Landsat 7 ETM+ Geometric Calibration Plan

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1.0 Introduction

1.1 Purpose

This document describes the activities which will be performed to geometrically calibrate the Landsat 7 Enhanced Thematic Mapper Plus (ETM+) with emphasis on how the Image Assessment System (IAS) will support these activities. This includes descriptions of the calibration techniques and their frequencies during the pre-launch testing, initial on-orbit checkout, and normal operations phases of the Landsat 7 system life cycle.

1.2 Geometric Calibration Requirements

The requirements for Landsat 7 ETM+ geometric calibration are defined in section 3.7.7 of the Landsat 7 System Specification (reference 1), where they are allocated to the IAS ground system element. These requirements are presented in more detail in the IAS Element Specification (reference 2). The IAS is the primary tool which will be used to carry out post-launch calibration activities.

In the IAS algorithm and system design documents, a distinction is made between those calibration activities which seek to measure and evaluate (or characterize) system geometric performance and those activities which attempt to estimate improved values for (or calibrate) the geometric processing parameters. These are the parameters contained in the Landsat 7 Calibration Parameter File (CPF) for use by the level 1 product generation algorithms and software. The measurement and evaluation activities are referred to as *characterization* operations, while the parameter estimation activities are referred to as *calibration*. Although both types of activities contribute to the “geometric calibration” of the Landsat 7 ETM+ system, the remainder of this document will use the term *characterization* to refer to geometric assessment and evaluation operations and the term *calibration* to refer to geometric processing parameter estimation operations.

The Landsat 7 geometric calibration requirements have been allocated to seven algorithms: four for characterization and three for calibration. Software implementations of these algorithms will be used to:

1) Assess the geodetic accuracy of ETM+ Level 1G data (Geodetic Characterization);
2) Assess the internal geometric accuracy of Level 1G ETM+ data (Geometric Characterization);
3) Assess the accuracy of multi-temporal ETM+ image-to-image registration (Image-to-Image Registration Characterization);
4) Assess the accuracy of band-to-band registration (Band-to-Band Registration Characterization);
5) Determine the alignment between the spacecraft navigation base reference and the ETM+ payload line of sight (Sensor Alignment Calibration);

6) Determine corrections to the pre-launch scan mirror profiles (Scan Mirror Calibration);
7) Determine corrections to the band location field angles and (post-launch) to the along-scan and across-scan detector locations and delays (Focal Plane Calibration).

These four characterization and three calibration algorithms are described in the IAS Algorithm Theoretical Basis Document (reference 3). The ways in which the software implementations of these algorithms will be used to operationally calibrate the Landsat 7 ETM+ system are the subject of the remainder of this document.

1.3 Geometric Calibration Philosophy

The most critical geometric calibration requirements are to measure and verify the Landsat 7 ETM+ system performance during the Initial On-orbit Checkout (IOC) period using the geodetic, geometric, band-to-band, and image-to-image characterization capabilities, and to perform the initial sensor alignment calibration. Refining the pre-launch sensor alignment knowledge is critical to ensure that the Level 1Gs product geodetic accuracy specification can be met. Sufficient supporting data sets (e.g., ground control, terrain data) to perform these characterization and calibration activities must be available at launch. The second priority during the IOC period will be to verify and, if necessary, update the pre-launch focal plane (particularly band placement) and scan mirror profile calibrations. The results of these initial calibration activities will be used to verify that the system is performing within specifications and to create an initial post-launch release of the Calibration Parameter File which can be used by the IAS or the Landsat 7 Level-1 Product Generation System (LPGS) to create Level 1G products which meet the Landsat 7 geodetic accuracy requirements.

After the IOC period, ongoing calibration activities will monitor the stability of the Landsat 7 ETM+ system's geometric performance and attempt to identify and characterize any systematic variations in the system's geometric parameters. This will include processing additional calibration scenes under a variety of acquisition conditions (e.g., orbital position, ETM+ time on) to measure the system's geometric performance as a function of time, temperature, and location. A longer sequence of calibration observations over a variety of conditions will be needed to isolate, model, and characterize these higher-order behaviors. This will probably require the collection of additional supporting information such as ground control, terrain data, and high-resolution reference imagery to cover additional calibration test sites post-launch. Funding for support data purchases should be included in post-launch operations budgets.

1.4 Document Overview

Section 1 describes the purpose of this document, presents an overview of the Landsat 7 ETM+ geometric calibration requirements, and provides a high level view of the approach to geometric calibration. Section 2 contains a list of relevant references. Section 3 describes the geometric calibration activities in detail, breaking them down into pre-launch activities, geodetic test site calibration activities, geometric super-site calibration activities, and focal plane calibration activities. Section 4 defines the requirements for supporting data sets needed to carry out some of the calibration operations. Section 5 contains a glossary of terms and an acronym list.

2.0 References

[1] Landsat 7 System Specification, Revision H, 430-L-0002-H, NASA Goddard Space Flight Center, Greenbelt, Maryland, June 1996.
[2] Landsat 7 System Image Assessment System (IAS) Element Specification, Baseline, 430-15-01-0001-0, NASA Goddard Space Flight Center, Greenbelt, Maryland, October, 1996.
[3] Landsat 7 Image Assessment System (IAS) Geometric Algorithm Theoretical Basis Document, Version 2.0, USGS EROS Data Center, December 1996.
[4] Landsat 7 Calibration Parameter File Definition, Review, 430-15-01-002-0, NASA Goddard Space Flight Center, Greenbelt, Maryland, July 11, 1996.
[5] Landsat 7 Program Coordinates System Standard, Revision B, PS23007610B, Martin Marietta Astro Space, Philadelphia, Pennsylvania, December 1994.

3.0 Geometric Characterization and Calibration Activities

Geometric characterization and calibration will be performed over the life of the Landsat 7 mission using the software tools developed as part of the Landsat 7 Image Assessment System. The IAS provides the capability to routinely perform four types of geometric characterization to verify and monitor system geometric performance, and three types of geometric calibration to estimate improved values for key system geometric parameters.

The geometric characterizations include: 1) geodetic accuracy assessment to measure the absolute accuracy of Level 1Gs (systematic) corrected products; 2) geometric accuracy assessment to qualitatively and quantitatively evaluate residual internal geometric distortions within Level 1Gs images; 3) band to band registration assessment to measure and monitor the relative alignment of the eight ETM+ spectral bands; and 4) image-to-image registration assessment to measure and monitor multi-temporal image registration accuracy. The geometric calibration capabilities provided by the IAS include: 1) sensor alignment calibration to provide improved knowledge of the geometric relationship between the ETM+ optical axis and the Landsat 7 attitude control reference system; 2) scan mirror calibration to measure and correct any systematic deviations in the ETM+ scan mirror along and across scan profiles; and 3) focal plane calibration to measure and provide improved estimates of the eight band center locations on the two ETM+ focal planes relative to the ETM+ optical axis. Techniques for measuring and estimating improved values for individual detector locations and delays are being researched and may be added to the IAS as a post-launch capability.

Image products generated by the IAS Level 1 processing software are used as inputs to the custom characterization software tools to accomplish the four characterizations. Each of these characterizations will be performed during the IOC period to verify system performance, and at regular intervals during normal operations to monitor the Landsat 7/ETM+ system's geometric stability. The band to band registration assessment will provide the raw measurements used for subsequent band placement calibration. In addition to acquiring system performance data for use in geometric calibration, geometric characterization measurements will be taken under a variety of image, instrument, and spacecraft conditions (e.g., scene content, ETM+ time-on/temperature, position in orbit) to ensure that geometric performance is consistent under differing acquisition conditions.

The discussion of Landsat 7 ETM+ geometric calibration activities which follows is divided into four sections. The first discusses pre-launch calibration activities which will determine the initial Landsat 7 geometric calibration parameters. The second section addresses geodetic test site calibration activities which will measure system on-orbit geodetic performance and ETM+ sensor-to-Landsat 7-spacecraft alignment using ground control points. The third section describes geometric super-site calibration activities which will provide geometric accuracy and image-to-image registration assessments, as well as scan mirror calibration parameter updates using ground control, digital terrain data, and reference images. The fourth section discusses band registration test site calibration activities which will measure band to band registration accuracy and provide band alignment parameter updates.

3.1 Pre-Launch Calibration Activities

Pre-launch calibration is required to ensure that the Landsat 7 spacecraft and ETM+ instrument are adequately characterized on the ground to provide the geometric parameters needed for accurate image data processing after launch. This phase is critical since the majority of the parameters used in Level 1 geometric processing will not be updated after launch.

3.1.1 Objective

Pre-launch geometric calibration activities are directed toward four primary goals: 1) to determine whether the ETM+ instrument (as it is being constructed and integrated with the Landsat 7 spacecraft) will meet its performance specifications; 2) to accurately measure the geometric characteristics (which must be known to process ETM+ image data); 3) to assemble the auxiliary data sets (which will be needed at launch to support characterization and calibration activities during the IOC period); and 4) to assemble the initial version of the Landsat 7 Calibration Parameter File. Some of the data collected during pre-launch testing will also be used to test the newly developed calibration and characterization algorithms described below.

3.1.2 Methodology

The pre-launch verification of instrument and spacecraft geometric performance specifications will be carried out as part of the instrument and spacecraft manufacturers' development, integration, and test programs. This will include measuring key characteristics (such as the scan mirror profile) in test configurations, reducing the collected test data, and reporting the results to NASA as well as providing test outputs (e.g., jitter test data) to NASA for additional analysis. The geometric characteristics of the ETM+ instrument will be measured during instrument fabrication and testing at Hughes' Santa Barbara Remote Sensing (SBRS) facility. Additional measurements and tests will be performed at Lockheed-Martin Missiles and Space (LMMS) as the Landsat 7 spacecraft is being fabricated and integrated with the ETM+ payload. The specific geometric measurements, test analyses, and preparations for on-orbit calibration to be performed by SBRS, LMMS, NASA, and the EROS Data Center (EDC) are discussed by organization in the next section.

3.1.3 Personnel

Pre-launch calibration activities will be carried out by personnel from Hughes' Santa Barbara Remote Sensing (SBRS), Lockheed-Martin Missiles and Space (LMMS), NASA Goddard Space Flight Center (GSFC), and the USGS EROS Data Center (EDC). The specific activities to be performed and/or calibration information to be provided by each organization are described in the following sections.

3.1.3.1 Hughes' Santa Barbara Remote Sensing

The geometric characteristics of the ETM+ instrument will be measured pre-launch at the Santa Barbara Remote Sensing facility. Parameters which will be measured and included in the initial Landsat 7 Calibration Parameter File include:

- Scan Angle Limits (Field of View)
- Nominal Scan Times
- Scan Mirror Profiles
- Scan Line Corrector (SLC) Profiles
- Band Placement (Band Center Locations)
- Detector Placement and Delays
- Detector Instantaneous Field of View (IFOV)

3.1.3.2 Lockheed-Martin Missiles and Space

Geometric characteristics of the Landsat 7 spacecraft (including particularly its attitude control system and its integration with the ETM+ instrument) will be measured pre-flight at the Lockheed-Martin facility in Valley Forge, Pennsylvania. These include the Inertial Measurement Unit (IMU) and Angular Displacement Sensor (ADS) transfer functions which characterize the frequency response of the low-frequency attitude (IMU gyros) and high-frequency jitter (ADS accelerometers) sensors. The relative alignment of the various attitude control system (ACS) components as well as the alignment of the ETM+ instrument to the ACS reference system (the Navigation Base Reference) will also be measured. These alignments are provided in the form of rotation matrices which can be used to transform vectors from one coordinate system to another. These coordinate systems and the relationships between them are described in [5]. Alignment matrices of particular interest for geometric processing include:

- Inertial Measurement Unit to Navigation Base Reference
- Angular Displacement Sensor to ETM+
- Navigation Base Reference to ETM+

3.1.3.3 Goddard Space Flight Center

The NASA Goddard Space Flight Center (GSFC) has the responsibility to process and analyze the results of the key ground tests performed at SBRS and LMMS. The Geometric Performance Test (also known as the jitter test) is of particular interest for geometric calibration. GSFC will process and analyze the Payload Correction Data (PCD) output from this test, with support from the EROS Data Center.

During the pre-launch period GSFC will also finalize the definition of the content and format of the Landsat 7 Calibration Parameter File (CPF). The CPF will be documented along with the Level 0R product in a Landsat 7 Data Format Control Book (DFCB).

3.1.3.4 EROS Data Center

Prior to Landsat 7 launch, the USGS EROS Data Center (EDC) will identify and assemble the supporting data and information for geometric calibration sites. This will include acquiring the required supporting data (see section 4), and performing any necessary preprocessing to pre-load the IAS databases and data files. This will ensure that sufficient support data are available at launch to begin characterization and calibration operations during the IOC period.

In addition to assembling the geometric test site data, the EDC is responsible for testing and verifying the geometric characterization and calibration algorithms developed for the IAS, and populating the geometric parameter values for the pre-launch version of the CPF using the results of the GSFC analysis and evaluation of the pre-launch ground test data.

3.1.4 Schedule

TBS

3.1.5 Data Reduction

Most of the pre-launch geometric parameters measured by SBRS and LMMS will be provided in a form which can be directly used in the Calibration Parameter File. One item which may require additional data reduction and analysis are the Angular Displacement Sensor (ADS) transfer functions provide by LMMS. These transfer functions characterize the frequency response of the jitter sensors, and are derived from empirical measurements. The ADS tests which provide these transfer functions include measurements under varying thermal conditions. If the transfer functions exhibit significant temperature dependence, additional GSFC pre-launch data analysis effort will be required to characterize and develop a parametric representation of the thermal effects. This will enable the IAS attitude data processing software to use the ADS temperatures measured on board to compensate for this effect.

The gyro and ADS data readouts from the Geometric Performance (jitter) ground test will be analyzed to ensure that the attitude data sensors are functioning properly and to detect the primary vibration modes of the Landsat 7 spacecraft. On Landsat 6 these were the odd harmonics of the scan mirror frequency. Although this data reduction and analysis is a GSFC responsibility, it would be beneficial to process the attitude Payload Correction Data (PCD) through the IAS attitude data processing software to ensure that the IMU (gyro) and ADS filters are working correctly on real Landsat 7 data. This would require the development of test software to allow the attitude processing steps to be performed as a standalone operation on an incomplete PCD data set.

Significant data reduction and pre-processing will be required to construct the supporting data sets required for the geometric calibration test sites. This includes digital terrain data, ground control points, and reference images. These data and the associated processing required are discussed in section 4.

3.2 Geodetic Test Site Calibration Activities

Geodetic test site data acquisitions are used to measure the Landsat 7/ETM+ system's on-orbit geodetic accuracy performance, and to improve geodetic accuracy by deriving improved estimates of the sensor to spacecraft alignment parameters.

3.2.1 Objective

The geodetic characterization and calibration activities will evaluate Landsat 7/ETM+ geodetic accuracy performance and attempt to improve that performance by estimating improvements to the sensor/spacecraft alignment knowledge during the IOC period, and routinely monitor system geodetic performance over the life of the mission, providing periodic updates to the sensor alignment calibration parameters as necessary.

3.2.2 Methodology

The geodetic accuracy assessment and sensor alignment calibration operations are both performed using test scene acquisitions covering pre-selected geodetic test sites for which ground control points are available. These test scenes are processed twice, using the Level 1 processor precision correction capability each time: once using the PCD ephemeris, and once using definitive ephemeris data from the GSFC Flight Dynamics Facility (FDF). The precision correction control point residuals generated by processing the scene with the PCD ephemeris are used to provide a measure of system geodetic accuracy performance. The precision correction solution results based on the definitive ephemeris are used for sensor alignment calibration as described below. The operational flow for geodetic test site processing (including geodetic accuracy assessment and sensor alignment calibration operations) is shown in figures 3.2.2-1 through 3.2.2-4.

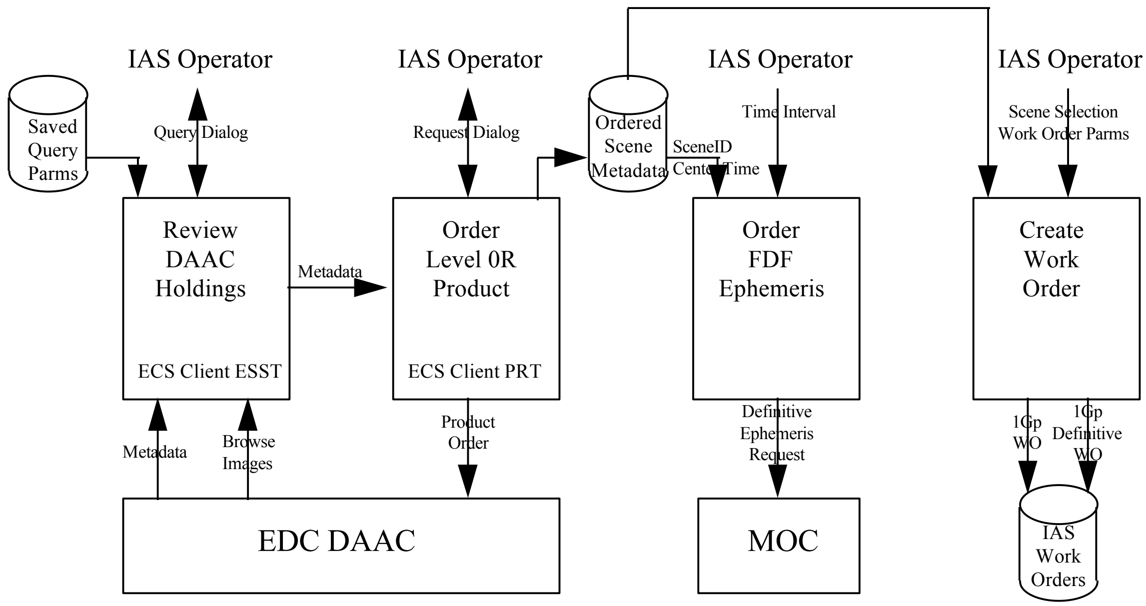

Figure 3.2.2-1: Geodetic Test Site Operational Flow - Step 1: Order Data

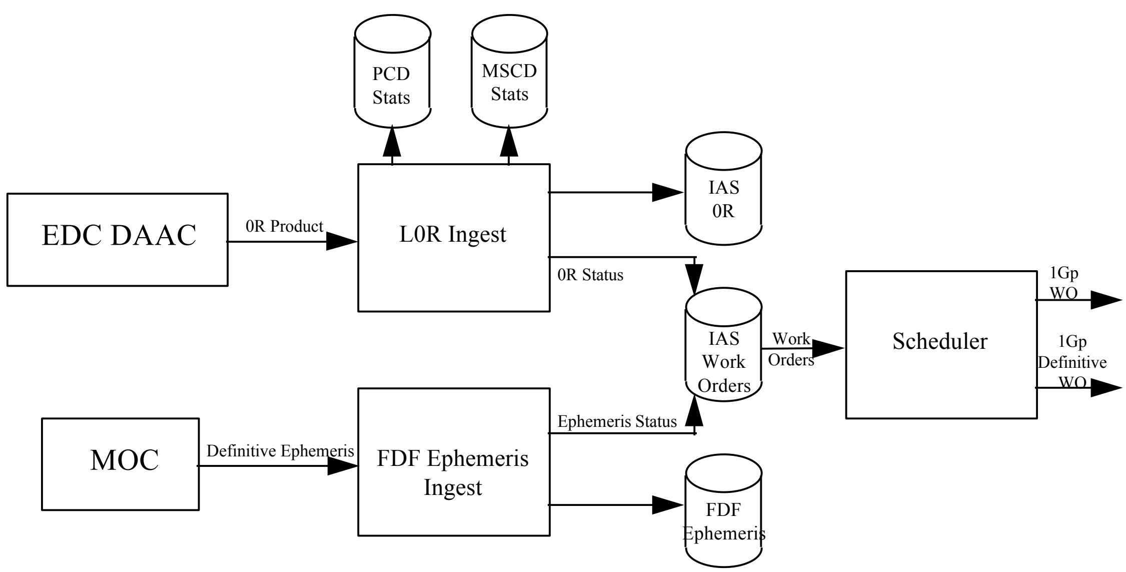

Figure 3.2.2-2: Geodetic Test Site Operational Flow - Step 2: Receive Data

Figures 3.2.2-3 and 3.2.2-4 show the 1Gp work order used for geodetic accuracy assessment and the 1Gp (definitive) work order used for sensor alignment calibration as independent parallel flows. These flows have many common processing steps and include many of the same data items. Some of these common data items are identical, the 1R Image for example. Inputs and outputs are shown shaded in the definitive flow to indicate where the data item contents differ even though they have the same name in the two flows. This shows how the use of definitive ephemeris affects the processing results.

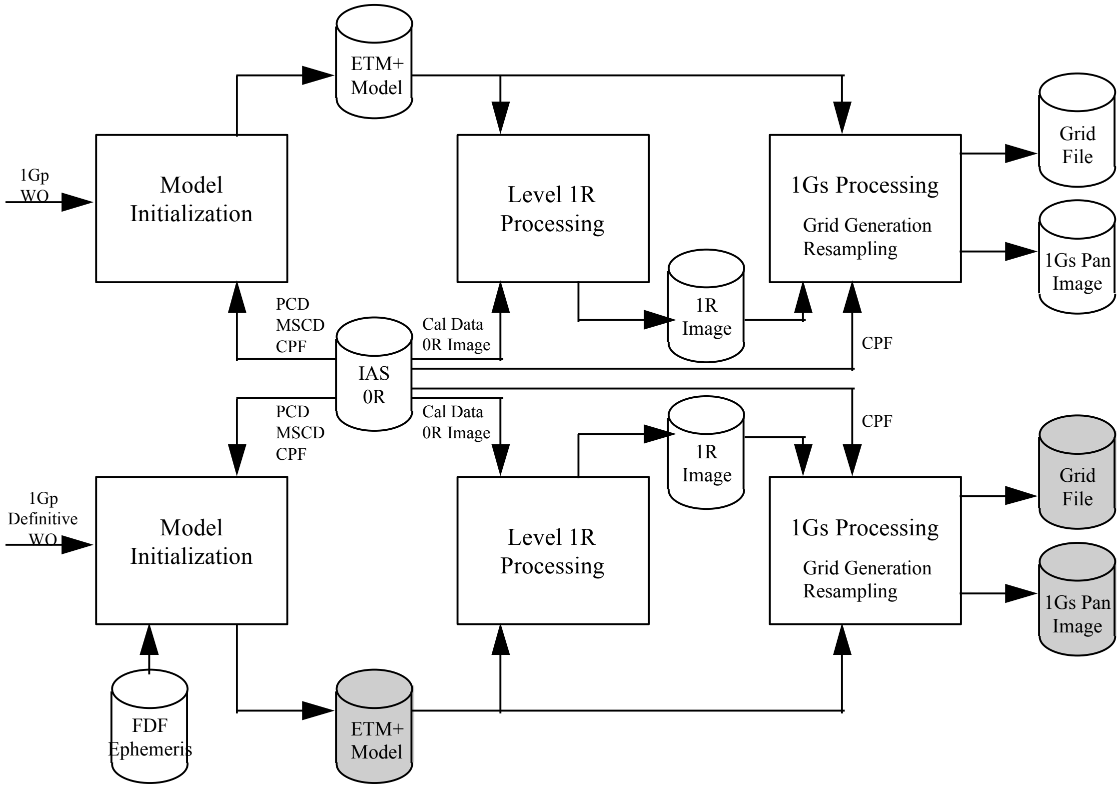

Figure 3.2.2-3: Geodetic Test Site Operational Flow - Step 3: Process 1Gs

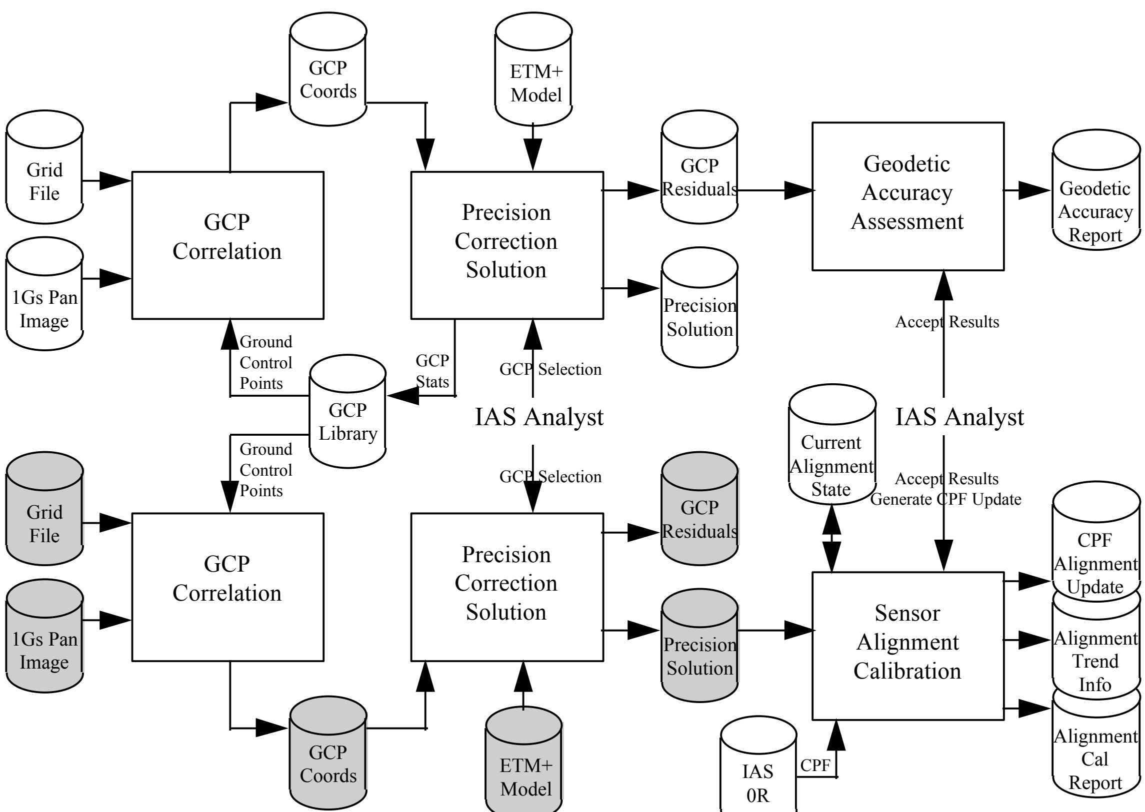

Figure 3.2.2-4: Geodetic Test Site Operational Flow - Step 4: Apply GCPs

3.2.2.1 Geodetic Accuracy Assessment

Purpose: The purpose of the geodetic accuracy assessment is to ensure that the Landsat 7 Level 0R product data can be successfully processed into Level 1 systematic products which meet the Landsat 7 system requirement of 250 meters (1 sigma) per axis horizontal accuracy, as stated in [1].

Approach: Pre-defined ground control points (consisting of panchromatic image chips with known geodetic positions, as described in section 4) will be automatically correlated with data from the ETM+ panchromatic band to measure the discrepancy between the known ground location and the position predicted by the Landsat 7/ETM+ geometric model. The IAS Level 1 processing software will be used to create Level 1Gs panchromatic image products of test scenes containing ground control using the downlinked Payload Correction Data (PCD) and Mirror Scan Correction Data (MSCD). The IAS precision correction software will then be used to correlate the systematic image with the ground control image chips to measure the position errors in the systematic image. The precision correction software will also be used to report the raw control point residuals (with no precision correction applied) and to apply an outlier filter to detect and identify correlation errors. The results of this control point mensuration and outlier filtering are output by the precision correction software for analysis by the IAS geodetic characterization software. This software will process the residuals (deleting those identified as outliers) to generate summary statistics and a geodetic accuracy analysis report. This characterization will be performed each time a sufficiently-cloud-free image of one of the geodetic test sites is acquired. This will nominally occur once or twice per week.

Inputs: The inputs used by the geodetic characterization process include: a Level 0R product corresponding to one of the geodetic test sites, and ground control image chips with corresponding geodetic positions (latitude, longitude, and height). It is the availability of ground control which makes a particular Landsat WRS path-row a geodetic test site.

- Level 0R Product - Level 0R products are requested from and delivered by the EDC Distributed Active Archive Center (DAAC). The entire product will be provided but the geodetic characterization process only requires the PCD, MSCD, CPF, calibration data, and the panchromatic band image data.
- Ground Control - Reference image chips with precisely-located geodetic positions are used to measure the position errors in the Level 1Gs panchromatic image generated using the 0R product data. Ground control points accurate to 15 meters (1 sigma) or better should be used if available. USGS 1:24,000-scale maps can be used to exceed this accuracy in the conterminous United States. Enough control points will be selected to provide 30-40 well-distributed points in each WRS test site. This number of control points should make it possible to acquire at least 20 successful control point correlations in scenes with less than 20% cloud cover. Three or four test sites will provide six to eight opportunities to acquire test scenes in the US each month, and should result in at least two or three sufficiently-cloud-free scenes per month. A

second set of test sites outside the US will be generated after launch to provide geodetic accuracy measurements under varying acquisition conditions.

Procedure: The primary set of geodetic test sites will be within the Sioux Falls, South Dakota ground station's acquisition circle and will therefore be collected routinely. Overseas test sites will only be acquired as part of the global collection plan unless special calibration acquisition requests are made. Current plans call for providing the Landsat 7 Mission Operations Center (MOC) with a list of 10-20 test sites outside the US which should be collected at least once per quarter to support characterization and calibration activities. Each day, the IAS operator will query the EDC DAAC's Landsat 7 metadata holdings against the pre-defined list of WRS scenes containing ground control to see if any new geodetic test site acquisitions are available. If so, the cloud cover and image quality fields in the metadata and the browse images will be used to determine if the scene is sufficiently cloud-free to use for geodetic accuracy assessment.

When a suitable scene is identified, the IAS operator orders it from the EDC DAAC and places a Level 1 processing work order requesting a 1Gp (precision corrected) product for the test scene. After the Level 0R data is delivered by the DAAC, the IAS ingest software loads and verifies the 0R data. After the 0R data is successfully loaded, the associated Level 1 processing work order is activated and executed by the IAS scheduling software. The IAS analyst monitors the status of calibration work orders submitted for processing. Once the Level 1 work order has been completed, the IAS analyst invokes the geodetic assessment software and retrieves the control point residual data (including outlier flags) from the precision correction solution. The geodetic assessment software computes statistics on the control point residuals as described in [3], and presents the results to the analyst for interactive review. The analyst reviews the control point residuals and the summary statistics to determine if the geodetic accuracy assessment is valid (i.e., enough points have been successfully correlated). If so, a geodetic assessment report is generated and the assessment results are stored for comparison with earlier assessments and geodetic accuracy trend analysis. If not, the analyst may edit the control point list to reject additional points as outliers or to declare previously rejected points as valid. In an extreme case, the analyst may decide that there were not enough valid control point measurements collected to provide a meaningful accuracy assessment, and cancel the assessment operation.

Outputs: The geodetic accuracy assessment process generates a geodetic accuracy assessment file containing the valid control point residuals, the outlier residuals, the summary statistics, and a flag indicating whether the 250-meter accuracy specification was met; and an assessment summary report which contains the same information formatted for ease of reading by an IAS analyst.

Accuracy/Performance: The assessment accuracy is limited by the accuracy of the ground control points and the image correlation mensuration technique. If the correlation is accurate to 0.25 pixels, the net control/mensuration error is approximately 16 meters (1 sigma). When root-sum-squared with the 250-meter geodetic error budget, this additional control and mensuration error increases the expected geodetic error by less than a meter.

One important note on the interpretation of the geodetic accuracy results is that the most significant sources of geodetic error (alignment, attitude, and ephemeris error) are highly correlated over a single scene. This means that each scene represents a single realization of the random geodetic error, rather than each control point. Data from many scenes will be required to obtain a reliable estimate of the actual geodetic error variance. Two scenes per week would provide 26 observations per quarter. If the geodetic error variance estimated from 26 test scenes is taken to be a chi-squared distributed random variable with 25 degrees of freedom, then the true geodetic error standard deviation will be less than 1.25 times the estimated error standard deviation with 90% probability. Rather than estimating the actual geodetic error variance, a simpler check for conformance to the 250-meter requirement would be to verify that at least 68.3% of the test scenes have their mean control point residuals within 250 meters.

3.2.2.2 Sensor Alignment Calibration

Purpose: The goal of the sensor alignment calibration is to improve the in-flight knowledge of the relationship between the ETM+ instrument and the Landsat 7 navigation base reference. The IAS is required to estimate this alignment to an accuracy of 24 arc seconds (per axis) at least once per quarter. This calibration will use discrete ground control points in a set of pre-defined calibration reference scenes.

Approach: The primary challenge in alignment calibration is the need to estimate the underlying alignment trend (assumed initially to be a bias) from a series of precision correction solutions which measure a combination of orbit, attitude, and alignment errors. Landsat 7 will have more accurate (estimated to be in the 10-50 meter range versus 133 meter accuracy for the ephemeris downlinked in the Payload Correction Data) post-pass definitive ephemeris data available for the alignment calibration test scenes, reducing the uncertainty due to orbital errors. This precise ephemeris is provided by the GSFC Flight Dynamics Facility (FDF) upon request from the IAS. Multiple precision correction solutions will be integrated using a Kalman filter algorithm to estimate the best fit systematic alignment bias. As additional precision correction solutions are processed by the Kalman filter, the filter’s estimates of the alignment biases will improve.

Periodically, an IAS analyst will decide that the alignment knowledge has changed enough to warrant generating an updated sensor alignment matrix for inclusion in the Calibration Parameter File. Initially, this decision would be based on the alignment bias covariance estimates generated by the Kalman filter. A new set of CPF parameters would be generated as soon as the bias estimate standard deviation moved below the 24-arc second alignment accuracy requirement threshold. During normal operations, a new alignment matrix would be generated whenever a new version of the CPF was scheduled for release. This will happen at least once per quarter.

Inputs: The inputs used by the sensor alignment calibration software are described in [3]. The following list describes each of the information inputs needed by the end-to-end sensor alignment calibration process at a more conceptual level.

- Calibration scene Level 0R product - The Level 0R product is requested from the EDC DAAC and includes the raw scene image data, PCD, MSCD, Calibration Parameter File, and other supporting information. These are the same scenes used in the geodetic accuracy assessment.
- FDF precise ephemeris data - The GSFC FDF will provide definitive ephemeris data for specific time periods upon request. Five minute (TBR) intervals spanning the calibration scene will be requested resulting in improved ephemeris state vectors at 4.096 second intervals (corresponding to the PCD sampling interval).
- Ground control - Reference image chips with precisely located geodetic positions are used to measure the position errors in a Level 1Gs image generated using the 0R product and the definitive ephemeris. Since the sensor alignment calibration control accuracy requirements can be met by using USGS 1:24,000-scale maps, these will be the same ground control points used for geodetic accuracy assessment. The Landsat 7 16-day repeat cycle (and assuming that one-third of the imaged scenes will be sufficiently cloud-free to use for calibration) leads to a requirement for three or four test scenes in different WRS paths. Each test scene should have 30-40 control points to ensure that 15 well distributed, cloud-free points are available for the precision correction solution, leaving additional check and verification points.
- Level 1 processor precision correction solution output - The precision correction process output includes the date and time of the calibration scene, estimates of the ephemeris and attitude (bias and rate) errors in the calibration scene, and a covariance matrix characterizing the reliability of the ephemeris and attitude error estimates. Since definitive ephemeris data is used to process alignment calibration scenes, the ephemeris correction estimates (computed by the precision correction solution) should be small.
- Previous alignment filter state vector and covariance matrix - The alignment calibration software maintains the current best knowledge of the sensor alignment offset angles and any position bias offsets in the form of a state vector and its associated covariance matrix. This information is created as an output each time the alignment calibration software is used to process the results of a new calibration scene, for use by the next invocation of the software.

Procedure: Each day, an IAS analyst searches the Landsat 7 metadata in the EDC DAAC to determine whether any new images of calibration test scenes have been acquired, as described above for geodetic accuracy assessment. If a suitable image is found, the Level 0R data product is requested from the EDC DAAC, and the IAS analyst notes the date and time of the calibration scene acquisition and places a request to the FDF, via the MOC, for definitive ephemeris data for that time period. This could be done by simultaneously activating the graphical user interfaces (GUIs) for interaction with the DAAC (the ECS client interface) and the FDF ephemeris request GUI, and cutting and pasting the scene center time from the 0R metadata into the FDF request GUI. The operator would specify the center time and time interval length for the definitive ephemeris and the software would automatically construct and forward the request to the MOC. The IAS operator then places an IAS Level 1Gp precision correction work order that includes the fact that definitive ephemeris data is to be used in the processing.

Once the Level 0R product is received from the DAAC and ingested by the IAS, and the definitive ephemeris is received from the FDF (via the MOC), the associated 1Gp work order is activated. The IAS Level 1 Processor will then accept and schedule the work order for processing. Once initiated, the precision correction process uses ground control from the IAS control library (containing ground control points for the IAS calibration and test sites) in the Level 1 processing flow to create a Level 1Gp image of the calibration scene. As part of this processing, the precision correction software generates estimates of the spacecraft position, velocity, attitude, and attitude rate errors as well as a covariance matrix for the estimated parameters. This output data (along with a copy of the Calibration Parameter File from the Level 0R product used to process the scene) is saved for subsequent use as input to the alignment calibration software. The precision correction algorithm is described in [3].

The IAS analyst monitors the status of calibration work orders submitted for processing, notes that the precision correction job is complete, and invokes the sensor alignment calibration software. The analyst uses the sensor alignment software to load and pre-process the new precision correction solution. This involves extracting the attitude and ephemeris position bias terms from the precision correction solution vector, applying the alignment matrix from the Calibration Parameter File to the attitude roll, pitch, and yaw bias estimates (to convert them to measurements of net alignment) and constructing an alignment observation covariance matrix from the precision correction solution covariance and an analyst-defined estimate of the random attitude error variance. The analyst then directs the alignment calibration software to integrate the new observation with the previous best estimate of the sensor alignment state vector, to produce a new alignment estimate. After reviewing the new alignment estimate and the associated filter statistics, the analyst accepts the new alignment state vector as the current best estimate. The current state estimate is stored for use as input to the next invocation of the sensor alignment calibration software. The precision correction data preprocessing and alignment state-filtering algorithms are described in more detail in [3].

After completing the alignment filtering operation, the analyst may decide that alignment knowledge has improved sufficiently to justify generating an update to the sensor alignment matrix in the Calibration Parameter File. This decision could also be driven by time: if a new Calibration Parameter File is to be generated at least once per quarter, the best available alignment estimate should be included. In this case, the analyst selects an option in the alignment calibration software which retrieves the current alignment state vector and computes the corresponding sensor alignment matrix for inclusion in the new version of the Calibration Parameter File. One of the geodetic test scenes would be reprocessed (using the updated alignment matrix) and tested to ensure that the parameter update is performing as expected prior to releasing the new Calibration Parameter File.

Alignment errors are indistinguishable from attitude errors in flight. The sensor alignment calibration will actually be compensating for errors in the alignment of the Celestial Sensor Assembly (CSA) to the Navigation Base Reference (NBR) as well as errors in the NBR to ETM+ alignment. As such, the "absolute" NBR to ETM+ alignment discussed above is actually relating the NBR as it is defined by the CSA to NBR alignment, to the ETM+. If the CSA alignment is updated post-launch, it will affect the observed ETM+ alignment. The likelihood of this occurring is low unless the MOC discovers significant on-orbit attitude data processing problems caused by poor pre-launch knowledge of the relative alignments of the CSA and the Inertial Measurement Unit (IMU) gyros.

Outputs: Each time precision correction data from a calibration scene becomes available, an image analyst will use the alignment calibration software to integrate the new observations into the current sensor alignment estimate. The outputs of this process include: 1) a new alignment filter state vector and covariance matrix; 2) a new entry in the table of attitude offset estimates and standard deviations; 3) a new entry in the table of orbit offset estimates and standard deviations; and 4) a new entry in the Kalman filter innovation sequence table which shows how well the new calibration scene data fit the alignment filter's prediction. As an option, the image analyst may decide to generate an update to the NBR to ETM+ alignment matrix for the Calibration Parameter File. In this case, the output consists of the nine terms of the alignment matrix which is used to rotate vectors from the spacecraft NBR coordinate system to the ETM+ coordinate system. This matrix is stored in the Attitude_Parameters data group of the CPF as the Attitude_To_ETM+_Matrix field.

Accuracy/Performance: Error propagation analysis has shown that the ability to estimate the alignment bias is less sensitive to the accuracy of the control points (assuming they are accurate to at least 50 meters) than to the number of independent test site observations. The error propagation model suggests that five or six test site observations, each containing at least 15 well distributed control points accurate to at least 15 meters (1 sigma) will be sufficient to achieve the 24 arc second alignment determination accuracy. A further description of the assumptions, methods, and results of this analysis can be found in [3].

3.2.3 Personnel

All of the geodetic test site characterization and calibration operations will be performed at the EROS Data Center. Support in generating definitive ephemeris data will be provided by the GSFC Flight Dynamics Facility. Additional acquisition scheduling support may be required from the Flight Operations Team at the Landsat 7 Mission Operations Center if special calibration scene acquisitions are required.

3.2.4 Schedule

Geodetic test sites will be processed as frequently as they can be acquired during the IOC phase. The number of scenes processed will depend on the spacecraft and instrument status as well as cloud-cover at the geodetic test sites. Once the initial sensor alignment calibration has been completed (to achieve the 24 arc-second alignment knowledge requirement) geodetic test site calibrations will be performed on a routine schedule to support system performance monitoring.

3.2.4.1 Pre-Launch Phase

Pre-launch geodetic test site operations are limited to the acquisition and preparation of ground control for the selected test sites. This is discussed in section 4.

3.2.4.2 IOC Phase

During the IOC phase, geodetic test site calibration will be required to refine the pre-launch sensor alignment knowledge in order to meet the system geodetic accuracy specification. The IAS will be used to process as many geodetic test site images as can be acquired during this period. The US test sites will be used to perform the initial sensor alignment calibration and to verify that the 250-meter accuracy requirement is met. Images of overseas test sites acquired during the IOC period will be used to identify and extract control point image chips if no suitable pre-launch source for this information is found. The overseas test sites will also be used to measure system geodetic accuracy to determine whether geodetic performance is consistent globally.

3.2.4.3 Operational Phase

During routine operations, geodetic test sites will be processed at least every two weeks and not more than twice per week, depending on the number of cloud-free test site scenes acquired. The US test sites will be used to monitor geodetic performance and measure the stability of the sensor to spacecraft alignment over time. Sensor alignment updates will be prepared for inclusion in new versions of the Calibration Parameter File as they are released, nominally once per quarter.

The overseas test sites will be used to acquire test scenes under varying conditions (e.g., ETM+ temperature, position in orbit) in order to provide a more comprehensive measure of geodetic performance. The geodetic accuracy results will be trended (using the IAS Evaluation and Assessment tools) against time, temperature, and WRS row to determine whether there are systematic alignment dependencies on any of these variables. Without requesting special calibration acquisitions the overseas sites would normally be acquired once per quarter. Special acquisitions will probably be required early in the mission to collect enough data to determine whether there is significant variability in geodetic performance. If nothing is detected, routine acquisitions will be sufficient to monitor global geodetic accuracy. If any anomalies are observed additional acquisitions will probably be required to isolate, characterize, and model the underlying phenomena.

3.2.5 Data Reduction

The geodetic test site data reduction performed by the IAS software is described in the precision correction, geodetic assessment, and sensor alignment calibration algorithm descriptions presented in [3]. Additional data reduction and analysis will be performed by the IAS Evaluation and Assessment (E&A) subsystem to trend the geodetic accuracy and sensor alignment calibration results. This will include generating plots of geodetic accuracy versus time, temperature, or WRS row and performing linear regressions using the same combinations of variables. It will also include plotting the sensor alignment precision correction solution results and corresponding alignment roll, pitch, and yaw bias estimates versus time to visually portray the extraction of the alignment trend from the attitude correction data.

3.3 Geometric Super-Site Characterization and Calibration

The term "geometric super-site" is used to describe those pre-selected WRS path-row locations for which ground control, digital terrain data, and reference imagery have been collected. This supporting data set makes it possible to produce precision and terrain corrected ETM+ images, and to compare them to accurately geo-registered reference images.

3.3.1 Objective

Geometric super-site test data sets will be used to detect and measure high frequency internal image distortions, especially those due to the ETM+ scan mirror motion. The set of characterization and calibration activities supported by the geometric super-sites includes geometric accuracy assessment, image-to-image registration assessment, and scan mirror calibration.

3.3.2 Methodology

Landsat 7 ETM+ image acquisitions covering one or two pre-selected geometric super-sites will be retrieved from the EDC DAAC and processed through the IAS Level 1 processing subsystem to create 1Gs (systematic) and 1Gt (precision/terrain corrected) image products. These processed images, along with the output of the precision correction process, will be used in three characterization and calibration operations. These include the IAS geometric accuracy assessment capability which presents the 1Gs and 1Gt ETM+ images to an IAS analyst for visual inspection, and analyzes the results of the precision correction solution used to produce the 1Gt image. This analysis tests the control point residual errors to determine whether there is significant uncompensated internal scale, offset, rotation, or non-orthogonality (skew) distortion in the corrected image.

Internal distortions are also assessed by measuring the accuracy with which multi-temporal images of the same WRS scene can be registered to each other. The IAS image-to-image registration assessment capability will be used to automatically correlate image features common to the newly generated 1Gt image and a previously generated reference 1Gt image of the geometric super-site, to sub-pixel accuracy. The measured image displacements will then be analyzed to determine whether the image products meet the IAS requirement to be able to register multiple images to within 0.4 pixels as defined in [2].

The behavior of the ETM+ scan mirror is measured and, if necessary, calibrated using the IAS scan mirror calibration capability. This process compares the 1Gt image to a high accuracy reference image constructed from a higher resolution source, to detect systematic deviations of the scan mirror motion from its nominal profile. The support data used to construct the 1Gt image is used to generate test points which can be related to a particular time within a particular forward or reverse scan. By comparing these test points to the reference image and analyzing the measured deviations as a function of scan direction and scan time, it will be possible to estimate corrections to the pre-launch scan mirror profiles, if needed.

The end-to-end geometric super-site operational flow, including Level 0R data retrieval, IAS Level 1 processing, and the three characterization and calibration operations just mentioned, is depicted in figures 3.3.2-1 through 3.3.2-4.

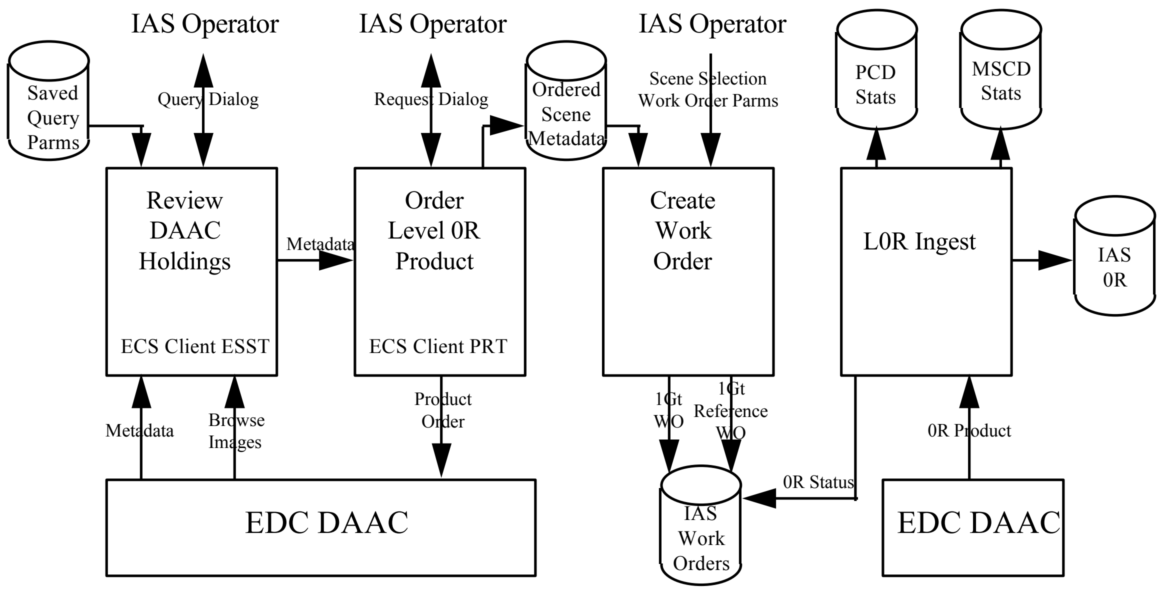

Figure 3.3.2-1: Geometric Super-Site Operational Flow - Step 1: Order & Receive Data

In the following figures, the 1Gt work orders using absolute and reference ground control points are shown as parallel flows. Where the content of common data items differs due to the use of reference control points, these items are shown shaded on the lower flow.

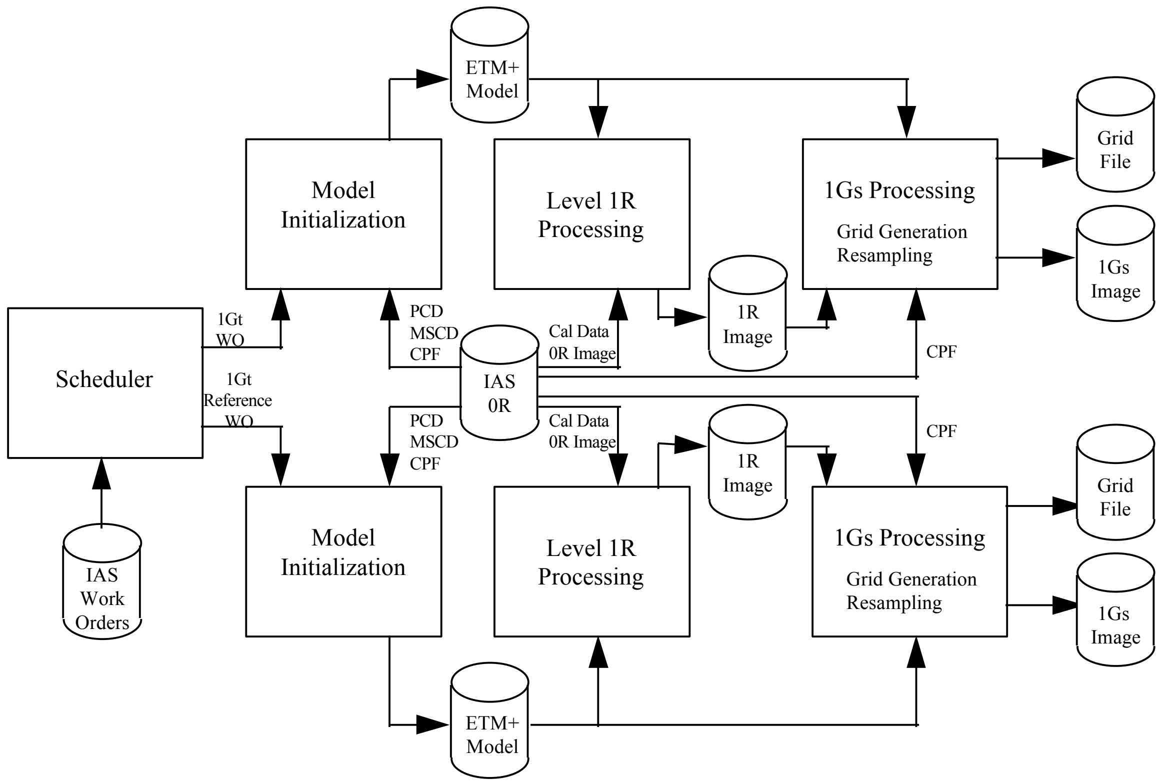

Figure 3.3.2-2: Geometric Super-Site Operational Flow - Step 2: Process 1Gs

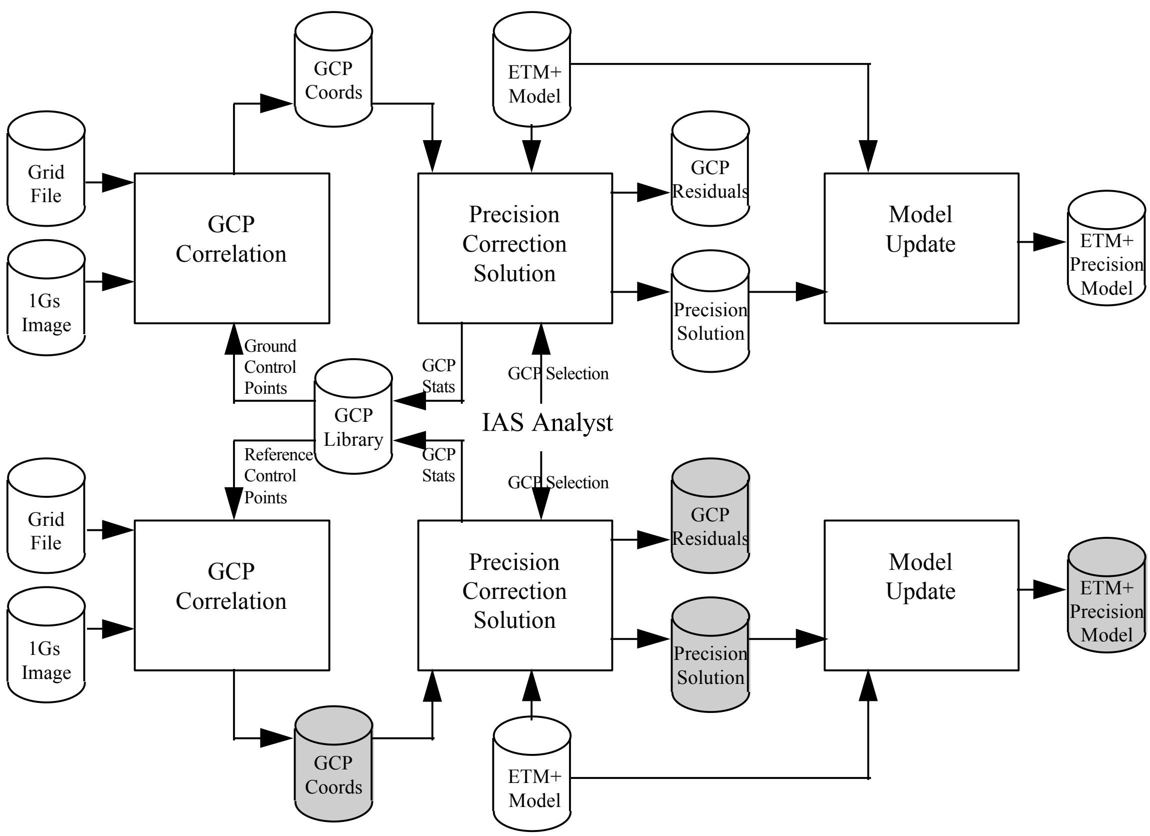

Figure 3.3.2-3: Geometric Super-Site Operational Flow - Step 3: Precision Correct

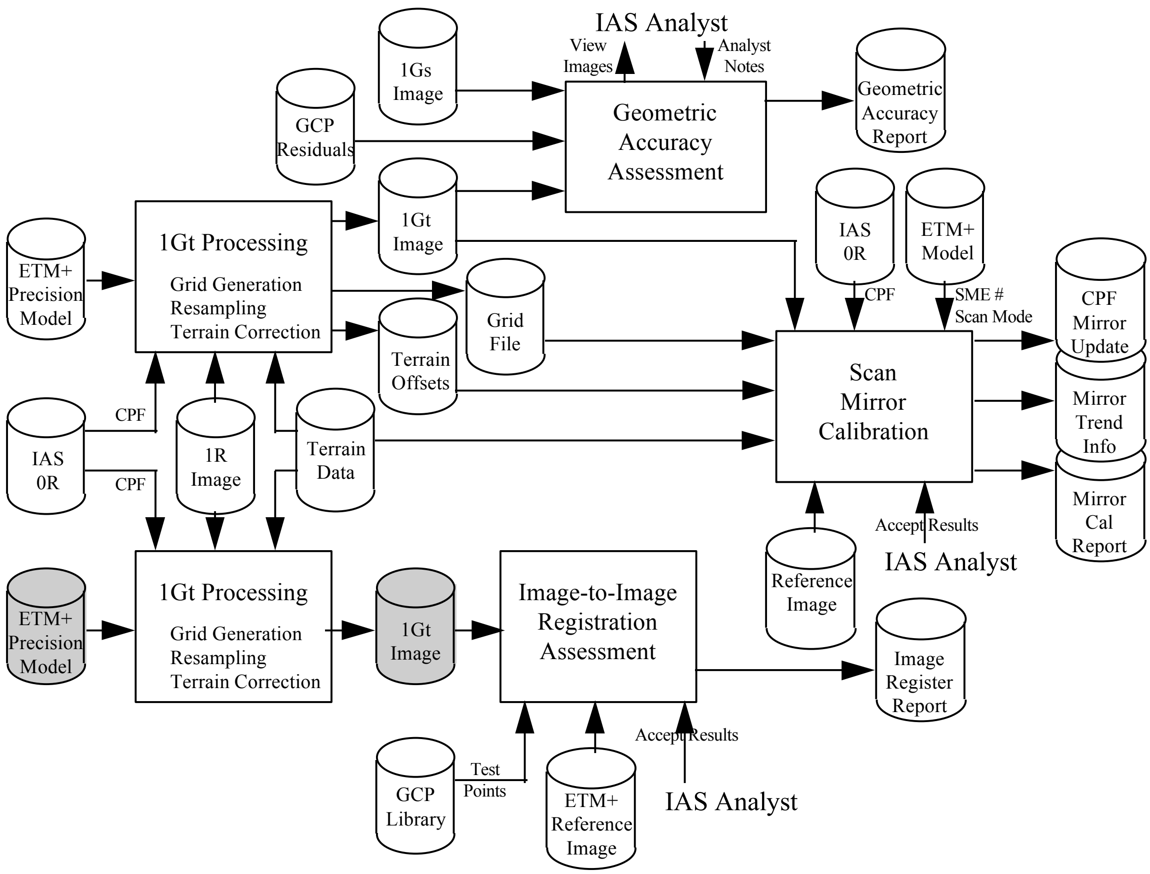

Figure 3.3.2-4: Geometric Super-Site Operational Flow - Step 4: Terrain Correct, Assess, and Calibrate

3.3.2.1 Geometric Accuracy Assessment

Purpose: The purpose of the geometric accuracy assessment is to evaluate Level 1 image products to detect residual internal image distortions such as scan to scan misalignment, excessive image rotation, scale error, or skewing.

Approach: Scan misalignment, scan mirror non-linear errors, and other high frequency image disturbances will be evaluated qualitatively by a visual inspection of the processed Level 1 imagery (all bands). Both Level 1Gs and 1Gt images will be produced and retained for inspection and analysis. The post-fit control point residuals from the precision correction solution will be used to quantitatively measure image offset, scale, rotation, and non-orthogonality (skewing) errors. The equations used to perform this analysis are presented in [3]. Geometric accuracy assessment could also be performed on the scenes used for geodetic accuracy assessment, but the anticipated frequency of this assessment (approximately once per month) makes this operation better suited to the geometric super-site operational flow.

Inputs: The minimum inputs required for the geometric assessment procedure are a subset of the data sets used for geometric super-site processing.

- Level 0R Product - Level 0R products are requested from and delivered by the EDC Distributed Active Archive Center (DAAC). The entire product (all image bands and supporting data) is required by the geometric accuracy assessment process.
- Ground Control - The ground control requirement for geometric assessment is the same as for the geodetic test site processes described above. The GCP image chips are correlated with the 1Gs panchromatic image generated using the 0R product data. Approximately 30-40 well distributed points are needed in each geometric super-site to make it possible to acquire at least 20 successful control point correlations in scenes with less than 20% cloud cover. One or two geometric super-sites will provide two to four opportunities to acquire test scenes in the US each month, and should result in one or two sufficiently cloud free scenes per month. No geometric super-sites will be selected outside the US.
- Digital Terrain Data - Digital elevation data for the super-site is required to perform the terrain correction. This data will be derived from Digital Terrain Elevation Data (DTED) products provided by the Defense Mapping Agency (DMA, now known as the National Imagery and Mapping Agency or NIMA). The DTED data will be preprocessed to match the pre-defined image frame used for the 1Gt images - Space Oblique Mercator (SOM) map projection, rotated to be approximately aligned with the nominal Landsat 7 ground track (path).

Procedure: All of the geometric super-sites will be within the Sioux Falls, South Dakota ground station's acquisition circle and will therefore be collected routinely. Each day, the IAS operator will query the EDC DAAC's Landsat 7 metadata holdings against the pre-defined list of geometric super-site WRS path-row coordinates to see if any new super-site acquisitions are available. If so, the cloud cover and image quality fields in the metadata and the browse images will be used to determine if the scene is sufficiently cloud-free to use for geometric accuracy assessment.

When a suitable scene is identified, the IAS operator orders it from the EDC DAAC and places a Level 1 processing work order requesting a 1Gt (terrain corrected) product for the scene. This work order will include a flag which indicates that the 1Gs image generated for control point mensuration (as part of the precision/terrain correction process) is to be saved for analysis. After the Level 0R data is delivered by the DAAC, the IAS ingest software loads and verifies the 0R data. After the 0R data is successfully loaded, the associated Level 1 processing work order is activated and executed by the IAS scheduling software. The IAS analyst monitors the status of calibration work orders submitted for processing. Once the Level 1 work order has been completed, the IAS analyst invokes the geometric assessment software and retrieves the control point residual data (including outlier flags) from the precision correction solution. The geometric assessment software computes a best fit six parameter polynomial using the control point residuals as described in [3], calculates the corresponding offset, scale, rotation, and skewing parameters, and presents the results to the analyst for review. The analyst reviews the control point residuals and the distortion parameters to determine if the geometric accuracy assessment is valid (i.e., enough points have been successfully correlated). If so, the analyst uses the IAS display tools to examine the 1Gs and 1Gt image files, looking especially for scan to scan discontinuities. While viewing the images, the analyst uses the geometric assessment graphical user interface window to enter notes or comments about any geometric artifacts observed. Once the visual inspection is complete, the geometric assessment software assembles the analyst's notes and the results of the polynomial fit to the control point residuals into a geometric assessment report. The assessment report is printed out to provide a hard copy record and the assessment results are stored for comparison with earlier assessments and geometric accuracy trend analysis.

Outputs: The only output from the geometric accuracy assessment process is the geometric quality report containing any notes or comments entered by the IAS analyst regarding observed visual anomalies, and the results of the control point residual polynomial fit. This includes measured scale errors in the map projection X and Y directions, the residual mean offset in the map X and Y directions, the residual rotation angle, and the angle of non-orthogonality or skewing. This information is displayed on the analyst's screen and is saved in a file for future trending and hard copy output.

Accuracy/Performance: The geometric accuracy assessment is primarily a qualitative evaluation of the Level 1G image geometry which would be used to trigger other more quantitative analyses if problems are detected. The geometric distortion parameters computed by the geometric assessment software can be scaled to image pixels using the equations presented in [3]. These distortions, expressed in pixels, should be no larger than the residual error in the precision correction solution as measured by the control point root mean square error.

3.3.2.2 Image-to-Image Registration Assessment

Purpose: The goal of the image-to-image registration assessment is to verify the IAS requirement that multi-temporal images of the same WRS scene can be successfully co-registered.

Approach: The image-to-image assessment procedure uses ground control points extracted from a previously generated 1Gt image to precision and terrain correct a new acquisition to Level 1Gt, and then performs a point by point comparison of the two images. Although this analysis could be performed using 1Gp images, terrain correction is applied so that the reference image can be used as a source of control chips in the normal IAS precision correction process. Control chips extracted from a 1Gp image would contain terrain offsets which could degrade the performance of the precision correction solution somewhat, even though these offsets would be largely replicated in the new acquisition due to the repeatability of the Landsat 7 viewing geometry. The image-to-image registration measurements are performed using automated image correlation techniques and the panchromatic bands of the newly generated and reference images. The panchromatic band is used to achieve the highest possible correlation measurement accuracy even though the 0.4 pixel registration specification is relative to the multi-spectral bands. The ability to register the panchromatic bands demonstrates the accuracy of the overall precision correction solution as well as the internal geometric fidelity of the images.

Inputs: The inputs to the image-to-image registration assessment process are slightly different from those used by the other calibration operations in the geometric super-site flow in that the source of ground control is a pre-existing 1Gt image rather than absolute ground control chips. In practice, these reference control points would be pre-extracted and loaded into the GCP library with a flag indicating that they are to be used for image-to-image registration only.

- Level 0R Product - Level 0R products are requested from and delivered by the EDC Distributed Active Archive Center (DAAC). The entire product will be provided but the image-to-image registration assessment process only requires the PCD, MSCD, CPF, calibration data, and the panchromatic band image data.
- ETM+ Reference Image - A reference Landsat 7 ETM+ 1Gt image will be stored in the IAS as the registration reference image. This image could be replaced during the life of the mission if significant ground cover change occurs at the geometric super-site. The super-sites used for image-to-image registration will be selected to minimize the likelihood of seasonal variations or scene content changes. Seasonal reference images will be used if the availability of support data forces the use of test sites with significant season-to-season variation.
- Reference Ground Control - Ground control image chips extracted from the 1Gt reference image will be stored in the IAS GCP library. The geodetic positions associated with these chips will be extracted from the 1Gt image along with the image chips so that they reflect the "as-built" reference image rather than actual ground truth. The reference chips will be identified by a special flag in the control point library so that they can be identified for use by the image-to-image registration process but will not be used for the other geometric super-site calibration operations.
- Digital Terrain Data - Digital elevation data for the super-site is required to perform the terrain correction. This is the same data set described for the geometric accuracy assessment procedure.
- Image-to-Image Test Point Locations - To achieve the best possible image-to-image correlation accuracy, test points will be pre-identified to ensure that they contain good target imagery. An analyst will select approximately 50 (TBR) points to provide a good distribution over the reference image and to be disjoint from the set of reference control points (to provide an independent evaluation of image-to-image registration). The reference image pixel/line locations of these points will be stored and used to guide the image-to-image comparison process.

Procedure: All of the geometric super-sites will be within the Sioux Falls, South Dakota ground station's acquisition circle and will therefore be collected routinely, as noted above. Each day, the IAS operator will query the EDC DAAC's Landsat 7 metadata holdings against the pre-defined list of geometric super-site WRS path-row coordinates to see if any new super-site acquisitions are available. If so, the cloud cover and image quality fields in the metadata and the browse images will be used to determine if the scene is sufficiently cloud-free to use for image-to-image registration assessment. Since a relatively dense array of test points must be matched to the reference image, the cloud cover tolerance for this operation will be more stringent than for the geodetic test sites or for geometric accuracy assessment.

When a suitable scene is identified, the IAS operator orders it from the EDC DAAC and places a Level 1 processing work order requesting a 1Gt (terrain corrected) product for the scene. This work order will include a flag which indicates that the ground control points used for the precision correction process are to be those extracted from the reference image. This would be indicated by selecting the reference rather than the absolute control option. Using reference control points will provide the best image-to-image rather than the best image-to-ground precision correction fit. After the Level 0R data is delivered by the DAAC, the IAS ingest software loads and verifies the 0R data. After the 0R data is successfully loaded, the associated Level 1 processing work order is activated and executed by the IAS scheduling software. The IAS analyst monitors the status of calibration work orders submitted for processing.

Once the Level 1 work order has been completed, the IAS analyst invokes the image-to-image registration assessment software which loads the pre-defined test point locations (from the GCP library) based on the test scene's WRS coordinates. The assessment software then performs image correlation between the 1Gt image and the reference scene at the test point locations, as described in [3]. The test point correlations are filtered to remove outliers caused by correlation failure. The valid test point image location differences and summary statistics are presented to the analyst for review. The test point residuals can be viewed in tabular form or they may be plotted in the form of an error vector plot on the analyst's display. The analyst also has the option to visually inspect either the new 1Gt or the reference image. Once the analyst determines that all outlier test points have been removed and the assessment results are valid, an assessment report is generated. This report is printed out to provide a hard copy record and is stored for future trending and analysis.

Outputs: The output of the image-to-image registration assessment process is an assessment report which contains the measured test point discrepancies and their summary statistics including: mean, median, and root mean square errors. These statistics are provided for each image coordinate separately and for the combined net error.

Accuracy/Performance: Error propagation analysis indicates that the image-to-image registration requirement is one of the most challenging. The expected internal random errors due to limitations in the scan mirror stability and the attitude sensor accuracy (which must be root sum squared to account for random errors in both the reference and object images) when combined with the test point correlation mensuration accuracy, use up most of the image registration error budget. Very little error budget margin is left for the precision correction solution process. This consideration motivates the use of the panchromatic band and pre-selected test points to minimize test point mensuration error.

3.3.2.3 Scan Mirror Calibration

Purpose: The scan mirror calibration will attempt to detect and measure systematic deviations of the ETM+ scan mirror motion from the profiles measured pre-launch. Any significant deviations detected will be folded back into the Calibration Parameter file as updates to the mirror profile polynomial coefficients.

Approach: This calibration applies in both the along and across scan directions so it will detect and compensate for Scan Line Corrector (SLC) deviations as well. In practice, SLC deviations will be indistinguishable from scan mirror deviations so we have chosen to model the deviations as part of the scan mirror motion. Detecting systematic deviations which can be attributed to mirror motion requires reference points which can be uniquely associated with individual forward and reverse ETM+ scans and which provide a good distribution of observations as a function of scan angle. The current approach to acquiring such a control reference is to use spatially accurate reference imagery for one or more calibration areas. The scan mirror calibration procedure will compare a precision and terrain corrected ETM+ panchromatic band image with the reference image constructed from USGS Digital Orthophoto Quadrangle (DOQ) data to detect within-scan mirror deviations. This involves constructing an array of points in the ETM+ scan geometry which are mapped to the output terrain corrected product. These points, with known scan number and time in scan coordinates will be correlated with the reference image to measure the (sub-pixel) residual distortion. The distortion patterns from many scans will be analyzed to detect systematic deviations from the pre-launch forward and reverse scan mirror profiles.

Inputs: The inputs required by the scan mirror calibration procedure include those used for geometric accuracy assessment as well as a high precision, non-ETM+ reference image.

- Level 0R Product - Level 0R products are requested from and delivered by the EDC Distributed Active Archive Center (DAAC). The entire product will be provided but the scan mirror calibration process only requires the PCD, MSCD, CPF, calibration data, and the panchromatic band image data.
- High Resolution Reference Image - A reference image will be generated from a high resolution source, such as USGS Digital Orthophoto Quadrangle (DOQ) data. An independent reference image source which does not contain any residual ETM+ scan mirror distortions will make it easier to isolate these effects in the ETM+ 1Gt image. The reference image will be resolution reduced to 15 meter equivalent resolution for correlation with the ETM+ panchromatic band. The reference image will be created using the SOM map projection with a slight rotation to provide nominal alignment with the ETM+ scan orientation. This standard frame will provide approximate alignment with the ETM+ scans without requiring the reference image to be regenerated each time to match a uniquely framed, path oriented ETM+ product. The difficulty in creating these reference images leads us to seek geometric super-sites for which DOQ data are available, which are likely to be cloud free, and which are in geographical areas where the likelihood of seasonal variations or scene content

changes is minimized. This has proven difficult to achieve given the current availability of DOQ data.

- Ground Control - The ground control requirement for geometric assessment is the same as for the geodetic test site processes described above. The GCP image chips are correlated with the 1Gs panchromatic image generated using the 0R product data. If possible, the GCP chips used for geometric super-site processing will be created pre-launch from a higher resolution image source (such as the DOQ data used to create the scan mirror reference image). Selecting the point locations in a high resolution image will make it possible to reduce the point identification component of the overall ground control point error. Coupling this with geodetic positions established from Global Positioning System (GPS) field surveys would provide the highest absolute accuracy ground control. However, for scan mirror calibration it is the geometric registration between the DOQ reference image and the ETM+ image which is of paramount importance. With this in mind, current plans call for using the DOQ data as the source for ground control, with GPS field surveys used only to verify the accuracy of the DOQ products.
- Digital Terrain Data - Digital elevation data for the super-site is required to perform the terrain correction. This will probably be the same data set described for the geometric accuracy assessment procedure, however, if the geometric super-sites contain significant relief it may be necessary to use terrain data derived from USGS Digital Elevation Models (DEMs) which have a finer grid spacing (30 meters versus 3 arc-seconds) and higher accuracy (7 meters versus 50 meters) than the DTED data.

Procedure: Each day, the IAS operator will query the EDC DAAC's Landsat 7 metadata holdings against the pre-defined list of geometric super-site WRS path-row coordinates to see if any new super-site acquisitions are available. If so, they will be evaluated as described above, to determine their suitability for scan mirror calibration. As with image-to-image assessment, a dense array of test points must be matched to the reference image, so the cloud cover tolerance for this operation will be more stringent than for the geodetic test sites or for geometric accuracy assessment.

When a suitable scene is identified, the IAS operator orders it from the EDC DAAC and places a Level 1 processing work order requesting a 1Gt (terrain corrected) product for the scene. This work order will include a flag which indicates that the geometric correction grid, digital terrain data, and terrain correction look-up table used to create the terrain corrected product are to be saved for analysis. After the Level 0R data is delivered by the DAAC, the IAS ingest software loads and verifies the 0R data. After the 0R data is successfully loaded, the associated Level 1 processing work order is activated and executed by the IAS scheduling software. The IAS analyst monitors the status of calibration work orders submitted for processing. Once the Level 1 work order has been completed, the IAS analyst invokes the scan mirror calibration software. This software uses the geometric correction grid for the panchromatic band to generate an array of test points which fall entirely within ETM+ scans. These test points are correlated with the reference image to assemble sets of output space deviations (which can be related back to the ETM+ scan time) for both forward and reverse scans. After outlier rejection, the measured test point deviations are then mapped back to the ETM+ instrument using the terrain elevation at the test point location (from the digital elevation data), the terrain correction look-up table, and the geometric correction grid. This provides measurements of along scan and across scan deviation as a function of scan time.

The along and across scan deviations for the forward and reverse scans are each fitted to a set of Legendre polynomials to determine whether there is any significant systematic deviation for either scan direction. The mathematics underlying this process is described in [3]. The results of this processing are displayed to the IAS analyst for review and evaluation. If the Legendre polynomials demonstrate systematic deviations which exceed the allowable random mirror variation of 1.75 microradians, the analyst may decide to generate a new set of mirror profile coefficients for the Scan Mirror Electronics (SME) number (one or two) and scan mode (scan angle monitor or bumper) used to collect the test scene. This is done by reading the appropriate mirror profile fifth order polynomial coefficients out of the Calibration Parameter File, converting them to Legendre polynomial form, adding the computed Legendre coefficients, and regenerating the mirror profile. This procedure is also described in [3]. These coefficients would be output along with the SME number and scan mode, for inclusion in an update to the Calibration Parameter File. The geometric super-site test scene would be reprocessed (using the updated mirror profile) and assessed to ensure that the parameter updates were providing improved performance prior to releasing the new Calibration Parameter File.

Outputs: The outputs of the scan mirror calibration procedure include the generated test point locations, the measured test point deviations, the corresponding best fit Legendre polynomial coefficients, the test image SME number and scan mode, and, if the analyst selects the mirror profile update option, a new version of the scan mirror profile coefficients appropriate to the SME number and mode. These coefficients would be used to populate the appropriate mirror coefficient fields in the Mirror_Parameters data group of the CPF.

Accuracy/Performance: Error propagation analyses to determine accuracy requirements for the reference imagery, the geodetic control used for precision correction, and the supporting terrain data suggest that the specified accuracy of the DOQ data (6 meters CE 1 sigma) will meet the requirements for both reference image and geodetic control accuracy. Further analysis is ongoing to determine whether three arc-second DTED data (50 meter LE 90%) or 30 meter USGS DEM data (7 meter LE 90%) will be needed to provide the supporting terrain information. Although the DOQ specifications suggest that this will be a suitable source of reference imagery, the EDC expects to perform GPS field surveys to verify the DOQ accuracy. These GPS points could then also be used to provide a high accuracy control network for at least one of the calibration scenes. Current limitations in DOQ availability have restricted the options for test area locations. The only scan mirror calibration site identified so far is in southwestern Minnesota. Additional sites should become available as DOQ production progresses.

3.3.3 Personnel

All of the in-flight geometric characterization and calibration operations will be performed at the EROS Data Center.

3.3.4 Schedule

Significant effort will be expended in the pre-launch phase to assemble the geometric super-site supporting data sets, particularly the high resolution reference imagery. At least two acquisitions of the same geometric super-site will be needed during the IOC period in order to perform the image-to-image registration characterization. One or both of these would be used to perform geometric accuracy assessment and scan mirror calibration operations to ensure that the ETM+ is functioning as expected. If any problems are detected, as many cloud-free images of the test sites as can be acquired would be used to perform a scan mirror calibration update. During the routine operations phase the entire suite of geometric super-site calibration operations would be performed two or three times per quarter, with a summary report generated once per quarter, to monitor system performance.

3.3.4.1 Pre-Launch Phase

Assembling the pre-launch geometric super-site support data will require significant effort due to the effort required to acquire and manage the USGS DOQ reference imagery and the extensive preprocessing required to prepare it for use in the IAS. Hundreds of 3.75 arc-minute DOQ files must be mosaicked and resolution reduced to produce one reference image. This is discussed in section 4.

3.3.4.2 IOC Phase

During the IOC phase, geometric super-site calibration will be required to verify the image-to-image registration accuracy specification. The IAS will be used to process at least two acquisitions of the same super-site during this period. The most cloud-free of the two will become the initial reference image for subsequent image-to-image assessments. These first two images will be used to perform the initial verification of the 0.4 pixel image registration requirement. The first geodetic or geometric test site acquired will be processed through the geometric accuracy assessment procedure so that this assessment can be performed as soon as a test scene with ground control becomes available. In the case of a geodetic test scene, the assessment would be performed using a 1Gp image and the geometric assessment would be invoked manually as an ad hoc analysis after completion of the geodetic test site operational flow. Scan mirror calibration will be performed on the first available geometric super-site image to verify the performance of the ETM+ scan mirror.

3.3.4.3 Operational Phase

During routine operations geometric super-sites will be processed at least quarterly and not more than once per month, unless observed geometric performance problems prompt more frequent review. The geometric super-sites will be used to monitor geometric performance and measure the stability of the ETM+ scan mirror profile over time. Scan mirror profile updates will only be candidates for inclusion in new versions of the Calibration Parameter File if the mirror is observed to be performing outside of its specifications using the pre-launch profiles.

3.3.5 Data Reduction

The data reduction performed by the IAS precision correction, terrain correction, geometric accuracy assessment, image-to-image registration assessment and scan mirror calibration software is described in [3]. Additional data reduction and analysis will be performed by the IAS Evaluation and Assessment (E&A) subsystem to trend the geometric distortion parameters, the image-to-image registration accuracy, and the scan mirror calibration results. This will include generating plots of the geometric distortions or the image-to-image registration accuracy versus time, temperature, or WRS row and performing linear regressions using the same combinations of variables. It will also include plotting the computed scan mirror profiles as functions of scan time and comparing them to plots of the scan mirror profiles from the CPF. This will provide a visual check on the measured variation of the scan mirror motion.

3.4 Focal Plane Calibration Activities

Landsat 7 ETM+ images of focal plane calibration test sites will be used to measure and calibrate the internal alignment of the detectors on the two ETM+ focal planes. These test sites are selected based on image content rather than the availability of supporting data. Band to band registration assessment requires scenes which contain significant high spatial frequency content that is common to all eight ETM+ bands. Although it is anticipated that scenes with long linear features would be used to assess the alignment of individual detectors, detector placement calibration techniques are still under investigation and are not discussed in detail in the following sections.

3.4.1 Objective

The focal plane calibration operations will measure the alignment of the eight ETM+ bands to ensure that band registration accuracy meets the 0.28 pixel requirement as stated in [2]. If the band-to-band comparisons detect any uncompensated misalignment the band placement calibration procedure will be used to update the band center location parameters in the Calibration Parameter File accordingly. Detector to detector alignment will also be monitored to ensure that image discontinuities are not introduced by using incorrect detector locations and delays in the Level 1G image resampling process.

3.4.2 Methodology

Landsat 7 ETM+ images from pre-selected WRS path-row locations will be used to assess the band-to-band registration of 1Gs images processed by the IAS level 1 processing software. These focal plane calibration test sites will be selected to provide images with high spatial frequency content that will be visible in all eight ETM+ bands. Arid regions with little vegetation but with some human development (e.g., road, railroads, towns) and some open water (e.g., reservoirs) provide good target areas for this type of assessment. When mostly cloud-free (less than 20%) acquisitions of the candidate WRS scenes become available in the EDC DAAC, they will be retrieved and processed to level 1Gs by the IAS. All eight bands will be included in the 1Gs product. An IAS analyst will select 50-100 (TBR) test point windows where image features which are visible in all bands are present. Automated image correlation will then be used to measure the sub-pixel band to band displacements at each test point. The measured displacements will be assessed to determine if the band alignment specification is met. The cross-band measurements collected by the band-to-band registration assessment process can be used by the band placement calibration procedure to compute improved estimates of the band center focal plane locations in order to improve registration accuracy, if necessary. Band alignment will be measured over a variety of acquisition conditions to ensure that the registration accuracy specification is met over the life of the mission.

Detector alignment will be assessed using test scenes from pre-selected WRS locations known to contain long linear features. Lake Ponchartrain, Louisiana is one such site. Detector alignment will be verified by examining the linear features for sub-pixel discontinuities. The algorithms to be used to perform this linear feature analysis are still under development. Detailed procedures for this assessment and any subsequent detector placement and delay calibration will be provided when available and are not discussed further in this document.

The operational flow for focal plane calibration is depicted in figures 3.4.2-1 through 3.4.2-3.

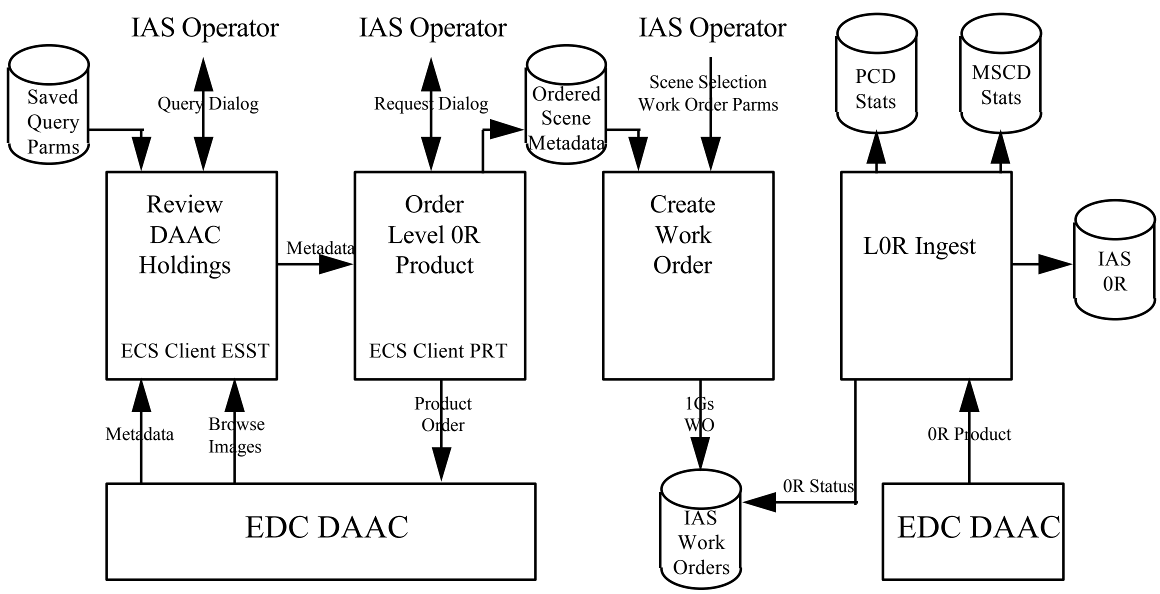

Figure 3.4.2-1: Focal Plane Calibration Operational Flow - Step 1: Order and Receive Data

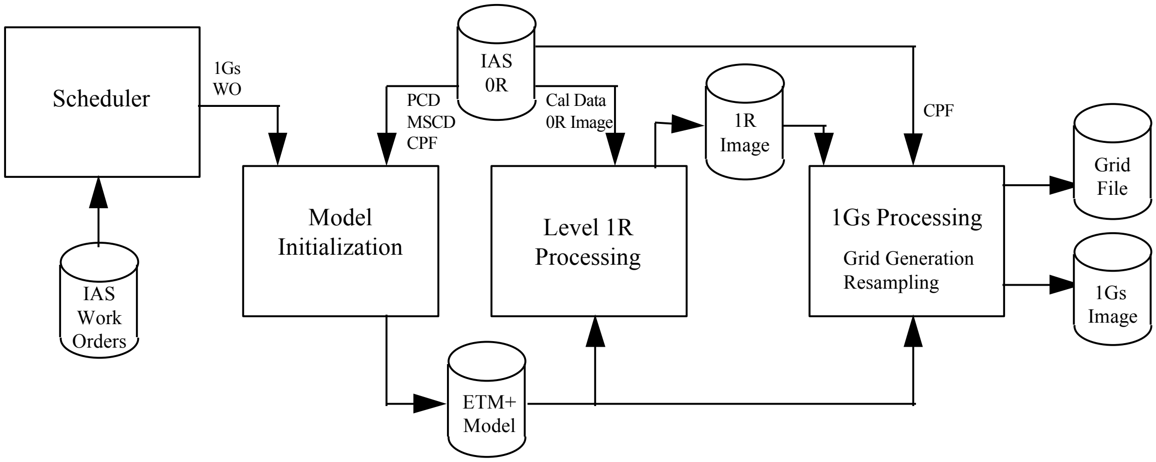

Figure 3.4.2-2: Focal Plane Calibration Operational Flow - Step 2: Process 1Gs

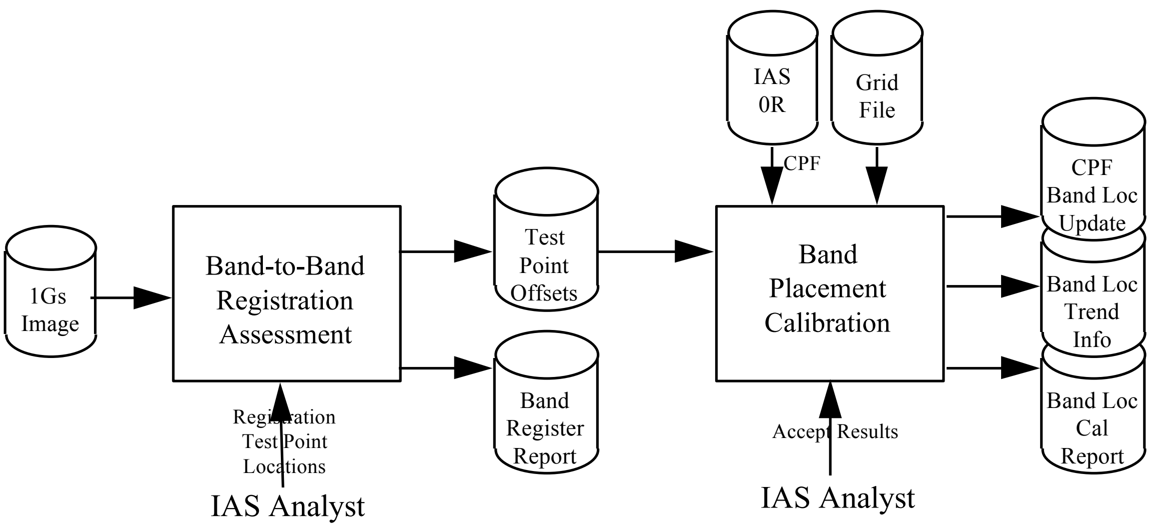

Figure 3.4.2-3: Focal Plane Calibration Operational Flow - Step 3: Assess and Calibrate

3.4.2.1 Band-to-Band Registration Assessment

Purpose: The objective of the band-to-band registration assessment is to measure the relative alignment of the eight ETM+ spectral bands after processing to Level 1Gs to verify that the 0.28 pixel band-to-band registration requirement, as stated in [2], is met.

Approach: Test scenes which contain significant high spatial frequency content and have relatively uniform spectral response over the eight ETM+ bands will be retrieved from the EDC DAAC and processed to Level 1Gs using the IAS Level 1 processing capability. Desert scenes with little vegetation are good candidates - a scene from southeastern California (Edwards Air Force Base area) has been used successfully in prototype testing. Common points (selected manually or generated automatically in a regular grid) are correlated across each band-pair using sub-pixel peak estimation to measure the small band-to-band displacements. Image pyramid pixel aggregation will be used to reduce the resolution of the panchromatic band (band 8) to equal the other reflective bands, and to reduce the resolution of the reflective bands for comparison with the thermal band (band

6). The band-to-band measurements are made at the coarser band resolution so that the measurements can be related directly to the alignment specification which is referenced to the lower resolution band.

Inputs: The only input required by the band-to-band registration assessment procedure is a Level 0R product covering one of the band alignment calibration test sites.

Procedure: Since there are no special support data requirements for band alignment calibration sites, a global set of candidate WRS locations will be identified to provide a variety of acquisition conditions for band-to-band registration assessment. Each day, the IAS operator will query the EDC DAAC's Landsat 7 metadata holdings using the list of band/detector calibration WRS path-row coordinates to see if any new test site acquisitions are available. If so, the metadata cloud cover and image quality fields and the browse images will be used to determine if the scene is sufficiently cloud-free to use for band-to-band registration assessment. Since any recognizable image feature likely to appear in all bands can be used as a target for band-to-band registration, the cloud cover constraints on band calibration test sites are less severe than for the other calibration operations.

When a scene suitable for band registration assessment is identified, the IAS operator orders it from the EDC DAAC and places a Level 1 processing work order requesting a 1Gs product for the scene. The work order will include a flag indicating that the geometric correction grid used to create the 1Gs product is to be saved for analysis. Although not required for the band-to-band registration assessment itself, the grid file is needed for the band placement calibration operations which follow. After the Level 0R data is delivered by the DAAC, the IAS ingest software loads and verifies the 0R data. Once the 0R data is successfully loaded, the associated Level 1 processing work order is activated and executed by the IAS scheduling software.

The IAS analyst monitors the status of calibration work orders submitted for processing. Once the Level 1 work order has been completed, the IAS analyst invokes the band-to-band registration assessment software. This software preprocesses the Level 1Gs image product, performing resolution reduction on bands 1-5, and 7 to create 60 meter resolution versions for comparison to band 6, and creating 30 meter and 60 meter resolution versions of band 8 for comparison with the other bands. The resolution reduction process uses a Gaussian pyramid approach and is described in [3]. The resolution reduction processing could also be performed as part of the automated work order, prior to analyst intervention. After the preprocessing is complete (or perhaps in parallel) the IAS analyst views the 1Gs image and interactively identifies candidate registration points, looking at all bands to verify that the points are suitable for all band-pairs. The software will also include an option to automatically generate a test point grid for use in scenes with rich cross-band feature content and little or no cloud cover. Once the test points are identified, the assessment software performs band-to-band correlation to measure the sub-pixel band displacements at each point. The results of the image correlation process are filtered for outliers and summarized in the form of average band differences with associated standard deviations. The assessment process is described in detail in [3].

Outputs: The band-to-band registration assessment procedure creates two outputs: 1) a file containing the band alignment test point measurements with outliers flagged; and 2) an assessment report which shows the band registration errors computed from the test point measurements. The band alignment test point file is saved for use by the band placement calibration software. The report is printed out to provide a hard copy record of the assessment, and is also saved for future trending and analysis.

Accuracy/Performance: Experiments performed during the development of the band-to-band registration assessment algorithm have shown that cross-band correlation accuracy of 0.25 pixels or better is achievable with randomly selected targets, given a suitable source image. Correlation performance of 0.1 pixels can be achieved with targets selected by an analyst. Averaging over 50 automatically generated points yields an expected accuracy for the mean band offset on the order of 0.04 pixels. This accuracy should be sufficient to verify that the band differences are all less than 0.28 pixels.

3.4.2.2 Band Placement Calibration

Purpose: The purpose of band placement calibration is to estimate improved values for the band center locations on the ETM+ primary and cold focal planes for inclusion in an updated version of the Landsat 7 Calibration Parameter File.

Approach: The band-to-band registration test point measurements collected by the band-to-band registration assessment procedure are observations in a least squares solution for the best fit updates to the band center locations. The panchromatic band is used as the reference for this solution since it is the band used to perform the other calibrations (sensor alignment, scan mirror). Since all twenty-eight band-pairs are measured in the band-to-band assessment, the solution for the remaining seven sets of band center offsets is over determined.

Inputs: The inputs required by the band placement calibration procedure are:

- The Calibration Parameter File from the Level 0R data product (acquired over a focal plane calibration test site) which was processed to Level 1Gs for use in the band-to-band registration assessment process.
- The geometric grid file (created by the IAS Level 1 processing software) used to create the Level 1Gs product.
- The band displacement measurements output by the band-to-band registration assessment.

Procedure: The band placement calibration procedure is performed on the same test scenes used for band-to-band registration assessment, and uses the output of the assessment process to perform further analysis and calibration parameter estimation. Test scene acquisition and band-to-band registration processing are performed as described above. The IAS analyst then invokes the band placement calibration software and loads the band registration test point file created by the band-to-band assessment software. The band placement calibration software converts the band displacements measured in the 1Gs product to focal plane offsets (using the geometric grid file) and performs a least squares fit to estimate band center offsets for bands 1-7, relative to band 8. The software also computes residuals for the measured test points and summarizes the residuals by band so that the analyst can determine whether the measurements from the 28 possible band-pairs have produced a consistent result.

The analyst reviews the results of the solution, withholding additional test points and repeating the least squares process if necessary. If the solution is acceptable, the current values of the band center locations are read from the Calibration Parameter File used to create the 1Gs product. The computed band center updates are added to the CPF values and the resulting band center location estimates are stored for trending. The band center estimates and the test point residuals and summary statistics are compiled in a band placement calibration report which is printed out to provide a hard copy record, and saved for future trending and analysis.

After several band placement calibration operations have been performed, the IAS analyst will review the results and determine if a band center calibration update is needed. If so, the analyst selects one or more band center location estimates for use in generating an update to the Calibration Parameter File. The estimates computed from individual images are averaged to produce a new set of band center offsets for inclusion in a new version of the CPF.

Outputs: The band placement calibration procedure produces a new set of band center field angles for inclusion in the Focal_Plane_Parameters data group of the Calibration Parameter File in the Along_Scan_Band_Center_Locations and Across_Scan_Band_Center_Locations fields (TBR). It also produces a report containing the computed residual errors for each of the input band displacement measurements and summaries of the residuals by band-pair to demonstrate the internal consistency of the solution. This report would be printed out, to provide a hard copy record, and saved for future analysis and trending.

Accuracy/Performance: Error propagation analysis has been used to predict the expected accuracy of the band placement calibration procedure. This analysis is presented in [3]. This analysis is based on the assumption (verified by the empirical evidence collected to date) that a band-to-band correlation accuracy of 0.25 pixels can be reliably achieved. It shows that measuring 50 band-to-band test points in each of the reflective band pairs (1-5,7-8) and 75 test points in all band pairs which include the thermal band (band 6) yields an estimation error covariance of less than 0.18 arc-seconds for all of the band center locations. This meets the IAS requirement for field angle determination accuracy stated in [2].

3.4.2.3 Detector Placement/Delay Calibration

Purpose: The purpose of detector placement/delay calibration is to verify and, if necessary, update the pre-launch values for the individual offsets for each detector on the two ETM+ focal planes.

Approach: An initial approach to performing detector placement/delay calibration has been developed and tested. Further development of this algorithm has been deferred to post-launch based on the accuracy limitations of the initial method as compared to the expected high accuracy of the pre-launch detector location and delay measurements. Detector placement/delay calibration will not be part of the IAS at-launch geometric calibration tool set.

Inputs: TBD

Procedure: TBD

Outputs: TBD

Accuracy/Performance: TBD

3.4.3 Personnel

All of the band/detector calibration operations will be performed at the EROS Data Center.

3.4.4 Schedule

Focal plane test site selection will be performed pre-launch, focusing on candidate sites for band-to-band registration assessment. Sites for detector calibration will be identified in conjunction with continued development of the associated algorithms. During the IOC period, focal plane calibration will be performed as soon as possible and as often as possible to detect any focal plane launch shift and to verify the stability of the band alignment. Once the Landsat 7 system enters normal operations the frequency of focal plane calibration operations will decline and the focus will change to monitoring the band alignment stability and searching for second order alignment variations which can be attributed to thermal variations.

3.4.4.1 Pre-Launch Phase

Pre-launch focal plane calibration activities will include selecting an initial set of band registration test sites and continuing development of the detector placement calibration algorithm. Band registration test sites will be selected based on scene content and geographical distribution. A globally distributed set of sites is desirable to enable the collection of band registration test scenes under a variety of acquisition (i.e., thermal) conditions. Historically, some thermal sensitivity in the relative alignment of the primary and cold focal planes has been observed in Landsat 4/5 data. Test sites will be selected to detect, characterize, and model this effect, if it exists in Landsat 7.

Detector placement/delay technique development will continue in a research and development mode. Deployment of an operational capability to perform detector calibration will be deferred until after launch.

3.4.4.2 IOC Phase

The main goal of focal plane calibration activities during the IOC phase will be to verify that the primary and cold focal plane alignment was not disturbed during launch. Band-to-band registration assessments will be performed as soon as suitable Level 0R data sets become available. Band calibration test sites in the US will be processed at every opportunity during IOC. These data sets will be used to verify band-to-band registration stability and to provide enough band alignment data to perform an initial post-launch band placement calibration.

3.4.4.2 Operational Phase

Routine band-to-band registration assessment and band placement calibration will be performed once or twice per month using US test sites. These operations will monitor the band alignment and determine whether CPF updates are required. Additional test scenes from the global set will be processed and the results saved for trending. The combined workload for US and global scenes is expected to average one scene per week.

3.4.5 Data Reduction

The data reduction performed by the band-to-band registration assessment and the band placement calibration procedure are described in [3]. Additional data reduction and analysis will be performed by the IAS E&A subsystem to trend the computed band center locations as functions of time and temperature. This will include generating plots of band center location trajectory over time and plots of along and across scan offsets, by band and by focal plane, versus ETM+ on-time or focal plane temperature. The band center locations will also be analyzed by performing linear regressions of the offsets versus temperature to determine if there is a systematic effect which could be included in the ETM+ geometric model.

4.0 Geometric Calibration Data Requirements

The geometric characterization and calibration operations described above require three primary types of supporting information: ground control points, reference images, and digital terrain data. The required characteristics, potential sources, and preprocessing requirements for each of these support data types are described in the following subsections.

4.1 Ground Control Points

The Landsat 7 IAS will use ground control for two of its geometric characterization and two of its geometric calibration activities: geodetic characterization, image to image registration characterization, sensor alignment calibration, and scan mirror calibration. In each case, the ground control points will be used to perform a precision correction solution, the results of which will be used in subsequent analysis. Since the control point accuracy and distribution requirements are similar for all of these algorithms, common test sites will be used as much as possible to reduce the volume of ground control which must be collected to support IAS operations.

4.1.1 Characteristics

Current plans call for two sets of test scenes, one set in the United States, selected to be at approximately the same latitude to provide consistent acquisition conditions (position in orbit, ETM+ time-on), and one set distributed over the range of WRS rows. The second set is intended to provide a range of orbital geometry and thermal conditions to determine whether and how the ETM+ alignment varies under conditions different from the nominally stable primary calibration sites. Specific test scenes have not yet been selected, but current investigations are focusing on selecting scenes every 10 degrees of latitude along a WRS path in the range 168 through 174. The availability of maps and reference imagery (for chip extraction) is being investigated in cooperation with the EOS-AM1 ASTER, MISR, and MODIS instrument teams through the Science Working Group for the AM Project (SWAMP) Ground Control Working Group.

4.1.2 Source

The test site control geodetic accuracy requirements can be met using published maps (1:24,000-scale in the US, 1:50,000-scale abroad). Although not strictly necessary, it is desirable to have a pre-launch set of GCP image chips available to support automated control point correlation at launch. Alternatively, control could be manually identified in ETM+ panchromatic band imagery as it becomes available for the test sites during initial operations. To generate pre-launch control chips, it is necessary to identify a source of sufficiently high resolution reference imagery which closely matches the panchromatic band's spectral characteristics, and is available for the test sites. Current plans call for acquiring USGS Digital Orthophoto Quadrangle (DOQ) data for the US test sites to provide panchromatic image chips. SPOT panchromatic data could be acquired for all of the test sites but cost considerations have led to a baseline assumption that the US test sites will have pre-launch control chips generated from DOQ data while the overseas sites will have chips created post-launch using the ETM+ panchromatic data. Imagery from the Japanese ADEOS AVNIR instrument and the Indian IRS-1C have recently become available and are also being investigated as possible sources for control point image chips outside the US.

4.1.3 Preprocessing Requirements

Reference images oriented to either north-up or to the Landsat 7 path, will be generated and used for chip extraction. Reference image control point locations will be measured to sub-pixel accuracy by analysts at the EDC. Image chips surrounding the identified point will be extracted for inclusion in the control point library. The control point geodetic positions will be measured on USGS 1:24,000-scale maps using the high precision digitizing systems in place at the EROS Data Center. The geodetic positions will be converted to NAD83/WGS84 if NAD27 maps are used in the digitizing process. The point elevations will be read off the maps as spot heights or interpolated from contours. These elevations will be checked against the digital terrain data if available. The mean sea level elevations will be converted to WGS84 ellipsoid heights by applying the geoid separation prior to entry into the control library. This conversion is necessary to account for the possibility of using high precision definitive ephemeris in the precision correction process. The precision correction algorithms are based on the geometry of the WGS84 ellipsoid and do not consider the actual deviations of mean sea level from the ellipsoid. If the ephemeris is locked down in the precision correction solution, it cannot adjust to compensate for the local geoid separation.

Absolute ground control points, reference image control points, and test points will all be stored in a GCP library which will contain the reference image chips and WGS84 geodetic positions as well as metadata which describes each control point. This metadata will include information about the image chip:

- sub-pixel location of the reference point corresponding to the geodetic position (i.e., the sub-pixel line, sample coordinates of the point corresponding to the recorded latitude, longitude, height),
- chip map projection,
- pixel size (in meters),
- orientation (grid north up or path oriented),
- chip size (in pixels),
- chip image source (e.g., ETM+ or DOQ),
- band(s) used in the chip,
- chip image acquisition date,
- date loaded into the library,
- type of control point (absolute, reference, or test),
- number of times the point was successfully used, number of times the point was unsuccessful, mean residuals, and mean square residuals.

4.2 Reference Images

Two types of reference images are used by the geometric super-site calibration operations described above. The first type, are terrain corrected ETM+ products previously generated by the IAS, used in the image-to-image registration assessment process. These reference images will be generated by processing Landsat 7 0R data through the IAS Level 1 processing software after launch, and are not discussed further here. The second type of reference images are constructed pre-launch using a high resolution image source. These images are used to provide the reference for scan mirror calibration as described above. These reference images are the subject of the remainder of this section.

4.2.1 Characteristics

The key characteristics of the scan mirror reference images are: 1) high absolute geodetic accuracy (including removal of any terrain displacement effects); 2) internal geometric integrity (no systematic internal distortions which could be confounded with ETM+ scan mirror effects); 3) spectral similarity to the ETM+ panchromatic band; 4) resolution as good or better than the ETM+ panchromatic band; and 5) availability in areas of minimal seasonal change and low average cloud cover. Geodetic accuracy of one-half of a panchromatic pixel (7.5 meters) should be sufficient although higher accuracy would be desirable. The internal geometry requirement disqualifies ETM+ itself as a source of reference imagery. Imagery from frame cameras or linear array sensors would be good candidates. High resolution panchromatic imagery from aerial photographs which meets the geodetic accuracy requirement has been available for years. Panchromatic satellite imagery is available from SPOT and, more recently ADEOS/AVNIR and IRS-1C, with more commercial missions planned, but the ability to achieve the geodetic accuracy requirement with these sensors remains to be proved.

4.2.2 Source

The most promising source of high resolution reference imagery identified to date are the Digital Orthophoto Quadrangles (DOQ) produced by, and under contract to, the USGS. The DOQs are created by digitizing and analytically orthorectifying panchromatic aerial photography. The DOQ products are distributed as 3.75 arc-minute quarter quads at one meter resolution. The DOQ geodetic accuracy is specified to meet National Map Accuracy Standards (NMAS) for 1:24,000-scale maps. This standard calls for a circular error (CE) of 40 feet at the 90% confidence level which converts to approximately 6 meters CE one sigma. This meets the one-half ETM+ pixel requirement. The most important problem with the DOQ data is its current limited availability, particularly the lack of large contiguous areas of DOQ coverage which could be used to assemble reference images spanning the full width of an ETM+ scan. Scan mirror technique development was performed using DOQ data from Minnesota where nearly state-wide coverage is available. Minnesota is not ideal from the seasonal variation point of view, so other sites are being sought as DOQ production continues.

4.2.3 Preprocessing Requirements

The DOQ data will require extensive preprocessing including: 1) mosaicking the individual quarter quad files into a single contiguous image (radiometric balancing may be required as part of the mosaicking process); 2) reducing the DOQ image resolution from 1 meter to 15 meters; and 3) resampling the DOQ data from the UTM projection to the SOM projection with a slight rotation from SOM grid north to nominally align the reference image with the Landsat 7 ground track. The small amount of rotation needed to align the SOM projection grid with the Landsat 7 path varies as a function of latitude (or WRS row) but is constant for a given test site. Procedures to automate the DOQ preprocessing are being developed.

4.3 Terrain Data

Digital terrain data is needed to provide the elevation information used by the IAS Level 1 terrain correction process. Terrain corrected images are used in the geometric super-site calibration operations described above.

4.3.1 Characteristics

The elevation information must completely cover the geometric super-sites to support the terrain correction process. The height values should be referenced to the WGS84 ellipsoid rather than mean sea level to be consistent with the ground control height values. Vertical accuracy better than 15 meters (one sigma) would be desirable. This would keep terrain induced errors below 0.1 panchromatic pixels at the end of scan. An accuracy of 30 meters (one sigma) would be acceptable.

4.3.2 Source

The National Imagery and Mapping Agency's Digital Terrain Elevation Data (DTED) products will be the principal source of terrain data used by the Landsat 7 IAS. The Level 1 DTED products are distributed in cells, each covering a one degree in latitude by one degree in longitude area. Each cell contains elevations at three arc-second intervals in latitude and longitude (except at high latitudes where the longitude interval increases). The vertical accuracy specification for DTED products calls for 50 meter linear error (LE) at the 90% confidence level. This is equivalent to approximately 30 meters LE one sigma, which meets the minimum requirement. As a practical matter, DTED data in areas of low relief typically exceeds the accuracy specification which applies globally.

DTED cells are grouped geographically and are available on CD-ROM. DTED cells have been produced for approximately two-thirds of the Earth's land surface. Although distribution of DTED data is restricted, the global data set has been made available to the USGS for internal use, and would be available as a resource to the Landsat 7 IAS.

More accurate digital terrain data is available for parts of the US from the USGS. The USGS Digital Elevation Model (DEM) product provides 7 meter LE 90% accuracy for elevation points at a 30 meter spacing in the UTM projection. DEM data is packaged in 7.5 minute quadrangles. Complete coverage of the conterminous US is not yet available but DEM production is proceeding in parallel with DOQ generation, so DEM data would probably be available for any site with a corresponding DOQ reference image.

4.3.3 Preprocessing Requirements

The digital terrain data must be preprocessed into the output space used for the ETM+ test scenes. This means the DTED or DEM data must be corrected to WGS84 ellipsoid height, mosaicked to form a contiguous area which covers an entire ETM+ scene, and then resampled into the SOM map projection grid north up frame used by the calibration scenes. Versions of the terrain data set will be generated at 15 meter, 30 meter, and 60 meter resolution for use with all eight ETM+ bands.

5.0 Notes

The following subsections provide a glossary of definitions for key terms and concepts, and a list of acronyms used in this document.

5.1 Glossary

Calibration - An activity which seeks to estimate new values for one or more Landsat 7 ETM+ geometric parameters in an effort to improve end-to-end system geometric accuracy performance.

Characterization - An activity which seeks to measure and evaluate Landsat 7 ETM+ geometric performance.

Focal Plane Calibration Test Site - A pre-selected Landsat 7 WRS path/row location known to contain features visible in all bands which provide good targets for cross-band correlation. Images of these test sites are used to perform band-to-band registration assessment and focal plane band placement calibration.

Geodetic Test Site - A pre-selected Landsat 7 WRS path/row location for which ground control points have been collected to support geodetic accuracy assessment and sensor alignment calibration.

Geometric-Super Site - A pre-selected Landsat 7 WRS path/row location for which ground control points, digital elevation data, and reference images have been collected for use in geometric accuracy assessment, image-to-image registration assessment, and scan mirror calibration.

Ground Control Point - A feature with a known geodetic position (latitude, longitude, height) which is image identifiable so that the image position can be precisely measured and associated with the corresponding ground position.

Ground Control Point Chip - An image window containing a ground control point for use in image point transfer and mensuration.

5.2 Acronyms

ACS	Attitude Control System
ADEOS	Advanced Earth Observing Satellite
ADS	Angular Displacement Sensor
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
AVNIR	Advanced Visible and Near-Infrared Radiometer
CE	Circular Error
CPF	Calibration Parameter File
CSA	Celestial Sensor Assembly
DAAC	Distributed Active Archive Center
DEM	Digital Elevation Model
DFCB	Data Format Control Book
DMA	Defense Mapping Agency
DOQ	Digital Orthophoto Quadrangle

DTED	Digital Terrain Elevation Data
E&A	Evaluation and Assessment Subsystem
ECS	EOSDIS Core System
EDC	EROS Data Center
EOSDIS	Earth Observing System Data and Information System
ETM+	Enhanced Thematic Mapper Plus
FDF	Flight Dynamics Facility
FOT	Flight Operations Team
GCP	Ground Control Point
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GUI	Graphical User Interface
IAS	Image Assessment System
IFOV	Instantaneous Field of View
IMU	Inertial Measurement Unit
IOC	In-Orbit Checkout
IRS	Indian Remote Sensing
LE	Linear Error
LMMS	Lockheed-Martin Missiles and Space
LPGS	Level-1 Product Generation System
MISR	Multiangle Imaging Spectral Radiometer
MOC	Mission Operations Center
MODIS	Moderate-Resolution Imaging Spectroradiometer
MSCD	Mirror Scan Correction Data
NAD27	North American Datum of 1927
NAD83	North American Datum of 1983
NBR	Navigation Base Reference
NIMA	National Imagery and Mapping Agency
NMAS	National Map Accuracy Standards
PCD	Payload Correction Data
SAM	Scan Angle Monitor
SBRS	Hughes' Santa Barbara Remote Sensing
SLC	Scan Line Corrector
SME	Scan Mirror Electronics
SOM	Space Oblique Mercator
SWAMP	Science Working Group for the AM Project
TBD	To Be Determined
TBR	To Be Resolved
TBS	To Be Supplied
USGS	United States Geological Survey
UTM	Universal Transverse Mercator
WGS84	World Geodetic System 1984
WRS	World Reference System