     EQU     -3349
C104     EQU     -3406
C105     EQU     -3461
C106     EQU     -3513
C107     EQU     -3564
C108     EQU     -3612
C109     EQU     -3659
C110     EQU     -3703
C111     EQU     -3745
C112     EQU     -3784
C113     EQU     -3822
C114     EQU     -3857
C115     EQU     -3889
C116     EQU     -3920
C117     EQU     -3948
C118     EQU     -3973
C119     EQU     -3996
C120     EQU     -4017
C121     EQU     -4036
C122     EQU     -4052
C123     EQU     -4065
C124     EQU     -4076
C125     EQU     -4085
C126     EQU     -4091
C127     EQU     -4094
*
S000     EQU     0
S001     EQU     101
S002     EQU     201
S003     EQU     301
S004     EQU     401
S005     EQU     501
S006     EQU     601
S007     EQU     700
S008     EQU     799
S009     EQU     897
S010     EQU     995
S011     EQU     1092
S012     EQU     1189
S013     EQU     1285
S014     EQU     1380
S015     EQU     1474
S016     EQU     1567
S017     EQU     1660
S018     EQU     1751
S019     EQU     1842
S020     EQU     1931
S021     EQU     2019
S022     EQU     2106
S023     EQU     2191
S024     EQU     2276
S025     EQU     2359
S026     EQU     2440
S027     EQU     2520
S028     EQU     2598
S029     EQU     2675
S030     EQU     2751
S031     EQU     2824
S032     EQU     2896
S033     EQU     2967
S034     EQU     3035
S035     EQU     3102
S036     EQU     3166
S037     EQU     3229
S038     EQU     3290
S039     EQU     3349
S040     EQU     3406
S041     EQU     3461
S042     EQU     3513
S043     EQU     3564
```

```
S044    EQU     3612
S045    EQU     3659
S046    EQU     3703
S047    EQU     3745
S048    EQU     3784
S049    EQU     3822
S050    EQU     3857
S051    EQU     3889
S052    EQU     3920
S053    EQU     3948
S054    EQU     3973
S055    EQU     3996
S056    EQU     4017
S057    EQU     4036
S058    EQU     4052
S059    EQU     4065
S060    EQU     4076
S061    EQU     4085
S062    EQU     4091
S063    EQU     4094
S064    EQU     4095
S065    EQU     4094
S066    EQU     4091
S067    EQU     4085
S068    EQU     4076
S069    EQU     4065
S070    EQU     4052
S071    EQU     4036
S072    EQU     4017
S073    EQU     3996
S074    EQU     3973
S075    EQU     3948
S076    EQU     3920
S077    EQU     3889
S078    EQU     3857
S079    EQU     3822
S080    EQU     3784
S081    EQU     3745
S082    EQU     3703
S083    EQU     3659
S084    EQU     3612
S085    EQU     3564
S086    EQU     3513
S087    EQU     3461
S088    EQU     3406
S089    EQU     3349
S090    EQU     3290
S091    EQU     3229
S092    EQU     3166
S093    EQU     3102
S094    EQU     3035
S095    EQU     2967
S096    EQU     2896
S097    EQU     2824
S098    EQU     2751
S099    EQU     2675
S100    EQU     2598
S101    EQU     2520
S102    EQU     2440
S103    EQU     2359
S104    EQU     2276
S105    EQU     2191
S106    EQU     2106
S107    EQU     2019
S108    EQU     1931
S109    EQU     1842
S110    EQU     1751
S111    EQU     1660
S112    EQU     1567
S113    EQU     1474
S114    EQU     1380
S115    EQU     1285
S116    EQU     1189
S117    EQU     1092
S118    EQU     995
S119    EQU     897
S120    EQU     799
S121    EQU     700
S122    EQU     601
S123    EQU     501
S124    EQU     401
S125    EQU     301
S126    EQU     201
S127    EQU     101
*
        AORG    0
        B       INIT
*
*       SYSTEM INITIALIZATION
*
        AORG    >20
*
*       16-BIT TWIDDLE FACTOR FOR SPECIAL MACROS
*
WVAL    DATA    >5A82
*
INIT    SPM     0
        CNFD
        ROVM
        SSXM
        LARP    AR0
        LRLK    AR0,W
        LALK    WVAL
        TBLR    *,AR1
*
*       FFT CODE WITH BIT-REVERSED INPUT SAMPLES
*
FFT256  BITRVI  X001,X128,512
        BITRVI  X002,X064,512
        BITRVI  X003,X192,512
        BITRVI  X004,X032,512
        BITRVI  X005,X160,512
        BITRVI  X006,X096,512
        BITRVI  X007,X224,512
        BITRVI  X008,X016,512
        BITRVI  X009,X144,512
        BITRVI  X010,X080,512
        BITRVI  X011,X208,512
        BITRVI  X012,X048,512
        BITRVI  X013,X176,512
```

```
         BITRVI    X014,X112,512
         BITRVI    X015,X240,512
         BITRVI    X017,X136,512
         BITRVI    X018,X072,512
         BITRVI    X019,X200,512
         BITRVI    X020,X040,512
         BITRVI    X021,X168,512
         BITRVI    X022,X104,512
         BITRVI    X023,X232,512
         BITRVI    X025,X152,512
         BITRVI    X026,X088,512
         BITRVI    X027,X216,512
         BITRVI    X028,X056,512
         BITRVI    X029,X184,512
         BITRVI    X030,X120,512
         BITRVI    X031,X248,512
         BITRVI    X033,X132,512
         BITRVI    X034,X068,512
         BITRVI    X035,X196,512
         BITRVI    X037,X164,512
         BITRVI    X038,X100,512
         BITRVI    X039,X228,512
         BITRVI    X041,X148,512
         BITRVI    X042,X084,512
         BITRVI    X043,X212,512
         BITRVI    X044,X052,512
         BITRVI    X045,X180,512
         BITRVI    X046,X116,512
         BITRVI    X047,X244,512
         BITRVI    X049,X140,512
         BITRVI    X050,X076,512
         BITRVI    X051,X204,512
         BITRVI    X053,X172,512
         BITRVI    X054,X108,512
         BITRVI    X055,X236,512
         BITRVI    X057,X156,512
         BITRVI    X058,X092,512
         BITRVI    X059,X220,512
         BITRVI    X061,X188,512
         BITRVI    X062,X124,512
         BITRVI    X063,X252,512
         BITRVI    X065,X130,512
         BITRVI    X067,X194,512
         BITRVI    X069,X162,512
         BITRVI    X070,X098,512
         BITRVI    X071,X226,512
         BITRVI    X073,X146,512
         BITRVI    X074,X082,512
         BITRVI    X075,X210,512
         BITRVI    X077,X178,512
         BITRVI    X078,X114,512
         BITRVI    X079,X242,512
         BITRVI    X081,X138,512
         BITRVI    X083,X202,512
         BITRVI    X085,X170,512
         BITRVI    X086,X106,512
         BITRVI    X087,X234,512
         BITRVI    X089,X154,512
         BITRVI    X091,X218,512
         BITRVI    X093,X186,512
         BITRVI    X094,X122,512
         BITRVI    X095,X250,512
         BITRVI    X097,X134,512
         BITRVI    X099,X198,512
         BITRVI    X101,X166,512
         BITRVI    X103,X230,512
         BITRVI    X105,X150,512
         BITRVI    X107,X214,512
         BITRVI    X109,X182,512
         BITRVI    X110,X118,512
         BITRVI    X111,X246,512
         BITRVI    X113,X142,512
         BITRVI    X115,X206,512
         BITRVI    X117,X174,512
         BITRVI    X119,X238,512
         BITRVI    X121,X158,512
         BITRVI    X123,X222,512
         BITRVI    X125,X190,512
         BITRVI    X127,X254,512
         BITRVI    X131,X193,512
         BITRVI    X133,X161,512
         BITRVI    X135,X225,512
         BITRVI    X137,X145,512
         BITRVI    X139,X209,512
         BITRVI    X141,X177,512
         BITRVI    X143,X241,512
         BITRVI    X147,X201,512
         BITRVI    X149,X169,512
         BITRVI    X151,X233,512
         BITRVI    X155,X217,512
         BITRVI    X157,X185,512
         BITRVI    X159,X249,512
         BITRVI    X163,X197,512
         BITRVI    X167,X229,512
         BITRVI    X171,X213,512
         BITRVI    X173,X181,512
         BITRVI    X175,X245,512
         BITRVI    X179,X205,512
         BITRVI    X183,X237,512
         BITRVI    X187,X221,512
         BITRVI    X191,X253,512
         BITRVI    X199,X227,512
         BITRVI    X203,X211,512
         BITRVI    X207,X243,512
         BITRVI    X215,X235,512
         BITRVI    X223,X251,512
         BITRVI    X239,X247,512
*
*        FFT CODE FOR STAGES 1 AND 2
*
         LDPK      4
         COMBOI    X000,X001,X002,X003,0
         COMBOI    X004,X005,X006,X007,0
         COMBOI    X008,X009,X010,X011,0
         COMBOI    X012,X013,X014,X015,0
         COMBOI    X016,X017,X018,X019,0
         COMBOI    X020,X021,X022,X023,0
         COMBOI    X024,X025,X026,X027,0
         COMBOI    X028,X029,X030,X031,0
         COMBOI    X032,X033,X034,X035,0
```

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         COMBOI    X036,X037,X038,X039,0
         COMBOI    X040,X041,X042,X043,0
         COMBOI    X044,X045,X046,X047,0
         COMBOI    X048,X049,X050,X051,0
         COMBOI    X052,X053,X054,X055,0
         COMBOI    X056,X057,X058,X059,0
         COMBOI    X060,X061,X062,X063,0
         LDPK      5
         COMBOI    X064,X065,X066,X067,128
         COMBOI    X068,X069,X070,X071,128
         COMBOI    X072,X073,X074,X075,128
         COMBOI    X076,X077,X078,X079,128
         COMBOI    X080,X081,X082,X083,128
         COMBOI    X084,X085,X086,X087,128
         COMBOI    X088,X089,X090,X091,128
         COMBOI    X092,X093,X094,X095,128
         COMBOI    X096,X097,X098,X099,128
         COMBOI    X100,X101,X102,X103,128
         COMBOI    X104,X105,X106,X107,128
         COMBOI    X108,X109,X110,X111,128
         COMBOI    X112,X113,X114,X115,128
         COMBOI    X116,X117,X118,X119,128
         COMBOI    X120,X121,X122,X123,128
         COMBOI    X124,X125,X126,X127,128
         LDPK      6
         COMBOI    X128,X129,X130,X131,256
         COMBOI    X132,X133,X134,X135,256
         COMBOI    X136,X137,X138,X139,256
         COMBOI    X140,X141,X142,X143,256
         COMBOI    X144,X145,X146,X147,256
         COMBOI    X148,X149,X150,X151,256
         COMBOI    X152,X153,X154,X155,256
         COMBOI    X156,X157,X158,X159,256
         COMBOI    X160,X161,X162,X163,256
         COMBOI    X164,X165,X166,X167,256
         COMBOI    X168,X169,X170,X171,256
         COMBOI    X172,X173,X174,X175,256
         COMBOI    X176,X177,X178,X179,256
         COMBOI    X180,X181,X182,X183,256
         COMBOI    X184,X185,X186,X187,256
         COMBOI    X188,X189,X190,X191,256
         LDPK      7
         COMBOI    X192,X193,X194,X195,384
         COMBOI    X196,X197,X198,X199,384
         COMBOI    X200,X201,X202,X203,384
         COMBOI    X204,X205,X206,X207,384
         COMBOI    X208,X209,X210,X211,384
         COMBOI    X212,X213,X214,X215,384
         COMBOI    X216,X217,X218,X219,384
         COMBOI    X220,X221,X222,X223,384
         COMBOI    X224,X225,X226,X227,384
         COMBOI    X228,X229,X230,X231,384
         COMBOI    X232,X233,X234,X235,384
         COMBOI    X236,X237,X238,X239,384
         COMBOI    X240,X241,X242,X243,384
         COMBOI    X244,X245,X246,X247,384
         COMBOI    X248,X249,X250,X251,384
         COMBOI    X252,X253,X254,X255,384
*
*        FFT CODE FOR STAGE 3
*
         ZEROI     X000,X004,512
         PBY4I     X001,X005,512
         PBY2I     X002,X006,512
         P3BY4I    X003,X007,512
         ZEROI     X008,X012,512
         PBY4I     X009,X013,512
         PBY2I     X010,X014,512
         P3BY4I    X011,X015,512
         ZEROI     X016,X020,512
         PBY4I     X017,X021,512
         PBY2I     X018,X022,512
         P3BY4I    X019,X023,512
         ZEROI     X024,X028,512
         PBY4I     X025,X029,512
         PBY2I     X026,X030,512
         P3BY4I    X027,X031,512
         ZEROI     X032,X036,512
         PBY4I     X033,X037,512
         PBY2I     X034,X038,512
         P3BY4I    X035,X039,512
         ZEROI     X040,X044,512
         PBY4I     X041,X045,512
         PBY2I     X042,X046,512
         P3BY4I    X043,X047,512
         ZEROI     X048,X052,512
         PBY4I     X049,X053,512
         PBY2I     X050,X054,512
         P3BY4I    X051,X055,512
         ZEROI     X056,X060,512
         PBY4I     X057,X061,512
         PBY2I     X058,X062,512
         P3BY4I    X059,X063,512
         ZEROI     X064,X068,512
         PBY4I     X065,X069,512
         PBY2I     X066,X070,512
         P3BY4I    X067,X071,512
         ZEROI     X072,X076,512
         PBY4I     X073,X077,512
         PBY2I     X074,X078,512
         P3BY4I    X075,X079,512
         ZEROI     X080,X084,512
         PBY4I     X081,X085,512
         PBY2I     X082,X086,512
         P3BY4I    X083,X087,512
         ZEROI     X088,X092,512
         PBY4I     X089,X093,512
         PBY2I     X090,X094,512
         P3BY4I    X091,X095,512
         ZEROI     X096,X100,512
         PBY4I     X097,X101,512
         PBY2I     X098,X102,512
         P3BY4I    X099,X103,512
         ZEROI     X104,X108,512
         PBY4I     X105,X109,512
         PBY2I     X106,X110,512
         P3BY4I    X107,X111,512
         ZEROI     X112,X116,512
         PBY4I     X113,X117,512
         PBY2I     X114,X118,512
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         P3BY4I   X115,X119,512
         ZEROI    X120,X124,512
         PBY4I    X121,X125,512
         PBY2I    X122,X126,512
         P3BY4I   X123,X127,512
         ZEROI    X128,X132,512
         PBY4I    X129,X133,512
         PBY2I    X130,X134,512
         P3BY4I   X131,X135,512
         ZEROI    X136,X140,512
         PBY4I    X137,X141,512
         PBY2I    X138,X142,512
         P3BY4I   X139,X143,512
         ZEROI    X144,X148,512
         PBY4I    X145,X149,512
         PBY2I    X146,X150,512
         P3BY4I   X147,X151,512
         ZEROI    X152,X156,512
         PBY4I    X153,X157,512
         PBY2I    X154,X158,512
         P3BY4I   X155,X159,512
         ZEROI    X160,X164,512
         PBY4I    X161,X165,512
         PBY2I    X162,X166,512
         P3BY4I   X163,X167,512
         ZEROI    X168,X172,512
         PBY4I    X169,X173,512
         PBY2I    X170,X174,512
         P3BY4I   X171,X175,512
         ZEROI    X176,X180,512
         PBY4I    X177,X181,512
         PBY2I    X178,X182,512
         P3BY4I   X179,X183,512
         ZEROI    X184,X188,512
         PBY4I    X185,X189,512
         PBY2I    X186,X190,512
         P3BY4I   X187,X191,512
         ZEROI    X192,X196,512
         PBY4I    X193,X197,512
         PBY2I    X194,X198,512
         P3BY4I   X195,X199,512
         ZEROI    X200,X204,512
         PBY4I    X201,X205,512
         PBY2I    X202,X206,512
         P3BY4I   X203,X207,512
         ZEROI    X208,X212,512
         PBY4I    X209,X213,512
         PBY2I    X210,X214,512
         P3BY4I   X211,X215,512
         ZEROI    X216,X220,512
         PBY4I    X217,X221,512
         PBY2I    X218,X222,512
         P3BY4I   X219,X223,512
         ZEROI    X224,X228,512
         PBY4I    X225,X229,512
         PBY2I    X226,X230,512
         P3BY4I   X227,X231,512
         ZEROI    X232,X236,512
         PBY4I    X233,X237,512
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         ZEROI    X248,X252,512
         PBY4I    X249,X253,512
         PBY2I    X250,X254,512
         P3BY4I   X251,X255,512
*
*        FFT CODE FOR STAGE 4
*
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         BTRFLI   X003,X011,C048,S048,512
         PBY2I    X004,X012,512
         BTRFLI   X005,X013,C080,S080,512
         P3BY4I   X006,X014,512
         BTRFLI   X007,X015,C112,S112,512
         ZEROI    X016,X024,512
         BTRFLI   X017,X025,C016,S016,512
         PBY4I    X018,X026,512
         BTRFLI   X019,X027,C048,S048,512
         PBY2I    X020,X028,512
         BTRFLI   X021,X029,C080,S080,512
         P3BY4I   X022,X030,512
         BTRFLI   X023,X031,C112,S112,512
         ZEROI    X032,X040,512
         BTRFLI   X033,X041,C016,S016,512
         PBY4I    X034,X042,512
         BTRFLI   X035,X043,C048,S048,512
         PBY2I    X036,X044,512
         BTRFLI   X037,X045,C080,S080,512
         P3BY4I   X038,X046,512
         BTRFLI   X039,X047,C112,S112,512
         ZEROI    X048,X056,512
         BTRFLI   X049,X057,C016,S016,512
         PBY4I    X050,X058,512
         BTRFLI   X051,X059,C048,S048,512
         PBY2I    X052,X060,512
         BTRFLI   X053,X061,C080,S080,512
         P3BY4I   X054,X062,512
         BTRFLI   X055,X063,C112,S112,512
         ZEROI    X064,X072,512
         BTRFLI   X065,X073,C016,S016,512
         PBY4I    X066,X074,512
         BTRFLI   X067,X075,C048,S048,512
         PBY2I    X068,X076,512
         BTRFLI   X069,X077,C080,S080,512
         P3BY4I   X070,X078,512
         BTRFLI   X071,X079,C112,S112,512
         ZEROI    X080,X088,512
         BTRFLI   X081,X089,C016,S016,512
         PBY4I    X082,X090,512
         BTRFLI   X083,X091,C048,S048,512
         PBY2I    X084,X092,512
         BTRFLI   X085,X093,C080,S080,512
         P3BY4I   X086,X094,512
         BTRFLI   X087,X095,C112,S112,512
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         ZEROI    X128,X132,512
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         PBY2I    X130,X134,512
         P3BY4I   X131,X135,512
         ZEROI    X136,X140,512
         PBY4I    X137,X141,512
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         PBY4I    X145,X149,512
         PBY2I    X146,X150,512
         P3BY4I   X147,X151,512
         ZEROI    X152,X156,512
         PBY4I    X153,X157,512
         PBY2I    X154,X158,512
         P3BY4I   X155,X159,512
         ZEROI    X160,X164,512
         PBY4I    X161,X165,512
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         ZEROI    X176,X180,512
         PBY4I    X177,X181,512
         PBY2I    X178,X182,512
         P3BY4I   X179,X183,512
         ZEROI    X184,X188,512
         PBY4I    X185,X189,512
         PBY2I    X186,X190,512
         P3BY4I   X187,X191,512
         ZEROI    X192,X196,512
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         PBY4I    X201,X205,512
         PBY2I    X202,X206,512
         P3BY4I   X203,X207,512
         ZEROI    X208,X212,512
         PBY4I    X209,X213,512
         PBY2I    X210,X214,512
         P3BY4I   X211,X215,512
         ZEROI    X216,X220,512
         PBY4I    X217,X221,512
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         PBY2I    X226,X230,512
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         PBY4I    X233,X237,512
         PBY2I    X234,X238,512
         P3BY4I   X235,X239,512
         ZEROI    X240,X244,512
         PBY4I    X241,X245,512
         PBY2I    X242,X246,512
         P3BY4I   X243,X247,512
         ZEROI    X248,X252,512
         PBY4I    X249,X253,512
         PBY2I    X250,X254,512
         P3BY4I   X251,X255,512
*
*        FFT CODE FOR STAGE 4
*
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         BTRFLI   X001,X009,C016,S016,512
         PBY4I    X002,X010,512
         BTRFLI   X003,X011,C048,S048,512
         PBY2I    X004,X012,512
         BTRFLI   X005,X013,C080,S080,512
         P3BY4I   X006,X014,512
         BTRFLI   X007,X015,C112,S112,512
         ZEROI    X016,X024,512
         BTRFLI   X017,X025,C016,S016,512
         PBY4I    X018,X026,512
         BTRFLI   X019,X027,C048,S048,512
         PBY2I    X020,X028,512
         BTRFLI   X021,X029,C080,S080,512
         P3BY4I   X022,X030,512
         BTRFLI   X023,X031,C112,S112,512
         ZEROI    X032,X040,512
         BTRFLI   X033,X041,C016,S016,512
         PBY4I    X034,X042,512
         BTRFLI   X035,X043,C048,S048,512
         PBY2I    X036,X044,512
         BTRFLI   X037,X045,C080,S080,512
         P3BY4I   X038,X046,512
         BTRFLI   X039,X047,C112,S112,512
         ZEROI    X048,X056,512
         BTRFLI   X049,X057,C016,S016,512
         PBY4I    X050,X058,512
         BTRFLI   X051,X059,C048,S048,512
         PBY2I    X052,X060,512
         BTRFLI   X053,X061,C080,S080,512
         P3BY4I   X054,X062,512
         BTRFLI   X055,X063,C112,S112,512
         ZEROI    X064,X072,512
         BTRFLI   X065,X073,C016,S016,512
         PBY4I    X066,X074,512
         BTRFLI   X067,X075,C048,S048,512
         PBY2I    X068,X076,512
         BTRFLI   X069,X077,C080,S080,512
         P3BY4I   X070,X078,512
         BTRFLI   X071,X079,C112,S112,512
         ZEROI    X080,X088,512
         BTRFLI   X081,X089,C016,S016,512
         PBY4I    X082,X090,512
         BTRFLI   X083,X091,C048,S048,512
         PBY2I    X084,X092,512
         BTRFLI   X085,X093,C080,S080,512
         P3BY4I   X086,X094,512
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BTRFLI  X097,X105,C016,S016,512
PBY4I   X098,X106,512
BTRFLI  X099,X107,C048,S048,512
PBY2I   X100,X108,512
BTRFLI  X101,X109,C080,S080,512
P3BY4I  X102,X110,512
BTRFLI  X103,X111,C112,S112,512
ZEROI   X112,X120,512
BTRFLI  X113,X121,C016,S016,512
PBY4I   X114,X122,512
BTRFLI  X115,X123,C048,S048,512
PBY2I   X116,X124,512
BTRFLI  X117,X125,C080,S080,512
P3BY4I  X118,X126,512
BTRFLI  X119,X127,C112,S112,512
ZEROI   X128,X136,512
BTRFLI  X129,X137,C016,S016,512
PBY4I   X130,X138,512
BTRFLI  X131,X139,C048,S048,512
PBY2I   X132,X140,512
BTRFLI  X133,X141,C080,S080,512
P3BY4I  X134,X142,512
BTRFLI  X135,X143,C112,S112,512
ZEROI   X144,X152,512
BTRFLI  X145,X153,C016,S016,512
PBY4I   X146,X154,512
BTRFLI  X147,X155,C048,S048,512
PBY2I   X148,X156,512
BTRFLI  X149,X157,C080,S080,512
P3BY4I  X150,X158,512
BTRFLI  X151,X159,C112,S112,512
ZEROI   X160,X168,512
BTRFLI  X161,X169,C016,S016,512
PBY4I   X162,X170,512
BTRFLI  X163,X171,C048,S048,512
PBY2I   X164,X172,512
BTRFLI  X165,X173,C080,S080,512
P3BY4I  X166,X174,512
BTRFLI  X167,X175,C112,S112,512
ZEROI   X176,X184,512
BTRFLI  X177,X185,C016,S016,512
PBY4I   X178,X186,512
BTRFLI  X179,X187,C048,S048,512
PBY2I   X180,X188,512
BTRFLI  X181,X189,C080,S080,512
P3BY4I  X182,X190,512
BTRFLI  X183,X191,C112,S112,512
ZEROI   X192,X200,512
BTRFLI  X193,X201,C016,S016,512
PBY4I   X194,X202,512
BTRFLI  X195,X203,C048,S048,512
PBY2I   X196,X204,512
BTRFLI  X197,X205,C080,S080,512
P3BY4I  X198,X206,512
BTRFLI  X199,X207,C112,S112,512
ZEROI   X208,X216,512
BTRFLI  X209,X217,C016,S016,512
PBY4I   X210,X218,512
BTRFLI  X211,X219,C048,S048,512
PBY2I   X212,X220,512
BTRFLI  X213,X221,C080,S080,512
P3BY4I  X214,X222,512
BTRFLI  X215,X223,C112,S112,512
ZEROI   X224,X232,512
BTRFLI  X225,X233,C016,S016,512
PBY4I   X226,X234,512
BTRFLI  X227,X235,C048,S048,512
PBY2I   X228,X236,512
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P3BY4I  X230,X238,512
BTRFLI  X231,X239,C112,S112,512
ZEROI   X240,X248,512
BTRFLI  X241,X249,C016,S016,512
PBY4I   X242,X250,512
BTRFLI  X243,X251,C048,S048,512
PBY2I   X244,X252,512
BTRFLI  X245,X253,C080,S080,512
P3BY4I  X246,X254,512
BTRFLI  X247,X255,C112,S112,512
*
*       FFT CODE FOR STAGE 5
*
ZEROI   X000,X016,512
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BTRFLI  X002,X018,C016,S016,512
BTRFLI  X003,X019,C024,S024,512
PBY4I   X004,X020,512
BTRFLI  X005,X021,C040,S040,512
BTRFLI  X006,X022,C048,S048,512
BTRFLI  X007,X023,C056,S056,512
PBY2I   X008,X024,512
BTRFLI  X009,X025,C072,S072,512
BTRFLI  X010,X026,C080,S080,512
BTRFLI  X011,X027,C088,S088,512
P3BY4I  X012,X028,512
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BTRFLI  X014,X030,C112,S112,512
BTRFLI  X015,X031,C120,S120,512
ZEROI   X032,X048,512
BTRFLI  X033,X049,C008,S008,512
BTRFLI  X034,X050,C016,S016,512
BTRFLI  X035,X051,C024,S024,512
PBY4I   X036,X052,512
BTRFLI  X037,X053,C040,S040,512
BTRFLI  X038,X054,C048,S048,512
BTRFLI  X039,X055,C056,S056,512
PBY2I   X040,X056,512
BTRFLI  X041,X057,C072,S072,512
BTRFLI  X042,X058,C080,S080,512
BTRFLI  X043,X059,C088,S088,512
P3BY4I  X044,X060,512
BTRFLI  X045,X061,C104,S104,512
BTRFLI  X046,X062,C112,S112,512
BTRFLI  X047,X063,C120,S120,512
ZEROI   X064,X080,512
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BTRFLI  X066,X082,C016,S016,512
BTRFLI  X067,X083,C024,S024,512
PBY4I   X068,X084,512
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BTRFLI    X070,X086,C048,S048,512
BTRFLI    X071,X087,C056,S056,512
PBY2I     X072,X088,512
BTRFLI    X073,X089,C072,S072,512
BTRFLI    X074,X090,C080,S080,512
BTRFLI    X075,X091,C088,S088,512
P3BY4I    X076,X092,512
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BTRFLI    X078,X094,C112,S112,512
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ZEROI     X096,X112,512
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PBY4I     X100,X116,512
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BTRFLI    X103,X119,C056,S056,512
PBY2I     X104,X120,512
BTRFLI    X105,X121,C072,S072,512
BTRFLI    X106,X122,C080,S080,512
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BTRFLI    X110,X126,C112,S112,512
BTRFLI    X111,X127,C120,S120,512
ZEROI     X128,X144,512
BTRFLI    X129,X145,C008,S008,512
BTRFLI    X130,X146,C016,S016,512
BTRFLI    X131,X147,C024,S024,512
PBY4I     X132,X148,512
BTRFLI    X133,X149,C040,S040,512
BTRFLI    X134,X150,C048,S048,512
BTRFLI    X135,X151,C056,S056,512
PBY2I     X136,X152,512
BTRFLI    X137,X153,C072,S072,512
BTRFLI    X138,X154,C080,S080,512
BTRFLI    X139,X155,C088,S088,512
P3BY4I    X140,X156,512
BTRFLI    X141,X157,C104,S104,512
BTRFLI    X142,X158,C112,S112,512
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BTRFLI    X163,X179,C024,S024,512
PBY4I     X164,X180,512
BTRFLI    X165,X181,C040,S040,512
BTRFLI    X166,X182,C048,S048,512
BTRFLI    X167,X183,C056,S056,512
PBY2I     X168,X184,512
BTRFLI    X169,X185,C072,S072,512
BTRFLI    X170,X186,C080,S080,512
BTRFLI    X171,X187,C088,S088,512
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BTRFLI    X173,X189,C104,S104,512
BTRFLI    X174,X190,C112,S112,512
BTRFLI    X175,X191,C120,S120,512
ZEROI     X192,X208,512
BTRFLI    X193,X209,C008,S008,512
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BTRFLI    X195,X211,C024,S024,512
PBY4I     X196,X212,512
BTRFLI    X197,X213,C040,S040,512
BTRFLI    X198,X214,C048,S048,512
BTRFLI    X199,X215,C056,S056,512
PBY2I     X200,X216,512
BTRFLI    X201,X217,C072,S072,512
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BTRFLI    X205,X221,C104,S104,512
BTRFLI    X206,X222,C112,S112,512
BTRFLI    X207,X223,C120,S120,512
ZEROI     X224,X240,512
BTRFLI    X225,X241,C008,S008,512
BTRFLI    X226,X242,C016,S016,512
BTRFLI    X227,X243,C024,S024,512
PBY4I     X228,X244,512
BTRFLI    X229,X245,C040,S040,512
BTRFLI    X230,X246,C048,S048,512
BTRFLI    X231,X247,C056,S056,512
PBY2I     X232,X248,512
BTRFLI    X233,X249,C072,S072,512
BTRFLI    X234,X250,C080,S080,512
BTRFLI    X235,X251,C088,S088,512
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BTRFLI    X237,X253,C104,S104,512
BTRFLI    X238,X254,C112,S112,512
BTRFLI    X239,X255,C120,S120,512
*
*         FFT CODE FOR STAGE 6
*
ZEROI     X000,X032,512
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BTRFLI    X002,X034,C008,S008,512
BTRFLI    X003,X035,C012,S012,512
BTRFLI    X004,X036,C016,S016,512
BTRFLI    X005,X037,C020,S020,512
BTRFLI    X006,X038,C024,S024,512
BTRFLI    X007,X039,C028,S028,512
PBY4I     X008,X040,512
BTRFLI    X009,X041,C036,S036,512
BTRFLI    X010,X042,C040,S040,512
BTRFLI    X011,X043,C044,S044,512
BTRFLI    X012,X044,C048,S048,512
BTRFLI    X013,X045,C052,S052,512
BTRFLI    X014,X046,C056,S056,512
BTRFLI    X015,X047,C060,S060,512
PBY2I     X016,X048,512
BTRFLI    X017,X049,C068,S068,512
BTRFLI    X018,X050,C072,S072,512
BTRFLI    X019,X051,C076,S076,512
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BTRFLI    X023,X055,C092,S092,512
P3BY4I    X024,X056,512
BTRFLI    X025,X057,C100,S100,512
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BTRFLI    X027,X059,C108,S108,512
BTRFLI    X028,X060,C112,S112,512
BTRFLI    X029,X061,C116,S116,512
BTRFLI    X030,X062,C120,S120,512
BTRFLI    X031,X063,C124,S124,512
ZEROI     X064,X096,512
BTRFLI    X065,X097,C004,S004,512
BTRFLI    X066,X098,C008,S008,512
BTRFLI    X067,X099,C012,S012,512
BTRFLI    X068,X100,C016,S016,512
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BTRFLI    X070,X102,C024,S024,512
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BTRFLI    X078,X110,C056,S056,512
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BTRFLI    X090,X122,C104,S104,512
BTRFLI    X091,X123,C108,S108,512
BTRFLI    X092,X124,C112,S112,512
BTRFLI    X093,X125,C116,S116,512
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BTRFLI    X131,X163,C012,S012,512
BTRFLI    X132,X164,C016,S016,512
BTRFLI    X133,X165,C020,S020,512
BTRFLI    X134,X166,C024,S024,512
BTRFLI    X135,X167,C028,S028,512
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BTRFLI    X138,X170,C040,S040,512
BTRFLI    X139,X171,C044,S044,512
BTRFLI    X140,X172,C048,S048,512
BTRFLI    X141,X173,C052,S052,512
BTRFLI    X142,X174,C056,S056,512
BTRFLI    X143,X175,C060,S060,512
PBY2I     X144,X176,512
BTRFLI    X145,X177,C068,S068,512
BTRFLI    X146,X178,C072,S072,512
BTRFLI    X147,X179,C076,S076,512
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BTRFLI    X149,X181,C084,S084,512
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BTRFLI    X151,X183,C092,S092,512
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BTRFLI    X153,X185,C100,S100,512
BTRFLI    X154,X186,C104,S104,512
BTRFLI    X155,X187,C108,S108,512
BTRFLI    X156,X188,C112,S112,512
BTRFLI    X157,X189,C116,S116,512
BTRFLI    X158,X190,C120,S120,512
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BTRFLI    X194,X226,C008,S008,512
BTRFLI    X195,X227,C012,S012,512
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BTRFLI    X197,X229,C020,S020,512
BTRFLI    X198,X230,C024,S024,512
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PBY4I     X200,X232,512
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BTRFLI    X205,X237,C052,S052,512
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BTRFLI    X207,X239,C060,S060,512
PBY2I     X208,X240,512
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BTRFLI    X210,X242,C072,S072,512
BTRFLI    X211,X243,C076,S076,512
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BTRFLI    X213,X245,C084,S084,512
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BTRFLI    X218,X250,C104,S104,512
BTRFLI    X219,X251,C108,S108,512
BTRFLI    X220,X252,C112,S112,512
BTRFLI    X221,X253,C116,S116,512
BTRFLI    X222,X254,C120,S120,512
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*         FFT CODE FOR STAGE 7
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BTRFLI    X004,X068,C008,S008,512
BTRFLI    X005,X069,C010,S010,512
BTRFLI    X006,X070,C012,S012,512
BTRFLI    X007,X071,C014,S014,512
BTRFLI    X008,X072,C016,S016,512
BTRFLI    X009,X073,C018,S018,512
BTRFLI    X010,X074,C020,S020,512
BTRFLI    X011,X075,C022,S022,512
BTRFLI    X012,X076,C024,S024,512
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BTRFLI    X014,X078,C028,S028,512
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BTRFLI   X022,X086,C044,S044,512
BTRFLI   X023,X087,C046,S046,512
BTRFLI   X024,X088,C048,S048,512
BTRFLI   X025,X089,C050,S050,512
BTRFLI   X026,X090,C052,S052,512
BTRFLI   X027,X091,C054,S054,512
BTRFLI   X028,X092,C056,S056,512
BTRFLI   X029,X093,C058,S058,512
BTRFLI   X030,X094,C060,S060,512
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BTRFLI   X033,X097,C066,S066,512
BTRFLI   X034,X098,C068,S068,512
BTRFLI   X035,X099,C070,S070,512
BTRFLI   X036,X100,C072,S072,512
BTRFLI   X037,X101,C074,S074,512
BTRFLI   X038,X102,C076,S076,512
BTRFLI   X039,X103,C078,S078,512
BTRFLI   X040,X104,C080,S080,512
BTRFLI   X041,X105,C082,S082,512
BTRFLI   X042,X106,C084,S084,512
BTRFLI   X043,X107,C086,S086,512
BTRFLI   X044,X108,C088,S088,512
BTRFLI   X045,X109,C090,S090,512
BTRFLI   X046,X110,C092,S092,512
BTRFLI   X047,X111,C094,S094,512
P3BY4I   X048,X112,512
BTRFLI   X049,X113,C098,S098,512
BTRFLI   X050,X114,C100,S100,512
BTRFLI   X051,X115,C102,S102,512
BTRFLI   X052,X116,C104,S104,512
BTRFLI   X053,X117,C106,S106,512
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BTRFLI   X056,X120,C112,S112,512
BTRFLI   X057,X121,C114,S114,512
BTRFLI   X058,X122,C116,S116,512
BTRFLI   X059,X123,C118,S118,512
BTRFLI   X060,X124,C120,S120,512
BTRFLI   X061,X125,C122,S122,512
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BTRFLI   X134,X198,C012,S012,512
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BTRFLI   X137,X201,C018,S018,512
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BTRFLI   X139,X203,C022,S022,512
BTRFLI   X140,X204,C024,S024,512
BTRFLI   X141,X205,C026,S026,512
BTRFLI   X142,X206,C028,S028,512
BTRFLI   X143,X207,C030,S030,512
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BTRFLI   X146,X210,C036,S036,512
BTRFLI   X147,X211,C038,S038,512
BTRFLI   X148,X212,C040,S040,512
BTRFLI   X149,X213,C042,S042,512
BTRFLI   X150,X214,C044,S044,512
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BTRFLI   X156,X220,C056,S056,512
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BTRFLI   X158,X222,C060,S060,512
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BTRFLI   X162,X226,C068,S068,512
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BTRFLI   X173,X237,C090,S090,512
BTRFLI   X174,X238,C092,S092,512
BTRFLI   X175,X239,C094,S094,512
P3BY4I   X176,X240,512
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BTRFLI   X178,X242,C100,S100,512
BTRFLI   X179,X243,C102,S102,512
BTRFLI   X180,X244,C104,S104,512
BTRFLI   X181,X245,C106,S106,512
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BTRFLI   X183,X247,C110,S110,512
BTRFLI   X184,X248,C112,S112,512
BTRFLI   X185,X249,C114,S114,512
BTRFLI   X186,X250,C116,S116,512
BTRFLI   X187,X251,C118,S118,512
BTRFLI   X188,X252,C120,S120,512
BTRFLI   X189,X253,C122,S122,512
BTRFLI   X190,X254,C124,S124,512
BTRFLI   X191,X255,C126,S126,512
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*        FFT CODE FOR STAGE 8
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BTRFLI   X003,X131,C003,S003,512
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BTRFLI    X014,X142,C014,S014,512
BTRFLI    X015,X143,C015,S015,512
BTRFLI    X016,X144,C016,S016,512
BTRFLI    X017,X145,C017,S017,512
BTRFLI    X018,X146,C018,S018,512
BTRFLI    X019,X147,C019,S019,512
BTRFLI    X020,X148,C020,S020,512
BTRFLI    X021,X149,C021,S021,512
BTRFLI    X022,X150,C022,S022,512
BTRFLI    X023,X151,C023,S023,512
BTRFLI    X024,X152,C024,S024,512
BTRFLI    X025,X153,C025,S025,512
BTRFLI    X026,X154,C026,S026,512
BTRFLI    X027,X155,C027,S027,512
BTRFLI    X028,X156,C028,S028,512
BTRFLI    X029,X157,C029,S029,512
BTRFLI    X030,X158,C030,S030,512
BTRFLI    X031,X159,C031,S031,512
PBY4I     X032,X160,512
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BTRFLI    X034,X162,C034,S034,512
BTRFLI    X035,X163,C035,S035,512
BTRFLI    X036,X164,C036,S036,512
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BTRFLI    X038,X166,C038,S038,512
BTRFLI    X039,X167,C039,S039,512
BTRFLI    X040,X168,C040,S040,512
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BTRFLI    X051,X179,C051,S051,512
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BTRFLI    X061,X189,C061,S061,512
BTRFLI    X062,X190,C062,S062,512
BTRFLI    X063,X191,C063,S063,512
PBY2I     X064,X192,512
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BTRFLI    X066,X194,C066,S066,512
BTRFLI    X067,X195,C067,S067,512
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BTRFLI    X069,X197,C069,S069,512
BTRFLI    X070,X198,C070,S070,512
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BTRFLI    X080,X208,C080,S080,512
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BTRFLI    X082,X210,C082,S082,512
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BTRFLI    X084,X212,C084,S084,512
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BTRFLI    X087,X215,C087,S087,512
BTRFLI    X088,X216,C088,S088,512
BTRFLI    X089,X217,C089,S089,512
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BTRFLI    X091,X219,C091,S091,512
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BTRFLI    X095,X223,C095,S095,512
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BTRFLI    X098,X226,C098,S098,512
BTRFLI    X099,X227,C099,S099,512
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BTRFLI    X110,X238,C110,S110,512
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BTRFLI    X114,X242,C114,S114,512
BTRFLI    X115,X243,C115,S115,512
BTRFLI    X116,X244,C116,S116,512
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BTRFLI    X121,X249,C121,S121,512
BTRFLI    X122,X250,C122,S122,512
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BTRFLI    X125,X253,C125,S125,512
BTRFLI    X126,X254,C126,S126,512
BTRFLI    X127,X255,C127,S127,512
END
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APPENDIX D
A 1024-POINT, RADIX-2 DIT FFT IMPLEMENTATION

```
          A P P E N D I X   D
          -------------------

          IDT       'FT1024'
*************************************************************
*                                                           *
*   A 1024-POINT RADIX-2 DIT COMPLEX FFT FOR THE TMS32020   *
*   -----------------------------------------------------   *
*                                                           *
*   THE FOLLOWING FILE RAD2FFT.MAC CONSISTS OF ALL THE      *
*   MACROS LISTED IN APPENDIX B                             *
*                                                           *
*************************************************************
*
          COPY      RAD2FFT.MAC
*
*************************************************************
*                                                           *
*   DATA MEMORY MAP FOR PAGES 4, 5, 6 AND 7 (BLOCKS B0,B1)  *
*                                                           *
*************************************************************
*
          DORG     0
*
*         DATA MEMORY PAGE 4 (STARTING ADDRESS 512 OR >200)
*
X000      DATA     0,0
X001      DATA     0,0
X002      DATA     0,0
X003      DATA     0,0
X004      DATA     0,0
X005      DATA     0,0
X006      DATA     0,0
X007      DATA     0,0
X008      DATA     0,0
X009      DATA     0,0
X010      DATA     0,0
X011      DATA     0,0
X012      DATA     0,0
X013      DATA     0,0
X014      DATA     0,0
X015      DATA     0,0
X016      DATA     0,0
X017      DATA     0,0
X018      DATA     0,0
X019      DATA     0,0
X020      DATA     0,0
X021      DATA     0,0
X022      DATA     0,0
X023      DATA     0,0
X024      DATA     0,0
X025      DATA     0,0
X026      DATA     0,0
X027      DATA     0,0
X028      DATA     0,0
X029      DATA     0,0
X030      DATA     0,0
X031      DATA     0,0
X032      DATA     0,0
X033      DATA     0,0
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X034      DATA    0,0
X035      DATA    0,0
X036      DATA    0,0
X037      DATA    0,0
X038      DATA    0,0
X039      DATA    0,0
X040      DATA    0,0
X041      DATA    0,0
X042      DATA    0,0
X043      DATA    0,0
X044      DATA    0,0
X045      DATA    0,0
X046      DATA    0,0
X047      DATA    0,0
X048      DATA    0,0
X049      DATA    0,0
X050      DATA    0,0
X051      DATA    0,0
X052      DATA    0,0
X053      DATA    0,0
X054      DATA    0,0
X055      DATA    0,0
X056      DATA    0,0
X057      DATA    0,0
X058      DATA    0,0
X059      DATA    0,0
X060      DATA    0,0
X061      DATA    0,0
X062      DATA    0,0
X063      DATA    0,0
*
*         DATA MEMORY PAGE 5 (STARTING ADDRESS 640 OR >280)
*
X064      DATA    0,0
X065      DATA    0,0
X066      DATA    0,0
X067      DATA    0,0
X068      DATA    0,0
X069      DATA    0,0
X070      DATA    0,0
X071      DATA    0,0
X072      DATA    0,0
X073      DATA    0,0
X074      DATA    0,0
X075      DATA    0,0
X076      DATA    0,0
X077      DATA    0,0
X078      DATA    0,0
X079      DATA    0,0
X080      DATA    0,0
X081      DATA    0,0
X082      DATA    0,0
X083      DATA    0,0
X084      DATA    0,0
X085      DATA    0,0
X086      DATA    0,0
X087      DATA    0,0
X088      DATA    0,0
X089      DATA    0,0
X090      DATA    0,0
X091      DATA    0,0
X092      DATA    0,0
X093      DATA    0,0
X094      DATA    0,0
X095      DATA    0,0
X096      DATA    0,0
X097      DATA    0,0
X098      DATA    0,0
X099      DATA    0,0
X100      DATA    0,0
X101      DATA    0,0
X102      DATA    0,0
X103      DATA    0,0
X104      DATA    0,0
X105      DATA    0,0
X106      DATA    0,0
X107      DATA    0,0
X108      DATA    0,0
X109      DATA    0,0
X110      DATA    0,0
X111      DATA    0,0
X112      DATA    0,0
X113      DATA    0,0
X114      DATA    0,0
X115      DATA    0,0
X116      DATA    0,0
X117      DATA    0,0
X118      DATA    0,0
X119      DATA    0,0
X120      DATA    0,0
X121      DATA    0,0
X122      DATA    0,0
X123      DATA    0,0
X124      DATA    0,0
X125      DATA    0,0
X126      DATA    0,0
X127      DATA    0,0
*
*         DATA MEMORY PAGE 6 (STARTING ADDRESS 768 OR >300)
*
X128      DATA    0,0
X129      DATA    0,0
X130      DATA    0,0
X131      DATA    0,0
X132      DATA    0,0
X133      DATA    0,0
X134      DATA    0,0
X135      DATA    0,0
X136      DATA    0,0
X137      DATA    0,0
X138      DATA    0,0
X139      DATA    0,0
X140      DATA    0,0
X141      DATA    0,0
X142      DATA    0,0
X143      DATA    0,0
X144      DATA    0,0
X145      DATA    0,0
X146      DATA    0,0
X147      DATA    0,0
```

```
X148     DATA     0,0
X149     DATA     0,0
X150     DATA     0,0
X151     DATA     0,0
X152     DATA     0,0
X153     DATA     0,0
X154     DATA     0,0
X155     DATA     0,0
X156     DATA     0,0
X157     DATA     0,0
X158     DATA     0,0
X159     DATA     0,0
X160     DATA     0,0
X161     DATA     0,0
X162     DATA     0,0
X163     DATA     0,0
X164     DATA     0,0
X165     DATA     0,0
X166     DATA     0,0
X167     DATA     0,0
X168     DATA     0,0
X169     DATA     0,0
X170     DATA     0,0
X171     DATA     0,0
X172     DATA     0,0
X173     DATA     0,0
X174     DATA     0,0
X175     DATA     0,0
X176     DATA     0,0
X177     DATA     0,0
X178     DATA     0,0
X179     DATA     0,0
X180     DATA     0,0
X181     DATA     0,0
X182     DATA     0,0
X183     DATA     0,0
X184     DATA     0,0
X185     DATA     0,0
X186     DATA     0,0
X187     DATA     0,0
X188     DATA     0,0
X189     DATA     0,0
X190     DATA     0,0
X191     DATA     0,0
*
*        DATA MEMORY PAGE 7 (STARTING ADDRESS 896 OR >380)
*
X192     DATA     0,0
X193     DATA     0,0
X194     DATA     0,0
X195     DATA     0,0
X196     DATA     0,0
X197     DATA     0,0
X198     DATA     0,0
X199     DATA     0,0
X200     DATA     0,0
X201     DATA     0,0
X202     DATA     0,0
X203     DATA     0,0
X204     DATA     0,0
X205     DATA     0,0
X206     DATA     0,0
X207     DATA     0,0
X208     DATA     0,0
X209     DATA     0,0
X210     DATA     0,0
X211     DATA     0,0
X212     DATA     0,0
X213     DATA     0,0
X214     DATA     0,0
X215     DATA     0,0
X216     DATA     0,0
X217     DATA     0,0
X218     DATA     0,0
X219     DATA     0,0
X220     DATA     0,0
X221     DATA     0,0
X222     DATA     0,0
X223     DATA     0,0
X224     DATA     0,0
X225     DATA     0,0
X226     DATA     0,0
X227     DATA     0,0
X228     DATA     0,0
X229     DATA     0,0
X230     DATA     0,0
X231     DATA     0,0
X232     DATA     0,0
X233     DATA     0,0
X234     DATA     0,0
X235     DATA     0,0
X236     DATA     0,0
X237     DATA     0,0
X238     DATA     0,0
X239     DATA     0,0
X240     DATA     0,0
X241     DATA     0,0
X242     DATA     0,0
X243     DATA     0,0
X244     DATA     0,0
X245     DATA     0,0
X246     DATA     0,0
X247     DATA     0,0
X248     DATA     0,0
X249     DATA     0,0
X250     DATA     0,0
X251     DATA     0,0
X252     DATA     0,0
X253     DATA     0,0
X254     DATA     0,0
X255     DATA     0,0
*
*************************************************************
*                                                           *
*    DATA LOCATION IN BLOCK B2 FOR W=COS(45) OR SIN(45)     *
*                                                           *
*************************************************************
*
         DORG     96
W        DATA     0
```

```
*
****************************************************************
*                                                              *
*   13-BIT TWIDDLE FACTORS FOR 256-POINT COMPLEX FFT           *
*                                                              *
****************************************************************
*
C000      EQU      4095
C001      EQU      4094
C002      EQU      4091
C003      EQU      4085
C004      EQU      4076
C005      EQU      4065
C006      EQU      4052
C007      EQU      4036
C008      EQU      4017
C009      EQU      3996
C010      EQU      3973
C011      EQU      3948
C012      EQU      3920
C013      EQU      3889
C014      EQU      3857
C015      EQU      3822
C016      EQU      3784
C017      EQU      3745
C018      EQU      3703
C019      EQU      3659
C020      EQU      3612
C021      EQU      3564
C022      EQU      3513
C023      EQU      3461
C024      EQU      3406
C025      EQU      3349
C026      EQU      3290
C027      EQU      3229
C028      EQU      3166
C029      EQU      3102
C030      EQU      3035
C031      EQU      2967
C032      EQU      2896
C033      EQU      2824
C034      EQU      2751
C035      EQU      2675
C036      EQU      2598
C037      EQU      2520
C038      EQU      2440
C039      EQU      2359
C040      EQU      2276
C041      EQU      2191
C042      EQU      2106
C043      EQU      2019
C044      EQU      1931
C045      EQU      1842
C046      EQU      1751
C047      EQU      1660
C048      EQU      1567
C049      EQU      1474
C050      EQU      1380
C051      EQU      1285
C052      EQU      1189
C053      EQU      1092
C054      EQU      995
C055      EQU      897
C056      EQU      799
C057      EQU      700
C058      EQU      601
C059      EQU      501
C060      EQU      401
C061      EQU      301
C062      EQU      201
C063      EQU      101
C064      EQU      0
C065      EQU      -101
C066      EQU      -201
C067      EQU      -301
C068      EQU      -401
C069      EQU      -501
C070      EQU      -601
C071      EQU      -700
C072      EQU      -799
C073      EQU      -897
C074      EQU      -995
C075      EQU      -1092
C076      EQU      -1189
C077      EQU      -1285
C078      EQU      -1380
C079      EQU      -1474
C080      EQU      -1567
C081      EQU      -1660
C082      EQU      -1751
C083      EQU      -1842
C084      EQU      -1931
C085      EQU      -2019
C086      EQU      -2106
C087      EQU      -2191
C088      EQU      -2276
C089      EQU      -2359
C090      EQU      -2440
C091      EQU      -2520
C092      EQU      -2598
C093      EQU      -2675
C094      EQU      -2751
C095      EQU      -2824
C096      EQU      -2896
C097      EQU      -2967
C098      EQU      -3035
C099      EQU      -3102
C100      EQU      -3166
C101      EQU      -3229
C102      EQU      -3290
C103      EQU      -3349
C104      EQU      -3406
C105      EQU      -3461
C106      EQU      -3513
C107      EQU      -3564
C108      EQU      -3612
C109      EQU      -3659
C110      EQU      -3703
C111      EQU      -3745
C112      EQU      -3784
```

```
C113    EQU    -3822
C114    EQU    -3857
C115    EQU    -3889
C116    EQU    -3920
C117    EQU    -3948
C118    EQU    -3973
C119    EQU    -3996
C120    EQU    -4017
C121    EQU    -4036
C122    EQU    -4052
C123    EQU    -4065
C124    EQU    -4076
C125    EQU    -4085
C126    EQU    -4091
C127    EQU    -4094
*
S000    EQU    0
S001    EQU    101
S002    EQU    201
S003    EQU    301
S004    EQU    401
S005    EQU    501
S006    EQU    601
S007    EQU    700
S008    EQU    799
S009    EQU    897
S010    EQU    995
S011    EQU    1092
S012    EQU    1189
S013    EQU    1285
S014    EQU    1380
S015    EQU    1474
S016    EQU    1567
S017    EQU    1660
S018    EQU    1751
S019    EQU    1842
S020    EQU    1931
S021    EQU    2019
S022    EQU    2106
S023    EQU    2191
S024    EQU    2276
S025    EQU    2359
S026    EQU    2440
S027    EQU    2520
S028    EQU    2598
S029    EQU    2675
S030    EQU    2751
S031    EQU    2824
S032    EQU    2896
S033    EQU    2967
S034    EQU    3035
S035    EQU    3102
S036    EQU    3166
S037    EQU    3229
S038    EQU    3290
S039    EQU    3349
S040    EQU    3406
S041    EQU    3461
S042    EQU    3513
S043    EQU    3564
S044    EQU    3612
S045    EQU    3659
S046    EQU    3703
S047    EQU    3745
S048    EQU    3784
S049    EQU    3822
S050    EQU    3857
S051    EQU    3889
S052    EQU    3920
S053    EQU    3948
S054    EQU    3973
S055    EQU    3996
S056    EQU    4017
S057    EQU    4036
S058    EQU    4052
S059    EQU    4065
S060    EQU    4076
S061    EQU    4085
S062    EQU    4091
S063    EQU    4094
S064    EQU    4095
S065    EQU    4094
S066    EQU    4091
S067    EQU    4085
S068    EQU    4076
S069    EQU    4065
S070    EQU    4052
S071    EQU    4036
S072    EQU    4017
S073    EQU    3996
S074    EQU    3973
S075    EQU    3948
S076    EQU    3920
S077    EQU    3889
S078    EQU    3857
S079    EQU    3822
S080    EQU    3784
S081    EQU    3745
S082    EQU    3703
S083    EQU    3659
S084    EQU    3612
S085    EQU    3564
S086    EQU    3513
S087    EQU    3461
S088    EQU    3406
S089    EQU    3349
S090    EQU    3290
S091    EQU    3229
S092    EQU    3166
S093    EQU    3102
S094    EQU    3035
S095    EQU    2967
S096    EQU    2896
S097    EQU    2824
S098    EQU    2751
S099    EQU    2675
S100    EQU    2598
S101    EQU    2520
S102    EQU    2440
S103    EQU    2359
```

```
S104    EQU     2276
S105    EQU     2191
S106    EQU     2106
S107    EQU     2019
S108    EQU     1931
S109    EQU     1842
S110    EQU     1751
S111    EQU     1660
S112    EQU     1567
S113    EQU     1474
S114    EQU     1380
S115    EQU     1285
S116    EQU     1189
S117    EQU     1092
S118    EQU     995
S119    EQU     897
S120    EQU     799
S121    EQU     700
S122    EQU     601
S123    EQU     501
S124    EQU     401
S125    EQU     301
S126    EQU     201
S127    EQU     101
*
        LIST
        AORG    0
        B       INIT
*
        AORG    >20
*
WVAL    DATA    >5A82
*
*       SYSTEM INITIALIZATION
*
INIT    SPM     0
        CNFD
        ROVM
        SSXM
        LARP    AR0
        LRLK    AR0,W
        LALK    WVAL
        TBLR    *,AR1
        B       FT1024
*
*************************************************************
*                                                           *
*       256-POINT FFT KERNEL - STAGES 1 AND 2               *
*                                                           *
*************************************************************
*
KNL256  LDPK    4
        COMBOI  X000,X001,X002,X003,0
        COMBOI  X004,X005,X006,X007,0
        COMBOI  X008,X009,X010,X011,0
        COMBOI  X012,X013,X014,X015,0
        COMBOI  X016,X017,X018,X019,0
        COMBOI  X020,X021,X022,X023,0
        COMBOI  X024,X025,X026,X027,0
        COMBOI  X028,X029,X030,X031,0
        COMBOI  X032,X033,X034,X035,0
        COMBOI  X036,X037,X038,X039,0
        COMBOI  X040,X041,X042,X043,0
        COMBOI  X044,X045,X046,X047,0
        COMBOI  X048,X049,X050,X051,0
        COMBOI  X052,X053,X054,X055,0
        COMBOI  X056,X057,X058,X059,0
        COMBOI  X060,X061,X062,X063,0
        LDPK    5
        COMBOI  X064,X065,X066,X067,128
        COMBOI  X068,X069,X070,X071,128
        COMBOI  X072,X073,X074,X075,128
        COMBOI  X076,X077,X078,X079,128
        COMBOI  X080,X081,X082,X083,128
        COMBOI  X084,X085,X086,X087,128
        COMBOI  X088,X089,X090,X091,128
        COMBOI  X092,X093,X094,X095,128
        COMBOI  X096,X097,X098,X099,128
        COMBOI  X100,X101,X102,X103,128
        COMBOI  X104,X105,X106,X107,128
        COMBOI  X108,X109,X110,X111,128
        COMBOI  X112,X113,X114,X115,128
        COMBOI  X116,X117,X118,X119,128
        COMBOI  X120,X121,X122,X123,128
        COMBOI  X124,X125,X126,X127,128
        LDPK    6
        COMBOI  X128,X129,X130,X131,256
        COMBOI  X132,X133,X134,X135,256
        COMBOI  X136,X137,X138,X139,256
        COMBOI  X140,X141,X142,X143,256
        COMBOI  X144,X145,X146,X147,256
        COMBOI  X148,X149,X150,X151,256
        COMBOI  X152,X153,X154,X155,256
        COMBOI  X156,X157,X158,X159,256
        COMBOI  X160,X161,X162,X163,256
        COMBOI  X164,X165,X166,X167,256
        COMBOI  X168,X169,X170,X171,256
        COMBOI  X172,X173,X174,X175,256
        COMBOI  X176,X177,X178,X179,256
        COMBOI  X180,X181,X182,X183,256
        COMBOI  X184,X185,X186,X187,256
        COMBOI  X188,X189,X190,X191,256
        LDPK    7
        COMBOI  X192,X193,X194,X195,384
        COMBOI  X196,X197,X198,X199,384
        COMBOI  X200,X201,X202,X203,384
        COMBOI  X204,X205,X206,X207,384
        COMBOI  X208,X209,X210,X211,384
        COMBOI  X212,X213,X214,X215,384
        COMBOI  X216,X217,X218,X219,384
        COMBOI  X220,X221,X222,X223,384
        COMBOI  X224,X225,X226,X227,384
        COMBOI  X228,X229,X230,X231,384
        COMBOI  X232,X233,X234,X235,384
        COMBOI  X236,X237,X238,X239,384
        COMBOI  X240,X241,X242,X243,384
        COMBOI  X244,X245,X246,X247,384
        COMBOI  X248,X249,X250,X251,384
        COMBOI  X252,X253,X254,X255,384
*
```

```
**************************************************************
*                                                            *
*         256-POINT FFT KERNEL - STAGE 3                     *
*                                                            *
**************************************************************
*
          ZEROI     X000,X004,512
          PBY4I     X001,X005,512
          PBY2I     X002,X006,512
          P3BY4I    X003,X007,512
          ZEROI     X008,X012,512
          PBY4I     X009,X013,512
          PBY2I     X010,X014,512
          P3BY4I    X011,X015,512
          ZEROI     X016,X020,512
          PBY4I     X017,X021,512
          PBY2I     X018,X022,512
          P3BY4I    X019,X023,512
          ZEROI     X024,X028,512
          PBY4I     X025,X029,512
          PBY2I     X026,X030,512
          P3BY4I    X027,X031,512
          ZEROI     X032,X036,512
          PBY4I     X033,X037,512
          PBY2I     X034,X038,512
          P3BY4I    X035,X039,512
          ZEROI     X040,X044,512
          PBY4I     X041,X045,512
          PBY2I     X042,X046,512
          P3BY4I    X043,X047,512
          ZEROI     X048,X052,512
          PBY4I     X049,X053,512
          PBY2I     X050,X054,512
          P3BY4I    X051,X055,512
          ZEROI     X056,X060,512
          PBY4I     X057,X061,512
          PBY2I     X058,X062,512
          P3BY4I    X059,X063,512
          ZEROI     X064,X068,512
          PBY4I     X065,X069,512
          PBY2I     X066,X070,512
          P3BY4I    X067,X071,512
          ZEROI     X072,X076,512
          PBY4I     X073,X077,512
          PBY2I     X074,X078,512
          P3BY4I    X075,X079,512
          ZEROI     X080,X084,512
          PBY4I     X081,X085,512
          PBY2I     X082,X086,512
          P3BY4I    X083,X087,512
          ZEROI     X088,X092,512
          PBY4I     X089,X093,512
          PBY2I     X090,X094,512
          P3BY4I    X091,X095,512
          ZEROI     X096,X100,512
          PBY4I     X097,X101,512
          PBY2I     X098,X102,512
          P3BY4I    X099,X103,512
          ZEROI     X104,X108,512
          PBY4I     X105,X109,512
          PBY2I     X106,X110,512
          P3BY4I    X107,X111,512
          ZEROI     X112,X116,512
          PBY4I     X113,X117,512
          PBY2I     X114,X118,512
          P3BY4I    X115,X119,512
          ZEROI     X120,X124,512
          PBY4I     X121,X125,512
          PBY2I     X122,X126,512
          P3BY4I    X123,X127,512
          ZEROI     X128,X132,512
          PBY4I     X129,X133,512
          PBY2I     X130,X134,512
          P3BY4I    X131,X135,512
          ZEROI     X136,X140,512
          PBY4I     X137,X141,512
          PBY2I     X138,X142,512
          P3BY4I    X139,X143,512
          ZEROI     X144,X148,512
          PBY4I     X145,X149,512
          PBY2I     X146,X150,512
          P3BY4I    X147,X151,512
          ZEROI     X152,X156,512
          PBY4I     X153,X157,512
          PBY2I     X154,X158,512
          P3BY4I    X155,X159,512
          ZEROI     X160,X164,512
          PBY4I     X161,X165,512
          PBY2I     X162,X166,512
          P3BY4I    X163,X167,512
          ZEROI     X168,X172,512
          PBY4I     X169,X173,512
          PBY2I     X170,X174,512
          P3BY4I    X171,X175,512
          ZEROI     X176,X180,512
          PBY4I     X177,X181,512
          PBY2I     X178,X182,512
          P3BY4I    X179,X183,512
          ZEROI     X184,X188,512
          PBY4I     X185,X189,512
          PBY2I     X186,X190,512
          P3BY4I    X187,X191,512
          ZEROI     X192,X196,512
          PBY4I     X193,X197,512
          PBY2I     X194,X198,512
          P3BY4I    X195,X199,512
          ZEROI     X200,X204,512
          PBY4I     X201,X205,512
          PBY2I     X202,X206,512
          P3BY4I    X203,X207,512
          ZEROI     X208,X212,512
          PBY4I     X209,X213,512
          PBY2I     X210,X214,512
          P3BY4I    X211,X215,512
          ZEROI     X216,X220,512
          PBY4I     X217,X221,512
          PBY2I     X218,X222,512
          P3BY4I    X219,X223,512
          ZEROI     X224,X228,512
          PBY4I     X225,X229,512
```

```
         PBY2I    X226,X230,512
         P3BY4I   X227,X231,512
         ZEROI    X232,X236,512
         PBY4I    X233,X237,512
         PBY2I    X234,X238,512
         P3BY4I   X235,X239,512
         ZEROI    X240,X244,512
         PBY4I    X241,X245,512
         PBY2I    X242,X246,512
         P3BY4I   X243,X247,512
         ZEROI    X248,X252,512
         PBY4I    X249,X253,512
         PBY2I    X250,X254,512
         P3BY4I   X251,X255,512
*
*************************************************************
*                                                           *
*        256-POINT FFT KERNEL - STAGE 4                     *
*                                                           *
*************************************************************
*
         ZEROI    X000,X008,512
         BTRFLI   X001,X009,C016,S016,512
         PBY4I    X002,X010,512
         BTRFLI   X003,X011,C048,S048,512
         PBY2I    X004,X012,512
         BTRFLI   X005,X013,C080,S080,512
         P3BY4I   X006,X014,512
         BTRFLI   X007,X015,C112,S112,512
         ZEROI    X016,X024,512
         BTRFLI   X017,X025,C016,S016,512
         PBY4I    X018,X026,512
         BTRFLI   X019,X027,C048,S048,512
         PBY2I    X020,X028,512
         BTRFLI   X021,X029,C080,S080,512
         P3BY4I   X022,X030,512
         BTRFLI   X023,X031,C112,S112,512
         ZEROI    X032,X040,512
         BTRFLI   X033,X041,C016,S016,512
         PBY4I    X034,X042,512
         BTRFLI   X035,X043,C048,S048,512
         PBY2I    X036,X044,512
         BTRFLI   X037,X045,C080,S080,512
         P3BY4I   X038,X046,512
         BTRFLI   X039,X047,C112,S112,512
         ZEROI    X048,X056,512
         BTRFLI   X049,X057,C016,S016,512
         PBY4I    X050,X058,512
         BTRFLI   X051,X059,C048,S048,512
         PBY2I    X052,X060,512
         BTRFLI   X053,X061,C080,S080,512
         P3BY4I   X054,X062,512
         BTRFLI   X055,X063,C112,S112,512
         ZEROI    X064,X072,512
         BTRFLI   X065,X073,C016,S016,512
         PBY4I    X066,X074,512
         BTRFLI   X067,X075,C048,S048,512
         PBY2I    X068,X076,512
         BTRFLI   X069,X077,C080,S080,512
         P3BY4I   X070,X078,512
         BTRFLI   X071,X079,C112,S112,512
         ZEROI    X080,X088,512
         BTRFLI   X081,X089,C016,S016,512
         PBY4I    X082,X090,512
         BTRFLI   X083,X091,C048,S048,512
         PBY2I    X084,X092,512
         BTRFLI   X085,X093,C080,S080,512
         P3BY4I   X086,X094,512
         BTRFLI   X087,X095,C112,S112,512
         ZEROI    X096,X104,512
         BTRFLI   X097,X105,C016,S016,512
         PBY4I    X098,X106,512
         BTRFLI   X099,X107,C048,S048,512
         PBY2I    X100,X108,512
         BTRFLI   X101,X109,C080,S080,512
         P3BY4I   X102,X110,512
         BTRFLI   X103,X111,C112,S112,512
         ZEROI    X112,X120,512
         BTRFLI   X113,X121,C016,S016,512
         PBY4I    X114,X122,512
         BTRFLI   X115,X123,C048,S048,512
         PBY2I    X116,X124,512
         BTRFLI   X117,X125,C080,S080,512
         P3BY4I   X118,X126,512
         BTRFLI   X119,X127,C112,S112,512
         ZEROI    X128,X136,512
         BTRFLI   X129,X137,C016,S016,512
         PBY4I    X130,X138,512
         BTRFLI   X131,X139,C048,S048,512
         PBY2I    X132,X140,512
         BTRFLI   X133,X141,C080,S080,512
         P3BY4I   X134,X142,512
         BTRFLI   X135,X143,C112,S112,512
         ZEROI    X144,X152,512
         BTRFLI   X145,X153,C016,S016,512
         PBY4I    X146,X154,512
         BTRFLI   X147,X155,C048,S048,512
         PBY2I    X148,X156,512
         BTRFLI   X149,X157,C080,S080,512
         P3BY4I   X150,X158,512
         BTRFLI   X151,X159,C112,S112,512
         ZEROI    X160,X168,512
         BTRFLI   X161,X169,C016,S016,512
         PBY4I    X162,X170,512
         BTRFLI   X163,X171,C048,S048,512
         PBY2I    X164,X172,512
         BTRFLI   X165,X173,C080,S080,512
         P3BY4I   X166,X174,512
         BTRFLI   X167,X175,C112,S112,512
         ZEROI    X176,X184,512
         BTRFLI   X177,X185,C016,S016,512
         PBY4I    X178,X186,512
         BTRFLI   X179,X187,C048,S048,512
         PBY2I    X180,X188,512
         BTRFLI   X181,X189,C080,S080,512
         P3BY4I   X182,X190,512
         BTRFLI   X183,X191,C112,S112,512
         ZEROI    X192,X200,512
         BTRFLI   X193,X201,C016,S016,512
         PBY4I    X194,X202,512
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         BTRFLI    X195,X203,C048,S048,512
         PBY2I     X196,X204,512
         BTRFLI    X197,X205,C080,S080,512
         P3BY4I    X198,X206,512
         BTRFLI    X199,X207,C112,S112,512
         ZEROI     X208,X216,512
         BTRFLI    X209,X217,C016,S016,512
         PBY4I     X210,X218,512
         BTRFLI    X211,X219,C048,S048,512
         PBY2I     X212,X220,512
         BTRFLI    X213,X221,C080,S080,512
         P3BY4I    X214,X222,512
         BTRFLI    X215,X223,C112,S112,512
         ZEROI     X224,X232,512
         BTRFLI    X225,X233,C016,S016,512
         PBY4I     X226,X234,512
         BTRFLI    X227,X235,C048,S048,512
         PBY2I     X228,X236,512
         BTRFLI    X229,X237,C080,S080,512
         P3BY4I    X230,X238,512
         BTRFLI    X231,X239,C112,S112,512
         ZEROI     X240,X248,512
         BTRFLI    X241,X249,C016,S016,512
         PBY4I     X242,X250,512
         BTRFLI    X243,X251,C048,S048,512
         PBY2I     X244,X252,512
         BTRFLI    X245,X253,C080,S080,512
         P3BY4I    X246,X254,512
         BTRFLI    X247,X255,C112,S112,512
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*                                                           *
*        256-POINT FFT KERNEL - STAGE 5                     *
*                                                           *
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*
         ZEROI     X000,X016,512
         BTRFLI    X001,X017,C008,S008,512
         BTRFLI    X002,X018,C016,S016,512
         BTRFLI    X003,X019,C024,S024,512
         PBY4I     X004,X020,512
         BTRFLI    X005,X021,C040,S040,512
         BTRFLI    X006,X022,C048,S048,512
         BTRFLI    X007,X023,C056,S056,512
         PBY2I     X008,X024,512
         BTRFLI    X009,X025,C072,S072,512
         BTRFLI    X010,X026,C080,S080,512
         BTRFLI    X011,X027,C088,S088,512
         P3BY4I    X012,X028,512
         BTRFLI    X013,X029,C104,S104,512
         BTRFLI    X014,X030,C112,S112,512
         BTRFLI    X015,X031,C120,S120,512
         ZEROI     X032,X048,512
         BTRFLI    X033,X049,C008,S008,512
         BTRFLI    X034,X050,C016,S016,512
         BTRFLI    X035,X051,C024,S024,512
         PBY4I     X036,X052,512
         BTRFLI    X037,X053,C040,S040,512
         BTRFLI    X038,X054,C048,S048,512
         BTRFLI    X039,X055,C056,S056,512
         PBY2I     X040,X056,512
         BTRFLI    X041,X057,C072,S072,512
         BTRFLI    X042,X058,C080,S080,512
         BTRFLI    X043,X059,C088,S088,512
         P3BY4I    X044,X060,512
         BTRFLI    X045,X061,C104,S104,512
         BTRFLI    X046,X062,C112,S112,512
         BTRFLI    X047,X063,C120,S120,512
         ZEROI     X064,X080,512
         BTRFLI    X065,X081,C008,S008,512
         BTRFLI    X066,X082,C016,S016,512
         BTRFLI    X067,X083,C024,S024,5_2
         PBY4I     X068,X084,512
         BTRFLI    X069,X085,C040,S040,512
         BTRFLI    X070,X086,C048,S048,512
         BTRFLI    X071,X087,C056,S056,512
         PBY2I     X072,X088,512
         BTRFLI    X073,X089,C072,S072,512
         BTRFLI    X074,X090,C080,S080,512
         BTRFLI    X075,X091,C088,S088,512
         P3BY4I    X076,X092,512
         BTRFLI    X077,X093,C104,S104,512
         BTRFLI    X078,X094,C112,S112,512
         BTRFLI    X079,X095,C120,S120,512
         ZEROI     X096,X112,512
         BTRFLI    X097,X113,C008,S008,512
         BTRFLI    X098,X114,C016,S016,512
         BTRFLI    X099,X115,C024,S024,512
         PBY4I     X100,X116,512
         BTRFLI    X101,X117,C040,S040,512
         BTRFLI    X102,X118,C048,S048,512
         BTRFLI    X103,X119,C056,S056,512
         PBY2I     X104,X120,512
         BTRFLI    X105,X121,C072,S072,512
         BTRFLI    X106,X122,C080,S080,512
         BTRFLI    X107,X123,C088,S088,512
         P3BY4I    X108,X124,512
         BTRFLI    X109,X125,C104,S104,512
         BTRFLI    X110,X126,C112,S112,512
         BTRFLI    X111,X127,C120,S120,512
         ZEROI     X128,X144,512
         BTRFLI    X129,X145,C008,S008,512
         BTRFLI    X130,X146,C016,S016,512
         BTRFLI    X131,X147,C024,S024,512
         PBY4I     X132,X148,512
         BTRFLI    X133,X149,C040,S040,512
         BTRFLI    X134,X150,C048,S048,512
         BTRFLI    X135,X151,C056,S056,512
         PBY2I     X136,X152,512
         BTRFLI    X137,X153,C072,S072,512
         BTRFLI    X138,X154,C080,S080,512
         BTRFLI    X139,X155,C088,S088,512
         P3BY4I    X140,X156,512
         BTRFLI    X141,X157,C104,S104,512
         BTRFLI    X142,X158,C112,S112,512
         BTRFLI    X143,X159,C120,S120,512
         ZEROI     X160,X176,512
         BTRFLI    X161,X177,C008,S008,512
         BTRFLI    X162,X178,C016,S016,512
         BTRFLI    X163,X179,C024,S024,512
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         PBY4I     X164,X180,512
         BTRFLI    X165,X181,C040,S040,512
         BTRFLI    X166,X182,C048,S048,512
         BTRFLI    X167,X183,C056,S056,512
         PBY2I     X168,X184,512
         BTRFLI    X169,X185,C072,S072,512
         BTRFLI    X170,X186,C080,S080,512
         BTRFLI    X171,X187,C088,S088,512
         P3BY4I    X172,X188,512
         BTRFLI    X173,X189,C104,S104,512
         BTRFLI    X174,X190,C112,S112,512
         BTRFLI    X175,X191,C120,S120,512
         ZEROI     X192,X208,512
         BTRFLI    X193,X209,C008,S008,512
         BTRFLI    X194,X210,C016,S016,512
         BTRFLI    X195,X211,C024,S024,512
         PBY4I     X196,X212,512
         BTRFLI    X197,X213,C040,S040,512
         BTRFLI    X198,X214,C048,S048,512
         BTRFLI    X199,X215,C056,S056,512
         PBY2I     X200,X216,512
         BTRFLI    X201,X217,C072,S072,512
         BTRFLI    X202,X218,C080,S080,512
         BTRFLI    X203,X219,C088,S088,512
         P3BY4I    X204,X220,512
         BTRFLI    X205,X221,C104,S104,512
         BTRFLI    X206,X222,C112,S112,512
         BTRFLI    X207,X223,C120,S120,512
         ZEROI     X224,X240,512
         BTRFLI    X225,X241,C008,S008,512
         BTRFLI    X226,X242,C016,S016,512
         BTRFLI    X227,X243,C024,S024,512
         PBY4I     X228,X244,512
         BTRFLI    X229,X245,C040,S040,512
         BTRFLI    X230,X246,C048,S048,512
         BTRFLI    X231,X247,C056,S056,512
         PBY2I     X232,X248,512
         BTRFLI    X233,X249,C072,S072,512
         BTRFLI    X234,X250,C080,S080,512
         BTRFLI    X235,X251,C088,S088,512
         P3BY4I    X236,X252,512
         BTRFLI    X237,X253,C104,S104,512
         BTRFLI    X238,X254,C112,S112,512
         BTRFLI    X239,X255,C120,S120,512
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*                                                           *
*        256-POINT FFT KERNEL - STAGE 6                     *
*                                                           *
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*
         ZEROI     X000,X032,512
         BTRFLI    X001,X033,C004,S004,512
         BTRFLI    X002,X034,C008,S008,512
         BTRFLI    X003,X035,C012,S012,512
         BTRFLI    X004,X036,C016,S016,512
         BTRFLI    X005,X037,C020,S020,512
         BTRFLI    X006,X038,C024,S024,512
         BTRFLI    X007,X039,C028,S028,512
         PBY4I     X008,X040,512
         BTRFLI    X009,X041,C036,S036,512
         BTRFLI    X010,X042,C040,S040,512
         BTRFLI    X011,X043,C044,S044,512
         BTRFLI    X012,X044,C048,S048,512
         BTRFLI    X013,X045,C052,S052,512
         BTRFLI    X014,X046,C056,S056,512
         BTRFLI    X015,X047,C060,S060,512
         PBY2I     X016,X048,512
         BTRFLI    X017,X049,C068,S068,512
         BTRFLI    X018,X050,C072,S072,512
         BTRFLI    X019,X051,C076,S076,512
         BTRFLI    X020,X052,C080,S080,512
         BTRFLI    X021,X053,C084,S084,512
         BTRFLI    X022,X054,C088,S088,512
         BTRFLI    X023,X055,C092,S092,512
         P3BY4I    X024,X056,512
         BTRFLI    X025,X057,C100,S100,512
         BTRFLI    X026,X058,C104,S104,512
         BTRFLI    X027,X059,C108,S108,512
         BTRFLI    X028,X060,C112,S112,512
         BTRFLI    X029,X061,C116,S116,512
         BTRFLI    X030,X062,C120,S120,512
         BTRFLI    X031,X063,C124,S124,512
         ZEROI     X064,X096,512
         BTRFLI    X065,X097,C004,S004,512
         BTRFLI    X066,X098,C008,S008,512
         BTRFLI    X067,X099,C012,S012,512
         BTRFLI    X068,X100,C016,S016,512
         BTRFLI    X069,X101,C020,S020,512
         BTRFLI    X070,X102,C024,S024,512
         BTRFLI    X071,X103,C028,S028,512
         PBY4I     X072,X104,512
         BTRFLI    X073,X105,C036,S036,512
         BTRFLI    X074,X106,C040,S040,512
         BTRFLI    X075,X107,C044,S044,512
         BTRFLI    X076,X108,C048,S048,512
         BTRFLI    X077,X109,C052,S052,512
         BTRFLI    X078,X110,C056,S056,512
         BTRFLI    X079,X111,C060,S060,512
         PBY2I     X080,X112,512
         BTRFLI    X081,X113,C068,S068,512
         BTRFLI    X082,X114,C072,S072,512
         BTRFLI    X083,X115,C076,S076,512
         BTRFLI    X084,X116,C080,S080,512
         BTRFLI    X085,X117,C084,S084,512
         BTRFLI    X086,X118,C088,S088,512
         BTRFLI    X087,X119,C092,S092,512
         P3BY4I    X088,X120,512
         BTRFLI    X089,X121,C100,S100,512
         BTRFLI    X090,X122,C104,S104,512
         BTRFLI    X091,X123,C108,S108,512
         BTRFLI    X092,X124,C112,S112,512
         BTRFLI    X093,X125,C116,S116,512
         BTRFLI    X094,X126,C120,S120,512
         BTRFLI    X095,X127,C124,S124,512
         ZEROI     X128,X160,512
         BTRFLI    X129,X161,C004,S004,512
         BTRFLI    X130,X162,C008,S008,512
         BTRFLI    X131,X163,C012,S012,512
         BTRFLI    X132,X164,C016,S016,512
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         BTRFLI    X133,X165,C020,S020,512
         BTRFLI    X134,X166,C024,S024,512
         BTRFLI    X135,X167,C028,S028,512
         PBY4I     X136,X168,512
         BTRFLI    X137,X169,C036,S036,512
         BTRFLI    X138,X170,C040,S040,512
         BTRFLI    X139,X171,C044,S044,512
         BTRFLI    X140,X172,C048,S048,512
         BTRFLI    X141,X173,C052,S052,512
         BTRFLI    X142,X174,C056,S056,512
         BTRFLI    X143,X175,C060,S060,512
         PBY2I     X144,X176,512
         BTRFLI    X145,X177,C068,S068,512
         BTRFLI    X146,X178,C072,S072,512
         BTRFLI    X147,X179,C076,S076,512
         BTRFLI    X148,X180,C080,S080,512
         BTRFLI    X149,X181,C084,S084,512
         BTRFLI    X150,X182,C088,S088,512
         BTRFLI    X151,X183,C092,S092,512
         P3BY4I    X152,X184,512
         BTRFLI    X153,X185,C100,S100,512
         BTRFLI    X154,X186,C104,S104,512
         BTRFLI    X155,X187,C108,S108,512
         BTRFLI    X156,X188,C112,S112,512
         BTRFLI    X157,X189,C116,S116,512
         BTRFLI    X158,X190,C120,S120,512
         BTRFLI    X159,X191,C124,S124,512
         ZEROI     X192,X224,512
         BTRFLI    X193,X225,C004,S004,512
         BTRFLI    X194,X226,C008,S008,512
         BTRFLI    X195,X227,C012,S012,512
         BTRFLI    X196,X228,C016,S016,512
         BTRFLI    X197,X229,C020,S020,512
         BTRFLI    X198,X230,C024,S024,512
         BTRFLI    X199,X231,C028,S028,512
         PBY4I     X200,X232,512
         BTRFLI    X201,X233,C036,S036,512
         BTRFLI    X202,X234,C040,S040,512
         BTRFLI    X203,X235,C044,S044,512
         BTRFLI    X204,X236,C048,S048,512
         BTRFLI    X205,X237,C052,S052,512
         BTRFLI    X206,X238,C056,S056,512
         BTRFLI    X207,X239,C060,S060,512
         PBY2I     X208,X240,512
         BTRFLI    X209,X241,C068,S068,512
         BTRFLI    X210,X242,C072,S072,512
         BTRFLI    X211,X243,C076,S076,512
         BTRFLI    X212,X244,C080,S080,512
         BTRFLI    X213,X245,C084,S084,512
         BTRFLI    X214,X246,C088,S088,512
         BTRFLI    X215,X247,C092,S092,512
         P3BY4I    X216,X248,512
         BTRFLI    X217,X249,C100,S100,512
         BTRFLI    X218,X250,C104,S104,512
         BTRFLI    X219,X251,C108,S108,512
         BTRFLI    X220,X252,C112,S112,512
         BTRFLI    X221,X253,C116,S116,512
         BTRFLI    X222,X254,C120,S120,512
         BTRFLI    X223,X255,C124,S124,512
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*                                                           *
*         256-POINT FFT KERNEL - STAGE 7                    *
*                                                           *
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*
         ZEROI     X000,X064,512
         BTRFLI    X001,X065,C002,S002,512
         BTRFLI    X002,X066,C004,S004,512
         BTRFLI    X003,X067,C006,S006,512
         BTRFLI    X004,X068,C008,S008,512
         BTRFLI    X005,X069,C010,S010,512
         BTRFLI    X006,X070,C012,S012,512
         BTRFLI    X007,X071,C014,S014,512
         BTRFLI    X008,X072,C016,S016,512
         BTRFLI    X009,X073,C018,S018,512
         BTRFLI    X010,X074,C020,S020,512
         BTRFLI    X011,X075,C022,S022,512
         BTRFLI    X012,X076,C024,S024,512
         BTRFLI    X013,X077,C026,S026,512
         BTRFLI    X014,X078,C028,S028,512
         BTRFLI    X015,X079,C030,S030,512
         PBY4I     X016,X080,512
         BTRFLI    X017,X081,C034,S034,512
         BTRFLI    X018,X082,C036,S036,512
         BTRFLI    X019,X083,C038,S038,512
         BTRFLI    X020,X084,C040,S040,512
         BTRFLI    X021,X085,C042,S042,512
         BTRFLI    X022,X086,C044,S044,512
         BTRFLI    X023,X087,C046,S046,512
         BTRFLI    X024,X088,C048,S048,512
         BTRFLI    X025,X089,C050,S050,512
         BTRFLI    X026,X090,C052,S052,512
         BTRFLI    X027,X091,C054,S054,512
         BTRFLI    X028,X092,C056,S056,512
         BTRFLI    X029,X093,C058,S058,512
         BTRFLI    X030,X094,C060,S060,512
         BTRFLI    X031,X095,C062,S062,512
         PBY2I     X032,X096,512
         BTRFLI    X033,X097,C066,S066,512
         BTRFLI    X034,X098,C068,S068,512
         BTRFLI    X035,X099,C070,S070,512
         BTRFLI    X036,X100,C072,S072,512
         BTRFLI    X037,X101,C074,S074,512
         BTRFLI    X038,X102,C076,S076,512
         BTRFLI    X039,X103,C078,S078,512
         BTRFLI    X040,X104,C080,S080,512
         BTRFLI    X041,X105,C082,S082,512
         BTRFLI    X042,X106,C084,S084,512
         BTRFLI    X043,X107,C086,S086,512
         BTRFLI    X044,X108,C088,S088,512
         BTRFLI    X045,X109,C090,S090,512
         BTRFLI    X046,X110,C092,S092,512
         BTRFLI    X047,X111,C094,S094,512
         P3BY4I    X048,X112,512
         BTRFLI    X049,X113,C098,S098,512
         BTRFLI    X050,X114,C100,S100,512
         BTRFLI    X051,X115,C102,S102,512
         BTRFLI    X052,X116,C104,S104,512
         BTRFLI    X053,X117,C106,S106,512
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         BTRFLI    X054,X118,C108,S108,512
         BTRFLI    X055,X119,C110,S110,512
         BTRFLI    X056,X120,C112,S112,512
         BTRFLI    X057,X121,C114,S114,512
         BTRFLI    X058,X122,C116,S116,512
         BTRFLI    X059,X123,C118,S118,512
         BTRFLI    X060,X124,C120,S120,512
         BTRFLI    X061,X125,C122,S122,512
         BTRFLI    X062,X126,C124,S124,512
         BTRFLI    X063,X127,C126,S126,512
         ZEROI     X128,X192,512
         BTRFLI    X129,X193,C002,S002,512
         BTRFLI    X130,X194,C004,S004,512
         BTRFLI    X131,X195,C006,S006,512
         BTRFLI    X132,X196,C008,S008,512
         BTRFLI    X133,X197,C010,S010,512
         BTRFLI    X134,X198,C012,S012,512
         BTRFLI    X135,X199,C014,S014,512
         BTRFLI    X136,X200,C016,S016,512
         BTRFLI    X137,X201,C018,S018,512
         BTRFLI    X138,X202,C020,S020,512
         BTRFLI    X139,X203,C022,S022,512
         BTRFLI    X140,X204,C024,S024,512
         BTRFLI    X141,X205,C026,S026,512
         BTRFLI    X142,X206,C028,S028,512
         BTRFLI    X143,X207,C030,S030,512
         PBY4I     X144,X208,512
         BTRFLI    X145,X209,C034,S034,512
         BTRFLI    X146,X210,C036,S036,512
         BTRFLI    X147,X211,C038,S038,512
         BTRFLI    X148,X212,C040,S040,512
         BTRFLI    X149,X213,C042,S042,512
         BTRFLI    X150,X214,C044,S044,512
         BTRFLI    X151,X215,C046,S046,512
         BTRFLI    X152,X216,C048,S048,512
         BTRFLI    X153,X217,C050,S050,512
         BTRFLI    X154,X218,C052,S052,512
         BTRFLI    X155,X219,C054,S054,512
         BTRFLI    X156,X220,C056,S056,512
         BTRFLI    X157,X221,C058,S058,512
         BTRFLI    X158,X222,C060,S060,512
         BTRFLI    X159,X223,C062,S062,512
         PBY2I     X160,X224,512
         BTRFLI    X161,X225,C066,S066,512
         BTRFLI    X162,X226,C068,S068,512
         BTRFLI    X163,X227,C070,S070,512
         BTRFLI    X164,X228,C072,S072,512
         BTRFLI    X165,X229,C074,S074,512
         BTRFLI    X166,X230,C076,S076,512
         BTRFLI    X167,X231,C078,S078,512
         BTRFLI    X168,X232,C080,S080,512
         BTRFLI    X169,X233,C082,S082,512
         BTRFLI    X170,X234,C084,S084,512
         BTRFLI    X171,X235,C086,S086,512
         BTRFLI    X172,X236,C088,S088,512
         BTRFLI    X173,X237,C090,S090,512
         BTRFLI    X174,X238,C092,S092,512
         BTRFLI    X175,X239,C094,S094,512
         P3BY4I    X176,X240,512
         BTRFLI    X177,X241,C098,S098,512
         BTRFLI    X178,X242,C100,S100,512
         BTRFLI    X179,X243,C102,S102,512
         BTRFLI    X180,X244,C104,S104,512
         BTRFLI    X181,X245,C106,S106,512
         BTRFLI    X182,X246,C108,S108,512
         BTRFLI    X183,X247,C110,S110,512
         BTRFLI    X184,X248,C112,S112,512
         BTRFLI    X185,X249,C114,S114,512
         BTRFLI    X186,X250,C116,S116,512
         BTRFLI    X187,X251,C118,S118,512
         BTRFLI    X188,X252,C120,S120,512
         BTRFLI    X189,X253,C122,S122,512
         BTRFLI    X190,X254,C124,S124,512
         BTRFLI    X191,X255,C126,S126,512
*
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*                                                           *
*        256-POINT FFT KERNEL - STAGE 8                     *
*                                                           *
*************************************************************
*
         ZEROI     X000,X128,512
         BTRFLI    X001,X129,C001,S001,512
         BTRFLI    X002,X130,C002,S002,512
         BTRFLI    X003,X131,C003,S003,512
         BTRFLI    X004,X132,C004,S004,512
         BTRFLI    X005,X133,C005,S005,512
         BTRFLI    X006,X134,C006,S006,512
         BTRFLI    X007,X135,C007,S007,512
         BTRFLI    X008,X136,C008,S008,512
         BTRFLI    X009,X137,C009,S009,512
         BTRFLI    X010,X138,C010,S010,512
         BTRFLI    X011,X139,C011,S011,512
         BTRFLI    X012,X140,C012,S012,512
         BTRFLI    X013,X141,C013,S013,512
         BTRFLI    X014,X142,C014,S014,512
         BTRFLI    X015,X143,C015,S015,512
         BTRFLI    X016,X144,C016,S016,512
         BTRFLI    X017,X145,C017,S017,512
         BTRFLI    X018,X146,C018,S018,512
         BTRFLI    X019,X147,C019,S019,512
         BTRFLI    X020,X148,C020,S020,512
         BTRFLI    X021,X149,C021,S021,512
         BTRFLI    X022,X150,C022,S022,512
         BTRFLI    X023,X151,C023,S023,512
         BTRFLI    X024,X152,C024,S024,512
         BTRFLI    X025,X153,C025,S025,512
         BTRFLI    X026,X154,C026,S026,512
         BTRFLI    X027,X155,C027,S027,512
         BTRFLI    X028,X156,C028,S028,512
         BTRFLI    X029,X157,C029,S029,512
         BTRFLI    X030,X158,C030,S030,512
         BTRFLI    X031,X159,C031,S031,512
         PBY4I     X032,X160,512
         BTRFLI    X033,X161,C033,S033,512
         BTRFLI    X034,X162,C034,S034,512
         BTRFLI    X035,X163,C035,S035,512
         BTRFLI    X036,X164,C036,S036,512
         BTRFLI    X037,X165,C037,S037,512
         BTRFLI    X038,X166,C038,S038,512
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         BTRFLI   X039,X167,C039,S039,512
         BTRFLI   X040,X168,C040,S040,512
         BTRFLI   X041,X169,C041,S041,512
         BTRFLI   X042,X170,C042,S042,512
         BTRFLI   X043,X171,C043,S043,512
         BTRFLI   X044,X172,C044,S044,512
         BTRFLI   X045,X173,C045,S045,512
         BTRFLI   X046,X174,C046,S046,512
         BTRFLI   X047,X175,C047,S047,512
         BTRFLI   X048,X176,C048,S048,512
         BTRFLI   X049,X177,C049,S049,512
         BTRFLI   X050,X178,C050,S050,512
         BTRFLI   X051,X179,C051,S051,512
         BTRFLI   X052,X180,C052,S052,512
         BTRFLI   X053,X181,C053,S053,512
         BTRFLI   X054,X182,C054,S054,512
         BTRFLI   X055,X183,C055,S055,512
         BTRFLI   X056,X184,C056,S056,512
         BTRFLI   X057,X185,C057,S057,512
         BTRFLI   X058,X186,C058,S058,512
         BTRFLI   X059,X187,C059,S059,512
         BTRFLI   X060,X188,C060,S060,512
         BTRFLI   X061,X189,C061,S061,512
         BTRFLI   X062,X190,C062,S062,512
         BTRFLI   X063,X191,C063,S063,512
         PBY2I    X064,X192,512
         BTRFLI   X065,X193,C065,S065,512
         BTRFLI   X066,X194,C066,S066,512
         BTRFLI   X067,X195,C067,S067,512
         BTRFLI   X068,X196,C068,S068,512
         BTRFLI   X069,X197,C069,S069,512
         BTRFLI   X070,X198,C070,S070,512
         BTRFLI   X071,X199,C071,S071,512
         BTRFLI   X072,X200,C072,S072,512
         BTRFLI   X073,X201,C073,S073,512
         BTRFLI   X074,X202,C074,S074,512
         BTRFLI   X075,X203,C075,S075,512
         BTRFLI   X076,X204,C076,S076,512
         BTRFLI   X077,X205,C077,S077,512
         BTRFLI   X078,X206,C078,S078,512
         BTRFLI   X079,X207,C079,S079,512
         BTRFLI   X080,X208,C080,S080,512
         BTRFLI   X081,X209,C081,S081,512
         BTRFLI   X082,X210,C082,S082,512
         BTRFLI   X083,X211,C083,S083,512
         BTRFLI   X084,X212,C084,S084,512
         BTRFLI   X085,X213,C085,S085,512
         BTRFLI   X086,X214,C086,S086,512
         BTRFLI   X087,X215,C087,S087,512
         BTRFLI   X088,X216,C088,S088,512
         BTRFLI   X089,X217,C089,S089,512
         BTRFLI   X090,X218,C090,S090,512
         BTRFLI   X091,X219,C091,S091,512
         BTRFLI   X092,X220,C092,S092,512
         BTRFLI   X093,X221,C093,S093,512
         BTRFLI   X094,X222,C094,S094,512
         BTRFLI   X095,X223,C095,S095,512
         P3BY4I   X096,X224,512
         BTRFLI   X097,X225,C097,S097,512
         BTRFLI   X098,X226,C098,S098,512
         BTRFLI   X099,X227,C099,S099,512
         BTRFLI   X100,X228,C100,S100,512
         BTRFLI   X101,X229,C101,S101,512
         BTRFLI   X102,X230,C102,S102,512
         BTRFLI   X103,X231,C103,S103,512
         BTRFLI   X104,X232,C104,S104,512
         BTRFLI   X105,X233,C105,S105,512
         BTRFLI   X106,X234,C106,S106,512
         BTRFLI   X107,X235,C107,S107,512
         BTRFLI   X108,X236,C108,S108,512
         BTRFLI   X109,X237,C109,S109,512
         BTRFLI   X110,X238,C110,S110,512
         BTRFLI   X111,X239,C111,S111,512
         BTRFLI   X112,X240,C112,S112,512
         BTRFLI   X113,X241,C113,S113,512
         BTRFLI   X114,X242,C114,S114,512
         BTRFLI   X115,X243,C115,S115,512
         BTRFLI   X116,X244,C116,S116,512
         BTRFLI   X117,X245,C117,S117,512
         BTRFLI   X118,X246,C118,S118,512
         BTRFLI   X119,X247,C119,S119,512
         BTRFLI   X120,X248,C120,S120,512
         BTRFLI   X121,X249,C121,S121,512
         BTRFLI   X122,X250,C122,S122,512
         BTRFLI   X123,X251,C123,S123,512
         BTRFLI   X124,X252,C124,S124,512
         BTRFLI   X125,X253,C125,S125,512
         BTRFLI   X126,X254,C126,S126,512
         BTRFLI   X127,X255,C127,S127,512
         RET
*
************************************************************
*                                                          *
*   1024-POINT FFT CODE WITH BIT-REVERSED INPUT SAMPLES    *
*                                                          *
*   ALL INPUT REAL AND IMAGINARY DATA POINTS ARE ASSUMED   *
*   TO BE IN CONSECUTIVE LOCATIONS (A TOTAL OF 2048 ) IN   *
*   EXTERNAL DATA MEMORY STARTING FROM LOCATION 1024 IN    *
*   PAGE 8.  OUT OF THE 1024 COMPLEX POINTS, THERE ARE     *
*   ALTOGETHER 496 PAIRS OF INPUT DATA WHICH NEED TO BE    *
*   SCRAMBLED AS SHOWN BELOW.                              *
*                                                          *
************************************************************
*
FT1024   BITRVI   2,1024,1024
         BITRVI   4,512,1024
         BITRVI   6,1536,1024
         BITRVI   8,256,1024
         BITRVI   10,1280,1024
         BITRVI   12,768,1024
         BITRVI   14,1792,1024
         BITRVI   16,128,1024
         BITRVI   18,1152,1024
         BITRVI   20,640,1024
         BITRVI   22,1664,1024
         BITRVI   24,384,1024
         BITRVI   26,1408,1024
         BITRVI   28,896,1024
         BITRVI   30,1920,1024
         BITRVI   32,64,1024
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BITRVI    34,1088,1024
BITRVI    36,576,1024
BITRVI    38,1600,1024
BITRVI    40,320,1024
BITRVI    42,1344,1024
BITRVI    44,832,1024
BITRVI    46,1856,1024
BITRVI    48,192,1024
BITRVI    50,1216,1024
BITRVI    52,704,1024
BITRVI    54,1728,1024
BITRVI    56,448,1024
BITRVI    58,1472,1024
BITRVI    60,960,1024
BITRVI    62,1984,1024
BITRVI    66,1056,1024
BITRVI    68,544,1024
BITRVI    70,1568,1024
BITRVI    72,288,1024
BITRVI    74,1312,1024
BITRVI    76,800,1024
BITRVI    78,1824,1024
BITRVI    80,160,1024
BITRVI    82,1184,1024
BITRVI    84,672,1024
BITRVI    86,1696,1024
BITRVI    88,416,1024
BITRVI    90,1440,1024
BITRVI    92,928,1024
BITRVI    94,1952,1024
BITRVI    98,1120,1024
BITRVI    100,608,1024
BITRVI    102,1632,1024
BITRVI    104,352,1024
BITRVI    106,1376,1024
BITRVI    108,864,1024
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BITRVI    112,224,1024
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BITRVI    118,1760,1024
BITRVI    120,480,1024
BITRVI    122,1504,1024
BITRVI    124,992,1024
BITRVI    126,2016,1024
BITRVI    130,1040,1024
BITRVI    132,528,1024
BITRVI    134,1552,1024
BITRVI    136,272,1024
BITRVI    138,1296,1024
BITRVI    140,784,1024
BITRVI    142,1808,1024
BITRVI    146,1168,1024
BITRVI    148,656,1024
BITRVI    150,1680,1024
BITRVI    152,400,1024
BITRVI    154,1424,1024
BITRVI    156,912,1024
BITRVI    158,1936,1024
BITRVI    162,1104,1024
BITRVI    164,592,1024
BITRVI    166,1616,1024
BITRVI    168,336,1024
BITRVI    170,1360,1024
BITRVI    172,848,1024
BITRVI    174,1872,1024
BITRVI    176,208,1024
BITRVI    178,1232,1024
BITRVI    180,720,1024
BITRVI    182,1744,1024
BITRVI    184,464,1024
BITRVI    186,1488,1024
BITRVI    188,976,1024
BITRVI    190,2000,1024
BITRVI    194,1072,1024
BITRVI    196,560,1024
BITRVI    198,1584,1024
BITRVI    200,304,1024
BITRVI    202,1328,1024
BITRVI    204,816,1024
BITRVI    206,1840,1024
BITRVI    210,1200,1024
BITRVI    212,688,1024
BITRVI    214,1712,1024
BITRVI    216,432,1024
BITRVI    218,1456,1024
BITRVI    220,944,1024
BITRVI    222,1968,1024
BITRVI    226,1136,1024
BITRVI    228,624,1024
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BITRVI    232,368,1024
BITRVI    234,1392,1024
BITRVI    236,880,1024
BITRVI    238,1904,1024
BITRVI    242,1264,1024
BITRVI    244,752,1024
BITRVI    246,1776,1024
BITRVI    248,496,1024
BITRVI    250,1520,1024
BITRVI    252,1008,1024
BITRVI    254,2032,1024
BITRVI    258,1032,1024
BITRVI    260,520,1024
BITRVI    262,1544,1024
BITRVI    266,1288,1024
BITRVI    268,776,1024
BITRVI    270,1800,1024
BITRVI    274,1160,1024
BITRVI    276,648,1024
BITRVI    278,1672,1024
BITRVI    280,392,1024
BITRVI    282,1416,1024
BITRVI    284,904,1024
BITRVI    286,1928,1024
BITRVI    290,1096,1024
BITRVI    292,584,1024
BITRVI    294,1608,1024
BITRVI    296,328,1024
BITRVI    298,1352,1024
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BITRVI    300,840,1024
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BITRVI    306,1224,1024
BITRVI    308,712,1024
BITRVI    310,1736,1024
BITRVI    312,456,1024
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BITRVI    318,1992,1024
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BITRVI    332,808,1024
BITRVI    334,1832,1024
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BITRVI    340,680,1024
BITRVI    342,1704,1024
BITRVI    344,424,1024
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BITRVI    350,1960,1024
BITRVI    354,1128,1024
BITRVI    356,616,1024
BITRVI    358,1640,1024
BITRVI    362,1384,1024
BITRVI    364,872,1024
BITRVI    366,1896,1024
BITRVI    370,1256,1024
BITRVI    372,744,1024
BITRVI    374,1768,1024
BITRVI    376,488,1024
BITRVI    378,1512,1024
BITRVI    380,1000,1024
BITRVI    382,2024,1024
BITRVI    386,1048,1024
BITRVI    388,536,1024
BITRVI    390,1560,1024
BITRVI    394,1304,1024
BITRVI    396,792,1024
BITRVI    398,1816,1024
BITRVI    402,1176,1024
BITRVI    404,664,1024
BITRVI    406,1688,1024
BITRVI    410,1432,1024
BITRVI    412,920,1024
BITRVI    414,1944,1024
BITRVI    418,1112,1024
BITRVI    420,600,1024
BITRVI    422,1624,1024
BITRVI    426,1368,1024
BITRVI    428,856,1024
BITRVI    430,1880,1024
BITRVI    434,1240,1024
BITRVI    436,728,1024
BITRVI    438,1752,1024
BITRVI    440,472,1024
BITRVI    442,1496,1024
BITRVI    444,984,1024
BITRVI    446,2008,1024
BITRVI    450,1080,1024
BITRVI    452,568,1024
BITRVI    454,1592,1024
BITRVI    458,1336,1024
BITRVI    460,824,1024
BITRVI    462,1848,1024
BITRVI    466,1208,1024
BITRVI    468,696,1024
BITRVI    470,1720,1024
BITRVI    474,1464,1024
BITRVI    476,952,1024
BITRVI    478,1976,1024
BITRVI    482,1144,1024
BITRVI    484,632,1024
BITRVI    486,1656,1024
BITRVI    490,1400,1024
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BITRVI    570,1476,1024
BITRVI    572,964,1024
BITRVI    574,1988,1024
BITRVI    578,1060,1024
BITRVI    582,1572,1024
BITRVI    586,1316,1024
BITRVI    588,804,1024
BITRVI    590,1828,1024
BITRVI    594,1188,1024
BITRVI    596,676,1024
BITRVI    598,1700,1024
BITRVI    602,1444,1024
BITRVI    604,932,1024
BITRVI    606,1956,1024
BITRVI    610,1124,1024
BITRVI    614,1636,1024
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BITRVI    618,1380,1024
BITRVI    620,868,1024
BITRVI    622,1892,1024
BITRVI    626,1252,1024
BITRVI    628,740,1024
BITRVI    630,1764,1024
BITRVI    634,1508,1024
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BITRVI    638,2020,1024
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BITRVI    654,1812,1024
BITRVI    658,1172,1024
BITRVI    662,1684,1024
BITRVI    666,1428,1024
BITRVI    668,916,1024
BITRVI    670,1940,1024
BITRVI    674,1108,1024
BITRVI    678,1620,1024
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BITRVI    684,852,1024
BITRVI    686,1876,1024
BITRVI    690,1236,1024
BITRVI    692,724,1024
BITRVI    694,1748,1024
BITRVI    698,1492,1024
BITRVI    700,980,1024
BITRVI    702,2004,1024
BITRVI    706,1076,1024
BITRVI    710,1588,1024
BITRVI    714,1332,1024
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BITRVI    726,1716,1024
BITRVI    730,1460,1024
BITRVI    732,948,1024
BITRVI    734,1972,1024
BITRVI    738,1140,1024
BITRVI    742,1652,1024
BITRVI    746,1396,1024
BITRVI    748,884,1024
BITRVI    750,1908,1024
BITRVI    754,1268,1024
BITRVI    758,1780,1024
BITRVI    762,1524,1024
BITRVI    764,1012,1024
BITRVI    766,2036,1024
BITRVI    770,1036,1024
BITRVI    774,1548,1024
BITRVI    778,1292,1024
BITRVI    782,1804,1024
BITRVI    786,1164,1024
BITRVI    790,1676,1024
BITRVI    794,1420,1024
BITRVI    796,908,1024
BITRVI    798,1932,1024
BITRVI    802,1100,1024
BITRVI    806,1612,1024
BITRVI    810,1356,1024
BITRVI    812,844,1024
BITRVI    814,1868,1024
BITRVI    818,1228,1024
BITRVI    822,1740,1024
BITRVI    826,1484,1024
BITRVI    828,972,1024
BITRVI    830,1996,1024
BITRVI    834,1068,1024
BITRVI    838,1580,1024
BITRVI    842,1324,1024
BITRVI    846,1836,1024
BITRVI    850,1196,1024
BITRVI    854,1708,1024
BITRVI    858,1452,1024
BITRVI    860,940,1024
BITRVI    862,1964,1024
BITRVI    866,1132,1024
BITRVI    870,1644,1024
BITRVI    874,1388,1024
BITRVI    878,1900,1024
BITRVI    882,1260,1024
BITRVI    886,1772,1024
BITRVI    890,1516,1024
BITRVI    892,1004,1024
BITRVI    894,2028,1024
BITRVI    898,1052,1024
BITRVI    902,1564,1024
BITRVI    906,1308,1024
BITRVI    910,1820,1024
BITRVI    914,1180,1024
BITRVI    918,1692,1024
BITRVI    922,1436,1024
BITRVI    926,1948,1024
BITRVI    930,1116,1024
BITRVI    934,1628,1024
BITRVI    938,1372,1024
BITRVI    942,1884,1024
BITRVI    946,1244,1024
BITRVI    950,1756,1024
BITRVI    954,1500,1024
BITRVI    956,988,1024
BITRVI    958,2012,1024
BITRVI    962,1084,1024
BITRVI    966,1596,1024
BITRVI    970,1340,1024
BITRVI    974,1852,1024
BITRVI    978,1212,1024
BITRVI    982,1724,1024
BITRVI    986,1468,1024
BITRVI    990,1980,1024
BITRVI    994,1148,1024
BITRVI    998,1660,1024
BITRVI    1002,1404,1024
BITRVI    1006,1916,1024
BITRVI    1010,1276,1024
BITRVI    1014,1788,1024
BITRVI    1018,1532,1024
BITRVI    1022,2044,1024
```

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BITRVI    1030,1538,1024
BITRVI    1034,1282,1024
BITRVI    1038,1794,1024
BITRVI    1042,1154,1024
BITRVI    1046,1666,1024
BITRVI    1050,1410,1024
BITRVI    1054,1922,1024
BITRVI    1058,1090,1024
BITRVI    1062,1602,1024
BITRVI    1066,1346,1024
BITRVI    1070,1858,1024
BITRVI    1074,1218,1024
BITRVI    1078,1730,1024
BITRVI    1082,1474,1024
BITRVI    1086,1986,1024
BITRVI    1094,1570,1024
BITRVI    1098,1314,1024
BITRVI    1102,1826,1024
BITRVI    1106,1186,1024
BITRVI    1110,1698,1024
BITRVI    1114,1442,1024
BITRVI    1118,1954,1024
BITRVI    1126,1634,1024
BITRVI    1130,1378,1024
BITRVI    1134,1890,1024
BITRVI    1138,1250,1024
BITRVI    1142,1762,1024
BITRVI    1146,1506,1024
BITRVI    1150,2018,1024
BITRVI    1158,1554,1024
BITRVI    1162,1298,1024
BITRVI    1166,1810,1024
BITRVI    1174,1682,1024
BITRVI    1178,1426,1024
BITRVI    1182,1938,1024
BITRVI    1190,1618,1024
BITRVI    1194,1362,1024
BITRVI    1198,1874,1024
BITRVI    1202,1234,1024
BITRVI    1206,1746,1024
BITRVI    1210,1490,1024
BITRVI    1214,2002,1024
BITRVI    1222,1586,1024
BITRVI    1226,1330,1024
BITRVI    1230,1842,1024
BITRVI    1238,1714,1024
BITRVI    1242,1458,1024
BITRVI    1246,1970,1024
BITRVI    1254,1650,1024
BITRVI    1258,1394,1024
BITRVI    1262,1906,1024
BITRVI    1270,1778,1024
BITRVI    1274,1522,1024
BITRVI    1278,2034,1024
BITRVI    1286,1546,1024
BITRVI    1294,1802,1024
BITRVI    1302,1674,1024
BITRVI    1306,1418,1024
BITRVI    1310,1930,1024
BITRVI    1318,1610,1024
BITRVI    1322,1354,1024
BITRVI    1326,1866,1024
BITRVI    1334,1738,1024
BITRVI    1338,1482,1024
BITRVI    1342,1994,1024
BITRVI    1350,1578,1024
BITRVI    1358,1834,1024
BITRVI    1366,1706,1024
BITRVI    1370,1450,1024
BITRVI    1374,1962,1024
BITRVI    1382,1642,1024
BITRVI    1390,1898,1024
BITRVI    1398,1770,1024
BITRVI    1402,1514,1024
BITRVI    1406,2026,1024
BITRVI    1414,1562,1024
BITRVI    1422,1818,1024
BITRVI    1430,1690,1024
BITRVI    1438,1946,1024
BITRVI    1446,1626,1024
BITRVI    1454,1882,1024
BITRVI    1462,1754,1024
BITRVI    1466,1498,1024
BITRVI    1470,2010,1024
BITRVI    1478,1594,1024
BITRVI    1486,1850,1024
BITRVI    1494,1722,1024
BITRVI    1502,1978,1024
BITRVI    1510,1658,1024
BITRVI    1518,1914,1024
BITRVI    1526,1786,1024
BITRVI    1534,2042,1024
BITRVI    1550,1798,1024
BITRVI    1558,1670,1024
BITRVI    1566,1926,1024
BITRVI    1574,1606,1024
BITRVI    1582,1862,1024
BITRVI    1590,1734,1024
BITRVI    1598,1990,1024
BITRVI    1614,1830,1024
BITRVI    1622,1702,1024
BITRVI    1630,1958,1024
BITRVI    1646,1894,1024
BITRVI    1654,1766,1024
BITRVI    1662,2022,1024
BITRVI    1678,1814,1024
BITRVI    1694,1942,1024
BITRVI    1710,1878,1024
BITRVI    1718,1750,1024
BITRVI    1726,2006,1024
BITRVI    1742,1846,1024
BITRVI    1758,1974,1024
BITRVI    1774,1910,1024
BITRVI    1790,2038,1024
BITRVI    1822,1934,1024
BITRVI    1838,1870,1024
BITRVI    1854,1998,1024
BITRVI    1886,1966,1024
BITRVI    1918,2030,1024
BITRVI    1982,2014,1024
```

```
*
***************************************************************
*                                                             *
*   THE FIRST 8 STAGES OF THE 10-STAGE 1024-POINT COMPLEX     *
*   FFT WILL BE PERFORMED AS 4 SEPARATE 256-POINT COMPLEX     *
*   FFT'S USING THE ON-CHIP DATA BLOCKS B0 AND B1.  THE       *
*   KERNEL CODE BELOW WILL THEREFORE BE CALLED 4 TIMES TO     *
*   ACCOMPLISH THIS WHILE EXTERNAL DATA MEMORY WILL HAVE      *
*   MOVE ON-CHIP USING THE BLKD INSTRUCTION.                  *
*                                                             *
***************************************************************
*
        LARP    AR1             BLOCK MOVE FIRST GROUP OF 256
        LRLK    AR1,512         COMPLEX POINTS (1024-1535) FROM
        RPTK    255             EXTERNAL RAM TO ON-CHIP RAM
        BLKD    1024,*+
        RPTK    255
        BLKD    1280,*+
        CALL    KNL256          EXECUTE 256-POINT KERNEL FFT
        LRLK    AR1,1024        AND RETURN RESULTS TO
        RPTK    255             EXTERNAL RAM (1024-1535)
        BLKD    512,*+
        RPTK    255
        BLKD    768,*+
*
        LRLK    AR1,512         BLOCK MOVE SECOND GROUP OF 256
        RPTK    255             COMPLEX POINTS (1536-2047) FROM
        BLKD    1536,*+         EXTERNAL RAM TO ON-CHIP RAM
        RPTK    255
        BLKD    1792,*+
        CALL    KNL256          EXECUTE 256-POINT KERNEL FFT
        LRLK    AR1,1536        AND RETURN RESULTS TO
        RPTK    255             EXTERNAL RAM (1536-2047)
        BLKD    512,*+
        RPTK    255
        BLKD    768,*+
*
        LRLK    AR1,512         BLOCK MOVE THIRD GROUP OF 256
        RPTK    255             COMPLEX POINTS (2048-2559) FROM
        BLKD    2048,*+         EXTERNAL RAM TO ON-CHIP RAM
        RPTK    255
        BLKD    2304,*+
        CALL    KNL256          EXECUTE 256-POINT KERNEL FFT
        LRLK    AR1,2048        AND RETURN RESULTS TO
        RPTK    255             EXTERNAL RAM (2048-2559)
        BLKD    512,*+
        RPTK    255
        BLKD    768,*+
*
        LRLK    AR1,512         BLOCK MOVE FOURTH GROUP OF 256
        RPTK    255             COMPLEX POINTS (2560-3071) FROM
        BLKD    2560,*+         EXTERNAL RAM TO ON-CHIP RAM
        RPTK    255
        BLKD    2816,*+
        CALL    KNL256          EXECUTE 256-POINT KERNEL FFT
        LRLK    AR1,2560        AND RETURN RESULTS TO
        RPTK    255             EXTERNAL RAM (2560-3071)
        BLKD    512,*+
        RPTK    255
        BLKD    768,*+
```

```
*
***************************************************************
*                                                             *
*   PERFORM STAGE 9 OF THE 1024-POINT FFT -- TWIDDLE          *
*   FACTOR VALUES ARE TABLE-READ FROM EXTERNAL PROGRAM        *
*   MEMORY TO ON-CHIP RAM AND THE GENERAL 'BUTTERFLY'         *
*   SUBROUTINE IS EXECUTED 512 TIMES WITH ALL DATA IN         *
*   EXTERNAL DATA MEMORY.  A SPEED IMPROVEMENT CAN BE         *
*   ACHIEVED BY MOVING FFT DATA ON-CHIP INSTEAD OF TWIDDLE    *
*   FACTOR VALUES FOR EXECUTION.  HOWEVER, THE TWIDDLE        *
*   FACTOR VALUES WILL HAVE TO BE STORED IN EXTERNAL DATA     *
*   RAM.                                                      *
*                                                             *
***************************************************************
*
STAGE9  LRLK    AR0,512         INITIALISE TWIDDLE FACTORS
        LRLK    AR1,255         SET UP TWIDDLE TABLE SIZE
        LARP    AR0             USE AR0 TO POINT AT TABLE
        LALK    W000            SET UP TWIDDLE TABLE ADDRESS
LOOP    TBLR    *+              AND STORE IN INTERNAL RAM
        ADLK    1
        TBLR    *+,AR1          AND STORE IN INTERNAL RAM
        ADLK    3
        BANZ    LOOP,*-,AR0
*
        LRLK    AR0,512         INITIALISE STEP SIZE
        LRLK    AR1,512         AR1 POINTS AT TWIDDLE FACTORS
        LRLK    AR2,1024+512    AR2 POINTS AT REAL DATA
        LRLK    AR3,255         INITIALISE LOOP COUNT
        LARP    AR2
LOOP1   CALL    BTRFLY          PERFORM LOOPED FFT FOR STAGE 9
        LARP    AR3
        BANZ    LOOP1,*-,AR2
*
        LRLK    AR1,512         AR1 POINTS AT TWIDDLE FACTORS
        LRLK    AR2,2048+512    AR2 POINTS AT REAL DATA
        LRLK    AR3,255         INITIALISE LOOP COUNT
        LARP    AR2
LOOP2   CALL    BTRFLY          PERFORM LOOPED FFT FOR STAGE 9
        LARP    AR3
        BANZ    LOOP2,*-,AR2
*
***************************************************************
*                                                             *
*   PERFORM STAGE 10 OF THE 1024-POINT FFT -- TWIDDLE         *
*   FACTOR VALUES ARE TABLE-READ FROM EXTERNAL PROGRAM        *
*   MEMORY TO ON-CHIP RAM AND THE GENERAL 'BUTTERFLY'         *
*   SUBROUTINE IS EXECUTED 512 TIMES WITH ALL DATA IN         *
*   EXTERNAL DATA MEMORY.  A SPEED IMPROVEMENT CAN BE         *
*   ACHIEVED BY MOVING FFT DATA ON-CHIP INSTEAD OF TWIDDLE    *
*   FACTOR VALUES FOR EXECUTION.  HOWEVER, THE TWIDDLE        *
*   FACTOR VALUES WILL HAVE TO BE STORED IN EXTERNAL DATA     *
*   RAM.                                                      *
*                                                             *
***************************************************************
*
STGE10  LARP  . AR0
        LRLK    AR0,512         INITIALISE TWIDDLE FACTORS
        RPTK    255             AND STORE IN INTERNAL RAM.
        BLKP    W000,*+
```

```
         RPTK      255
         BLKP      W128,*+
*
         LARP      AR0
         LRLK      AR0,1024       INITIALISE STEP SIZE
         LRLK      AR1,512        AR1 POINTS AT TWIDDLE FACTORS
         LRLK      AR2,2048       AR2 POINTS AT REAL DATA
         LRLK      AR3,255        INITIALISE LOOP COUNT
         LARP      AR2
LOOP3    CALL      BTRFLY         PERFORM LOOPED FFT FOR STAGE 10
         LARP      AR3
         BANZ      LOOP3,*-,AR2
*
         LARP      AR0
         LRLK      AR0,512        INITIALISE TWIDDLE FACTORS
         RPTK      255            AND STORE IN INTERNAL RAM.
         BLKP      W256,*+
         RPTK      255
         BLKP      W384,*+
*
         LARP      AR0
         LRLK      AR0,1024       INITIALISE STEP SIZE
         LRLK      AR1,512        AR1 POINTS AT TWIDDLE FACTORS
         LRLK      AR2,2048+512   AR2 POINTS AT REAL DATA
         LRLK      AR3,255        INITIALISE LOOP COUNT
         LARP      AR2
LOOP4    CALL      BTRFLY         PERFORM LOOPED FFT FOR STAGE 10
         LARP      AR3
         BANZ      LOOP4,*-,AR2
         B         DONE
*
*************************************************************
*                                                           *
*        RADIX-2 GENERAL BUTTERFLY SUBROUTINE               *
*                                                           *
*                                                           *
*       P=(PR+jQI)   P+Q*W=(PR+Re[Q*W])+j(PI+Im[Q*W])       *
*                 \ /                                       *
*                 / \                                       *
*       Q=(QR+jQI)   P-Q*W=(PR-Re[Q*W])+j(PI+Im[Q*W])       *
*                                                           *
*           -j(2(pi)/N)k                                       *
*       W =e          =COS(X)-jSIN(X)                       *
*        N                                                  *
*                     =WR+jWI                               *
*                                                           *
*************************************************************
*
*      CALCULATE QR*COS(X) + QI*SIN(X) AND STORE RESULT IN QR
*
BTRFLY LT   *+,AR1      LOAD T-REGISTER WITH QR
       MPY  *+,AR2      P-REGISTER = (1/2)(QR*COSX)
       LTP  *-,AR1      ACC= (1/2)(QR*COSX); LOAD TR WITH QI
       MPY  *-          P-REGISTER = (1/2)(QI*SINX)
       APAC             ACC= (1/2)(QR*COSX+QI*SINX)
       MPY  *+,AR2      P-REGISTER = (1/2)(QI*COSX)
       LT   *           LOAD T-REGISTER WITH QR
       SACH *+,0,AR1    QR = (1/2)(QR*COSX+QI*SINX)
*
*      CALCULATE QI*COS(X) - QR*SIN(X) AND STORE RESULT IN QI
*
       PAC              ACC= (1/2)(QI*COSX)
       MPY  *+,AR2      P-REGISTER = (1/2)(QR*SINX)
       SPAC             ACC= (1/2)(QI*COSX-QR*SINX)
       SACH *0-         QI = (1/2)(QI*COSX-QR*SINX)
*
*      CALCULATE Re[Pm+1] & Re[Qm+1] STORE RESULTS in PR & QR
*
       MAR  *-
       LAC  *0+,14      ACC= (1/4)PR
       ADD  *0-,15      ACC= (1/4)[PR+(QR*COSX+QI*SINX)]
       SACH *0+,1       PR = (1/2)[PR+(QR*COSX+QI*SINX)]
       SUBH *           ACC= (1/4)[PR-(QR*COSX+QI*SINX)]
       SACH *0-,1       QR = (1/2)[PR-(QR*COSX+QI*SINX)]
*
*      CALCULATE Im[Pm+1] & Im[Qm+1] STORE RESULTS in PI & QI
*
       MAR  *+
       LAC  *0+,14      ACC= (1/4)PI
       ADD  *0-,15      ACC= (1/4)[PI+(QI*COSX-QR*SINX)]
       SACH *0+,1       PI = (1/2)[PI+(QI*COSX-QR*SINX)]
       SUBH *           ACC= (1/4)[PI-(QI*COSX-QR*SINX)]
       SACH *+,1        QI = (1/2)[PI-(QI*COSX-QR*SINX)]
       RET
*
*************************************************************
*                                                           *
*   16-BIT TWIDDLE FACTORS FOR 1024-POINT COMPLEX FFT       *
*                                                           *
*************************************************************
*
W000     DATA     32767,0
W001     DATA     32766,201
W002     DATA     32765,402
W003     DATA     32762,603
W004     DATA     32758,804
W005     DATA     32752,1005
W006     DATA     32746,1206
W007     DATA     32738,1407
W008     DATA     32728,1608
W009     DATA     32718,1809
W010     DATA     32706,2009
W011     DATA     32693,2210
W012     DATA     32679,2410
W013     DATA     32664,2611
W014     DATA     32647,2811
W015     DATA     32629,3012
W016     DATA     32610,3212
W017     DATA     32590,3412
W018     DATA     32568,3612
W019     DATA     32545,3811
W020     DATA     32521,4011
W021     DATA     32496,4210
W022     DATA     32470,4410
W023     DATA     32442,4609
W024     DATA     32413,4808
W025     DATA     32383,5007
W026     DATA     32352,5205
W027     DATA     32319,5404
W028     DATA     32285,5602
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W029     DATA     32250,5800
W030     DATA     32214,5998
W031     DATA     32177,6195
W032     DATA     32138,6393
W033     DATA     32098,6590
W034     DATA     32057,6786
W035     DATA     32015,6983
W036     DATA     31972,7179
W037     DATA     31927,7375
W038     DATA     31881,7571
W039     DATA     31834,7767
W040     DATA     31786,7962
W041     DATA     31736,8157
W042     DATA     31686,8351
W043     DATA     31634,8546
W044     DATA     31581,8739
W045     DATA     31527,8933
W046     DATA     31471,9126
W047     DATA     31415,9319
W048     DATA     31357,9512
W049     DATA     31298,9704
W050     DATA     31238,9896
W051     DATA     31176,10088
W052     DATA     31114,10279
W053     DATA     31050,10469
W054     DATA     30985,10660
W055     DATA     30919,10850
W056     DATA     30852,11039
W057     DATA     30784,11228
W058     DATA     30715,11417
W059     DATA     30644,11605
W060     DATA     30572,11793
W061     DATA     30499,11980
W062     DATA     30425,12167
W063     DATA     30350,12354
W064     DATA     30274,12540
W065     DATA     30196,12725
W066     DATA     30117,12910
W067     DATA     30038,13095
W068     DATA     29957,13279
W069     DATA     29875,13462
W070     DATA     29791,13645
W071     DATA     29707,13828
W072     DATA     29622,14010
W073     DATA     29535,14191
W074     DATA     29448,14372
W075     DATA     29359,14553
W076     DATA     29269,14733
W077     DATA     29178,14912
W078     DATA     29086,15091
W079     DATA     28993,15269
W080     DATA     28899,15447
W081     DATA     28803,15624
W082     DATA     28707,15800
W083     DATA     28609,15976
W084     DATA     28511,16151
W085     DATA     28411,16326
W086     DATA     28310,16500
W087     DATA     28209,16673
W088     DATA     28106,16846
W089     DATA     28002,17018
W090     DATA     27897,17190
W091     DATA     27791,17360
W092     DATA     27684,17531
W093     DATA     27576,17700
W094     DATA     27467,17869
W095     DATA     27357,18037
W096     DATA     27245,18205
W097     DATA     27133,18372
W098     DATA     27020,18538
W099     DATA     26906,18703
W100     DATA     26790,18868
W101     DATA     26674,19032
W102     DATA     26557,19195
W103     DATA     26439,19358
W104     DATA     26319,19520
W105     DATA     26199,19681
W106     DATA     26078,19841
W107     DATA     25956,20001
W108     DATA     25832,20160
W109     DATA     25708,20318
W110     DATA     25583,20475
W111     DATA     25457,20632
W112     DATA     25330,20788
W113     DATA     25202,20943
W114     DATA     25073,21097
W115     DATA     24943,21250
W116     DATA     24812,21403
W117     DATA     24680,21555
W118     DATA     24548,21706
W119     DATA     24414,21856
W120     DATA     24279,22005
W121     DATA     24144,22154
W122     DATA     24007,22302
W123     DATA     23870,22449
W124     DATA     23732,22595
W125     DATA     23593,22740
W126     DATA     23453,22884
W127     DATA     23312,23028
W128     DATA     23170,23170
W129     DATA     23028,23312
W130     DATA     22884,23453
W131     DATA     22740,23593
W132     DATA     22595,23732
W133     DATA     22449,23870
W134     DATA     22302,24007
W135     DATA     22154,24144
W136     DATA     22005,24279
W137     DATA     21856,24414
W138     DATA     21706,24548
W139     DATA     21555,24680
W140     DATA     21403,24812
W141     DATA     21250,24943
W142     DATA     21097,25073
W143     DATA     20943,25202
W144     DATA     20788,25330
W145     DATA     20632,25457
W146     DATA     20475,25583
W147     DATA     20318,25708
W148     DATA     20160,25832
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W149     DATA     20001,25956
W150     DATA     19841,26078
W151     DATA     19681,26199
W152     DATA     19520,26319
W153     DATA     19358,26439
W154     DATA     19195,26557
W155     DATA     19032,26674
W156     DATA     18868,26790
W157     DATA     18703,26906
W158     DATA     18538,27020
W159     DATA     18372,27133
W160     DATA     18205,27245
W161     DATA     18037,27357
W162     DATA     17869,27467
W163     DATA     17700,27576
W164     DATA     17531,27684
W165     DATA     17360,27791
W166     DATA     17190,27897
W167     DATA     17018,28002
W168     DATA     16846,28106
W169     DATA     16673,28209
W170     DATA     16500,28311
W171     DATA     16326,28411
W172     DATA     16151,28511
W173     DATA     15976,28609
W174     DATA     15800,28707
W175     DATA     15624,28803
W176     DATA     15447,28899
W177     DATA     15269,28993
W178     DATA     15091,29086
W179     DATA     14912,29178
W180     DATA     14733,29269
W181     DATA     14553,29359
W182     DATA     14372,29448
W183     DATA     14191,29535
W184     DATA     14010,29622
W185     DATA     13828,29707
W186     DATA     13645,29791
W187     DATA     13462,29875
W188     DATA     13279,29957
W189     DATA     13095,30038
W190     DATA     12910,30117
W191     DATA     12725,30196
W192     DATA     12540,30274
W193     DATA     12354,30350
W194     DATA     12167,30425
W195     DATA     11980,30499
W196     DATA     11793,30572
W197     DATA     11605,30644
W198     DATA     11417,30715
W199     DATA     11228,30784
W200     DATA     11039,30852
W201     DATA     10850,30920
W202     DATA     10660,30986
W203     DATA     10469,31050
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W205     DATA     10087,31176
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W207     DATA     9704,31298
W208     DATA     9512,31357
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W210     DATA     9126,31471
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W212     DATA     8739,31581
W213     DATA     8546,31634
W214     DATA     8351,31686
W215     DATA     8157,31736
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W222     DATA     6786,32057
W223     DATA     6590,32098
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W234     DATA     4410,32470
W235     DATA     4211,32496
W236     DATA     4011,32521
W237     DATA     3811,32545
W238     DATA     3612,32568
W239     DATA     3412,32590
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W241     DATA     3012,32629
W242     DATA     2811,32647
W243     DATA     2611,32664
W244     DATA     2410,32679
W245     DATA     2210,32693
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W247     DATA     1809,32718
W248     DATA     1608,32728
W249     DATA     1407,32738
W250     DATA     1206,32746
W251     DATA     1005,32752
W252     DATA     804,32758
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W255     DATA     201,32766
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W258     DATA     -402,32765
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W260     DATA     -804,32758
W261     DATA     -1005,32752
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W263     DATA     -1407,32738
W264     DATA     -1608,32728
W265     DATA     -1809,32718
W266     DATA     -2009,32706
W267     DATA     -2210,32693
W268     DATA     -2410,32679
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W283    DATA    -5404,32319
W284    DATA    -5602,32285
W285    DATA    -5800,32250
W286    DATA    -5998,32214
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W299    DATA    -8546,31634
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W327    DATA    -13828,29707
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W329    DATA    -14191,29535
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W351    DATA    -18037,27357
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W362    DATA    -19841,26078
W363    DATA    -20001,25956
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W373    DATA    -21555,24680
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W375    DATA    -21856,24414
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W385    DATA    -23312,23028
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W388    DATA    -23732,22595
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W402    DATA    -25583,20475
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W440    DATA    -29622,14010
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W450    DATA    -30425,12167
W451    DATA    -30499,11980
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W455    DATA    -30784,11228
W456    DATA    -30852,11039
W457    DATA    -30920,10850
W458    DATA    -30985,10660
W459    DATA    -31050,10469
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W461    DATA    -31176,10087
W462    DATA    -31238,9896
W463    DATA    -31298,9704
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W466    DATA    -31471,9126
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W468    DATA    -31581,8739
W469    DATA    -31634,8546
W470    DATA    -31686,8351
W471    DATA    -31736,8157
W472    DATA    -31786,7962
W473    DATA    -31834,7767
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W475    DATA    -31927,7375
W476    DATA    -31972,7179
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W479    DATA    -32098,6589
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W482    DATA    -32214,5997
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W484    DATA    -32285,5602
W485    DATA    -32319,5404
W486    DATA    -32352,5205
W487    DATA    -32383,5007
W488    DATA    -32413,4808
W489    DATA    -32442,4609
W490    DATA    -32470,4410
W491    DATA    -32496,4210
W492    DATA    -32521,4011
W493    DATA    -32545,3811
W494    DATA    -32568,3612
W495    DATA    -32590,3412
W496    DATA    -32610,3212
W497    DATA    -32629,3012
W498    DATA    -32647,2811
W499    DATA    -32664,2611
W500    DATA    -32679,2410
W501    DATA    -32693,2210
W502    DATA    -32706,2009
W503    DATA    -32718,1809
W504    DATA    -32728,1608
W505    DATA    -32738,1407
W506    DATA    -32746,1206
W507    DATA    -32752,1005
W508    DATA    -32758,804
W509    DATA    -32762,603
W510    DATA    -32765,402
W511    DATA    -32766,201
DONE    NOP
        END
```

APPENDIX E
A 256-POINT, RADIX-4 DIF FFT IMPLEMENTATION

```
                    A P P E N D I X   E
                   ----------------------

        IDT 'S4FFT256'
*
*
*    COOLEY-TUKEY RADIX-4, DIF FFT PROGRAM - 256-POINT STRAIGHT-LINE.
*
*       FOUR STAGES OF THREE TYPES RADIX-4 BUTTERFLIES -
*       ZERO, SPECIAL, AND NORMAL - IMPLEMENTED WITH MACROS.
*       COMPLEX INPUT DATA LOCATED ON PAGES 4-7  OF DATA MEMORY.
*       RESULTS ARE LEFT IN DATA RAM.
*       USES 13-BIT COEFFICIENTS FROM MPYK INSTRUCTIONS.
*       INTERMEDIATE VALUES ARE SCALED BY 1/4 AT EACH STAGE TO PREVENT
*        OVERFLOW.
*
*****************************************************************************
*
* DATA MEMORY ALLOCATION.
*
*****************************************************************************
N      EQU  256        * FFT LENGTH
*
T1     EQU  96         * TEMPORARY LOCATIONS ADDRESSED
T2     EQU  97         * BY AUXILIARY REGISTERS.
*
X0      EQU  512
X1      EQU  514
X2      EQU  516
X3      EQU  518
X4      EQU  520
X5      EQU  522
X6      EQU  524
X7      EQU  526
X8      EQU  528
X9      EQU  530
X10     EQU  532
X11     EQU  534
X12     EQU  536
X13     EQU  538
X14     EQU  540
X15     EQU  542
X16     EQU  544
X17     EQU  546
X18     EQU  548
X19     EQU  550
X20     EQU  552
X21     EQU  554
X22     EQU  556
X23     EQU  558
X24     EQU  560
X25     EQU  562
X26     EQU  564
X27     EQU  566
X28     EQU  568
X29     EQU  570
```

```
X30     EQU   572
X31     EQU   574
X32     EQU   576
X33     EQU   578
X34     EQU   580
X35     EQU   582
X36     EQU   584
X37     EQU   586
X38     EQU   588
X39     EQU   590
X40     EQU   592
X41     EQU   594
X42     EQU   596
X43     EQU   598
X44     EQU   600
X45     EQU   602
X46     EQU   604
X47     EQU   606
X48     EQU   608
X49     EQU   610
X50     EQU   612
X51     EQU   614
X52     EQU   616
X53     EQU   618
X54     EQU   620
X55     EQU   622
X56     EQU   624
X57     EQU   626
X58     EQU   628
X59     EQU   630
X60     EQU   632
X61     EQU   634
X62     EQU   636
X63     EQU   638
X64     EQU   640
X65     EQU   642
X66     EQU   644
X67     EQU   646
X68     EQU   648
X69     EQU   650
X70     EQU   652
X71     EQU   654
X72     EQU   656
X73     EQU   658
X74     EQU   660
X75     EQU   662
X76     EQU   664
X77     EQU   666
X78     EQU   668
X79     EQU   670
X80     EQU   672
X81     EQU   674
X82     EQU   676
X83     EQU   678
X84     EQU   680
X85     EQU   682
X86     EQU   684
X87     EQU   686
X88     EQU   688
X89     EQU   690
X90     EQU   692
X91     EQU   694
X92     EQU   696
X93     EQU   698
X94     EQU   700
X95     EQU   702
X96     EQU   704
X97     EQU   706
X98     EQU   708
X99     EQU   710
X100    EQU   712
X101    EQU   714
X102    EQU   716
X103    EQU   718
X104    EQU   720
X105    EQU   722
X106    EQU   724
X107    EQU   726
X108    EQU   728
X109    EQU   730
X110    EQU   732
X111    EQU   734
X112    EQU   736
X113    EQU   738
X114    EQU   740
X115    EQU   742
X116    EQU   744
X117    EQU   746
X118    EQU   748
X119    EQU   750
X120    EQU   752
X121    EQU   754
X122    EQU   756
X123    EQU   758
X124    EQU   760
X125    EQU   762
X126    EQU   764
X127    EQU   766
X128    EQU   768
X129    EQU   770
X130    EQU   772
X131    EQU   774
X132    EQU   776
X133    EQU   778
X134    EQU   780
X135    EQU   782
X136    EQU   784
X137    EQU   786
X138    EQU   788
X139    EQU   790
X140    EQU   792
X141    EQU   794
X142    EQU   796
X143    EQU   798
X144    EQU   800
X145    EQU   802
X146    EQU   804
X147    EQU   806
X148    EQU   808
X149    EQU   810
```

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X150    EQU  812
X151    EQU  814
X152    EQU  816
X153    EQU  818
X154    EQU  820
X155    EQU  822
X156    EQU  824
X157    EQU  826
X158    EQU  828
X159    EQU  830
X160    EQU  832
X161    EQU  834
X162    EQU  836
X163    EQU  838
X164    EQU  840
X165    EQU  842
X166    EQU  844
X167    EQU  846
X168    EQU  848
X169    EQU  850
X170    EQU  852
X171    EQU  854
X172    EQU  856
X173    EQU  858
X174    EQU  860
X175    EQU  862
X176    EQU  864
X177    EQU  866
X178    EQU  868
X179    EQU  870
X180    EQU  872
X181    EQU  874
X182    EQU  876
X183    EQU  878
X184    EQU  880
X185    EQU  882
X186    EQU  884
X187    EQU  886
X188    EQU  888
X189    EQU  890
X190    EQU  892
X191    EQU  894
X192    EQU  896
X193    EQU  898
X194    EQU  900
X195    EQU  902
X196    EQU  904
X197    EQU  906
X198    EQU  908
X199    EQU  910
X200    EQU  912
X201    EQU  914
X202    EQU  916
X203    EQU  918
X204    EQU  920
X205    EQU  922
X206    EQU  924
X207    EQU  926
X208    EQU  928
X209    EQU  930
X210    EQU  932
X211    EQU  934
X212    EQU  936
X213    EQU  938
X214    EQU  940
X215    EQU  942
X216    EQU  944
X217    EQU  946
X218    EQU  948
X219    EQU  950
X220    EQU  952
X221    EQU  954
X222    EQU  956
X223    EQU  958
X224    EQU  960
X225    EQU  962
X226    EQU  964
X227    EQU  966
X228    EQU  968
X229    EQU  970
X230    EQU  972
X231    EQU  974
X232    EQU  976
X233    EQU  978
X234    EQU  980
X235    EQU  982
X236    EQU  984
X237    EQU  986
X238    EQU  988
X239    EQU  990
X240    EQU  992
X241    EQU  994
X242    EQU  996
X243    EQU  998
X244    EQU  1000
X245    EQU  1002
X246    EQU  1004
X247    EQU  1006
X248    EQU  1008
X249    EQU  1010
X250    EQU  1012
X251    EQU  1014
X252    EQU  1016
X253    EQU  1018
X254    EQU  1020
X255    EQU  1022
*
*  TABLE WITH COSINES
*
C0     EQU  4095
C1     EQU  4094
C2     EQU  4090
C3     EQU  4084
C4     EQU  4075
C5     EQU  4064
C6     EQU  4051
C7     EQU  4035
C8     EQU  4016
C9     EQU  3996
C10    EQU  3972
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C11     EQU   3947
C12     EQU   3919
C13     EQU   3888
C14     EQU   3856
C15     EQU   3821
C16     EQU   3783
C17     EQU   3744
C18     EQU   3702
C19     EQU   3658
C20     EQU   3611
C21     EQU   3563
C22     EQU   3512
C23     EQU   3460
C24     EQU   3405
C25     EQU   3348
C26     EQU   3289
C27     EQU   3228
C28     EQU   3165
C29     EQU   3101
C30     EQU   3034
C31     EQU   2966
C32     EQU   2896
C33     EQU   2824
C34     EQU   2750
C35     EQU   2675
C36     EQU   2598
C37     EQU   2519
C38     EQU   2439
C39     EQU   2358
C40     EQU   2275
C41     EQU   2191
C42     EQU   2105
C43     EQU   2018
C44     EQU   1930
C45     EQU   1841
C46     EQU   1751
C47     EQU   1659
C48     EQU   1567
C49     EQU   1474
C50     EQU   1380
C51     EQU   1285
C52     EQU   1189
C53     EQU   1092
C54     EQU   995
C55     EQU   897
C56     EQU   799
C57     EQU   700
C58     EQU   601
C59     EQU   501
C60     EQU   401
C61     EQU   301
C62     EQU   201
C63     EQU   100
C64     EQU   0
C65     EQU   -99
C66     EQU   -200
C67     EQU   -300
C68     EQU   -400
C69     EQU   -500
C70     EQU   -600
C71     EQU   -699
C72     EQU   -798
C73     EQU   -896
C74     EQU   -994
C75     EQU   -1091
C76     EQU   -1188
C77     EQU   -1284
C78     EQU   -1379
C79     EQU   -1473
C80     EQU   -1566
C81     EQU   -1658
C82     EQU   -1750
C83     EQU   -1840
C84     EQU   -1929
C85     EQU   -2017
C86     EQU   -2104
C87     EQU   -2190
C88     EQU   -2274
C89     EQU   -2357
C90     EQU   -2438
C91     EQU   -2518
C92     EQU   -2597
C93     EQU   -2674
C94     EQU   -2749
C95     EQU   -2823
C96     EQU   -2895
C97     EQU   -2965
C98     EQU   -3033
C99     EQU   -3100
C100    EQU   -3164
C101    EQU   -3227
C102    EQU   -3288
C103    EQU   -3347
C104    EQU   -3404
C105    EQU   -3459
C106    EQU   -3511
C107    EQU   -3562
C108    EQU   -3610
C109    EQU   -3657
C110    EQU   -3701
C111    EQU   -3743
C112    EQU   -3782
C113    EQU   -3820
C114    EQU   -3855
C115    EQU   -3887
C116    EQU   -3918
C117    EQU   -3946
C118    EQU   -3971
C119    EQU   -3995
C120    EQU   -4015
C121    EQU   -4034
C122    EQU   -4050
C123    EQU   -4063
C124    EQU   -4074
C125    EQU   -4083
C126    EQU   -4089
C127    EQU   -4093
C128    EQU   -4094
C129    EQU   -4093
C130    EQU   -4089
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C131  EQU  -4083
C132  EQU  -4074
C133  EQU  -4063
C134  EQU  -4050
C135  EQU  -4034
C136  EQU  -4015
C137  EQU  -3995
C138  EQU  -3971
C139  EQU  -3946
C140  EQU  -3918
C141  EQU  -3887
C142  EQU  -3855
C143  EQU  -3820
C144  EQU  -3782
C145  EQU  -3743
C146  EQU  -3701
C147  EQU  -3657
C148  EQU  -3610
C149  EQU  -3562
C150  EQU  -3511
C151  EQU  -3459
C152  EQU  -3404
C153  EQU  -3347
C154  EQU  -3288
C155  EQU  -3227
C156  EQU  -3164
C157  EQU  -3100
C158  EQU  -3033
C159  EQU  -2965
C160  EQU  -2895
C161  EQU  -2823
C162  EQU  -2749
C163  EQU  -2674
C164  EQU  -2597
C165  EQU  -2518
C166  EQU  -2438
C167  EQU  -2357
C168  EQU  -2274
C169  EQU  -2190
C170  EQU  -2104
C171  EQU  -2017
C172  EQU  -1929
C173  EQU  -1840
C174  EQU  -1750
C175  EQU  -1658
C176  EQU  -1566
C177  EQU  -1473
C178  EQU  -1379
C179  EQU  -1284
C180  EQU  -1188
C181  EQU  -1091
C182  EQU  -994
C183  EQU  -896
C184  EQU  -798
C185  EQU  -699
C186  EQU  -600
C187  EQU  -500
C188  EQU  -400
C189  EQU  -300
C190  EQU  -200
C191  EQU  -99
C192  EQU  0
C193  EQU  100
C194  EQU  201
C195  EQU  301
C196  EQU  401
C197  EQU  501
C198  EQU  601
C199  EQU  700
C200  EQU  799
C201  EQU  897
C202  EQU  995
C203  EQU  1092
C204  EQU  1189
C205  EQU  1285
C206  EQU  1380
C207  EQU  1474
C208  EQU  1567
C209  EQU  1659
C210  EQU  1751
C211  EQU  1841
C212  EQU  1930
C213  EQU  2018
C214  EQU  2105
C215  EQU  2191
C216  EQU  2275
C217  EQU  2358
C218  EQU  2439
C219  EQU  2519
C220  EQU  2598
C221  EQU  2675
C222  EQU  2750
C223  EQU  2824
C224  EQU  2896
C225  EQU  2966
C226  EQU  3034
C227  EQU  3101
C228  EQU  3165
C229  EQU  3228
C230  EQU  3289
C231  EQU  3348
C232  EQU  3405
C233  EQU  3460
C234  EQU  3512
C235  EQU  3563
C236  EQU  3611
C237  EQU  3658
C238  EQU  3702
C239  EQU  3744
C240  EQU  3783
C241  EQU  3821
C242  EQU  3856
C243  EQU  3888
C244  EQU  3919
C245  EQU  3947
C246  EQU  3972
C247  EQU  3996
C248  EQU  4016
C249  EQU  4035
C250  EQU  4051
```

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C253  EQU  4084
C254  EQU  4090
C255  EQU  4094
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S2    EQU  201
S3    EQU  301
S4    EQU  401
S5    EQU  501
S6    EQU  601
S7    EQU  700
S8    EQU  799
S9    EQU  897
S10   EQU  995
S11   EQU  1092
S12   EQU  1189
S13   EQU  1285
S14   EQU  1380
S15   EQU  1474
S16   EQU  1567
S17   EQU  1659
S18   EQU  1751
S19   EQU  1841
S20   EQU  1930
S21   EQU  2018
S22   EQU  2105
S23   EQU  2191
S24   EQU  2275
S25   EQU  2358
S26   EQU  2439
S27   EQU  2519
S28   EQU  2598
S29   EQU  2675
S30   EQU  2750
S31   EQU  2824
S32   EQU  2896
S33   EQU  2966
S34   EQU  3034
S35   EQU  3101
S36   EQU  3165
S37   EQU  3228
S38   EQU  3289
S39   EQU  3348
S40   EQU  3405
S41   EQU  3460
S42   EQU  3512
S43   EQU  3563
S44   EQU  3611
S45   EQU  3658
S46   EQU  3702
S47   EQU  3744
S48   EQU  3783
S49   EQU  3821
S50   EQU  3856
S51   EQU  3888
S52   EQU  3919
S53   EQU  3947
S54   EQU  3972
S55   EQU  3996
S56   EQU  4016
S57   EQU  4035
S58   EQU  4051
S59   EQU  4064
S60   EQU  4075
S61   EQU  4084
S62   EQU  4090
S63   EQU  4094
S64   EQU  4095
S65   EQU  4094
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S70   EQU  4051
S71   EQU  4035
S72   EQU  4016
S73   EQU  3996
S74   EQU  3972
S75   EQU  3947
S76   EQU  3919
S77   EQU  3888
S78   EQU  3856
S79   EQU  3821
S80   EQU  3783
S81   EQU  3744
S82   EQU  3702
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S85   EQU  3563
S86   EQU  3512
S87   EQU  3460
S88   EQU  3405
S89   EQU  3348
S90   EQU  3289
S91   EQU  3228
S92   EQU  3165
S93   EQU  3101
S94   EQU  3034
S95   EQU  2966
S96   EQU  2896
S97   EQU  2824
S98   EQU  2750
S99   EQU  2675
S100  EQU  2598
S101  EQU  2519
S102  EQU  2439
S103  EQU  2358
S104  EQU  2275
S105  EQU  2191
S106  EQU  2105
S107  EQU  2018
S108  EQU  1930
S109  EQU  1841
S110  EQU  1751
S111  EQU  1659
```

```
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S113  EQU  1474
S114  EQU  1380
S115  EQU  1285
S116  EQU  1189
S117  EQU  1092
S118  EQU  995
S119  EQU  897
S120  EQU  799
S121  EQU  700
S122  EQU  601
S123  EQU  501
S124  EQU  401
S125  EQU  301
S126  EQU  201
S127  EQU  100
S128  EQU  0
S129  EQU  -99
S130  EQU  -200
S131  EQU  -300
S132  EQU  -400
S133  EQU  -500
S134  EQU  -600
S135  EQU  -699
S136  EQU  -798
S137  EQU  -896
S138  EQU  -994
S139  EQU  -1091
S140  EQU  -1188
S141  EQU  -1284
S142  EQU  -1379
S143  EQU  -1473
S144  EQU  -1566
S145  EQU  -1658
S146  EQU  -1750
S147  EQU  -1840
S148  EQU  -1929
S149  EQU  -2017
S150  EQU  -2104
S151  EQU  -2190
S152  EQU  -2274
S153  EQU  -2357
S154  EQU  -2438
S155  EQU  -2518
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S157  EQU  -2674
S158  EQU  -2749
S159  EQU  -2823
S160  EQU  -2895
S161  EQU  -2965
S162  EQU  -3033
S163  EQU  -3100
S164  EQU  -3164
S165  EQU  -3227
S166  EQU  -3288
S167  EQU  -3347
S168  EQU  -3404
S169  EQU  -3459
S170  EQU  -3511
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S174  EQU  -3701
S175  EQU  -3743
S176  EQU  -3782
S177  EQU  -3820
S178  EQU  -3855
S179  EQU  -3887
S180  EQU  -3918
S181  EQU  -3946
S182  EQU  -3971
S183  EQU  -3995
S184  EQU  -4015
S185  EQU  -4034
S186  EQU  -4050
S187  EQU  -4063
S188  EQU  -4074
S189  EQU  -4083
S190  EQU  -4089
S191  EQU  -4093
S192  EQU  -4094
S193  EQU  -4093
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S198  EQU  -4050
S199  EQU  -4034
S200  EQU  -4015
S201  EQU  -3995
S202  EQU  -3971
S203  EQU  -3946
S204  EQU  -3918
S205  EQU  -3887
S206  EQU  -3855
S207  EQU  -3820
S208  EQU  -3782
S209  EQU  -3743
S210  EQU  -3701
S211  EQU  -3657
S212  EQU  -3610
S213  EQU  -3562
S214  EQU  -3511
S215  EQU  -3459
S216  EQU  -3404
S217  EQU  -3347
S218  EQU  -3288
S219  EQU  -3227
S220  EQU  -3164
S221  EQU  -3100
S222  EQU  -3033
S223  EQU  -2965
S224  EQU  -2895
S225  EQU  -2823
S226  EQU  -2749
S227  EQU  -2674
S228  EQU  -2597
S229  EQU  -2518
S230  EQU  -2438
S231  EQU  -2357
```

```
S232  EQU  -2274
S233  EQU  -2190
S234  EQU  -2104
S235  EQU  -2017
S236  EQU  -1929
S237  EQU  -1840
S238  EQU  -1750
S239  EQU  -1658
S240  EQU  -1566
S241  EQU  -1473
S242  EQU  -1379
S243  EQU  -1284
S244  EQU  -1188
S245  EQU  -1091
S246  EQU  -994
S247  EQU  -896
S248  EQU  -798
S249  EQU  -699
S250  EQU  -600
S251  EQU  -500
S252  EQU  -400
S253  EQU  -300
S254  EQU  -200
S255  EQU  -99


        PAGE
*
*
*    COOLEY-TUKEY RADIX-4, DIF FFT PROGRAM - 256-POINT STRAIGHT-LINE.
*
*       FOUR STAGES OF THREE TYPES RADIX-4 BUTTERFLIES -
*       ZERO, SPCIAL, AND NORMAL - IMPLEMENTED WITH MACROS.
*       COMPLEX INPUT DATA LOCATED ON PAGES 4-7  OF DATA MEMORY.
*       RESULTS ARE LEFT IN DATA RAM.
*       USES 13-BIT COEFFICIENTS FROM MPYK INSTRUCTIONS.
*       INTERMEDIATE VALUES ARE SCALED BY 1/4 AT EACH STAGE TO PREVENT
*        OVERFLOW.
*
**************************************************************************
*
* MACROS TO PRODUCE STRAIGHT-LINE 256-POINT COMPLEX FFT.
*
**************************************************************************
*
*  ZERO FOR CASE W = 1 (THETA = 0).
*
*  X'S AND Y'S ARE INPUT AND OUTPUT LOCATIONS FOR BUTTERFLY.
*  ENTER WITH ARP = 1, AR1 --> XI1, AR2 --> XI, AR0 = [XI3]-[XI1]
*  EXIT WITH ARP = 1, AR1 --> NEXT XI1, AR2 --> NEXT XI
*
ZERO    $MACRO
*
        LAC  *0+,15             * (1/2)XI1
        ADD  *0-,15             * (1/2)XI3
        SACH *0+                * XI1 = (1/2)(XI1 + XI3)
        SUBH *                  * XI3
        SACH *0-,0,AR2          * XI3 = (1/2)(XI1 - XI3)
        LAC  *0+,14             * (1/4)XI
        SUB  *,14               * (1/4)XI2
        SACH T1                 * T1 = (1/4)(XI - XI2)
        ADD  *,15,AR1           * R1 (ACC) = (1/4)(XI + XI2)
        SUB  *,15,AR2           * (1/2)XI1
        SACH *0-,0,AR1          * XI2 = R1 - (1/2)XI1
        ADDH *+,AR2             * XI1
        SACH *+,0,AR1           * XI  = R1 + (1/2)XI1
*
        LAC  *0+,15             * (1/2)YI1
        ADD  *0-,15             * (1/2)YI3
        SACH *0+                * YI1 = (1/2)(YI1 + YI3)
        SUBH *                  * YI3
        SACH *0-,0,AR2          * YI3 = (1/2)(YI1 - YI3)
        LAC  *0+,14             * (1/4)YI
        SUB  *,14               * (1/4)YI2
        SACH T2                 * T2 = (1/4)(YI - YI2)
        ADD  *,15,AR1           * S1 (ACC) = (1/4)(YI + YI2)
        SUB  *,15,AR2           * (1/2)YI1
        SACH *0-,0,AR1          * YI2 = S1 - (1/2)YI1
        ADDH *0+,AR2            * YI1
        SACH *+,0,AR1           * YI  = S1 + (1/2)YI1, POINT TO NEXT XI
*
        ZALH T1
        ADD  *0-,15             * (1/2)YI3
        MAR  *-                 * POINT TO XI1
        SACH *+                 * XI1 = T1 + (1/2)YI3
        MAR  *0+                * POINT TO YI3
        SUBH *-                 * YI3
        SACH T1                 * T1 = T1 - (1/2)YI3
        ZALH T2
        ADD  *+,15              * (1/2)XI3
        SACH *-                 * YI3 = T2 + (1/2)XI3
        SUBH *                  * XI3
        LAR  AR3,T1             * AR3 = T1
        SAR  AR3,*+             * XI3 = T1
        MAR  *0-                * POINT TO YI1
        SACH *+                 * YI1 = T2 - (1/2)XI3 , POINT TO NEXT XI1
*
        $END
**************************************************************************
*
*  NORMAL - STANDARD RADIX-4 BUTTERFLY.
*
*  X'S AND Y'S ARE INPUT AND OUTPUT LOCATIONS FOR BUTTERFLY.
*  IA'S SPECIFY TWIDDLE FACTOR LOCATIONS.
*  ENTER WITH ARP = 1, AR1 --> XI1, AR2 --> XI, AR0 = [XI3] - [XI1]
*  EXIT WITH ARP = 1, AR1 --> NEXT XI1, AR2 --> NEXT XI
*
NORMAL  $MACRO  IA1,IA2,IA3
*
        LAC  *0+,15             * (1/2)XI1
        ADD  *0-,15             * (1/2)XI3
        SACH *0+                * XI1 = (1/2)(XI1 + XI3)
        SUBH *                  * XI3
        SACH *0-,0,AR2          * XI3 = (1/2)(XI1 - XI3)
        LAC  *0+,14             * (1/4)XI
        SUB  *,14               * (1/4)XI2
        SACH T1                 * T1 = (1/4)(XI - XI2)
        ADD  *,15,AR1           * R1 (ACC) = (1/4)(XI + XI2)
        SUB  *,15,AR2           * (1/2)XI1
        SACH *0-,0,AR1          * XI2 = R1 - (1/2)XI1
```

```
ADDH *+,AR2             * XI1
SACH *+,0,AR1           * XI  = R1 + (1/2)XI1

LAC  *0+,15             * (1/2)YI1
ADD  *0-,15             * (1/2)YI3
SACH *0+                * YI1 = (1/2)(YI1 + YI3)
SUBH *                  * YI3
SACH *0-,0,AR2          * YI3 = (1/2)(YI1 - YI3)
LAC  *0+,14             * (1/4)YI
SUB  *,14               * (1/4)YI2
SACH T2                 * T2 = (1/4)(YI - YI2)
ADD  *,15,AR1           * S1 (ACC) = (1/4)(YI + YI2)
SUB  *,15,AR2           * (1/2)YI1
SACH *0-,0,AR1          * YI2 = S1 - (1/2)YI1
ADDH *0+,AR2            * YI1
SACH *0+,0,AR1          * YI  = S1 + (1/2)YI1, POINT TO YI2

ZALH T1
ADD  *0-,15             * (1/2)YI3
MAR  *-                 * POINT TO XI1
SACH *+                 * XI1 = T1 + (1/2)YI3
MAR  *0+                * POINT TO YI3
SUBH *-                 * YI3
SACH T1                 * T1 = T1 - (1/2)YI3
ZALH T2
ADD  *,15               * (1/2)XI3
SACH T2                 * T2 = T2 + (1/2)XI3
SUBH *+                 * XI3, POINT TO YI3
MAR  *0-                * POINT TO YI1
SACH *                  * YI1 = T2 - (1/2)XI3

LT   *-                 * YI1
MPYK C:IA1:             * CO1 * YI1
LTP  *+                 * XI1
MPYK S:IA1:             * SI1 * XI1
LTS  *                  * YI1
SACH *-,4               * YI1 = YI1*CO1 - XI1*SI1
MPYK S:IA1:             * SI1 * YI1
LTP  *,AR2              * XI1
MPYK C:IA1:             * CO1 * XI1
LTA  *-,AR1             * YI2
SACH *0+,4,AR2          * XI1 = YI1*SI1 + XI1*CO1, POINT TO XI3

MPYK C:IA2:             * CO2 * YI2
LTP  *+                 * XI2
MPYK S:IA2:             * SI2 * XI2
LTS  *                  * YI2
SACH *-,4               * YI2 = YI2*CO2 - XI2*SI2
MPYK S:IA2:             * SI2 * YI2
LTP  *                  * XI2
MPYK C:IA2:             * CO2 * XI2
LTA  T1                 * T1
SACH *0-,4              * XI2 = YI2*SI2 + XI2*CO2
MAR  *+,AR1

MPYK C:IA3:             * CO3 * T1
LTP  T2                 * T2
MPYK S:IA3:             * SI3 * T2
APAC
SACH *+,4,AR2           * XI3 = T1*CO3 + T2*SI3
```

```
        MPYK C:IA3:             * CO3 * T2
        LTP  T1                 * T1
        MPYK S:IA3:             * SI3 * T1
        LTS  *+,AR1             * SPAC, POINT TO NEXT XI, (LT = DUMMY OP)
        SACH *+,4               * YI3 = T2*CO3 - T1*SI3
        MAR  *0-                * POINT TO NEXT XI1
*
        $END
*******************************************************************************
*
* SPCIAL FOR CASE THETA = pi/4
*
*  X'S AND Y'S ARE INPUT AND OUTPUT LOCATIONS FOR BUTTERFLY.
*  ENTER WITH ARP = 1, AR1 --> XI1, AR2 --> XI, AR0 = [XI3] - [XI1]
*  EXIT WITH ARP = 1, AR1 --> NEXT XI1, AR2 --> NEXT XI
*
SPCIAL $MACRO
*
        LAC  *0+,14             * (1/4)XI1
        ADD  *0-,14             * (1/4)XI3
        SACH *0+                * XI1 = (1/4)(XI1 + XI3)
        SUB  *,15               * (1/2)XI3
        SACH *+                 * XI3 = (1/4)(XI1 - XI3)
*
        LAC  *0-,14             * (1/4)YI3
        ADD  *,14               * (1/4)YI1
        SACH *0+                * YI1 = (1/4)(YI1 + YI3)
        SUB  *,15               * (1/2)YI3
        SACH *0-,0,AR2          * YI3 = (1/4)(YI1 - YI3), POINT TO YI1
*
        LAC  *0+,14             * (1/4)XI
        ADD  *0-,14             * (1/4)XI2
        SACH *0+                * XI = (1/4)(XI + XI2)
        SUB  *,15               * (1/2)XI2
        SACH *+                 * XI2 = (1/4)(XI - XI2)
*
        LAC  *0-,14             * (1/4)YI2
        ADD  *,14               * (1/4)YI
        SACH *0+                * YI = (1/4)(YI + YI2)
        SUB  *,15               * (1/2)YI2
        SACH *0-                * YI2 = (1/4)(YI - YI2), POINT TO YI
*
        LAC  *,0,AR1            * YI
        ADD  *,0,AR2            * YI1
        SACL *-,0,AR1           * YI = YI + YI1
        SUB  *-,1               * 2 YI1
        SACL T2                 * T2 = YI - YI1
        LAC  *0+,0,AR2          * XI1, POINT TO XI3
        SUB  *                  * XI
        SACL T1                 * T1 = XI1 - XI
        ADD  *,1                * 2 XI
        SACL *0+                * XI = XI1 + XI, POINT TO XI2
*
        LT   *+,AR1             * XI2
        MPYK C32
        MAR  *+
        LTP  *                  * YI3
        MPYK C32
        SPAC
        SACH *-,4               * YI3 = (XI2-YI3)*C32
```

```
       APAC
       LTA  *0-                * XI3
       SACH *0+,4,AR2          * XI1 = (XI2+YI3)*C32
*
       MPYK C32
       LTP  *,AR1              * YI2
       MPYK C32
       APAC
       SACH *0-,4              * XI3 = (YI2+XI3)*C32
       SPAC
       SPAC
       NEG
       MAR  *+
       SACH *,4,AR2            * YI1 = (YI2-XI3)*C32
*
       LAC  T1
       SACL *-                 * YI2 = T1
       LAC  T2
       SACL *0-                * XI2 = T2
       MAR  *+
       MAR  *+,AR1             * POINT TO NEXT XI
*
       LAC  *-                 * YI1
       SUB  *+                 * XI1
       SACL *-                 * YI1 = YI1 - XI1
       ADD  *,1                * 2 XI1
       SACL *0+                * XI1 = YI1 + XI1
       LAC  *+                 * XI3
       SUB  *-                 * YI3
       SACL *+                 * XI3 = XI3 - YI3
       ADD  *,1                * 2 YI3
       NEG
       SACL *0-                * YI3 = -(YI3 + XI3)
       MAR  *+                 * POINT TO NEXT XI1
*
       $END
*****************************************************************************
*
* DIGREV MACRO TO DO EXCHANGE OF LOCATIONS FOR DIGIT REVERSAL.
*
DIGREV $MACRO I,J
*
       LRLK AR1,X:I:           * AR1 POINTS TO XI
       LRLK AR2,X:J:           * AR1 POINTS TO XJ
*
       ZALH *,AR2
       ADDS *,AR1
       SACL *+,0,AR2
       SACH *+,0,AR1
       ZALH *,AR2
       ADDS *,AR1
       SACL *,0,AR2
       SACH *,0,AR1
*
       $END
*
*****************************************************************************
*
*      MAIN ROUTINE TO CALL ABOVE MACROS WITH APPROPRIATE PARAMETERS.
*
*****************************************************************************
       AORG 0
       B    32
*
       AORG 32
FF256  LDPK 0                         * STORE ALL TEMPORARY VARIABLES IN B2.
       SOVM
       SSXM
       SPM  0
       LARP 1
*
*         INPUT DATA (256 REAL AND 256 IMAGINARY VALUES)
*
       LRLK AR1,X0
       RPTK 255
       IN   *+,PA0
       RPTK 255
       IN   *+,PA0
*****************************************************************************
*
* PASS 1
*
*****************************************************************************
       LRLK    AR0,256                * STEP VALUE BETWEEN BUTTERFLY "LEGS"
       LRLK    AR1,X64
       LRLK    AR2,X0
       ZERO                           * X0,X64,X128,X192,Y0,Y64,Y128,Y192
*
       NORMAL  1,2,3                  * X1,X65,X129,X193,Y1,Y65,Y129,Y193
       NORMAL  2,4,6                  * X2,X66,X130,X194,...
       NORMAL  3,6,9
       NORMAL  4,8,12
       NORMAL  5,10,15
       NORMAL  6,12,18
       NORMAL  7,14,21
       NORMAL  8,16,24
       NORMAL  9,18,27
       NORMAL  10,20,30
       NORMAL  11,22,33
       NORMAL  12,24,36
       NORMAL  13,26,39
       NORMAL  14,28,42
       NORMAL  15,30,45
       NORMAL  16,32,48
       NORMAL  17,34,51
       NORMAL  18,36,54
       NORMAL  19,38,57
       NORMAL  20,40,60
       NORMAL  21,42,63
       NORMAL  22,44,66
       NORMAL  23,46,69
       NORMAL  24,48,72
       NORMAL  25,50,75
       NORMAL  26,52,78
```

```
      NORMAL  27,54,81
      NORMAL  28,56,84
      NORMAL  29,58,87
      NORMAL  30,60,90
      NORMAL  31,62,93          * X31,X95,X159,X223,Y31,Y95,Y159,Y223
*
      SPCIAL                    * X32,X96,X160,X224,Y32,Y96,Y160,Y224
*
      NORMAL  33,66,99          * X33,X97,X161,X225,Y33,Y97,Y161,Y225
      NORMAL  34,68,102         * X34,X98,X162,X226,...
      NORMAL  35,70,105
      NORMAL  36,72,108
      NORMAL  37,74,111
      NORMAL  38,76,114
      NORMAL  39,78,117
      NORMAL  40,80,120
      NORMAL  41,82,123
      NORMAL  42,84,126
      NORMAL  43,86,129
      NORMAL  44,88,132
      NORMAL  45,90,135
      NORMAL  46,92,138
      NORMAL  47,94,141
      NORMAL  48,96,144
      NORMAL  49,98,147
      NORMAL  50,100,150
      NORMAL  51,102,153
      NORMAL  52,104,156
      NORMAL  53,106,159
      NORMAL  54,108,162
      NORMAL  55,110,165
      NORMAL  56,112,168
      NORMAL  57,114,171
      NORMAL  58,116,174
      NORMAL  59,118,177
      NORMAL  60,120,180
      NORMAL  61,122,183
      NORMAL  62,124,186
      NORMAL  63,126,189        * X63,X127,X191,X255,Y63,Y127,Y191,Y255
*
*******************************************************************************
*
* PASS 2
*
*******************************************************************************
*
*  FIRST SET OF BUTTERFLIES
*
      LARK    AR0,64            * STEP VALUE BETWEEN BUTTERFLY "LEGS"
      LRLK    AR1,X16
      LRLK    AR2,X0
      ZERO                      * X0,X16,X32,X48,Y0,Y16,Y32,Y48
*
      NORMAL  4,8,12            * X1,X17,X33,X49,Y1,Y17,Y33,Y49
      NORMAL  8,16,24           * X2,X18,X34,X50,...
      NORMAL  12,24,36
      NORMAL  16,32,48
      NORMAL  20,40,60
      NORMAL  24,48,72
      NORMAL  28,56,84          * X7,X23,X39,X55,Y7,Y23,Y39,Y55
*
      SPCIAL                    * X8,X24,X40,X56,Y8,Y24,Y40,Y56
*
      NORMAL  36,72,108         * X9,X25,X41,X57,Y9,Y25,Y41,Y57
      NORMAL  40,80,120         * X10,X26,X42,X58,...
      NORMAL  44,88,132
      NORMAL  48,96,144
      NORMAL  52,104,156
      NORMAL  56,112,168
      NORMAL  60,120,180        * X15,X31,X47,X63,Y15,Y31,Y47,Y63
*
*  SECOND SET OF BUTTERFLIES
*
      LRLK    AR1,X80
      LRLK    AR2,X64
      ZERO                      * X64,X80,X96,X112,Y64,Y80,Y96,Y112
*
      NORMAL  4,8,12            * X65,X81,X97,X113,Y65,Y81,Y97,Y113
      NORMAL  8,16,24           * X66,X82,X98,X114,...
      NORMAL  12,24,36
      NORMAL  16,32,48
      NORMAL  20,40,60
      NORMAL  24,48,72
      NORMAL  28,56,84          * X71,X87,X103,X119,Y71,Y87,Y103,Y119
*
      SPCIAL                    * X72,X88,X104,X120,Y72,Y88,Y104,Y120
*
      NORMAL  36,72,108         * X73,X89,X105,X121,Y73,Y89,Y105,Y121
      NORMAL  40,80,120         * X74,X90,X106,X122,...
      NORMAL  44,88,132
      NORMAL  48,96,144
      NORMAL  52,104,156
      NORMAL  56,112,168
      NORMAL  60,120,180        * X79,X95,X111,X127,Y79,Y95,Y111,Y127
*
*  THIRD SET OF BUTTERFLIES
*
      LRLK    AR1,X144
      LRLK    AR2,X128
      ZERO                      * X128,X144,X160,X176,Y128,Y144,Y160,Y176
*
      NORMAL  4,8,12            * X129,X145,X161,X177,Y129,Y145,Y161,Y177
      NORMAL  8,16,24           * X130,X146,X162,X178,...
      NORMAL  12,24,36
      NORMAL  16,32,48
      NORMAL  20,40,60
      NORMAL  24,48,72
      NORMAL  28,56,84          * X135,X151,X167,X183,Y135,Y151,Y167,Y183
*
      SPCIAL                    * X136,X152,X168,X184,Y136,Y152,Y168,Y184
*
      NORMAL  36,72,108         * X137,X153,X169,X185,Y137,Y153,Y169,Y185
      NORMAL  40,80,120         * X138,X154,X170,X186,...
      NORMAL  44,88,132
      NORMAL  48,96,144
      NORMAL  52,104,156
      NORMAL  56,112,168
      NORMAL  60,120,180        * X143,X159,X175,X191,Y143,Y159,Y175,Y191
*
*  FOURTH SET OF BUTTERFLIES
```

```
*
      LRLK    AR1,X208
      LRLK    AR2,X192
      ZERO                        * X192,X208,X224,X240,Y192,Y208,Y224,Y240
*
      NORMAL  4,8,12              * X193,X209,X225,X241,Y193,Y209,Y225,Y241
      NORMAL  8,16,24             * X194,X210,X226,X242,...
      NORMAL  12,24,36
      NORMAL  16,32,48
      NORMAL  20,40,60
      NORMAL  24,48,72
      NORMAL  28,56,84            * X199,X215,X231,X247,Y199,Y215,Y231,Y247
*
      SPCIAL                      * X200,X216,X232,X248,Y200,Y216,Y232,Y248
*
      NORMAL  36,72,108           * X201,X217,X233,X249,Y201,Y217,Y233,Y249
      NORMAL  40,80,120           * X202,X218,X234,X250,...
      NORMAL  44,88,132
      NORMAL  48,96,144
      NORMAL  52,104,156
      NORMAL  56,112,168
      NORMAL  60,120,180          * X207,X223,X239,X255,Y207,Y223,Y239,Y255
*
*
*******************************************************************************
*
* PASS 3
*
*******************************************************************************
*
      LARK    AR0,16              * STEP VALUE BETWEEN BUTTERFLY "LEGS"
*
      LRLK    AR1,X4
      LRLK    AR2,X0
*
      ZERO                        * X0,X4,X8,X12,Y0,Y4,Y8,Y12
      NORMAL  16,32,48            * X1,X5,X9,X13,Y1,Y5,Y9,Y13
      SPCIAL                      * X2,X6,X10,X14,Y2,Y6,Y10,Y14
      NORMAL  48,96,144           * X3,X7,X11,X15,Y3,Y7,Y11,Y15
*
      LRLK    AR1,X20
      LRLK    AR2,X16
*
      ZERO                        * X16,X20,X24,X28,Y16,Y20,Y24,Y28
      NORMAL  16,32,48            * X17,X21,X25,X29,Y17,Y21,Y25,Y29
      SPCIAL                      * X18,X22,X26,X30,Y18,Y22,Y26,Y30
      NORMAL  48,96,144           * X19,X23,X27,X31,Y19,Y23,Y27,Y31
*
      LRLK    AR1,X36
      LRLK    AR2,X32
*
      ZERO                        * X32,X36,X40,X44,Y32,Y36,Y40,Y44
      NORMAL  16,32,48            * X33,X37,X41,X45,Y33,Y37,Y41,Y45
      SPCIAL                      * X34,X38,X42,X46,Y34,Y38,Y42,Y46
      NORMAL  48,96,144           * X35,X39,X43,X47,Y35,Y39,Y43,Y47
*
      LRLK    AR1,X52
      LRLK    AR2,X48
*
      ZERO                        * X48,X52,X56,X60,Y48,Y52,Y56,Y60
      NORMAL  16,32,48            * X49,X53,X57,X61,Y49,Y53,Y57,Y61
      SPCIAL                      * X50,X54,X58,X62,Y50,Y54,Y58,Y62
      NORMAL  48,96,144           * X51,X55,X59,X63,Y51,Y55,Y59,Y63
*
      LRLK    AR1,X68
      LRLK    AR2,X64
*
      ZERO                        * X64,X68,X72,X76,Y64,Y68,Y72,Y76
      NORMAL  16,32,48            * X65,X69,X73,X77,Y65,Y69,Y73,Y77
      SPCIAL                      * X66,X70,X74,X78,Y66,Y70,Y74,Y78
      NORMAL  48,96,144           * X67,X71,X75,X79,Y67,Y71,Y75,Y79
*
      LRLK    AR1,X84
      LRLK    AR2,X80
*
      ZERO                        * X80,X84,X88,X92,Y80,Y84,Y88,Y92
      NORMAL  16,32,48            * X81,X85,X89,X93,Y81,Y85,Y89,Y93
      SPCIAL                      * X82,X86,X90,X94,Y82,Y86,Y90,Y94
      NORMAL  48,96,144           * X83,X87,X91,X95,Y83,Y87,Y91,Y95
*
      LRLK    AR1,X100
      LRLK    AR2,X96
*
      ZERO                        * X96,X100,X104,X108,Y96,Y100,Y104,Y108
      NORMAL  16,32,48            * X97,X101,X105,X109,Y97,Y101,Y105,Y109
      SPCIAL                      * X98,X102,X106,X110,Y98,Y102,Y106,Y110
      NORMAL  48,96,144           * X99,X103,X107,X111,Y99,Y103,Y107,Y111
*
      LRLK    AR1,X116
      LRLK    AR2,X112
*
      ZERO                        * X112,X116,X120,X124,Y112,Y116,Y120,Y124
      NORMAL  16,32,48            * X113,X117,X121,X125,Y113,Y117,Y121,Y125
      SPCIAL                      * X114,X118,X122,X126,Y114,Y118,Y122,Y126
      NORMAL  48,96,144           * X115,X119,X123,X127,Y115,Y119,Y123,Y127
*
      LRLK    AR1,X132
      LRLK    AR2,X128
*
      ZERO                        * X128,X132,X136,X140,Y128,Y132,Y136,Y140
      NORMAL  16,32,48            * X129,X133,X137,X141,Y129,Y133,Y137,Y141
      SPCIAL                      * X130,X134,X138,X142,Y130,Y134,Y138,Y142
      NORMAL  48,96,144           * X131,X135,X139,X143,Y131,Y135,Y139,Y143
*
      LRLK    AR1,X148
      LRLK    AR2,X144
*
      ZERO                        * X144,X148,X152,X156,Y144,Y148,Y152,Y156
      NORMAL  16,32,48            * X145,X149,X153,X157,Y145,Y149,Y153,Y157
      SPCIAL                      * X146,X150,X154,X158,Y146,Y150,Y154,Y158
      NORMAL  48,96,144           * X147,X151,X155,X159,Y147,Y151,Y155,Y159
*
      LRLK    AR1,X164
      LRLK    AR2,X160
*
      ZERO                        * X160,X164,X168,X172,Y160,Y164,Y168,Y172
      NORMAL  16,32,48            * X161,X165,X169,X173,Y161,Y165,Y169,Y173
      SPCIAL                      * X162,X166,X170,X174,Y162,Y166,Y170,Y174
      NORMAL  48,96,144           * X163,X167,X171,X175,Y163,Y167,Y171,Y175
*
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```
        LRLK    AR1,X180
        LRLK    AR2,X176
*
        ZERO                    * X176,X180,X184,X188,Y176,Y180,Y184,Y188
        NORMAL  16,32,48        * X177,X181,X185,X189,Y177,Y181,Y185,Y189
        SPCIAL                  * X178,X182,X186,X190,Y178,Y182,Y186,Y190
        NORMAL  48,96,144       * X179,X183,X187,X191,Y179,Y183,Y187,Y191
*
        LRLK    AR1,X196
        LRLK    AR2,X192
*
        ZERO                    * X192,X196,X200,X204,Y192,Y196,Y200,Y204
        NORMAL  16,32,48        * X193,X197,X201,X205,Y193,Y197,Y201,Y205
        SPCIAL                  * X194,X198,X202,X206,Y194,Y198,Y202,Y206
        NORMAL  48,96,144       * X195,X199,X203,X207,Y195,Y199,Y203,Y207
*
        LRLK    AR1,X212
        LRLK    AR2,X208
*
        ZERO                    * X208,X212,X216,X220,Y208,Y212,Y216,Y220
        NORMAL  16,32,48        * X209,X213,X217,X221,Y209,Y213,Y217,Y221
        SPCIAL                  * X210,X214,X218,X222,Y210,Y214,Y218,Y222
        NORMAL  48,96,144       * X211,X215,X219,X223,Y211,Y215,Y219,Y223
*
        LRLK    AR1,X228
        LRLK    AR2,X224
*
        ZERO                    * X224,X228,X232,X236,Y224,Y228,Y232,Y236
        NORMAL  16,32,48        * X225,X229,X233,X237,Y225,Y229,Y233,Y237
        SPCIAL                  * X226,X230,X234,X238,Y226,Y230,Y234,Y238
        NORMAL  48,96,144       * X227,X231,X235,X239,Y227,Y231,Y235,Y239
*
        LRLK    AR1,X244
        LRLK    AR2,X240
*
        ZERO                    * X240,X244,X248,X252,Y240,Y244,Y248,Y252
        NORMAL  16,32,48        * X241,X245,X249,X253,Y241,Y245,Y249,Y253
        SPCIAL                  * X242,X246,X250,X254,Y242,Y246,Y250,Y254
        NORMAL  48,96,144       * X243,X247,X251,X255,Y243,Y247,Y251,Y255
*
*
******************************************************************************
*
* PASS 4
*
******************************************************************************
*
        LARK    AR0,4           * STEP VALUE BETWEEN BUTTERFLY "LEGS"
*
        LRLK    AR1,X1
        LRLK    AR2,X0
        ZERO                    * X0,X1,X2,X3,Y0,Y1,Y2,Y3
        LRLK    AR1,X5
        LRLK    AR2,X4
        ZERO                    * X4,X5,X6,X7,Y4,Y5,Y6,Y7
        LRLK    AR1,X9
        LRLK    AR2,X8
        ZERO                    * X8,X9,X10,X11,Y8,Y9,Y10,Y11
        LRLK    AR1,X13
        LRLK    AR2,X12
        ZERO                    * X12,X13,X14,X15,Y12,Y13,Y14,Y15
        LRLK    AR1,X17
        LRLK    AR2,X16
        ZERO                    * X16,X17,X18,X19,Y16,Y17,Y18,Y19
        LRLK    AR1,X21
        LRLK    AR2,X20
        ZERO                    * X20,X21,X22,X23,Y20,Y21,Y22,Y23
        LRLK    AR1,X25
        LRLK    AR2,X24
        ZERO                    * X24,X25,X26,X27,Y24,Y25,Y26,Y27
        LRLK    AR1,X29
        LRLK    AR2,X28
        ZERO                    * X28,X29,X30,X31,Y28,Y29,Y30,Y31
        LRLK    AR1,X33
        LRLK    AR2,X32
        ZERO                    * X32,X33,X34,X35,Y32,Y33,Y34,Y35
        LRLK    AR1,X37
        LRLK    AR2,X36
        ZERO                    * X36,X37,X38,X39,Y36,Y37,Y38,Y39
        LRLK    AR1,X41
        LRLK    AR2,X40
        ZERO                    * X40,X41,X42,X43,Y40,Y41,Y42,Y43
        LRLK    AR1,X45
        LRLK    AR2,X44
        ZERO                    * X44,X45,X46,X47,Y44,Y45,Y46,Y47
        LRLK    AR1,X49
        LRLK    AR2,X48
        ZERO                    * X48,X49,X50,X51,Y48,Y49,Y50,Y51
        LRLK    AR1,X53
        LRLK    AR2,X52
        ZERO                    * X52,X53,X54,X55,Y52,Y53,Y54,Y55
        LRLK    AR1,X57
        LRLK    AR2,X56
        ZERO                    * X56,X57,X58,X59,Y56,Y57,Y58,Y59
        LRLK    AR1,X61
        LRLK    AR2,X60
        ZERO                    * X60,X61,X62,X63,Y60,Y61,Y62,Y63
*
        LRLK    AR1,X65
        LRLK    AR2,X64
        ZERO                    * X64,X65,X66,X67,Y64,Y65,Y66,Y67
        LRLK    AR1,X69
        LRLK    AR2,X68
        ZERO                    * X68,X69,X70,X71,Y68,Y69,Y70,Y71
        LRLK    AR1,X73
        LRLK    AR2,X72
        ZERO                    * X72,X73,X74,X75,Y72,Y73,Y74,Y75
        LRLK    AR1,X77
        LRLK    AR2,X76
        ZERO                    * X76,X77,X78,X79,Y76,Y77,Y78,Y79
        LRLK    AR1,X81
        LRLK    AR2,X80
        ZERO                    * X80,X81,X82,X83,Y80,Y81,Y82,Y83
        LRLK    AR1,X85
        LRLK    AR2,X84
        ZERO                    * X84,X85,X86,X87,Y84,Y85,Y86,Y87
        LRLK    AR1,X89
        LRLK    AR2,X88
        ZERO                    * X88,X89,X90,X91,Y88,Y89,Y90,Y91
        LRLK    AR1,X93
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        LRLK    AR2,X92
        ZERO                    * X92,X93,X94,X95,Y92,Y93,Y94,Y95
        LRLK    AR1,X97
        LRLK    AR2,X96
        ZERO                    * X96,X97,X98,X99,Y96,Y97,Y98,Y99
        LRLK    AR1,X101
        LRLK    AR2,X100
        ZERO                    * X100,X101,X102,X103,Y100,Y101,Y102,Y103
        LRLK    AR1,X105
        LRLK    AR2,X104
        ZERO                    * X104,X105,X106,X107,Y104,Y105,Y106,Y107
        LRLK    AR1,X109
        LRLK    AR2,X108
        ZERO                    * X108,X109,X110,X111,Y108,Y109,Y110,Y111
        LRLK    AR1,X113
        LRLK    AR2,X112
        ZERO                    * X112,X113,X114,X115,Y112,Y113,Y114,Y115
        LRLK    AR1,X117
        LRLK    AR2,X116
        ZERO                    * X116,X117,X118,X119,Y116,Y117,Y118,Y119
        LRLK    AR1,X121
        LRLK    AR2,X120
        ZERO                    * X120,X121,X122,X123,Y120,Y121,Y122,Y123
        LRLK    AR1,X125
        LRLK    AR2,X124
        ZERO                    * X124,X125,X126,X127,Y124,Y125,Y126,Y127

        LRLK    AR1,X129
        LRLK    AR2,X128
        ZERO                    * X128,X129,X130,X131,Y128,Y129,Y130,Y131
        LRLK    AR1,X133
        LRLK    AR2,X132
        ZERO                    * X132,X133,X134,X135,Y132,Y133,Y134,Y135
        LRLK    AR1,X137
        LRLK    AR2,X136
        ZERO                    * X136,X137,X138,X139,Y136,Y137,Y138,Y139
        LRLK    AR1,X141
        LRLK    AR2,X140
        ZERO                    * X140,X141,X142,X143,Y140,Y141,Y142,Y143
        LRLK    AR1,X145
        LRLK    AR2,X144
        ZERO                    * X144,X145,X146,X147,Y144,Y145,Y146,Y147
        LRLK    AR1,X149
        LRLK    AR2,X148
        ZERO                    * X148,X149,X150,X151,Y148,Y149,Y150,Y151
        LRLK    AR1,X153
        LRLK    AR2,X152
        ZERO                    * X152,X153,X154,X155,Y152,Y153,Y154,Y155
        LRLK    AR1,X157
        LRLK    AR2,X156
        ZERO                    * X156,X157,X158,X159,Y156,Y157,Y158,Y159
        LRLK    AR1,X161
        LRLK    AR2,X160
        ZERO                    * X160,X161,X162,X163,Y160,Y161,Y162,Y163
        LRLK    AR1,X165
        LRLK    AR2,X164
        ZERO                    * X164,X165,X166,X167,Y164,Y165,Y166,Y167
        LRLK    AR1,X169
        LRLK    AR2,X168
        ZERO                    * X168,X169,X170,X171,Y168,Y169,Y170,Y171
        LRLK    AR1,X173
        LRLK    AR2,X172
        ZERO                    * X172,X173,X174,X175,Y172,Y173,Y174,Y175
        LRLK    AR1,X177
        LRLK    AR2,X176
        ZERO                    * X176,X177,X178,X179,Y176,Y177,Y178,Y179
        LRLK    AR1,X181
        LRLK    AR2,X180
        ZERO                    * X180,X181,X182,X183,Y180,Y181,Y182,Y183
        LRLK    AR1,X185
        LRLK    AR2,X184
        ZERO                    * X184,X185,X186,X187,Y184,Y185,Y186,Y187
        LRLK    AR1,X189
        LRLK    AR2,X188
        ZERO                    * X188,X189,X190,X191,Y188,Y189,Y190,Y191
*
        LRLK    AR1,X193
        LRLK    AR2,X192
        ZERO                    * X192,X193,X194,X195,Y192,Y193,Y194,Y195
        LRLK    AR1,X197
        LRLK    AR2,X196
        ZERO                    * X196,X197,X198,X199,Y196,Y197,Y198,Y199
        LRLK    AR1,X201
        LRLK    AR2,X200
        ZERO                    * X200,X201,X202,X203,Y200,Y201,Y202,Y203
        LRLK    AR1,X205
        LRLK    AR2,X204
        ZERO                    * X204,X205,X206,X207,Y204,Y205,Y206,Y207
        LRLK    AR1,X209
        LRLK    AR2,X208
        ZERO                    * X208,X209,X210,X211,Y208,Y209,Y210,Y211
        LRLK    AR1,X213
        LRLK    AR2,X212
        ZERO                    * X212,X213,X214,X215,Y212,Y213,Y214,Y215
        LRLK    AR1,X217
        LRLK    AR2,X216
        ZERO                    * X216,X217,X218,X219,Y216,Y217,Y218,Y219
        LRLK    AR1,X221
        LRLK    AR2,X220
        ZERO                    * X220,X221,X222,X223,Y220,Y221,Y222,Y223
        LRLK    AR1,X225
        LRLK    AR2,X224
        ZERO                    * X224,X225,X226,X227,Y224,Y225,Y226,Y227
        LRLK    AR1,X229
        LRLK    AR2,X228
        ZERO                    * X228,X229,X230,X231,Y228,Y229,Y230,Y231
        LRLK    AR1,X233
        LRLK    AR2,X232
        ZERO                    * X232,X233,X234,X235,Y232,Y233,Y234,Y235
        LRLK    AR1,X237
        LRLK    AR2,X236
        ZERO                    * X236,X237,X238,X239,Y236,Y237,Y238,Y239
        LRLK    AR1,X241
        LRLK    AR2,X240
        ZERO                    * X240,X241,X242,X243,Y240,Y241,Y242,Y243
        LRLK    AR1,X245
        LRLK    AR2,X244
        ZERO                    * X244,X245,X246,X247,Y244,Y245,Y246,Y247
        LRLK    AR1,X249
        LRLK    AR2,X248
```

```
      ZERO                       * X248,X249,X250,X251,Y248,Y249,Y250,Y251
      LRLK     AR1,X253
      LRLK     AR2,X252
      ZERO                       * X252,X253,X254,X255,Y252,Y253,Y254,Y255
*
*
* DIGIT REVERSE COUNTER FOR RADIX-4 FFT COMPUTATION.
*
        LARP 1
      DIGREV  1,64
      DIGREV  2,128
      DIGREV  3,192
      DIGREV  4,16
      DIGREV  5,80
      DIGREV  6,144
      DIGREV  7,208
      DIGREV  8,32
      DIGREV  9,96
      DIGREV  10,160
      DIGREV  11,224
      DIGREV  12,48
      DIGREV  13,112
      DIGREV  14,176
      DIGREV  15,240
      DIGREV  17,68
      DIGREV  18,132
      DIGREV  19,196
      DIGREV  21,84
      DIGREV  22,148
      DIGREV  23,212
      DIGREV  24,36
      DIGREV  25,100
      DIGREV  26,164
      DIGREV  27,228
      DIGREV  28,52
      DIGREV  29,116
      DIGREV  30,180
      DIGREV  31,244
      DIGREV  33,72
      DIGREV  34,136
      DIGREV  35,200
      DIGREV  37,88
      DIGREV  38,152
      DIGREV  39,216
      DIGREV  41,104
      DIGREV  42,168
      DIGREV  43,232
      DIGREV  44,56
      DIGREV  45,120
      DIGREV  46,184
      DIGREV  47,248
      DIGREV  49,76
      DIGREV  50,140
      DIGREV  51,204
      DIGREV  53,92
      DIGREV  54,156
      DIGREV  55,220
      DIGREV  57,108
      DIGREV  58,172
      DIGREV  59,236
      DIGREV  61,124
      DIGREV  62,188
      DIGREV  63,252
      DIGREV  66,129
      DIGREV  67,193
      DIGREV  69,81
      DIGREV  70,145
      DIGREV  71,209
      DIGREV  73,97
      DIGREV  74,161
      DIGREV  75,225
      DIGREV  77,113
      DIGREV  78,177
      DIGREV  79,241
      DIGREV  82,133
      DIGREV  83,197
      DIGREV  86,149
      DIGREV  87,213
      DIGREV  89,101
      DIGREV  90,165
      DIGREV  91,229
      DIGREV  93,117
      DIGREV  94,181
      DIGREV  95,245
      DIGREV  98,137
      DIGREV  99,201
      DIGREV  102,153
      DIGREV  103,217
      DIGREV  106,169
      DIGREV  107,233
      DIGREV  109,121
      DIGREV  110,185
      DIGREV  111,249
      DIGREV  114,141
      DIGREV  115,205
      DIGREV  118,157
      DIGREV  119,221
      DIGREV  122,173
      DIGREV  123,237
      DIGREV  126,189
      DIGREV  127,253
      DIGREV  131,194
      DIGREV  134,146
      DIGREV  135,210
      DIGREV  138,162
      DIGREV  139,226
      DIGREV  142,178
      DIGREV  143,242
      DIGREV  147,198
      DIGREV  151,214
      DIGREV  154,166
      DIGREV  155,230
      DIGREV  158,182
      DIGREV  159,246
      DIGREV  163,202
      DIGREV  167,218
      DIGREV  171,234
      DIGREV  174,186
      DIGREV  175,250
      DIGREV  179,206
      DIGREV  183,222
      DIGREV  187,238
      DIGREV  191,254
      DIGREV  199,211
      DIGREV  203,227
      DIGREV  207,243
      DIGREV  219,231
      DIGREV  223,247
      DIGREV  239,251
*
*        OUTPUT FFT DATA
*
        LARP 1
        LRLK AR1,X0
        RPTK 255
        OUT  *+,PA1
        RPTK 255
        OUT  *+,PA1
*
*  FFT COMPLETE.
*
WHOA    B    WHOA
        END
```

APPENDIX F

A 128-POINT, RADIX-2 DIF FFT IMPLEMENTATION (LOOPED CODE)

```
        IDT 'FFT2'
*
*    COOLEY-TUKEY 128-POINT, RADIX-2, DIF FFT PROGRAM FOR THE TMS32020.
*
*       SINGLE FFT BUTTERFLY.
*       REAL INPUT DATA, STORED IN PAGE 4 OF BLOCK B0.
*       FFT COMPUTATION IS DONE IN PAGES 6, 7 OF BLOCK B1 (COMPLEX NUMBERS).
*       USES TABLE LOOKUP (FROM PROGRAM MEMORY) OF THE TWIDDLE FACTORS.
*       INTERMEDIATE VALUES ARE SCALED BY .5 AT EACH STAGE SO AS TO PREVENT
*        THE POSSIBILITY OF OVERFLOW.
*       NO EXTERNAL RAM IS USED.
*       THE MAGNITUDE OF THE FFT IS COMPUTED AND NORMALIZED SO THAT ITS MAXIMUM
*       VALUE HAS A NONZERO BIT AFTER THE BINARY POINT.
*
*****************************************************************************
*
* N IS THE SIZE OF THE TRANSFORM.  N = 2**M.
*
N EQU 128
M EQU 7
*
XIN     EQU 512         * LOCATION OF REAL INPUT DATA
XOUT    EQU 640         * LOCATION OF REAL OUTPUT DATA
XFFT    EQU 768         * LOCATION OF COMPLEX DATA FOR THE FFT
*
* BLOCK B2 DATA MEMORY ALLOCATION (DP = 0 WILL ALWAYS POINT TO B2).
*
XT      EQU 96          * TEMPORARY - REAL PART
YT      EQU 97          * TEMPORARY - IMAGINARY PART
I       EQU 98          * 1ST INDEX
IA      EQU 99          * INDEX TO TWIDDLE FACTORS
IE      EQU 100         * INCREMENT TO IA
HOLDN   EQU 101         * CONTAINS VALUE N
QUARTN  EQU 102         * CONTAINS VALUE N/4
N1      EQU 103         * INCREMENT TO I.
N2      EQU 104         * SEPARATION OF I AND L
J       EQU 105         * LOOP COUNTER
K       EQU 106         * BIT REVERSAL INDEX COUNTER
ONE     EQU 107         * CONTAINS VALUE 1
IADDR   EQU 108         * CONTAINS INPUT
SINTBL  EQU 109         * SINE TABLE POINTER
SIN     EQU 110         * SINE LOCATION
COS     EQU 111         * COSINE LOCATION
MAX     EQU 112         * MAX VALUE OF THE SQR MAGNITUDE OF FFT
*
*
* BEGIN PROGRAM MEMORY SECTION.
*
*****************************************************************************
*
        AORG 0
RSVECT  B    32
        AORG 32
INIT    LDPK 0                  * ALWAYS POINT TO B2 FOR TEMP STORAGE
        CNFD
        SOVM
        SSXM                    * 32010 ARITHMETIC
        SPM  1                  * SHIFT PRODUCT LEFT BY 1
        LACK 1
        SACL ONE
        SACL IE                 * INITIALIZE IE = 1
        LALK N
        SACL HOLDN              * HOLDN = N
```

```
        SACL N2                 * INITIALIZE N2 = N
        LAC  HOLDN,14
        SACH QUARTN             * QUARTN = N/4
        LRLK AR3,XFFT           * ADDRESS OF COMPLEX INPUT DATA
        SAR  AR3,IADDR          * STORE ON PAGE 0
        LARP 2
        LARK AR1,M-1            * AR1 CONTAINS K COUNTER
*
*  READ IN 128 REAL POINTS
*
        LRLK    AR2,XIN
        RPTK    127
        IN      *+,PA0
*
*  INITIALIZE FFT RAM
*
        LRLK    AR2,XFFT
        ZAC
        SACL    MAX
        RPTK    255
        SACL    *+
*
*  MOVE REAL DATA FROM INPUT LOCATIONS TO COMPLEX FFT LOCATIONS
*
        LRLK    AR2,XFFT
        LARK    AR0,2
        RPTK    127
        BLKD    XIN,*0+
*
*  MOVE SQUARED MAGNITUDE OF PREVIOUS COMPUTATION TO OUTPUT LOCATIONS
*
        LRLK    AR2,XOUT
        RPTK    127
        BLKD    XFFT,*+
*
*  FFT COMPUTATION
*
KLOOP       LAC  N2,15
            SACH N1,1           * N1 = N2
            SACH N2             * N2 = N2/2
            ZAC
            SACL IA             * IA = 0
            SACL J              * J = 0
            LAR  AR2,N2         * AR2 CONTAINS J VALUE
            MAR  *-,AR3         * START AT N2-1
*
           LALK    SINE
           SACL    SINTBL       * SINE TABLE BASE ADDRESS
*
JLOOP          LAC  J,1
               SACL I           * I = J  (DATA ORGANIZED AS REAL VALUE FOLLOWED
*                                 BY IMAGINARY SO THAT ADDRESS I IS 2 TIMES J).
*
ILOOP             LAR  AR0,I
                  LAR  AR3,IADDR      * LOAD INPUT BASE ADDRESS
                  MAR  *0+            * AR3 = I + IADDR
                  LAR  AR0,N1         * ADD N2*2 (N1 = N2*2)
                  LAC  *0+,15         * LOAD (1/2)XI, POINT TO XL
*                                       (L = I + N2)
                  SUB  *,15           * XT = (1/2)(XI - XL)
                  SACH XT             * STORE XT ON PAGE 0
                  ADDH *0-            * XI = (1/2)(XI + XL), POINT TO XI
                  SACH *+             * STORE XI, POINT TO YI
```

```
          LAC  *0+,15          * LOAD (1/2)YI, POINT TO YL
          SUB  *,15            * YT = (1/2)(YI - YL)
          SACH YT
          ADDH *0-             * YI = (1/2)(YI + YL), POINT TO YI
          SACH *0+             * STORE YI, POINT TO YL
*
        LAC     SINTBL
        TBLR    SIN            * READ IN SINE
        ADD     QUARTN
        TBLR    COS            * READ IN COSINE
*
        LT      COS
        MPY     YT             * YT*COS-->P
        LTP     SIN
        MPY     XT             * XT*SIN-->P
        SPAC
        SACH    *-             * YL = XT*COS - XT*SIN
        MPY     YT             * YT*SIN-->P
        LTP     COS
        MPY     XT             * XT*COS-->P
        APAC
        SACH    *              * XL = XT*COS + YT*SIN
*
*
* ADD INCREMENT FOR NEXT LOOP.
*
          LAC  I
          ADD  N1,1            * I = I + N1
          SACL I
          SUB  HOLDN,1         * WHILE I < N
          BLZ  ILOOP
*
        LAC  SINTBL          * INDEX SINTBL POINTER BY IE
        ADD  IE
        SACL SINTBL
*
        LAC  J
        ADD  ONE               * J = J + 1
        SACL J
        LARP 2
        BANZ JLOOP,*-,AR3
*
      LAC  IE,1
      SACL IE                  * IE = 2 * IE
      LARP 1
      BANZ KLOOP,*-,AR2
*
* DIGIT REVERSE COUNTER FOR RADIX-2 FFT COMPUTATION.
*
DRC2    ZAC
        SACL I
        SACL J
        LAR  AR0,IADDR
        LARP 4
        LAR  AR4,HOLDN         * FOR I = 0 TO N-2
        MAR  *-
        MAR  *-,AR2
DRLOOP       SUB  J            * IF I < J, THEN SWAP
             BGEZ NOSWAP
*
                 LAR  AR2,J
                 MAR  *0+,AR3  * J = J + IADDR
                 LAR  AR3,I

                   MAR  *0+,AR2    * I = I + IADDR
* SWAP I AND L VALUES.
                   ZALH *,AR3
                   ADDS *
                   SACH *+,0,AR2   * X(I) = X(J)
                   SACL *+         * X(J) = X(I)
*
                   ZALH *,AR3
                   ADDS *
                   SACH *,0,AR2    * Y(I) = Y(J)
                   SACL *,0,AR3    * Y(J) = Y(I)
NOSWAP        LAC  HOLDN
              SACL K                       * K = N
INLOOP             LAC  J
                   SUB  K                  * IF J >= K THEN
                   BLZ  OUTLOP,*,AR4
                        SACL J             * J = J - K
                        LAC  K,15
                        SACH K             * K = K/2.
                        B    INLOOP
OUTLOP        ADD  K,1
              SACL J                       * L = L + J
              LAC  I
              ADD  ONE,1
              SACL I                       * INCREMENT I
              BANZ DRLOOP,*-,AR2
*
*
*   COMPUTE THE MAXIMUM VALUE OF THE SQUARED MAGNITUDE OF FFT
*
        LRLK    AR2,XFFT
        LARK    AR3,127
*
LOOP1   ZAC
        MPYK    0
        SQRA    *+                   * X(I)**2
        SQRA    *+,AR3               * Y(I)**2
        APAC
        SACH    IADDR                * IADDR = X(I)**2 + Y(I)**2
        SUBH    MAX
        BLEZ    CONT
        LAC     IADDR
        SACL    MAX
CONT    BANZ    LOOP1,*-,AR2
*
*   NORMALIZE THE MAX VALUE TO FIND EXPONENT
*
        LARK    AR2,0
        ZALH    MAX
        RPTK    14
        NORM                         * AR2 CONTAINS EXPONENT
        SAR     AR2,I                * STORE EXPONENT IN I
*
*   COMPUTE SQUARED MAGNITUDE OF FFT
*
        LRLK    AR2,XFFT
        LRLK    AR1,XFFT
        LARK    AR3,127
*
LOOP2   ZAC
        MPYK    0
        SQRA    *+                   * X(I)**2
        SQRA    *+,AR1               * Y(I)**2
```

```
        APAC
        SFR
        RPT     I
        SFL                                 * NORMALIZE RESULT
        SACH    *+,0,AR3                    * XOUT(I) = X(I)**2 + Y(I)**2
        BANZ    LOOP2,*-,AR2
*
*   OUTPUT SQUARED MAGNITUDE
*
        LRLK    AR2,XFFT
        RPTK    127
        OUT     *+,PA2
*
*  FFT COMPLETE.
*
WHOA    B WHOA
*
* COEFFICIENT TABLE (SIZE OF TABLE IS 3N/4).
*
SINE EQU $
      DATA >0
      DATA >648
      DATA >C8C
      DATA >12C8
      DATA >18F9
      DATA >1F1A
      DATA >2528
      DATA >2B1F
      DATA >30FC
      DATA >36BA
      DATA >3C57
      DATA >41CE
      DATA >471D
      DATA >4C40
      DATA >5134
      DATA >55F6
      DATA >5A82
      DATA >5ED7
      DATA >62F2
      DATA >66D0
      DATA >6A6E
      DATA >6DCA
      DATA >70E3
      DATA >73B6
      DATA >7642
      DATA >7885
      DATA >7A7D
      DATA >7C2A
      DATA >7D8A
      DATA >7E9D
      DATA >7F62
      DATA >7FD9
COSINE EQU $
      DATA >7FFF
      DATA >7FD9
      DATA >7F62
      DATA >7E9D
      DATA >7D8A
      DATA >7C2A
      DATA >7A7D
      DATA >7885
      DATA >7642
      DATA >73B6
      DATA >70E3
      DATA >6DCA
      DATA >6A6E
      DATA >66D0
      DATA >62F2
      DATA >5ED7
      DATA >5A82
      DATA >55F6
      DATA >5134
      DATA >4C40
      DATA >471D
      DATA >41CE
      DATA >3C57
      DATA >36BA
      DATA >30FC
      DATA >2B1F
      DATA >2528
      DATA >1F1A
      DATA >18F9
      DATA >12C8
      DATA >C8C
      DATA >648
      DATA >0
      DATA >F9B8
      DATA >F374
      DATA >ED38
      DATA >E707
      DATA >E0E6
      DATA >DAD8
      DATA >D4E1
      DATA >CF04
      DATA >C946
      DATA >C3A9
      DATA >BE32
      DATA >B8E3
      DATA >B3C0
      DATA >AECC
      DATA >AA0A
      DATA >A57E
      DATA >A129
      DATA >9D0E
      DATA >9930
      DATA >9592
      DATA >9236
      DATA >8F1D
      DATA >8C4A
      DATA >89BE
      DATA >877B
      DATA >8583
      DATA >83D6
      DATA >8276
      DATA >8163
      DATA >809E
      DATA >8027
      END
```

APPENDIX G

A 256-POINT, RADIX-2 DIF FFT IMPLEMENTATION (LOOPED CODED)

```
        IDT 'FFT2'
*
*    COOLEY-TUKEY 256-POINT, RADIX-2, DIF FFT PROGRAM FOR THE TMS32020.
*
*       SINGLE FFT BUTTERFLY.
*       COMPLEX INPUT DATA, STORED AS X(I), Y(I), X(I+1), Y(I+1), ...
*       USES TABLE LOOKUP (FROM EXTERNAL DATA MEMORY) OF THE TWIDDLE FACTORS.
*       INTERMEDIATE VALUES ARE SCALED BY .5 AT EACH STAGE SO AS TO PREVENT
*        THE POSSIBILITY OF OVERFLOW.
*
*******************************************************************************
*
* N IS THE SIZE OF THE TRANSFORM.  N = 2**M.
*
N EQU 256
M EQU 8
*
INPUT   EQU 512          * LOCATION OF COMPLEX INPUT DATA IN INTERNAL DATA MEM
TABLE   EQU 1024         * LOCATION OF COEFFICIENT TABLE IN EXTERNAL DATA MEM
*
* BLOCK B2 DATA MEMORY ALLOCATION (DP = 0 WILL ALWAYS POINT TO B2).
*
XT      EQU 96           * TEMPORARY - REAL PART
YT      EQU 97           * TEMPORARY - IMAGINARY PART
I       EQU 98           * 1ST INDEX
IA      EQU 99           * INDEX TO TWIDDLE FACTORS
IE      EQU 100          * INCREMENT TO IA
HOLDN   EQU 101          * CONTAINS VALUE N
QUARTN  EQU 102          * CONTAINS VALUE N/4
N1      EQU 103          * INCREMENT TO I.
N2      EQU 104          * SEPARATION OF I AND L
J       EQU 105          * LOOP COUNTER
K       EQU 106          * BIT REVERSAL INDEX COUNTER
ONE     EQU 107          * CONTAINS VALUE 1
IADDR   EQU 108          * CONTAINS INPUT
COSTBL  EQU 109          * COSTBL = TABLE + N/4
*
*
* BEGIN PROGRAM MEMORY SECTION.
*
*******************************************************************************
*
         AORG 0
RSVECT   B    32
         AORG 32
INIT     LDPK 0               * ALWAYS POINT TO B2 FOR TEMP STORAGE
         SOVM
         SSXM                 * 32010 ARITHMETIC
         SPM  1               * SHIFT PRODUCT LEFT BY 1
         LACK 1
         SACL ONE
         SACL IE              * INITIALIZE IE = 1
         LALK N
         SACL HOLDN           * HOLDN = N
         SACL N2              * INITIALIZE N2 = N
         LAC  HOLDN,14
         SACH QUARTN          * QUARTN = N/4
         LRLK AR3,INPUT       * ADDRESS OF COMPLEX INPUT DATA
         SAR  AR3,IADDR       * STORE ON PAGE 0
         LRLK AR4,TABLE       * ADDRESS OF SINE TABLE
         LARP 4
         RPTK 191             * MOVE 192 COEFFICIENTS
         BLKP SINE,*+
         LRLK AR4,TABLE       * ADDRESS OF SINE TABLE
         LAR  AR0,QUARTN
         MAR  *0+,AR2         * COSTBL = TABLE + N/4, point to J counter
         SAR  AR4,COSTBL
         LARK AR1,M-1         * AR1 CONTAINS K COUNTER
*
*  READ IN 256 COMPLEX POINTS
*
        LRLK    AR2,INPUT
        RPTK    255
        IN      *+,PA0
        RPTK    255
        IN      *+,PA0
*
*  FFT COMPUTATION
*
KLOOP         LAC  N2,15
              SACH N1,1         * N1 = N2
              SACH N2           * N2 = N2/2
              ZAC
              SACL IA           * IA = 0
              SACL J            * J = 0
              LAR  AR2,N2       * AR2 CONTAINS J VALUE
              MAR  *-,AR3       * START AT N2-1
*
              LAR  AR4,COSTBL   * COSINE TABLE BASE ADDRESS
*
JLOOP            LAC  J,1
                 SACL I         * I = J  (DATA ORGANIZED AS REAL VALUE FOLLOWED
*                                 BY IMAGINARY SO THAT ADDRESS I IS 2 TIMES J).
*
ILOOP               LAR  AR0,I
                    LAR  AR3,IADDR       * LOAD INPUT BASE ADDRESS
                    MAR  *0+             * AR3 = I + IADDR
                    LAR  AR0,N1          * ADD N2*2 (N1 = N2*2)
                    LAC  *0+,15          * LOAD (1/2)XI, POINT TO XL
*                                          (L = I + N2)
                    SUB  *,15            * XT = (1/2)(XI - XL)
                    SACH XT              * STORE XT ON PAGE 0
                    ADDH *0-             * XI = (1/2)(XI + XL), POINT TO XI
                    SACH *+              * STORE XI, POINT TO YI
                    LAC  *0+,15          * LOAD (1/2)YI, POINT TO YL
                    SUB  *,15            * YT = (1/2)(YI - YL)
                    SACH YT
                    ADDH *0-             * YI = (1/2)(YI + YL), POINT TO YI
                    SACH *0+,0,AR4       * STORE YI, POINT TO YL
*                                          AR4 POINTS TO COSTBL
                    LAR  AR0,QUARTN
                    LT   *0-             * LOAD T WITH COS, POINT TO SIN
                    MPY  YT
                    LTP  *0+,AR3         * ACC <-- C*YT, POINT TO YL
                    MPY  XT
                    SPAC                 * YL = C*YT - S*XT
                    SACH *-,0,AR4        * STORE YL
                    MPY  YT
                    LTP  *,AR3           * ACC <-- S*YT, POINT TO XL
                    MPY  XT
                    APAC                 * XL = C*XT + S*YT
                    SACH *               * STORE XL
*
*
* ADD INCREMENT FOR NEXT LOOP.
```

```
*
                LAC   I
                ADD   N1,1              * I = I + N1
                SACL  I
                SUB   HOLDN,1           * WHILE I < N
                BLZ   ILOOP
*
            LAR   AR0,IE            * INDEX COSTBL POINTER BY IE
            LARP  4
            MAR   *0+,AR2
            LAC   J
            ADD   ONE                   * J = J + 1
            SACL  J
            BANZ  JLOOP,*-,AR3
*
         LAC   IE,1
         SACL  IE                       * IE = 2 * IE
         LARP  1
         BANZ  KLOOP,*-,AR2
*
* DIGIT REVERSE COUNTER FOR RADIX-2 FFT COMPUTATION.
*
DRC2     ZAC
         SACL  I
         SACL  J
         LAR   AR0,IADDR
         LARP  4
         LAR   AR4,HOLDN                * FOR I = 0 TO N-2
         MAR   *-
         MAR   *-,AR2
DRLOOP          SUB   J                 * IF I < J, THEN SWAP
                BGEZ  NOSWAP
*
                        LAR   AR2,J
                        MAR   *0+,AR3   * J = J + IADDR
                        LAR   AR3,I
                        MAR   *0+,AR2   * I = I + IADDR
* SWAP I AND L VALUES.
                        ZALH  *,AR3
                        ADDS  *
                        SACH  *+,0,AR2  * X(I) = X(J)
                        SACL  *+        * X(J) = X(I)
*
                        ZALH  *,AR3
                        ADDS  *
                        SACH  *,0,AR2   * Y(I) = Y(J)
                        SACL  *,0,AR3   * Y(J) = Y(I)
NOSWAP          LAC   HOLDN
                SACL  K                         * K = N
INLOOP                  LAC   J
                        SUB   K                 * IF J >= K THEN
                        BLZ   OUTLOP,*,AR4
                                SACL  J         * J = J - K
                                LAC   K,15
                                SACH  K         * K = K/2.
                                B     INLOOP
OUTLOP          ADD   K,1
                SACL  J                         * L = L + J
                LAC   I
                ADD   ONE,1
                SACL  I                         * INCREMENT I
                BANZ  DRLOOP,*-,AR2
*
*   OUTPUT FFT VALUES
*
        LRLK    AR2,INPUT
        RPTK    255
        OUT     *+,PA1
        RPTK    255
        OUT     *+,PA1
*
*  FFT COMPLETE.
*
WHOA    B WHOA
*
* COEFFICIENT TABLE (SIZE OF TABLE IS 3N/4).
*
SINE EQU $
      DATA >0
      DATA >324
      DATA >648
      DATA >96B
      DATA >C8C
      DATA >FAB
      DATA >12C8
      DATA >15E2
      DATA >18F9
      DATA >1C0C
      DATA >1F1A
      DATA >2224
      DATA >2528
      DATA >2827
      DATA >2B1F
      DATA >2E11
      DATA >30FC
      DATA >33DF
      DATA >36BA
      DATA >398D
      DATA >3C57
      DATA >3F17
      DATA >41CE
      DATA >447B
      DATA >471D
      DATA >49B4
      DATA >4C40
      DATA >4EC0
      DATA >5134
      DATA >539B
      DATA >55F6
      DATA >5843
      DATA >5A82
      DATA >5CB4
      DATA >5ED7
      DATA >60EC
      DATA >62F2
      DATA >64E9
      DATA >66D0
      DATA >68A7
      DATA >6A6E
      DATA >6C24
      DATA >6DCA
      DATA >6F5F
      DATA >70E3
      DATA >7255
      DATA >73B6
      DATA >7505
```

```
       DATA >7642
       DATA >776C
       DATA >7885
       DATA >798A
       DATA >7A7D
       DATA >7B5D
       DATA >7C2A
       DATA >7CE4
       DATA >7D8A
       DATA >7E1E
       DATA >7E9D
       DATA >7F0A
       DATA >7F62
       DATA >7FA7
       DATA >7FD9
       DATA >7FF6
COSINE EQU $
       DATA >7FFF
       DATA >7FF6
       DATA >7FD9
       DATA >7FA7
       DATA >7F62
       DATA >7F0A
       DATA >7E9D
       DATA >7E1E
       DATA >7D8A
       DATA >7CE4
       DATA >7C2A
       DATA >7B5D
       DATA >7A7D
       DATA >798A
       DATA >7885
       DATA >776C
       DATA >7642
       DATA >7505
       DATA >73B6
       DATA >7255
       DATA >70E3
       DATA >6F5F
       DATA >6DCA
       DATA >6C24
       DATA >6A6E
       DATA >68A7
       DATA >66D0
       DATA >64E9
       DATA >62F2
       DATA >60EC
       DATA >5ED7
       DATA >5CB4
       DATA >5A82
       DATA >5843
       DATA >55F6
       DATA >539B
       DATA >5134
       DATA >4EC0
       DATA >4C40
       DATA >49B4
       DATA >471D
       DATA >447B
       DATA >41CE
       DATA >3F17
       DATA >3C57
       DATA >398D
       DATA >36BA
       DATA >33DF
       DATA >30FC
       DATA >2E11
       DATA >2B1F
       DATA >2827
       DATA >2528
       DATA >2224
       DATA >1F1A
       DATA >1C0C
       DATA >18F9
       DATA >15E2
       DATA >12C8
       DATA >FAB
       DATA >C8C
       DATA >96B
       DATA >648
       DATA >324
       DATA >0
       DATA >FCDC
       DATA >F9B8
       DATA >F695
       DATA >F374
       DATA >F055
       DATA >ED38
       DATA >EA1E
       DATA >E707
       DATA >E3F4
       DATA >E0E6
       DATA >DDDC
       DATA >DAD8
       DATA >D7D9
       DATA >D4E1
       DATA >D1EF
       DATA >CF04
       DATA >CC21
       DATA >C946
       DATA >C673
       DATA >C3A9
       DATA >C0E9
       DATA >BE32
       DATA >BB85
       DATA >B8E3
       DATA >B64C
       DATA >B3C0
       DATA >B140
       DATA >AECC
       DATA >AC65
       DATA >AA0A
       DATA >A7BD
       DATA >A57E
       DATA >A34C
       DATA >A129
       DATA >9F14
       DATA >9D0E
       DATA >9B17
       DATA >9930
       DATA >9759
       DATA >9592
       DATA >93DC
       DATA >9236
       DATA >90A1
       DATA >8F1D
       DATA >8DAB
       DATA >8C4A
       DATA >8AFB
       DATA >89BE
       DATA >8894
       DATA >877B
       DATA >8676
       DATA >8583
       DATA >84A3
       DATA >83D6
       DATA >831C
       DATA >8276
       DATA >81E2
       DATA >8163
       DATA >80F6
       DATA >809E
       DATA >8059
       DATA >8027
       DATA >800A
       END
```