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PRECISION ANNOTATION OF PREDETERMINED PRIMARY SAMPLING UNITS ON ERTS-1 MSS IMAGES

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ABSTRACT

Resectioning programs were developed for projecting the boundary corners of sample units, management units, and counties into U2 RC-10 and ERTS-1 MSS images. The technique used includes corrections for earth curvature, terrain elevation, and MSS distortions. The minimum standard error obtained was about 0.15 mm or 150 meters on the ground. This technique now makes it possible to include land ownership as an integral part of forest resource sampling plans using ERTS imagery.

1. INTRODUCTION

As an integral part of our ERTS-1 investigation, "The Development of a Multistage Forest Sampling Inventory System" we developed a subsystem to locate sample unit boundaries on the various stages of aerial and space imagery. The development of this subsystem was prompted by the demands for forest inventories of lands with irregular ownership patterns. These patterns defied the approach used in the early stages of multistage forest inventories using Apollo 9 photography (Langley, et al, 1969).[1] At that time, the sample units were simply defined by superimposing a grid on the satellite image. Thus, to insure greater spatial correspondence between the sample units of the various stages and to insure that the inventory would be conducted within the property limits, we developed a computational method for transferring basic sample units from ownership maps to ERTS and U2 imagery.

Also of interest was the accuracy with which a single point could be located on the ERTS images so that we could define the minimum size sample unit that could be used at the ERTS stage of a multistage resource inventory. The significant findings of the resulting investigation are presented in this paper.

2. BACKGROUND

Multistage variable probability sampling is a method in which the probabilities for the selection of sample units at stage n + 1 are based on criteria evaluated from the sample units at stage n. With n increasing, the total ground area sampled decreases until in the final stage a number of ground plots is visited. At the same time the expense incurred in the evaluation of a unit on the ground increases with n. The extremes are the complete evaluation of a tree on the ground on one hand and the separation of land into forest and non-forest classes on space imagery on the other. The direct combination of these extremes is not always possible. Therefore, to tie the extremes together intermediate stages, consisting of aerial imagery, are used to provide a correlation chain through which the first and the last stage are connected. If this chain had a bad link, the survey would be clearly inefficient and ineffective.

In our opinion, a fundamental requirement for a high linear correlation between sample units is a good spatial correspondence between adjacent stages of aerial or space imagery. To our knowledge, no research has yet been performed to establish the sensitivity of the sampling variance in relation to spatial mismatches between sample units at different stages. However, by using a precision annotation process, mismatches can be avoided so that this type of error can be omitted from consideration, thereby leaving fewer and more important issues for investigation at the present stage of our research.

A recent application of the multistage inventory concept to commercial property in the State of California demonstrated the need for the annotation of ownership patterns on aerial imagery. In this instance clusters of GLO sections proved to be the natural sample units for this kind of forest inventory. Unfortunately, an approximately one-square-mile land unit is by no means square on the map due to early primitive surveying techniques. In addition, the section is sometimes rather heavily subdivided.

The annotation problem for the commercial survey, in which the first stage consisted of 1:40,000 scale aerial photography was solved by performing an individual resection for each photograph, followed by a perspective projection of all the relevant corner points of the land sections onto the photographs. In the present ERTS-1 investigation, we are adding two additional stages, namely a high altitude stage of U2 RC-10 photography and a space stage of ERTS MSS imagery. Thus we were faced with the problem of also having to project the land sections or multiples thereof onto the U2 photographs and the ERTS images.

3. APPROACH

We obtained good results with individual spatial resections of the 1:40,000 aerial photographs, which were performed with an efficient program with semi-automatic quality control. The same resection program also worked well for the U2 RC-10 photographs. As input for the resection, a set of known identifiable ground points was needed which could be identified and measured on the photographs. These points were taken from USGS topographic maps and put into digital form with a map digitizer. For the ERTS image it was also possible to perform a space resection, but we thought it necessary to obtain a much larger number of points to make possible the evaluation of residual image distortions. As it is somewhat difficult to identify map features on ERTS imagery in rugged, mountainous terrain, we set out to identify a set of natural landmarks on the U2 RC-10 photographs that could also be readily identified on the ERTS images. We then used the U2 photographs to determine the ground coordinates of these points by executing a block adjustment. The block adjustment was also thought more desirable for the U2 stage because of its inherent greater accuracy due to simultaneous adjustments and the use of a precision MANN TA1/P monocomparator.

To minimize the programming effort, ground coordinates determined with the block adjustment, together with their measured plate coordinates, were fed into the existing resection program to perform the final transformation of the digitized section corners for the U2 stage.

The block adjustment was performed after the two strips of U2 photographs with ten photos each had been triangulated. Schuts triangulation and block adjustment programs were used for this purpose. Coordinates were expressed in a secant plane system, with its origin in the test area, to remove the influence of earth curvature. The standard errors computed with the control points and tie points used in the adjustment proved to be 12.8, 10.3 and 4.4 m, respectively, for Easting, Northing and height. The planimetric errors correspond to a point identification error of about 0.1 mm on the photographic plate. The results can be considered very good in view of the 1:126,000 scale of the RC-10 photography.

With the block adjustment completed and the coordinates of all ERTS identifiable points in hand, we then concentrated on the space resections of the ERTS MSS images.

4. RESECTION OF ERTS MSS IMAGES

Background and Theory

In contrast to the resectioning of aerial photographs, the ERTS MSS images present two problems: (1) the MSS image is produced by a multispectral scanner with a geometry different than that of aerial cameras, and (2) there is little relief displacement in the image which is needed to determine all parameters of the resection.

The first problem is in part solved by the NASA data processing facility where the geometry of the MSS image is shaped to resemble the geometry of an aerial photograph not considering relief displacement (Forrest, 1970)[2]. As for the second problem, it can be shown that at least one parameter cannot be estimated when all the object points are in a plane. With the object points situated on a curved surface, such as the earth's surface, possibilities exist for additional ambiguities between parameters. The problem can be solved by calculating some of the resection parameters from the orbital elements with high accuracy. These values can then be inserted into the solution so that a fewer number of parameters need to be finally determined.

In the resection program for the annotation of the ERTS MSS images, we decided to take a completely general approach in which any parameter could be enforced at the value of its initial approximation by assigning appropriate weights. This approach can be implemented by using the parameter approximations in auxiliary equations in the linearized equation system:

$$\Delta p = p^{\circ\circ} - p^{\circ} + \varepsilon \qquad (1)$$

where:

Δp represents the correction to the approximation at the ith iteration

$p^{\circ\circ}$ is the approximation of the parameter value

p° denotes the parameter estimate to be enforced in the solution

ε is the difference between the least squares adjusted value of the parameter and the value to be enforced in the solution.

For the first iteration, $p^{\circ\circ}$ is taken equal to p°. Then, if we place a large weight on the auxiliary equation, ε will be close to zero, and Δp will also be close to zero, and the initial approximation, which is equal to the desired parameter value will not receive any corrections in the iterative process. Thus, the intially assigned parameter value will remain unchanged throughout the solution.

The normal equations take on the following form for n data points:

$$(\underline{X}\,\underline{W}^{-1}\,\underline{X}')^{-1}\,\Delta = \underline{X}\,\underline{W}^{-1}\,\underline{Y} \qquad (2)$$

with X' of the following form:

$$\underset{(11,9,n)}{X'} = \begin{bmatrix} a_x^1 & a_x^2 & \cdots\cdots & a_x^9 \\ a_y^1 & a_y^2 & \cdots\cdots & a_y^9 \\ 1 & 0 & \cdots\cdots & 0 \\ 0 & 1 & \cdots\cdots & 0 \\ \vdots & & & \vdots \\ 0 & \cdots\cdots & & 1 \end{bmatrix} \quad \text{(the third dimension is not shown)}$$

where a_x^1, a_x^2 ..., a_y^1, a_y^2 are the partial derivatives of the collinearity equations with respect to the nine resection parameters for a particular point.

The matrix has the following elements (only the first row is shown):

$$\underset{(9 \times n)}{Y'} = [\varepsilon_x \ \varepsilon_y \ (p_1^{\circ\circ} - p_1^{\circ}) \ (p_2^{\circ\circ} - p_2^{\circ}) \ \ldots\ldots \ (p_9^{\circ\circ} - p_9^{\circ})] \quad (3)$$

where ε_x and ε_y are the discrepancies resulting from an evaluation of the collinearity equations for the point under consideration with the current set of parameter approximations.

The matrix W is a diagonal 11 x 11 weight matrix with unit weights in the first two positions, zero weights for those parameters that need to be estimated, and large weights (for instance 100 unit weights) for those parameters that are to remain constant.

Thus, with the indicated solution we were free to fix or estimate parameters as needed. As the orbital path of the ERTS satellite is known quite accurately, the likely parameters to be enforced in the solution are the exposure station coordinates for the center of the image. For this purpose, the indicated latitude and longitude of the photocenters were taken from the ERTS catalog. To obtain the satellite altitude we prepared a program that computes the exposure station coordinates from orbital data furnished by NASA, given the GMT pertaining to the image center. However, we anticipated that the latitude and longitude indicated in the catalog would be more accurate than the estimates computed by our program, as we only included first-order harmonic terms. In the solution either the artificial focal length or the altitude needs to be enforced.

We selected the altitude, since we assumed that scale change would be introduced in the bulk process through the introduction of an artificial focal length.

Coordinate Systems

The same secant plane coordinate system used for the block adjustment of the U2 photographs was used for the resection of the ERTS MSS images. The conversion from the geographic coordinate system to the secant plane coordinate system yields coordinates of the control points in a cartesian coordinate system. The XY plane of this system slices through the reference ellipsoid, so that the point elevations also reflect earth curvature.

The earth curvature accounts for part of the perspective displacement encountered in the bulk processed MSS image so that the use of the collinearity equation for the along-track direction in conjunction with the secant plane elevations was therefore partly justified.

Polynomial Fitting of the Residuals

To eliminate systematic trends remaining in the point residuals after the resection had been performed, we included in the resection program a general polynomial fitting routine, with which we could fit separate trend surfaces through the x and y residuals of the plate coordinates. This part of the program could then account for the unexplained remaining systematic distortions.

For the polynomial surface fitting we used hybrid orthogonal polynomials in the x and y plate coordinates, generated with a recurrence relation. The maximum power of the polynomials is automatically determined by the program and then discounted to evaluate all possible power surface fits. For each power Root Mean Square Errors (RMSEs) were computed to assess the goodness of fit.

In the testing phase of the program we discovered that the polynomial fitting routine is general enough that, in terms of the residuals, almost identical results can be obtained by either performing a resection or by keeping all parameters fixed and then making the polynomial adjustment. Thus with the present program one can either opt for the classical resection technique or obtain the optimum polynomial fit.

Experimental Results

Two ERTS MSS images, designated 103 and 104, were resected. These images covered our Redding (Northern California) test area. The ground control points were not distributed over the entire images. Rather, we confined them to those portions covering our forest inventory test site.

In this regard, only 1/16 of image 103 was resected while the resection area for image 104 was approximately 1/6 of the total image area. A total of 18 points were used for image 103, while 30 points were used as input for the resection of image 104. In both cases we only attempted to estimate the three rotation parameters and the artificial focal length in the resection. The other parameters were held fixed as described before. The estimated values for the rotation parameters (yaw, roll and pitch) were: -11.173°, -0.156°, -0.025°, -10.984°, -0.161° and -0.019°, respectively, for images 103 and 104. To investigate the change in the rotation parameters and the exposure station coordinates in the case when the ground coordinates of the image center would be allowed to change we removed the weights from the image center coordinates and obtained the following results: the image center shifted by approximately 7.2 and 35.3 km in Easting and Northing, respectively, while roll and pitch increased to 2.056° and 0.423°, respectively. The combined RMSE for x and y remained practically unchanged. This experiment reinforced the notion that shifts of the image center can be compensated for by rotational changes, causing an ambiguity when trying to estimate both types of parameters.

The quality of the resections of images 103 and 104 is indicated in the following table.

Table I

RMSEs FOR RESECTION OF MSS IMAGES 103 AND 104
(millimeters)
(x 1000:meters on the ground)

Image	Resection Result	After polynomial adjustment		
		Power 1	Power 2	Power 3
<u>Image 103</u> (18 points)				
RMSE for x	0.142	0.129	0.123	--
RMSE for y	0.146	0.138	0.116	--
Resultant	0.144	0.133	0.119	--
<u>Image 104</u> (30 points)				
RMSE for x	0.233	0.225	0.217	0.187
RMSE for y	0.196	0.181	0.176	0.146
Resultant	0.215	0.204	0.198	0.167

First, we can see in Table I that the RMSEs vary from 0.119 to 0.233 mm. This variation amounts from one to two times the identification accuracy of the U2 RC-10 photography (0.1 mm), which is reasonable considering that the resolution of the MSS images in considerably less than that of the RC-10 photographs. Thus we can conclude that the point identification accuracy is the limiting factor with respect to the resection quality.

Secondly, we can see in Table I that the polynomial adjustment does not appreciably improve the RMSEs. To test this hypothesis we can compare the RMSEs before and after polynomial adjustment by combining them in the form of an F statistic. For instance, an F value of 1.29 can be computed from the resultant RMSE of image 104 before polynomial adjustment (0.215) and from the resultant value after a third-degree adjustment (0.167). At the 90% confidence level this value should be greater than 1.51 to reject the hypothesis. This is not the case and thus we cannot confirm that the polynomial adjustment contributes significantly to the overall accuracy.

An interesting result of some further experimentation was that the polynomial adjustment is useful when, for instance, all the parameters but yaw (azimuth) are held fixed. In this case we would have to compare an RMSE of 0.575 with one of 0.199 after a third-degree polynomial adjustment, giving rise to an F statistic of 6.49. In this particular case a first-power adjustment (fitting of a plane) still gave an RMSE of 0.232 indicating that a scale change in the form of an adjustable focal length was the most important adjustment mechanism that was not allowed to function when held constant.

With the resection results in the form of the covariance matrix of the estimated parameters, it should be possible to propagate the variances to determine the accuracy of individual projected points. However, we know that the accuracy of the individual point is bounded by the RMSEs for x and y obtained from the resection. Thus, it seems reasonable to assume a maximum standard error of 220 meters on the ground for any point projected on the MSS image within the resection area. Had we only made a scale change and used the image directly as a map, the error would have been in the neighborhood of 743 meters according to the data users handbook.

5. THE PRODUCTION OF IMAGE OVERLAYS

After the resectioning of the space images was completed, the results were stored for subsequent use in the production of the image overlays. We decided to use the second-degree residual estimation in both cases even though the benefits of this estimation were not clear-cut, but we were convinced that the accuracy would not be degraded because of it.

Three types of points needed to be annotated on the space image, namely: the primary sample unit corner, the county line points, and the management unit boundaries. For the primary sample units we decided to take blocks of 4 x 4 GLO land sections. Thus, one primary unit would cover approximately 16 square miles. All points were digitized from three maps at a scale of 1/2-inch to the mile. Geographic coordinates were then assigned to each point by means of an interpolation method using a set of map control points with known coordinates. The geographic coordinates were subsequently converted to secant plane coordinates. At this point no elevations had as yet been assigned to the digitized map points.

To produce elevations for the digitized points we developed a digital terrain model of which a hypsocline chart is shown in Figure 1. This model covers an area of 125 x 125 km of our Redding test area and includes part of the central valley, the Trinity Alps and the Mount Shasta area. In this area the maximum terrain variation is 14,000 ft. Elevations for the model were obtained by sampling an aeronautical chart with an 18 x 18 grid.

A test of the model showed that the RMSE of the actual terrain around the model surface amounted to 330 m. Under the assumption that the space image has a perspective geometry (including relief displacement), it can be shown that elevation errors in the order of 330 m would induce plate position errors of 37 micrometers whereas errors of 111 micrometers would be incurred by assuming a mean terrain elevation. However, the MSS image is formed by perspective projection (including terrain relief) in the cross-track direction only, while in the along-track direction after bulk processing the perspective projection would only be valid for general earth curvature. Thus, one would actually need two different terrain models to account for both types of perspective variation. At the present stage we used the one model shown in Figure 1 which accounts both for relief displacement and earth curvature since the elevations were transformed to the secant plane system.

After the elevations were assigned to the digitized points they were processed through a program that sorts the points by image and projects them onto the image in a rectangular coordinate system defined by the registration marks at the four corners of the image. These coordinates were then plotted on stable transparent material with a Hewlett Packard 9125A calculator-plotter at an enlargement ratio calculated by measuring a set of known distances on the enlargement.

The resultant overlay is shown in Figure 2a. In this figure the county line is indicated by A, the management unit boundary by B, and a primary sample unit corner by B. Note how the county line follows a set of mountain ridges extremely well.

At D in Figure 2a we have indicated a clear-cut GLO land section, which in terms of the primary 4 x 4 section sample unit occupies the second row, third position, counted from the upper left corner. The same cut-over section is indicated by D in Figure 2b. Figure 2a shows a section of a U2 RC-10 1:126,000 scale photograph with a computer-produced overlay of the second stage sampling units, which in this case are the land sections and their subdivisions.

6. SUMMARY AND CONCLUSIONS

As a part of our investigation, "The Development of a Multistage Forest Sampling Inventory System Using ERTS-1 Imagery," we developed a system to provide precision annotation of predetermined primary sampling units on the ERTS-1 MSS images. In the development of this system we aimed for accurate results, but we realized there is a certain limit beyond which further refinement was not justified for a particular application; in our case, a forest inventory.

Therefore, we applied generalized resection theory for the development of the system realizing that the geometry of the MSS imagery after bulk processing is not entirely commensurate with this theory. However, the results obtained with the investigation showed that at present the limiting factor with respect to overall accuracy is not the basic model but the accuracy with which known points can be identified on the MSS image. In any case entirely satisfactory results were obtained for the purpose of annotating sample units for a forest inventory. The maximum position error of 220 meters indicates that the delination of the one-square-mile land section itself on ERTS-1 MSS imagery would be technically feasible.

7. REFERENCES

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2. Forrest, R.B., "Geometric Processing of ERTS Images," Bendix Research Laboratories, Southfield, Michigan 48076.

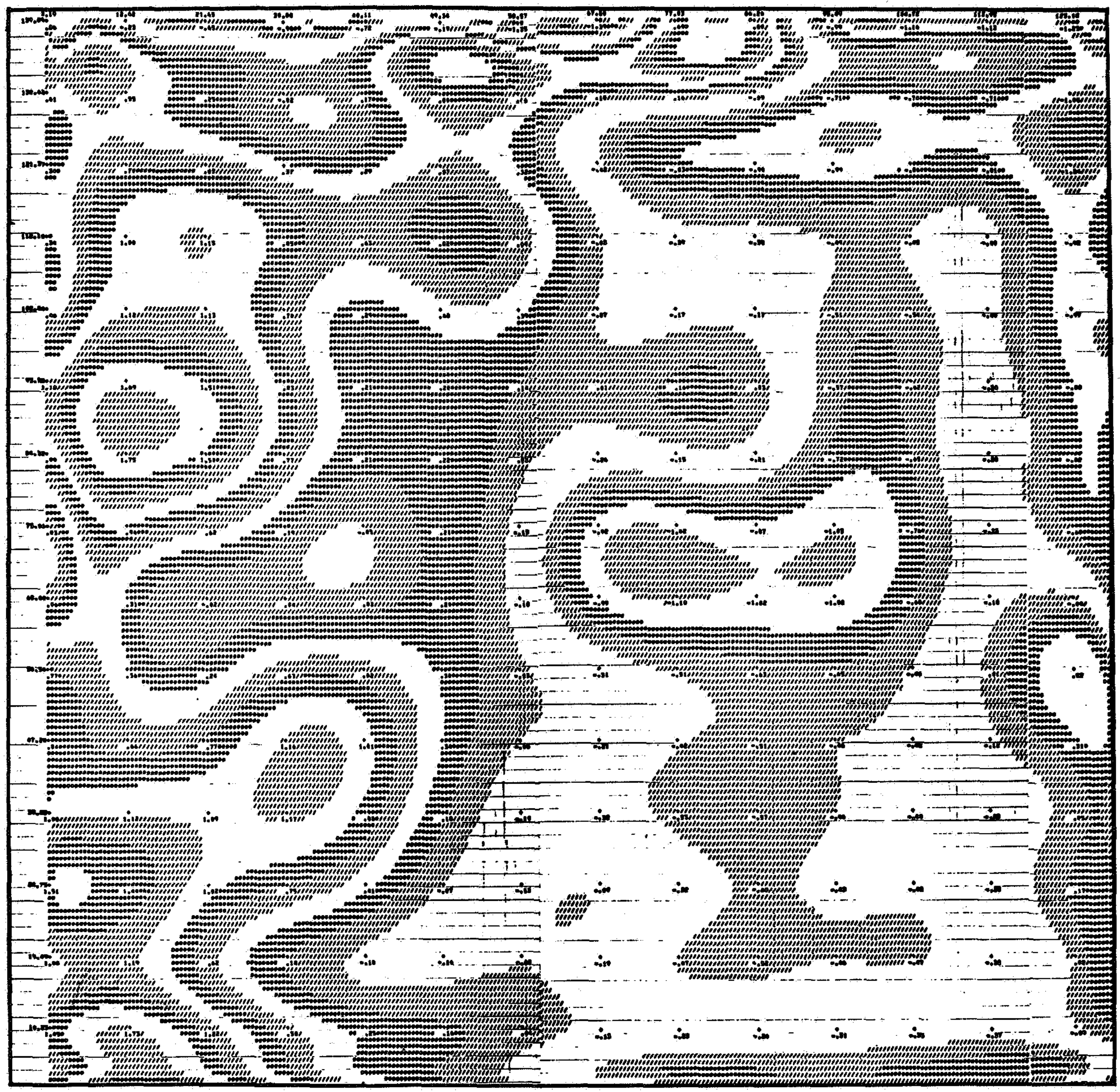

Figure 1

The digital terrain model illustrated by the hypsocline chart was used to assign elevations to digitized map points for subsequent correction of the boundary corners in the ERTS image overlay. The model covers an 125 x 125 km area, and includes a correction for earth curvature.

Figure 2a

U2 RC-10 photograph, scale 1:126,000 with second stage sample unit boundaries annotated by means of analytical resectioning. The light toned square indicated by "D" is a clear cut section which is also shown on the ERTS image of Figure 2b.

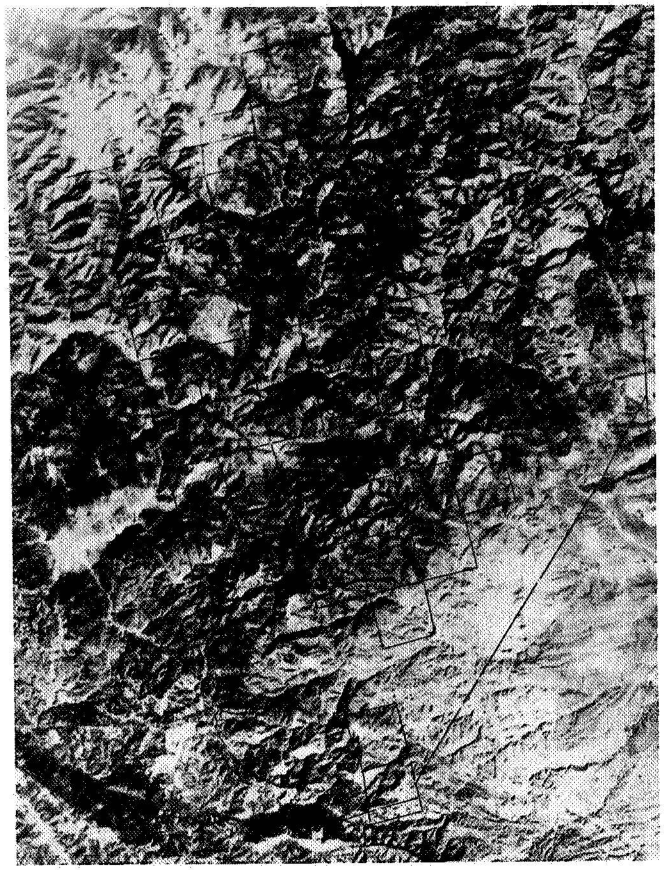

Figure 2b

ERTS-1 MSS band 5 image, with primary sample unit boundaries annotated by means of analytical resectioning. County lines are indicated by "A", management boundaries by "B", and sample unit boundaries by "C". "D" indicates the one square mile clear cut area shown in Figure 2a.