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CORRELATION OF ERTS MSS DATA AND EARTH COORDINATE SYSTEMS

William A. Maillia, Ross H. Nieber and
Arthur T. McCleer

Environmental Research Institute of Michigan (ERIM)
Ann Arbor, Michigan

I. ABSTRACT

Experience has revealed a problem in the analysis and interpretation of ERTS multispectral scanner (MSS) data. The problem is one of accurately correlating ERTS MSS pixels with analysis areas specified on aerial photographs or topographic maps for training recognition computers and/or evaluating recognition results. It is difficult for an analyst to accurately identify which MSS pixels (picture elements) on a digital image display belong to specific areas and test plots, especially when they are small.

A computer-aided procedure to correlate coordinates from topographic maps and/or aerial photographs with ERTS data coordinates has been developed. In the procedure, a map transformation from Earth coordinates to ERTS scan line and point numbers is calculated using selected ground control points and the method of least squares. The map transformation is then applied to the Earth coordinates of selected areas to obtain the corresponding ERTS point and line numbers. An optional provision allows moving the boundaries of the plots inwards by variable distances (typically ≥ half a resolution element) so the selected pixels will not overlap adjacent features.

II. INTRODUCTION

The computer-compatible-tape (CCT) form of ERTS-1 MSS data is well suited to analysis and recognition processing on digital computers. Examples of varied applications were reported by a number of investigators at the Goddard Space Flight Center's "Symposium on Significant Results from ERTS-1 Data" in March, 1973.

It is desirable to evaluate the accuracy of large-area resource surveys made by computer processing of ERTS, or other remote sensor, data. Such evaluations require the checking of recognition results for areas whose identities are known from field observations or other "ground truth" information sources. Even before recognition processing, the training of the classifiers usually involves the use of other areas of known identity that can be located in the remote sensor data.

The location of specific areas and assignment of pixels to individual fields and plots is more of a problem in ERTS data than in airborne scanner data which have finer spatial resolution. For instance, there are less than 600 ERTS pixels per square mile and a maximum of 10*** wholly

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** Formerly Willow Run Laboratories of The University of Michigan.

*** Even this number is optimistic because the ERTS scan lines do not generally follow field boundaries. Further, as discussed under Section III, the oversampling along ERTS scan lines means that there is overlap between the areas viewed by the scanner for adjacent pixels and thus one must move away from boundaries to eliminate their effects.
within the boundaries of a 20-acre field. Section and field boundaries are frequently indistinct on ERDS data displays; consequently, errors are made in the visual location of fields and the subsequent assignments of pixels. Pixel misassignments potentially can cause errors in classification results and lead to incorrect conclusions. Even if detected, additional resources are required to correct errors.

ERDS images of two types are produced by the National Data Processing Facility at NASA/Goddard — system-corrected images and precision-processed images. They both represent photo maps but with different degrees of accuracy. The system-corrected images are corrected for the major distortions introduced by spacecraft orientation, sensor characteristics, and Earth's rotation. Precision-processed images include additional adjustments based on a number of in-scene ground-control points in each frame.

The bulk digital computer-compatible tape (CCT) data, however, are not corrected for any of these distortions. (Bulk data are preferred to precision CCT data for recognition processing because in the latter, the radiometric accuracy of the data is degraded by re-scanning.) Therefore, when displayed on a line-printer gray-tone or CCT, substantial distortions are evident in bulk CCT data. Square sections are displayed as parallelograms, and other distortions are present. These distortions increase the difficulty of assigning pixels to specific ground areas, but the major cause of difficulty is the relatively large instantaneous field of view of the MSS scanner.

The problem of correctly assigning ERDS pixels to specific areas is somewhat different from two related problems which are under investigation elsewhere [Refs. 1-3]. Some investigators are studying the cartographic aspects of ERDS data, e.g., image quality and techniques to digitally correct ERDS data to match an Earth coordinate system, using spacecraft attitude information and/or ground control points spread throughout a frame. Others are studying the spatial registration of data from two or more frames that cover the same scene, using ground control points and/or image correlation techniques. The cartographic studies will simplify pixel assignments for areas that are readily identified by their latitude and longitude coordinates, but do not directly address procedures for assigning pixels for areas that are only identifiable on aerial photographs. The spatial registration studies will expedite the transfer of field coordinates from one frame to the next, but again do not consider the problem of initially assigning pixels to fields and test plots.

Techniques for both cartographic correction and spatial registration of ERDS data move data values from their original positions to an underlying grid by nearest-neighbor or interpolation rules. Then, the assignment of pixels to specific fields and test plots can take place; operations on a nearest-neighbor basis increase the uncertainty of true field boundary locations, while interpolation degrades radiometric fidelity. The procedure we have developed warps Earth coordinates to match ERDS coordinates, effectively computing the location of each pixel, and makes pixel assignments without any movement or interpolation of ERDS data.

III. PROCEDURE

The procedure described here for the computer-aided assignment of ERDS pixels relies on an empirical map transformation derived by least squares calculations from a local network of control points on and around the area of interest, e.g., a 20 x 25-km area on a 15° quadrangle map. These control points can be located on topographic maps and/or on aerial photographs. Differing scales can be handled, and the locations of control points and analysis areas on the maps and/or photographs can be obtained on a relative basis.

The empirical transformation produces rotations to account for the non-polar orbit of ERDS and the difference in orientation between Earth and ERDS-data coordinates, and also corrects for effects of the Earth's rotation and other sources of distortion and error, in a least-squares manner. The distortions in ERDS imagery are discussed in the Appendix and, for purposes of illustration only, two transformation matrices are computed: (1) a theoretical transformation that considers the major effects in ERDS data and (2) a similar transformation obtained by scaling the corresponding empirical Earth-to-ERDS coordinate transformation. Good, but not exact, agreement is shown between the two transformation matrices.

As noted earlier, we developed our computer-aided procedure because it is often difficult to distinguish "by eye" the corners of sections, fields, and plots of interest on digital displays of ERDS data, and more difficult to locate them accurately. Lack of contrast between materials and any bending or stringing in the ERDS data can complicate matters. On the other hand, there generally are some road intersections and other features in the scene around and within the areas of interest that can be distinguished readily in digital displays.

2B-2
Application

A description of the system and the components that make up the system is provided. The system includes the following components:

1. The input data
2. The processing unit
3. The output data

The input data is fed into the processing unit, which performs various calculations and processing steps. The output data is then generated from the processing unit.

The system operates on the principles of efficiency and accuracy. The processing unit is designed to handle large amounts of data and perform calculations with high precision.

The output data is then analyzed and interpreted to provide meaningful information to the user. This information can be used for decision-making, planning, and other purposes.

In conclusion, the system is a powerful tool that can be used to analyze and interpret complex data. Its efficiency and accuracy make it an invaluable resource for various industries and applications.
procedure was developed. Errors in the assignment of pixels to a few fields were identified during the course of the processing. One particular example is presented here.

Section roads were not always clearly discernible and were not present along all sides of every section, so several section lines were placed on line printer maps by simple interpolation between more distinct roads. The section in question is located on a boundary between two townships and happens to be less than one mile long in the N-S direction. Partly because of the smaller size, the lower section boundary was initially placed below the true boundary. Figure 3a presents the original manual assignment of pixels for four fields; the correct section lines are shown on the line printer map (of ERTS Band 5) and the actual field boundaries, as obtained from an aerial photograph, are mapped on the right. Fields 21, 22, and 23 were originally mis-assigned by the analyst. After poor agreement was observed between recognition results and the assigned crop types, these field delineations were checked and revised manually.

After the computer-aided pixel assignment procedure was developed, it was used to assign pixels to these same fields with a 0.5 resolution element inset. The resulting pixel assignments are presented in Figure 3b. Note the apparent good agreement between the selected pixels and the field boundaries, for example, around the notch in the upper right-hand corner of Field 21 and middle of Field 22. In this example, a USGS topographical map served as the standard coordinate reference for several road intersections that were readily identified in the ERTS data. The derived transformation then was applied to the standard coordinates of the section corners to locate them accurately within the ERTS data. Field vertices were determined relative to these section corners in an aerial photograph taken at the time of the ERTS pass. These relative locations of field vertices then were transformed to ERTS coordinates and pixels were selected.

It is difficult to make a quantitative assessment of the accuracy of our procedure, because of the lack of an absolute knowledge of pixel locations. One attempt is presented and discussed below, using Gull Lake, in Kalamazoo and Barry Counties, Michigan, as imaged in Frame 1033-15580.

A lake was selected because there generally is a large contrast between land and water in ERTS Band 7, so that the accuracy of boundary locations can be assessed. Gull Lake is one of the largest in the area, has some distinctive shoreline features and an island, and is in a region for which topographic maps were on hand. Since the topographic maps are several years old, it is important that the water level in Gull Lake is regulated so as to maintain a fixed level.

Our goals were (1) to select only those pixels that were completely within the lake and (2) to determine whether map-based coordinates of the shoreline features could be accurately placed in the ERTS data. The results discussed below show that a good job was done in selecting only water pixels and that shoreline features were accurately placed around the lake.

Eighteen control points were selected from a 6 x 20 mile area with Gull Lake roughly at the center. None of the control points were on the Gull Lake shoreline and few were near it because of indistinct roads in the immediate vicinity. Latitude and longitude for these points were extracted from three different USGS maps of different scales. Approximately 90 points along the shoreline of Gull Lake on the USGS map also were digitized for transformation to ERTS coordinates. An inset of 0.5 resolution elements was used along the major shoreline and 0.5 along the shoreline of the island at the South end of the lake. The negative inset, or outset, was necessary to exclude island shoreline points from the water, because the island was the area outlined.

The line printer map in Figure 4 presents the results of the Gull Lake analysis. Five gray levels are displayed, three for values determined by the procedure to be within the lake and two for those outside. The choice of symbols within each of these two groups was determined by the value of the signal in ERTS Band 7. Observation showed that open water points were all at levels of 5 or less, while the surrounding land was generally at levels of 12 or greater; intermediate values were found along the shoreline. For points determined to be within the lake by the procedure, the predominant darkest symbol (M over $) corresponds to the 1554 points with values ≤5, the intermediate symbol (X over =) corresponds to 18 points with values of 6 or 7, and the lightest symbol (+) corresponds to points with values ≥8. Only 9 points with values ≥8 were said to be within the lake, and the highest of these values was 9. Since land values generally are ≥12, the lighter pixels included at most only partial land observations. Further some of them might have been caused by the presence of weeds near the shore; current aerial photography is not available to check for the presence of weeds. In summary, <1% of the lake points, or <3% of the shoreline points, seem to have been misclassified as being open water.

On the other side of the computer shoreline, 93 points with values ≤5 were placed (symbol $). These points correspond to open water values that were excluded from Gull Lake. This result was not unexpected since the shoreline is irregular and was approximated by a multi-sided polygon.

2B-4
and

\[
\vec{T} = \vec{F}_t + \vec{F}_w = 0.16 \cos \frac{\theta}{\pi} \vec{r}
\]

from which

\[
\vec{r} = \frac{\vec{T}}{0.16 \cos \frac{\theta}{\pi}}
\]

where

\[
H = \frac{\vec{T} \cdot \cos \theta}{\vec{r} \cdot \cos \frac{\theta}{\pi}}
\]

Proof of the assertion that the integral of the electric field over any closed surface is zero.

\[\int \mathbf{E} \cdot d\mathbf{A} = 0\]

This statement is known as Gauss's law. It expresses the idea that there is no net outward flow of electric field through any closed surface.

The proof is based on the divergence theorem, which states that the surface integral of the electric field over a closed surface is equal to the volume integral of the divergence of the electric field over the enclosed volume.

\[\int \mathbf{E} \cdot d\mathbf{A} = \int \nabla \cdot \mathbf{E} \, dV\]

In the case of the electric field, the divergence of the electric field is zero, which implies that the electric field is irrotational.

\[\nabla \cdot \mathbf{E} = 0\]

This is known as the Gauss's law in its differential form.

The integral form of Gauss's law is

\[\int \mathbf{E} \cdot d\mathbf{A} = \int \nabla \cdot \mathbf{E} \, dV = 0\]

The electric field \(\mathbf{E}\) is determined by the charge distribution \(\rho\) and the medium's permittivity \(\varepsilon\) and magnetic permeability \(\mu\), which are measured at the surface and transferred to the enclosed volume by the appropriate medium.

The surface integral can be evaluated by taking the limit of the volume integral as the volume approaches zero.

\[\lim_{V \to 0} \int \nabla \cdot \mathbf{E} \, dV = 0\]

This limit is equal to zero, which implies that the surface integral is also zero.

\[\int \mathbf{E} \cdot d\mathbf{A} = 0\]

This is the integral form of Gauss's law.

The divergence theorem relates the surface integral of the electric field to the volume integral of the divergence of the electric field.

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This is the integral form of Gauss's law.
The Earth's rotation causes both the actual sub-satellite track to deviate from the nominal track and the actual heading to deviate from the nominal heading. Kratky (op. cit.) approximates the deviation in heading as follows:

\[ H_e = \tan^{-1} \left[ \frac{\omega_e}{\omega_s} \right] \cos \epsilon \sin \rho \]  

(2)

where \( \omega_e \) = angular velocity of the Earth,
\( \omega_s \) = angular velocity of the satellite \((\omega_e/\omega_s = 0.071713 \text{ for ERTS-1})\),

and \( \epsilon \) = orbital travel angle as measured southward from the vertex of the orbit (\( \rho = \pi/2 \) at equator).

or, since \( \sin \rho = \sin \lambda_s = \tan \epsilon / \tan h_s \)

\[ H_e = \tan^{-1} \left[ \left( \frac{\omega_e}{\omega_s} \right) \cos \epsilon \left( \frac{\sin \lambda_s}{\cos \phi} \right) \right] = \tan^{-1} \left[ \left( \frac{\omega_e}{\omega_s} \right) \sin \epsilon / \tan h_s \right] \]  

(3)

where \( \lambda_s \), the nominal longitude of the satellite, can be computed from the actual longitude, \( \lambda \), and latitude, \( \phi \), by the following relationship:

\[ \lambda_s = \lambda - \left( \frac{\omega_e}{\omega_s} \right) \cos^{-1} \left[ \frac{\sin \phi}{\sin \epsilon} \right] \]  

(4)

The Earth's rotation causes a shift along lines of constant latitude, converting squares to acute parallelograms (with tops rotated counter-clockwise by the angle, \( H_e \)) in uncorrected ERTS data.

The geometric relationships between Earth coordinates and ERTS data coordinates in a localized area can be represented by the product of several transformation matrices:

\[ \begin{bmatrix} P - P_0 \\ L - L_0 \end{bmatrix} = M_5 \cdot M_4 \cdot M_3 \cdot M_2 \cdot M_1 \begin{bmatrix} \lambda - \lambda_o \\ \phi - \phi_o \end{bmatrix} \]  

(5)

where \( P \) is the point count coordinate along scan lines,
\( L \) is the scan line count coordinate along the satellite track,
\( P_0 \) and \( L_0 \) are the ERTS data coordinates of the reference point,
\( M_1, \ldots, M_5 \) are transformation matrices,
\( \lambda \) is longitude, measured positive to the West,
\( \phi \) is latitude, measured positive to the North,

and \( \lambda_o \) and \( \phi_o \) are the Earth coordinates of the reference point.

A representation of the major effects is given by the following transformation matrices for specific effects:
\[
\begin{bmatrix}
P - P_o \\
L - L_o
\end{bmatrix}
= \begin{bmatrix}
\frac{1}{P_{scl}} & 0 \\
0 & \frac{1}{L_{scl}}
\end{bmatrix}
\begin{bmatrix}
1 + \tan H_e & -1 & 0 & \cos H_s & \sin H_s \\
0 & \frac{1}{\cos H_e} & 0 & -\sin H_s & \cos H_s \\
0 & 0 & 1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
\lambda_{scl} & 0 \\
0 & 1_{scl}
\end{bmatrix}
\begin{bmatrix}
\lambda - \lambda_o \\
1 - \lambda_o
\end{bmatrix}
\]

\[M_5 \\ M_4 \\ M_3 \\ M_2 \\ M_1\]

(6)

\(M_1\) converts minutes of latitude and longitude to a standard unit of length, like meters, for the given latitude.

\(M_2\) rotates the Earth coordinate axes by an angle, \(H_e\), so the \(z'\) axis is parallel to the satellite track (assuming no Earth rotation at this point).

\(M_3\) rotates the axes by an additional 180° so the positive directions of the transformed \(\lambda\) and \(\phi\) axes correspond to the positive directions of the \(P\) and \(L\) axes, respectively.

\(M_4\) accounts for the distortion caused by the Earth's rotation.

\(M_5\) converts length measurements from standard units to ERIM pixel units, e.g.,

\[P_{scl} = \# \text{ standard units/pixel width.}\]

If we multiply the three middle matrices of Equation (6), they reduce to:

\[\begin{bmatrix}
-\cos H_s + \tan H_e \sin H_s \\
\sin H_s \\
\frac{\sin H_s}{\cos H_e} \\
-\cos H_s
\end{bmatrix}\]

(7)

(M_{4M_3M_2})_{\text{Theoretical}} =

A corresponding relationship can be computed from an empirical transformation, since the empirical matrix, \(M\), can equal:

\[M = M_5M_4M_3M_2M_1\]

(8)

Pre- and post-multiplying by inverses,

\[M^{-1}_5M^{-1}_4 = M_5M_3M_2\]

(9)

Thus, the empirical version of \(M_5M_3M_2\) is:

\[M_{5M_3M_2}^{\text{Empirical}} = \begin{bmatrix}
P_{scl} & 0 \\
0 & L_{scl}
\end{bmatrix}
\begin{bmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{bmatrix}
\begin{bmatrix}
1 & 0 \\
0 & 1_{scl}
\end{bmatrix}
\]

(10)

\[= \begin{bmatrix}
(P_{scl})^{-1} & (P_{scl})^{-1} \\
(L_{scl})^{-1} & (L_{scl})^{-1}
\end{bmatrix}
\begin{bmatrix}
m_{11} & m_{12} \\
m_{21} & m_{22}
\end{bmatrix}
\]

(11)
A.2. COMPARISON OF THEORETICAL AND EMPIRICAL TRANSFORMATIONS

It is of interest to compare an empirical transformation matrix obtained from one of the examples discussed in Section IV and the corresponding theoretical matrix for effects of non-polar orbit and Earth's rotation.

Assume:

\[ \phi = 42.4^\circ \]
\[ \varepsilon = 9.114 \]
\[ \omega_e/\omega_a = 0.071713 \]

and the matrix of Equation (7) becomes:

\[
\begin{bmatrix}
-0.9656 & -0.2650 \\
0.2149 & -0.9780
\end{bmatrix}
\]  \hspace{1cm} (12)

The corresponding empirical transformation matrix, scaled as in Equation (11), is:

\[
\begin{bmatrix}
-0.9628 & -0.2682 \\
0.2101 & -0.9712
\end{bmatrix}
\]  \hspace{1cm} (13)

It can be seen that the two matrices are in good agreement, but are not exactly the same. There are several possible reasons for the small differences present. They include:

1. Spacecraft motions, such as yaw, pitch, and roll, and other sources of error are not included in the theoretical transformation.
2. Nominal orbit parameters were used for the theoretical transformation.
3. There are residual errors in the locations of the control points in ERIS data, although the use of least-squares techniques minimizes them.
4. The factors used to scale the empirical matrix depend on an assignment of dimensions to the pixels, and the exact dimensions depend on the MIS mirror scan velocity (a non-constant function) and the sampling rate, among other factors. A 57 x 79 m pixel size was used here.

A.3. COMPUTATION OF TYPICAL ERRORS

The actual heading of the spacecraft ground track, neglecting satellite perturbations, is the sum of the nominal heading and the deviation due to Earth's rotation:

\[ H = H_b + H_e \]  \hspace{1cm} (14)

It can be seen from Equations (1) and (6) that \( H_b \) decreases with decreasing latitude while \( H_e \) increases. Therefore, the two effects tend to cancel and minimize the change in heading across a portion of an ERIS frame.

Across a typical 15' quadrant topographic map (10 x 25 km) the net change in heading is small and results in a displacement that is small in comparison to an ERIS pixel size. The heading is a function of only latitude for a spherical Earth. In passing from \( 42^\circ 45'N \) to \( 42^\circ 30'N \) latitude, the change in actual ERIS-1 headings is calculated to be:

\[ AH = H_{42^\circ 45'} - H_{42^\circ 30'} = -0.0384^\circ = -2.3' \]
where \[ H_{42030} = 12.3092 + 2.9557 = 15.2649^\circ \]
and \[ H_{42045} = 12.3587 + 2.9445 = 15.3032^\circ \]

For an area 20 km wide, this amounts to a total differential displacement of 13 m due to heading change. Therefore, it is a good assumption that the spacecraft flies along a straight line over a local area \( \pm 20 \) km wide.

Spacecraft motions also introduce additional variations during a pass over the same size area, \( \pm 20 \) km x 25 km. If we consider differential angles of \( 0.13 \times 10^{-3} \) rad for yaw, \( 0.20 \times 10^{-3} \) rad for pitch, and \( 0.11 \times 10^{-3} \) rad for roll, the corresponding differential displacements would be \( \pm 3 \) m for yaw, \( 180 \) m for pitch, and \( 100 \) m for roll. Differential yaw and pitch affect the spacing of data primarily along the flight line, whereas roll affects it primarily along the scan line. Effects of such spacecraft motions are not included in the theoretical transformation described earlier, but are included in the empirical procedure used for pixel assignments which averages over them in a least-squares sense.

REFERENCES

(References 1-6 were presented at the "Symposium on Significant Results Obtained from ERTS-1", March 5-9, 1973, New Carrollton, Md., sponsored by NASA/Goddard Space Flight Center, Greenbelt, Md.)


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Note Added in Publication: R. Kauth has pointed out that Equation (7) can be reduced to:

\[
(M_{43} M_{34}) \text{ Theoretical} = \frac{1}{\cos H} \begin{bmatrix} -\cos H & -\sin H \\ \sin H & -\cos H \end{bmatrix} \quad (7')
\]
EFFECT OF INSET PARAMETER ON PIXEL SELECTION FOR 40-ACRE FIELDS
(Inset Parameter is Measured in MSS Resolution Elements)

FIGURE 1
EFFECT OF FIELD SIZE ON PIXEL SELECTION FOR 0.5-RESOLUTION-ELEMENT INSET

FIGURE 2

640 ACRE FIELD

160 ACRE FIELDS

80 ACRE FIELDS

10 ACRE FIELDS
EXAMPLE OF FIELD LOCATION IN ERIS DATA

FIGURE 3a

FIGURE 3b
RESULTS OF COMPUTED-AIDED ASSIGNMENT OF ERTS PIXELS TO OPEN WATER IN GULL LAKE

FIGURE 4