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Geometric Correction of ERTS-1 Digital Multispectral Scanner Data

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ERTS-1 Multispectral Scanner Data is received from the satellite by NASA, processed, and delivered to users recorded on computer compatible tape and in photographic form. The computer tape form of the data is calibrated and line length adjusted by NASA but no geometric corrections are applied [1]. The system-corrected photographic products are corrected for many geometric distortions including earth rotation effects in addition to the above two corrections. Also, these images are rescaled so that the horizontal and vertical scales are the same. Thus, the digital form of the MSS data contains many geometric distortions and users of this data are faced with the problem of compensating for these errors.

When digital MSS data is reproduced in image form on a standard IBM computer line printer the resulting scale factor is approximately 1" = 22400" in the horizontal direction and 1" = 25200" in the vertical direction. This scale differential exists in addition to the skew due to earth rotation and all other geometric errors. Similarly when this data is reproduced on a video display device the horizontal scale is 56 meters per point and the vertical scale is 79 meters per point. Correction of these geometric distortions has become highly desirable by certain researchers who require that the ERTS images exactly match maps of terrain areas under study. The techniques discussed in this note are an attempt to improve the geometric quality of the ERTS digital data for research purposes.

MSS Digital Data Geometric Characteristics

The ERTS-1 MSS system produces four spectral band digitized imagery of approximately 100 (185 Km) nautical mile wide strips beneath the satellite path. The scanner has an instantaneous resolution of 79 meters and scan lines are sampled at a rate such that samples are spaced approximately 56 meters apart and successive scan lines are spaced approximately 79 meters apart as determined by the forward motion of the satellite. The image data are edited so that the along size is approximately 96.3 nautical miles (155 Km). The resulting data set consists of nominally 3240 samples horizontally (E-W) and 2340 samples vertically (N-S). The geometric distortions are due to sensor, satellite, and earth effects. The major sources of error are listed briefly here:

1. Scale Differential - This is the 79 meter horizontal

versus 56 meter vertical sample ratio mentioned above. These are approximate values since sensor and satellite motion effects influence the sample rate as will be discussed below.

2. Altitude Variations - The orbit is not circular and the earth is not spherical thus the altitude varies with position in orbit about the nominal 494 N mi value. Changing altitude causes the 79 meter resolution to vary and the 56 meter horizontal sample spacing also varies (i.e. horizontal scale). The magnitude is of the order $\Delta X = 9.26 \times 10^4 \frac{\Delta h}{h}$ where Δh is the altitude change over the frame, h is the nominal altitude and ΔX is the change in width of the image.

3. Attitude Variations - The satellite undergoes random roll, pitch, and yaw variations due to errors in its attitude control system. Roll causes a skew in the horizontal direction of magnitude $\Delta X = h\theta_R$ where h is the nominal altitude, θ_R is the roll variation over the frame, and ΔX is the amount of horizontal skew. Pitch variations cause a change in the vertical scale by changing the vertical size of the frame. The magnitude is $\Delta Y = h\theta_p$ where θ_p is the pitch variation

from the top to bottom of the frame. Yaw variation causes a variable vertical skew distortion which is difficult to simply describe.

4. Earth Rotation Skew - The Eastward rotation of the earth under the satellite path causes the area scanned for a frame to be a parallelogram skewed about 5% from square or about a 5 mile shift from top to bottom.

5. Orbit Velocity Change - The variation in satellite velocity due to the eccentricity of the orbit and non-sphericity of the earth causes a vertical scale change. The change in height of the frame due to this effect is $\Delta Y \approx 8.88 \times 10^4 \frac{\Delta V}{V}$, where ΔV is the velocity change over the frame and V is the nominal velocity.

6. Scan Time Skew - The scanning mirror takes a finite time to scan on line across the scene and in that period the satellite is moving forward. A line skew occurs which is approximately 216 meters in magnitude, i.e., one side of the scan line is 216 meters advanced along the track of the satellite than the other side.

7. Nonlinear Scan Sweep - The scanning mirror does not move evenly across the scene and the deviation from linearity is estimated to be at most 395 meters at any point across the image.

8. Scan Angle Error - The look angle from nadir causes a

horizontal scale error proportional to the angle. This is a very small error since the maximum look angle is $\pm 5.78°$ and amounts to a maximum of 115 meters.

9. Frame Rotation - The orientation of the frame with respect to North is approximately 13° in the U.S.A. clockwise due to the fact that the orbit inclination at the equator is approximately 99.114°. This rotation is not considered an error; however, it is convenient to work with image products which are North-oriented.

The magnitudes of most of these errors are unknown, at least by LARS CCT users at present. The major errors are the scale and skew errors. Also, rotation to North-orientation is considered highly desirable. A two step process was developed to correct this data for small areas.

II. Geometric Correction

The geometric correction task was divided into two steps. Corrections that could be predicted reasonably well such as scaling and skew would be performed "open loop", i.e., without feedback from ground control points, to approximately correct the data. This approach makes improved data available to users rapidly. The second stage is a "fine" correction which uses ground control checkpoints to remove the remaining several hundred meter error in the initial correction. The coarse or initial correction would be useful to those wishing to visually relate points on maps and ERTS data and especially to those studying the millions of rectangular North South-oriented agricultural fields which exist in certain areas. The fine correction would produce images which would exactly (within 1 pixel) match the image the checkpoints were taken from over the area that the points were taken from.

The coarse correction consists of five linear transformations which act on the entire image block. This is contrasted to a nonlinear transformation which could compensate for randomly varying scale, skew and other distortions. The ERTS image consists of discrete samples of reflected energy over a two-dimensional space. The image can be thought of as a three-dimensional array $P(i,j,k)$ where i are the rows or lines of data points, j are the columns or samples across the image and the k are the channels. The data values themselves are nonnegative integers having values between 0 and 128. The four channels are assumed to be in perfect registration in this discussion so the problem can be studied as a two-dimensional single channel image problem. The ERTS image is thus defined as an array of points P with:

$$0 \leq P(i,j) \leq 128 \qquad 1 \leq i \leq 2340, \qquad 1 \leq j \leq 3232$$

Transformation of this array into another array which when displayed on a certain type of output device has given geometric characteristics is the geometric correction problem.

Linear transformation of elements of a two-dimensional space into another two-dimensional space is accomplished by the linear combinations:

$$Y_1 = a_{11} x_1 + a_{12} x_2$$

$$Y_2 = a_{21} x_1 + a_{22} x_2$$

Or in matrix form:

$$Y = AX$$

$$Y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix}$$

$$X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$$

$$A = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix}$$

The physical meaning of such a transformation is depicted in Figure 1. The nodes of the X grid represents original ERTS samples of reflected energy from discrete points on the earth. These samples are stored as a two-dimensional array of integers.

The desired samples are represented by the Y grid. These samples are oriented in a rescaled, rotated, and deskewed coordinate system. The geometric correction process assigns radiance values to nodes in the new grid using the data available from the existing grid, i.e., the raw ERTS data. Clearly the conceptually simplest way to match a map grid to the ERTS data grid is to distort the map or its topographic coordinates to match the ERTS data. This is not practical in general because large number of maps already exist in normal topographic coordinates and users wish to match ERTS data to these maps.

The linear transformation A can correct for skew and scale errors as well as rotate the image. Note that in general no original sample exists in the new grid at the desired sample points. Thus,some form of interpolation is required to perform any geometric transformation on the data. This problem is discussed in a following section. The transformations are represented by the following matrices:

1. Scale Change

The ERTS sampling ratio is approximately 3 to 2 as determined by the ratio of horizontal samples to vertical samples for the same terrain distance. The linear transformation matrix which will change the scale of the twodimensions different amounts is:

$$M = \begin{bmatrix} a_{11} & 0 \\ 0 & a_{22} \end{bmatrix}$$

Note that in order to change the scale of the data some samples will have to be skipped or duplicated at some points. This can be considered elimination of information or duplication of information. Since the resolution of the ERTS MSS is nominally 79 meters and the across track or horizontal sampling is every 56 meters redundancy already exists due to the overlap in this dimension. The vertical or along track sampling is the same as the resolution thus no overlap exists. The question thus arises - is it preferable to eliminate partially redundant samples or duplicate independent samples to effect a scale change? It was decided that significant information would not be lost if horizontal samples were dropped. Thus the matrix to correct the horizontal scale factor from nominally 56 meters per point to 79 meters per point is:

$$M_1 = \begin{bmatrix} 1.41 & 0 \\ 0 & 1 \end{bmatrix}$$

A basic feel for what this matrix will do can be obtained by observing the coordinate limits for a total frame. At line one and column one the transformed coordinates are:

$$\begin{bmatrix} 1.41 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1.41 \\ 1 \end{bmatrix} \cong \begin{bmatrix} 1 \\ 1 \end{bmatrix}$$

The resultant coordinate is rounded to the nearest integer under the nearest neighbor rule which will be discussed. At the lower right corner of the new "square" image the point 2340 lines, 2340 columns should come from the lower right corner of the original data or line 2340, column 3232. Thus when output column coordinate is 2340 the coordinate for the input is 1.41 x 2340 $\cong$ 3232. This is not an equality since 1.41 = 79/56 and 3232/2340 = 1.38. The first ratio is used since it is assumed that it is more stable, i.e., the number of samples tends to be variable. This matrix is referred to as M_1 and is labeled the scanner scale correction.

2. Rotation

Rotation through an angle θ of the "squared up" image obtained from the M_1 transformation is accomplished by a standard coordinate rotation:

$$M_2 = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix}$$

The amount of rotation of the ERTS frame required to bring it square with North varies with latitude. The ERTS orbit crosses the equator with an inclination of approximately 99.119°, i.e., clockwise from North 9.119°. At the highest latitude reached (about 80°) the heading of the satellite is 90° in the Southern hemisphere, 270° in the Northern. Thus the θ varies from 9.119 to 90. The spherical trigonometric function for the required θ for rotating the data to North is:

$$\theta = 90 - \cos^{-1}\left[\frac{\sin \theta_E}{\cos \lambda}\right]$$

WHERE: θ_E is the inclination at the equator (9.119°)

λ is the latitude

The θ obtained is approximate because the heading is varying over the entire image and the orbit does not exactly have the assumed inclination. The errors involved are small; however, ground control data will be needed to remove the remaining errors.

3. Skew due to Earth Rotation

The earth is rotating inside the orbit of the satellite as the ERTS data is being scanned. The rotation results in an Eastward surface velocity which causes a skew in the resulting ERTS frame. The Eastward surface velocity beneath the satellite is approximately:

$$V_e = R_e \cos\lambda \, \omega_e$$

WHERE:

V_e = Velocity to East

R_e = Radius of earth = 6.37816×10^6 meters

λ = Latitude of satellite

ω_e = Angular rate of the earth = $.7272 \times 10^{-4}$ radians/sec.

The satellite period is approximately 106 minutes so the angular rate is $\omega_o = 9.87 \times 10^{-4}$ radians/second. A 161 km (100 N mi) frame would be scanned in:

$$t_s = \frac{L}{R_e \ \omega_o}$$

$$= \frac{161000}{6.37816x10^7 x 9.87x10^{-4}} = 25.5 \text{ sec.}$$

WHERE: L is the height (along track length) of a frame

R_e is earth radius

ω_o is the orbital angular rate

The Eastward displacement of the earth during the scanning of a frame would be:

$$\Delta X_E = t_s V_e$$

For example, at 40°N latitude V_E = 355.29 meters/second and the Eastward displacement would be:

$$\Delta X_E = 25.5x355.29 = 8060.5 \text{ meters}$$

This is 8.0605/161 of a frame or about 5%. The earth rotation effect is actually acting at an angle to the scan lines due to the non-polar orbit thus the distance the bottom of the frame is actually displaced is:

$$\Delta X = \Delta X_E \cos\theta$$

If the skew correction is performed after rotation to North the cosine factor above becomes unity however the apparent orbital velocity is reduced by a cosθ factor. The skew correction matrix for correction after rotation is:

$$M_3 = \begin{bmatrix} 1 & a_{sk} \\ 0 & 1 \end{bmatrix}$$

WHERE:

$$a_{sk} = \frac{LR_e\ \omega_e \cos\lambda}{R_e\ \omega_o\ L} = \frac{\omega_e \cos\lambda}{\omega_o \cos\theta} = \frac{.071713 \cos\lambda}{\cos\theta}$$

For a latitude of 37.5° the matrix is:

$$M_3 = \begin{bmatrix} 1 & .0586 \\ 0 & 1 \end{bmatrix}$$

4. Output Scale Factor

The three transformations given above approximately correct the ERTS image to a North-oriented image having a sampling scale of 79 meters per data point in both the horizontal

(E-W) and vertical (N-W) directions. The data are reproduced in pictorial form on two different devices at the LARS laboratory. One is an IBM computer line printer and the other is a custombuilt IBM digital video display system. The line printer has a 10 column per inch print line and normally prints 8 lines to the inch down the page. This 8 to 10 aspect ratio must be compensated for if the printed image is to be "square" in scale. The matrix for this correction is:

$$M_4 = \begin{bmatrix} .8 & 0 \\ 0 & 1 \end{bmatrix}$$

The physical scale which will result if the above four transformations are applied to the data to be printed the line printer is 1" on the page = 25200" on the ground (denoted 1:25200). To correct this to a standard map scale of 1:24000 the scale adjustment matrix is used:

$$M_5 = \begin{bmatrix} a_s & o \\ o & a_s \end{bmatrix} = \begin{bmatrix} .9527 & o \\ o & .9527 \end{bmatrix}$$

The resulting scale can be adjusted to any value by proper choice of a_s.

The digital image display has an aspect ratio of 1:1 so the correction matrix M_4 is not needed. Also, since the scale of photographs produced from the digital display depends on the size of the print no scale adjustment is needed. The sampling scale of data prepared for the digital display is 79 meters per point in both directions and the final physical scale can be determined only after a photo print is generated. The scale of the image on the 16" (horizontal width) screen of the display is approximately 1:151000 if every screen point represents one data point.

All of the transformations can be performed at once by multiplying the matrices in the appropriate order. A 1:24000 scale line printer correction is performed by the product of the five example matrices given above:

$$M = M_1 \times M_2 \times M_3 \times M_4 \times M_5 = \begin{bmatrix} 1.03574 & .34312 \\ -.15222 & .93351 \end{bmatrix}$$

The word "approximate" was used throughout the discussion and it should be emphasized that most of the parameters used are not known accurately, thus these corrections are not exact. The sensor and satellite induced errors vary randomly over the frame thus the "rigid body" assumption implicit in the use of the linear transformation is also invalid. The accuracy of the correction is therefore unknown; however, measurements made using topographic maps indicate about a 1 to 2% scale error. This means that if a point in the data is exactly lined up with a known ground point that, in say 1000 meters, the image would be 10 to 20 meters in error from the true ground point. Figure 2 is a comparison of digital display images of uncorrected and corrected data.

III. Intersample Interpolation

It can be seen from Figure 1 that when the geometric transformation is applied to a sampled image new samples will be needed between existing samples, i.e. where there is no data. Thus, some interpolation scheme is required to produce new samples if a uniform output grid is required. The preferred way of performing geometric transformation would be to place existing samples in the correct locations in the output image; however, this requires a randomly addressable output device with variable sample spacing. The computer line printer, LARS digital display and most other digital-to-analog image output devices have a fixed uniform point spacing so there is no way to randomly address the output image with these devices. Thus, sample interpolation is required when fixed grid output devices are to be used.

Sample interpolation can be performed in two ways: 1.) A combination of values of samples near the desired sample can be used to estimate the value at the desired point, 2.) The point nearest the desired sample location can be used to represent the value at the desired location, this is called the "Nearest Neighbor Rule". Method 1 distorts the original values of the data and it is generally assumed that the new values created this way would generate spurious multispectral vectors and would cause classification results unrelated to that of the surrounding points. Method 2 does not alter the values of the multispectral vectors so the classifications for these points will be predictable. Also, inspection of the grids in Figure 1 will reveal that the new point generated by the nearest neighbor rule will not be more than one sample space away from its true position in the image. The bound on the position error is:

$$o \leq \varepsilon_T \leq \frac{1}{2} \sqrt{\Delta L^2 + \Delta C^2} = \varepsilon_{MAX}$$

Where: ε_T = Total Euclidian Error Distance

ΔL = Line Spacing in the Data (ft or meters)

ΔC = Column Spacing in the Data (ft or meters)

For ERTS-1 data $\Delta L \hat{=} 79$ meters and $\Delta C = 56$ meters thus the upper bound on the position error is 48.4 meters or 158.5 feet. The distribution of the error over the interval (o, ε_{MAX}) would intuitively seem to be uniform for which the mean value would be $\varepsilon_{MAX/2}$.

The error for each point can be computed explicitly. The locations of points required from the original data are given by the transformation:

$$X_L = f_L(y_L, y_C)$$

$$X_C = f_C(y_L, y_C)$$

Where:

$y_{L,C}$ = Line, Column Coordinates of the new Data Set.

$X_{L,C}$ = Coordinates of required points in the "old" original data set.

The new or Y coordinates are integer line and column numbers. Thus $y_{L,C} = 1, 2, \ldots . N$. The $X_{L,C}$ will in general be real numbers. The error under the nearest neighbor rule will be :

$$\varepsilon_L = \begin{cases} \varepsilon = X_L - [X_L] \\ \text{If } 0 \leq |\varepsilon| \leq .5 \quad \varepsilon_L = |\varepsilon| \quad \text{for lines,} \\ \text{If } .5 < |\varepsilon| < 1 \quad \varepsilon_L = |\varepsilon| - 1 \end{cases}$$

$$\varepsilon_c = \begin{cases} \varepsilon = X_c - [X_c] \\ \text{If } 0 \leq |\varepsilon| \leq .5 \quad \varepsilon_c = |\varepsilon| \quad \text{for columns,} \\ \text{If } .5 < |\varepsilon| \leq 1 \quad \varepsilon_c = 1 - |\varepsilon| \end{cases}$$

where [X] denotes greatest integer less than X.

For image rotation, deskewing and rescaling a linear transformation of the form:

$$X_L = a_{11}Y_L + a_{12}Y_c$$

$$X_c = a_{21}Y_L + a_{22}Y_c \quad \text{is used.}$$

Section II gave an example matrix for a rotation of approximately 12 degrees, rescaling to a line printer scale of 1"=24000", and deskewing 5% which is typical of operations for ERTS data. The transformation is:

$$\begin{pmatrix} X_C \\ X_L \end{pmatrix} = \begin{bmatrix} 1.03574 & .34312 \\ -.15222 & .93351 \end{bmatrix} \begin{pmatrix} Y_C \\ Y_L \end{pmatrix}$$

The distribution was evaluated using a simple program which computes the error mean and distribution for 1000 values of Y_L and 1000 values of Y_c for a total of 10^6 points. The experimental mean was .23 for each dimension which agrees well with the intuitive value of .25 . The average distance error is:

$$\varepsilon_T = \quad (79x.23)^2+(56x.23)^2= 19.6 \text{ meters}$$

Thus, on the average about 20M or 66 feet of position error is introduced by geometric transformation of ERTS data using the nearest neighbor rule. This error is only slightly more than the 50 feet tolerance for 1:24000 scale topographic maps generated by the U.S. Geological Survey.

IV. Geometric Correction using Ground Control Points

The correction process described above uses no ground reference points to aid in determining the values of the correction parameters. The ERTS digital aspect ratio, orbit inclination and satellite velocity are all estimated values and all are slightly in error. Improved geometric accuracy can be achieved through precise knowledge of all parameters or by finding matching points in the scene and in the data and using these points to correct the data. The second approach was investigated and preliminary results are discussed next.

An experimental precision correction was carried out in conjunction with a project funded by the U. S. Geological Survey and excellent results were obtained as determined by visual inspection. CCT data from ERTS frame 1003-18175 was first corrected for scale, rotation, and skew using techniques discussed above. The data was scaled so that when printed in pictorial form on a computer line printer the scale is approximately 1" = 24000". Easily identifiable features such as schoolyards and parks were manually located on 1:24000 topographic maps. The corresponding areas were located in the ERTS data printouts. The map used was USGS 7 1/2 minute quad: San Jose West. Thirty-six matching points were found covering a 10 x 7 1/2 mile area. The coordinate system used for the map points was the UTM system. Vertical and horizontal coordinates were measured to the nearest 10 meters and punched in standard LARS checkpoint format on cards along with the line and column coordinates for the same point in the data. These coordinates were processed by a geometric distortion function estimation program and parameters were computed to correct the remaining geometric error in the data for the given area. The data was then re-geometrically corrected to produce the final version. The results were overlayed on the topographic map to inspect the accuracy of the fit. No error could be visually observed over the 7 1/2 x 10 mile area although it is extremely difficult to estimate locations to better than one or two pixels in ERTS-1 data. The correction function used was a quadratic polynomial with terms up to xy. A least squares fit was used to the given checkpoints. The error in estimating the checkpoints by the polynomial was .6 of a resolution element RMS.

This approach holds promise for accurately correcting ERTS type data to map coordinates. The main problem is finding matching points in the scene and the data. Various automatic techniques are being investigated; however, the method which will most likely be used for the near future at LARS will be the laborious manual matched point finding process.

Reference

1. ERTS Data Users' Handbook, Document No. 7154249, Goddard Space Flight Center, NASA, Greenbelt, Maryland, 1972.

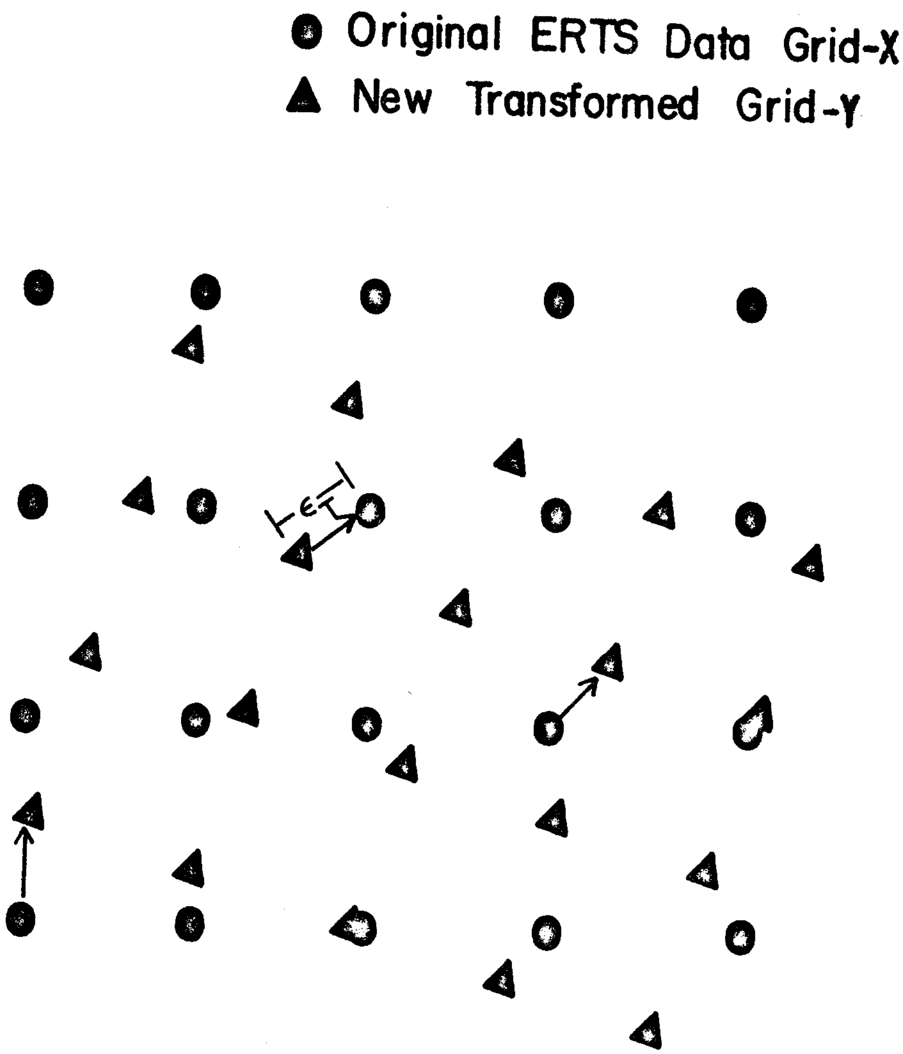

Figure 1. Relationship of original and transformed ERTS data points. The new grid represents a clockwise rotation and rescaling of the original grid.

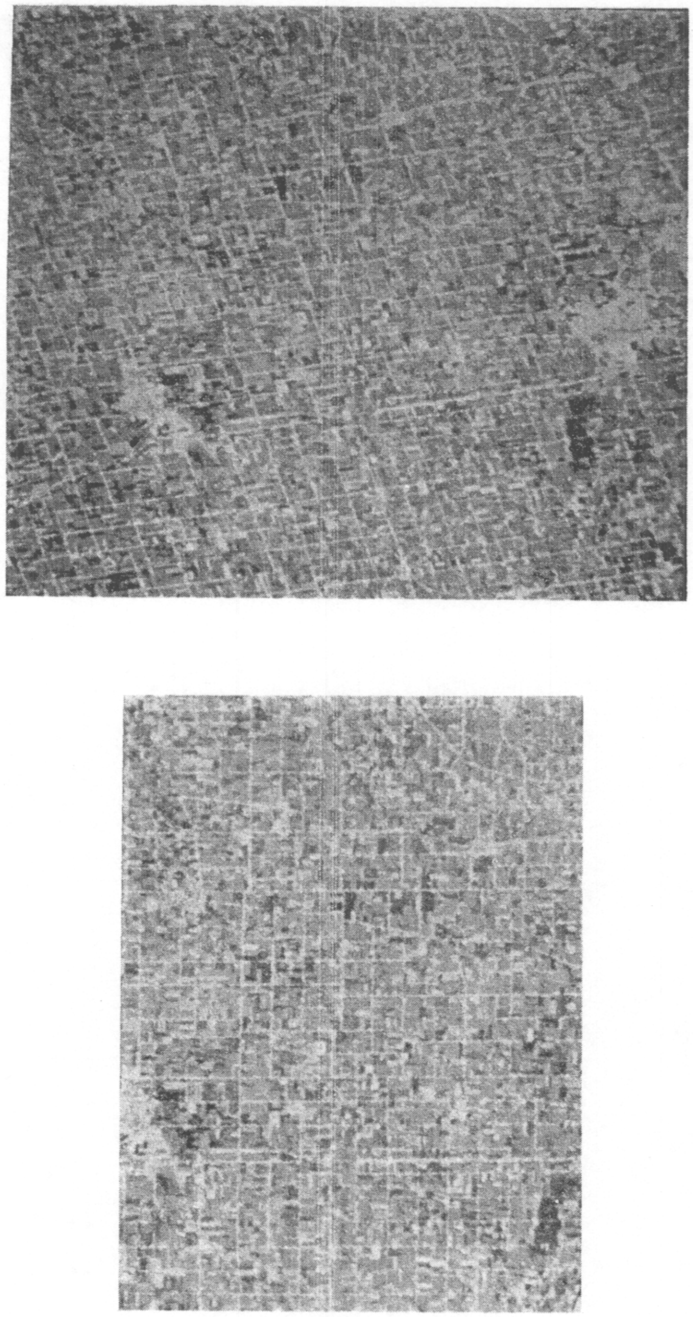

Figure 2. Comparison of original and geometrically corrected and rotated ERTS-1 MSS digital imagery. Upper image is the original. Lower image is skew and scale corrected and rotated to North. Scale is such that when this data is printed on an 8 line per inch, 10 column per inch computer line printer the resulting scale will be approximately 1:24000.