GEOPOSITIONAL ACCURACY ASSESSMENT OF EARTHSAT GEOCOVER LANDSAT ORTHORECTIFIED IMAGERY

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ABSTRACT

NASA purchased EarthSat GeoCover orthorectified Landsat imagery of global land areas covering three historical time frames: (1) mid-1970s imagery from the Landsat Multispectral Scanner (MSS); (2) late 1980s – early 1990s imagery from the Landsat Thematic Mapper (TM); and (3) year 2000 imagery from the Landsat Enhanced Thematic Mapper Plus (ETM+). Because of the distinct time frames covered by these datasets, this imagery is valuable to land cover change research. Because geopositional accuracy plays a critical role in this area of scientific research, NASA performed an independent assessment of the geopositional accuracy of each EarthSat dataset using an independent set of government-provided ground control points (GCPs). These points were instrumental in the geopositional accuracy assessment of the TM imagery. Because of the orthorectification processes of the MSS imagery and the MSS pixel size, the aforementioned GCPs could not be used, and an alternate relative assessment procedure using the previously validated TM imagery as a "truth" dataset was used for the MSS data. Finally, the ETM+ data specification was defined in both an absolute sense with respect to ground coordinates and relative to the previously validated TM dataset. Therefore, two separate methods were used in validating the ETM+ data. Results of the NASA independent assessments showed that the accuracies of the EarthSat GeoCover datasets met the defined specifications or were within the errors and limitations of the verification methods employed.

INTRODUCTION

The National Aeronautics and Space Administration (NASA) purchased Earth Satellite Corporation (EarthSat) GeoCover™ orthorectified Landsat imagery of global land areas through the Scientific Data Purchase program. The Landsat imagery covers three historical time frames: (1) mid-1970s imagery from the Landsat Multispectral Scanner (MSS); (2) late 1980s – early 1990s imagery from the Landsat Thematic Mapper (TM); and (3) year 2000 imagery from the Landsat Enhanced Thematic Mapper Plus (ETM+). Because of the distinct time frames covered by these datasets, this imagery is valuable to land cover change research. The nature of this type of research hinges on confidence in the geometric accuracy to ground coordinates of the imagery as well as the cross-data co-registration of the different imagery time periods. NASA performed an independent assessment of the geopositional accuracy of orthorectified imagery from each sensor. A brief description of the sensors and imagery orthorectification methods are presented followed by a discussion of the details of the validation procedures, its limitations, and results.

LANDSAT REMOTE SENSING SYSTEMS

Multispectral Scanner System

Launched in July 1972, the Earth Resources Technology Satellite-1 (ERTS-1), later renamed Landsat 1, had as a part of its sensor suite the first Multispectral Scanner. The MSS remote sensing system is a 4-band visible and near infrared (NIR) cross-track line scanning device. The primary mission of the MSS system is to provide repetitive, synoptic, global coverage of high-resolution (80-meter ground sample distance (GSD)) multispectral imagery for detecting and monitoring different types of Earth resources, land cover and land use change, and vegetation dynamics (EROS Data Center, 2003a; Kramer, 2002). Note: the MSS imagery utilized in this assessment was resampled to 57-meter GSD (Earth Science Applications Directorate, 2004).

Thematic Mapper System

Launched on Landsat 4 in 1982, the Thematic Mapper remote sensing system is a 7-band whisk-broom scanner designed for the monitoring and repetitive imagery acquisition of Earth's land mass, coastal boundaries, and coral reefs for research in land cover, resource use, and vegetation dynamics. The TM system is capable of detecting energy in the visible, NIR, short-wavelength infrared (SWIR), and thermal infrared (TIR) regions of the electromagnetic spectrum. The TM system has a 30-meter GSD in all of its bands except the TIR, which has a GSD of 120 meters (EROS Data Center, 2003b; Kramer, 2002).

Enhanced Thematic Mapper Plus System

Launched in April 1999, the Landsat 7 satellite included the Enhanced Thematic Mapper Plus sensor as its remote sensing instrument. The ETM+ sensor is also a high-spatial-resolution (30-meter GSD) passive remote sensing system with 7 multispectral bands spanning the visible through IR spectral regions and an additional panchromatic band for a total of 8 bands. In addition to the advancements in radiometric stability inherent to the ETM+ sensor system, the Landsat 7 vehicle records its position and velocity at the time of imagery acquisition, yielding a very accurate model of the vehicle ephemeris. This highly accurate ephemeris data has been referred to as the Landsat 7 "definitive ephemeris" model. Although not used in this assessment, the definitive ephemeris data can be used as a cross check of the validity of the orthorectification of the ETM+ orthorectified imagery (EROS Data Center, 2004; Kramer, 2002).

ORTHORECTIFICATION METHODS

The methods utilized for orthorectification of the different sets of imagery mandate that the discussion depart from the chronological timeline of each of these sensors. Therefore for the rest of this paper TM imagery will be discussed first, followed by MSS, and concluding with ETM+.

TM Orthorectification

The method employed for TM imagery orthorectification by EarthSat involved a two-step process. The first step orthorectified TM scenes that had available government-provided ground control points (GCPs). The second step used the initially orthorectified scenes as control to tie the remaining raw imagery together using a single block adjustment. These orthorectified blocks correspond to general land areas, or blocks, throughout the world (Dykstra et al., 2000).

MSS Orthorectification

MSS imagery used in this assessment was orthorectified by EarthSat using an "image mapping" method. This method orthorectified the individual MSS scenes to their corresponding orthorectified TM scenes. Unlike the TM orthorectification process, which yielded a block-orthorectified dataset, the result of the image mapping process was a set of MSS imagery where each scene was orthorectified individually (Dykstra, 2002).

ETM+ Orthorectification

The method employed for ETM+ imagery orthorectification by EarthSat utilized a two-step process that was very similar to the TM orthorectification process. The first step used the TM scenes that had previously been orthorectified using government-provided GCPs as ground control for a relative (thin-plate spline) orthorectification of the corresponding ETM+ image. The second step in the ETM+ orthorectification was identical to the second step in the TM validation process where the remaining raw ETM+ imagery was then tied together using a block adjustment, yielding a near-world coverage of orthorectified ETM+ imagery. Exceptions to this orthorectification process were ETM+ geographic blocks identified as "Greenland," "Indonesia," "Islands," "Upper South America," and "Siberia." In these cases, the horizontal control was provided for these regions through the ETM+ definitive ephemeris (Dykstra, 2002).

VALIDATION METHODS

During the planning phase of this undertaking, it was decided that 3-band color images would be used instead of individual single-band images during this independent assessment. The choice of bands was left to the evaluator's discretion. The desire was to find the 3-band combination that enhanced points of note in the imagery. In general a green, red, NIR combination was used; however, some images were better viewed by using other 3-band combinations.

TM Absolute Block Validation

Because of the methods employed by EarthSat to orthorectify the TM data, and because the geolocational specification was relative to ground coordinates, it was decided that the correct method for validating the geolocational accuracy of the TM data was to acquire reference GCPs from around the world. The United States government provided an independent set of GCP data packets that were used in this assessment. These data packets included electronic sets of GCPs as well as hard copies of the GCPs and simple pencil drawings corresponding to the geographical landmarks surrounding the actual locations of the GCPs. The location of these points dictated which scenes were used in the TM geolocational assessment.

The actual process of assessing the geolocational accuracy of the TM imagery involved using ERDAS IMAGINE software to compare the location of the government-provided GCPs to the locations in the imagery that corresponded to the geographic landmarks specified in the GCP data packet pencil drawings. After examining the scene and selecting the usable control points, the analyst exported the pertinent data (ERDAS®, LLC, 2002).

The Federal Geographic Data Committee (FGDC) specifies that a minimum of 20 GCPs be used to assess the geolocational accuracy of remotely sensed imagery. Because most of the exported files contained fewer test points than the FGDC recommends, and because the TM orthorectification process corrected individual scenes based on their geographic block, the exported files for each individual scene were combined into larger files based on orthorectification block. These files provided the input required to execute a Stennis Space Center (SSC) remote sensing Visual Basic program that computed the x-differences and y-differences and the squares of the x-differences and y-differences of each validation point. Additionally, the program computed the root mean square error in the x direction ($RMSE_x$), the root mean square error in the y direction ($RMSE_y$), and the net root mean square error ($RMSE_{net}$) for the entire geographic block. Because the root mean square error (RMSE) is defined as a statistical measure of the magnitude of a varying quantity, it was chosen as the measure for these assessments. The mathematical definition of RMSE (Wikipedia, 2004) is

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\Delta X_i^2\right)}$$

Using this definition, RMSE can be calculated in the x and y directions. From the $RMSE_x$ and $RMSE_y$, the net root mean square error can be calculated:

$$RMSE_{net} = \sqrt{RMSE_x^2 + RMSE_y^2}$$

MSS Relative Scene-By-Scene Validation

Because of the methods employed to orthorectify the MSS data, a scene-by-scene relative assessment was performed to validate the imagery geolocational specifications. This assessment was accomplished by using the previously validated TM imagery as a "truth" dataset and comparing the coordinates of coincident geographic landmarks in the MSS imagery. When specific landmarks, such as rock formations, roads, and waterways were identifiable in both scenes, these landmarks were selected and geographically located. The Universal Transverse Mercator (UTM) coordinates associated with each landmark in the MSS scene were compared to the UTM coordinates associated with each corresponding landmark in the TM scene.

After locating a minimum of 20 usable points within each MSS-TM scene pair, the analyst exported the pertinent data for each examined scene. These individual files provided the required input into the aforementioned SSC remote sensing Visual Basic program written to compute relative geopositional accuracy. As before, the Visual Basic program computed the x-differences and y-differences and the squares of the x-differences and y-differences for each point, and the $RMSE_x$, the $RMSE_y$, and the $RMSE_{net}$ for the entire scene.

ETM+ Relative and Absolute Block Validation

Because of the method in which the ETM+ data was orthorectified, a geolocational assessment of this imagery relative to the previously validated TM imagery was performed. This assessment was very similar to the scene-by-scene assessment performed on the MSS data. Various areas in both the TM and the ETM+ images were simultaneously studied for distinct and coincidental landmarks using ERDAS IMAGINE. Once a set of appropriate landmarks was recognized throughout the ETM+ and TM images, the analyst exported the pertinent data.

Additionally, because the ETM+ pixel size was sufficiently small, an absolute geolocational assessment of this imagery could be performed. The procedure used in this assessment was identical to that of the TM absolute assessment. After examining the ETM+ scene and selecting the usable control points, the analyst exported the pertinent data.

In both the ETM+ relative and absolute accuracy assessments, the exported data was combined into larger files based on orthorectification block to provide the input required to execute an SSC remote sensing Visual Basic program that computed the x-differences and y-differences and the squares of the x-differences and y-differences of each validation point, and the $RMSE_x$, the $RMSE_y$, and the $RMSE_{net}$ for the entire geographic block. In all, 100 ETM+ scenes were used for both the relative and absolute geolocation assessments.

RESULTS

The geolocational accuracy specifications for Landsat TM and MSS imagery are stipulated in NASA contract NAS 13-98046. Additionally, the geolocational accuracy specifications for Landsat ETM+ imagery are stipulated in NASA contract NAS 13-02032. The geolocational specifications for all of the EarthSat orthorectified imagery used in these analyses are listed in Table 1.

Table 1. EarthSat Orthorectified Imagery Geolocational Specification

Product / Assessment Method	Imagery Specification - $RMSE_{net}$
TM Orthorectified Imagery / Absolute Assessment	50 meters to ground coordinates
MSS Orthorectified Imagery / Relative Assessment	100 meters to ground coordinates
ETM+ Orthorectified Imagery / Relative Assessment	40 meters to TM coordinates
ETM+ Orthorectified Imagery / Absolute Assessment	64 meters to ground coordinates

TM Validation Results

Each of the 18 TM blocks passed their respective accuracy assessments. Of the 18 blocks assessed, the geographic blocks identified as "Central America," "Central Asia," "North Africa," "Northwest Asia," and "Southern South America" had fewer than the recommended 20 GCPs suggested by the FGDC as a minimum needed to calculate statistics for geographic accuracy analysis (FGDC, 1998). Nonetheless, statistics were generated for these blocks, and the results for each of the TM block assessments are presented in Table 2.

Table 2. TM Validation Results

TM Block	$RMSE_x$ (meters)	$RMSE_y$ (meters)	$RMSE_{net}$ (meters)	Number of GCPs Available	Number of GCPs Utilized
Alaska	30.57	33.40	45.28	61	43
Balkans	23.17	21.53	31.62	78	49
Caribbean	19.17	19.87	27.61	67	53
Central America	19.44	15.32	24.75	12	6
Central Asia	18.45	27.53	33.14	27	18
Central North America	19.33	18.56	26.80	57	47
East Africa	20.88	18.97	28.21	149	135
Eastern North America	18.66	18.90	26.56	62	50
Europe	24.46	26.64	36.16	140	96
Middle East	32.84	29.12	43.89	89	56
North Africa	28.95	38.28	48.00	6	6
Northeast Asia	24.42	25.61	35.39	80	49
Northern South America	17.57	39.36	43.11	92	73
Northwest Asia	35.81	27.39	45.09	12	10
South Africa	17.86	19.22	26.24	82	50
Southeast Asia	24.38	26.45	35.97	130	90
Southern South America	1.58	2.40	2.87	9	9
Western North America	16.08	14.45	21.62	73	55

NOTE: Highlighted data denotes blocks where fewer than 20 ground control points were available for statistical analysis.

MSS Validation Results

In 87 percent of the MSS scenes, the $RMSE_{net}$ was 50 meters or less, or the scenes produced results such that the worst-case scenario (i.e., TM $RMSE_{net}$ plus MSS $RMSE_{net}$) yielded an absolute geometric accuracy of 100 meters or less. Four percent of the imagery was unable to be evaluated for reasons including but not limited to extreme scene uniformity. The scenes that could not be evaluated were in the geographic regions of Alaska, the Balkans, East Africa, and Europe. The remaining 9 percent of the imagery failed to meet the specification in a worst-case scenario. Of this 9 percent, 4 images violated the $RMSE_{net}$ worst-case scenario by less than 10 meters. The scenes that failed the validation were in the geographic regions of East Africa (2 scenes), Eastern North America, Europe, North Africa, and Southeast Asia (3 scenes). Table 3 depicts a brief summary of the results.

Table 3. MSS Validation Summary

Pass / Fail Criteria	Number of Scenes	Percentage of Scenes
Pass	80	87%
Failed: Exceeded worst case absolute $RMSE_{net}$	8	9%
Scenes unable to validate	4	4%
Total Scenes	92	

The data results for each individual scene are recorded in Appendix A. Included in this appendix are the Path/Row of the Landsat MSS and TM imagery, as well as the $RMSE_x$, $RMSE_y$, and the $RMSE_{net}$ for each scene.

ETM+ Validation Results

The relative assessment utilized all 100 ETM+ scenes located throughout the world. From these scenes, a total of 1065 geographic landmarks were utilized for analysis. All 18 of the blocks passed the 40-meter $RMSE_{net}$ relative geographic accuracy specification. The statistics calculated on the ETM+ relative assessment are presented in Table 4. The maximum $RMSE_{net}$ found for the relative assessment was 34.90 meters, the minimum $RMSE_{net}$ found for the relative assessment was 13.89 meters, and the average $RMSE_{net}$ found for the relative assessment was 25.84 meters.

Table 4. ETM+ Relative Horizontal Geometric Accuracy Calculations

ETM+ Geographic Block	$RMSE_x$ (meters)	$RMSE_y$ (meters)	$RMSE_{net}$ (meters)	Number of Point Pairs
Africa - World Summit on Sustainable Development	23.29	25.15	34.28	30
Caribbean	15.61	19.37	24.88	30
Europe	20.50	18.15	27.38	70
Europe 2	17.95	17.67	25.19	60
Indonesia	23.63	25.38	34.68	25
Lower North America	16.97	17.35	24.26	140
Lower South America	26.21	18.73	32.22	20
NE Africa	17.19	19.40	25.92	100
NE Asia	16.46	14.87	22.18	40
NW Africa	22.12	27.00	34.90	20
NW Asia	12.68	13.51	18.53	30
SE Asia	25.62	18.78	31.76	130
South Africa	14.04	14.27	20.02	80
SW Asia	20.60	20.99	29.41	50
SW Asia 2	14.41	14.78	20.64	30
Upper North America 2	10.14	9.49	13.89	20
Upper North America 3 (Alaska)	18.10	19.70	26.76	110
Upper South America	12.84	12.88	18.19	80

The absolute assessment also utilized all 100 ETM+ scenes located throughout the world. From these scenes, a total of 750 government-provided control points were used for analysis. Table 5 presents the results of the ETM+ absolute geometric assessment. Note that the geographic blocks identified as "Africa -World Summit on Sustainable Development," "Indonesia," "Lower South America," "Northwest Africa," and "Upper North America 2" blocks contained fewer than the 20 points suggested by the FGDC for statistical analysis. The statistics for these four blocks were nonetheless calculated and included in Table 5. All 18 of the blocks passed the 64-meter $RMSE_{net}$ absolute accuracy specification. The maximum $RMSE_{net}$ found for the absolute assessment was 51.92 meters, the minimum $RMSE_{net}$ found for the absolute assessment was 22.98 meters, and the average $RMSE_{net}$ found for the absolute assessment was 34.88 meters.

Table 5. ETM+ Absolute Horizontal Geometric Accuracy Calculations

ETM+ Geographic Block	$RMSE_x$ (meters)	$RMSE_y$ (meters)	$RMSE_{net}$ (meters)	Number of GCPs Used
Africa - World Summit on Sustainable Development	43.37	28.54	51.92	10
Caribbean	17.39	27.26	32.33	35
Europe	20.04	24.99	32.04	42
Europe 2	18.88	25.05	31.37	39
Indonesia	21.63	20.60	29.87	17
Lower North America	23.08	24.23	33.46	96
Lower South America	13.17	19.20	23.29	8
NE Africa	15.65	16.83	22.98	60
NE Asia	17.43	23.12	28.95	25
NW Africa	17.87	35.17	39.45	3
NW Asia	22.52	23.23	32.36	20
SE Asia	23.42	24.28	33.73	119
South Africa	18.55	24.30	30.57	78
SW Asia	30.76	34.62	46.31	57
SW Asia 2	26.75	37.81	46.31	30
Upper North America 2	15.73	23.22	28.04	7
Upper North America 3 (Alaska)	18.80	28.70	34.31	45
Upper South America	34.37	37.04	50.53	59

NOTE: Highlighted data denotes blocks where fewer than 20 ground control points were available for statistical analysis.

VALIDATION LIMITATIONS

TM Validation Limitations

Sample size and selection of test points were dependent upon the quantity, quality, and utility of the data available. These test points were selected from surplus ground control information that is available only for certain parts of the globe.

The possibility exists for inherent analyst bias because of the variability in image interpretation and pattern recognition capabilities. Final selection of points reflected analyst subjectivity.

MSS Validation Limitations

Because the validated Landsat TM imagery was treated as a "truth" dataset for the relative accuracy assessment of the MSS imagery, any errors that might exist in the validated TM imagery could potentially have adverse effects on the relative accuracy assessment of the ETM+ imagery. Additionally, the same TM dataset was used in the MSS orthorectification process and in the MSS accuracy assessment process, so the validation method is not truly independent.

The MSS validation approach was also dependent on the geographic distribution of the available MSS-TM scene pairs used in the assessment. This distribution is shown in Figure 1.

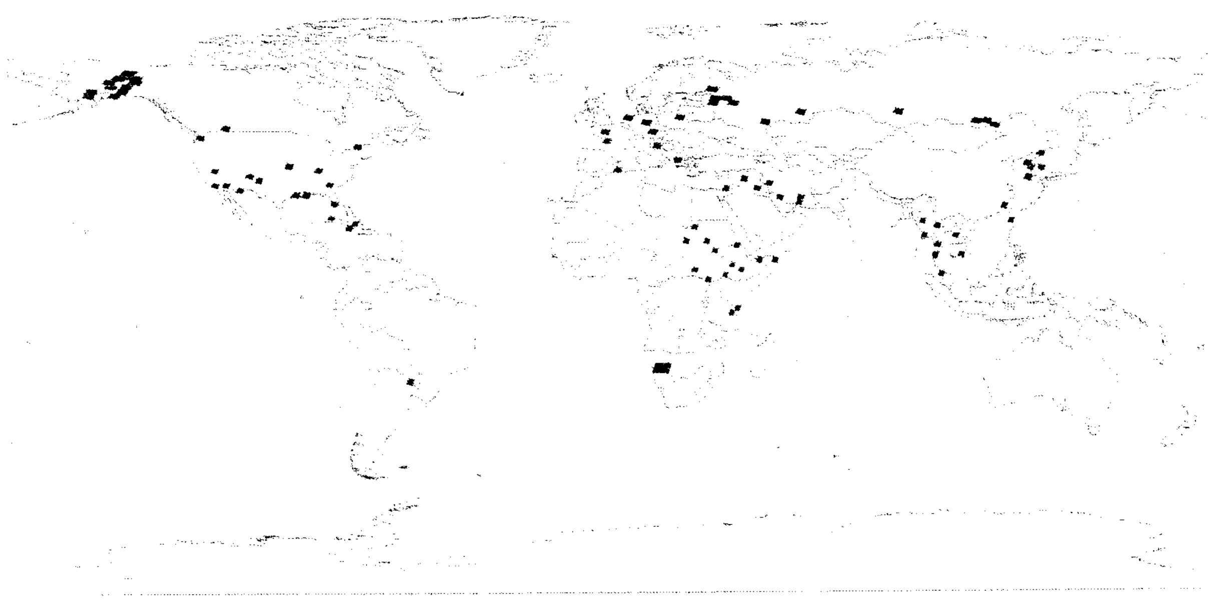

Figure 1. MSS Scene Distribution

This validation procedure assumes that the scenes selected represent a large enough sample of imagery to be extrapolated to the rest of the MSS imagery covering the globe.

The possibility exists for inherent analyst bias because of the variability in image interpretation and pattern recognition capabilities. Final selection of points reflects analyst subjectivity.

ETM+ Validation Limitations

Because the validated Landsat TM imagery was treated as a "truth" dataset for the relative accuracy assessment of the ETM+ imagery, any errors that might exist in the validated TM imagery could potentially have adverse effects on the relative accuracy assessment of the ETM+ imagery.

Inconsistencies could arise during the absolute accuracy assessment as a result of differences in the interpretations of the government-provided GCP drawings and imagery. The hand-drawn target area descriptions also reflect subjectivity; they are based on the perception of the artist, which may differ from that of the analyst.

Finally, the possibility exists for an inherent bias specific to the analyst as a result of the variability in image interpretation skills. The final selection of points also reflects analyst subjectivity.

CONCLUSIONS

TM Validation Conclusions

Despite the small set of GCPs used in the TM geolocational accuracy assessment, the different geographic blocks clearly met their specifications. The five blocks that had fewer than 20 GCPs for analysis should be treated with a small degree of caution; however, the imagery in those areas did not show anomalies that would cast doubt as to the geometric accuracy of the imagery.

MSS Validation Conclusions

Given the limitations inherent in this analysis, to a great extent the MSS imagery meets specifications. EarthSat has been notified of the few scenes that failed to meet the geolocational specifications or that were unable to be validated. For various reasons, EarthSat was willing to accept the failures of the 8 scenes and the inability to validate the remaining 4 scenes for the purposes of this report. No further deliveries or analyses of validation data are expected at this time.

ETM+ Validation Conclusions

The relative ETM+ geolocational assessment yielded results that show a high degree of TM to ETM+ geometric continuity. All of the geographic blocks evaluated produced statistics below the 40-meter specification. Similarly, the absolute ETM+ geolocational assessment yielded results that were below the 64-meter specification. As with the TM geolocational accuracy assessment, 5 of the ETM+ geographic blocks had fewer than the 20 GCPs suggested for statistical analysis in the absolute accuracy assessment case. However, because these blocks passed the relative geometric assessment, these 5 ETM+ blocks may be regarded with confidence. Although the absolute specification was not a criteria that would cause summary rejection of the imagery, the fact that all of the ETM+ data did pass the absolute accuracy tests provides additional confidence in the geometric accuracy of the ETM+ imagery that was orthorectified by EarthSat.

REFERENCES

Dykstra, Jon D., 2002. *Earth Satellite Production of Year 2000 GeoCover™ - Ortho Products*. Earth Satellite White Paper, December 2002.

Dykstra, Jon D., Michael C. Place, and Roger A. Mitchell, 2000. GeoCover-Ortho: Creation of a seamless, geodetically accurate, digital base map of the entire Earth's land mass using Landsat multispectral data. *Proceedings of the DC 2000 ASPRS Annual Conference*, May 22-25. Washington, DC.

Earth Science Applications Directorate, 2004. *Data Specifications, Phase II: GeoCover Ortho-rectified Multispectral Scanner (MSS) Imagery*. National Aeronautics and Space Administration, https://www.esad.ssc.nasa.gov/datapurchase/earthsat/ES4.htm, accessed March 3, 2004.

ERDAS®, LLC, 2002. ERDAS IMAGINE Tour Guides™. ERDAS IMAGINE® V8.6. Atlanta, GA.

EROS Data Center, 2004. *Enhanced Thematic Mapper Plus (ETM+)*. United States Geological Survey, http://edc.usgs.gov/products/satellite/landsat7.html, accessed February 27, 2004.

EROS Data Center, 2003a. *Multispectral Scanner (MSS)*. United States Geological Survey, http://edc.usgs.gov/products/satellite/mss.html, accessed February 27, 2004.

EROS Data Center, 2003b. *Thematic Mapper (TM)*. United States Geological Survey, http://edc.usgs.gov/products/satellite/tm.html, accessed February 27, 2004.

Federal Geographic Data Committee, 1998. *Geospatial Positioning Accuracy Standards, Part 3: National Standard for Spatial Data Accuracy*. FGDC Standard 007.3-1998.

Kramer, H., 2002. *Observations of the Earth and its Environment: Survey of Missions and Sensors*. New York, NY, pp. 442-451.

Wikipedia, 2004. *Root Mean Square*. Wikipedia, http://en.wikipedia.org/wiki/Root_mean_square, accessed March 5, 2004.

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APPENDIX A
MSS VALIDATION RESULTS

Corresponding TM Block	TM Path	TM Row	MSS Path	MSS Row	X RMSE (meters)	Y RMSE (meters)	$RMSE_{net}$ (meters)
Alaska	65	15	71	15	27.70	26.83	38.57
Alaska	66	14	73	14	29.85	23.72	38.13
Alaska	66	16	73	16	18.61	18.78	26.43
~~Alaska~~	~~66~~	~~17~~	~~69~~	~~17~~	-	-	-
Alaska	67	18	73	18	14.66	25.59	29.49
Alaska	69	14	75	14	25.61	28.17	38.07
Alaska	69	16	75	16	28.44	25.69	38.32
Alaska	70	15	76	15	25.66	26.37	36.79
Alaska	72	17	78	17	30.86	22.68	38.30
Alaska	72	18	78	18	23.32	27.37	35.96
Balkans	165	22	178	22	32.41	22.80	39.63
Balkans	171	24	184	24	30.77	29.11	42.36
Balkans	179	20	193 / 194	20	28.26	28.96	40.46
Balkans	181	19	195	19	34.58	29.88	45.70
Balkans	183	19	198	19	27.78	37.07	46.32
~~Balkans~~	~~183~~	~~20~~	~~197~~	~~20~~	-	-	-
Caribbean	11	45	12	45	33.09	30.82	45.22
Caribbean	12	46	12	46	32.75	31.98	45.77
Caribbean	16	44	17	44	31.40	23.48	39.20
Central America	35	38	37/38	38	22.12	30.28	37.50
Central Asia	128	24	138	24	41.22	37.59	55.79
Central Asia	130	24	140	24	34.19	38.12	51.20
Central North America	24	39	26	39	35.24	31.16	47.04
Central North America	27	33	29	33	32.50	33.80	46.89
Central North America	32	36	34	36	30.99	29.65	42.89
Central North America	34	32	37	32	28.15	33.45	43.72
East Africa	161	53	173	53	28.81	31.30	42.54
East Africa	166	63	178	63	27.49	17.39	32.53
East Africa	167	55	179	55	29.64	25.13	38.86
East Africa	167	64	179	64	23.40	23.43	33.11
East Africa	169	50	182	50	28.94	27.23	39.74
East Africa	169	54	181	54	27.76	36.33	45.72
~~East Africa~~	~~170~~	~~56~~	~~182~~	~~56~~	-	-	-
East Africa	173	51	186	51	29.74	38.20	48.41
East Africa	173	57	186	57	34.42	43.14	55.19
East Africa	174	38	187	38	28.53	28.32	40.20
East Africa	175	49	188	49	31.46	39.23	50.29

Corresponding TM Block	TM Path	TM Row	MSS Path	MSS Row	X RMSE (meters)	Y RMSE (meters)	$RMSE_{net}$ (meters)
East Africa	176	55	189	55	82.28	73.69	110.45
East Africa	178	46	191	46	51.43	51.55	72.82
East Africa	179	49	192	49	30.47	25.24	30.47
East Africa	165 (164)	53	177	53	21.39	26.16	33.80
Eastern North America	15	29	16	29	40.81	27.03	48.95
Eastern North America	16	41	17	41	48.54	45.29	66.39
Eastern North America	18	37	19	37	28.31	31.49	42.64
Eastern North America	21	34	23	34	22.70	23.65	32.77
Eastern North America	22	39	23	39	64.79	38.99	75.62
Europe	185	17	199	17	44.65	33.10	55.58
~~Europe~~	~~185~~	~~32~~	~~199~~	~~32~~	-	-	-
Europe	188	23	203	23	28.46	35.49	45.49
Europe	190	29	205	29	35.36	27.47	44.77
Europe	192	26	207	26	28.89	26.04	38.89
Europe	194	24	209	24	25.47	24.78	35.53
Europe	198	23	213	23	48.68	51.79	71.08
Europe	200	28	216	28	25.49	16.20	30.20
Europe	201	26	217	26	35.43	36.51	50.87
Middle East	159	40	171	40	29.14	37.72	47.66
Middle East	159	41	171	41	25.77	32.72	41.64
Middle East	163	40	175	40	29.72	40.81	50.49
Middle East	166	37	178	37	24.23	32.93	40.89
Middle East	168	38	181	38	26.86	26.06	37.42
Middle East	171	36	184	36	29.29	33.14	44.23
North Africa	196	34	211	34	31.52	52.10	60.89
Northeast Asia	114	34	123	34	25.17	32.85	41.38
Northeast Asia	115	31	124	31	36.64	30.75	47.84
Northeast Asia	116	34	125	34	27.84	25.46	37.72
Northeast Asia	116	36	125	36	25.20	24.80	35.36
Northeast Asia	117	33	126	33	24.87	26.91	36.64
Northeast Asia	126	25	136	25	33.90	28.56	44.33
Northwest Asia	146	22	157	22	32.62	30.57	44.71
South Africa	177	75	190	75	33.84	43.88	55.41
South Africa	177	76	190	76	29.75	27.09	40.27
South Africa	178	75	191	75	35.36	46.09	58.09
South Africa	178	76	191	76	47.03	33.86	47.03
South Africa	179	75	192	75	26.37	30.17	40.07
South Africa	179	76	192	76	23.92	28.66	37.33
Southeast Asia	117	45	126	44	40.90	35.75	54.33
Southeast Asia	118	42	127	42	26.99	32.48	42.23

Corresponding TM Block	TM Path	TM Row	MSS Path	MSS Row	X RMSE (meters)	Y RMSE (meters)	$RMSE_{net}$ (meters)
Southeast Asia	125	52	134	52	26.88	24.79	36.56
Southeast Asia	127	48	136	48	32.95	33.20	46.78
Southeast Asia	128	56	137	56	22.49	25.78	34.21
Southeast Asia	130	50	140	50	81.98	27.38	86.43
Southeast Asia	130	52	139	52	82.00	22.97	85.15
Southeast Asia	131	46	140	46	27.29	24.07	36.39
Southeast Asia	133	48	143	48	62.76	65.27	90.55
Southeast Asia	134	45	144	45	30.34	32.99	44.82
Southern South America	226	78	242	78	52.13	34.92	62.74
Western North America	38	37	41	37	38.49	24.70	45.73
Western North America	40	37	43	37	28.57	31.63	42.62
Western North America	41	34	44	34	23.74	30.61	38.74
Western North America	42	25	45	25	51.52	52.26	73.38
Western North America	46	27	50	27	27.17	36.72	45.68

NOTE: Rows highlighted in grey indicate that the imagery analysis was unable to be completed. Rows with red text indicate that the data failed to meet specification.