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A QUANTITATIVE APPLICATIONS-ORIENTED EVALUATION OF THEMATIC MAPPER DESIGN SPECIFICATIONS

FINAL REPORT

Philip H. Swain
Principal Investigator

Laboratory for Applications of Remote Sensing
Purdue University
West Lafayette, Indiana 47907

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ABSTRACT

Simulated Thematic Mapper data sets were created from aircraft multispectral scanner data in order to predict the sensitivity of applications-oriented classification results to variations in selected sensor parameters. It was found that band-to-band misregistration as little as 0.3 pixel can have a pronounced effect on the classification of both field-center pixels and pixels associated with edges and small objects in the scene. Moreover, a significant price in terms of achievable classification accuracy will be paid because the resolution of the thermal band on Thematic Mapper will be 120m rather than the 30m of the other six bands.

Key Words: Thematic Mapper, remote sensing, multispectral scanner, registration, sensor design, classification.

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PART I: OVERVIEW

I.1 Project Rationale

As engineering design and development proceed towards the fabrication of Thematic Mapper hardware, the real costs of achieving the design specifications are becoming increasingly apparent. In some instances, savings in terms of cost, instrument complexity and reliability, and time-to-completion might be effected if some of the harder-to-achieve design specifications could be relaxed. Since the instrument specifications were derived largely from applications-oriented considerations by a panel of experts in sensor system design, data processing, information extraction and various earth resources applications disciplines[6], it is important to assess quantitatively the impact of such deviations on the utility of the sensor data for these applications. With this information, it would be possible to make judicious tradeoffs among those system parameters which are still somewhat flexible.

I.2 Project Objectives

This one-year project had two specific objectives:

(1) To quantify the benefits to be expected from the Thematic Mapper data under the assumption that the current sensor design specifications are achieved.

(2) To assess the degree to which these benefits would be affected by modification of certain of the specifications, in particular the specifications concerning band-to-band registration accuracy, system noise level, and spectral band definition.

These objectives were to be achieved through analysis of field spectral data and multispectral scanner data, taking into account the information requirements of specific applications, the principles of scanner design and pertinent information extraction techniques, and lessons learned through extensive experience with data from the Landsat multispectral scanner.

I.3 Summary of the Investigation

The effects of band-to-band misregistration on classification accuracy have been investigated for two flightlines of aircraft multispectral scanner data acquired on one date during the 1971 Corn Blight Watch Experiment.

One data set represents a typical agricultural area in the western portion of north central Indiana. The fields in this flightline are large and contain principally corn and soybeans. In the second flightline of data, from southwestern Indiana, the fields tend to be smaller and wooded areas are more common than in north central Indiana.

The selected data sets have an effective across-track and along-track sampling interval of approximately 8m at nadir. Software was prepared to:

- Perform radiometric normalization to adjust for across-track intensity variations related to view angle;

- Resample to achieve uniform across-track sample intervals;

- Simulate band-to-band misregistration by shifting selected bands relative to each other;

- Simulate 30m resolution for the visible and near IR bands, 30m and 120m resolution for the thermal IR band.

The resulting simulated Thematic Mapper data sets were analyzed using typical supervised training and classification procedures. To the extent possible, training and test fields selected during the Corn Blight Watch Experiment were used. The results were evaluated by

- Determining, as a function of misregistration, the number of pixels which had a classification different from the no-misregistration result; and

- Tabulating test-field classification accuracy as a function of degree of misregistration.

The first of these criteria attempted to assess the gross impact of misregistration on the total scene, including border pixels and relatively small features in the data as well as the larger agricultural fields. The second evaluated essentially the effects of misregistration on "pure" or "field center" pixels.

The results have shown that band-to-band misregistration of the data can adversely affect the correct classification of pure field-center pixels and particularly border pixels. The effect is pronounced even for misregistration as little as 0.3 pixel. The results suggest that the quality of Thematic Mapper data, as measured by the accuracy achieved upon classification, will be significantly reduced by measurable band-to-band misregistration in the data.

It was also discovered that a significant improvement in classification accuracy could be achieved if the resolution of the thermal band of Thematic Mapper were to be improved to be the same as the other spectral bands. The projected 120m resolution results in fewer "pure" pixels available for classification and for classifier training, both of which adversely affect classification accuracy. With the available resources, it was not possible to assess definitively the net utility of the 120m thermal band resolution.

Significant results related to assessment of the effects of system noise and spectral band definition were not achieved during the contract period. Reasons for this are discussed in Part II of this report.

I.4 Conclusions and Recommendations

The results of this study show clearly that accurate band-to-band misregistration of the Thematic Mapper is critical to good classification performance in areas typified by the Corn Blight Watch Experiment data; that is, for such areas, including "analog" areas with similar field sizes, accurate registration (within a few tenths of a pixel) is essential if the potential benefits of the improved resolution of the sensor are to be realized.

Since there remain questions about the utility of some of the spectral bands defined for the Thematic Mapper and particularly their incremental utility as compared to the Landsat MSS bands, an applications-oriented investigation of these questions should be undertaken. The impact of the lower resolution of the thermal band compared to other spectral bands is of particular concern; the results of the present study have demonstrated that the impact on classification accuracy is significant, but just how significant for a general class of applications remains an open question. Given the availability of a field research data base and analysis software for pursuing answers to such questions, the cost could be relatively small for determining whether in fact the instrumentation, communication, and data analysis facilities for Thematic Mapper should be burdened by the data volume to be produced by the totality of the projected spectral channels.

Apparently no previous empirical study has considered the effects of amplitude-dependent noise on classification of Thematic Mapper data. Amplitude-dependent noise is the dominant noise source in many of the Thematic Mapper channels. Therefore, we recommend continuation of the study of the influence on classification accuracy of various types and magnitudes of noise in Thematic Mapper data. Minimally, a follow-on study should investigate the effects of various magnitudes of white Gaussian noise in addition to amplitude-dependent noise.

PART II: TECHNICAL REPORT

II.1 State-of-the-Science

ERIM publications[1,10] consider the theoretical and practical aspects of band-to-band and multitemporal misregistration. The study, summarized in [1], simulated the effects of misregistration on classification accuracy. Although there was no serious effect on the classification of field-center pixels, it was observed that even small amounts of band-to-band misregistration significantly reduced the number of pure field-center pixels potentially available for classifier training purposes. For example, one-pixel misregistration of data from the Skylab S-192 scanner reduced the number of pure field-center pixels in the test scene by 85.4 percent (from 10313 to 1460).

The ERIM publication[10] also reports that classification accuracy is significantly reduced for mixture or multiclass pixels. The proportion of multiclass pixels in a scene increased with (1) increasing pixel size, (2) decreasing field size, and (3) an increasing amount of misregistration. The increased percentage of multiclass pixels present in a misregistered scene adversely affects classification performance because fewer single-class pixels are available both for training and for recognition. The likelihood of recognition errors and related crop estimation bias among multiclass pixels is increased.

The ERIM report[10] concludes that overall classification accuracy is degraded by misregistration. Furthermore, overestimates of the proportions of certain crops are linked directly to misregistration. This is because the spectral properties of a mixture pixel containing crops A and B may appear similar to the spectral properties of a third crop C. Therefore, multiclass pixels of A and B are classified as belonging to class C. The report questions the common belief that mixture pixels and misregistration effects produce compensating errors.

Both ERIM[11] and LARS[9] have reported results of empirical investigations of the spatial, radiometric, and spectral specifications of the Thematic Mapper. ERIM found area estimation accuracy was best at 30m ground resolution, inferior at 60m, and significantly worse at 90m resolution. The trend of decreased proportion estimation accuracy with decreased spatial resolution coincided with the increase in the number of boundary pixels, mixture or multiclass pixels. Furthermore, the study showed that in the typical Corn Belt scenes analyzed, almost no pure 120m pixels existed. Thus, in the thermal band of Thematic Mapper, most pixels were mixtures of different classes. The study results also suggested that radiometric sensitivity (the system noise level) is of great importance vis-a-vis classification accuracy. Overall, the study results supported the spectral bands selected for Thematic Mapper as of 1976. (The second middle-infrared band, centered at 2.2μm, was added more recently to the Thematic Mapper specifications.)

Results of the empirical investigation of Thematic Mapper specifications performed at LARS[9] support the conclusions in[1,10] noted above in the areas of system noise effects and spectral band selection. However, the results of the spatial resolution investigation indicated that classification accuracy increases as spatial resolution decreases, exactly opposite to the trend found by ERIM. The discrepancy is conjectured to have arisen from the method used at LARS to simulate the various resolutions by averaging pixel neighborhoods in the original data. Thus, for example, each 60m pixel was simulated by averaging approximately one hundred 6m pixels, whereas each 30m pixel was simulated by averaging approximately twenty-five 6m pixels. As a result, the data corresponding to the larger IFOV had a slightly better signal-to-noise ratio and, consequently, better classification accuracy.

The Hughes Space and Systems Group investigated the sensitivity of user applications to variations in TM system performance in three areas[8]: (1) geometric accuracy, (2) radiometric accuracy, and (3) the interrelationship between the Thematic Mapper and the General Electric Data Management System (DMS). Results of the study indicate that an alignment error of 0.1 pixel between the cold focal plane detector array and the warm focal plane array (i.e., band-to-band misregistration between the two groups of wavelength bands) caused virtually no change in the classification accuracy. A 0.5 pixel bias caused a degradation of about 1 percent in classification accuracy for boundary pixels. The study found no compounding effects between the along-scan and the across-scan directions.

Publication[13] examines in detail the addition of white Gaussian noise to one run of aircraft scanner data. The results demonstrate that with the addition of noise to the scanner data, the classification accuracy declines precipitously. The publication discusses the problem of separately considering noise and signal in the analysis because variances due to both noise and ground-scene variability contribute to misclassification. How to quantify the data noise level in a meaningful and useful way in the face of this interaction remains an interesting research issue.

The remaining references in the bibliography provide background information, one providing general information about the Thematic Mapper[14], another discussing in detail the hardware and engineering aspects of the design of the Thematic Mapper[6], and yet another[5] discussing the peculiarities of Thematic Mapper data which make it particularly susceptible to band-to-band misregistration. Two references[4,12] consider multilinear arrays as an alternative to the multispectral scanner. The design of satellite sensors other than Thematic Mapper is considered in[3,7].

II.2 Registration Error Study

This section contains a detailed discussion of our investigation into the effects of band-to-band misregistration on the classification of simulated Thematic Mapper data. The analysis results were obtained for an agricultural area in White County, Indiana, with large fields, and an agricultural area in Posey County, Indiana, with somewhat smaller fields. The analyzed areas are typical of the western portions of north central and south central Indiana. Corn and soybeans were the predominant crops in both areas. Other information classes represented in the flightlines (flightlines 208 and 230, mission 44M of the 1971 Corn Blight Watch Experiment) included wheat stubble, hay, oats, pasture, and deciduous forest, but the classification was performed into classes corn, soybeans, and "other."

Analysis of the results shows, not surprisingly, that classification accuracy decreases with increasing misregistration. The results suggest that the decrease may be related to the spectral/spatial properties of the information classes involved in the classification.

II.2.1 Methods of Analysis

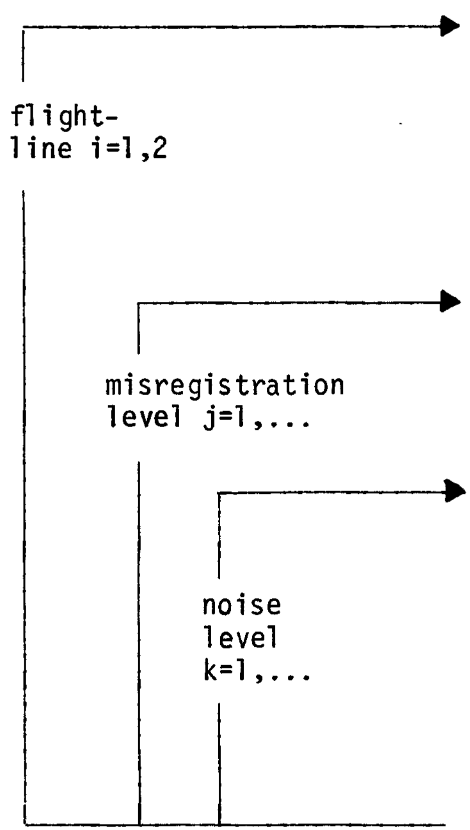
Thematic Mapper data were simulated by appropriately averaging wavelength bands and spatially degrading 12-channel aircraft multispectral scanner data acquired during the 1971 Corn Blight Watch experiment. The data were then misregistered band-to-band, classified, and the classification accuracy determined. As shown in Figure II.1, the processing steps involved extensive use of LARSYS computer programs which are widely used and well documented. Two steps in the plan required programs not in LARSYS and three steps required modifications to existing LARSYS programs.

The first step in preparing the simulated TM data was to normalize each column of data in a flightline to obtain a response which, averaged over the full length of the flightline, was constant as a function of scan angle (view angle) across the flightline. Scanner response variations with scan angle are due fundamentally to the properties of both the atmosphere and the scene geometry. For example, the ratio of the amount of shadowed to illuminated foliage in the instantaneous field of view of the scanner may change significantly with scan angle, even becoming zero in the anti-solar direction of the "hot spot." The normalization process represents the best available procedure for reducing the effects of these variations upon the classification process.

In step 2, data for the Thematic Mapper channels were simulated by selecting and, where necessary, averaging data from the aircraft scanner channels (Table II.1).

Step 3 involved resampling the data in each scan line to obtain standard-sized pixels (3m resolution) in the across-track direction. The resampling process, accomplished using a nearest-neighbor algorithm, compensates for the variation as a function of scan angle in the ground size of the instantaneous field of view of the aircraft scanner. The effective 3m ground size of the resampled pixels facilitated later degradation of the spatial resolution to 30m. A computer program, RESAMP, was written and DUPRUN, a LARSYS processor, was modified to carry out this step.

In step 4, misregistration was created between two sets of bands and the spatial resolution of the data was degraded to 30m. The combined set of visible and near-infrared wavelength bands from non-cooled detectors was misregistered relative to the set of middle and thermal bands, the cooled detectors. The rationale for this choice was that the two sets of detectors are physically separated in the current Thematic Mapper design, increasing the potential for misregistration between the two sets. The effects of misregistration among bands within each set were not considered in the investigation. The spatial degradation of each band was accomplished using a Gaussian window with a half-power cutoff giving spatial resolution of 30 meters.



Step	Description	Computer Program
1	Radiometric adjustment for view angle	MANREA
2	Select/combine aircraft spectral bands to simulate TM spectral bands	DUPRUN (LARSYS)
3	Resample to obtain standard-sized pixels across track	RESAMP and modified version of DUPRUN
4	Misregister bands and degrade spatial resolution of each band to 30m	Modification of DUPRUN (LARSYS)
5	Degrade band 7 to 120m resolution	
6	Add noise	
7	Compute statistics	STATISTICS (LARSYS)
8	Compute separability	SEPARABILITY (LARSYS)
9	Classify	CLASSIFYPOINTS (LARSYS)
10	Compare overall classification results to baseline results	COMPARERESULTS (LARSYS)
11	Compare classification accuracy to baseline result	PRINTRESULTS (LARSYS)

Figure II.1. Thematic Mapper data simulation and analysis procedure.

Table II.1. Simulation of Thematic Mapper Wavelength Bands From Aircraft Data.

Aircraft Bands(μm)	Aircraft Bands Used to Simulate Thematic Mapper Bands(μm)	Corresponding Thematic Mapper Bands(μm)
0.46 - 0.49	(0.46-0.49)+(0.48-0.51)	0.45 - 0.52
0.48 - 0.51		
0.50 - 0.54		
0.52 - 0.57	(0.52-0.57)+(0.54-0.60)	0.52 - 0.60
0.54 - 0.60		
0.58 - 0.65		
0.61 - 0.72	0.61 - 0.70	0.63 - 0.69
0.72 - 0.92	0.72 - 0.92	0.76 - 0.90
1.00 - 1.40		
1.50 - 1.80	1.50 - 1.80	1.55 - 1.75
2.00 - 2.60	2.00 - 2.60	2.08 - 2.35
9.30 - 11.70	9.30 - 11.70	10.40 - 12.50

In step 5, the resolution of the thermal band was further degraded to 120m by Gaussian averaging each 4x4 set of 30m pixels[9].

Step 6 of the procedure shown in Figure II.1 was not required for the misregistration study and was never actually carried out before the resources available to the project were exhausted. However, the computer programs necessary to add noise to the data were completed and are available if further research is to be performed in this area.

Steps 7-11, the classification and evaluation steps, were accomplished using standard LARSYS programs. The training and test fields selected during the 1971 Corn Blight Watch Experiment were reused in this study when possible. Some fields could not be used because they contained too few of the Thematic Mapper scale pixels. For each training/test field, the coordinates of a pixel in Thematic Mapper space were determined using the following decision rule:

A TM pixel belonged to the training/test field if and only if all of the aircraft pixels to be averaged into the 30m TM pixel belonged to the original training or test field.

Training/test fields which, according to the decision rule, contained no TM-size pixels were excluded from the analysis. Also, test fields in the original set which were not classified at least 80 percent correctly in a baseline analysis with all 7 channels at 30m resolution were eliminated from consideration in order to assure that the classes were spectrally well-defined. (Of primary interest in this study was the effect of instrument design variations on spectral characterization of the classes.) When necessary and appropriate, small training classes were combined with other training classes. Thematic Mapper channels 3, 4, 6, and 7 were chosen for classifying the data, for two reasons: First, the transformed divergence, a measure of the separability of various classes, was consistently good for these channels compared to most other combinations of channels. Second, unlike Thematic Mapper bands 1 and 2, each of which were simulated by averaging two aircraft bands, bands 3, 4, 5, 6, and 7 are taken directly from the aircraft data. Thus, using channels 3, 4, 6, and 7 avoided adding to the data quantization error by averaging the two integer-valued aircraft channels to simulate one Thematic Mapper band. Use of bands 3, 4, 6, and 7 also satisfied the tendency, often observed in empirical studies, to choose one band from each spectral region, visible, near-infrared, middle-infrared, and thermal.

Two procedures were used to quantify the effects of misregistration on the data and classification results. First, using as a standard of comparison the classification result for the case of no band-to-band misregistration, the percentage of pixels in the entire flightline (34,800 pixels in flightline 208 and 26,400 pixels in flightline 230) which were classified differently than in the standard classification was tabulated as a function of the degree of misregistration. These results included the effects on classification of misregistration of not only "pure" pixels but also border pixels at the edges of fields or at boundaries between fields. The number of border pixels in the image is highly dependent on the sensor resolution.

Second, the classification accuracy for the test fields (7422 pixels in flightline 208 and 4253 pixels in flightline 230) was tabulated as a function of the degree of misregistration. These results provided a measure based on predominantly "pure" pixels from "field centers."

II.2.2 Results

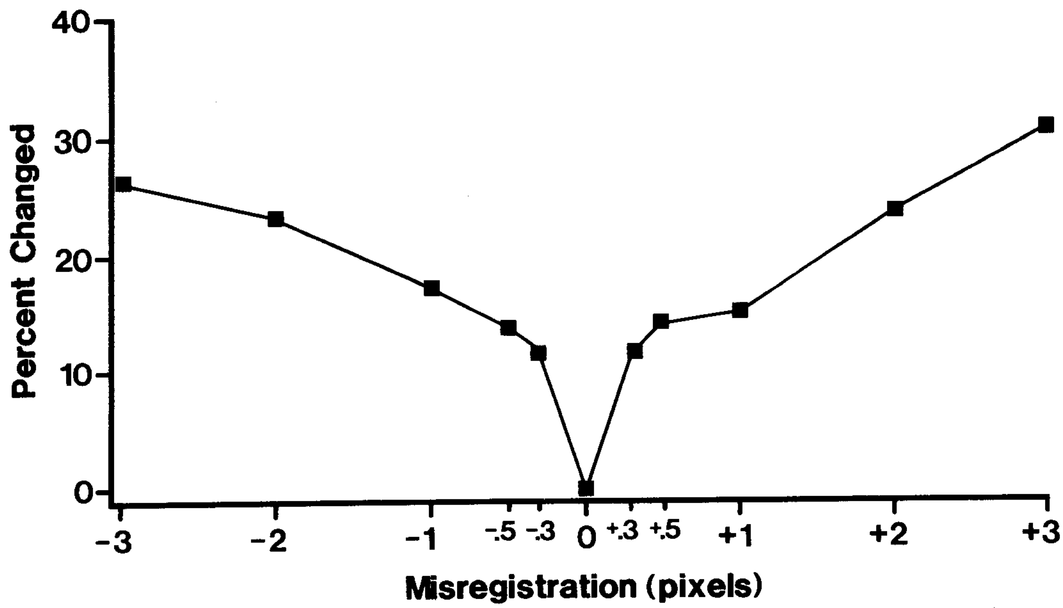
Evaluation of the effects of band-to-band misregistration on classification consisted of three parts. First, for each flightline the entire flightline classification was compared to a baseline classification and the number of pixels of differing classification was noted, an approach which included effects of misregistration on both field-center and mixed-class pixels. Second, the classification accuracy of test fields of corn, soybeans, and "other" was analyzed, the test fields having been selected carefully to contain only field-center pixels. Third, similar classifications were performed on simulated data having 30m resolution in all bands, including the thermal band, and the results of these classifications were compared to those obtained from the simulated Thematic Mapper data. This section of the report provides a summary of the results; the following section contains a detailed discussion of the significance of these results.

For the first part of the investigation, the misregistered classification results for every pixel in each flightline were compared to a baseline standard for that flightline, a classification of the flightline made with no band-to-band misregistration. (The comparison was made without regard to whether either classification was "correct.") Results of the comparisons, Table II.2 and Figure II.2, reveal that the classification of 11.4% of the pixels in flightline 208 was affected by as small an along-track misregistration error as +0.3 pixel between the cooled and uncooled detectors. That is, the classification of 11.4% of the pixels of flightline 208 changed when the hot-detector bands were misregistered relative to the cooled detector bands by +0.3 pixel in the along-track direction. The result for flightline 230 was similar, 12.1%. Similar trends are also evident for both positive and negative misregistration in both the along-track and across-track directions for both flightlines; for example, for a large misregistration error, ±3.0 pixels, the percentage of pixels changed from the baseline classification varied from 24.5% (flightline 230, +3 pixels along-track and +3 pixels across-track). As many as one-fourth to one-third of the pixels in the flightlines changed class when the bands in each flightline were misregistered by three pixels.

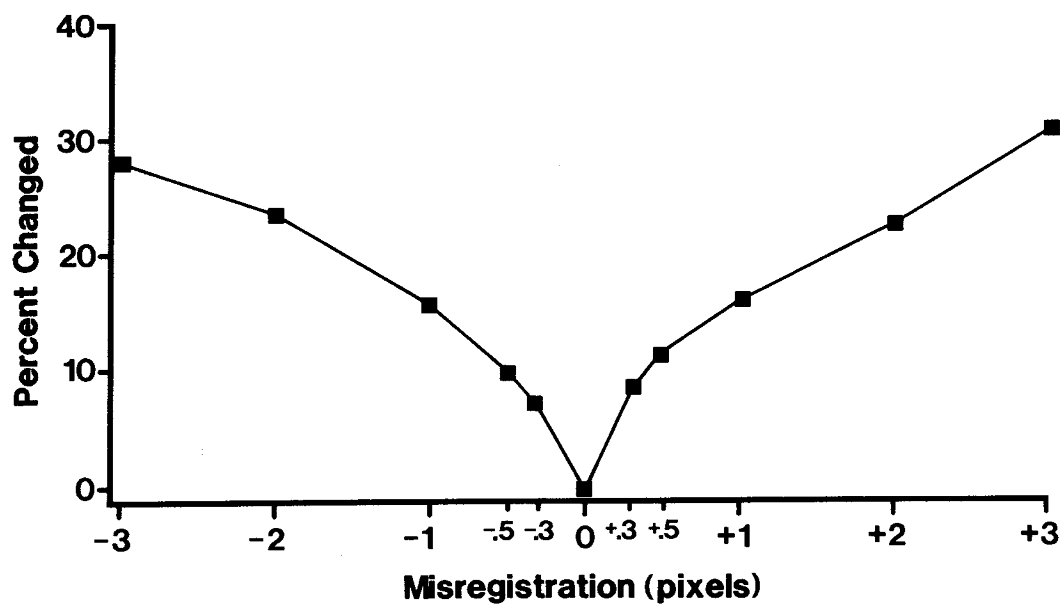
To further illustrate the effect of band-to-band misregistration on the classification of both field-center and mixed-class pixels, two segments of flightline 230 were mapped to display only those pixels which changed classification as a result of misregistration. Figure II.3 shows that both field-center and mixed-class pixels increasingly changed classification with increasing misregistration. The horizontal and vertical lines of Xs in the figures are due to border pixels which changed class. Solid blocks of Xs, evident in the maps for larger misregistrations, represent entire fields which changed classification as a result of misregistration. Classification of the large forested area in Figure II.3(b) did not change significantly even when the misregistration was as great as 3 pixels.

Table II.2. Classification Results: Change From Baseline

Misregistration Direction	Misregistration Amount	Percentage of All Pixels That Changed Class: Flightline 208	Percentage of All Pixels That Changed Class: Flightline 230
Along-Track	3	30.8	24.5
	2	23.9	21.0
	1	15.1	18.1
	0.5	14.0	15.7
	0.3	11.4	12.1
	0	0.0	0.0
	-0.3	11.9	14.6
	-0.5	13.8	19.2
	-1.0	17.4	24.8
	-2	23.3	28.4
	-3	26.4	30.0
Across-Track	3	31.0	24.5
	2	22.9	23.5
	1	16.3	18.3
	0.5	11.6	12.0
	0.3	8.4	8.5
	0.0	0.0	0.0
	-0.3	7.2	10.7
	-0.5	10.1	15.3
	-1.0	15.8	23.7
	-2.0	23.5	29.9
	-3.0	28.0	32.2



(a) Along-track misregistration, flightline 208.



(b) Across-track misregistration, flightline 208.

Figure II.2. Classification results: change from baseline.

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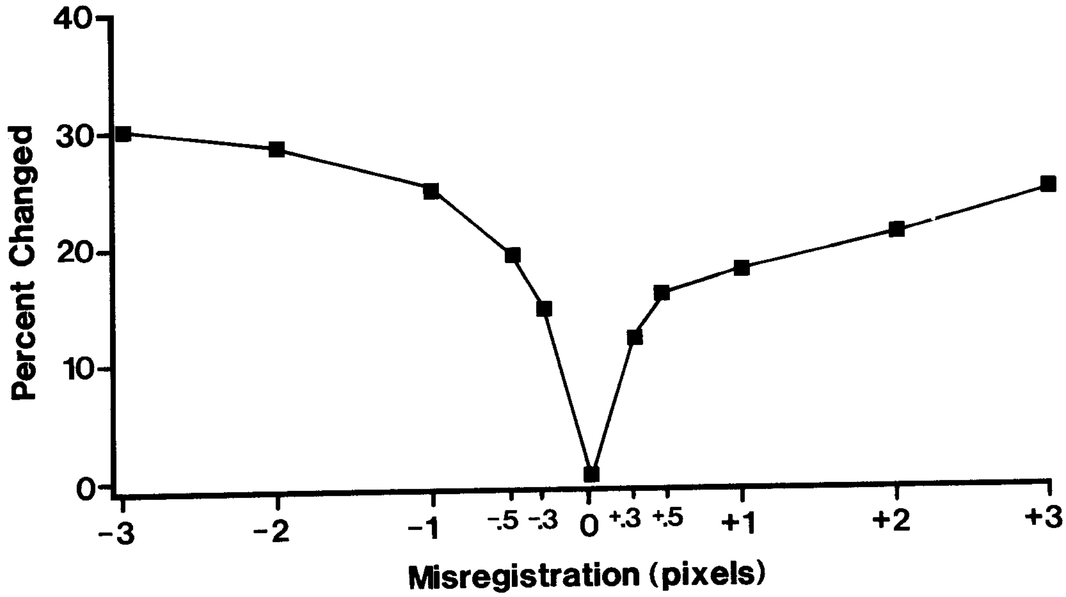
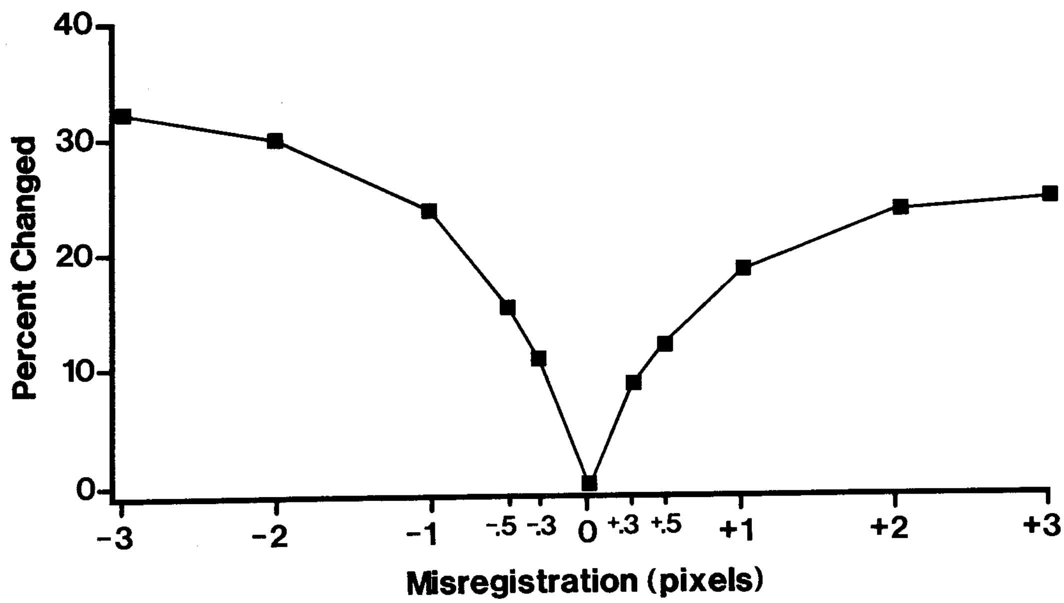


(c) Along-track misregistration, flightline 230.



(d) Across-track misregistration, flightline 230

Figure II.2 (concluded). Classification results: Change from baseline.

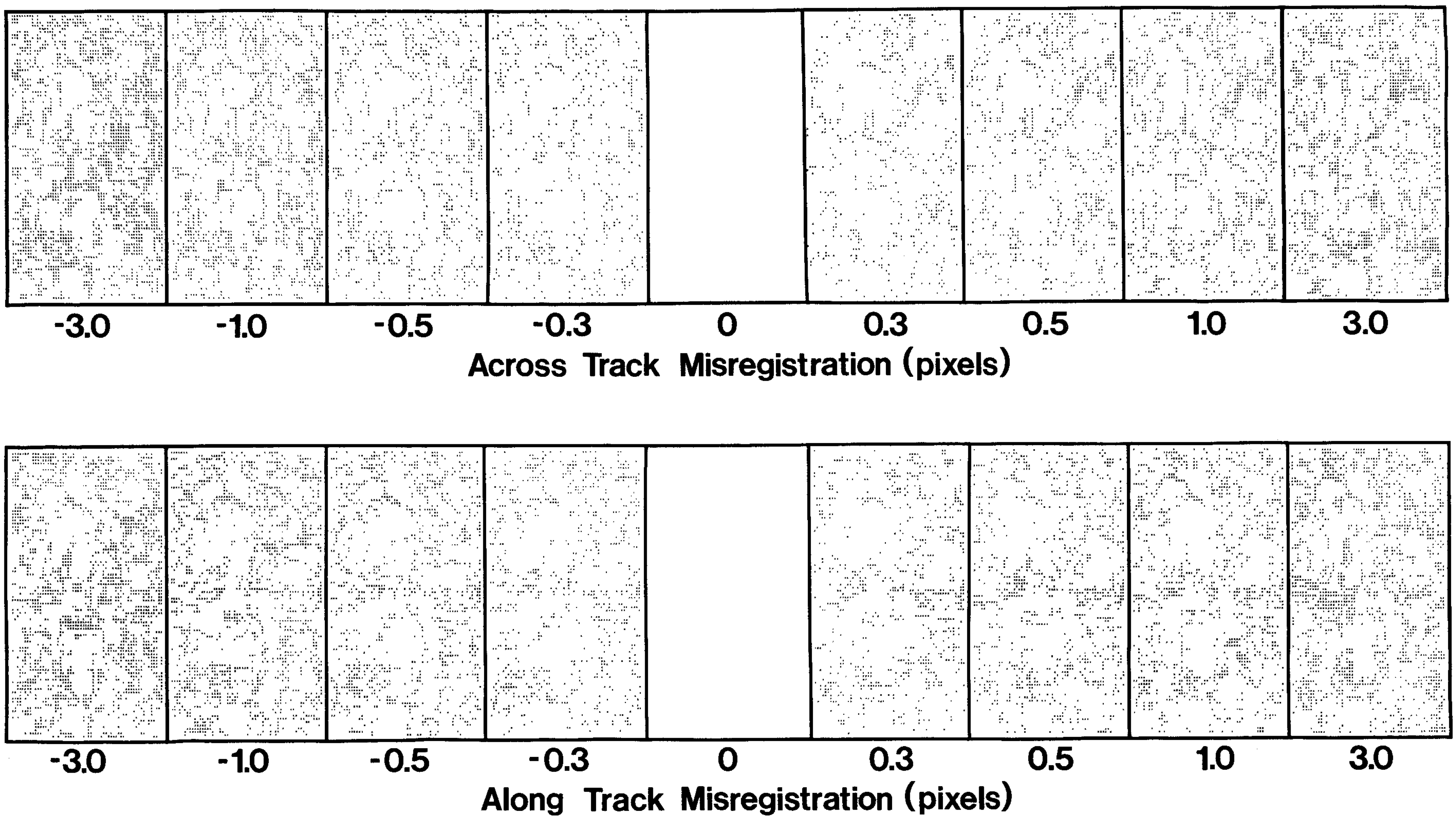


Figure II.3. Map display of classification changes (flightline 230).
(a) Area containing primarily agricultural fields.

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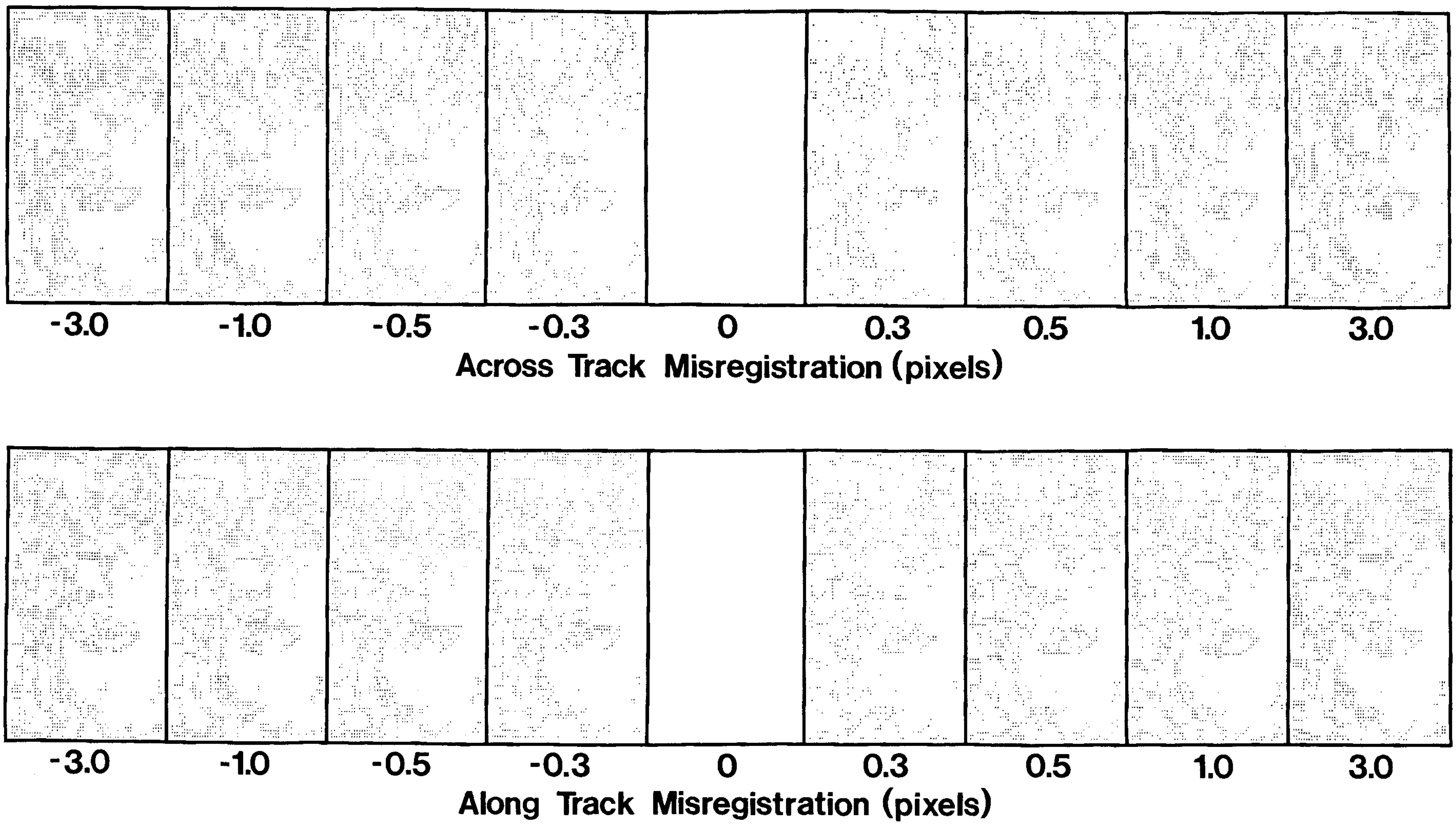


Figure II.3. Map display of classification changes (concluded).
(b) Area containing a large forested area (lower right).

In the second part of the investigation, the classification accuracies of numerous test fields in both flightlines were determined as a function of the amount of band-to-band misregistration. The results, Tables II.3 and II.4 and Figure II.4, show that the classification accuracy generally decreased with increasing misregistration of the soybean and "other" test fields. For example, in flightline 208, classification accuracy changed by an insignificant amount, a few tenths of a percent, for a misregistration of $\pm$0.3 pixel either along or across track. But the change was significant in flightline 230 where classification accuracy of soybeans decreased as much as 11%, from 89.4% for zero misregistration to 78.4% for -0.3 pixel misregistration in the along-track direction. Classification of "other" showed a similar but less pronounced trend with misregistration. For "other," the greatest decrease for a misregistration of 0.3 pixel was 93.5% to 91.0% in flightline 230, across-track misregistration.

The classification accuracy of the corn test fields showed the same general decreasing trend with misregistration of one flightline (230) but not the other (208). For flightline 230, the classification accuracy decreased from 91.3% for zero misregistration to 90.4%, 89.3%, and 90.3% for +0.3 and -0.3 pixels along-track and -0.3 across-track misregistration, respectively. Curiously, classification accuracy increased slightly for +0.3 across-track misregistration. In flightline 208, the test-field accuracy for corn increased with misregistration in one direction (from 56.1% for zero misregistration to 74.3% and 64.2% for -3 pixels along-track and -3 pixels across-track, respectively) and decreased for misregistration in the other direction (from 56.1% to 42.9% (+3 along-track) and 45.3% (+3 across track)).

In the third part of the evaluation, the classification results of the second part were compared with the classification results for a hypothetical sensor with 30m resolution in all bands. (In the second part of the investigation, the results were derived for a sensor like the Thematic Mapper, having a spatial resolution of 30m/120m for the nonthermal/thermal bands.) The results, Tables II.5 and II.6 and Figure II.5 show, as before, that classification accuracy decreased with increasing misregistration. For example, for soybeans in flightline 230, classification accuracy decreased from 97.2% for zero misregistration to 90.1% for -0.3 pixel misregistration in the along-track direction. The same trend is evident in both flightlines and both along track and across track. For a particular amount of misregistration (including zero misregistration) the classification accuracy of the hypothetical sensor with 30m resolution in the thermal band was almost always higher than for an instrument with the specifications of the Thematic Mapper; for example, for no misregistration in flightline 230, the classification accuracy of soybeans for the hypothetical sensor was 97.2% compared to 89.4% for the Thematic Mapper.

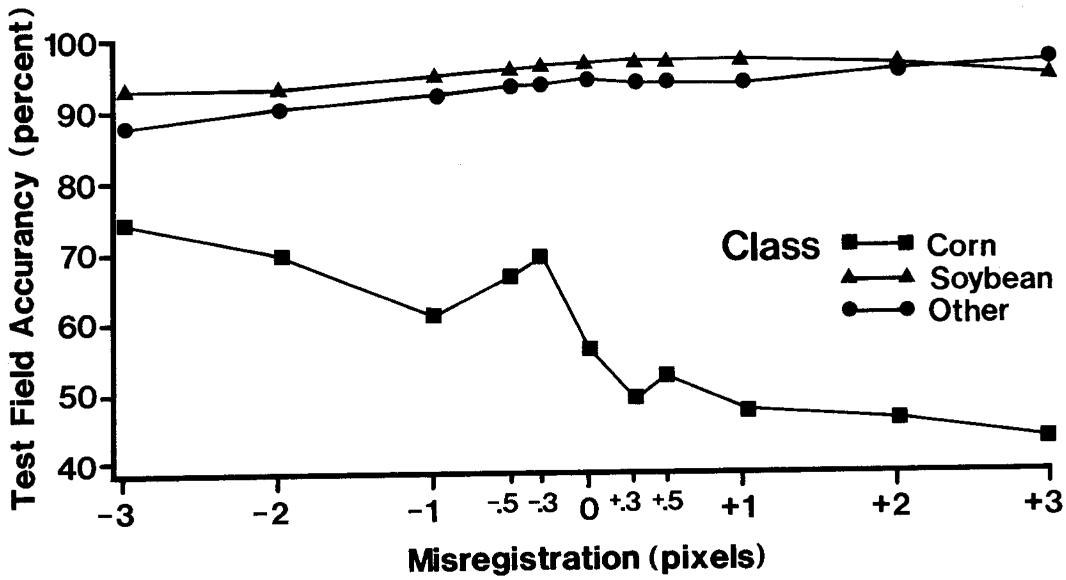
This last observation raised a question as to whether the 120m thermal band was more of a liability than an asset with respect to classification accuracy. To investigate this possibility, the baseline (zero misregistration) classifications of both test flightlines were rerun, deleting the thermal band. The results are summarized in Table II.7, which shows the test-field results for the 4-band classification using the 30m resolution thermal band, the 4 bands with 120m resolution thermal band, and 3 bands (no thermal band). Only the accuracy of the corn class was worse when the 120m thermal band was used than when no thermal band was used at all.

Table II.3. Test-Field Classification Accuracy, Flightline 208.

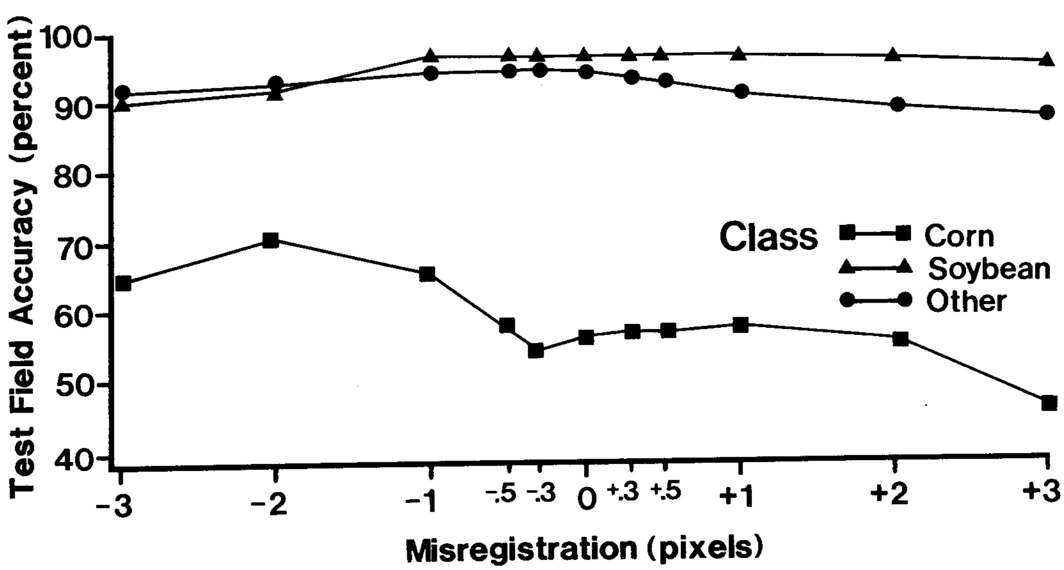
Misregistration Direction	Amount	Corn	Soybeans	Other	Overall
		Classification Accuracy (Percent)			
Along-Track	+3	42.9	94.6	95.8	64.5
	2	46.0	96.3	95.0	66.6
	1	47.5	96.9	93.4	67.3
	0.5	52.1	96.6	93.5	70.0
	0.3	49.0	96.7	93.5	68.2
	0	56.1	96.3	94.2	72.3
	-0.3	69.3	95.9	93.4	79.9
	-0.5	66.2	95.4	93.4	77.9
	-1	60.9	94.7	91.8	74.4
	-2	69.5	92.9	90.0	78.7
	-3	74.3	92.8	87.5	81.1
Across-Track	+3	45.3	95.1	87.6	64.6
	2	55.3	95.9	88.8	70.9
	1	57.4	96.5	90.7	72.6
	0.5	56.7	96.3	92.6	72.5
	0.3	56.8	96.4	93.3	72.6
	0	56.1	96.3	94.2	72.3
	-0.3	54.3	96.3	94.6	71.4
	-0.5	57.1	96.5	94.2	73.0
	-1	65.2	96.4	94.2	77.7
	-2	70.3	91.7	92.4	79.3
	-3	64.2	90.0	91.4	75.1
Number of Pixels		4355	1816	1251	7422

Table II.4. Test-Field Classification Accuracy, Flightline 230.

Misregistration Direction	Misregistration Amount	Classification Accuracy (Percent) Corn	Soybeans	Other	Overall
Along-Track	+3	78.0	77.3	86.5	83.5
	+2	80.4	77.8	90.9	87.0
	+1	81.2	79.1	91.4	87.7
	+0.5	85.5	82.1	90.1	88.1
	+0.3	90.4	82.6	92.0	90.6
	0	91.3	89.4	93.5	92.5
	-0.3	89.3	78.4	92.6	90.3
	-0.5	87.6	77.1	92.1	89.4
	-1	85.5	78.0	85.6	84.8
	-2	79.7	72.2	85.0	82.4
	-3	79.3	59.4	85.2	81.1
Across-Track	+3	85.7	79.8	81.5	82.4
	+2	90.9	80.0	78.6	81.7
	+1	92.4	81.4	85.1	86.5
	+0.5	92.0	86.5	89.5	89.8
	+0.3	92.2	88.5	91.0	91.1
	0	91.3	89.4	93.5	92.5
	-0.3	90.3	84.4	92.8	91.3
	-0.5	89.4	80.5	91.1	89.6
	-1	80.8	74.8	86.0	83.6
	-2	74.1	72.0	81.3	78.6
	-3	65.2	64.9	80.4	75.1
Number of Pixels		1038	436	2779	4253



(a) Along-track misregistration, flightline 208.



(b) Across-track misregistration, flightline 208.

Figure II.4. Test-field classification accuracy.

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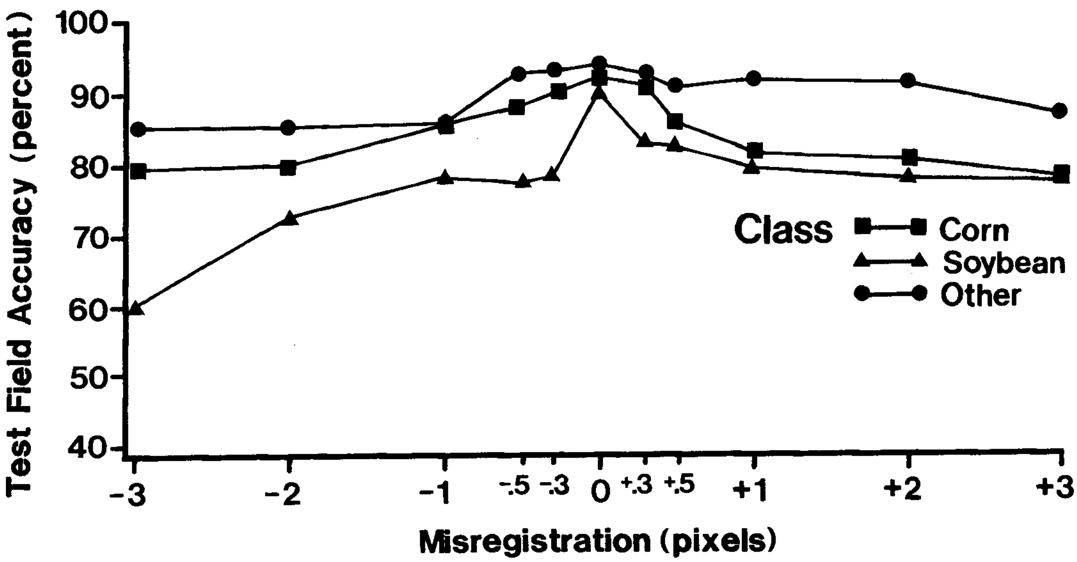
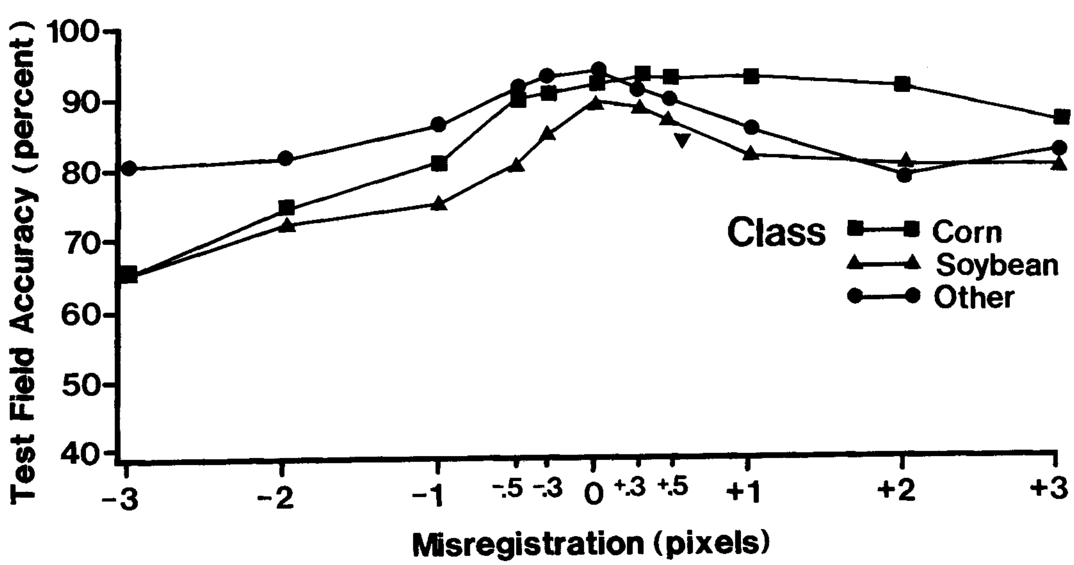


(c) Along-track misregistration, flightline 230.



(d) Across-track misregistration, flightline 230.

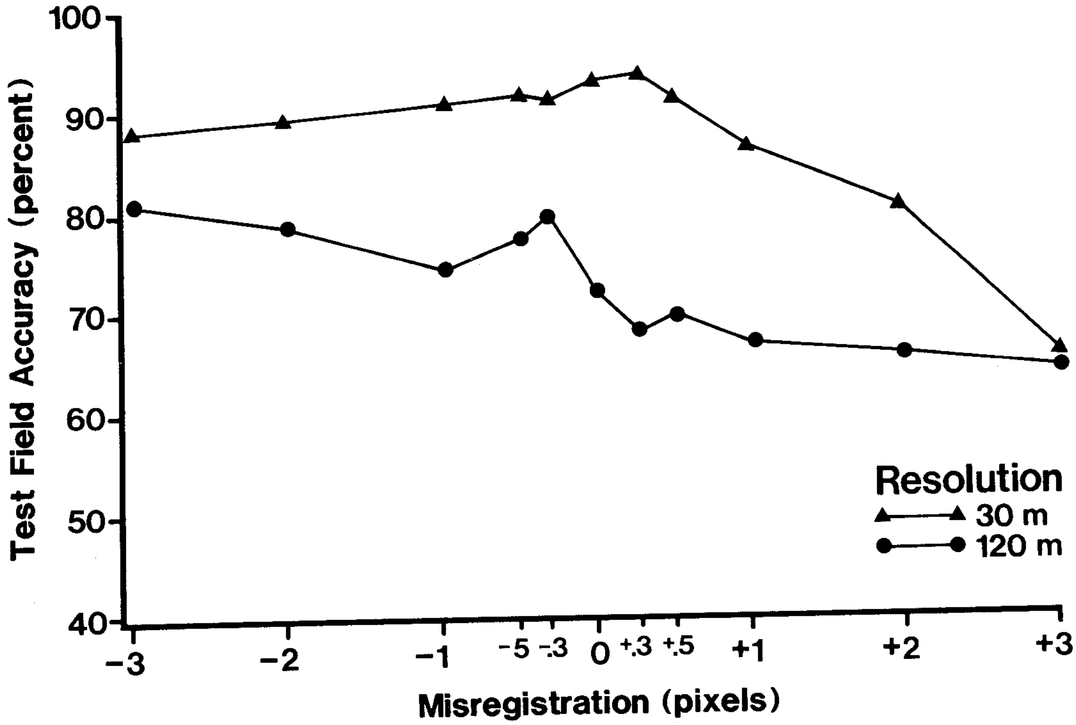
Figure II.4 (concluded). Test-field classification accuracy.

Table II.5. Classification Performance With 30m Resolution Thermal Band (Flightline 208).

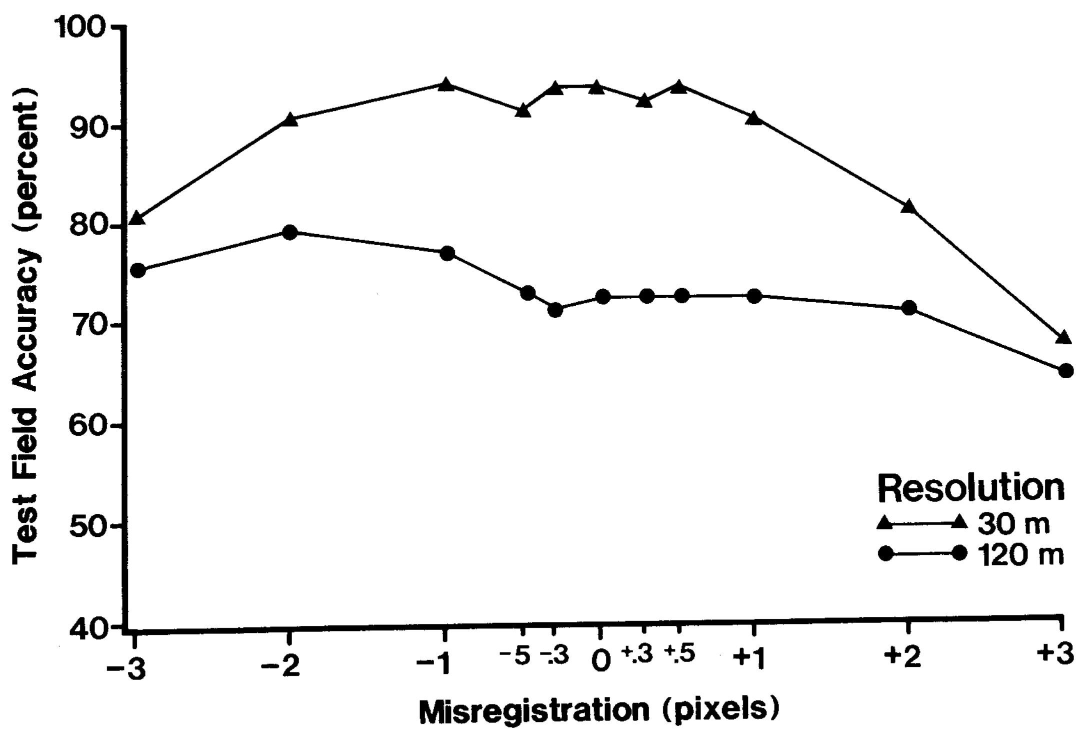
Misregistration Direction	Amount	Test-Field Accuracy (Percent) Corn	Soybeans	Other	Overall
Along-Track	3.0	46.2	95.3	92.6	66.0
	2.0	70.0	95.6	93.7	80.3
	1.0	81.4	96.9	89.9	86.7
	0.5	89.5	97.0	90.2	91.5
	+0.3	92.6	97.5	91.2	93.6
	0	91.9	97.6	92.4	93.4
	-0.3	88.3	97.2	92.6	91.2
	-0.5	89.7	96.8	92.4	91.9
	-1.0	88.8	96.6	89.8	90.9
	-2.0	87.6	94.6	88.2	89.4
	-3.0	86.2	95.2	84.9	88.2
Across-Track	3.0	51.2	95.4	87.1	68.0
	2.0	73.4	96.1	90.6	81.9
	1.0	87.7	96.9	92.5	90.7
	0.5	92.7	97.3	91.0	93.5
	0.3	91.0	97.7	91.4	92.7
	0	91.9	97.6	92.4	93.4
	-0.3	92.4	97.3	92.6	93.6
	-0.5	90.9	97.3	92.1	92.7
	-1.0	93.7	97.0	91.8	94.2
	-2.0	91.0	91.1	90.0	90.9
	-3.0	73.1	93.1	88.6	80.6
Number of Pixels		4355	1816	1251	7422

Table II.6. Classification Performance With 30m-Resolution Thermal Band (Flightline 230).

Misregistration Direction	Misregistration Amount	Test-Field Accuracy (Percent) Corn	Soybeans	Other	Overall
Along-Track	+3	79.6	76.8	82.7	81.3
	+2	84.8	77.3	84.8	84.0
	+1	90.4	76.4	85.9	86.0
	+0.5	96.2	92.9	88.3	90.7
	+0.3	96.5	91.5	89.3	91.3
	0	98.2	97.2	95.0	96.0
	-0.3	94.3	90.1	93.2	93.2
	-0.5	91.7	88.1	93.6	92.6
	-1	91.8	87.4	88.9	89.5
	-2	88.6	78.4	86.8	86.4
	-3	87.5	68.1	86.1	84.6
Across-Track	+3	86.2	78.0	81.9	82.6
	+2	93.2	81.9	80.7	83.9
	+1	94.8	87.6	90.2	91.0
	+0.5	96.5	93.3	92.0	93.3
	+0.3	97.0	95.9	93.1	94.4
	0	98.2	97.2	95.0	96.0
	-0.3	96.5	95.0	94.3	94.9
	-0.5	95.1	90.6	91.9	92.6
	-1	90.9	85.8	88.3	88.7
	-2	86.6	78.7	82.3	83.0
	-3	80.9	71.3	83.0	81.3
Number of Pixels		1038	436	2779	4253



(a) Along-track misregistration, flightline 208.



(b) Across-track misregistration, flightline 208.

Figure II.5. Comparison of overall test-field results for 30m and 120m resolution in the thermal band.

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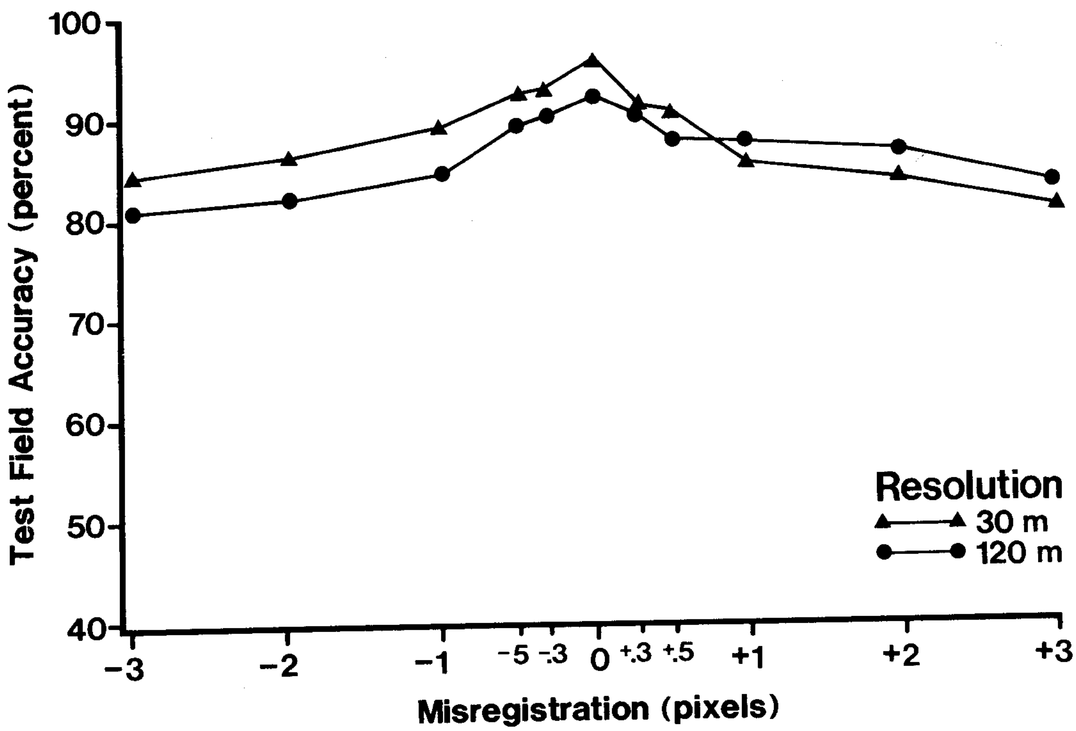
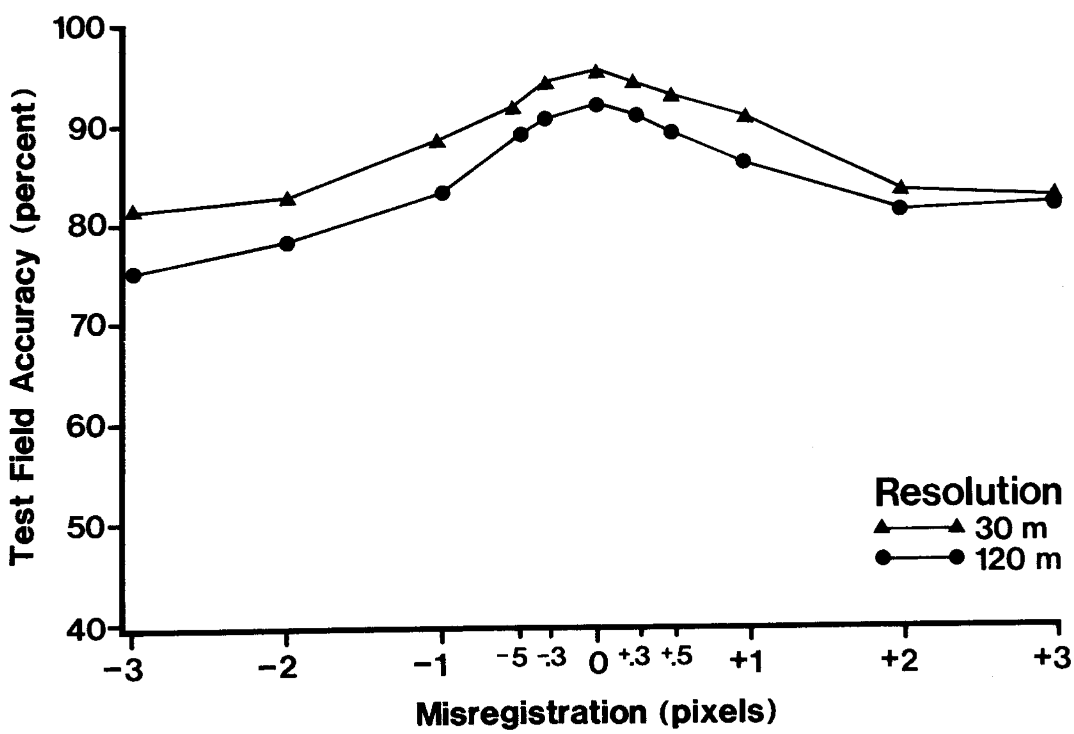


(c) Along-track misregistration, flightline 230.



(d) Across-track misregistration, flightline 230.

Figure II.5 (concluded). Comparison of overall test-field results for 30m and 120m resolution in the thermal band.

Table II.7. Comparison of Classifications With and Without the Thermal Band (No Misregistration).

(a) Flightline 208

Spectral Bands	Test-Field Accuracy (Percent) Corn	Soybeans	Other	Overall
4 bands, 30m thermal	91.9	97.6	92.4	93.4
4 bands, 120 thermal	56.1	96.3	94.2	72.3
3 bands (no thermal)	87.3	95.6	84.3	88.8
Number of Pixels	4355	1816	1251	7422

(b) Flightline 230

Spectral Bands	Test-Field Accuracy (Percent) Corn	Soybeans	Other	Overall
4 bands, 30m thermal	98.2	97.2	95.0	96.0
4 bands, 120m thermal	91.3	89.4	93.5	92.5
3 bands (no thermal)	95.3	85.6	89.5	90.5
Number of Pixels	1038	436	2779	4253

II.2.3 Discussion

The extent to which the overall classifications of the misregistered data differed from the baseline classifications (Table II.2 and Figures II.2, II.3) demonstrates that, for a sensor like Thematic Mapper, band-to-band misregistration as small as 0.3 pixel can have a substantial impact on classification accuracy. In fact, the greatest increase in the percentage of pixels affected by misregistration occurred at small misregistrations, as shown by the steep slope near zero misregistration in the curves of Figure II.2. These results are less optimistic than those obtained by the Hughes study[8] from which it was concluded that classification is not significantly affected by small amounts of misregistration. To understand how these differences could arise, it will be useful to consider the various ways in which band-to-band misregistration can impact classification accuracy.

Misregistration can adversely affect classification accuracy in at least three ways. The most obvious, of course, is the effect on boundaries and objects in the scene that are small relative to the size of the pixels (i.e., the ground resolution of the sensor). Another effect on classification which depends on the size of objects relative to the sensor resolution is the availability of training samples for characterizing the classes of interest. As misregistration increases, object boundaries become fuzzier and the number of "pure" pixels available for computing class statistics is decreased. Even in the U.S. Corn Belt, where agricultural fields are moderately large, training samples may be alarmingly scarce! As the number of training samples decreases and/or the analyst is forced to use pixels of marginal quality near field and object boundaries, the quality of estimation of the training statistics becomes poorer with consequent deleterious effects on classification accuracy.

The third effect of misregistration on classification accuracy is more subtle but may be quite important when the classes of interest are spectrally similar (e.g., classes of green vegetation). As shown in Table II.8, the band-to-band correlation in the data for each class falls off as misregistration increases, even though the in-band means and variances may not change. Figure II.6 illustrates how this can adversely affect class discriminability. The distributions of the classes in the spectral measurement space become more spherical as the bands become less correlated, resulting in increasing overlap of the classes and consequently higher probability of misclassification. Obviously the magnitude of this effect depends on the initial degree of correlation (with no misregistration) and the underlying spectral discriminability of the classes in question. For example, in Figure II.3 it may be seen that the spectrally distinctive forested area is much less affected by misregistration than are the centers of agricultural fields which are likely to contain crops difficult to discriminate among.

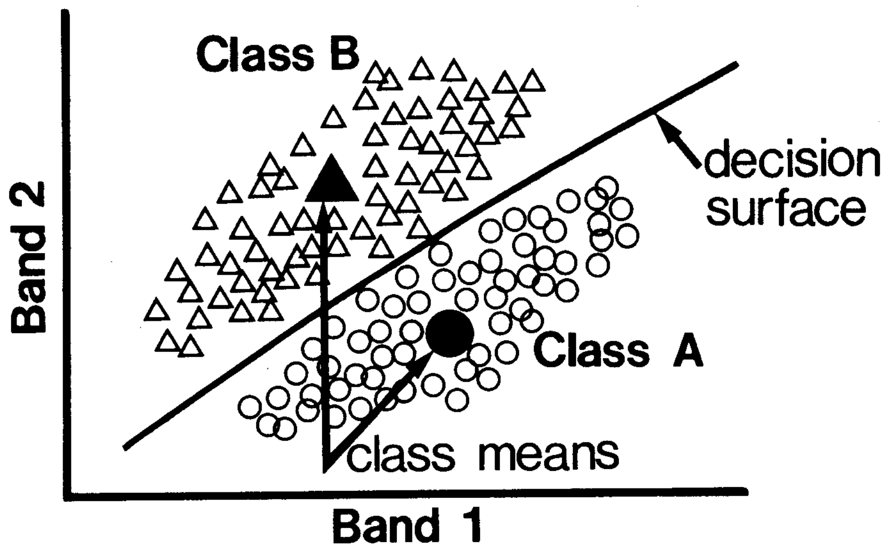
Although the analysis procedure used in the Hughes study is not described in detail in the final report[8], it is highly probable that the classifications performed for that study were based on the class statistics derived from the aircraft data. In this case, only the first of the three effects noted above is reflected in their results. The analysis procedure adopted for the present study, on the other hand, included recalculation

Table II.8. Correlation between spectral bands as a function of misregistration (flightline 230, hypothetical sensor).

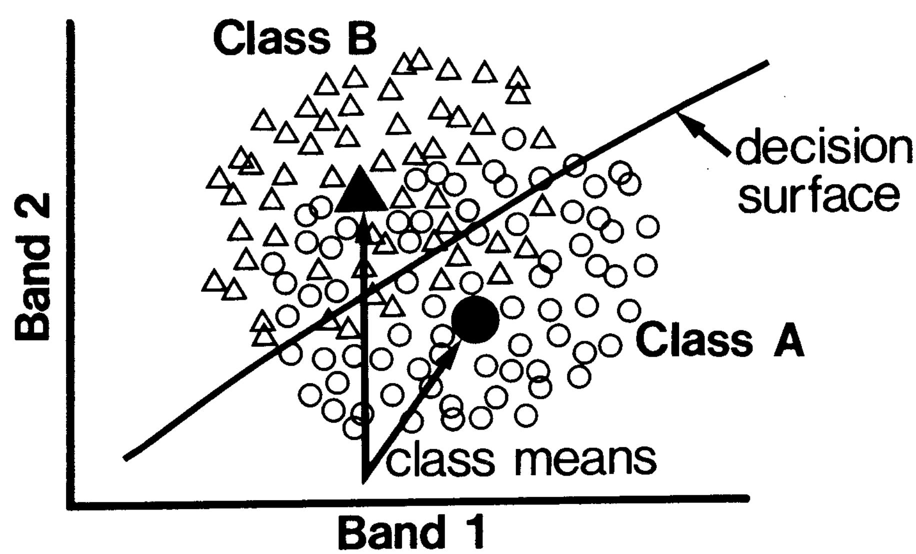
CLASS

Mis-reg.*	Corn (64 pixels) Spectral Bands 3-6	4-6	4-7	Idle (120 pixels) Spectral Bands 3-6	4-6	4-7	Soybeans (131 pixels) Spectral Bands 3-6	4-6	4-7	Trees (152 pixels) Spectral Bands 3-6	4-6	4-7
+3.0	.25	.25	-.27	.46	.48	0.23	.18	-.09	.09	-.10	-.07	-.17
+2.0	.39	.09	-.35	.66	.66	-.46	.27	-.13	-.03	.05	.14	-.09
+1.0	.61	-.13	-.30	.93	.91	-.69	.46	-.12	-.22	.37	.54	-.01
+0.5	.73	-.23	-.27	.96	.93	-.72	.57	-.13	-.28	.57	.73	.17
+0.3	.77	-.24	-.28	.96	.93	-.72	.59	-.12	-.31	.61	.76	.19
0	.79	-.24	-.30	.96	.93	-.72	.57	-.12	-.30	.63	.75	.18
-0.3	.79	-.22	-.31	.96	.93	-.72	.60	-.14	-.28	.59	.69	.13
-0.5	.80	-.21	-.27	.95	.93	-.72	.64	-.16	-.26	.54	.62	.06
-1.0	.76	-.18	-.27	.92	.90	-.69	.66	-.19	-.16	.29	.46	-.09
-2.0	.55	.03	-.14	.65	.77	-.64	.58	-.29	-.15	.06	.25	-.04
-3.0	.19	.29	-.02	.46	.60	-.59	.55	-.35	-.20	-.12	-.05	-.09

* Across-track



(a) Initial distributions.



(b) Decorrelated distributions

Figure II.6. Band-to-band decorrelation can reduce classification accuracy.

of the training statistics based on the actual simulated data; and furthermore, some of the classes used in this study were considerably less separable than those used in the Hughes study, which could result in higher sensitivity of the classification performance to band-to-band decorrelation. Consequently, it seems likely that the results reported here better represent the impact that misregistration will have on classification of Thematic Mapper data from areas typified by the Corn Blight Watch data.

The results of the second part of the analysis, involving test-field classification accuracy, support the observation that the classification accuracy of field-center pixels decreases gradually as misregistration increases. The decrease observed was not large in most cases and there was a slight increase in some cases. The one exception to the general trend was the corn class in flightline 208, for which the test-field classification accuracy decreased for positive misregistration and increased for negative misregistration. The asymmetric behavior of this corn class was anomalous and unexpected. Provided the corn training pixels truly represented the corn statistically and were field-center pixels, there was no apparent reason for the pronounced asymmetric trend in classification accuracy with misregistration direction. Further examination of the results revealed, however, that the corn training pixels did not adequately represent the statistical properties of the various subclasses of corn, for two reasons:

First, while the corn training pixels with a spatial resolution of 30m (all spectral bands except the thermal) were field-center pixels, the much larger pixels of the thermal band (with a spatial resolution of 120m) were actually mixed-class pixels. As a result, the corn training statistics did not adequately represent corn in the thermal channel but rather a mixture of corn and other classes. Consequently, in flightline 208 the classification accuracy of the corn test fields, even before misregistration, was lower than that of soybeans or "other."

Second, by coincidence, the corn training fields were bordered consistently by corn in one directon on the ground and by a non-corn class in the other direction. Eventually, with increasing band-to-band misregistration in one of the two directions, all of the corn training pixels in the misregistered bands were shifted beyond the boundary of corn training fields and therefore the corn class statistics no longer represented corn. Conversely, when bands were misregistered in the opposite direction -- toward the corn adjacent to the corn training pixels for zero misregistration -- then the pixels better represented the corn class as misregistration increased.

Results of the third part of the investigation, involving the comparison of the Thematic Mapper with a hypothetical sensor having a 30m resolution thermal band, show that Thematic Mapper data provide significantly lower classification accuracy than data from the hypothetical sensor. Results of this study support the conclusion by ERIM[10] that there are few field-center pixels of 120m resolution in the U.S. Corn Belt. As noted previously, this means that the ability to estimate statistics and train the classifier is impaired for data with a resolution of 120m. For every class, test-field accuracy was observed to be significantly better for 30m than 120m thermal-band resolution.

But the available results cannot be considered definitive with respect to the overall utility of the 120m resolution thermal band. Although the classification accuracy for corn was reduced when the 120m thermal band was used (compared to using a 30m thermal band or no thermal band at all), the results for the non-corn classes were significantly better than when no thermal band was used. No attempt has been made at this point to account for these differences.

The results point to a need to develop classification analysis procedures capable of fully exploiting the information content of the Thematic Mapper and handling the effects of the disparity in spatial resolution between the nonthermal and thermal bands. More fundamentally, the results provide a basis for directing research and development efforts towards improving the spatial resolution of the thermal imaging sensors when the data are to be used for classification purposes.

II.3 Effects of System Noise

Although the objectives of this project originally included assessment of the impact of system noise on the utility of the Thematic Mapper data, the registration study (given top priority by the technical monitor) consumed all of the available personnel and computational resources. The software required to add various types and levels of noise to the simulated Thematic Mapper data can be quickly obtained by relatively minor modification of the software developed for the registration study.

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