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Use of Scan Overlap Redundancy To Enhance Multispectral Aircraft Scanner Data

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USE OF SCAN OVERLAP REDUNDANCY TO ENHANCE MULTISPECTRAL AIRCRAFT SCANNER DATA*

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INTRODUCTION

The multispectral scanner has proved to be a basic data-gathering instrument for passive remote sensing systems.(1) (2) A multispectral scanner is basically a multiband spectrometer whose instantaneous field of view is scanned by means of a mirror rotating across the scene. A conceptual drawing of a multispectral scanner mounted in an aircraft is shown in Figure 1. At a given instant the device is gathering energy from a single resolution element. The energy from this element passes through appropriate optics, is separated into different frequency bands by means of a prism (for visible bands) or a grating (for infrared bands), and is measured by a bank of detectors. The detector outputs are recorded on board the aircraft or transmitted to a ground station.

As the mirror rotates, a path perpendicular to the forward motion of the aircraft is scanned (see Figure 1), and, successive scans cover the target area in the direction of flight. When parameters of the data-gathering system have the proper relationships, successive scans will be contiguous to each other. Scanner rotation which is slow relative to the other system parameters results in underscan, that is, successive scans separated from each other as shown in Figure 2; scanner rotation which is fast relative to other system parameters results in overscan, that is, successive scan lines overlapping each other. A typical situation is shown in Figure 3.

Most of LARS' multispectral aircraft scanner data is overscanned. As a result when the data are converted to digital format not every scan line is digitized. This study was undertaken to develop techniques which could make use of the infor-

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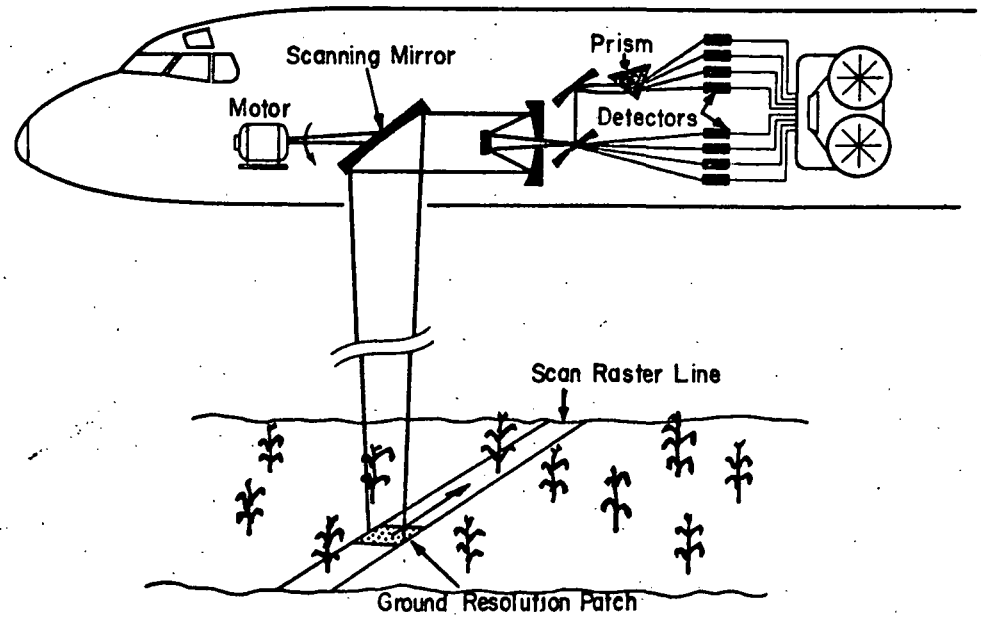


Figure 1. Aircraft mounted multispectral scanner.

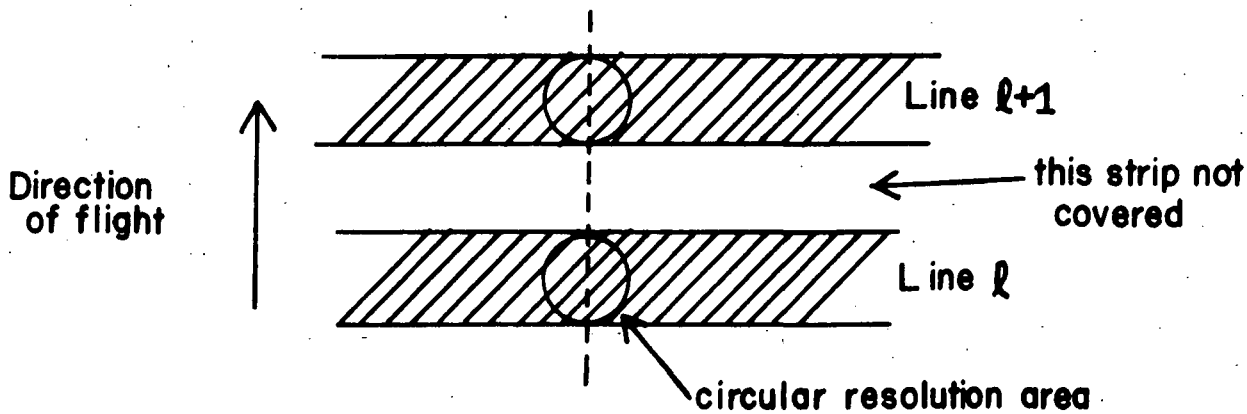


Figure 2. Example of successive scan lines when aircraft ground speed and scanner speed of rotation are such that under scanning occurs. The two circular resolution areas are drawn to emphasize the ground area represented by digitized data points from the same column and adjacent lines.

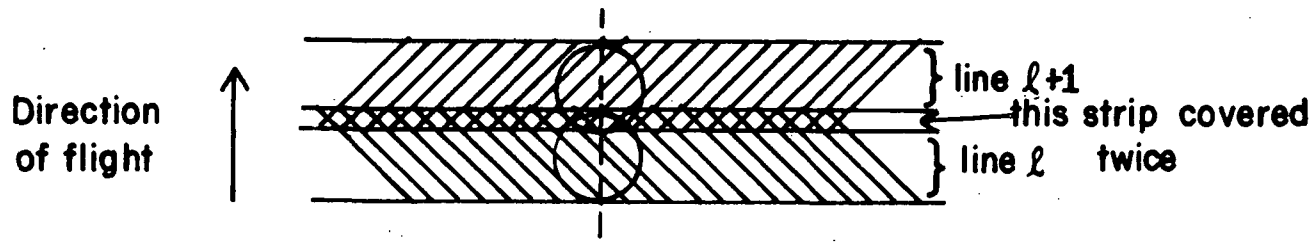


Figure 3a. Examples of successive scan lines when aircraft ground speed and scanner speed of rotation are such that over scanning occurs. (To keep the drawing simple, a case of only a small amount of overlap is shown.)

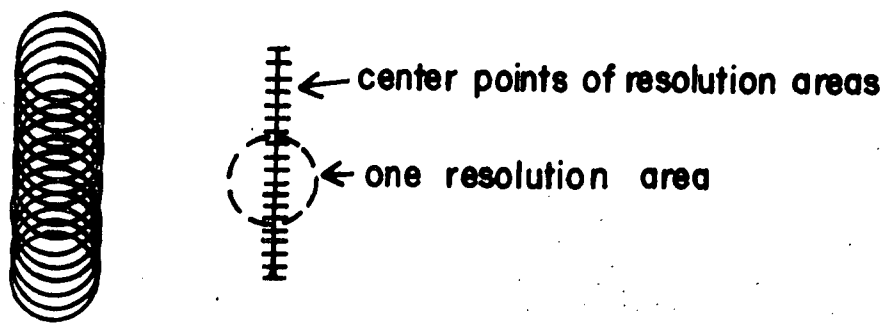


Figure 3b. Resolution elements corresponding to data points in the same column when the amount of scan overlap is large. (The number of redundant scan lines is large.)

mation contained in the scan lines not now digitized. Basically the idea is to average the sample values of several overlapping scan lines. The trade-offs between resolution and the signal-to-noise ratio resulting from this operation are discussed in the next section. Criteria for choosing the averaging coefficients are then presented, followed by a description of the implementation of the procedure and an evaluation based on using the method on a particular flightline.

RESOLUTION VS. SIGNAL-TO-NOISE RATIO TRADE-OFFS

In order to understand the trade-offs between signal-to-noise ratio and resolution which result from averaging several scan lines, it is necessary to understand the temporal and spatial relationships between sample values from the analog tape and ground resolution elements. Figure 4 shows these relationships for a situation in which there is no scan overlap or underlap. Note that samples in a row are adjacent in time whereas samples in a column are separated in time by an amount which corresponds to the time required for one revolution of the scanner.

The scanner-produced signal on the tape is noisy. Typical sources of noise include shot noise in the sensors, atmospheric scattering, electronic and mechnical tape recorder noise, etc. It is reasonable to assume that the signal on the tape is the sum of two components: a desired component proportional to the irradiance at the scanner aperture, and an undesired or noise component caused by imperfections in the electronic system. The noise is described by its mean value and autocorrelation function. The period of time over which the noise can be expected to be correlated is equal to one-half the reciprocal of the recorder system bandwidth. When typical scanner parameters are used, the noise components of adjacent values in the same row, because they are adjacent in time, can be expected to be correlated, while the noise components of adjacent values in the same column, because they are separated in time, can be expected to be uncorrelated. It is because the noise components in the column direction are uncorrelated that one can achieve an improvement in signal-to-noise ratio by averaging lines of data. For uncorrelated samples the noise standard deviation will decrease as $\frac{1}{\sqrt{N}}$ where N is the number of lineas averaged.

In the absence of scan overlap, averaging of scan lines has the effect of decreasing the resolution in the column direction. With scan overalp, the decrease in resolution does not become serious until the number of lines averaged begins to exceed the number of redundant scan lines.

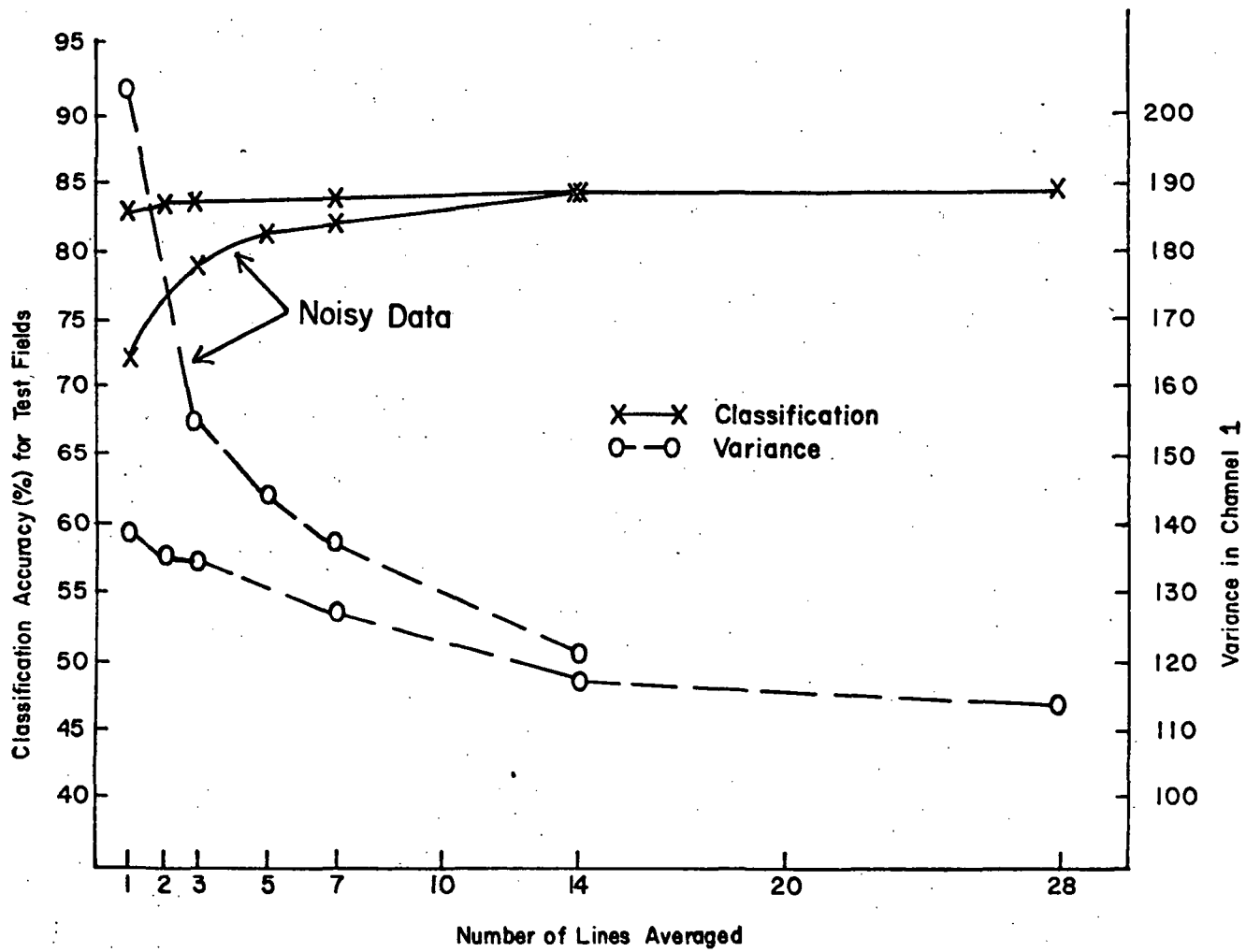


Figure 4. Time and spatial relationships between ground, sample values of tape, and gray scale print out.

The trade-off between resolution and signal-to-noise ratio is determined by the number of lines averaged. Averaging more lines will improve the signal-to-noise ratio but at the cost of decreased resolution. The next section proposes criteria for choosing the number of lines to average and the weighting coefficients to use.

CRITERIA FOR CHOOSING WEIGHTING COEFFICIENTS

Overview

Having pointed out the trade-off between the resolution and signal-to-noise ratio, we now consider the problem of choosing the weighting coefficients. In order to evaluate the seriousness of loss in resolution, a measure of resolution error must be devised. This is the first problem treated in this section of the report. It is shown that the size of the resolution error depends upon, among other things, the weighting coefficients. Then noise reduction as a function of the number and relative values of the weighting coefficients is treated. It is shown that maximum noise reduction is achieved with equal weighting coefficients.

Two approaches to optimizing the resolution/signal-to-noise-ratio trade-off are then presented. In the first approach equal weighting coefficients are used and the number of lines averaged is choosen so that the resolution error equals the noise error. In other words, the number of lines averaged is increased until the point is reached where the resolution error just equals the noise error. In the second approach the weighting coefficients are choosen so as to minimize the sum of the resolution error and the noise error.

Resolution Error Measurement and Computation

It is shown below that for a given scanner-aperture geometry the resolution error depends upon the number and relative magnitude of the weighting coefficients, the number of redundant scan lines, D, and the line increment, I.

It has been assumed in the following that the scanner optics are such that the detectors respond to a circular resolution area on the ground and that the response of the scanner is uniform over the resolution area. The relationship between D and I is shown in Figure 5. In this figure, the dots separated by distance S represent the centers of the resolution elements of adjacent scan lines. For simplicity it is assumed that the velocity of the

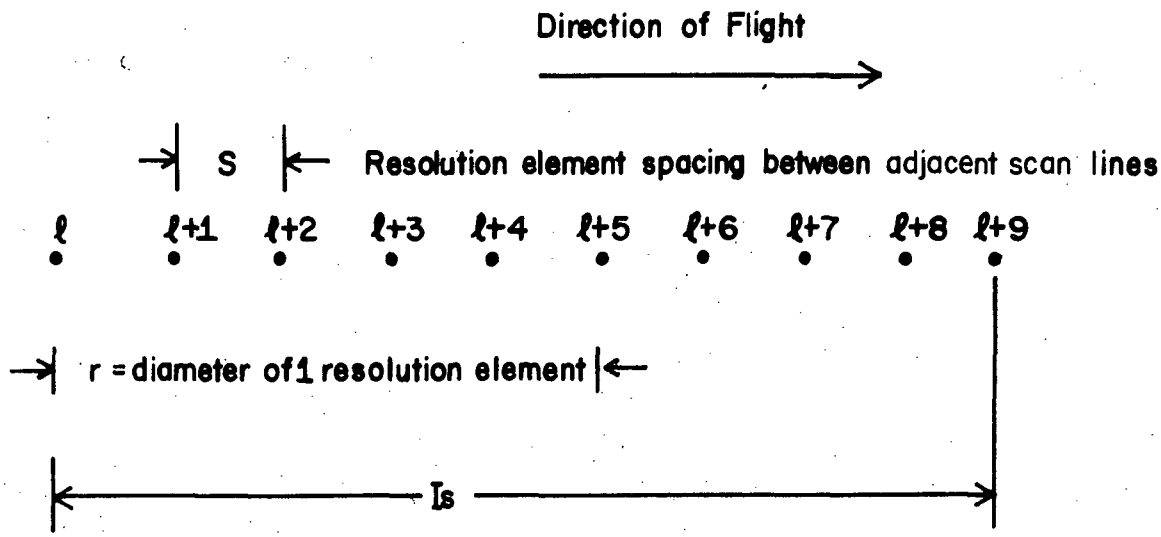


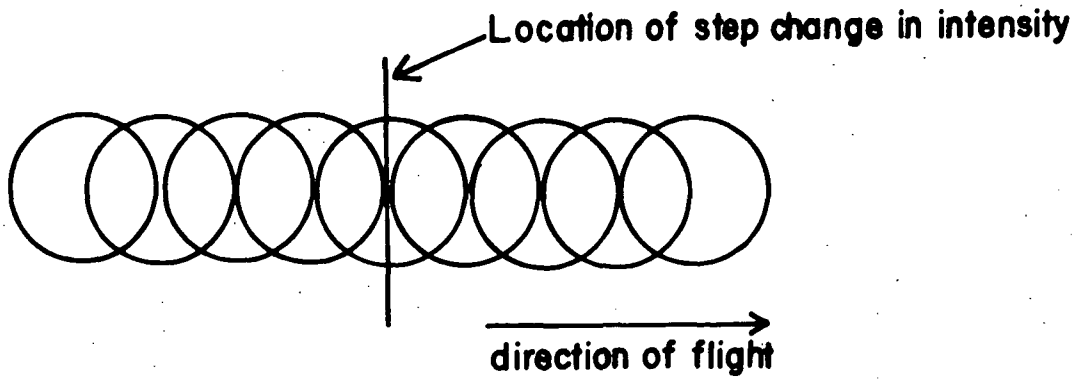
Figure 5. Number of redundant scan lines D is defined by the relation r=(D+1)s.

aircraft and scanner speed of rotation are related such that r, the diameter of one resolution element, is KS where K is an integer. The parameter I is best described in terms of how multispectral scanner data is handled when no line averaging is done. With no line averaging, only every Ith scan line is digitized; I and the sampling rates are determined so as to obtain the desired aspect ratio for display purposes. In order to maintain the proper aspect ratio when averaging lines, one line of averaged data must be produced for each Ith line of the original tape.

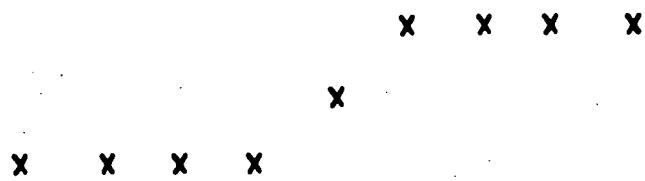
Resolution error will be defined with respect to a step change in ground intensity along a direction perpendicular to the direction of flight. The resolution error is defined as the average of the integral-squared error between the line-averaged signal and the step change. The "average" in this definition is with respect to the uncertainty of the location of the step which occurs when $I > D+1$. The steps in the computation are illustrated in Figure 6 for the case of one redundant scan line and $I=3$. Figure 6a shows the step boundary and resolution elements for several adjacent scan lines. If every line of the tape were used, sample points as shown in Figure 6b would result from the digitization process. If a signal were to be reconstructed by connecting the sample points with straight line segments, it would appear as in Figure 6c. Note here that the step change is distorted even without line averaging. If a series of pictures analogous to Figure 6c were drawn with the number of redundant scan lines increasing from picture to picture, the sample points would get closer together and approach a continuous curve. The shape of the curve is dependent upon the geometry of the resolution element and the direction of the boundary with respect to the flight direction. The curve for a circular aperture and a step change perpendicular to the direction of flight is shown in Figure 7.

Before introducing any line averaging into the example, consider what would happen if only every third scan line were used. Then, depending on where the counting process began, one of the three signals shown in Figure 6d could result. Note that selecting every Ith scan line introduces additional "spreading" of the boundary region and, assuming each of the cases is equally likely, introduces an uncertainty regarding the boundary location. It is with respect to this uncertainty in boundary location that the resolution error will be averaged.

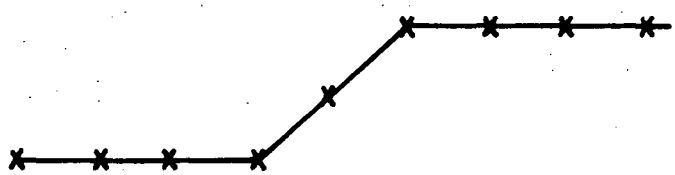
To continue the example, Figure 6e shows the result of averaging three lines using equal weighting coefficients. Each



a) Step change location and resolution elements of several adjacent scan lines.

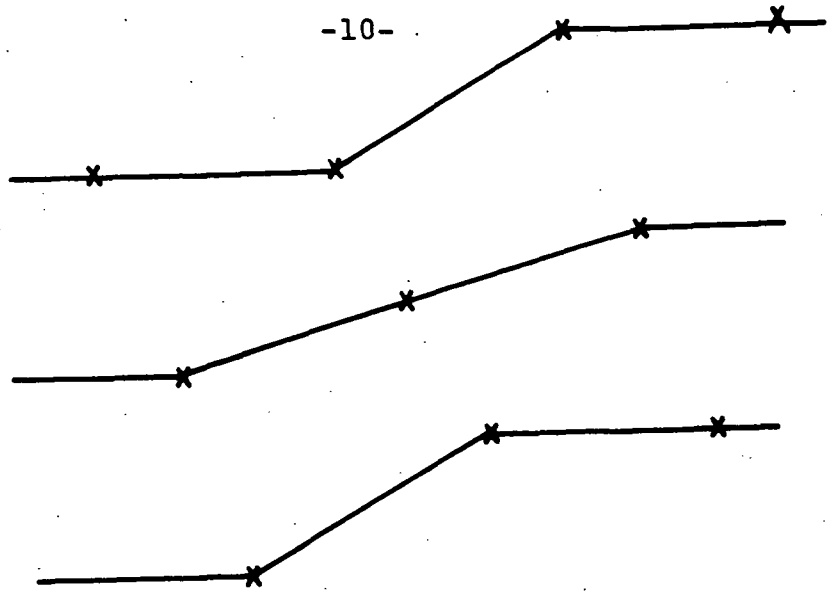


b) Sample values corresponding to Figure 6 a).

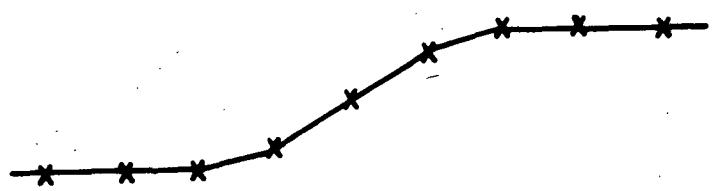


c) Signal that would result from linear interpolation between sample points. Note spread in boundry which results from sampling.

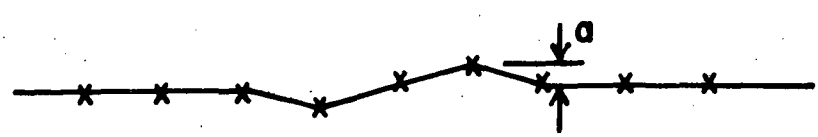
Figure 6. Steps in computing resolution error.



d) Three possible signals resulting from selecting every third sample. Note additional spreading of boundry.

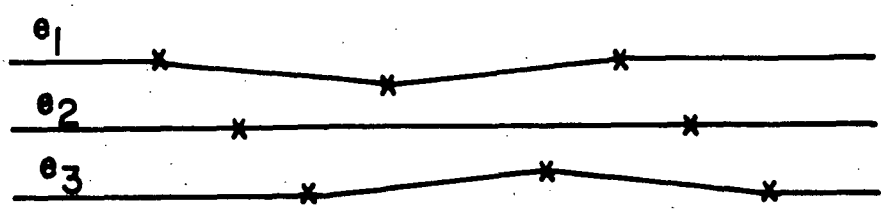


e) Result of averaging 3 lines with equal weighting coefficients.



f) Overscanned error signal. Figure 6 b) minus Figure 6 e).

Figure 6. (continued)



g) Three (I) possible error signals resulting from selecting every third sample of line averaged signal (Figure 6 e).

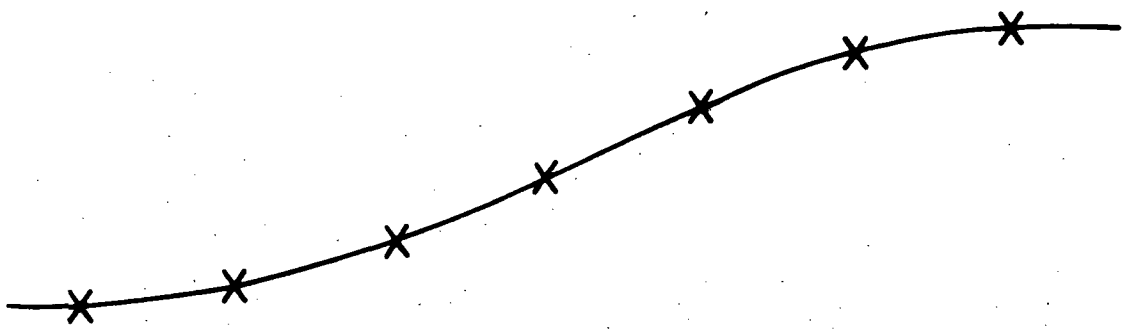
$$\overline{E_r^{\,2}} = \frac{1}{3}[E_1^{\,2} + E_2^{\,2} + E_3^{\,2}]$$

$$\overline{E_r^{\,2}} = \frac{1}{3}[(o + a^2 + o) + (o + o) + (o + a^2 + o)]$$

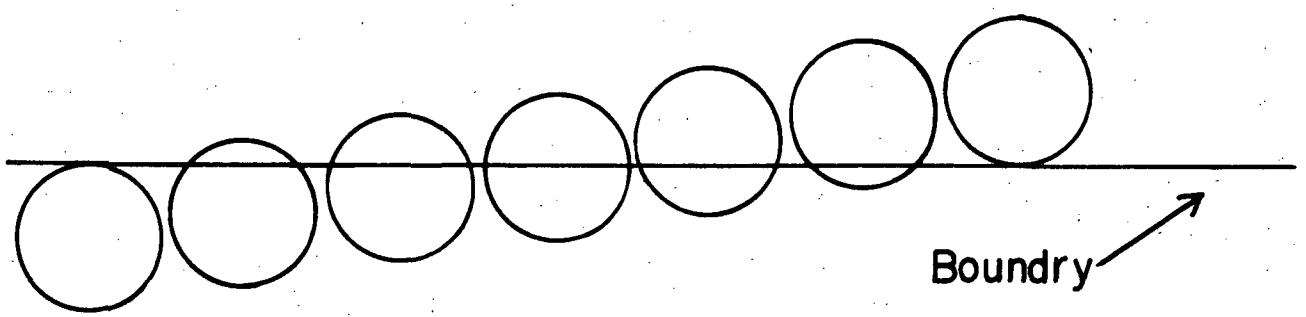
$$\overline{E_r^{\,2}} = \frac{2}{3}\, a^2$$

h) Computation of mean square resolution error. $E_1^{\,2}$ is squared error corresponding to e_1 of Figure 6 g).

Figure 6. (concluded)



a) Result of convolving circular aperture with step change in intensity.



b) Aperture position for sample points shown in a).

Figure 7. Response of circular aperture to step change in intensity.

new data point is computed using the relationship

$$X_{new}(i) = \sum_{j=-1}^{1} \frac{1}{3} X_{old}(i + j).$$

In general the weighting coefficients are constrained so that

$$\sum_{j=1}^{N} \alpha_j = 1$$

where N is the number of lines averaged.

An overscanned error signal is defined as the difference between the original step change and the line-average data. "Overscanned" signifies that this signal includes every scan line. The overscanned error signal for this example is shown in Figure 6f. Selecting every third data point (I=3) and considering the three possible starting points results in the three error signals shown in Figure 6g. Also shown are the corresponding squared errors. The final step in computing the resolution error is to average the I squared errors, Figure 6h.

Summarizing the computation of the resolution error for a given set of parameters, D, I, N, α_i, i=1, 2, ...N, one first computes the sample points corresponding to the output of the scanner for each scan line. This computation will be dependent upon the geometry of the resolution element. A new set of data points is then generated using the N weighting coefficients $\alpha_1, \alpha_2, \ldots \alpha_N$. An overscanned error signal is obtained by taking the difference of the averaged data points and the step change. I error signals are then obtained by choosing every Ith scan line. I such signals are formed depending on which sample point is chosen as the initial point. Finally, the sum squared errors are found for each of the I error signals and averaged. The resulting resolution error depends upon the scanner-aperture geometry, number of redundant scan lines D, the line increment I, and N weighting coefficients $\alpha_1, \alpha_2, \ldots \alpha_N$.

Noise Reduction by Averaging

The amount of noise reduction which is achieved by averaging N lines is now considered. Assuming that the noise is zero mean, and stationary and that noise samples from different scan lines are independent, the noise variance after averaging N lines is given by:

$$\sigma_N^2 = \sigma^2 \sum_{i=1}^{N} \alpha_i^2$$

where σ^2 is the noise variance before averaging. Recall that the weighting coefficients satisfy the relationship

$$\sum_{i=1}^{N} \alpha_i = 1$$

so that

$$\sigma_N^2 \leq \sigma^2.$$

If it were desired to minimize σ_N^2 without regard to resolution error the $\{\alpha_i\}$ should be chosen to minimize the sum of the squares of the α_i subject to the constrant given above. It can be shown that the sum of the squares will be minimized when

$$\alpha_i = \alpha = \frac{1}{N}.$$

The noise variance after averaging is then $\sigma_N^2 = \frac{1}{N}\sigma^2$. The rms value of the noise is reduced by $1/\sqrt{N}$.

Averaging scan lines to form new lines of data has opposite effects on the mean square resolution error and mean square noise. As the number of lines averaged increases, the noise decreases but the resolution error increases. Two criteria for choosing the weighting coefficients are discussed next. The first criterion uses equal weighting coefficients (because this gives maximum noise reduction for a fixed number of coefficients) and chooses the number of lines to be averaged so as to make the resultant noise error equal to the resolution error. The second criterion chooses the weighting coefficients so as to minimize the sum of the resolution error and mean square value of the noise.

Equal Error Criterion

Under this criterion equal weighting coefficients are used and the number of weighting coefficients is chosen so as to make the resolution error equal to the noise error. Another way to view this criterion is that more and more lines are averaged until the resolution error introduced by the averaging process equals the noise error. For a given signal-to-noise ratio the optimum number of lines to average can be found by equating the errors

$$\overline{E}_r\ (N)\ A^2 = \sigma^2\ \frac{1}{N}$$

where $\overline{E}_r{}^2(N)$ is the resolution error associated with a unit step change in signal and A is the amplitude of the step change. Rewriting

$$\frac{A^2}{\sigma^2} = \frac{1}{N\ E_r{}^2(N)}$$

Interpreting $\frac{A^2}{\sigma^2}$ as a measure of the signal-to-noise ratio before averaging, the last equation can be used to find the optimum number of weighting coefficients for a given input signal-to-noise ratio.

A computer program was written to determine the optimum number of lines to average for a given signal-to-noise ratio A^2/σ^2.

Minimization of Total Error Criterion

Although uniform weighting minimizes the noise variance of the averaged data, the mean square resolution error may be reduced if nonuniform weighting is used. A second criterion for choosing the weighting coefficients is to choose the number of lines to average, N, and the relative size of the coefficients, the α_i, so as to minimize the sum of the mean square resolution error and the mean square noise error.

For purposes of this study, a general minimization was not carried out. Instead, programs were written to find the best set of linearly or exponentially decaying coefficients. Results for these two weighting procedures were sufficiently close to conjecture that the total error is not highly dependent on the exact functional relationship between the weighting coefficients but depends more on the rate at which the coefficients decay.

IMPLEMENTATION OF LINE AVERAGING

The previous section has established criteria for choosing the number and value of the weighting coefficients. The selection of a criterion requires knowledge of the channel signal-to-noise ratios. Determining these ratios and a number of other practical problems associated with the implementation of the line-averaging technique are treated in this section.

A Working Definition of Signal-to-Noise Ratio

A measure of the noise power, σ_N^2, can be obtained by assuming that variations in the signal on the bulk tape corresponding to the dark part of the scanner are due solely to noise. This assumption seems reasonable for the visible channels, since the interior of the scanner is designed to be uniformly dark. For the IR channels it is also necessary to assume that the interior of the scanner is at a constant temperature. The mean square value of the noise was estimated by using a program called CENTROID. Used with the bulk data tape, CENTROID computes the variance of the signal corresponding to the dark region of the scanner.

By assuming that the signal on the portion of the scan line corresponding to the field of view is the sum of the desired signal plus noise, a measure of the total power (desired signal plus noise), σ_T^2, can be obtained. The working definition used for the total power was the square of 1/6 times the dynamic range of the signal associated with that part of the scan line corresponding to the field of view. The factor 1/6 arises from the fact that under appropriate assumptions the "peak-to-peak" value of a gaussian random process is six times the standard deviation. The total power was estimated by examining several typical lines of the bulk data tape.

As a check, another method of computing the total power was tried. The average line variance over the run $\tilde{\sigma}_T^2$, was defined as

$$\tilde{\sigma}_T^2 = \frac{1}{N_\ell} \sum_{i=1}^{N_\ell} \left[\frac{1}{222} \sum_{j=1}^{222} (S_{ij} - \mu_i)^2 \right]$$

where N_ℓ is the number of lines considered
S_{ij} is the jth sample in the ith line
222 is the number of samples in a line
and μ_i is the mean of the ith line.
$\tilde{\sigma}_T^2$ and σ_T^2 did not differ greatly in the cases tried.

Combining the methods for obtaining σ_N^2 and σ_T^2 the following working definition for signal-to-noise ratio (SNR) was used.

$$SNR = \frac{\sigma_T^2 - \sigma_N^2}{\sigma_N^2}$$

Note that as used here SNR represents a power ratio.

How to Handle Calibration Values

At the end of each line of data on a LARS data storage tape there are three calibration number denoted C0, C1, C2. These numbers may be used to calibrate the data in a variety of different ways (3). The question arises as to how to handle these calibration numbers when averaging lines of data.

Analysis shows that for a one-point calibration (clamping), the calibration values C0, C1 and C2 should be averaged in the same manner as the data points. This result is also true for two-point calibration provided the signal-to-noise ratio of the original data is large.

Data Storage Tape Generation

One of the requirements of the investigation was to produce a data storage tape in the standard LARS format. To the average user, this data storage tape should have the same format as the data storage tapes currently produced. Two approaches were possible:

1) Sample every line of the analog tape; reformat using the present reformatting program to produce an intermediate data storage tape which has every scan line on it; and use a program called LINAVE to produce a final data storage tape where each line is the average of several adjacent lines.

2) Sample every line of the analog tape; use a modified reformatting program to do the line averaging and produce a final data storage tape in one operation.

In the research phase the first of these approaches was used. This decision was based primarily on the fact that a version of LINAVE was available and could be used with only minor modifications.

Need to Degrade Signal

In the course of the investigation described in the next section, evaluation of the line-averaging technique was hampered by the fact that classification accuracies even without any line averaging were so high that it was virtually impossible to show any decisive improvement in classification accuracy as a result of line averaging. In order to evaluate the technique in a less marginal situation, the original data was degraded by adding independent gaussian noise samples to each sample point in each channel. The technique used was similar to that employed by Whitsitt (4).

EVALUATION: ACTUAL USE OF METHOD

It would be highly desirable to evaluate the use of scan overlap redundancy to enhance multispectral data from the standpoint of several user situations such as ground cover classification accuracy, thermal mapping of water resources, soils studies, crop yield studies, degree of plant stresses, etc. In this study, the use of scan overlap redundancy was evaluated in terms of classification accuracy. Its usefulness in other applications is yet to be evaluated.

LARS data run 69002901 was chosen for the study. This data set is representative of agricultural ground cover found in central Indiana. The data was gathered in June, 1969. To achieve the proper aspect ratio, every seventh line of the analog tape was originally digitized. In order to evaluate the line-averaging technique, all lines of the first part of the run, a total of 1600 X 7 = 11200 lines, were redigitized. This corresponds to the first 1600 lines of the original data storage tape or about 1/4 of the total flightline. The decision to redigitize up to line 1600 was based on the fact that, in a previous analysis of this flightline, most of the training fields and many test fields fell within this portion of the flightline. Redigitization of the entire run would have required an excessive number of bulk and data storage tapes. The redigitized run denoted as 69002904 required eight bulk tapes and two data storage tapes.

Channels 1, 7, 10 and 11 were selected as the subset of channels which would be used for classification. This was done upon the recommendation of Paul Anuta, who was familiar with the classification of run 69002901.

The noise variance, total signal variance, and SNR are shown below for each channel. Although the SNR's are different for different channels, which implies different weighting, only the case of equal weighting was considered for all channels. Weighting coefficients based on the channel with the lowest SNR were used on all channels since using a different set of coefficients on different channels would have the effect of introducing different resolution errors in different channels.

Channel	σ_T^2	σ_N^2	SNR
1	81.0	1.0	80.0
7	484.0	1.0	483.0
10	144.0	1.8	80.0
11	144.0	3.9	36.0

The number of redundant scan lines was found to be between one and two.*

Using the estimated values for the number of redundant scan lines (2), line increment (7), and SNR (40), the weighting programs were used to find the best weighting coefficients.

One program choose the α_j so as to produce triangular weighting. Using this program it was found that for N lines averaged, the weighting ratios and total square error (TERR) areas were as shown below.

N	Weighting Coefficient Ratios	TERR
1	1	1.972
2	1:1	2.1718
3	10:25:10	1.6220
4	10:103:103:10	2.1584

For N greater than four the total square error is greater than that for N=3. Thus, this program indicates that using three weighting coefficients having the ratio 10:25:10 or 0.222:0.556:0.222 is best. Using the program which ranks the fifty best weighting coefficients gave exactly the same weighting coefficients for the best case.

The large SNR's and correspondingly small number of lines to average indicated that noise was not a severe problem with this data and that averaging would probably not enhance the data much.

Because of possible differences in bias and gain levels between the original run 69002901 and the redigitized run 69002904, it was decided not to compare classifications of line-averaged data with 69002901 classifications directly. Instead the LINAVE program was used to generate a tape (69002907) which consisted of every seventh line of 69002904. If digitization has been started at exactly the same spot on the analog tape and if the bias and gains used when 69002904 was digitized had been equal to those used when 69002901 was digitized, 69002907 would have been identical to 69002901. Training and test fields used on 69002901 were found on 69002907 and a classification made. Results were nearly identical to those obtained by using the first 1600 lines of 69002901.

*In the theoretical considerations treated in previous sections it was assumed that the scanner overlap was such that it could be described in terms of an integer number of scan lines. In practice this may not be the case.

Trial line-averaging runs using equal weighting coefficients revealed that classification accuracy was not sensitive to resolution error. This result may be due to the fact that training and test field boundaries often lie within the physical boundaries of the field and that errors introduced near the boundaries do not have a large effect on classification accuracy when the fields are large. As a result of the observations it was decided to carry out the remainder of the evaluation using equal weighting coefficients.

Table 1 shows classification accuracies achieved by using LINAVE to average and select lines from run 69002904 so as to produce data storage tapes wherein each line is the average of several adjacent lines. It is seen from these results that no significant improvement in classification accuracy occurred. This fact is attributed to the relatively high signal-to-noise ratio on the original tape.

In order to evaluate the line-averaging concept under more noisy circumstances, LINAVE was revised to allow the addition of uncorrelated gaussian noise to each sample in all channels before averaging. The new program was named NOISEAV. The noise was generated by the subroutines GAUSS and RANDU.

A noisy run, run 69002908, was constructed by adding noise having $\sigma 8.0$ bins (out of 256) to run 69002904. Averaging over various numbers of lines was tried on the redigitized run with $\sigma=8.0$ noise added.

The SNR for each noisy channel is shown below for run 69002908.

Channel	σ_T^2	σ_N^2	SNR
1	155.0	65.0	1.23
7	548.0	65.0	7.45
10	208.0	65.8	2.16
11	208.0	67.9	2.07

Averaging had a very beneficial effect on the noisy data as can be seen in Table 1 and 2 and Figure 8.

It is seen that line averaging significantly improves data quality when the initial signal-to-noise ratio is small.

Table 1. Classification accuracy as a function of number of lines averaged (N) for run 69002904 (no noise added) and run 69002908 (gaussian noise with σ=8 added)

RUN	N	σ	TRAIN	TEST
69002904	1	-	94.9%	82.8%
69002905	2	-	95.6	83.2
69002906	3	-	95.9	83.5
69002907	7	-	95.9	83.7
69002915	14	-	95.7	84.2
69002917	28	-	95.4	84.3
69002908	1	8.0	80.4	72.1
69002909	3	8.0	88.3	78.7
69002911	5	8.0	91.0	82.2
69002910	7	8.0	91.9	82.2
69002916	14	8.0	93.4	84.6

Table 2. Average line variance for the runs shown in Table 1.

RUN	Channel 1	Channel 7	Channel 10	Channel 11
69002904	138.6	611.9	1047.1	529.2
69002905	135.8	605.2	1040.0	520.2
69002906	134.8	599.8	1035.5	515.3
69002907	127.5	578.2	1018.7	506.6
69002915	117.6	547.9	995.3	493.8
69002917	113.2	532.9	983.1	487.3
69002908	203.0	674.0	1111.7	593.7
69002909	156.3	620.8	1056.7	535.7
69002911	143.7	600.9	1038.8	523.6
69002910	136.7	586.4	1027.7	515.8
69002916	122.2	552.0	999.8	498.3

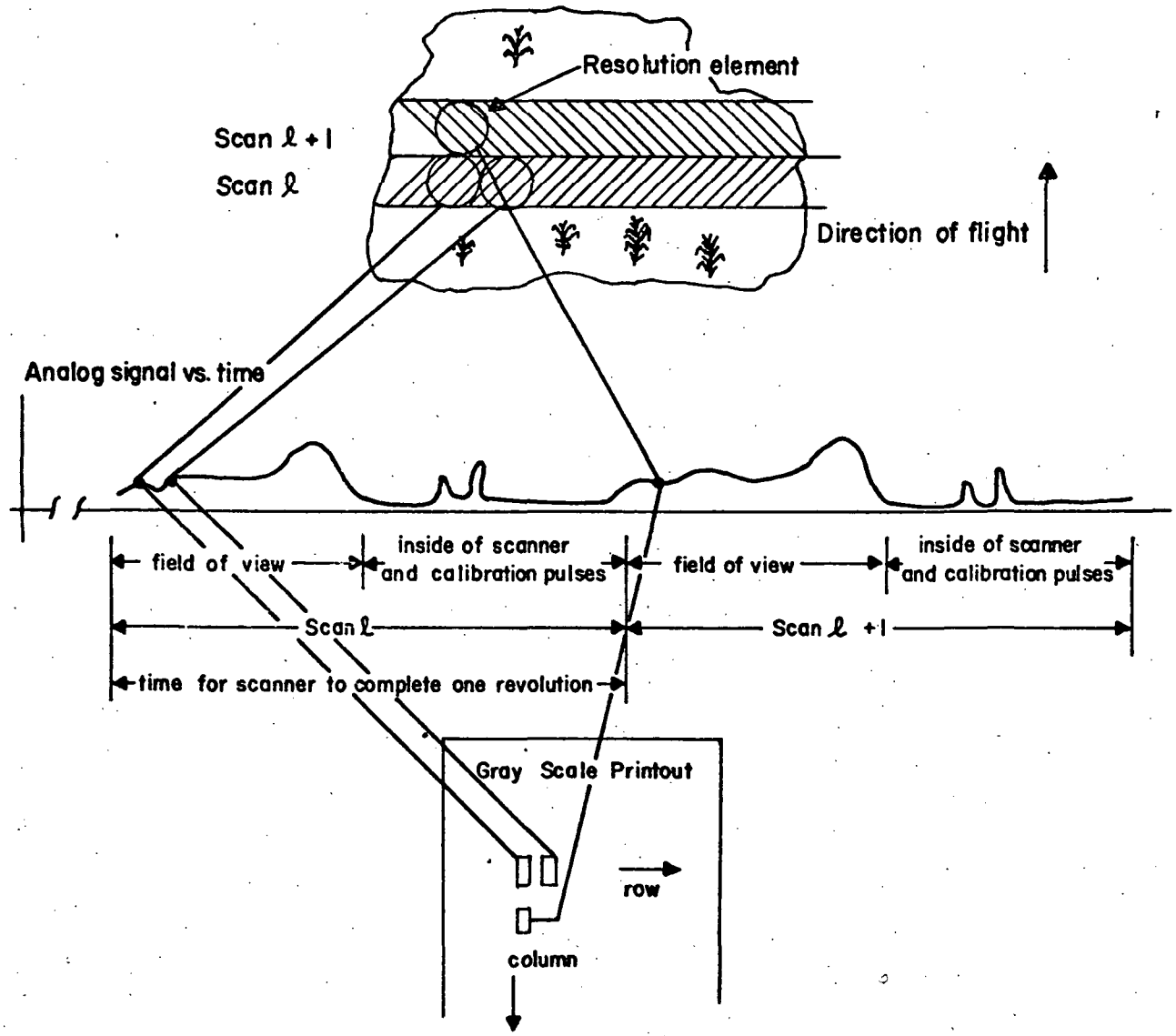


Figure 8. Test field classification accuracy and channel 1 variance vs. number of lines averaged.

SUMMARY

The use of scan overlap redundancy to enhance multispectral aircraft scanner data has been studied. Two criteria were suggested for optimizing the resolution error versus signal-to-noise-ratio trade-off. The first criterion uses equal weighting coefficients and chooses n, the number of lines averaged, so as to make the average resolution error equal to the noise error. The second criterion adjusts both the number and relative sizes of the weighting coefficients so as to minimize the total error (resolution error plus noise error). The optimum set of coefficients depends upon the geometry of the resolution element, the number of redundant scan lines (d), the scan line increment (I), and the original signal-to-noise ratio of the channel. Programs were developed to find the optimum number and relative weights of the averaging coefficients.

A working definition of signal-to-noise ratio was given and used to try line averaging on a typical set of LARS data. Line averaging was evaluated only with respect to its effect on classification accuracy. Trial runs indicated that classification accuracy was not very sensitive to resolution error.* Thus equal weighting coefficients were used in the evaluation. To illustrate the potential benefits of line averaging for very low signal-to-noise situations, noise was added to the original data before line averaging. Averaging of seven adjacent scan lines increased the correct classification from 73% to 82% for the noisy data.

For purposes of this study, line averaging was accomplished by generating one data storage tape from another data storage tape. If used operationally, it is recommended that the line-averaging operation be carried out as part of the reformatting operation.

*This result is obviously data-dependent. Border effects will be minimal if test fields are large and lie well within the physical boundaries of the field. Border effects may not be negligible if test fields are small.

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