Reprinted from

Tenth International Symposium

Machine Processing of

Remotely Sensed Data

with special emphasis on

Thematic Mapper Data and

Geographic Information Systems

June 12 - 14, 1984

Proceedings

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

THEMATIC MAPPER GEOMETRIC CORRECTION PERFORMANCE EVALUATION

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ABSTRACT

The quality of Landsat Thematic Mapper (TM) data products is of vital importance to the user community. TM data products are generated by NASA's Thematic Mapper Image Processing System (TIPS) and are available to the user from the EROS Data Center.

General Electric is presently engaged in evaluating and enhancing the performance of TIPS and its products. Two methods were used to determine the geometric correction accuracy. One involved estimating errors from system reports and the other was direct measurement of errors in corrected imagery.

The NASA specification requires a 90% geodetic correction accuracy of 0.5 pixels both cross track and along track (each pixel is 30 meters x 30 meters). Similar requirements for temporal registration are 0.3 pixels. Results to date indicate that TIPS is meeting its requirements for temporal registration. The geodetic correction requirements are also met based on direct measurements, but the estimates occasionally show along track errors slightly larger than the specification. Performance improvements are expected as the system is calibrated during the 1984 Research and Development period.

I. INTRODUCTION

This paper presents a performance evaluation of geometric correction in the Thematic Mapper Image Processing System (TIPS). TIPS which is a part of NASA's Thematic Mapper (TM) data processing facility, located at the Goddard Spaceflight Center in Greenbelt, MD., was developed by the General Electric Company. The TM data products are shipped to the EROS Data Center, Sioux Falls, SD for distribution to the users.

The geometric accuracy of TIPS is currently being evaluated during a TM Research and Development period which continues through 1984. TIPS has the capability to perform geodetic correction using ground control points with the requirement that a geodetically corrected image (one corrected with ground truth control points) have a 90% accuracy of 0.5 pixels or less (a TM pixel is 30 meters x 30 meters). Furthermore, the specification for images which have been corrected with relative control points from a reference image, is that they temporally register to the reference image with a 90% accuracy of 0.3 pixels or less.

Two methods of evaluation and their results are presented here. The two methods are:

a) Error estimation
b) Direct measurements

In the first method geodetic errors are estimated in TIPS by a Kalman filter which operates on control point dislocations, i.e., the differences between the ground truth and image locations. These dislocations are determined from correlation of control point chips in TM imagery. The Kalman filter has a twelve variable model to estimate geodetic errors including roll, pitch, and yaw errors and along track, cross track and radial ephemeris errors. The estimated geodetic errors are used to update the systematic correction data (see Section IIA) which is then used to geodetically correct the imagery. The residual error between the measured and estimated control point dislocations is an output of the Kalman filter. The Kalman filter also computes a model bias from the covariance matrix of the model variables. Root sum squaring the mean residual error and the mean model bias and scaling to a 90% value yields an estimate of the geodetic correction accuracy.

Direct measurement can be done using either correlation or designation of control points. In the direct correlation measurement method control points are selected from one interval of imagery and correlated in a corrected companion interval. The 1σ correlation measurement error is estimated to be about 0.1 pixel. In direct designation geodetic control points are designated in corrected imagery (see Section IIA). The 1σ filtered designation error measurement is estimated to be about 0.5 pixels. The temporal registration accuracy was measured using direct correlation, while geodetic accuracy was measured using direct designations.

Error estimates for several intervals of TM imagery were evaluated. Also three pairs of scenes were evaluated with the direct correlation method and three corrected intervals were evaluated by designation of control points. The following sections describe the geometric correction system in TIPS, the methods of measuring the accuracy and the results.

II. DESCRIPTION OF TIPS GEOMETRIC CORRECTION SYSTEM

A. TIPS OVERVIEW

The TIPS comprises several major processes. To start with, the Payload Correction Subsystem (PCS) processes the telemetry data and computes systematic correction data. The Thematic Mapper Archive Generation (TAG) combines raw video and telemetry data to produce a high density archive tape of radiometrically corrected video data with geometric correction data appended. This is followed by Thematic Mapper Initial Product Generation (TIG) which produces a high density product tape with geometrically corrected video data. The final process in the production pipeline is Thematic Mapper Final Product Generation (TFG) which generates 241mm film products and computer compatible tapes (CCT's) for shipment to the EROS Data Center. Thematic Mapper Control Point Library Build (TCL) generates control point chips that are stored in a library for subsequent use in TAG.

The geometric correction data are generated in two steps. The first step utilizes models of the spacecraft, scanner, and spinning Earth (with smoothed ephemeris and attitude deviations as input) to deduce systematic correction data. The systematic correction data suffer from random spacecraft pointing errors, and spacecraft location errors. If control point data are available the second step is invoked. This involves correlation of control point chips to the imagery, filtering of the measured dislocations between the control point and the image, estimating the spacecraft ephemeris and attitude errors, and updating the systematic correction data to geodetic correction data. Either the systematic correction data or geodetic correction data (if control points are available) are used in the geometric correction of the product imagery.

The systematic correction data are generated during the telemetry processing in PCS. A look point calculation is used to relate an input pixel to a ground location. The information used in this look point calculation are the spacecraft position based on actual ephemeris and the look angle based on mirror profile and scan line corrector profile and measured spacecraft and instrument attitude.

If control points are available for an interval then the systematic correction data are updated in TAG. Each control point chip (32 pixels x 32 pixels) is correlated in a neighborhood (128 pixels x 256 pixels) centered on the computed location of the control point as determined from the systematic correction data. The correlation location is expected to differ from the computed location due to spacecraft ephemeris errors, attitude errors, and random pointing errors. The location differences or dislocations are filtered and smoothed using a Kalman filtering technique (Arnold, et. al., 1982, P.382). The output of the filter is a twelve dimensional state error vector, consisting of estimates for the ephemeris and attitude errors and the associated rate errors. The state error vector, in turn, is converted to a linear perturbation of the systematic correction data by means of the measurement matrix. This is the matrix of partial derivatives of the cross track and along track look points with respect to the state error vector variables.

The updated or geodetic correction data are applied in TIG where resampling and geometric correction of the radiometrically corrected data is performed. The final products are thus geodetically corrected.

B. CONTROL POINT LIBRARY BUILD

Control points are built into the system in two modes. When no ground truth (map) is available, control point chips are generated by designating a feature in the systematically corrected imagery and extracting a 32 x 32 pixel chip surrounding the designated point. The latitude and longitude of the feature are based on systematic correction data. These points are called Relative Control Points (RCPs).

When ground truth (from maps) is available, a latitude and longitude is obtained by digitizing a point on a map with a sonic digitizer. The systematically corrected imagery is then displayed and overlaid on the map by means of a Zoom Transfer Scope. After map and imagery have been aligned, the point is designated with a cursor and a 32 x 32 pixel control point chip is extracted. The chip dislocations are passed through the Kalman filter which estimates geodetic errors (state vector) at each control point. The residuals at the control points are used to adjust the feature location in each chip so that they lie on a fitted surface. These points are called Geodetic Control Points (GCPs).

Once the filter has been applied, Supplemental Control Points (SCPs) can be designated in the imagery and using the state error vector a geodetic latitude and longitude can be associated with them.

III. METHODS FOR MEASURING ACCURACY

This section describes the two methods used to evaluate the geometric correction performance.

A. ERROR ESTIMATION

Registration error, whether temporal or geodetic is composed of two different elements: a) Random errors and b) Model bias errors. The first represents a random mismatch between corresponding points of two images. It is due to such phenomena as resampling inaccuracies, correlation error, uncorrected high frequency attitude deviation (jitter), scan repeatability errors, and other high frequency disturbances that cannot be completely removed. These errors are inherent in the spacecraft, sensor, and processing system. Although optimizing the control point density and distribution does not reduce these errors, it does improve our knowledge of their magnitude.

The second component of the registration error is related to the bias induced in the Kalman filter model surface due to establishing the model parameters from noisy data. These errors can be reduced by optimizing the control point density and distribution.

The random registration error can be estimated from the residual errors at the control points. After the Kalman filter has been applied the differences between the computed dislocation based on the estimated geodetic errors and the measured dislocation from correlation processing are collected at each control point for both cross and along track directions. The 1σ random registration error for an interval (N control points) is given by the root mean square of the control point residuals·

$$E_R = \text{Random Error} = \sqrt{\frac{\sum_{i=1}^{N} (\text{residual})_i^2}{N}}$$

The model bias at any control point can be estimated from the matrix product of the smoothed Kalman filter covariance matrix (P) and the measurement matrix (H). The covariance matrix gives an estimate of the variance of the model error at each filtered point, while the measurement matrix converts these errors to cross and along track variances on the ground. The 1σ modeling bias error for an interval (N control points) is given by

$$E_B = \text{Modeling Bias Error} = \sqrt{\frac{\sum_{i=1}^{N} (HPH^T)_i}{N}}$$

These estimated errors are adjusted for the correlation accuracy (E_C) which is estimated to be 0.1 pixel (1σ) (Gambhir and Su, 1983). The total adjusted 90% registration error (E_T) is given by

$$E_T = 1.645 \cdot \sqrt{E_R^2 + E_B^2 - E_C^2}$$

B. DIRECT MEASUREMENT

A direct correlation measurement method was developed to evaluate temporal registration. The procedure starts with the selection of a control point chip from a reference interval. The chip is then correlated in a companion interval that has been corrected with either relative or geodetic control point data from the reference interval. To do this a neighborhood of imagery, whose center is based on the control point chip location in the reference imagery, is extracted from the companion interval. The control point chip is correlated in the neighborhood. The correlation peak dislocation from the neighborhood center represents the registration error for that point, to within the correlation error. Registration data was collected for a sufficient number of control points to give a reliable measure of the 1σ registration error (E_M). These measured errors were adjusted for correlation accuracy (E_C) of 0.1 pixels (1σ). The total adjusted 90% registration error (E_T) is given by

$$E_T = 1.645 \cdot \sqrt{E_M^2 - E_C^2}$$

A direct designation method was used to measure geodetic accuracy. The procedure is the same as that used for generating GCP's in library build. The library control points including those used to geodetically correct the imagery are redesignated in the corrected imagery. This time the dislocations are the registration errors to within the designation error. After a sufficient number of control points were designated a 1σ registration error (E_M) was determined and adjusted for designation errors (E_D). The 1σ filtered designation error was found to be about 0.5 pixels. The total adjusted 90% registration error (E_T) is given by

$$E_T = 1.645 \cdot \sqrt{E_M^2 - E_D^2}$$

IV. PERFORMANCE EVALUATION

In this section we discuss the performance evaluation of temporal and geodetic registration using the methods described in section III. Note that all scenes in this section are identified by WRS path and row numbers and number of days since launch. Landsat-4 was launched on July 16, 1982 and Landsat-5 was launched on March 1, 1984.

A. TEMPORAL REGISTRATION EVALUATION FROM ERROR ESTIMATION

Three cross-correlation runs were made where the intervals were corrected with RCP's from a reference interval. Random errors, modeling errors and the resulting ninety percent error estimates are shown in Tables 1, 2 and 3. In these tables, the RMS residual error (an estimate of random error) and the RMS modeling error (an estimate of bias error) as reported by TAG are scaled to ninety percent values and given in pixels for cross track and along track directions in each scene of the three scene intervals. The estimate of the total error is the RSS of the random and modeling errors less an estimated correlation error. The final row of each table displays the component and total error for the interval. The number of successful correlations is indicated in the notes for each table.

It will be observed that the first two tables (days 123 and 187 vs. day 155 RCPs) are of similar quality, with average ninety percent errors of about 0.31 pixel cross track and 0.38 pixel along track. These numbers compare well with the 0.37 pixel cross track and 0.35 pixel along track errors projected by GE at a design review of October 1981. There were 28 successful control points in the first run and 29 in the second, with reasonable spatial distributions in both cases. However, the estimate of the random error is subject (for about 30 control points) to a relative error of about 20 percent for the interval and about 30 percent for each scene; hence the wide variation from scene to scene. Another point to be made about these two runs is that companion intervals were separated by only one month in time and were therefore not subject to seasonal variations in content.

Table 3 for day 181 vs. day 101, shows excellent scores in the cross track direction but decided degradation in the along track direction. There are several possible reasons for the degradation:

1) Day 101 is a fall day (October) while day 181 is a winter day (January). There was, in fact, visual evidence that features of the winter interval neighborhoods were different from those of the fall interval chips.
2) Only 22 of 32 control points were successful. Nine failed to correlate and one patently false correlation was rejected by the filter. This is further evidence of the seasonal effects stated above.
3) Of the 22 successful control points, six were from bands 2 and 5. In these bands there are bad detectors which result in repeated lines. It is speculated that the repeated lines soften the cross-correlation peak in the along track direction.

Only the last of these three problems is specific to the along track direction, rather than to this interval. Indeed, there is a trend toward larger along track random error in most of our experiments, and the bad detector problem is still being investigated as the source of the excess error.

Thus seasonal effects causing poor correlations, coupled with a high percentage of band 2 and band 5 chips, are the suspected causes of the poor showing of day 181 vs. day 101.

Table 1. Temporal Registration Performance (Error Estimates). Day 123 corrected with day 155 RCP's (Path 17). Total of 28 control points were used. Random errors have been reduced by a nominal correlation error of 0.16 pixel (90%).

	Cross Track (Pixels, 90%)			Along Track (Pixels, 90%)		
Row	Random Error	Modeling Error	Total Error	Random Error	Modeling Error	Total Error
35	0.325	0.142	0.35	0.331	0.145	0.36
36	0.071	0.125	0.14	0.420	0.125	0.44
37	0.195	0.183	0.27	0.361	0.179	0.40
Interval	0.236	0.147	0.28	0.379	0.147	0.41

Table 2. Temporal Registration Performance (Error Estimates). Day 187 corrected with day 155 RCP's (Path 17). Total of 29 control points were used. Random errors have been reduced by a nominal correlation error of 0.16 pixel (90%).

	Cross Track (Pixels, 90%)			Along Track (Pixels, 90%)		
Row	Random Error	Modeling Error	Total Error	Random Error	Modeling Error	Total Error
35	0.414	0.138	0.44	0.293	0.141	0.33
36	0.222	0.131	0.26	0.249	0.132	0.28
37	0.158	0.172	0.23	0.367	0.170	0.40
Interval	0.312	0.146	0.34	0.312	0.147	0.34

Table 3. Temporal Registration Performance (Error Estimates) Day 181 corrected with day 101 RCP's (Path 23). Total of 22 control points were used. Random errors have been reduced by a nominal correlation error of 0.16 pixel (90%).

	Cross Track (Pixels, 90%)			Along Track (Pixels, 90%)		
Row	Random Error	Modeling Error	Total Error	Random Error	Modeling Error	Total Error
35	0.180	0.178	0.25	0.592	0.186	0.62
36	0.190	0.135	0.23	0.655	0.140	0.67
37	0.239	0.168	0.29	0.813	0.165	0.83
Interval	0.216	0.165	0.27	0.733	0.167	0.75

B. TEMPORAL REGISTRATION EVALUATION FROM DIRECT MEASUREMENT

The basic tool for direct measurement of temporal registration performance is a software module which correlates chips extracted from one corrected scene with neighborhoods extracted from a companion corrected scene (see Section IIIB). The differences between the locations of the chips in the reference and the companion scene are reported for all such evaluation points. The RMS location difference was calculated, scaled to a ninety percent error, and reduced by a nominal 0.16 pixel (90%) correlation error.

The selection of evaluation points is a very time consuming process, hence few such registrations have been evaluated to date. Two instances, path 17 row 35 and 36 of days 123 (RCP corrected) and 155 (reference interval), are shown in Table 4. The scores based on 44 evaluation points are 0.32 pixels for both directions, in agreement with the error estimates. These numbers have a reliability of ±15 percent.

In Section IV D, we will show a direct measurement of temporal registration of two scenes geodetically corrected to the same parent scene. These numbers (see Table 10) are even more impressive, at 0.16 pixel cross track and 0.25 pixel along track.

TABLE 4. TEMPORAL REGISTRATION PERFORMANCE (DIRECT MEASUREMENT)

DAY 123 CORRECTED WITH DAY 155 RCP's (PATH 17). DIRECT MEASUREMENTS HAVE BEEN REDUCED BY A NOMINAL CORRELATION ERROR (0.16 PIXEL, 90%).

ROW	NUMBER OF POINTS	CROSS TRACK ERRORS (PIXELS, 90%)	ALONG TRACK ERRORS (PIXELS, 90%)
35	24	0.30	0.32
36	20	0.35	0.31
INTERVAL (2 SCENES)	44	0.32	0.32

C. GEODETIC CORRECTION EVALUATION FROM ERROR ESTIMATION

Geodetic correction performance and measurement involve some parameters and operational procedures that are not encountered in temporal registration. In this section we will discuss these special attributes of geodetic correction and then present some performance evaluation based on error estimates.

Geodetic correction differs from temporal registration only in the method of constructing control point chips. RCPs lie on a "Systematic Correction Surface" (SCS), based entirely on models. GCPs (or SCPs) lie on a "Geodetic Correction Surface" (GCS), based on a weighted combination of models and noisy measurements. The measurement noise that enters into the construction of the GCS in TCL has contributions from map error, digitization, designation and operator performance. The noise can be minimized by good procedures and by appropriate blunder processing. The noise and the resulting modeling error are estimated and reported by the filter/smoother. Results for intervals which have been processed through TCL are presented in Table 5. The first entry for Day 155 was processed early in the evaluation period and GCPs were drawn from all bands.

The blunder criterion was such as to eliminate GCPs with residuals greater than about 4σ. The GCPs for the intervals for days 101, 49 and 122 were limited to bands other than 2 and 5 and were eliminated if residuals were greater than 3σ.

Another source of noise in geodetic correction is an inaccurate modeling of the mirror profile. We have been monitoring the behavior of GCP residuals with respect to cross track location and have seen some slight evidence of a profile defect. However, much more data must be accumulated before a definitive calibration can be attempted.

Table 6 shows the system-based ninety percent error estimates for cross-correlation runs to date including one Landsat 5 run. The results range from .34 to .65 pixels cross track and .29 to 1.03 pixels along track. The model error is the RSS of the TAG and TCL estimates and the random error is that of TAG.

TABLE 5. ESTIMATES OF MEASUREMENT NOISE AND MODELING ERROR IN TCL.

	CROSS TRACK ERRORS (PIXELS, 90%)		ALONG TRACK ERRORS (PIXELS, 90%)	
	NOISE	MODELING ERROR	NOISE	MODELING ERROR
DAY 155 (PATH 17) (ALL BANDS, OUTLIERS >4σ)	1.03	0.23	1.34	0.27
DAY 101 (PATH 23) (NO BAND 2,5, OUTLIERS >3σ)	0.93	0.17	0.88	0.17
DAY 49 (PATH 27) (NO BAND 2,5, OUTLIERS >3σ)	0.92	0.24	1.09	0.25
DAY 122 (PATH 26) (NO BAND 2,5 OUTLIERS >3σ)	1.20	0.24	0.89	0.26

TABLE 6. GEODETIC CORRECTION PERFORMANCE (ERROR ESTIMATES).

A NOMINAL .16 PIXEL (90%) CORRELATION ERROR WAS REMOVED FROM THE RANDOM ERRORS. MODELING ERRORS COMBINE TAG AND TCL ERRORS. INTERVAL ID IS IN THE FORM OF MSPPPFFFLLLDDD (M = MISSION NUMBER, S = SENSOR, PPP = PATH NO., FFF = FIRST ROW NO., LLL = LAST ROW NO., DDD = DAYS SINCE LAUNCH).

		90% CROSS TRACK (PIXELS)			90% ALONG TRACK (PIXELS)		
INTERVAL ID	NO. OF CP'S	RANDOM	MODEL	TOTAL	RANDOM	MODEL	TOTAL
4T0170350390123	55	.29	.30	.42	.82	.31	.88
4T0170350390187	62	.27	.30	.40	.78	.30	.84
4T0230350390181	59	.58	.30	.65	.62	.30	.69
4T0230350360037	27	.30	.23	.38	.46	.24	.52
4T0230370380117	38	.34	.22	.40	.18	.23	.29
4T0260330390186	53	.22	.26	.34	.45	.26	.52
5T0260330390005	47	.47	.27	.54	.53	.28	.60
4T0270290330097	57	.38	.33	.50	.97	.35	1.03

D. GEODETIC CORRECTION EVALUATION FROM DIRECT MEASUREMENT

Direct measurement of geodetic correction accuracy using the equipment of TCL is, of course, limited by the same noise of measurement that is experienced in constructina GCPs. Since that noise is greater (See Table 5) than the specified accuracy of 0.5 pixel, the best one can hope to do with a limited number of measurements is to show that the ninety percent geodetic correction error is of the same order of magnitude as the ninety percent measurement noise. That this is indeed the case can be seen in Table 7, 8 and 9 where the data for days 155, 101 and 97 are shown. The measured ninety percent deviations from the map range from .67 to .87 pixel cross track and .48 to .93 pixel along track. We have reduced these numbers by an estimated designation error resulting in registration errors that are within specification.

A perhaps more important measurement is of the temporal registration success of two images that have been corrected to the same GCPs. A direct measurement of the temporal registration of path 17, row 36, days 123 and 187, both corrected with GCPs of day 155, was made using the tool described in Section III B.

The results, for 34 evaluation points, presented in Table 10, show that the system can meet temporal registration specifications even with the use of GCPs rather than RCPs.

TABLE 7. GEODETIC REGISTRATION PERFORMANCE (DIRECT MEASUREMENT) DESIGNATION FOR DAY 155 (PATH 17) CORRECTED WITH ITS OWN CONTROL POINTS.

PATH	ROW	CP'S DESIGNATED	90% CROSS TRACK ERRORS (PIXELS)	90% ALONG TRACK ERRORS (PIXELS)
17	35	23	.95	1.00
	36	23	.86	.77
	37	19	.94	1.00
	38	23	.76	.79
	39	21	.83	1.10
TOTAL FOR INTERVAL(108 CP's)			.87	.93
ESTIMATED DESIGNATION ERROR			.70	.74
REGISTRATION ERROR			.52	.56

TABLE 8. GEODETIC REGISTRATION PERFORMANCE (DIRECT MEASUREMENT). DESIGNATION FOR DAY 101 (PATH 23) CORRECTED WITH ITS OWN CONTROL POINTS.

PATH	ROW	CP'S DESIGNATED	90% CROSS TRACK ERRORS (PIXELS)	90% ALONG TRACK ERRORS (PIXELS)
23	36	17	.55	.50
	37	8	.86	.44
TOTAL FOR INTERVAL (25 CP's)			.67	.48
ESTIMATED DESIGNATION ERROR			.48	.35
REGISTRATION ERROR			.46	.32

TABLE 9. GEODETIC REGISTRATION PERFORMANCE (DIRECT MEASUREMENT) DESIGNATION FOR DAY 97 (PATH 27) CORRECTED WITH DAY 49 CONTROL POINTS.

PATH	ROW	CP'S DESIGNATED	90% CROSS TRACK ERRORS (PIXELS)	90% ALONG TRACK ERRORS (PIXELS)
27	32	13	0.78	1.00
	33	24	0.57	0.56
TOTAL FOR INTERVAL (37 CP's)			0.68	0.78
ESTIMATED DESIGNATION NOISE			0.50	0.55
REGISTRATION ERROR			0.47	0.55

TABLE 10. TEMPORAL REGISTRATION PERFORMANCE FOR TWO GEODETICALLY CORRECTED SCENES. DAY 123 VS. DAY 187 (PATH 17, ROW 36). BOTH SCENES CORRECTED WITH GCP'S FROM DAY 155.

	CROSS TRACK (PIXELS)	ALONG TRACK (PIXELS)
MEAN	0.004	0.111
RMS DEVIATION	0.138	0.183
90 PER CENT DEVIATION	0.227	0.302
CORRECTED FOR 90% CORRELATION ERROR (.16PIXEL)	0.16	0.25

V. SUMMARY OF RESULTS

The geometric correction performance of the Thematic Mapper Image Processing System (TIPS) which generates TM data products for Landsat users was evaluated using error estimation and direct measurement methods.

The results of the evaluations are summarized in Table 11. The range of 90% geodetic accuracy and temporal registration errors in cross track and along track directions are shown.

The results indicate that the TM data can meet the temporal registration specification. This is the case whether correction is with relative or geodetic control points. Furthermore, based on direct measurement results, the geodetic co··ection specification is also met. The along track error estimates are slightly large in some cases, and the reasons for this are presently under investigation. During the Research and Development phase the geometric correction system will be further calibrated and performance improvements are expected.

TABLE 11. SUMMARY OF 90% ERRORS (PIXELS)

CASE	CROSS TRACK RANGE	ALONG TRACK RANGE
TEMPORAL REGISTRATION:		
A. ERROR ESTIMATION	.27 - .34	.34 - .75
B. DIRECT MEASUREMENT	.16 - .32	.25 - .32
GEODETIC REGISTRATION:		
A. ERROR ESTIMATION	.34 - .65	.29 - 1.03
B. DIRECT MEASUREMENT	.46 - .52	.32 - .56

ACKNOWLEDGEMENTS

This work was supported by NASA under con-track number NAS5-25300. We acknowledge the efforts of systems engineering, software and operations groups, General Electric Space Systems Division, Lanham, MD for their assistance in this performance evaluation.

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Joan Brooks completed her B.A. and Ph.D. degrees in Physics at New York University and has divided her professional life between university and industry. Her fields of specialization are physical optics, particle transport theory and, more recently, satellite image processing techniques. She is currently manager of Ground Systems Engineering at General Electric's Lanham Center Operation.

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