

A Digital Mosaicking Algorithm Allowing for an Irregular Join "Line"

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ABSTRACT: Computer mosaicking of any type of digital images using intricate join "lines" can now be achieved through a simple algorithm. Prerequisites are two scenes, geometrically registered to each other and brightness-matched across the seam. The algorithm is used to define digitally every point of the join "line" in image space and to test each location to determine which scene brightness value (DN) will be used in the mosaic. An example is presented using daytime, thermal infrared data of the Arabian Peninsula from the NOAA-AVHRR satellite system. The mosaicking technique is simple, requires only minimal computation, and can be easily programmed on most mini-computers.

INTRODUCTION

FOR A VARIETY OF APPLICATIONS, the utility of satellite and aircraft digital images is increased if particular areal coverage can be reconstructed – mosaicked – from various data sets with minimum seam visibility. Two common uses of the irregular mosaicking algorithm are to eliminate spurious effects (i.e., clouds, shadows) and to mosaic two images that are not perfectly brightness matched. An extensive software package (Zobrist *et al.*, 1983) exists which includes variable seam mosaicking of Landsat Multispectral Scanner (MSS) images as an option. The mosaicking technique presented here does not require exclusive software to implement; the method can easily be programmed on most minicomputers; and it is applicable to any digital data set.

Considerations for the preparation of the scenes to be mosaicked are presented. Prior to mosaicking, compatible scenes are selected and prepared for merging by geometrically registering one to the other and matching the brightness of their common area. The basic concept of the mosaicking algorithm is described and the critical subroutine is presented. A daytime, thermal infrared mosaic of the Arabian Peninsula, constructed using data from the NOAA (National Oceanic and Atmospheric Administration) AVHRR (Advanced Very High Resolution Radiometer) system, is provided as an example of the method.

SCENE SELECTION CONSIDERATIONS

Selection of the scenes that will comprise the mosaic ultimately determines the quality of the final image product. It is important to preserve as much of the radiometric and geometric accuracy as possible. Criteria for selection of scenes should include minimal cloud cover and atmospheric effects, minimal brightness variations over common areas, and minimal ground resolution differences. (This is particularly important when using data with a wide-angle swath and thus variable ground resolution such as NOAA-AVHRR.) Cloud cover obscures and cloud shadows alter the ground signal. More difficult to detect are other meteorological phenomena such as the presence of scattered, thin cirrus clouds in reflectance and thermal data and cloudless, cold air masses on thermal data. The example presented later in this paper illustrates the latter effect on thermal data.

For mosaicking reflectance data, scenes should be selected that were acquired under similar solar illumination conditions in order to minimize the brightness variation problem. The intensity of the solar radiation at a given location and time is

dependent upon the solar declination, site latitude, the sun's hour angle, and the atmospheric transmission. As the solar illumination angle changes, surfaces with topographic relief will cast shadows differently. The reflected energy in turn depends on the photometric function of the surface and is an important factor as the illumination changes; vegetation is a strong back-scatterer whereas unconsolidated surficial materials are more Lambertian. The seasonal state of the vegetation is also a factor of consideration, particularly in cultivated or deciduously forested areas.

For mosaicking thermal data, scenes should be selected that were acquired under similar solar heating and meteorological conditions in order to minimize the brightness variation between scenes. Brightness matching of thermal image data can be significantly more difficult than for reflectance image data. The ground temperature varies due to the incident heating and cooling fluxes which have both a diurnal and a seasonal variation. In addition, both short- and long-term transient heating and cooling fluxes can strongly influence the thermal response of the ground.

SCENE PREPARATION

Digital images to be mosaicked must first be panoramically corrected along each scanline. Radiometric scanners record data at equal scan angle increments; therefore, the spatial distance between pixel (picture element) centers and the area of the ground covered by the pixel both increase outward from the nadir point of the scanner. A panoramic correction applied to a scanline resamples the data such that the pixel centers are now spatially equidistant; however, the effective area sampled for each pixel increases with increasing distance from the nadir point. The effect of this change in spatial frequency content makes the data appear sharpest at the center and fuzzier toward the edges of the image. Thus, a problem occurs in matching common areas acquired with different nadir angles. This effect can be reduced somewhat by employing selective high frequency filtering. The variability in pixel sharpness becomes a more significant problem when mosaicking two scenes acquired from different flight or orbital paths. Matching the pixel high frequency content is of greater necessity in areas of large ground variability (e.g., topographic relief) than in more homogeneous areas.

After the scenes have been selected for the mosaic, their common areas are determined and geometrically registered. This is easiest to do after registering each separate scene to a common base map; however, registration of one to the other is adequate.

A variety of registration techniques is available, the choice of which is dependent upon the geometric distortions that are present due to the stability of the acquisition platform. Landsat has a relatively stable platform. For each Landsat path/row coordinate in the United States, a Ground Control Point Chips Library (Niblack, 1981) is available which contains approximately 25 image chips. These 32 by 32 image chips allow registration of Landsat MSS data to a latitude/longitude coordinate base. Similar chips are used in the registration of the higher resolution Thematic Mapper (TM) data.

For thermal data, which have some unique characteristics as compared to reflectance data, several registration techniques have been employed (Watson *et al.*, 1982; Price, 1982; Watson *et al.*, 1984). These techniques include registering an image to a base map, one similar image product to another, and a nighttime thermal image to a daytime image. Aircraft data generally require a complex registration scheme due to the pitch, yaw, and roll of the plane. One algorithm that has given positive results involves using weighting factors based on the inverse distance to the four nearest control points for determining the correction at any pixel. For this method, a roughly uniform grid of control points with a higher density of points in areas of greatest distortion is preferred. More stable satellite data have been successfully registered using carefully selected control points and a simple affine transformation. (The example presented later was registered using this scheme.) Another registration scheme is one employed by Price (1982) that involves creating triangular regions with the control points at the vertices and applying an affine transformation to each region. Cross-correlation techniques have been used to register small areas of similar data products. A user, therefore, has many registration algorithms from which to choose.

THE MOSAICKING ALGORITHM

Using FORTRAN VII on a Perkin Elmer 3240 computer*, I developed the mosaicking algorithm that can easily be adapted to other computing systems. The crux of the algorithm is contained in the subroutine LINESORT (FORTRAN code is listed in Appendix A) which builds a two-dimensional lookup array. This subroutine is written to accommodate an irregular join "line" that approximately dissects two images horizontally. For a vertical dissection, the subroutine either can be rewritten to sort in the vertical direction (Figure 1) or the two images can be rotated and the subroutine applied in its present form.

The mosaicking technique is applied in digital image space. This space can be visualized by considering discrete pixels in an xyz integer coordinate system. Each pixel has an integer

brightness DN (data number) value (the z direction) associated with it; this value is a measure of intensity for the particular data set (i.e., reflectance for MSS data, temperature for thermal data). The location of each pixel is defined by x, y integer coordinates; the origin of the coordinate system is selected as the upper left hand corner of the image (Figure 1). A scanline is defined to be a sequential set of DNs that are associated with one y value and minimum to maximum x values.

THE SUBROUTINE LINESORT

This section discusses the selection of mapping-pair control points to define a join "line," the interpolation of these points to completely specify the join "line" in image space, the image selection criterion and how it is applied, the generation of the LINESORT array, and the resorting of the LINESORT array.

The user specifies a join "line" by identifying a sequential set of x, y mapping-pair control points (not necessarily adjacent) and forms them into two ordered input arrays, consisting of the x and y values of the mapping pairs. The first step of the subroutine is to interpolate the join "line" using the selected mapping pairs to form a spatially contiguous set of x, y locations in image space (Table 1). (When plotted in this space, this set of integers appears as a jagged "line" (Figure 1).) The simplest interpolation method to define the join "line" is a linear interpolation between the initially selected mapping pairs. Other interpolation schemes, such as cubic spline or a polynomial, are more computer intensive and can be replicated by short "line" segments. Therefore, the linear interpolation method using a sufficient number of initial x, y mapping pairs can closely approximate the more sophisticated schemes in image space. Figure 2 shows the mosaicking of a white and a black image using an irregular join "line." Figure 2b has three times more mapping pairs than Figure 2a and illustrates the smoothing effect that can be obtained.

As mentioned previously, the version of LINESORT described herein assumes that the two images are to be mosaicked with an upper and a lower image as opposed to left side and right side images. For this version of the subroutine (Appendix A), the two-dimensional lookup array is constructed in which each column number is associated with a particular x location; the rows of the array contain all the y locations of the join "line"

TABLE 1. LIST OF STEPS DESCRIBING THE SUBROUTINE LINESORT

- * Input the total number of selected mapping pairs of the join "line" and the two ordered input arrays containing the x and y values of the mapping pairs.
- * Determine the maximum and minimum x and y mapping pair values.
- * Linearly interpolate the join "line" and check for reversal in the x direction.
- * Initialize the two-dimensional lookup array.
- * Fill the lookup array and check for vertical segments and for the row dimension of 6 being exceeded.
- * Adjust the lookup array for reversal in the x direction.
- * Initialize the first row of the lookup array to the value 1.
- * Return to main program for mosaicking.

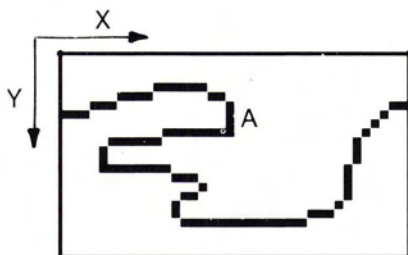


FIG. 1. A sample join "line" in image space. The x, y coordinate system is indicated. Point A is a mapping-pair control point at which a reversal in the x direction occurs.

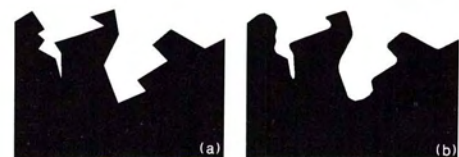


FIG. 2. A black-and-white mosaic illustrating the technique for (a) 24 mapping-pair control points and (b) 68 mapping-pair control points.

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for that particular x location. The basic criterion for image selection is that the upper image will be used until the join "line" is crossed. For subsequent scanlines, the lower image value will be used until the join "line" is again crossed. The image selected for the mosaic will alternate as the join "line" is crossed. The above criterion has an exception. If the (x, y) location is both a mapping-pair control point and represents a reversal in the x direction of the join "line" (see Figure 1, point A), the image selected for the mosaic remains unchanged. As the subroutine is interpolating between mapping pairs, it also determines at each mapping pair location if a reversal in the x direction of the join "line" has occurred. As each reversal in x direction is encountered, the sequence number of that mapping pair is stored in an array for later use.

The elements of the join "line" are now reordered into a two-dimensional lookup array. The reordering simplifies both the merging and the complexity of an intricate join "line." The lookup array is two-dimensional. The number of columns is equal to the maximum x coordinate in the image (i.e., the number of pixels across the width of the image). A vertical "line" on the image will cross the join "line" at least once and, in general, several times. The number of rows in the two-dimensional array will be equal to one plus the maximum number of possible vertical line crossings. The first row in this array is reserved for housekeeping information and contains the number of crossings of the join "line". (LINESORT was written for six rows.) During the filling of the two-dimensional array, the program checks for vertical segments in the join "line". Vertical segments do not constitute a change in the x direction and count collectively as one toward the maximum number of possible crossings.

Because the image files are accessed one scanline at a time (thus permitting processing of very large images), the column bins (i.e., rows 2 through 6 in Appendix A) in the two-dimensional array need to be rearranged in increasing y value. This is a simple sort routine (again see Appendix A). If the row dimension of the lookup array is increased beyond 6, this sorting part of the subroutine will have to be rewritten to reflect the new dimension.

At this point, the lookup array contains x maximum number of columns and six rows. The first row contains the number of crossings of the join "line" for that x location. The other five rows contain the y locations at which these crossings occur in increasing y value.

LINESORT now adjusts for reversal in x direction. The subroutine determines the column and row number at which the reversal occurs and readjusts the column by deleting that value. The last step in the subroutine is to reset all the first row elements of the lookup array to 1. Control now passes from LINESORT to the main program with the created two-dimensional lookup array and the minimum and maximum y values in the join "line."

IMPLEMENTING LINESORT

In the main program (Table 2), the common area of the two registered images are accessed one scanline at a time, and the mosaicking is performed for that scanline by interrogating the LINESORT array at each x location (column number of the array). If the y value of the scanline is less than or equal to the second element in column x , then the first element in column x defines which image to use in the mosaic. If the first element in column x is 1, then the upper image is used. The program now determines if the second element in the x column is equal to the current scanline y value. If it is, the first element is transposed between values of 1 and 2, the second element is eliminated, and the remaining elements of the column are move up. The mosaicking continues until the maximum y location of the input mapping pairs is reached.

TABLE 2. LIST OF PROCESSING STEPS DESCRIBING THE MAIN MOSAICKING PROGRAM.

- * Input the two image files, the two ordered input arrays that contain the x and y values of the mapping pairs of the join "line," and the total number of selected mapping pairs.
- * Call subroutine LINESORT which outputs a two-dimensional lookup array and the maximum and minimum y values of the input mapping pairs.
- * Read in the upper registered image, one scanline at a time, and directly output the upper image for (minimum y value minus one) scanlines.
- * Read in both the upper and lower registered images, one scanline at a time.
- * Interrogate the lookup array to determine which input image is used to form the output image.
Read in the lower image for (maximum y value plus one) scanlines to the end of lower image.

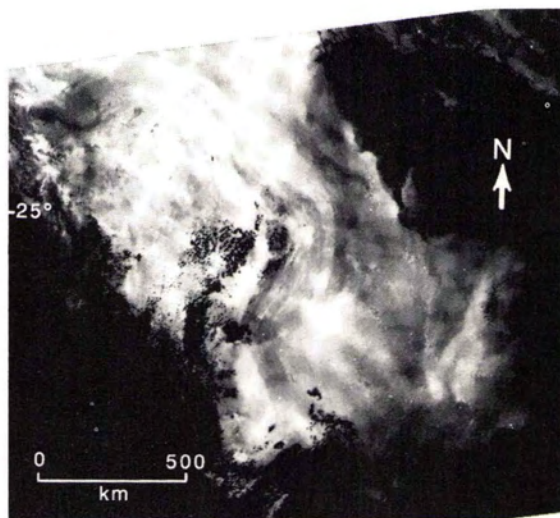


FIG. 3. Day thermal image acquired 31 August 1982. Bright areas are hot and dark areas are cold. Meteorological effects (dark) can be seen below about 25°N latitude.

AN EXAMPLE

The mosaicking technique was developed in support of a regional study of the Arabian Peninsula using NOAA-AVHRR data (U.S. National Oceanic and Atmospheric Administration, 1983). One of our program objectives was to produce cloud-free image mosaics of the entire peninsula. For this example, two day thermal satellite scenes (11.5 to 12.5 μm at 1 km resolution) covering the entire Arabian Peninsula were selected. The day thermal example is illustrated because the join "line" used to produce the mosaic was the most complicated of all the mosaics produced.

Two scenes were selected whose overlap would provide the required cloud free information, and both were registered to the same geometric base map using a simple affine transformation (Watson *et al.*, 1982). The one scene (Figure 3) was acquired 31 August 1982, and is relatively cloud free above 25°N latitude. To the south, some scattered clouds appear on the western edge of the scene; the central and eastern portions are clear. The second scene (Figure 4) was acquired 19 February 1984, and has a large cold air cloud mass evident in the northern portions of the image. Above approximately 25°N latitude, the cloud cover is virtually complete.

These two scenes are not the most ideal ones for mosaicking;

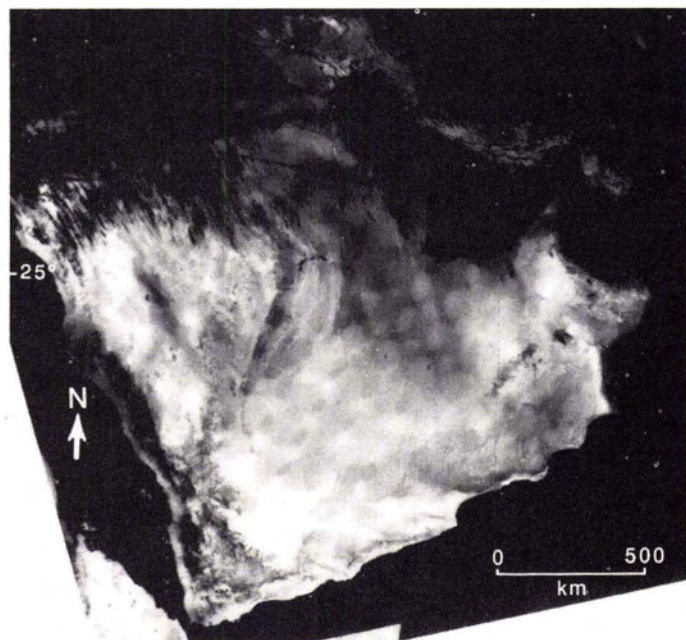


FIG. 4. Day thermal image acquired 19 February 1984. Clouds are evident (dark) from about 25°N latitude northward. The water bodies also appear cold in this daytime image.

the common cloud free area of the two scenes is not entirely void of meteorological effects. The flight paths for these two scenes were different, which resulted in different ground resolutions in the common overlap area. However, because this portion of the peninsula has minimal high frequency features, the difference in ground resolutions between scenes is not readily discernible on the images.

After registering the two images, the common cloud-free portion of the overlap area was examined for brightness differences. The February scene was chosen to be the base image for the mosaic and the August image was digitally stretched to achieve the best possible brightness match.

The variable join "line" used in this example was specified by a linear interpolation between 27 points and chosen to best eliminate clouds and to minimize obvious brightness differences. As can be seen on the mosaic (Figure 5), approximately 900 km down and 500 km in from the upper left hand corner, there is evident a contrast difference at the seam. This is a consequence of both scenes exhibiting meteorological effects in the overlap area: clouds in the August image and a cold air mass in the February image.

CONCLUSIONS

Intricate digital mosaicking of various image sets can be easily achieved with the algorithm described therein. The subroutine creates the lookup array by interpolation between the points chosen to define the seam and requires mathematical computations. The mosaicking or stitching portion of the program is merely a selection process and, therefore is constrained by the input/output characteristics of the particular computer. Because

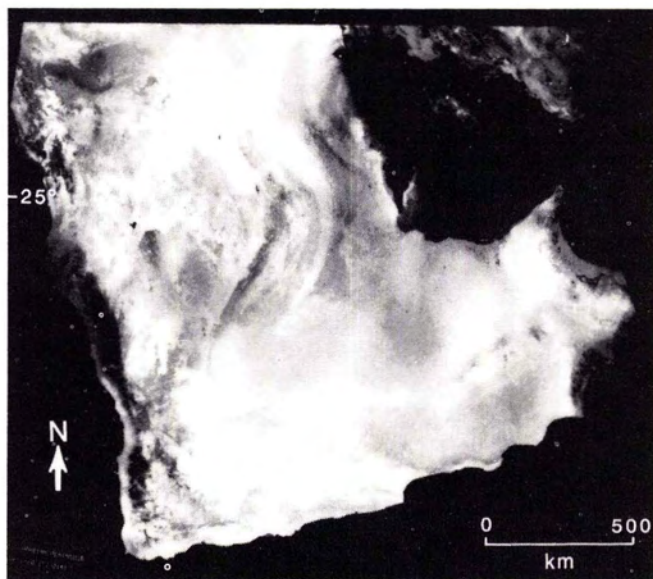


FIG. 5. Digital day thermal mosaic of the Arabian Peninsula.

the mosaic is created scanline-by-scanline, the technique requires minimal computation and memory.

The quality of the mosaic is strongly dependent on the quality of the input scenes. The better the scenes are matched in brightness and registered to each other, the better the final product. Thus, the availability of appropriate data can severely limit the quality of the final mosaic. The selection of an interpolation scheme to define the join "line" is the least critical portion of this mosaicking method.

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APPENDIX A

THE FORTRAN CODE FOR THE SUBROUTINE LINESORT

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SUBROUTINE LINESORT (XPT,YPT,NUM,LOUT,MXXY,MINY)
  INTEGER XPT(8),YPT(8),XOUT(2000),YOUT(2000),IPOINT(100)
  INTEGER LOUT(6,2000)

  C DEFINITION OF VARIABLES
  C XPT=INPUT ARRAY OF THE X VALUES OF THE JOIN "LINE" MAPPING
  C PAIRS
  C YPT=MATCHING INPUT ARRAY OF THE Y VALUES OF THE MAPPING
  C PAIRS
  C NUM=NUMBER OF MAPPING PAIRS
  C XOUT=ARRAY CONTAINING ALL INTERMEDIATE X VALUES
  C YOUT=ARRAY CONTAINING ALL INTERMEDIATE Y VALUES
  C LOUT=TWO-DIMENSIONAL LOOKUP ARRAY
  C MXXY=MAXIMUM VALUE IN THE YPT ARRAY
  C MINY=MINIMUM VALUE IN THE YPT ARRAY
  C M=COUNTER OF THE POINTS IN THE INTERPOLATED "LINE"
  C NC=COUNTER OF REVERSALS IN THE X DIRECTION
  C TOP=CHANGE IN Y VALUE BETWEEN ADJACENT MAPPING PAIRS
  C BOT=CHANGE IN X VALUE BETWEEN ADJACENT MAPPING PAIRS
  C BOTD=PREVIOUS BOT VALUE
  C IPOINT=ARRAY CONTAINING THE NUMBER OF THE MAPPING PAIRS
  C AT WHICH A REVERSAL IN THE X DIRECTION OCCURS
  C ATOP=ABSOLUTE VALUE OF TOP
  C ABOT=ABSOLUTE VALUE OF BOT
  C SG=SIGN OF TOP OR BOT
  C Z=CHANGE IN Y VALUE PER INCREMENT IN X VALUE

  C DETERMINE MINIMUM AND MAXIMUM X AND Y MAPPING PAIR VALUES
  MXXY=0
  MINX=2000
  MXXY=0
  MINY=2000
  DO 1 K=1,NUM
    IF (XPT(K).GT.MXXY) MXXY=XPT(K)
    IF (XPT(K).LT.MINX) MINX=XPT(K)
    IF (YPT(K).GT.MXXY) MXXY=YPT(K)
    IF (YPT(K).LT.MINY) MINY=YPT(K)
  1 CONTINUE

  C LINEAR INTERPOLATION OF JOIN "LINE"
  M=1
  NC=0
  DO 2 K=1,NUM-1
    XOUT(M)=XPT(K)
    YOUT(M)=YPT(K)
    TOP=YPT(K+1)-YPT(K)
    BOT=XPT(K+1)-XPT(K)

    C COMPUTING INTERMEDIATE POINTS
    IF (BOT.EQ.0) THEN
      ATOP=ABS(TOP)
      SG=TOP/ATOP
      DO 3 L=1,ATOP-1
        XOUT(M+L)=XPT(K)
        YOUT(M+L)=YPT(K)+L*SG
      3 M=M+ATOP
      BOTD=BOT
      GO TO 14
    END IF
    Z=TOP/BOT
    ABOT=ABS(BOT)
    SG=BOT/ABOT
    DO 4 L=1,ATOP-1
      X=XPT(K)+L*SG
      XOUT(M+L)=XPT(K)+L*SG
      YOUT(M+L)=X+YPT(K)
    4 M=M+ABOT
    BOTD=BOT

    C CHECKING FOR REVERSAL IN X DIRECTION
    IF (K.GT.1) THEN
      IF (BOTD.EQ.0) BOTD=1
      TEST=BOT/BOTD
      IF (TEST.LT.0) THEN
        NC=NC+1
        IPOINT(NC)=K
      END IF
    END IF
  2 CONTINUE
  XOUT(M)=XPT(NUM)
  YOUT(M)=YPT(NUM)

  C INITIALIZE THE OUTPUT TWO-DIMENSIONAL LOOKUP ARRAY - LOUT
  DO 5 L=1,6
    DO 6 J=MINX,MXXY
      LOUT(L,J)=10000
      IF (L.EQ.1) LOUT(1,J)=0
    5 CONTINUE

  C FILL THE OUTPUT TWO-DIMENSIONAL LOOKUP ARRAY
  DO 6 K=MINX,MXXY
    IF (LOUT(1,XOUT(K)).EQ.0) GO TO 7

  C CHECKING FOR VERTICAL SEGMENTS
  IF (XOUT(K).EQ.XOUT(K-1)) THEN
    IVAL=LOUT(LOUT(XOUT(K),1)+1,XOUT(K))
    IF (YOUT(K).EQ.IVAL+1.OR.YOUT(K).EQ.IVAL-1) GO TO 6
  END IF

  C PLACE VALUES IN ARRAY, INCREMENT THE COUNTER, AND CHECK
  C IF THE ARRAY ROW DIMENSION OF 6 HAS BEEN EXCEEDED
  LOUT(1,XOUT(K))=LOUT(1,XOUT(K))+1
  IF (LOUT(1,XOUT(K)).GT.6) THEN
    WRITE(6,*) 'ARRAY ROW DIMENSION EXCEEDS 6!'
    CALL EXIT(3)
  END IF
  6 LOUT(LOUT(XOUT(K),1)+1,XOUT(K))=YOUT(K)

  C REARRANGE COLUMN BINS IN INCREASING Y VALUE
  DO 8 NN=MINX,MXXY
    IF (LOUT(2,NN).GT.LOUT(3,NN)) THEN
      TEMP=LOUT(2,NN)
      LOUT(2,NN)=LOUT(3,NN)
      LOUT(3,NN)=TEMP
    END IF
    IF (LOUT(4,NN).GT.LOUT(5,NN)) THEN
      TEMP=LOUT(4,NN)
      LOUT(4,NN)=LOUT(5,NN)
      LOUT(5,NN)=TEMP
    END IF
    IF (LOUT(3,NN).LE.LOUT(4,NN).AND.LOUT(5,NN).LE.LOUT(6,NN)) GO TO 8
    IF (LOUT(3,NN).GT.LOUT(4,NN)) THEN
      TEMP=LOUT(3,NN)
      LOUT(3,NN)=LOUT(4,NN)
      LOUT(4,NN)=TEMP
    END IF
    IF (LOUT(5,NN).GT.LOUT(6,NN)) THEN
      TEMP=LOUT(5,NN)
      LOUT(5,NN)=LOUT(6,NN)
      LOUT(6,NN)=TEMP
    END IF
    IF (LOUT(2,NN).LE.LOUT(3,NN).AND.LOUT(4,NN).LE.LOUT(5,NN)) GO TO 8
    GO TO 9
  8 CONTINUE

  C ADJUST FOR REVERSAL IN X DIRECTION
  IF (NC.EQ.0) GO TO 10
  DO 11 J=1,NC
    LSTART=0
    LP=IPOINT(J)
    DO 12 L=2,6
      IF (YPT(LP).EQ.LOUT(L,XPT(LP))) LSTART=L
    12 CONTINUE
    IF (LSTART.EQ.0) CALL EXIT(7)
    LEND=LOUT(1,XPT(LP))+1
    DO 11 M=LSTART,LEND
      IF (M.EQ.LEND) THEN
        LOUT(M,XPT(LP))=LOUT(M+1,XPT(LP))
        GO TO 11
      END IF
      LOUT(M,XPT(LP))=LOUT(M+1,XPT(LP))
    11 CONTINUE

  C INITIALIZE FIRST ROW OF TWO-DIMENSIONAL LOOKUP ARRAY TO 1
  DO 10 J=MINX,MXXY
    LOUT(1,J)=1
  10 CONTINUE

  C RETURN OF MAIN PROGRAM
  RETURN
END

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