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A Full Field, 3-D Velocimeter for Microgravity Crystallization Experiments

Robert S. Brodkey and Keith M. Russ
Department of Chemical Engineering

NASA Lewis Research Center
Cleveland, Ohio 44135

Grant No. NAG 3-1039
Final Report

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ORIGINAL CONTAINS
COLOR ILLUSTRATIONS

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Contents

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Overview

In our proposal, we set forth to develop the programming and algorithms needed for implementing a full-field, 3D velocimeter for laminar flow systems, and to recommend appropriate hardware to fully implement this ultimate system. Over the course of the project, we realized that these two steps are not as distinctly separate as we once thought; the software solutions can be modified to take advantage of various hardware configurations.

This summary indicates one possible hardware solution, already provided in the informal report provided to NASA researchers in January, 1990. The current state of our programming efforts is also provided, as well as such code as is appropriate.

Basic experimental statement

The velocimeter should consist of two views of the flow system, in this case the interface area of a crystallization experiment. These views are directly digitized by the use of a video camera(s) and a computer digitizer board(s), and the velocities determined by a combination of hardware image processing and software image analysis.

View configuration

The simplest view configuration to visualize is a pair of video cameras mounted at right angles to each other (orthogonal views), with a common field of view in the flow system. This will require a synched pair of video cameras and digitizer boards, as well as synched rails for camera motion. These views were tested by NASA by simulating the flow in a crystallization ampoule (Plate I(a-b)). Although it is not readily apparant in the image pair, some 50% or more of the viewed volume is blocked for 3D analysis by the heater element images (after simple processing). This blockage made 3D path matching an almost impossible task, especially when the lack of registration points in the images and the difference in the view magnification (obvious in Plate I(a-b)) are considered.

It is recommended that the orthogonal viewing (90° angle) be replaced with a low to medium angle viewing, between stereo angle separation (approximately 10°) and about 30°. This will reduce blockage effects at the cost of depth accuracy. As the flow system is laminar, depth accuracy should be considered a minor point.

There has recently been developed a single camera 3D acquisition technique. Such a technique holds significant potential for replacing low angle stereo viewing, as well as reducing hardware costs without significantly degrading software computational requirements. We hope to investigate this option, pending further support.

Hardware configuration

This is perhaps the most flexible area, although dependent on (and instrumental in) the view configuration decided upon above. Two digitizer boards (to avoid image capture sequencing) and two video cameras would be required for stereo acquisition, each capable of 512x512 resolution (black and white). The EPIX 1MEG VIDEO Model 10 digitizer board appears to be an excellent choice for this work; it is capable of storing 4 images in its own memory, and has an on-board digital processor that can be programmed to perform the image processing we envision to be necessary. Such on-board processing should provide significant reductions to computation time.

The video cameras each need to be of around 512x512 non-interlaced resolution (either to the RS-170 resolution of 768x480 pixels, or perhaps the European CCIR standard of 768x580 pixels). Such units are relatively inexpensive ($1,500 apiece and up, without lenses). Of the two standards, the CCIR hardware appears to be more attractive with its higher resolution.

Computer configuration

The host computer for the imaging hardware would dictate the speed at which the images are analyzed for velocity, as well as any control actions one

may wish to take as a result of such data. For the computer, it seems necessary to obtain the absolute best performance at the most reasonable cost. Currently, this claim rests with Intel's 80486 processor, in whatever machine from whatever vendor. The majority of machines available now are based on Intel's 80386, which for similar clockspeeds operates up to 2 to 4 times more slowly than an 80486. Unfortunately, the 80486 is so recent that software availability is limited. The minimum requirements are an 80386 machine, at whatever clockspeeds are available (80386 computers can be found running at 16,20, 25 and 33 MHz; costs start rising significantly with the 25 and 33 MHz models), using at the absolute minimum 2 MB of RAM and preferably 4 MB. Video adapters and hard drives are of secondary importance, since all of the grunt work will take place between the CPU and the RAM. It is therefore essential that the RAM be of sufficient speed to match the CPU.

The 80386 can run the MS-DOS or UNIX operating systems. UNIX is perhaps the preferential system, especially when paired with the C programming language. Since C and UNIX are still in standardization, however, it is perhaps better to stick to the older FORTRAN language in MS-DOS, which provides all the numerical routines you could ever wish for at the expense of data handling. Such a compiler needs to run under a MS-DOS extension to allocate and utilize large arrays 512x512 or larger), and should be specific for the 80386 instruction set (or, if an 80486 is used it should be specific to it). A particularly inviting compiler and related software that fits this description is marketed by MicroWay. Their NDP Fortran-386, as illustrated by their data sheet, provides excellent number-crunching facilities. When combined with the Phar-Lap DOS extender, this PC-based compiler can access arrays limited only by the on-board RAM (in this case, the recommended 2-4 MB); additionally, a virtual memory manage can be added to utilize the hard drive as virtual RAM, thereby economically increasing potential array size.

Finally, an Assembler linker would be needed to best utilize the EPIX boards. The EPIX boards include an on-board digital signal processor, programmable in

Assembler. The EPIX people recommend the product of Avocet, at around $350.

Image processing

Our current technique is to take a sequence of images (at least 3, but it could be up to 8), create a series of binary images from these, and add them together to create one image for analysis. From this one image particle velocities and paths can be calculated for each resultant frame. The combination of the images can be accomplished by

$$S_{j,k}=\sum_{l=1}^{n} 2^{l-1} I_{l_{j,k}} \qquad (1)$$

for n=3,4,5,6,7, or 8, and for every (j,k)th point in the original images (I_l). Three of the NASA slides (of which Plate I(a) is the first), digitized and added together by the above equation, is given in Plate II(a). This represents the final output of image processing.

Image analysis

Image analysis of the particle paths, clearly visible in Plate II(a-b), represents three operations: *particle identification*, whereby the particles are located by their centers, grey levels, and size; *particle tracking*, whereby the particles are tracked within the image; and *3D track matching*, which matches tracks within the two views to determine the 3D information. The particle identification algorithm, a modification of that by Chang et al. (1985)[1], identifies the particles from top to bottom, left to right, row by row. The identified particles are screened to eliminate spurious anomalies left over from image processing (i.e. below a d_{min} or above a d_{max}). The particles found from this for Plate II(a) are given in Figure 1. The code is given in Appendix A, and a flowchart in Figure 2.

---

[1]Chang, T.P.K, Watson, A.T., and Tatterson, G.B., Image Processing of Tracer Particle Motions as Applied to Mixing and Turbulent Flow - I. The Technique, *Chem. Eng. Sci.* **40**, 269 (1985)

The particle tracking algorithm utilizes a rudimentary form of path and velocity coherence. The particles found from the previous step are sorted into four lists, one for each frame. Due to the nature of the particle ID algorithm, these particles are already approximately sorted in the lists from low to high y values. Starting from the beginning, each 1st frame particle is compared with candidate 2nd frame particles, and each 2nd frame with candidate 3rd frame particles, until one of the following conditions is met:

$$\Delta y > \Delta y_{max} \tag{2a}$$

$$\frac{|v_{1\to2} - v_{2\to3}|}{\left(\frac{v_{1\to2} + v_{2\to3}}{2}\right)} < tol_v \qquad and \qquad |\theta_{1\to2} - \theta_{2\to3}| < tol_\theta \tag{2b}$$

where 1,2, and 3 refer to frames, and θ is the angle as if the particle pair were in polar coordinates (of which the magnitude of the velocity is the other coordinate; see Figure 3). Δy_{max} is the maximum expected frame-to-frame particle movement in y, tol_v is the maximum change in average velocity between each pair of frames, and tol_θ is the maximum angular motion of the particle. This represents the *basic* tracking algorithm; its implementation was modified by using a simulated image.

Some of the particle paths in Figure 1 are clearly visible; others are not. It is not easy to quantify the particle tracking algorithm in such a case. To help determine the accuracy of the tracking algorithm, a test image was created having 200 randomly determined velocity vectors (Figure 4).

It was found that the tracking algorithm (Eq. 2) ran exceedingly fast. To increase the tracker's accuracy, multiple passes (varying Δy_{max}, tol_v, tol_θ) were implemented. In addition the lists were matched in reverse order, i.e. from bottom right to upper left,and compared to the forward direction; particle tracks that were found in both directions were kept, while the remaining were

discarded. The results of the tracking are given in Table I and Figure 5(a-b). The tracker only utilizes three frames' data; fourth frame data could be used to perhaps increase accuracy further.

Figure 6(a-b) represents the output of the tracker on the data from Figure 1. Not all particles represent a particle track, as some are the result of noise in the original image. There are approximately 94 actual tracks in view; of these, 81 (86.2%) were correctly matched, while 4 (4.3%) were mistracked. The code for the tracker is given in Appendix B, and a flowchart is given in Figure 7.

3-D matching has not, as yet, been implemented due to the problems mentioned in section 3. The identified particles and tracks for Plate II(b) are given in Figures 8 and 9(a-b), respectively.

Conclusions

It appears that imaging will provide a viable solution to the laminar tracking problem. Certainly the algorithms given here are simple, which in turn should speed processing. Accuracy is good, but processing times are unknown as we haven't the hardware or software to properly test the code, as a result of not being able to fully implement the second year of the proposed study. On a heavily loaded VAXstation 3100 the particle identification can take 15-30 seconds, and the tracking completed in under a second. It seems reasonable to assume that 4 image pairs can be thus be acquired and analyzed in under 1 minute.

The remaining stumbling blocks in the project appear to be the choice of tracer particle and two processing problems: 3-D matching and settling velocity estimation (the extent of this problem is dependent on tracer particle choice, obviously).

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Plate I: *(a) Left flow image, first frame (t=0), of particles in laminar flow in the crystallization furnace. (b) Right flow image, corresponding to (a).*

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COLOR PHOTOGRAPH

Plate II: *(a) Summation of binary images for left view flow, using Eq. 1. (b) Equivalent image for right view flow.*

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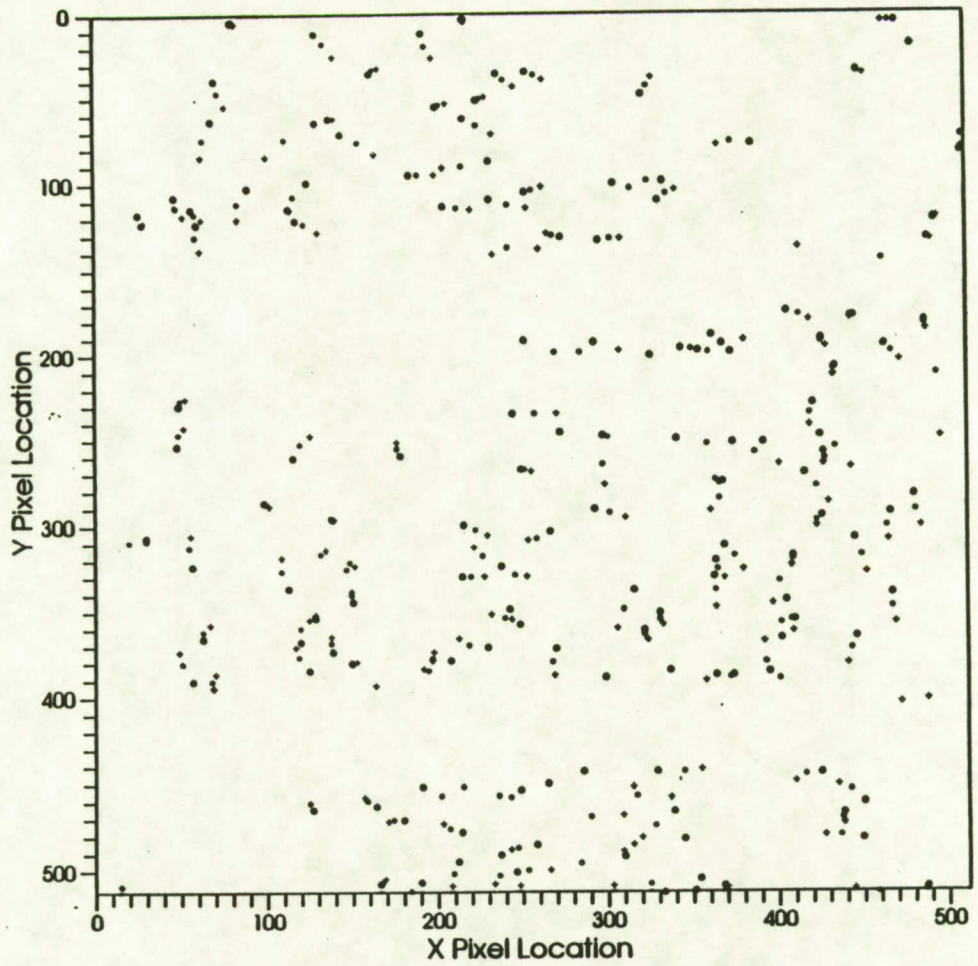


Figure 1: *Particles Identified for Plate II(a) (• first frame; * second frame; + third frame).*

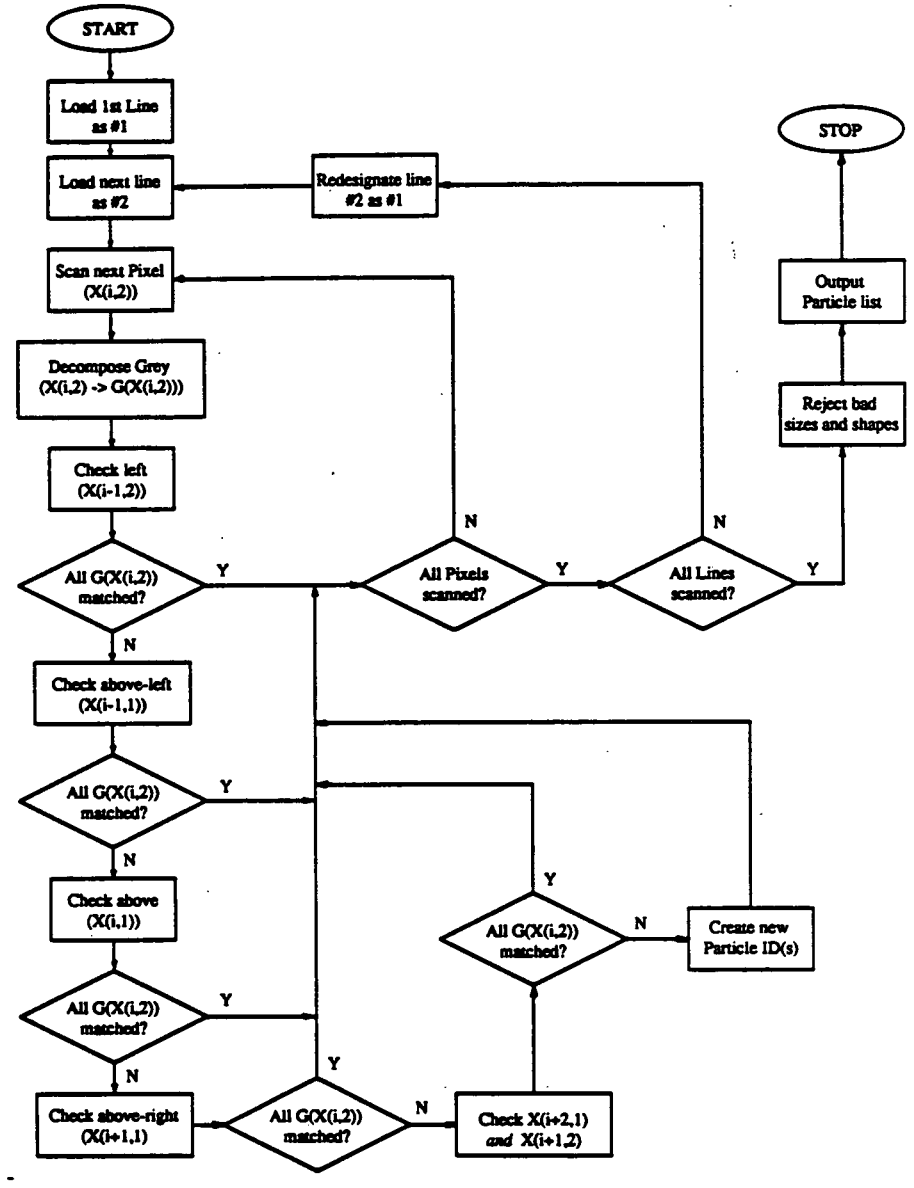


Figure 2: *Flowchart for PART_ID.FOR.*

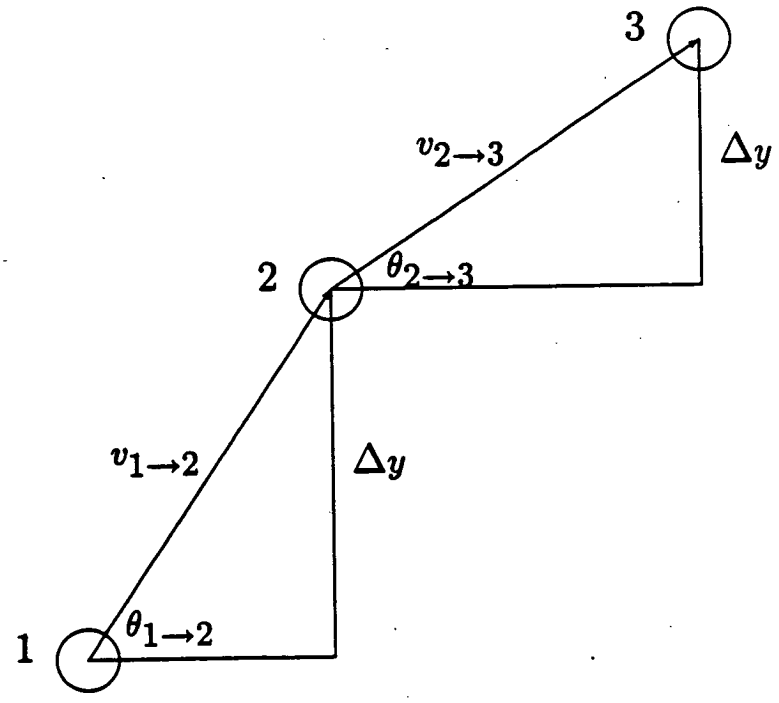


Figure 3: *3 point simplistic tracker.*

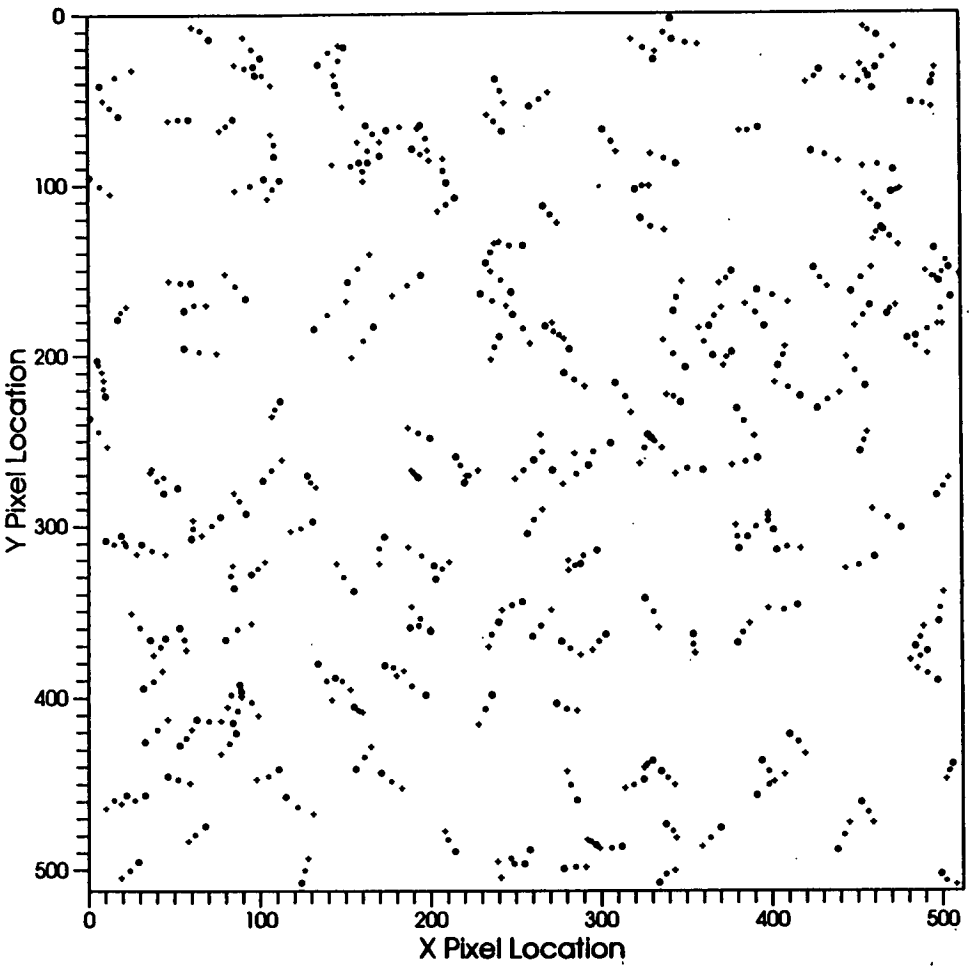


Figure 4: *Simulated image for testing tracker (• first frame; * second frame; + third frame).*

Table I: *Results of the tracker on the simulated image, Figure 4.*

Iteration	Δy_{max}	TOL_v	TOL_θ	% Not Found	% Wrong	% Correct
1	5	1.0	1.0	81.00	1.00	18.00
2	10	0.8	1.0	12.00	4.50	83.50
3	15	0.5	1.0	**5.00**	**5.50**	**89.50**

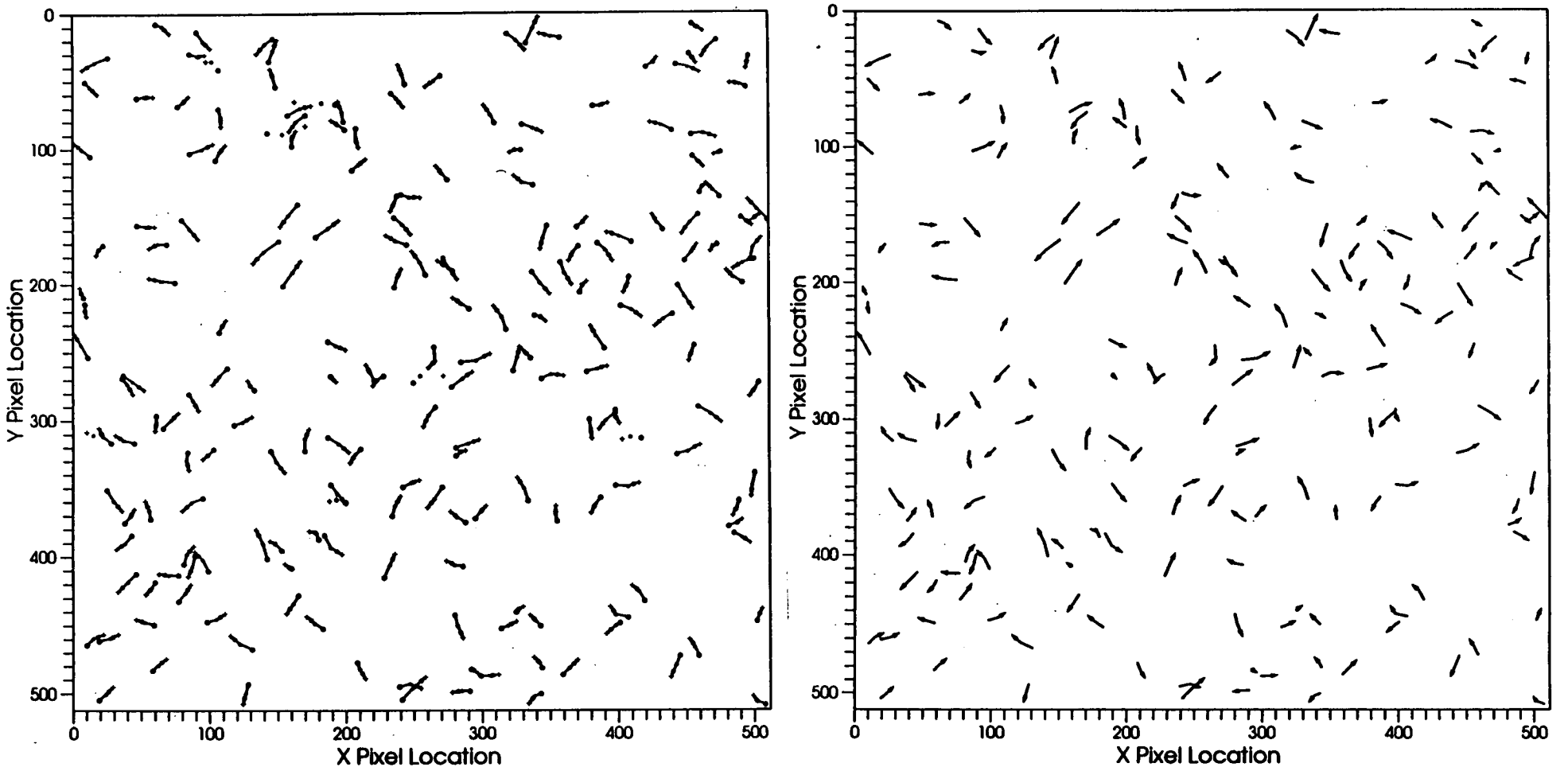


Figure 5: *(a) Particle tracks identified for the simulated image, Figure 4, including particle locations (• first frame; * second frame; + third frame). (b) Particle tracks identified for the simulated image, Figure 4, vectors only.*

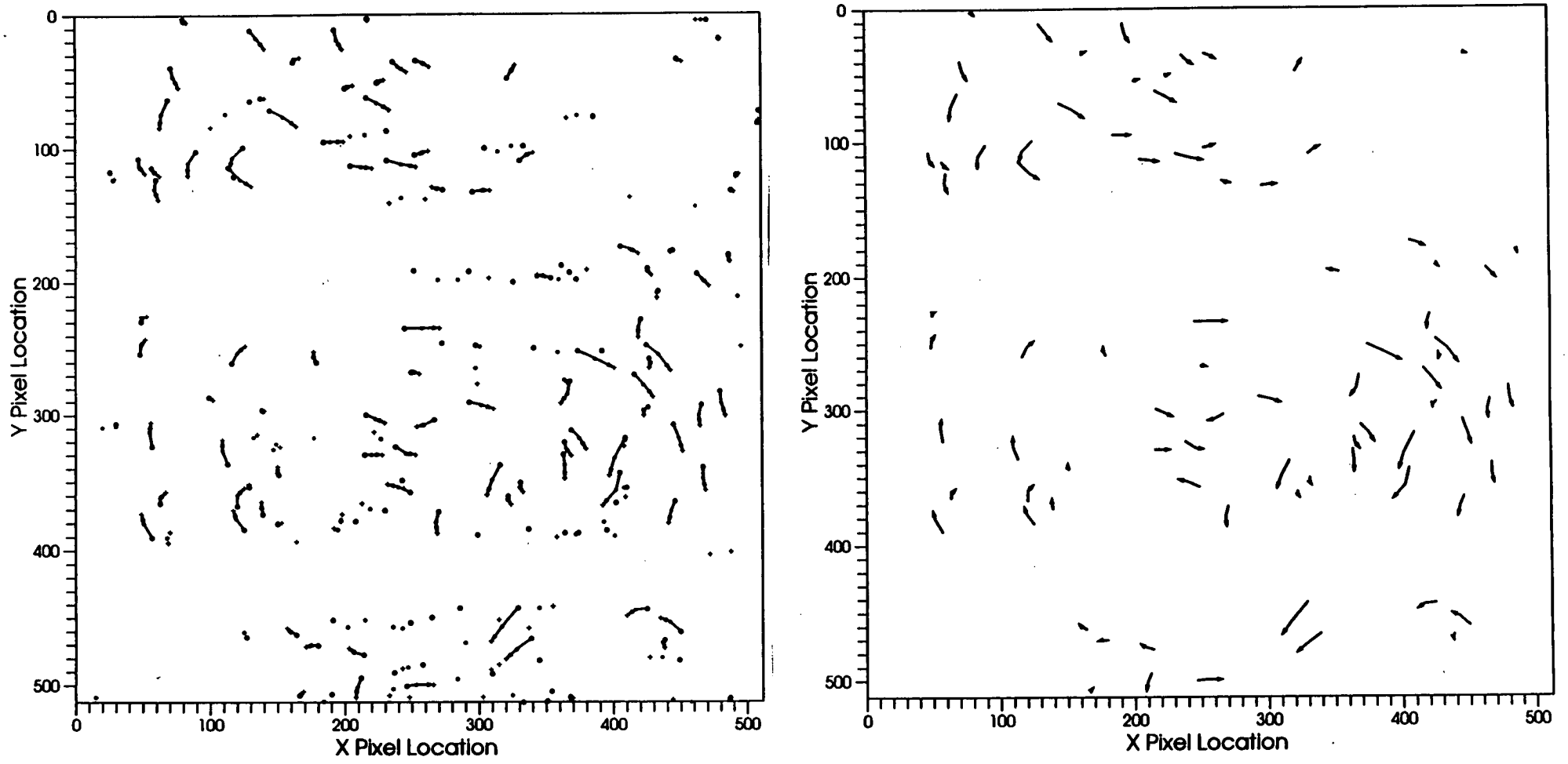


Figure 6: *(a) Particle tracks identified for the real image, Figure 1, including particle locations (• first frame; ∗ second frame; + third frame). (b) Particle tracks identified for the real image, Figure 1, vectors only.*

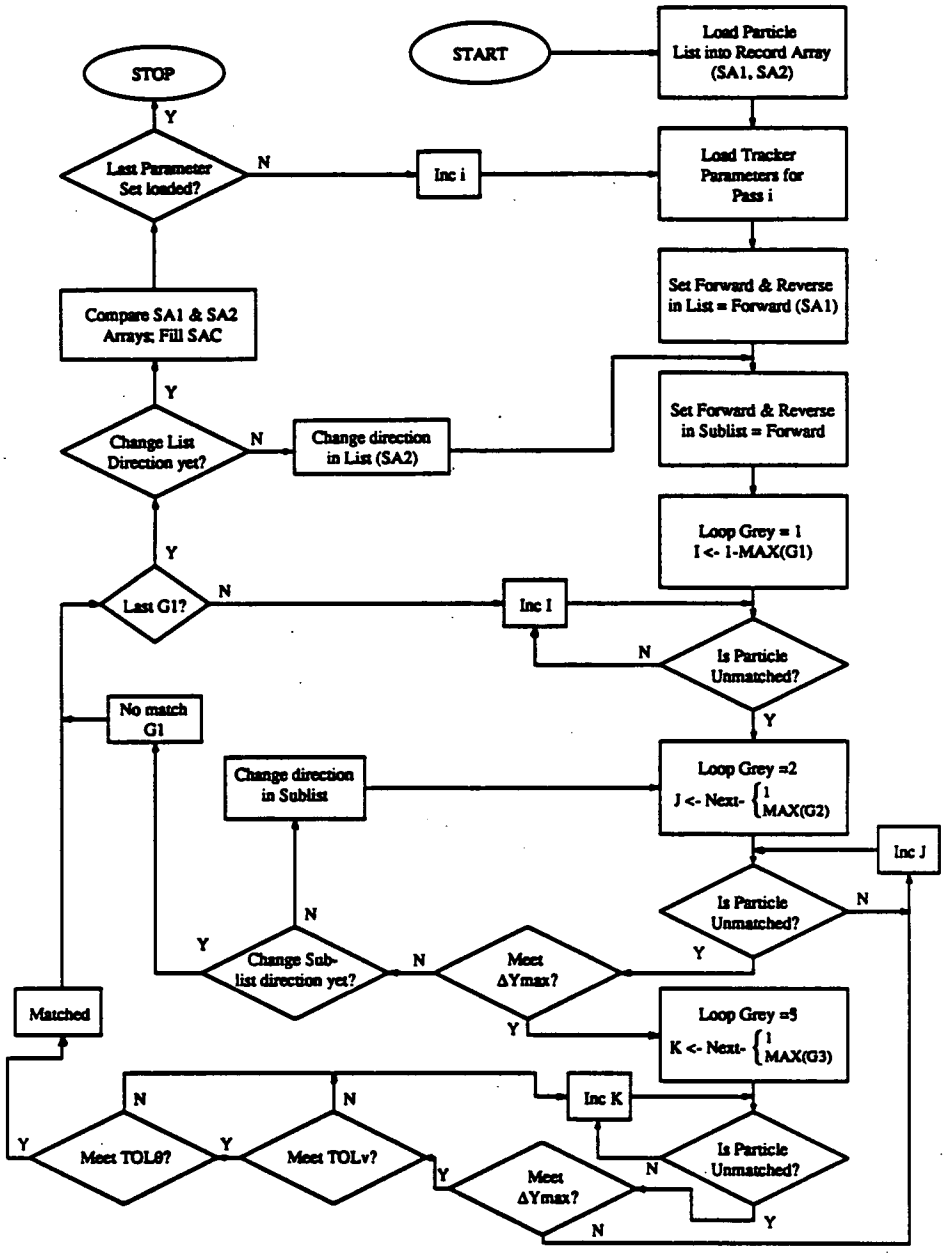


Figure 7: *Flowchart for DET_VECT.FOR.*

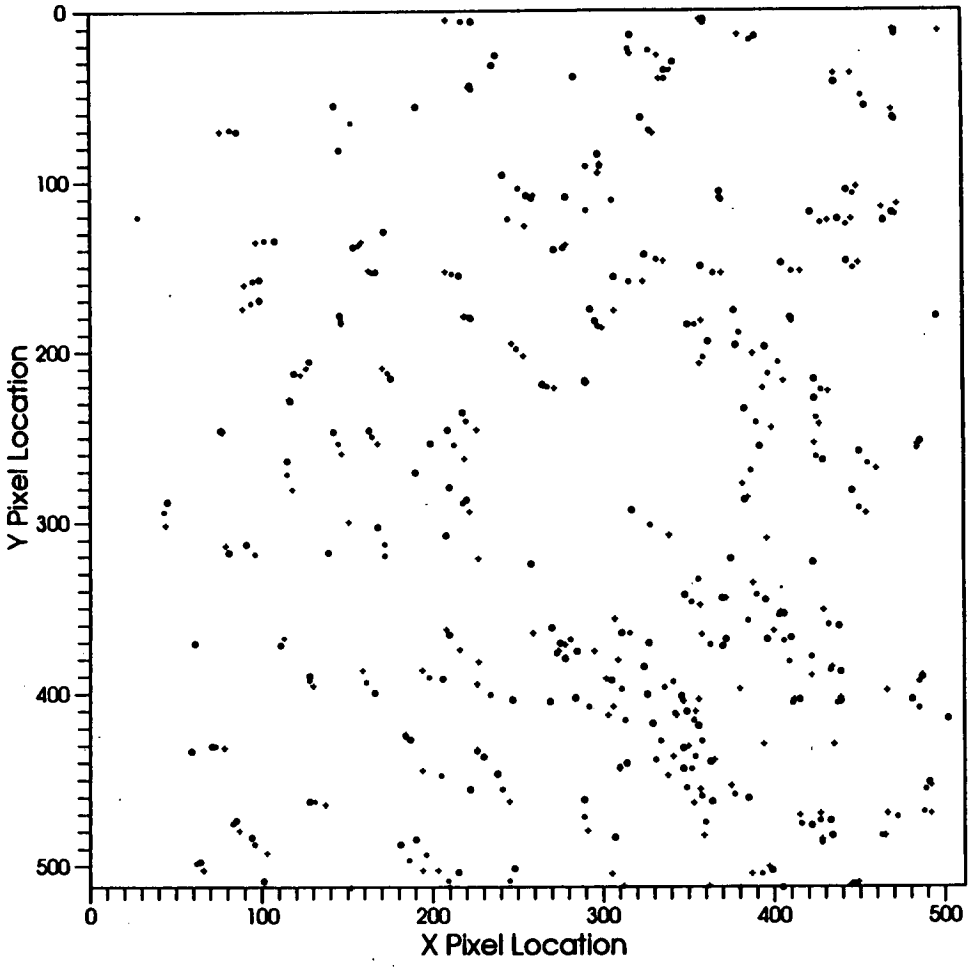


Figure 8: *Particles identified for Plate II(b) (• first frame; ∗ second frame; + third frame).*

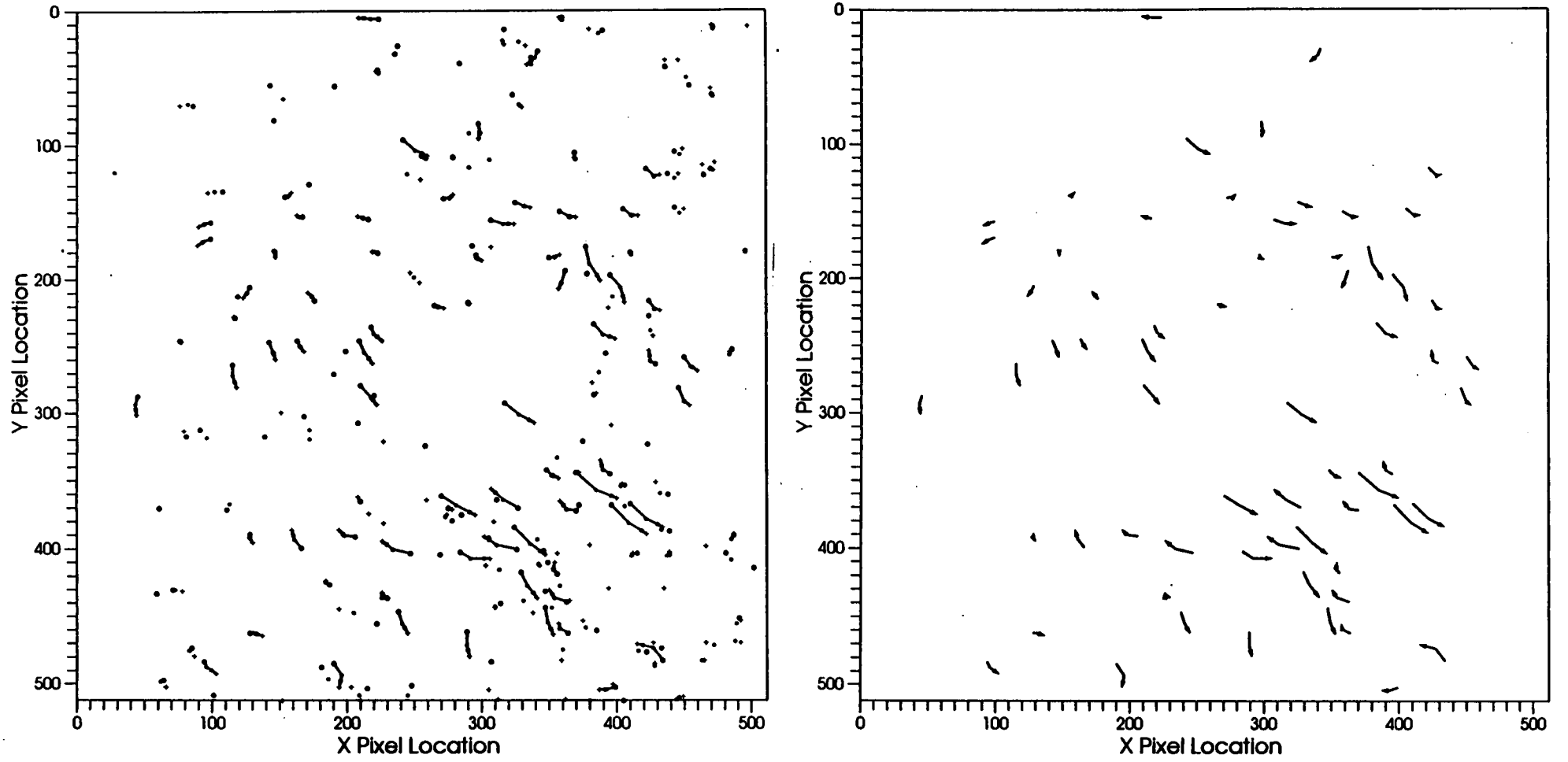


Figure 9: *(a) Particle tracks identified for the real image, Figure 8, including particle locations (• first frame; ∗ second frame; + third frame). (b) Particle tracks identified for the real image, Figure 8, vectors only.*

Appendix A

```
C
C  PART_ID.FOR
C
C  This program takes an ASCII image (formatted output
C  from program XF11_TO_ASCII.FOR) and identifies and
C  outputs particle locations by grey.  It is meant to work
C  with a 4-binary summed image, using 1, 2, 4, and 8 as
C  the binary image multipliers.  Output is directed to
C  FOR008.DAT
C
C-----------------------------------------------------------------
C
C  The structure /AREA_TYPE/ is used to hold the particle
C  information.  Particle centers are determined by presuming them
C  to be reasonably shaped, ie average between min & max
C  extensions are used.  NUM_PIX is used to count actual particle
C  size.  COLOR is actually grey level, ie 1, 2, 3, or 4.
C
      STRUCTURE /AREA_TYPE/
       INTEGER MINHOR,MAXHOR
       INTEGER MINVER,MAXVER
       INTEGER NUM_PIX
       INTEGER COLOR
      END STRUCTURE
      RECORD /AREA_TYPE/ AREA(2000)
      STRUCTURE /SORTED_AREA_TYPE/
       REAL XC,YC
       INTEGER NUM_PIX
       INTEGER NEXT,AVAIL,LINK,ACT
       END STRUCTURE
      RECORD /SORTED_AREA_TYPE/ SA(4,1000)
C
C  IMAGE holds the 512x512 image array.  Because of the size of
C  this array, this program works significantly better on the
C  VAX 8550 than on the MicroVAX.  IMTE is temporary storage;
C  this always contains the currect line and the line directly
C  above it.  Makes identification a lot easier.
C
      INTEGER IMAGE(512,512),X,Y,JUNK(54),IMTE(2,512,5)
      CHARACTER*20 FILENAME
      INTEGER AREA_COUNT,JUMP,COUNT(4),XEXTENT,YEXTENT
      INTEGER I,J,I2,J2,I3,J3,PSEUDO_GREY
      INTEGER ORIG(8),ORIG2(8),ORIG3(8),ORIG4(8)
      INTEGER PSEUDO_AREA,MIN_PIX,MAX_PIX,COL,NUM
C
C  Set some arbitrary tolerances on particle sizes, where
C  MIN_PIX represents the minimum number of pixels to define a
C  particle, and MAX_PIX defines the maximum number of pixels.
C
      MIN_PIX=4
      MAX_PIX=150
```

```
      TOL=0.5
      TYPE*,'Enter ASCII image Filename'
      READ(5,1) FILENAME
 1    FORMAT(A20)
      OPEN ( UNIT=3, STATUS='OLD', READONLY,
     1       FILE = FILENAME, DEFAULTFILE='.I' )
      READ(3,*) LINES,PIXELS
      DO 10 I=1,LINES
       TYPE*, I
       READ(3,5) (IMAGE(I,J), J=1,PIXELS)
       READ(3,5)
       READ(3,5)
 5     FORMAT(18I4)
10     CONTINUE
      AREA_COUNT=0
C
C  I1 and I2 are switching parameters for IMTE, allowing us
C  to only refill the row needed to be refilled.
C
      I1=1
C
C  Main iteration loop.  Since we check the line above the
C  current line, start at line 2.
C
      DO 100 I=2,LINES
       IF (I1.EQ.2) GOTO 220
       I1=2
       I2=1
       GOTO 230
220    I1=1
       I2=2
230    CONTINUE
C
C  Row iteration loop.  Since we check to left and right of
C  current particle position, loop so that these positions are
C  occupied.
C
       DO 200 J=2,(PIXELS-1)
C
C  Set IMTE storage.  IMTE at each point contains the original
C  grey level (IMTE(any,any,5)), and particle id for each grey
C  found in that pixel and identified (IMTE(any,any,1--4)).
C
         IMTE(I2,J,5)=IMAGE(I,J)
         IMTE(I2,J,1)=0
         IMTE(I2,J,2)=0
         IMTE(I2,J,3)=0
         IMTE(I2,J,4)=0
C
C  Check if background.
C
```

```
          IF (IMAGE(I,J).EQ.0) GOTO 200
C
C  DECOM_GREY takes the grey level and returns, in ORIG, a
C  1D matrix representing the original image flags.
C
          CALL DECOM_GREY(IMAGE(I,J),ORIG)
C
C  PSUEDO_GREY is a buildup of identified greys, which once
C  it equals IMAGE(I,J), a full match has been found.  This
C  is needed since we could match in more than one direction
C  correctly.  Continue matching until PSEUDO_GREY is satisfied
C  or all directions checked.
C
          PSEUDO_GREY=0
C
C  Check left, same row...
C
          IF (IMTE(I2,J-1,5).NE.0) GOTO 140
C
C  Check left, row above...
C
110       IF (IMTE(I1,J-1,5).NE.0) GOTO 150
C
C  Check above, row above...
C
120       IF (IMTE(I1,J,5).NE.0) GOTO 160
C
C  Check right, row above...
C
130       IF (IMTE(I1,J+1,5).NE.0) GOTO 170
          GOTO 400
C
C  The following set JUMP parameters from the above checks,
C  so that the next position can be checked if PSEUDO_GREY is
C  unfulfilled.
C
140       I3=I2
          J3=J-1
          JUMP=1
          GOTO 180
150       I3=I1
          J3=J-1
          JUMP=2
          GOTO 180
160       I3=I1
          J3=J
          JUMP=3
          GOTO 180
170       I3=I1
          J3=J+1
          JUMP=4
```

```
180       CONTINUE
C
C  Check, quick and dirty, if a complete match is made from
C  checked pixel to the current one.  If so, ignore all previous
C  matches and substitute, on a one-for-one basis, the matches
C  in IMTE(I3,J3,x).
C
          IF (IMTE(I3,J3,5).EQ.IMAGE(I,J)) GOTO 190
C
C  No quick and dirty.  Decompose the grey in the appropriate
C  pixel...
C
          CALL DECOM_GREY(IMTE(I3,J3,5),ORIG2)
C
C  Now check the grey, matrix element by matrix element, against
C  ORIG (ie the pixel greys to be added to some particle,
C  somewhere).
C
          DO 300 ICNT=1,4
           IF (IMTE(I2,J,ICNT).NE.0) GOTO 300
           IF ((ORIG(ICNT).EQ.0).OR.(ORIG2(ICNT).EQ.0)) GOTO 300
C
C  A match has been made; update PSEUDO_GREY, and set
C  IMTE(I2,J,ICNT) equal to the new grey, IMTE(I3,J3,ICNT).
C
           PSEUDO_GREY=PSEUDO_GREY+2**(ICNT-1)
           IMTE(I2,J,ICNT)=IMTE(I3,J3,ICNT)
300        CONTINUE
C
C  Quick; has PSEUDO_GREY been completed?
C
          IF (PSEUDO_GREY.EQ.IMAGE(I,J)) GOTO 320
C
C  Otherwise, jump back and check rest of directions.
C
          IF (JUMP.EQ.1) GOTO 110
          IF (JUMP.EQ.2) GOTO 120
          IF (JUMP.EQ.3) GOTO 130
C
C  OK, PSEUDO_GREY has not been completely filled, ie a
C  new particle area must be created.  Find out colors/areas
C  that need to be created.
C
400       CALL DECOM_GREY(PSEUDO_GREY,ORIG2)
          DO 330 ICNT=1,4
           IF (ORIG(ICNT).EQ.0) GOTO 330
           IF (ORIG(ICNT).EQ.ORIG2(ICNT)) GOTO 340
C
C  One last check; two to right and above.  A perfect sphere,
C  when digitized, will have this sort of structure.  If
C  the grey being created already exists at (I1,J+2), then
```

```
C  check at I2,J+1 for the same grey - ie a continuous path.
C  Otherwise, ignore and create a new particle.
C
          CALL DECOM_GREY(IMTE(I1,J+2,5),ORIG3)
          IF (ORIG(ICNT).EQ.ORIG3(ICNT)) GOTO 301
302       CALL START_NEW_AREA(I,J,AREA_COUNT,ICNT,AREA)
C
C  Particle identification number...
C
          IMTE(I2,J,ICNT)=AREA_COUNT
          GOTO 330
301       CALL DECOM_GREY(IMTE(I2,J+1,5),ORIG4)
          IF (ORIG4(ICNT).NE.ORIG3(ICNT)) GOTO 302
          IMTE(I2,J,ICNT)=IMTE(I1,J+2,ICNT)
C
C  Matched that guy, so UPDATE that area.
C
340       CALL UPDATE_AREA(I,J,IMTE(I2,J,ICNT),AREA)
330       CONTINUE
         GOTO 200
C
C  Update IMTE storage.
C
190      DO 310 ICNT=1,4
          IMTE(I2,J,ICNT)=IMTE(I3,J3,ICNT)
310       CONTINUE
320      CONTINUE
C
C  Complete set of grey level matches, ie no new particles
C  found for a pixel.  Update appropriate areas.
C
         DO 350 ICNT=1,4
          IF (ORIG(ICNT).EQ.0) GOTO 350
          CALL UPDATE_AREA(I,J,IMTE(I2,J,ICNT),AREA)
350       CONTINUE
200      CONTINUE
        WRITE(6,500)I,AREA_COUNT
500     FORMAT(' After ',I4,' lines, ',I4,' areas have been ',
     1 'found')
100     CONTINUE
C
C  Image has now been reduced to identified areas.  Check against
C  some preliminary idea of what is being identified, ie against
C  MIN_PIX and MAX_PIX (set at beginning of program), and for
C  a roughly spherical shape...
C
       DO 910 I=1,AREA_COUNT
        IF ((AREA(I).NUM_PIX).LT.(MIN_PIX)) GOTO 911
        IF ((AREA(I).NUM_PIX).GT.(MAX_PIX)) GOTO 911
C
C  PSEUDO_AREA represents area of square bounded by AREA's
```

```
C  min's and max's.  This is comparable to NUM_PIX, knowing
C  roughly what the expected shape is.
C  TOL is used to set the value of the shape parameter;
C  A perfect circle, for example, would be a TOL of
C  0.785 ((pi*d^2/4)/d^2, or (pi/4)).  Since this is a
C  finite world, a less restrictive TOL is required
C  (I generally use 0.5, which would allow a 3x3 particle,
C  identified as a '+', to pass (ie 5/9)).
C
        PSEUDO_AREA=(AREA(I).MAXHOR-AREA(I).MINHOR)
        PSEUDO_AREA=PSEUDO_AREA*(AREA(I).MAXVER-AREA(I).MINVER)
        IF ((TOL*PSEUDO_AREA).LT.(AREA(I).NUM_PIX)) GOTO 911
        XEXTENT=(AREA(I).MAXHOR-AREA(I).MINHOR+1)
        YEXTENT=(AREA(I).MAXVER-AREA(I).MINVER+1)
        IF ((MAX(XEXTENT,YEXTENT)/MIN(XEXTENT,YEXTENT)).GT.6)
        1   GOTO 911
C
C  OK, passes all tests... ready for output to FOR008.DAT
C
        COUNT(AREA(I).COLOR)=COUNT(AREA(I).COLOR)+1
        XC=FLOAT(AREA(I).MAXHOR+AREA(I).MINHOR)/2
        IF (AREA(I).COLOR.NE.4) GOTO 202
202     YC=FLOAT(AREA(I).MAXVER+AREA(I).MINVER)/2
        X=AREA(I).COLOR
        Y=COUNT(AREA(I).COLOR)
        SA(X,Y).XC=XC
        SA(X,Y).YC=YC
        SA(X,Y).NUM_PIX=AREA(I).NUM_PIX
        IF (X.EQ.1) GOTO 921
        SA(X,Y).NEXT=COUNT((AREA(I).COLOR)-1)
921     SA(X,Y).AVAIL=1
        SA(X,Y).LINK=0
        SA(X,Y).ACT=I
        MIH=AREA(I).MINHOR
        MXH=AREA(I).MAXHOR
        MIV=AREA(I).MINVER
        MXV=AREA(I).MAXVER
        COL=AREA(I).COLOR
        NUM=AREA(I).NUM_PIX
        WRITE(8,945) I,COL,NUM,XC,YC,MIH,MXH,MIV,MXV
945     FORMAT(' ',3I6,2F10.1,4I6)
        GOTO 910
911     XC=FLOAT(AREA(I).MAXHOR+AREA(I).MINHOR)/2
        YC=FLOAT(AREA(I).MAXVER+AREA(I).MINVER)/2
        MIH=AREA(I).MINHOR
        MXH=AREA(I).MAXHOR
        MIV=AREA(I).MINVER
        MXV=AREA(I).MAXVER
        COL=AREA(I).COLOR
        NUM=AREA(I).NUM_PIX
        WRITE(9,945) I,COL,NUM,XC,YC,MIH,MXH,MIV,MXV
```

```
920      FORMAT(' ',2I6,2I8)
930      FORMAT(' ',2F8.1)
940      FORMAT(' ',2I6)
950      FORMAT(' ',2I6,/)
910      CONTINUE
       WRITE(8,945) 0,0,0,0.0,0.0,0,0,0,0
       WRITE(8,920)0,0,0
       WRITE(8,961)NUMA
       WRITE(9,920)0,0,0
       WRITE(9,961)NUMB
961    FORMAT(' ',I6)
       STOP
       END
```

```
      SUBROUTINE DECOM_GREY(GREY_LEVEL,ORIG)
C
C  Subroutine to decompose the pixel value into its constituent
C  grey level components, namely 1, 2, 4 and 8.  These are
C  returned as flags in the ORIG matrix.
C
      INTEGER GREY_LEVEL,ORIG(8),GTEMP
       GTEMP=GREY_LEVEL
       DO 10 I=1,4
        IF (GTEMP.LT.(2**(4-I))) GOTO 20
        GTEMP=GTEMP-(2**(4-I))
        ORIG(5-I)=1
        GOTO 10
20      ORIG(5-I)=0
10      CONTINUE
      END
```

```
      SUBROUTINE START_NEW_AREA(I,J,AREA_COUNT,GREY,AREA)
C
C  Subroutine to start a new area, and initialize its
C  values.
C
      STRUCTURE /AREA_TYPE/
       INTEGER MINHOR,MAXHOR
       INTEGER MINVER,MAXVER
       INTEGER NUM_PIX
       INTEGER COLOR
      END STRUCTURE
      RECORD /AREA_TYPE/ AREA(7000)
      INTEGER AREA_COUNT,GREY
       AREA_COUNT=AREA_COUNT+1
       AREA(AREA_COUNT).MINHOR=J
       AREA(AREA_COUNT).MAXHOR=J
       AREA(AREA_COUNT).MINVER=I
       AREA(AREA_COUNT).MAXVER=I
       AREA(AREA_COUNT).NUM_PIX=1
       AREA(AREA_COUNT).COLOR=GREY
      END
```

```
      SUBROUTINE UPDATE_AREA(I,J,AREA_NUM,AREA)
C
C  Subroutine to update an area and its parameters.
C
      STRUCTURE /AREA_TYPE/
       INTEGER MINHOR,MAXHOR
       INTEGER MINVER,MAXVER
       INTEGER NUM_PIX
       INTEGER COLOR
      END STRUCTURE
      RECORD /AREA_TYPE/ AREA(7000)
      INTEGER AREA_NUM,IVAL
       IVAL=AREA_NUM
       IF ((AREA(IVAL).MINHOR).GT.J) AREA(IVAL).MINHOR=J
       IF ((AREA(IVAL).MAXHOR).LT.J) AREA(IVAL).MAXHOR=J
       IF ((AREA(IVAL).MAXVER).LT.I) AREA(IVAL).MAXVER=I
       AREA(IVAL).NUM_PIX=AREA(IVAL).NUM_PIX+1
      END
```

Appendix B

```
C
C  DET_VECT.FOR
C
C  This program takes particle location data (formatted output
C  from PART_ID.FOR) and compiles likely vector matches.
C  It reads sequential matching parameters from a file
C  VECTCONTROL.DAT, and will attempt a 3 point match directly
C  (1->2->3).  Output is directed to FOR090.DAT (vectors) and
C  FOR099.DAT (summary).
C
C-----------------------------------------------------------------
C
C  The structure /SORTED_AREA_TYPE/ is used to hold the particle
C  information found from PART_ID.FOR.  The array SA(4,1000)
C  is of /SORTED_AREA_TYPE/.  The first element in the array (1-4)
C  indicates the 'grey' of the particle, while the second is that
C  particles relative location within its own sorted list.  Because
C  of the nature of the particle identification, the particles are
C  already roughly sorted from top to bottom by Yc, where Xc and
C  Yc are located particle centers.
C
C  NEXT is an integer pointer to the element in the next grey
C  that would be the particle immediately above the current Yc of
C  the current color.  AVAIL is a flag to indicate the particle
C  has or has not been matched.  LINK is an integer pointer at
C  the next particle in a vector, ie to the next color.  Because
C  the algorithm is checking 1 --> 2 --> 3,  if AVAIL is false
C  (ie 0) for SA(1,any), then SA(1,,any).LINK has some non-zero
C  value, and SA(1,SA(2,any).LINK).LINK also has some non-zero
C  value (since a three-point match is required).
C
      STRUCTURE /SORTED_AREA_TYPE/
        REAL XC,YC
        INTEGER NUM_PIX
        INTEGER NEXT,AVAIL,LINK,ACT
        INTEGER ICNTVC
       END STRUCTURE
      RECORD /SORTED_AREA_TYPE/ SA(4,1000),SA_TWO(4,1000),
     1     SA_CORRECT(4,1000)
      CHARACTER*20 FILENAME
      CHARACTER*30 FILEVC
      INTEGER I,J,I2,J2,I3,J3,COUNT(4),MAXDIS,DIRECT,ICNTVC
      REAL TOLV,TOLR,BEST_TOLR,BEST_TOLV,BEST_TEST,BEST_XPTP,WF
      INTEGER BEST_MAXDIS,SUPERPASS
C
C  To prevent data corruption, data file outputs from PARTICLE_ID
C  were renumbered to whatever seemed appropriate at the time.
C  FOR008, FOR031, FOR041, and FOR051 were all commonly used;
C  this program is not limited to these values.
C
      WRITE(6,671)
```

```
 671    FORMAT(' Enter IO number for particle data')
        WRITE(6,672)
 672    FORMAT('  (8 for NASA, 51 for TURB, 31 for SIMULL',
        1      ' and 41 for SIMULR)')
        READ(5,*) IO2
C
C  At one point, the various iterations were being sent
C  to separate IO values.  These IO values were being
C  recorded in FOR001.DAT, so later consolidation could be
C  done.  This statement is almost useless without
C  the separation of IO values, but required for operation
C  of the consolidation programs (ie, VECTORT.FOR).
C  Writing IO2 to FOR001.DAT lets VECTORT.FOR know what
C  data file is being consolidated (changing output file names
C  correspondingly).
C
        WRITE(1,1010)IO2
C
C  Read in particle data.
C
C  Note secondary arrays, SA_TWO and SA_CORRECT.  SA_TWO is
C  reserved for backwards (in the list) matching, and SA_CORRECT
C  is reserved for matches between SA and SA_TWO
C
        DO I=1,4
          DO J=1,1000
            SA(I,J).LINK=0
            SA_TWO(I,J).LINK=0
            SA_CORRECT(I,J).LINK=0
            SA(I,J).ACT=0
            SA_TWO(I,J).ACT=0
            SA_CORRECT(I,J).ACT=0
          END DO
         END DO
C
C  Read in data point (format given in PARTICLE_ID).
C
 40     READ(IO2,*)I,COL,XC,YC
        IF (IO2.EQ.31) COL=COL-1
        IF (I.EQ.0) GOTO 30
        COUNT(COL)=COUNT(COL)+1
        X=COL
        Y=COUNT(COL)
        SA(X,Y).XC=XC
        SA(X,Y).YC=YC
        SA(X,Y).NUM_PIX=NUM
        SA_TWO(X,Y).XC=SA(X,Y).XC
        SA_TWO(X,Y).YC=SA(X,Y).YC
        SA_TWO(X,Y).NUM_PIX=SA(X,Y).NUM_PIX
        IF (X.EQ.4) GOTO 20
        SA(X,Y).NEXT=COUNT(COL+1)
```

```
        SA_TWO(X,Y).NEXT=SA(X,Y).NEXT
 20     SA(X,Y).AVAIL=1
        SA(X,Y).LINK=0
        SA(X,Y).ACT=I
        SA_TWO(X,Y).AVAIL=SA(X,Y).AVAIL
        SA_TWO(X,Y).LINK=SA(X,Y).LINK
        SA_TWO(X,Y).ACT=SA(X,Y).ACT
        GOTO 40
 30     CONTINUE
C
C  Vector determination.  Tolerances are set by the
C  file VECTCONTROL, which has one line per iteration.
C
        IO=90
        WRITE(1,1010) IO
        ITER=0
        TYPE*,'Do you want preset VECTCONTROL.DAT info? (1/0)'
        READ(5,*) IVC
        FILEVC='VECTCONTROL.DAT'
        IF (IVC.NE.1) THEN
          TYPE*,'Please enter control file data name',
        1       '  (usually VECTCONTROL.DAT or FOR003.DAT)'
          READ(5,5050) FILEVC
         END IF
 5050   FORMAT(A30)
C
C  Read in VECTCONTROL file, which contains the parameters
C  needed for particle vector matching.  Each line in
C  vectcontrol is executed sequentially on the particle list.
C  Order of parameters is TolV, TolR, and MAXDIS.  The
C  file must end with the line, "0.0 0.0 0".
C
C
C  Sample VECTCONTROL.DAT file:
C
C  0.5  0.5  10
C  0.5  0.5  20
C  0.5  1.0  30
C  0.5  1.5  30
C  0.0  0.0   0
C
        ICNTVC=0
C
C  Superpass is an integer counter; basically, VECTCONTROL.DAT
C  is opened twice; in the regular mode, the forward/backwards
C  error correction is in place.  In the superpass mode, the
C  error correction is disabled.  Superpass is implemented
C  after the error correction, under the premise that at that
C  point, the number of tracks are so few that overlap (and
C  hence error and the need for error correction) is diminished.
C
```

```
      SUPERPASS=0
 734  SUPERPASS=SUPERPASS+1
      OPEN(UNIT=2,FILE=FILEVC,STATUS='OLD')
 5555 TYPE*,' '
      TYPE*,'Iteration ',ICNTVC+1
 777  CONTINUE
      ICNTVC=ICNTVC+1
      READ(2,*) TOLV,TOLR,MAXDIS
 1010 FORMAT(I4)
      IF (TOLV.EQ.(0.0)) THEN
        IF (SUPERPASS.EQ.1) THEN
          CLOSE(UNIT=2)
          GOTO 734
         ELSE
          GOTO 778
         END IF
       END IF
      ITER=ITER+1
C
C  Main routine for matching.  Every iteration reduces the
C  eligible particles for matching, so VECTCONTROL can use
C  less and less restrictive parameters.
C
C  DIRECT=1 for forward match (SA), DIRECT=-1 for backward
C  match (SA_TWO).
C
      DIRECT=1
      CALL DO_VECT(COUNT,SA,TOLV,TOLR,MAXDIS,
      1   DIRECT,ICNTVC)
C
C  Record keeping; for simulated images, accurate
C  determination of correct and incorrect matching can
C  be done.  For non-simulated images, you can only gather
C  matched/unmatched percentages.
C
C  All percentages are based on the number of grey=1 particles
C  initially present.
C
C  TALLYVECT output is sent to the appropriate file.
C
      CALL TALLYVECT(SA,COUNT(1),ICNTVC,1,TOLV,TOLR,MAXDIS)
C
C  Backwards matching (SA_TWO, DIRECT=-1).
C
      DIRECT=-1
      CALL DO_VECT(COUNT,SA_TWO,TOLV,TOLR,MAXDIS,
      1   DIRECT,ICNTVC)
C
C  Tally up number found
C
      CALL TALLYVECT(SA_TWO,COUNT(1),ICNTVC,2,TOLV,TOLR,MAXDIS)
```

```
C
C  Time to start filling SA_CORRECT.  This is done by comparing
C  vector matches made in SA and SA_TWO; if they agree, they are
C  considered correct and the entry made in SA_CORRECT.  If they
C  do not agree, the particles are made available for further
C  matching.
C
      IF (SUPERPASS.EQ.1) THEN
        DO I=1,COUNT(1)
C
C  Check that the match was made in the most recent iteration
C  (otherwise already accounted for)...
C
          IF (SA(1,I).ICNTVC.EQ.ICNTVC) THEN
C
C  Check that Ith particle is matched...
C
            IF ((SA(1,I).LINK.NE.0).AND.(SA_TWO(1,I).LINK.NE.0))
     1         THEN
C
C  Check if Ith particles are equivalent...  if so, update
C  SA_CORRECT.
C
              IF ((SA(1,I).LINK.EQ.SA_TWO(1,I).LINK).AND.
     1           (SA(2,SA(1,I).LINK).LINK.EQ.
     2           SA_TWO(2,SA_TWO(1,I).LINK).LINK)) THEN
                SA_CORRECT(1,I).LINK=SA(1,I).LINK
                SA_CORRECT(1,I).ACT=SA(1,I).ACT
                SA_CORRECT(1,I).ICNTVC=SA(1,I).ICNTVC
                SA_CORRECT(2,SA(1,I).LINK).LINK=SA(2,SA(1,I)
     1             .LINK).LINK
                SA_CORRECT(2,SA(1,I).LINK).ACT=SA(2,SA(1,I)
     1             .LINK).ACT
                SA_CORRECT(3,SA(2,SA(1,I).LINK).LINK).ACT=
     1             SA(3,SA(2,SA(1,I).LINK).LINK).ACT
                SA_CORRECT(3,SA(2,SA(1,I).LINK).LINK).LINK=
     1             SA(3,SA(2,SA(1,I).LINK).LINK).LINK
              END IF
            END IF
          END IF
C
C  Update SA array for bad matches...
C
          IF ((SA(1,I).LINK.NE.0).AND.(SA(1,I).ICNTVC.EQ.ICNTVC)
     1       .AND.(SA_CORRECT(1,I).LINK.EQ.0)) THEN
            SA(3,SA(2,SA(1,I).LINK).LINK).AVAIL=1
            SA(2,SA(1,I).LINK).LINK=0
            SA(2,SA(1,I).LINK).AVAIL=1
            SA(1,I).LINK=0
            SA(1,I).ICNTVC=0
            SA(1,I).AVAIL=1
```

```
            END IF
C
C  Update SA_TWO array for bad matches...
C
           IF ((SA_TWO(1,I).LINK.NE.0).AND.(SA_TWO(1,I).ICNTVC
     1        .EQ.ICNTVC).AND.(SA_CORRECT(1,I).LINK.EQ.0)) THEN
             SA_TWO(3,SA_TWO(2,SA_TWO(1,I).LINK).LINK).AVAIL=1
             SA_TWO(2,SA_TWO(1,I).LINK).LINK=0
             SA_TWO(2,SA_TWO(1,I).LINK).AVAIL=1
             SA_TWO(1,I).LINK=0
             SA_TWO(1,I).ICNTVC=0
             SA_TWO(1,I).AVAIL=1
            END IF
          END DO
         ELSE
          DO I=1,COUNT(1)
            IF (SA(1,I).ICNTVC.EQ.ICNTVC) THEN
C
C  Check that Ith particle is matched...
C
              IF (SA_TWO(1,I).LINK.NE.0) THEN
                SA_CORRECT(1,I).LINK=SA(1,I).LINK
                SA_CORRECT(1,I).ACT=SA(1,I).ACT
                SA_CORRECT(1,I).ICNTVC=SA(1,I).ICNTVC
                SA_CORRECT(2,SA(1,I).LINK).LINK=SA(2,SA(1,I)
     1             .LINK).LINK
                SA_CORRECT(2,SA(1,I).LINK).ACT=SA(2,SA(1,I).LINK)
     1             .ACT
                SA_CORRECT(3,SA(2,SA(1,I).LINK).LINK).ACT=
     1             SA(3,SA(2,SA(1,I).LINK).LINK).ACT
                SA_CORRECT(3,SA(2,SA(1,I).LINK).LINK).LINK=
     1             SA(3,SA(2,SA(1,I).LINK).LINK).LINK
               ELSE IF (SA_TWO(1,I).LINK.NE.0) THEN
                SA_CORRECT(1,I).LINK=SA_TWO(1,I).LINK
                SA_CORRECT(1,I).ACT=SA_TWO(1,I).ACT
                SA_CORRECT(1,I).ICNTVC=SA_TWO(1,I).ICNTVC
                SA_CORRECT(2,SA_TWO(1,I).LINK).LINK=SA_TWO(2,
     1             SA_TWO(1,I).LINK).LINK
                SA_CORRECT(2,SA_TWO(1,I).LINK).ACT=SA_TWO(2,
     1             SA_TWO(1,I).LINK).ACT
                SA_CORRECT(3,SA_TWO(2,SA_TWO(1,I).LINK).LINK)
     1             .ACT=SA_TWO(3,SA_TWO(2,SA_TWO(1,I).LINK)
     2             .LINK).ACT
                SA_CORRECT(3,SA_TWO(2,SA_TWO(1,I).LINK).LINK)
     1             .LINK=SA_TWO(3,SA_TWO(2,SA_TWO(1,I).LINK)
     2             .LINK).LINK
               END IF
              END IF
             IF ((SA(1,I).LINK.EQ.0).AND.(SA(1,I).ICNTVC.EQ.ICNTVC)
     1          .AND.(SA_TWO(1,I).LINK.NE.0)) THEN
               SA(3,SA(2,SA(1,I).LINK).LINK).AVAIL=SA_TWO(3,
```

```
     1           SA_TWO(2,SA_TWO(1,I).LINK).LINK).AVAIL
                SA(2,SA(1,I).LINK).LINK=SA_TWO(2,SA_TWO(1,I).LINK)
     1             .LINK
                SA(2,SA(1,I).LINK).AVAIL=SA_TWO(2,SA_TWO(1,I)
     1             .LINK).AVAIL
                SA(1,I).LINK=SA_TWO(1,I).LINK
                SA(1,I).ICNTVC=SA_TWO(1,I).ICNTVC
                SA(1,I).AVAIL=SA_TWO(1,I).AVAIL
               END IF
C
C  Update SA_TWO array for bad matches...
C
             IF ((SA_TWO(1,I).LINK.EQ.0).AND.(SA_TWO(1,I).ICNTVC
     1          .EQ.ICNTVC).AND.(SA(1,I).LINK.NE.0)) THEN
               SA_TWO(3,SA_TWO(2,SA_TWO(1,I).LINK).LINK).AVAIL=
     1            SA(3,SA(2,SA(1,I).LINK).LINK).AVAIL
               SA_TWO(2,SA_TWO(1,I).LINK).LINK=SA(2,SA(1,I).LINK)
     1            .LINK
               SA_TWO(2,SA_TWO(1,I).LINK).AVAIL=SA(2,SA(1,I).LINK)
     1            .AVAIL
               SA_TWO(1,I).LINK=SA(1,I).LINK
               SA_TWO(1,I).ICNTVC=SA(1,I).ICNTVC
               SA_TWO(1,I).AVAIL=SA(1,I).AVAIL
              END IF
            END DO
          END IF
C
C  Determine %'s based on cumulative tracking/combination.
C
          CALL TALLYVECT(SA_CORRECT,COUNT(1),ICNTVC,3,
          1   TOLV,TOLR,MAXDIS)
C
C  Final piece of information: determine %'s based on most recent
C  iteration/combination, non-cumul.  Algorithm similar to
C  TALLYVECT.
C
          INOT_FOUND=0
          IWRONG=0
          ITHREE_PT=0
          ICNTNEW=0
          DO I=1,COUNT(1)
            IF ((SA(1,I).ICNTVC.EQ.ICNTVC).OR.(SA(1,I).ICNTVC.EQ.0))
          1   THEN
              ICNTNEW=ICNTNEW+1
              IF ((SA_CORRECT(1,I).LINK).EQ.0) THEN
                INOT_FOUND=INOT_FOUND+1
              ELSE
                IA=SA_CORRECT(1,I).ACT
                IB=SA_CORRECT(2,SA_CORRECT(1,I).LINK).ACT
                IC=SA_CORRECT(3,SA_CORRECT(2,SA_CORRECT(1,I).LINK)
          1        .LINK).ACT
```

```
            IX=SA_CORRECT(1,I).LINK
            IY=SA_CORRECT(2,IX).LINK
            WRITE(IO,120) I,IA,IB,IC,SA(1,I).XC,SA(1,I).YC,
     1         SA(2,IX).XC,SA(2,IX).YC,SA(3,IY).XC,SA(3,IY).YC
            IF ((IA.EQ.IB).AND.(IB.EQ.IC)) THEN
              ITHREE_PT=ITHREE_PT+1
             ELSE
              IWRONG=IWRONG+1
             ENDIF
           END IF
         ENDIF
        END DO
       IF (ICNTNEW.NE.0) THEN
         XPNF=FLOAT(INOT_FOUND)*100.0/FLOAT(ICNTNEW)
         XPTP=FLOAT(ITHREE_PT)*100.0/FLOAT(ICNTNEW)
         XPWR=FLOAT(IWRONG)*100.0/FLOAT(ICNTNEW)
         WRITE(99,561)ITER,MAXDIS,TOLV,TOLR,XPNF,XPTP,XPWR,ICNTNEW
         WRITE(6,561)ITER,MAXDIS,TOLV,TOLR,XPNF,XPTP,XPWR,ICNTNEW
        END IF
       GOTO 777
 561   FORMAT(' Iteration ',I3,'   MAXDIS - ',I4,' TOLV - ',F5.2,
       1  ' TOLR - ',F5.2,/,' Not Found - ',F6.2,/,
       2  ' Three - ',F6.2,/,' Wrong - ',F6.2,
       3  '  (Combined track),',' for ',I4, ' remaining tracks')
C
C  Out of loop.  Write final values to output and end.
C
 778   WRITE(1,1010) 0
C
C  Final record-keeping is to output all non-matched particles to
C  an output file (FOR020.DAT is used here).
C
       IO_NF=20
       DO I=1,COUNT(1)
         IF (SA(1,I).AVAIL.EQ.1) THEN
           WRITE(IO_NF,320) I,3,SA(1,I).XC,SA(1,I).YC,SA(1,I).ACT
          ELSE
           WRITE(IO,120) I,SA(1,I).ACT,SA(2,SA(1,I).LINK).ACT,
       1      SA(3,SA(2,SA(1,I).LINK).LINK).ACT,SA(1,I).XC,
       2      SA(1,I).YC,SA(2,SA(1,I).LINK).XC,SA(2,SA(1,I)
       3      .LINK).YC,SA(3,SA(2,SA(1,I).LINK).LINK).XC,
       4      SA(3,SA(2,SA(1,I).LINK).LINK).YC
          END IF
        END DO
       WRITE(IO,120)0,0,0,0,0.0,0.0,0.0,0.0,0.0,0.0
 120   FORMAT(' ',4I8,6F10.2)
       DO I=1,COUNT(2)
         IF (SA(2,I).AVAIL.EQ.1) WRITE(IO_NF,320) I,2,SA(2,I).XC,
       1    SA(2,I).YC,SA(2,I).ACT
        END DO
       DO I=1,COUNT(3)
```

```
        IF (SA(3,I).AVAIL.EQ.1) WRITE(IO_NF,320) I,3,SA(3,I).XC,
      1    SA(3,I).YC,SA(3,I).ACT
       END DO
      WRITE(IO_NF,320) 0,0,0.0,0.0
320   FORMAT(' ',2I8,2F10.2,I8)

      STOP
      END
```

```
      SUBROUTINE DO_VECT(COUNT,SA,TOLV,TOLR,MAXDIS,
      1          DIRECT,ICNTVC)
C
C  Subroutine that does the grunt work of particle matching,
C  using the parameters passed from the main program.
C
        STRUCTURE /SORTED_AREA_TYPE/
          REAL XC,YC
          INTEGER NUM_PIX
          INTEGER NEXT,AVAIL,LINK,ACT
          INTEGER ICNTVC
         END STRUCTURE
        RECORD /SORTED_AREA_TYPE/ SA(4,1000)
        INTEGER COUNT(4),DJ,DK,DL,DIRECT,DI,ICNTCV,ISWITCH
C
C  Set tolerances and limits (passed variables)
C  TOLR is maximal radial change in vector (in radians)
C  TOLV is maximal magnitude change in vector (as fraction of
C       average vector magnitude)
C  MAXDIS is maximum displacement frame-to-frame of particles
C
C
C  Begin main loop, on grey=4.  Start at 1 and go to end.
C  Do not match grey=2 or above if grey=1 particle is not
C  available.
C
        ISWITCH=0
        IF (DIRECT.EQ.1) THEN
          ID1=1
          ID2=COUNT(1)
          DI=1
         ELSE
          ID1=COUNT(1)
          ID2=1
          DI=-1
         END IF
        DO 110 I=ID1,ID2,DI
          IF (SA(1,I).AVAIL.EQ.0) GOTO 110
C
C  Switching parameters.  A double-switching search is used;
C  initial search is in the above direction (ie start at
C  SA(1,I).NEXT and decrement back to 1), and switches to the
C  below direction (start at SA(1,I).NEXT+1 and increment up
C  to max) if no match is found.
C
          IF (DIRECT.NE.1) GOTO 50
 250      DJ=-1
          I3=1
          I2=SA(1,I).NEXT+1
          IF (I2.GT.COUNT(2)) I2=COUNT(2)
          GOTO 60
```

```
 50         DJ=1
            I3=COUNT(2)
            I2=SA(1,I).NEXT
            IF (I2.LT.1) I2=1
C
C  Main grey=2 loop.
C
 60         DO 20 J=I2,I3,DJ
C
C  Check availability.  Also check MAXDIS (quickest elimination).
C
              IF (SA(2,J).AVAIL.EQ.0) GOTO 20
              DY1=(SA(1,I).YC-SA(2,J).YC)
              IF (ABS(DY1).GT.MAXDIS) GOTO 10
              DX1=(SA(1,I).XC-SA(2,J).XC)
              IF (ABS(DX1).GT.MAXDIS) GOTO 20
              DV1=SQRT(DX1*DX1+DY1*DY1)
              IF (DV1.EQ.0) GOTO 20
C
C  DV1 rep. 1->2 vector
C
              IF (DJ.EQ.1) GOTO 80
C
C  Switching parameters for the grey=3 loop, following the
C  same procedure as for grey=2.  It is likely that the
C  grey=3 particle is in the same direction as grey=2, and
C  this direction is checked first.  ISWITCH is used to
C  reverse the grey=3 track locally.
C
 280          DK=-1
              J3=1
              J2=SA(2,J).NEXT+1
              IF (J2.GT.COUNT(3)) J2=COUNT(3)
              GOTO 70
 80           DK=1
              J3=COUNT(3)
              J2=SA(2,J).NEXT
              IF (J2.LT.1) J2=1
C
C  Main grey=3 loop.
C
 70           DO 30 K=J2,J3,DK
C
C  Check availability.  Check MAXDIS for quick elimination.
C
              IF (SA(3,K).AVAIL.EQ.0) GOTO 30
              DY2=(SA(2,J).YC-SA(3,K).YC)
              IF (ABS(DY2).GT.MAXDIS) GOTO 31
              DX2=(SA(2,J).XC-SA(3,K).XC)
              IF (ABS(DX2).GT.MAXDIS) GOTO 30
              DV2=SQRT(DX2*DX2+DY2*DY2)
```

```
C
C  DV2 rep. 2->3 vector
C
           IF (DV2.EQ.0) GOTO 30
C
C  Check TolV...
C
           IF (ABS((DV2-DV1)/((DV2+DV1)/2)).GT.TOLV) GOTO 30
C
C  Check TolR (note 'heavy' calculations).
C
           IF (DY1.GT.0) THEN
             DR1=ACOS(DX1/DV1)
            ELSE
             DR1=2*3.14159-ACOS(DX1/DV1)
            ENDIF
           IF (DY2.GT.0) THEN
             DR2=ACOS(DX2/DV2)
            ELSE
             DR2=2*3.14159-ACOS(DX2/DV2)
            ENDIF
           IF (ABS(DR2-DR1).GT.TOLR) GOTO 30
C
C  At this point a three-point match exists, 1 --> 2 --> 3.
C  Set the appropriate linkages and availability flags, and
C  check whether a fourth-point match is required.  4 point
C  matching tends to significantly reduce matching, and is
C  not used.
C
            SA(3,K).AVAIL=0
            SA(2,J).LINK=K
            SA(2,J).AVAIL=0
            SA(1,I).LINK=J
            SA(1,I).AVAIL=0
            SA(1,I).ICNTVC=ICNTVC
            ISWITCH=0
            GOTO 11
30         CONTINUE
31        IF (ISWITCH.EQ.1) THEN
            ISWITCH=0
            GOTO 20
           ELSE
            ISWITCH=1
            IF (DJ.EQ.1) THEN
              GOTO 280
             ELSE
              GOTO 80
             END IF
           END IF
20        CONTINUE
10       IF (DIRECT.EQ.DJ) GOTO 11
```

```
          IF (DJ.EQ.1) GOTO 250
          GOTO 50
11        CONTINUE
110       CONTINUE
         RETURN
         END
```

```
      SUBROUTINE TALLYVECT(SA,IEND,ICNTVC,NUMB,TV,TR,MD)
C
C  Subroutine to output some simple stats on matched particles
C
       STRUCTURE /SORTED_AREA_TYPE/
         REAL XC,YC
         INTEGER NUM_PIX
         INTEGER NEXT,AVAIL,LINK,ACT
         INTEGER ICNTVC
        END STRUCTURE
       RECORD /SORTED_AREA_TYPE/ SA(4,1000)
       INTEGER IEND,ICNTVC,NUMB,MD,IO
       REAL TV,TR

       INOT_FOUND=0
       IWRONG=0
       ITHREE_PT=0
       IFOUR_PT=0
       DO I=1,IEND
         IF ((SA(1,I).LINK).EQ.0) THEN
           INOT_FOUND=INOT_FOUND+1
          ELSE
           IA=SA(1,I).ACT
           IB=SA(2,SA(1,I).LINK).ACT
           IC=SA(3,SA(2,SA(1,I).LINK).LINK).ACT
           IX=SA(1,I).LINK
           IY=SA(2,IX).LINK
           IF ((IA.EQ.IB).AND.(IB.EQ.IC)) THEN
             ITHREE_PT=ITHREE_PT+1
            ELSE
             IWRONG=IWRONG+1
            END IF
          ENDIF
        END DO
       XPNF=FLOAT(INOT_FOUND)*100.0/FLOAT(IEND)
       XPTP=FLOAT(ITHREE_PT)*100.0/FLOAT(IEND)
       XPWR=FLOAT(IWRONG)*100.0/FLOAT(IEND)
       IF (NUMB.EQ.1) THEN
         WRITE(99,571)ITER,MD,TV,TR,XPNF,XPTP,XPWR,IEND
         WRITE(6,571)ITER,MD,TV,TR,XPNF,XPTP,XPWR,IEND
        END IF
       IF (NUMB.EQ.2) THEN
         WRITE(99,572)ITER,MD,TV,TR,XPNF,XPTP,XPWR,IEND
         WRITE(6,572)ITER,MD,TV,TR,XPNF,XPTP,XPWR,IEND
        END IF
       IF (NUMB.EQ.3) THEN
         WRITE(99,573)ITER,MD,TV,TR,XPNF,XPTP,XPWR,IEND
         WRITE(6,573)ITER,MD,TV,TR,XPNF,XPTP,XPWR,IEND
        END IF
  571   FORMAT(' Iteration ',I3,'   MAXDIS - ',I4,' TOLV - ',F5.2,
      1  ' TOLR - ',F5.2,/,' Not Found - ',F6.2,/,
```

```
     2   ' Three - ',F6.2,/,' Wrong - ',F6.2,
     3   ' (Forward track),',' all ',I4,' tracks')
572   FORMAT(' Iteration ',I3,'   MAXDIS - ',I4,' TOLV - ',F5.2,
     1   ' TOLR - ',F5.2,/,' Not Found - ',F6.2,/,
     2   ' Three - ',F6.2,/,' Wrong - ',F6.2,
     3   ' (Backward track),',' all ',I4,' tracks')
573   FORMAT(' Iteration ',I3,'   MAXDIS - ',I4,' TOLV - ',F5.2,
     1   ' TOLR - ',F5.2,/,' Not Found - ',F6.2,/,
     2   ' Three - ',F6.2,/,' Wrong - ',F6.2,
     3   ' (Combined track),',' all ',I4,' tracks')
     RETURN
     END
```

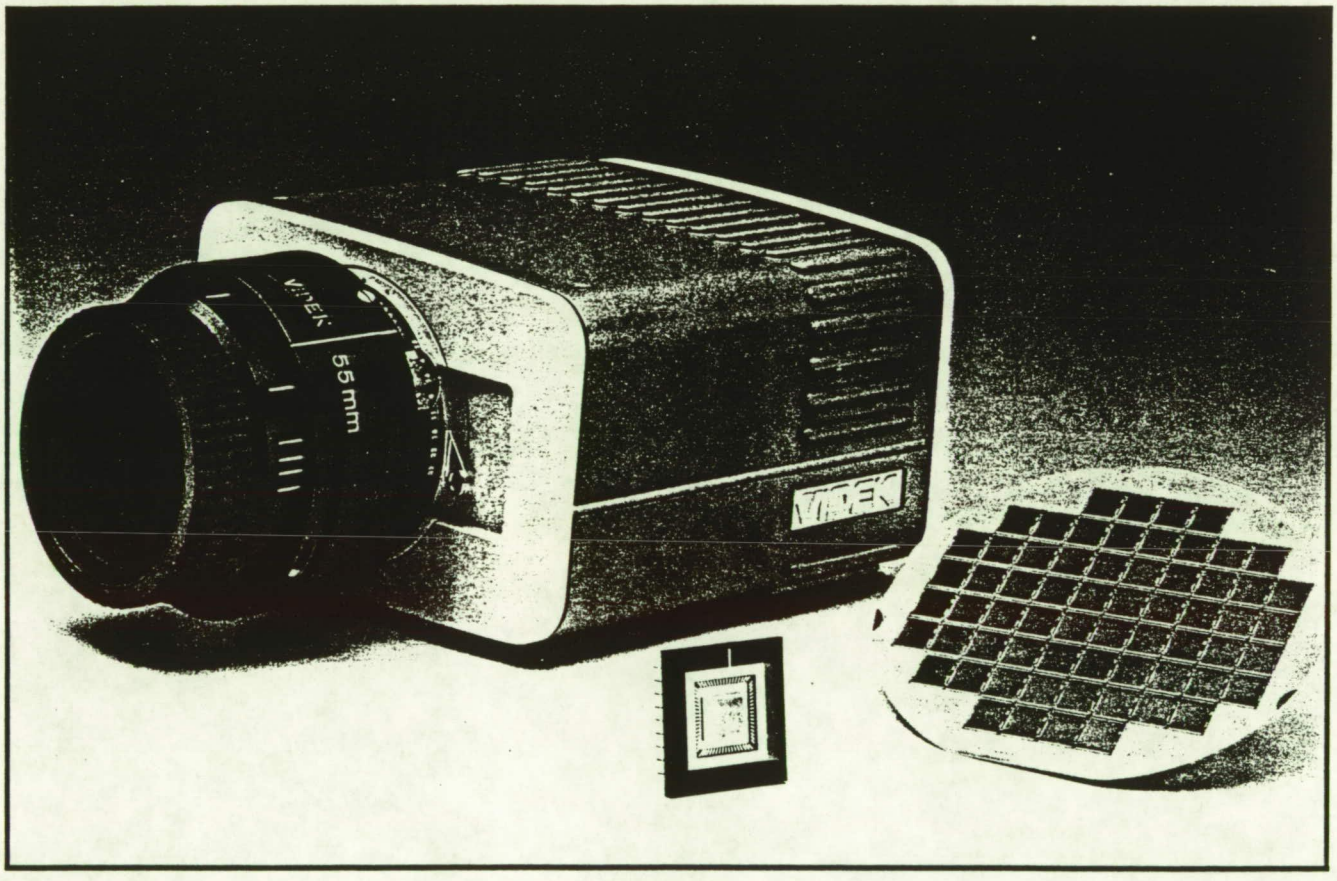
Appendix C

VIDEK

A Kodak Company

CCD Camera
For High Resolution
Applications

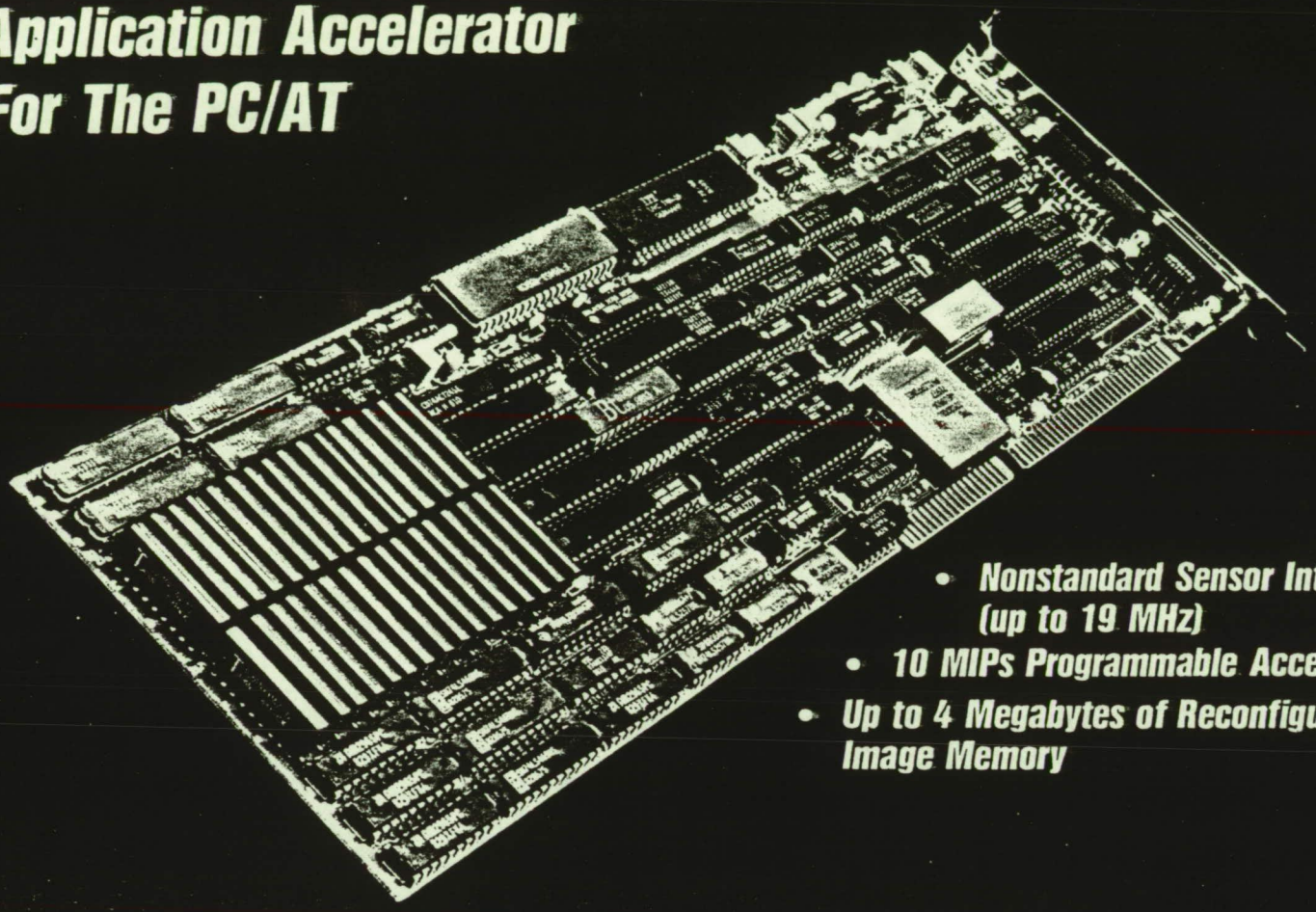
The VIDEK MEGAPLUS™ Camera



Feature	Benefit
• 1320 H x 1035 V pixel format	4 times greater resolution than other "Hi-Res" solid-state cameras
• Square pixels	Accurate and simplified dimensional measurements in any direction
• 100% fill (No space between pixels)	5 to 10 times improvement in sub-pixel measurement acuracy
• Digital output	Maximizes signal-to-noise ratio

4MEG VIDEO™ Model 10

Flexible Image Processor and Application Accelerator For The PC/AT



- **Nonstandard Sensor Interface (up to 19 MHz)**
- **10 MIPs Programmable Accelerator**
- **Up to 4 Megabytes of Reconfigurable Image Memory**

4MEG VIDEO Model 10 offers a flexible image processing platform for OEMs and VARs. An adaptable video timing generator allows easy integration with image sources such as line-scan cameras, high-resolution CCD cameras, and medical imaging equipment. A reconfigurable image memory can be organized as one or many images of arbitrary dimension. A programmable on-board processor accelerates imaging functions, including custom algorithms. All of this functionality is available on a single board that occupies one slot in a PC/AT (or compatible) computer.

EPIX, Inc. introduced the 4MEG VIDEO family in 1987. Successful applications of the product include:

- Automated Inspection
- Medical Imaging
- Motion Analysis
- Document Processing
- Military Data Acquisition

4MEG VIDEO Model 10 is a member of a continually evolving product line. The Model 10 offers twice the processing speed of the previous version. Planned enhancements to the product family include larger image memory, larger on-board program memory, C compiler support, higher resolution/bandwidth, and very high-speed mass storage access.

Flexible Video Acquisition/Display

4MEG VIDEO Model 10 offers unparalleled flexibility in video acquisition and display. Analog video signals can be digitized at up to 19 million samples per second. Alternatively, the board can accept direct 8-bit digital data. The pixel clock can be derived from an external source or generated internally. 4MEG VIDEO Model 10 can genlock to composite video, composite sync, or horizontal and vertical drive signals from a variety of video formats. Likewise, a variety of output formats can be generated.

Programmable video resolution is provided by a unique Horizontal Control Memory (HCM) that allows pixel-by-pixel control over image memory transfers during acquisition and display. Integer zoom and subsampling are supported. Sampling resolution can vary across a given line of video. The vertical resolution is also programmable.

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OF POOR QUALITY

4MEG VIDEO™ Model 10

Flexible Image Processor and Application Accelerator For The PC/AT

Fast On-Board Processor

4MEG VIDEO Model 10 facilitates acceleration of image processing functions with a 10 MIPS Texas Instruments TMS320C25 Digital Signal Processor. In addition to performing math-intensive image processing functions at high speed, the TMS320C25 can function much like a general-purpose microprocessor. This facilitates the implementation of custom image processing and inspection algorithms.

The TMS320C25 is programmed in assembly language. The 8K word on-board program memory is ample for most image processing functions. Programs may be downloaded rapidly via the PC/AT bus.

Reconfigurable Image Memory

Pixel data is stored in image memory as sequential 8-bit values. Using the HCM, this memory can be organized as one large image, or many smaller images. Portions of the memory can also be used to store intermediate results, menues, or overlays. A bit-plane write protect feature allows text and overlays to be written over image data.

Image memory is accessed by the PC/AT or the TMS320C25 in 64K byte blocks. A Memory Offset Register allows this window to be located on any 16 Kbyte boundary.

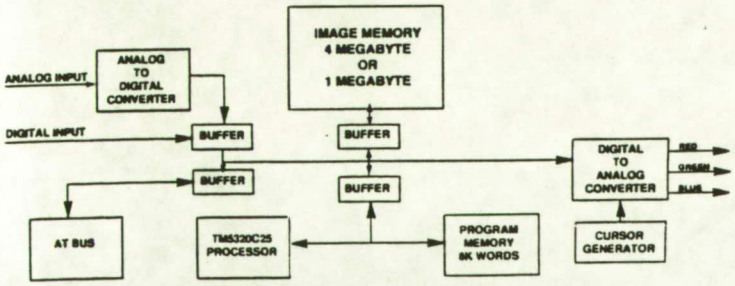
The memory has data paths for video acquisition, video display, and processing. One of these paths is utilized at any given time. During image acquisition the display is driven with live video. Image processing can be performed during video blanking intervals to maintain an uninterrupted display.

4MEG VIDEO Model 10 Software Support

4MEG VIDEO Model 10 is supported by driver software that allows easy application development by OEMs and VARs. A driver subroutine library (4MDRIVER) simplifies control of the board from programs written in C or other high-level languages. The library is easy to use; familiarity with structures, pointers, etc. is not required for fundamental operations.

An optional, interactive, menu driven program (4MIP) allows immediate access to 4MEG VIDEO Model 10 functionality. 4MDRIVER functions and image processing routines can be invoked via a mouse interface. 4MIP also allows the user to save sequences of operations in command files that can be re-executed on demand.

To develop loadable routines for the TMS320C25, standard macro-assembler development tools from Texas Instruments or Avocet Systems, Inc. can be employed. 4MDRIVER and 4MIP facilitate downloading of user-developed programs.



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Specifications:

4MEG VIDEO Model 10 Hardware

Video Acquisition/Display

- Up to 19 MHz sampling/display rate
- Up to 1984 pixels per line
- RS-170, RS-330, and CCIR input/output
- Analog or digital inputs
- Variable timing for nonstandard formats
- Genlock to external timing sources
- Generates master video timing
- Software programmable timing/resolution
- External input/output for event synchronization
- Pseudocolor display
- Nondestructive cursor
- PC or AT bus compatible

On-Board Processor

- TMS320C25 digital signal processor
- 10 million instructions per second
- 16-bit fixed point arithmetic w/ 32-bit accumulation
- 8K word program memory
- Direct image memory access

Image Memory

- 1 megabyte or 4 megabyte image memory options
- 8-bits per pixel
- Selectable bit plane write protect
- Configurable as one or many images
- Programmable image size

Options

- VIDEK MEGAPLUS camera interface card
- 16 input video multiplexor card
- Reticon camera interface (third party)

4MEG VIDEO Model 10 Software

4MDRIVER and 4MIP

- Simple-to-use functions/subroutines
- Image capture and display
- Adjustable video formats
  - resolution
  - blanking intervals
  - interlaced/noninterlaced
  - Serration/equalization
- Selectable timing source
- Split screen digitize/display
- Integer zoom (1-30X) • Pan, Scroll
- TMS320C25 convolution, image sequence average and difference

4MIP Only

- PC-based image processing
  - Arithmetic/logic functions
  - Convolution
  - Temporal average
  - Inter-image operations
  - Contrast enhancement
- Real-Time motion analysis
- Histogram display • Command file training/replay
- Disk File I/O • Image Printing

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NDP-386 COMPILERS

NDP Fortran-386™

Optimized FORTRAN 77 with VAX/VMS, UNIX BSD 4.2, and MIL STD-1753 Extensions for 80386-based Systems

NDP Fortran-386 is a globally optimizing compiler that has been developed at MicroWay for the Intel 80386. It generates native 80386 code that runs in protected mode under UNIX 386 System V Release 3, SCO XENIX Release 2.3, and Phar Lap extended DOS. Separate releases are available for each operating system. The execution speed of code generated by NDP Fortran-386 is exceptionally fast. Recompiling existing 16-bit 80286 compiler code with the 32-bit NDP Fortran-386 can increase the speed of execution by 200-500%. When the MicroWay mW1167 or the Weitek 3167 numeric coprocessor is added, performance of the NDP Fortran-386 equals that of a VAX 8600, or 60 times the speed of an IBM PC.

NDP Fortran-386 makes it possible to port mainframe FORTRAN applications to your 80386 machine that use as much memory as your system will hold: the upper limit on segment size in the linear address mode is 4 gigabytes!

The compiler generates code which optionally utilizes the Phar Lap Virtual Memory Manager, making it possible for a two megabyte 80386 system to run programs that are as large as the free memory on your hard disk! The compiler also supports any of five possible coprocessors for which your 80386 system is socketed, including the MicroWay mW1167, Weitek 3167, Intel 80387 and 80287, and Cyrix 83D87. The mW1167 provides two to four times the throughput of an 80387 as measured by popular benchmarks.

NDP Fortran-386 is a full implementation of FORTRAN 77 and includes the extensions needed to write new applications or port existing ones. These include the popular FORTRAN 66 extensions to FORTRAN 77, plus features added by the UNIX f77 portable FORTRAN compiler (including UNIX BSD 4.2 features), D.O.D., and DOS FORTRAN compilers. NDP Fortran-386 compiles most FORTRAN 66 and 77 applications without modification.

NDP Fortran-386 v.2.0 Features:

- 98% compatible with VAX/VMS extensions, including "NAMELIST."
- Incorporates several new optimizations, including loop unrolling, repeat common subexpression elimination, register caching, and peephole optimization.
- Includes a command line switch to allow the compiler to run in virtual memory.
- NDP-386 Virtual Memory option allows executable programs to run in virtual memory using the Phar Lap Virtual Memory Manager.
- Generates programs, procedures, and arrays limited only by the amount of memory in the system, up to 4 gigabytes.
- Exceptional runtime speed due to global optimizations, sophisticated register utilization to store 32-bit entities, use of inline 32-bit arithmetic instead of library calls, and the effective doubling of the system data bus.
- Simplifies the porting of existing applications by fully implementing FORTRAN 77 (full language) as specified by ANSI X3.9-1978, the D.O.D. supplement to FORTRAN 77 (MIL STD-1753), and the documented and undocumented extensions to the Berkeley 4.2 BSD UNIX f77 compiler for VAX/VMS.
- Generates inline code for coprocessors which makes excellent use of all numeric registers.
- Supports full 80387 and mW1167/3167 numeric instruction sets, including 80387 inline transcendentals.
- Allows customized coprocessor exception handling procedures to be designed and implemented by the user. (examples are provided)
- Includes a library of graphics and keyboard routines with enhanced features that supports the CGA, MDA, EGA VGA, and Hercules adapters. (DOS version only)
- Includes mouse support.
- Provides a trace facility to aid in debugging.
- Memory mapped devices and physical memory can be mapped into the program's linear address space.
- NDP Fortran-386 can call or be called from NDP C-386 or NDP Pascal-386 programs. Assembly language routines can be interfaced with compiled output.
- The f77 compiler driver makes it possible to use the same switches for compiling, assembling, and linking when working with DOS, UNIX V, or XENIX 2.3.
- Fast I/O feature in DOS version makes it possible to specify the size and number of runtime buffers, resulting in an I/O speed up that ranges up to 15 times faster.
- Can be used with the newest generation of Phar Lap tools to produce embedded and ROMable code.
- NDP Plot is an optional Calcomp-compatible package including high-level plotting and 3-D graphics routines.
- NDP to Halo '88 Interface is an optional graphics interface to Media Cybernetics Halo '88™.
- NDP Hoops is an optional advanced object-oriented graphics library.

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Optimization Features:

The compiler converts the ASCII FORTRAN text one procedure at a time into a memory-based operator tree. During global optimization, this tree is traversed from 5 to 50 times depending upon the options selected and the structure of the code. The primary goal of the global optimization is to store variables in registers as opposed to memory. Eliminating stores and loads to memory, on average, results in code that runs a factor of 3 faster while taking only 1/3 the space of code which stores variables in memory. The global analysis takes into account variable lifetime, activity, size, and the benefits of using faster running 16-bit addressing modes over the slower running 32-bit modes where possible. The optimizer produces code which takes maximum advantage of the registers available in the numeric coprocessors that the compiler supports. The generation of very high quality inline numeric code is one of the outstanding features of the compiler.

The process of traversing the tree includes the application of code transformations to the tree. These transformations include numeric strength reduction, dead code elimination, removal of loop invariant code from loops, hoisting of common code out of blocks, constant propagation, elimination of stack frame setup on procedure entry where possible, conversion of small procedures into inline code where possible, and a number of processor-related peephole optimizations. Loop optimizations which make the code larger but faster can also be optionally performed. These optimizations rearrange loops so that array base values are computed outside of loops, and then stored in registers where they are used indirectly for addressing, and incremented, when necessary. The optimizer also performs global common subexpression elimination, caches array elements in registers, and unrolls short "hot" loops into inline code.

VAX/VMS FORTRAN Extensions:

- Symbolic Names may be 31 characters long and contain the $ character.
- Nested INCLUDES are allowed up to 10 levels.
- IMPLICIT UNDEFINED (A-Z) turns off IMPLICIT typing.
- All MIL STD-1753 Binary and bit functions are supported including IOR, IAND, IEOR, NOT, ISHFT, ISHFTC, ISHFTL, ISHFTR, BTEST, IBSET, IBCLR, and MVBITS. Bessel, Gamma, and error functions are also included.
- Z and O field descriptors allow octal and hexadecimal editing of I/O list items.
- Hollerith, hexadecimal, binary, and octal constants are supported.
- One trip DO LOOPs compatible with FORTRAN 66 can be optionally turned on.
- Free formatted input using commas is supported.
- The $ can be used to eliminate the carriage return that normally follows a read or write.
- Conditional compiles are signaled in column 1 by x, X, d, or D. Continuation lines in free format are indicated by &.
- The mixing of numeric and character data types in COMMON and EQUIVALENCE statements is allowed.
- INTERNAL files are expanded from SEQUENTIAL only to include DIRECT.
- Types include REAL*4, REAL*8, INTEGER*1, INTEGER*2, INTEGER*4, LOGICAL*1, LOGICAL*2, LOGICAL*4, COMPLEX*8, and COMPLEX*16. Default of LOGICAL and INTEGER is 4 but can be changed to 2.

Other Key Words:

ACCEPT statement
ASSOCIATEVARIABLE
BUFFERCOUNT
BYTE data type
CARRIAGECONTROL
DATE and IDATE
DEFAULTFILE
DEFINE FILE
DELETE statement
DISPOSE
DO...WHILE, extended range
ENCODE and DECODE
EXIT
EXTENDSIZE
FIND statement
%LOC, %REF, %VAL
MAXREC
NAME
NAMELIST
NOSPANBLOCKS
OPTIONS statement
ORGANIZATION
PARAMETER statement
Q Edit descriptor
RAN
READONLY
RECORDSIZE
RECORDTYPE
REWRITE statements
SECNDS
STRUCTURE declaration
TIME
TYPE statement
USEROPEN
VOLATILE and VIRTUAL statements

UNIX/C-Like Features:

- Command line processing using getarg, iargc, and getenv are supported.
- Strings may be declared with quotes or apostrophes, and internal string members may be defined using backslash editing identical to C.
- Upper and lower case are supported. For compatibility with C, the compiler converts upper to lower except in strings; a compile time option shuts off this conversion.
- AUTOMATIC and STATIC variables in procedures make recursive procedures possible.
- Programs written with NDP Fortran-386 can call or be called from NDP C or Pascal-386. Assembly language routines can also be interfaced with the compiled output.

System Requirements:

- Any 80386-based system; or any PC, XT, AT, or compatible with an Intel Inboard/386 or MicroWay Number Smasher-386.
- A numeric coprocessor is not required to compile. However, an Intel 80287 or 80387, Cyrix 83D87, MicroWay mW1167, or Weitek 3167 coprocessor is necessary to execute programs containing floating point routines.
- Double-sided high density floppy drive.
- Hard disk drive with a minimum of two free megabytes.
- Two megabytes of extended memory (four megabytes recommended).
- DOS version 3.2 or later as extended by Phar Lap Development Tools (version 2.0 or later), UNIX 386 System V Release 3, or SCO XENIX Release 2.3.

MicroWay®

NDP-386 COMPILERS

NDP C-386™: Globally Optimizing,Native Code C Compiler for the Intel, Cyrix, and Weitek Coprocessors

NDP C-386 is a globally optimizing compiler developed at MicroWay for the Intel 80386. It generates native 80386 code that runs in protected mode under UNIX 386 System V Release 3, SCO XENIX Release 2.3, and Phar Lap extended DOS. NDP C-386 makes it possible to port mainframe C applications to your 80386 that use as much memory as your system will hold: the upper limit on segment size in the linear address mode used is 4 gigabytes. The compiler also supports the following coprocessors: Intel 80287 and 80387, Cyrix 83D87, MicroWay/Weitek mW1167, and Weitek 3167, which have two to four times the throughput of an 80387.

The compiler generates code which optionally takes advantage of the Phar Lap Virtual Memory Manager. The latter makes it possible for a two megabyte 80386 system to run programs as large as the free memory on your hard disk!

The compiler is a full implementation of PCC (the Bell Labs Portable C Compiler, whose syntax is a superset of Kernighan and Ritchie C). It includes all standard PCC extensions as well as the December, 1988, draft of ANSI C and many Microsoft C v:5.0 functions. Among these new extensions are a set of graphics and BASIC-like screen handling functions, in addition to hooks to the operating system. These features make NDP C-386 compatible enough to compile most existing 16-bit applications, regardless of the source environment, provided they conform to standard techniques for portability between computers.

NDP C-386 v.2.0 Features:

- Passes 98% of the Plum Hall Validity Suite for ANSI System V UNIX C.
- Incorporates several new optimizations, including loop unrolling, repeat common subexpression elimination, register caching, and peephole optimization.
- Includes a command line switch to allow the compiler to run in virtual memory.
- NDP-386 Virtual Memory option allows executable programs to run in virtual memory using the Phar Lap Virtual Memory Manager.
- Generates programs, procedures, and arrays limited only by the amount of memory in the system, up to 4 gigabytes.
- Exceptional runtime speed due to global optimizations, sophisticated register utilization to store 32-bit entities, use of inline 32-bit arithmetic instead of library calls, and the effective doubling of the system data bus.
- Ports existing applications by fully implementing AT&T's PCC and its K & R subset.
- Generates inline code for coprocessors which makes excellent use of all numeric registers.
- Supports full 80387 and mW1167/3167 numeric instruction sets, including 80387 inline transcendentals.
- Supports customized coprocessor exception handling procedures to be designed and implemented by the user (examples are provided).
- Allows function and variable names of 31 characters which may include the $ character.
- Includes the following types: 32-bit pointer and enum types along with 8 byte double, 4 byte floats, 4 byte longs, 4 byte int, 2 byte short int, 1 byte char.
- An extended error function gets (and optionally prints) DOS errors, mapping them separately through errno.
- Incorporates a library of graphics and keyboard routines with enhanced features that supports CGA, MDA, EGA, VGA, and Hercules adapters. (DOS version only)
- Includes mouse support.
- Provides a trace facility to aid in debugging.
- Memory mapped devices and physical memory can be mapped into the program's linear address space.
- NDP C-386 can call or be called from NDP Fortran-386 or NDP Pascal-386 programs. Assembly language routines can be interfaced with compiled output.
- The CC compiler driver makes it possible to use the same switches for compiling, assembling, and linking when working with DOS, UNIX V, or XENIX 2.3.
- Command line processing includes the name of the current process.
- Fast I/O feature in DOS version makes it possible to specify the size and number of runtime buffers, resulting in an I/O speed up that ranges up to15 times faster.
- Can be used with the newest generation of Phar Lap tools to produce embedded and ROMable code.
- NDP Windows is an optional library for creating menus and storing, moving, or saving windows. It runs on MDA, CGA, EGA, and Hercules adapters.
- NDP to Halo '88 Interface is an optional graphics interface to Media Cybernetics Halo '88™.
- NDP Hoops is an optional advanced object-oriented graphics library.
- MicroWay also has a port of the AT&T C++ preprocessor v.1.2 that runs in protected mode with the NDP C-386 compiler.

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Optimization Features:

NDP C-386 converts the ASCII C text, one procedure at a time, into a memory-based operator tree. During global optimization, this tree is traversed from 5 to 50 times depending upon the options selected and the structure of the code. The primary goal of the global optimization is to store variables in registers as opposed to memory. Eliminating stores and loads to memory, on average, results in code that runs a factor of 3 faster while taking only 1/3 the space of code which stores variables in memory. The global analysis takes into account variable lifetime, activity, size, and the benefits of using faster running 16-bit addressing modes over the slower running 32-bit modes where possible. The optimizer produces code which takes maximum advantage of the registers available in the numeric coprocessors that the compiler supports. The generation of very high quality inline numeric code is one of the outstanding features of the NDP compilers.

The process of traversing the tree includes the application of code transformations to the tree. These transformations include numeric strength reductions, dead code elimination, removal of loop invariant code from loops, hoisting of common code out of blocks, constant propagation, elimination of stack frame setup on procedure entry where possible, conversion of small procedures into inline code where possible, and a number of processor related peephole optimizations. Loop optimizations which make the code larger but faster can also be optionally performed. These optimizations rearrange loops so that array base values are computed outside of loops and then stored in registers where they are used indirectly for addressing and incremented when necessary. The optimizer also performs global common subexpression elimination, caches array elements in registers, and unrolls short "hot" loops into inline code.

Numeric Coprocessor Support:

The NDP C-386 compiler provides different code generation for the following numeric coprocessors: Intel 80287, 80387, and 80387SX; Cyrix 83D87; and Weitek 1167 and 3167. NDP C-386 generates code to use the Weitek 3167 multiply and accumulate instruction.

NDP C-386 supports IEEE-754 floating point arithmetic. The compiler provides a complete set of functions which allows the programmer to read and change any value in the numeric coprocessor control register.

The NDP C-386 compiler contains a general purpose numeric exception handler. Under DOS, users can change the response characteristics of the default handler, or write their own customized handlers. The user manual includes two examples of user-written handlers: one traps division by zero and substitutes a very large number for infinity on the NDP stack; the other traps underflows and substitutes zeros for the result in memory.

Inline Assembler Feature:

An inline assembler is included in NDP C-386 which helps in the development of embedded code, device drivers, and applications which take advantage of the underlying hardware. The NDP C-386 inline assembler is unusual in that it makes it possible to write assembly language in C! For example, to increment the EAX register in assembly language, you could write INC EAX. In NDP C-386, you simply declare EAX to be a register aliased variable of type unsigned, and use the conventional C statement, EAX++. The compiler translates this C code into its corresponding assembly language, INC EAX.

Register aliased variables come in very handy for reading and writing ports inline as well as setting up and using software interrupts inline. The following example puts the current directory path into the string "string":

```
char string[64];
reg$eax unsigned eax;
reg$edx unsigned edx;
reg$esi char *esi;
eax = 0x4700;
edx = 0;
esi = string;
asm (eax, edx, esi, "int 21h");
printf ("Current directory is \"%s\"\n",string);
```

The code that results is inline, as opposed to the MS-DOS INT386 technique. The latter, which is also supported for compatibility, requires two data structures to be set up and a 50 line procedure (INT86) to be called.

Graphics Support:

The DOS version of the NDP C-386 compiler comes with a library of over 100 functions to draw pixels, lines, ellipses and text, move images and graphics cursors, read and write ports, and execute interrupts. Special routines are included to provide compatibility with the Microsoft C graphics library. The NDP C-386 graphics library works with the MDA, CGA, EGA, VGA, Super VGA, and Hercules graphics adapters. It includes routines to automatically detect the hardware configuration and determine the best graphics mode. Complete documentation is provided, including simple, clear examples.

System Requirements:

- Any 80386-based system; or any PC, XT, AT, or compatible with an Intel Inboard/386 or MicroWay Number Smasher-386.
- A numeric coprocessor is not required to compile. However, an Intel 80287 or 80387, Cyrix 83D87, MicroWay mW1167, or Weitek 3167 coprocessor is necessary to execute programs containing floating point routines.
- Double-sided high density floppy drive.
- Hard disk drive with a minimum of two free megabytes.
- Two megabytes of extended memory (four megabytes recommended).
- DOS version 3.2 or later as extended by Phar Lap Development Tools (version 2.0 or later), UNIX 386 System V Release 3, or SCO XENIX Release 2.3.