ASTER Validation Plan

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Introduction

This document is the validation plan for the ASTER standard data products. The document follows the outline recommend by Dr Starr in his letter dated July 31st 1996 to the ASTER Science Team Leader. Initially the data products and the relevant instrument characteristics are listed. These are followed by the validation plans for each product. The interdependencies of the various data products are given in Figure 3-1.

Standard Data Products

Registered radiance at sensor (AST03)
Decorrelation stretch (AST06)
Brightness temperature (AST04)
Surface radiance - VNIR, SWIR (AST09)
Surface reflectance - VNIR, SWIR (AST07)
Surface radiance - TIR (AST09)
Surface kinetic temperature (AST08)
Surface emissivity (AST05)
Polar surface and cloud classification (AST13)
Digital Elevation Model (AST14)

Relevant Instrument Characteristics

The EOS AM platform, scheduled for launch in 1998, will be placed in a 10:30 a.m. descending, sun-synchronous, polar orbit at an altitude 705 km. The ASTER instrument is designed for a 6-year lifetime. It consists of three bore-sighted sub-systems for the visible and near infrared (VNIR), short wave infrared (SWIR) and the thermal infrared (TIR) respectively. ASTER has 14 spectral bands covering the range 0.56 to 11.3 µm, with 3 spectral bands in the VNIR, 6 in the SWIR, and 5 in the TIR.

VNIR:

- 15 m spatial resolution
- Pointing capability of ±24 degrees
- 3 spectral bands for nadir viewing between 0.52 and 0.86 µm
- 1 spectral band for backward viewing with a B/H ratio of 0.6
- 60 km swath width
- NEΔR of 0.5 % or better
- Absolute accuracy of 4 % or better
- MTF of 0.25 for cross track and 0.2 for along track or better
- 8-bit digitization.
- On-board calibration:
    1) Two independent, narrow-beam systems, except for the uncalibrated stereo camera

2) Tungsten lamp sources
3) Each lamp and each output monitored by a photodiode
4) Calibration every 17 days

SWIR:

30 m spatial resolution
Pointing capability of ±8.55 degrees
6 spectral bands between 1.60 and 2.43 μm
60 km swath width
NEΔR of 0.5 - 1.3 % or better depending on bands
Absolute accuracy of 4 % or better
MTF of 0.25 for cross track and 0.2 for along track or better
8-bit digitization
On-board calibration:

1) Single beam of radiation from tungsten source
2) No intervening optics except pointing mirror
3) Tungsten lamp monitored by photodetector
4) Calibration every 17 days

TIR:

90 m spatial resolution
Pointing capability of ±8.55 degrees
5 spectral bands between 8.125 and 11.65 μm
60 km swath width
NEdT of 0.3 K or better
Absolute accuracy of 1 - 3 K depending on bands
MTF of 0.25 for cross track and 0.2 for along track or better
12-bit digitization
On-board calibration:

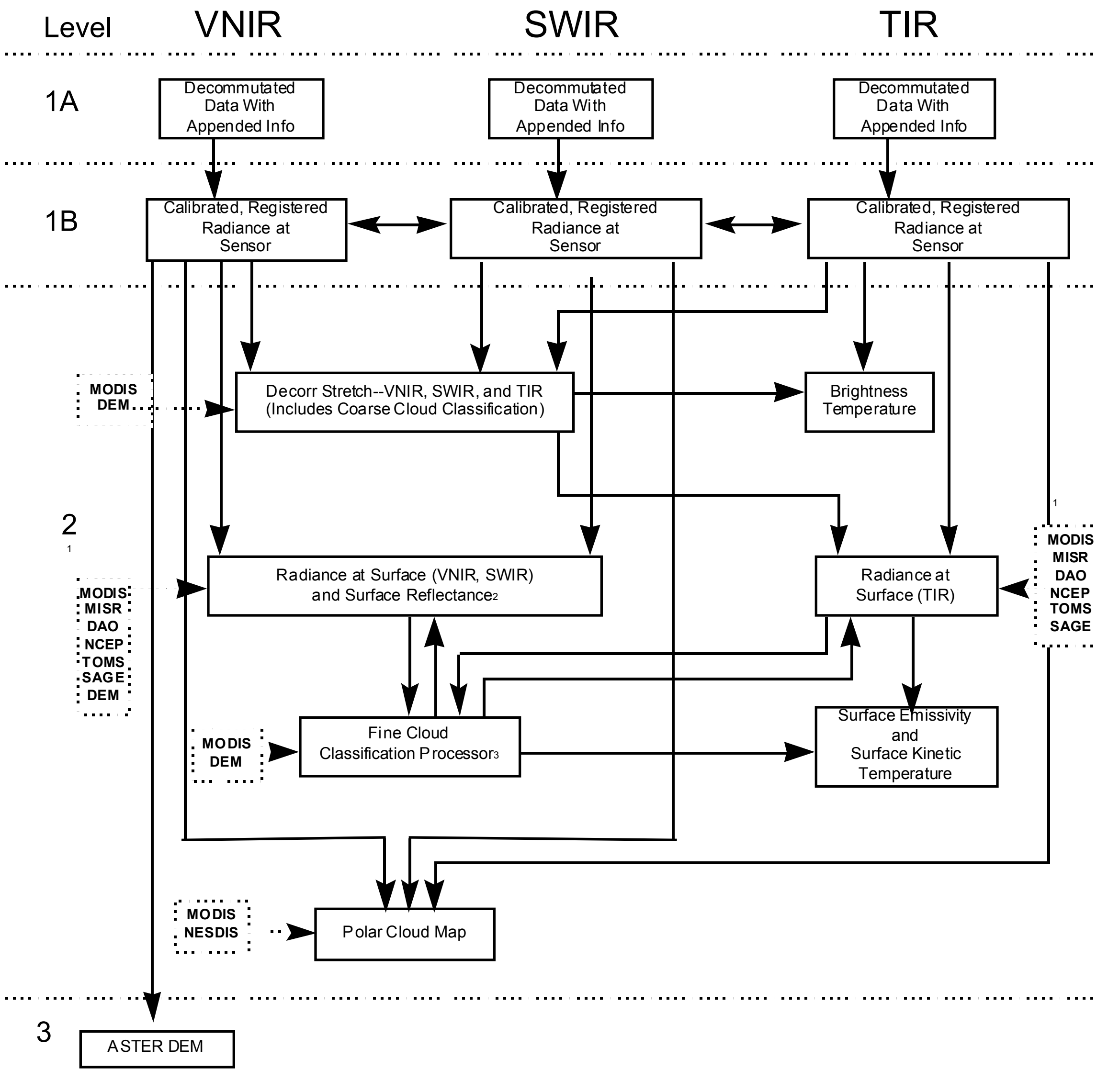
1) Blackbody source used in range 270 to 340 K
2) Long-term calibration every 17 days
3) Short-term calibration at 270 K before and after each image
4) Temperature scales from 270 - 200 K and 340 - 370 K by extrapolation

Channel Specifications

Subsystem (& detectors)	Band no.	Filter wavelengths for 0.5 of max transmittance (µm)	Radiometric resolution	Signal quantization (bits)	Uncertainty in absolute calibration, one sigma
VNIR (Si-CCD, 5000 _ 4)	1 2 3	0.52 - 0.60 0.63 - 0.69 0.76 - 0.86	0.5% applies to all bands	8 applies to all bands	±4% applies to all bands
SWIR (Cooled Pt Si 2048 _ 6)	4 5 6 7 8 9	1.600 - 1.700 2.145 - 2.185 2.185 - 2.225 2.235 - 2.285 2.295 - 2.365 2.360 - 2.430	0.5% 1.3% 1.3% 1.3% 1.0% 1.3%	8 applies to all bands	±4% applies to all bands
TIR (Cooled HgCdTe PC 10 _ 5)	10 11 12 13 14	8.125 - 8.475 8.475 - 8.825 8.925 - 9.275 10.25 - 10.95 10.95 - 11.65	2.5 K* 2.5 K* 2.5 K* 1.5 K* 1.5 K*	12 applies to all bands	3 K (200 - 240 K) 2 K (240 - 270 K) 1 K (270 - 340 K) 2 K (340 - 370 K) applies to all bands

* These values are for low-level input radiances. For high-level input radiances, 0.3 K applies to all bands.

ASTER Data Product Architecture



[1] This list contains a variety of alternate input sources, used when the primary input source is not available
[2] Computed simultaneously with Radiance at Surface
[3] Produces a cloud mask that is incorporated into other products

Figure 0-1 ASTER Product Interdependencies

Registered Radiance at Sensor (AST03) Radiometric – Japanese/US Effort

4.1 Introduction

This validation section does not cover the details of the Level-1B algorithm and its ATBD; rather it is the plan for validating and testing of the Level-1B algorithm data product. Although the requirements for Vicarious Calibration (VC) validation are in many ways unique, this plan adheres closely to the outline recommended by the EOS Validation Office for general algorithm validation.

VC is the use of calibrated sources external to ASTER in order to validate the On-Board Calibrator (OBC) derived radiances (Slater et al, 1996). For a selected site, the radiance or reflectance is measured either on the ground or from an aircraft. Also needed are measurements of atmosphere characteristics and a Radiative Transfer Code (RTC) to extrapolate to the top-of-the-atmosphere (TOA) radiance. VC-derived TOA radiance, when compared to the ASTER-determined radiance, constitutes the validation of the ASTER Level-1B data product. Other calibrated sources that are external to ASTER which will be used in the validation of the Level-1B data product are the moon (Kieffer and Wildey, 1996) and selected sites that have been calibrated by other satellite-borne sensors, i. e. cross calibrations with EOS and non-EOS sensors.

VC of the Level 1B radiances from ASTER will be undertaken independently by both the US and Japanese members of the ASTER Science Team. While independent, the two validation teams will cooperate closely to ensure the highest-accuracy product. As part of this cooperation, the two teams began cooperating closely with joint field campaigns in the summer of 1996, 1997, and 1998 in the US and a joint campaign in the winter of 1997 in Japan. We expect to continue these types of campaigns for the duration of the ASTER in-flight program.

4.1.1 Measurement and Science Objectives

Registered radiance at sensor is essential for the generation of the higher-level data products. Validation of the registered radiance at sensor allows us to compare these data with data from other instruments onboard EOS-AM1 and on other Earth Observation satellites. The measurement objective of this validation activity is to determine the TOA radiance of a selected site by means that are accurate and independent of the ASTER-determined radiance. The science objective is to verify the accuracy of the ASTER-determined TOA radiance that is the basis for many other science data products.

4.1.2 Product Description

There are both Level-1A and Level-1B data. Level 1A data are the reconstructed unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric calibration and geometric correction coefficients and georeferencing parameters computed and appended, but not applied to the Level-0 data. The Level-1B data are the Level-1A data processed using the radiometric calibration and geometric correction information.

The product of this validation is the difference between ASTER-derived Level-1B radiance, for a selected site and in a specific ASTER band, and that predicted by the VC for the same site. These measured differences will be used to validate the ASTER Level-1B algorithm and by inference the OBCs. In those instances where the difference in the VC-predicted and the ASTER-determined TOA radiances are larger than the combined uncertainty of the two techniques, the data product will be used to correct the radiometric calibration coefficients.

4.2 Validation Criterion

4.2.1 Overall Approach

Using VC and cross calibration, the ASTER calibration coefficients are to be validated. Although the calibration coefficients are primarily derived from the onboard calibration (OBC) data, other calibration data such as vicarious calibration data and cross calibration data are used to check the OBC data. The OBC data are acquired every 17 days with Lamp A and B systems alternatively. If both systems change consistently, and if there is a channel dependency, then calibration coefficients are calculated with OBC data.

The overall validation procedure of the VC approach is diagrammed in Figure 4.1. The TOA radiance from a VC site is measured by ASTER using the most recent set of calibration coefficients. These ASTER-derived radiances are compared to those predicted from the VC data collections. If the differences exceed their combined uncertainty then the calibration coefficients need to be adjusted. Three ground-reference methods of VC will be used: reflectance-based, irradiance-based, and radiance-based methods. In the VNIR and SWIR, all three approaches are used. Only the radiance-based approach is used in the TIR.

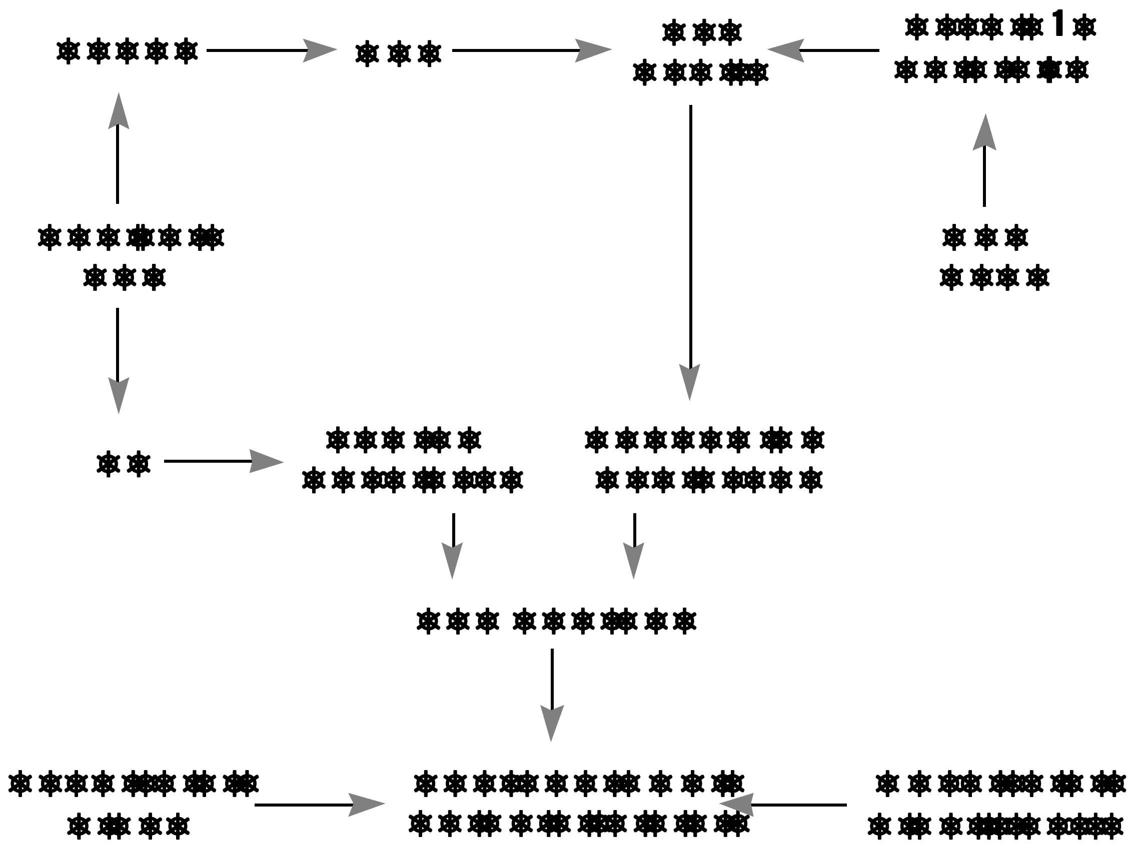


Figure 4-1 Validation process for ASTER calibration coefficients.

All three of these of these methods require careful selection of the test site used. High, but unsaturated, signal levels are required in the ASTER bands. The site should be flat and larger than several ASTER pixels. The site's surface properties should be uniform in reflectance for the VNIR and emissivity for the TIR. Ideally, the spectral emissivity and reflectance should be spectrally flat. Finally, the relative magnitude (compared to the radiance) of the corrections for atmospheric effects should be small so that the RTC can accurately predict the radiance at the TOA. Although it does not directly affect the accuracy of a VC measurement, an important practical consideration is the location of the site. It must be readily accessible by the members of the VC team along with their equipment.

There is no ideal calibration site that satisfies all of the above conditions. Furthermore, no one site can satisfy the requirements of all ASTER bands simultaneously. Obviously trade-offs among different sites will be made. In the Southwestern United States there exist several fairly uniform reflectance sites which have been used over the course of many years by the RSG for calibrations of Landsat-TM, SPOT-HRV, and other airborne and satellite-borne imaging sensors. Ivanpah Playa and Lunar Lake have reasonable reflectance levels and small spectral variations in the VNIR and SWIR. These are desert sites where the aerosol loading of the atmosphere is typically low with correspondingly reduced corrections. In the VNIR, the White Sands site has a fairly flat spectral reflectance that is quite high, however, the reflectance is much lower and spectrally structured in the SWIR. Railroad Valley in Nevada is a reasonably uniform reflectance site whose spectrum is fairly flat over most of the VNIR and SWIR. All of the sites, with the exception of Ivanpah Playa, are above 1.3 km so that atmospheric corrections are typically small.

For the TIR, Lake Tahoe, at a high altitude in Northern Nevada/California, will be used as the VC site. A large body of water is selected for the TIR VC site because of its uniformity and stability due to its large thermal mass and low thermal conductivity of water. Again the high altitude will provide smaller and more accurate atmospheric corrections. TIR VC measurements will employ the radiance-based approach and will be made from an aircraft.

Cross-calibration uses simultaneously acquired data from other instruments onboard the EOS-AM1 platform such as MODIS and MISR. The wavelength coverage of ASTER overlaps the MODIS and MISR instruments, and these instruments observe the same ground target through the same atmosphere so that it is expected that ASTER data can be validated with MODIS and MISR data. The uncertainty of the cross calibration is less than 2% relative to the calibration of one of the sensors.

4.2.2 Sampling Requirements and Trade-off

The OBC data are to be validated periodically in the three VNIR, six SWIR and five TIR bands of ASTER. Measurements of flat, homogeneous surface sites, and the atmospheres above them, will be used in conjunction with RTCs to predict the TOA spectral radiances in the bands of interest. These measurements will be made at the time ASTER acquires images of the sites.

Reflectance measurements for the reflectance-based method are made on the ground by transporting a downward looking spectroradiometer over the site. The spectroradiometer is calibrated in reflectance units by periodically viewing a target of known reflectance. Sampling is done at many regularly spaced intervals in a predetermined pattern over the site. The spacing of the samples depends on the non-uniformity of the site. The irradiance-based method uses the same data as the reflectance-based approach with additional measurements of the downwelling irradiance. For radiance-based VC measurements, the calibrated spectroradiometer directly measures the spectral radiance of the site. The spectroradiometer is calibrated in the laboratory by viewing a calibrated radiance source that is traceable to a NIST-calibrated spectral irradiance lamp standard.

The spectroradiometers that are used in these methods may also be mounted in an aircraft and flown in a raster pattern over the site. By using an aircraft, the time required to obtain a complete set of measurements is greatly reduced and the aircraft can be flown above most of the atmospheric effects.

Because of the complexity of a multi-band instrument that would include all the ASTER VNIR and SWIR bands, a trade-off will be made in the number and spectral location of the bands in the instrumentation used for ground-reference approaches. The multi-band VC radiometer will be built for optimum stability and calibrated to the highest accuracy possible. Using a spectrometer that is less stable (and consequently less accurate), narrow-band (about 1 nm) spectral information will be obtained for the site. These relative measurements will be used to interpolate the more accurate VC radiometer data. The interpolated reflectance (or radiance) data along with the spectrally detailed atmospheric characterization by the RTC will be used to predict the TOA radiance at 1 nm intervals.

It is planned that the TIR VC measurements will be made using Lake Tahoe as the selected site with the radiometer aboard an aircraft. A raster scan of the radiance will be made to determine the thermal uniformity of the lake surface. This will be done at several altitudes to determine the vertical profile of the atmospheric effects. Balloon radiosonde data will also be used in the determination of the vertical profile of the temperature and water content of the atmosphere. As in the VNIR and SWIR, the measured radiances will be extrapolated using an RTC calculation to obtain TOA radiance at the time of the sensor overpass.

In summary, the trade-offs are (1) use a radiance-based approach aboard an aircraft for the VC in the VNIR, SWIR and TIR; (2) on-ground reflectance based VCs will be performed and in some cases will serve to cross-check the airborne radiance VCs; (3) in those cases where aircraft data are not available a reflectance-based VC will be used in the validation of the Level-1B VNIR and SWIR data products; (4) not all ASTER VNIR and SWIR bands will be replicated by the radiometer, detailed spectral reflectance and atmospheric characterization information will be used for interpolation; (5) in the TIR two bands will be measured in the 10 to 12 mm region; and (6) several different sites will be used to perform VCs.

4.2.3 Measures of Success

The VC methods described here have been used for several years by researchers and National Space Agencies in Australia, Europe, Japan and the USA for the calibration of sensors with inadequate absolute calibration systems. VC methods are equally appropriate for validation of OBC results and sensor calibration. In fact, in most cases, they will be merged with OBC data to optimize the final calibration coefficients used the Level 1-B product.

Success of a VC is measured in terms of the accuracy attained in the determination of the TOA radiance. Success of the validation of the Level-1B data product is determined by the consistency of agreement, or disagreement, between the ASTER-measured and VC-predicted TOA radiances in successive VC campaigns. It is expected that the ASTER-measured TOA radiance will have better precision than that of the VC-predicted TOA radiance. The precision of the set of VC measurements is limited by the large variability of the atmospheric conditions and surface reflectance over the long time span covered by the measurement set.

The following steps will be used to confirm the precision and accuracy of the VC results. We will use peer reviews of VC error budgets as a first step. We will also include cross-comparisons of VC predictions of TOA spectral radiances from joint field campaigns as well as comparisons of reflectance-based, irradiance-based, and radiance-based methods and sensor-to-sensor comparison results. Comparisons with validated Level 2 products having high sensivity to calibration error can be used to determine whether there are large uncertainties VC results. For the radiance-based method, we will validate the accuracy of the laboratory standards used to calibrate the field radiometers through comparisons with other laboratories.

The comparisons of laboratory standards has been started in the VNIR and SWIR using highly stable transfer radiometers developed by the NRLM and the University of Arizona. These radiometers have been used in intercomparisons of the absolute radiance standard sources used for calibrations by the manufacturers of MODIS, MISR, ASTER, Landsat-7, SeaWiFS and OCTS. These comparisons involve the standards and calibration instrumentation of each of the aforementioned sensors.

In the VNIR and SWIR, the results of measurements made using all three ground-reference methods will be compared. Agreement within the combined predicted uncertainties will indicate that the measurements were successful. Previous comparisons of the two techniques indicated agreement to within 4% (Biggar et al, 1991). It is expected that further refinements of these techniques will show improved agreement.

The estimated uncertainties are presented in Table 4.1 for a irradiance-based (Slater et al, 1996). The estimates labeled “Present” are for a good VC day at White sands, New Mexico: cloud-free with good visibility of 100 km or more. It is estimated that at present the total uncertainty is 3.5%. It is anticipated that improvements will be made in the panel BRF and ground reflectance measurements so that the total uncertainty will be reduced to 2.8%. In Table 4.2 the estimated uncertainties for a radiance-based VC are listed for the present status of the measurements and the anticipated improvements (Slater et al, 1996). Again the “Present” uncertainty estimates are for a good VC day at White sands, New Mexico. The present and anticipated uncertainties are 2.8% and 1.8%, respectively. As in the case of the reflectance-based VC, panel calibration accuracy is expected to improve.

Source	Present		Anticipated	
	Uncer-tainty	**Total uncer-tainty**	**Uncer-tainty**	**Total Uncer-tainty**
Extinction optical depth	5.0	1.0	5.0	1.0
Diffuse-to-global ratio measurement		2.3		1.7
Field measurement	2.0	0.5	2.0	0.5
Blocked diffuse component	2.0	0.5	2.0	0.5
Extrapolation to new angles	1.0	0.25	1.0	0.25
Panel BRF correction ($\theta_{sun} \sim 50°$)	2.2	2.2	1.5	1.5
Ground reflectance measurement	2.1	2.1	1.2	1.2
Non-lambertian ground characteristic	1.2	1.2	1.2	1.2
Spherical albedo and atmospheric reflectance		1.0		1.0
Atmospheric model error	1.0		1.0	
Uncertainty in μ_{sun} and μ_{view}	0.4	0.1	0.4	0.1
Total uncertainty (root sum of squares)		3.5		2.8

Table 4-1 Estimated uncertainties for a reflectance-based VC measurement

The combined uncertainties of the reflectance- and radiance-based techniques are 4.5%. This is within the measured level of agreement reported by Biggar et al (1991) thereby confirming the combined estimated total uncertainty. If the anticipated improvements are realized then the combined uncertainty will be 3.3%, where the reflectance technique contributes less than 3% and the radiance technique less than 2%. The present levels of uncertainty are sufficient to validate the accuracy of the VNIR and SWIR bands of ASTER.

The TIR measurements using the airborne radiometer will be compared to temperature measured at the surface of the water. The predicted radiance of the water obtained from the measured temperature, corrected for the emissivity of water and the atmospheric effects will be compared to the radiance measured at the aircraft.

Source	Present		Anticipated	
	Uncer-tainty	**Total uncer-tainty**	**Uncer-tainty**	**Total uncer-tainty**
Radiometer calibration		2.5		1.6
Panel calibration	2.0		1.0	
Lamp calibration	1.3		0.9	
Scale uncertainty	1.2		0.8	
Transfer uncertainty	0.5		0.5	
Lamp positioning	0.3		0.3	
Lamp current stability	0.5		0.5	
Voltage measurement uncertainty	0.5		0.5	
Measurement accuracy		1.3		0.9
Data logger accuracy	0.5		0.5	
Radiometer stability	0.5		0.5	
Pointing angle uncertainties	1.1		0.5	
Correction for altitude difference		<0.1		<0.1
Uncertainty in the reflectance-based method	5.0		3.0	
Total uncertainty (root sum of squares)		2.8		1.8

Table 4-2 Estimated uncertainties for a radiance-based VC measurement

In addition to the above accuracy checks, the TOA radiance as predicted by several different VC calibration teams will be compared. The first of these cross-calibration campaigns took place in late May, early June of 1996. Participants included teams from MODIS, ASTER and MISR. It is expected that these campaigns will occur annually and will have broader international participation.

4.3 Pre-launch Algorithm Test/Development Activities

Pre-launch activities are divided into two parts, theoretical and experimental. The theoretical validation uses previously collected data sets to develop, improve, and test the software needed for the VC. The experimental validation will be used in the pre-launch time frame to test data collection methods, evaluate test sites, and develop cooperative efforts with other MTPE sensor teams.

One phase of the pre-launch testing of the VC methods is the recommendation for the development of international collaborative VC programs for EOS and non-EOS sensors. These should be considered by the EOS calibration scientists through CEOS and/or by direct contact with other space agencies. We also recommend the establishment of an EOS calibration panel sub-group to coordinate and oversee all the EOS related VC activities.

4.3.1 Field experiments and studies

Pre-launch field experiments and studies will focus on the joint campaigns that have been held in Nevada during the summers of 1996, 1997, and 1998 and the joint campaign held in Japan in winter 1997. Analysis of the results of these campaigns should lead to a set of consistent algorithms between both the US and Japanese Science Team Members. In addition, the results of the campaigns should lead to a better understanding of VC methods across the entire AM-1 platform.

4.3.2 Operational surface networks

No plans for the use of operational surface networks have been made in the pre-launch phase, and post-launch as well. The primary reason for this is the lack of surface reflectance and radiance data. For example, the DOE ARM CART site is an excellent resource for information regarding the atmospheric composition, which is needed for input to the RTC. However, use of these data is limited the spectral reflectance and uniformity of the surface of the site at the same time the atmospheric data are collected. For sensor-to-sensor cross calibration it may be possible to infer the surface properties of a test site, however, the non-uniformities and spectral features will increase the uncertainty to such an extent that the cross calibration may be of little value.

4.3.3 Existing satellite data

Existing satellite data will be used in two ways. The first is to evaluate the accuracy of VC methods. However, this requires that suitable ground-based or aircraft-based data be available at the time of the overpass of the sensor of interest. The other requirement is that the calibration of the sensor be well known. While sensors such as Thematic Mapper or SPOT-HRV are well understood, the requirement for their absolute radiometric calibration is much larger than the 4% requirement for ASTER. Thus, the use of current satellite data is of limited use in developing uncertainty estimates for VC methods. These satellite data are of use for developing and testing data collection methods and processing software.

The second phase for which current satellite data are useful is understanding the cross-calibration approach. EOS-AM1 will carry several sensors in addition to ASTER. These are the Moderate Resolution Imaging Spectroradiometer (MODIS), the Multi-angle Imaging Spectroradiometer (MISR), the Clouds and Earth's Radiant Energy System (CERES) and the Measurements of Pollution in the Troposphere (MOPITT) instrument. The wavelength coverage of ASTER overlaps MODIS and MISR. Because all three, ASTER, MODIS, and MISR, are on the same platform, they will observe the same surface through the same atmosphere at the same time. The data from the three sensors will have some registration error, each has slightly different IFOVs, and the spectral bands are slightly different. Even so, it should still be possible to cross-calibrate the instruments with reference to each other.

As an example, we could calibrate ASTER (referred to as instrument A) with either MODIS or MISR (referred to instrument as B). In order to perform an accurate cross-calibration, we must account for:

1) Different atmospheric effects due to differences in the spectral bands of each sensor,
2) Different spectral reflectance and or emissivity due to differences in the spectral bands of each sensor,
3) Mis-registration between instrument data,
4) Different IFOV's.

Taking these factors into account, we can use current satellite data to simulate instrument A data from instrument B data. A set of calibration coefficients is calculated by comparing the simulated instrument A data to the actual instrument A data collected of the target.

4.4 Post-launch Activities

4.4.1 Description of measurements

The plan described here relies on surface reflectance measurements of selected test sites, measurements of atmospheric properties over these sites, and radiance measurements made from aircraft at the time of sensor overpass.

Surface Reflectance Determination: The surface reflectance of a small area of the site is found by comparing radiometer measurements of the site to those from a diffusely reflecting panel of known reflectance calibrated at RSG facilities using a pressed polytetrafluoroethylene standard. The calibration reference is a directional-to-hemispheric reflectance standard provided by NIST. Polynomial fits are made to the measured data to calculate the reflectance of the barium sulfate for the sun-view geometry and wavelengths for a given set of field measurements (Biggar et al., 1988).

A spectroradiometer, transported across the entire site, measures the upwelling radiance at 1 nm intervals between 350 and 2500 nm. The spectroradiometer collects a number of samples along a straight-line path within some fraction of the area representing an ASTER pixel. Reflectance of the site is determined in each spectral channel by comparing measurements of the site to those of the calibrated panel and averaging all of the measurements. Sun-angle changes and the bi-directional reflectance of the reflectance panel are taken into account when determining the reflectance.

Atmospheric measurements: The primary instrument used to characterize the atmosphere over the site is the solar radiometer. The solar radiometers are relatively calibrated immediately prior to, during, or after each field campaign. Data are used in a Langley method retrieval scheme to determine spectral-atmospheric optical depths (Gellman et al., 1991). The optical depth results are used as part of an inversion scheme developed by the RSG to determine ozone optical depth and a Junge aerosol size distribution parameter (Biggar et al., 1990). The size distribution and columnar ozone are used to determine the optical depths at 1-nm intervals from 350 to 2500 nm. Columnar water vapor id derived using a modified Langley approach (Thome et al., 1992). Here, as for the optical depth retrieval, the primary uncertainty in water vapor is the instrument's relative calibration. The retrieved columnar water vapor is used as an input to MODTRAN3 to determine transmittance for the sun-to-surface-to-satellite path for 1-nm intervals from 350 to 2500 nm. In the thermal infrared, the atmospheric measurements concentrate on obtaining profiles of temperature and humidity using radiosonde balloons.

Radiance measurements: The two key factors in accurate radiance measurements are the calibration of the sensor and flying the sensor at a sufficient altitude to reduce atmospheric effects. Absolute spectral radiance in the VNIR/SWIR will be referenced to a NIST-calibrated spectral irradiance standard as well as checked against several NIST-traceable standard lamps. The absolute radiance of the sphere source is also traceable to NIST and to other EOS and non-EOS standard sources via the ultra-stable radiometers that have been developed for the VNIR and SWIR.

Another absolute radiance calibration method that will be used in the VNIR/SWIR is the SRBC. The accuracy of a SRBC is based on the irradiance-to-radiance BRF (bi-directional reflectance factor) of a diffusely reflecting panel and the absolute solar spectral irradiance. The BRF of the panel will be based on the same directional-hemispheric reflectance standard used in the calibration of the reflectance reference panels discussed above. Which set of spectral irradiance values should be used to quantitatively describe the sun in the SRBC method is still a matter for discussion. Calibration of TIR radiance will be done using a variable-temperature blackbody simulator.

Once the sensors have been calibrated, they will be flown in an aircraft that allows the measurements to be made above much of the effects of the water vapor and the scattering by aerosols. The radiometers will be flown up to about 3 km above sea level. Based on previous work by the RSG, this altitude is high enough so that the uncertainty due to the atmospheric correction of the radiance at the satellite sensor in the solar reflective range is within +/- 0.1%. Work is still being done to evaluate the effect of the atmosphere in the TIR above 3 km.

4.4.2 Initial Checkout Period

After the A&E phase, two VCs per campaign are planned at approximately two month intervals. A second intensive campaign will take place about one year after the first, followed by single VC campaigns at three-month intervals. The purpose and procedure of the validation plan for an initial checkout period is shown in Figures 4.2, 4.3, and 4.4.

During the initial checkout period, which occurs during the period shortly after launch, the methods described above will be reviewed using frequently acquired onboard calibration data as well as vicarious calibration and cross-calibration data. The current plans for the data acquisition of the onboard, vicarious and cross calibration data are shown in Figure 4.5. 40 days are required for platform and instrument checkouts and we need to determine calibration coefficients within 90 days after launch. This will allow us to have three repetition cycles, or 48 days (based upon the 16-day repeat cycle of ASTER), for onboard, cross-and vicarious calibration data acquisition. We need frequent acquisition of the onboard calibrators for VNIR, SWIR and TIR in the early stages after launch so that we can determine the calibration data acquisition plan shown in Figure 4.5. Once this is determined, we can check the consistency of the system using the onboard calibrators and we can also check the inter-band dependency.

4.4.3 Normal Operation Period

Figure 4-6,4-7,4-8 shows the purpose and procedure for validation in an operational phase. The frequency of calibrations will be partially determined by the behavior of the sensor. If the sensor response is changing significantly with time, then more frequent VC campaigns will be used. For the case when ASTER appears to be stable, then we will still plan on at least four successful VC campaigns per year and a single intensive campaign each year consisting of multiple sites and overpasses within a one-month period.

A recent field campaign to Lunar Lake, Nevada was made in late May, early June 1996. This campaign included VC teams from ASTER, MISR, and MODIS. The members from ASTER included both Japanese and US team members. This campaign was held to make comparisons between predicted TOA radiances made by each group as well as for practice for the EOS era when it is anticipated that additional coordinated field campaigns will be made.

A recommendation has been made that an international collaborative VC program be established for EOS sensors. This program should thereby provide more frequent and appropriately spaced calibration up-dates, as well as the possibility of cross comparison of results from VC teams operating at different sites throughout the world (Slater and Biggar, 1996). The EOS Calibration Scientist is also planning to form an EOS Calibration Panel subgroup to coordinate and oversee all EOS-related VC activities.

This coordination will be of two kinds. The first is to perform joint campaigns with representatives of ASTER, MISR, MODIS, and Landsat-7 at a minimum. As before the principal reason for these campaigns will be to allow the TOA radiances from several VC teams to be compared. The second kind of coordination will be to use the results from other VC teams to increase the database of ASTER VC results to validate the cross calibration of these sensors. For instance, data collected as part of an independent MISR campaign could be used for the validation of ASTER TOA radiances.

As yet, there are no formal dates set for the joint VC campaigns. It is anticipated that a joint campaign will be held during or shortly after the A&E phase of the EOS AM-1 platform. The location of such a VC campaign is also to be determined. The basis for this decision is one of the purposes of the preflight work. One difficulty in selecting a suitable target for joint work is that it must be large enough to serve the needs of the large-footprint satellites and withstand multiple groups working at the site without each group interfering with the other's work.

4.4.4 Needs for other satellite data

For the ground-reference methods, there is no need for satellite data other than ASTER data. However, there will be a need to coordinate the collection of MODIS, MISR, and Landsat-7 data for any cross-calibration work that will be done. This should not be a problem since MODIS and MISR are currently 100% duty-cycle sensors and Landsat-7 will not require scheduling for any of the selected sites.

4.4.5 Measurement needs at calibration/validation sites:

The measurements needed for this validation are those described in section 4.1. Each method has a variety of needs depending upon the accuracy that is needed. For instance, cross-calibrations between sensors can be done using only the data from each sensor. However, this would not be as accurate as the case in which ground- and aircraft-based spectral radiance and atmospheric data are also available.

4.4.6 Needs for instrument development (simulator)

Improvements in the accuracy of VC measurements could be achieved with the improvement of several types of instrumentation. For TIR radiance VC measurements a more stable, airborne TIR radiometer needs to be developed. This radiometer should also be made so as to be relatively easy to characterize and calibrate. For atmosphere characterization, better instrumentation for measuring the scattering phase function and aerosol index of refraction are needed. Also for atmosphere characterization an SWIR solar radiometer needs to be developed. Finally, for on-site surface characterization, an improved instrument to measure directional-hemispherical reflectance and one to measure two dimensional, simultaneous bi-directional reflectance factors need to be developed. Regarding the measurement of the complex index of refraction of aerosols in the atmosphere: this parameter has been determined to be one of the least known, yet most important factors in the reflectance-based method.

The successful collection of data to validate the Level-1B data product would be improved through the increased availability, and decreased cost of an airborne system suitable for simulating ASTER data. This is because the 16-day orbit of ASTER decreases the chances of successful validation data sets at near-nadir look angles due to possible poor weather over the selected target site. An airborne simulator would allow data to be collected on any suitable day. These data could be used to evaluate the accuracy of the validation approach, thus increasing confidence in the data sets that are successfully collected for ASTER.

4.4.7 Geometric registration site

Geometric registration will not be needed for the ground-reference methods since a set of ground control points will always be used to mark the test target by laying tarpaulins at two corners of the site. Geometric registration will be needed for cross-calibration approaches. The accuracy of this registration is dependent upon the test site, but knowledge of a pixels location on the ground must be known to better than 0.5 km. If the geometric registration is not known to better than this, image matching techniques will be relied upon to register the data from one sensor to the data of another sensor.

4.4.8 Intercomparisons (multi-instrument)

This is a critical part of this validation plan because of the importance for determining biases in the radiances between sensors on the AM-1 platform and other MTPE sensors. It is expected that joint, VC campaigns for ASTER, MISR, MODIS, and Landsat-7 will occur at least annually. The first step towards developing joint VC campaigns occurred with the May, June 1996 campaign discussed above.

4.4.9 Radiance based method with Airborne Data
Airborne based spectrometer data such as AVIRIS, HIS, etc. will also be used for the in-flight radiometric validation.

4.4.10 Validation of Stray Light
Observing high-contrast boundaries, such as harbors for the VNIR and SWIR bands, and wide runways for the TIR bands will assess the effect of stray light. From the edge response derived from these data, we can derive and validate the MTF and stray light effects.

4.5 Implementation of Validation Results in Data Production

4.5.1 Approach
The current role of the VC results will be to determine whether the calibration coefficients for ASTER need to be modified. Thus, if a VC campaign indicates that the calibration of the sensor has drifted more than the required accuracy, then on the recommendation of a radiometric calibration advisory panel the coefficients will be modified. The VC data will also be used to determine if the OBCs changed during launch. That is, a bias in the TOA radiance implies a change in the OBCs due to either shock, vibration, outgassing, water desorption, or zero gravity load release.

4.5.2 Role of EOSDIS
The primary role of EOSDIS in this validation plan is to supply the Level-1B image data needed to determine the TOA radiance reported by the sensor for the test target.

4.5.3 Plans for archival of validation data
Initial archiving of the validation data will be done at the PI facilities. The data will be archived in raw and processed format on Sun-based hard disks and 8-mm tapes using UNIX tar commands. Distribution of the data will be through ftp access. Worldwide web sites are currently being developed to allow others to see a list of available data, samples of the data, and summaries of the results. The site will also instruct users how to retrieve copies of the data from the ftp site.

Plans also call for vicarious calibration/validation field measurement data to be archived at the Oak Ridge National Laboratory, which is the designated DAAC for field data and, in some cases, related aircraft data.

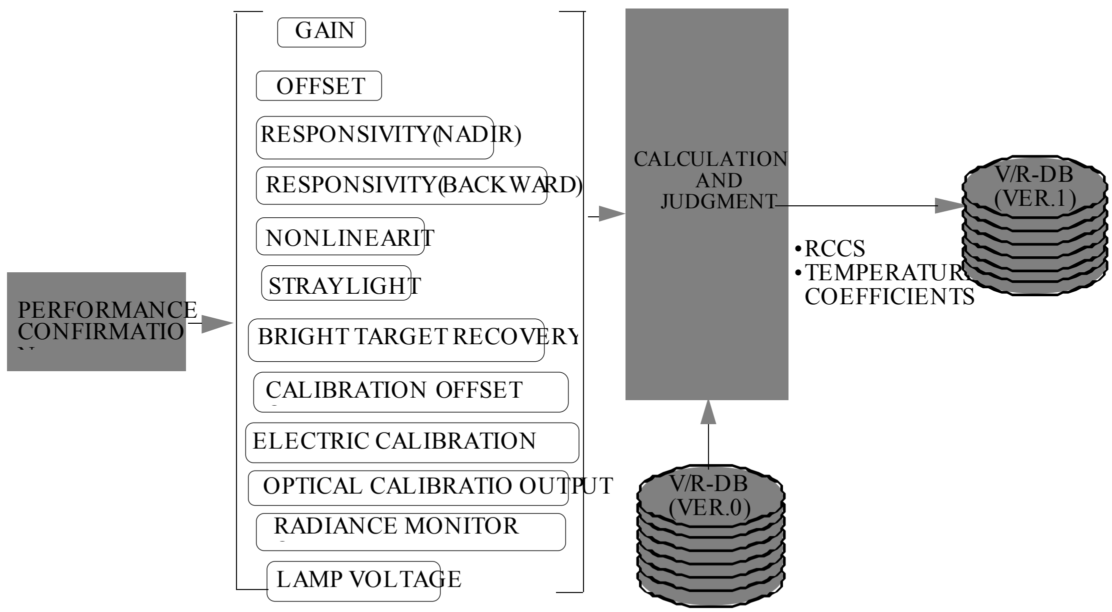


Figure 4-2 Initial Checkout Activity for VNIR

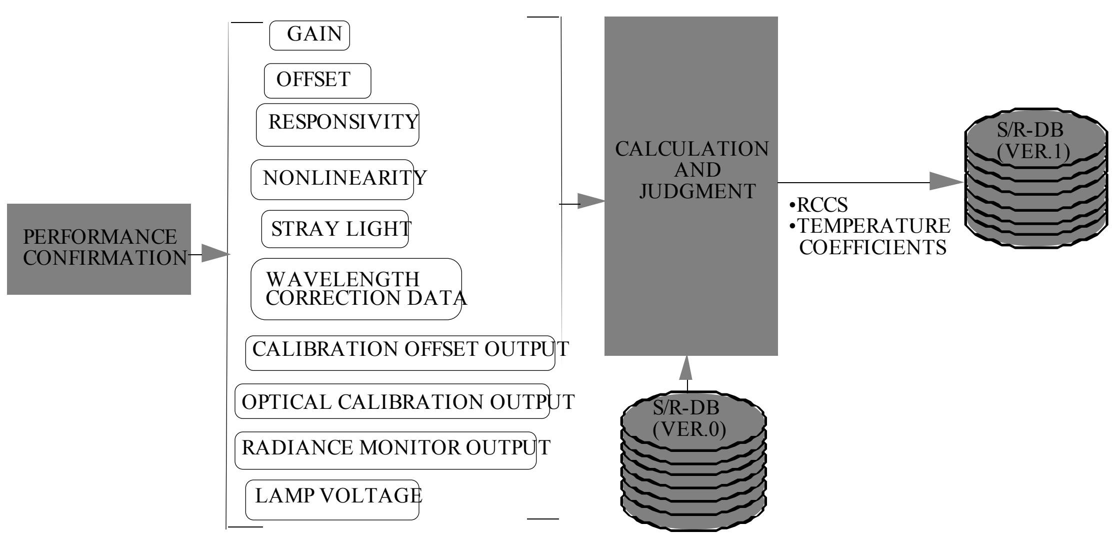


Figure 4-3 Initial Checkout Activity for SWIR

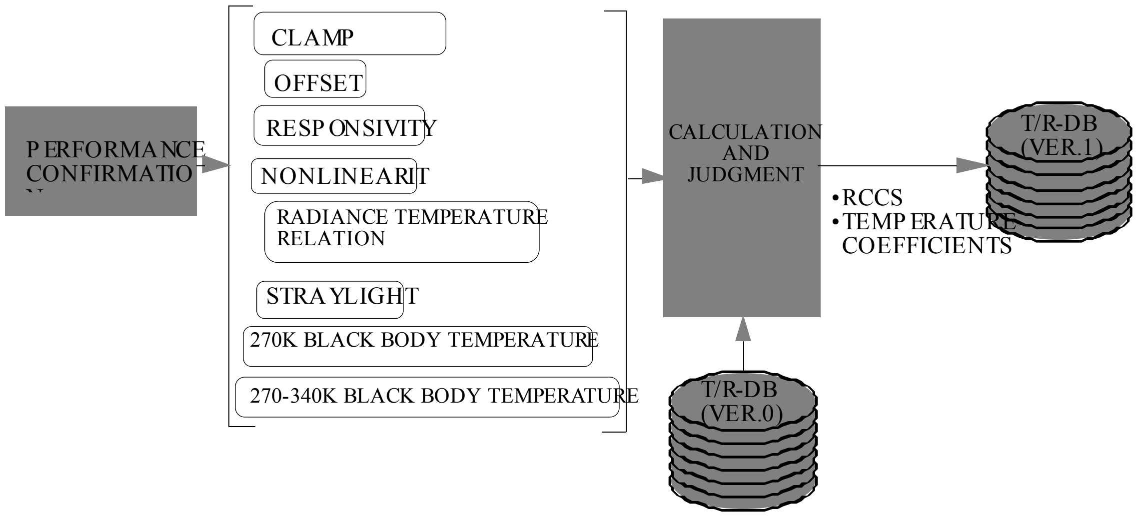


Figure 4-4 Initial Checkout Activity for TIR

```
.
Launch          40 days
<----------------------------------------->
Instruments and Platform Checkout     Once      Every     Every  Every     Every
                                      a day    two days          4 days8 days      17 days
                                      8 times     8 times            4 timesonce
                                      <---------><----------------><----------------><---------><----------------- - -
        Onboard Cal.Data******** * * * * * * * * *    *    *    *    *              *                *
       Vicarious Calibration                      o         o              oFieldCampaigns
        Cross Calibration ******** * * * * * * * * *    *    *    *    *              *                *
```

Figure 4-5 The Current Plans for the Data Acquisition of the Onboard, Vicarious and Cross Calibration Data

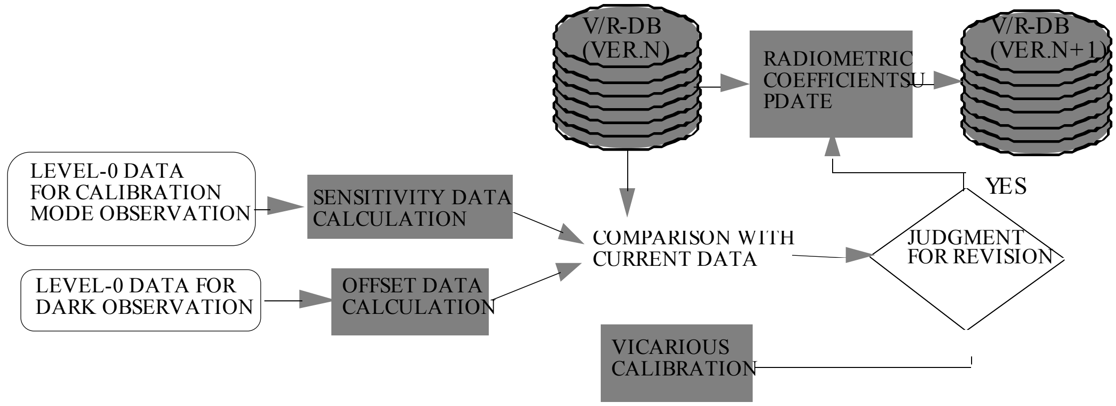


Figure 4-6 VNIR Radiometric Correction Data Update Flow

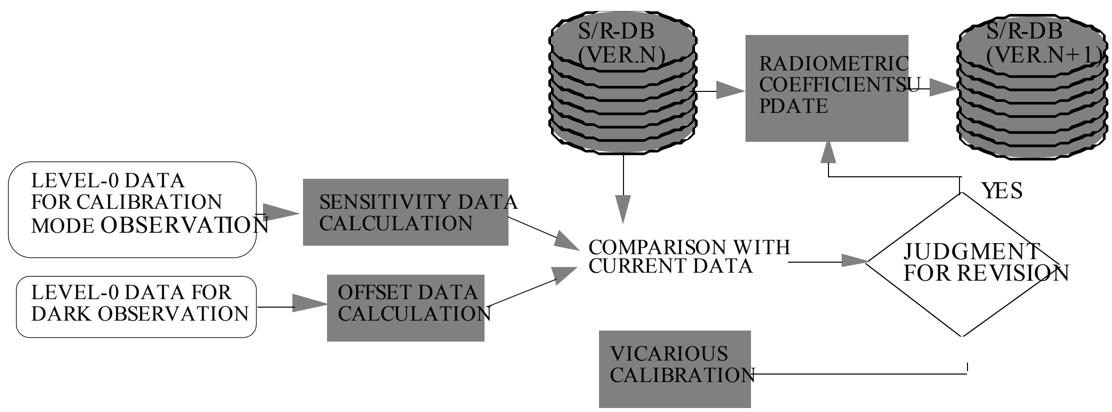


Figure 4-7 SWIR Radiometric Correction Data Base Update Flow

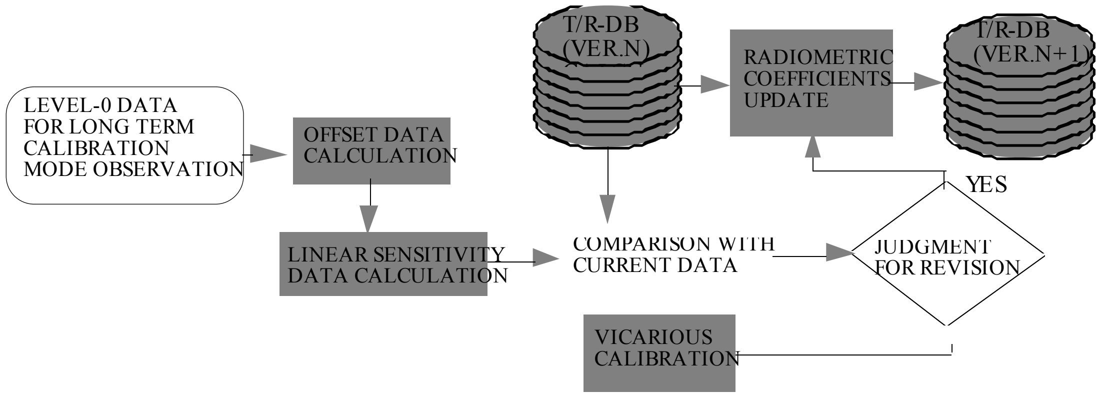


Figure 4-8 TIR Radiometric Correction Data Base Update Flow

4.7 Summary

The validation plan described above uses both pre-launch and post-launch work. Prelaunch activities are divided into two parts. The first uses a theoretical approach to develop, improve, and test the software needed for the VC. The second uses an experimental approach to test data collection methods, evaluate test sites, and develop cooperative efforts with other MTPE sensor teams

After launch, validation of the at-sensor radiances will occur in a fashion similar to the experimental approach in the pre-launch phase. For the reflectance-based approach, the surface reflectance of a selected test site is measured concurrent with an ASTER overpass. At the same time, ground-based atmospheric data are collected. These data are used in a radiative transfer code to predict the at-sensor radiance. In the radiance-based approach, the same measurements are made, but in addition, radiances from the test site are made from an aircraft flying at 3 km above sea level. These radiances are corrected for the effects of the intervening atmosphere between the aircraft sensor and the satellite sensor to predict the TOA radiance.

4.8 Calibration/Validation using the Moon

An additional VC approach for calibrating ASTER is the use of lunar views obtained by rotating the AM-1 platform. Since this method requires an entirely different approach to data collection, it is treated separately from the ground-reference and cross-calibration methods.

4.8.1 Introduction

The AM-1 Platform is expected to execute Calibration Attitude Maneuvers (CAM's) that sweep the platform "nadir" direction through deep space and past the Moon. The baseline maneuver is a pure pitch maneuver, so that the Moon will be imaged at a phase angle near 22 degree. Such CAM's have been requested for early in the mission and at 6-12 months intervals thereafter.

In a CAM, the Moon has an apparent diameter of 6.4 km and it will have this extent crosstrack in an image. The downtrack extent depends upon the inertial pitch rate as the platform reference Z axis goes past the Moon; rates of 0.12 to 3.1 degree/minutes are being considered; the corresponding downtrack extent of the lunar image is 1783 to 102 km. Because lunar data may extend over several "scenes"; it must be possible to reconstruct swaths from the Level 1 product with precise line concatenation. Because the normal spacecraft attitude information will be missing or incorrect, Level 1 processing of CAM data may require some special attention, and the generation of the latitude and longitude at the 2-D grid points, and resampling, should be turned off for Level 1B.

The first analysis step will be to determine the precise path of the Moon through the image. Edge location techniques will be used for each of the reflectance nadir bands to determine the midpoint in the cross-track brightness profile at both edges of the Moon for each image line; comparison with the Lunar Radiance Model (LRM) for the band can be used to locate the precise position of Moon in the swath. [The LRM will be produced from the Earth-based lunar radiometry program for the time and position of the AM-1 platform at the middle of the lunar observation.] Location of the down-track edges of the Moon in the image will provide determination of the actual inertial motion rate of platform. This is also expected to provide intra-telescope registration information to high precision (<0.1 IFOV). Because there will not be an LRM for the TIR, and because the TIR is expected to be saturated over much of the Moon (Lunar mid-day temperatures reach more than 400 K), analysis for the TIR will be experimental.

The Astronomical Ephemeris will be used to determine the location and attitude of the Moon in the J2000 system. Then, the selenographic location of each image pixel can be determined.

4.8.2 Spatial Resolution

Level 1B radiance data will be used, either the 1B product (8-bit), or the floating-point radiance derived by applying the Level-1A radiometric coefficients to the Level-1A product.

The initial assumption will be that all detectors in a band have the same Modulation Transfer Function (MTF). The image analysis will be in terms of a pseudo knife-edge test using the bright limb of the Moon; the wide Line Spread Function (LSF), determined by accumulating the normalized radiance response profile across the lunar limb, normalized to the lunar radiance of the nearest limb (smoothed over a radius equivalent to the off-limb angle).

The cross-track LSF determined in this manner can be directly applicable to the instrument. The downtrack LSF will require correction for the unusually slow motion of the image.

If there is spacecraft attitude jitter, which is not detected by the limb-matching, this will map into a broadening of the LSF, in which case the LSF does not apply to only the ASTER optical performance. However, assuming that attitude jitter during the lunar observations is representative of that during nadir observations, the derived LSF is appropriate at representing the spatial resolution of ASTER data.

4.8.3 Radiometric Accuracy and Stability

After adjusting for the apparent image motion rate, the integrated L-1B radiance can be integrated for the entire Moon, and compared to the Lunar radiance model for the precise geometry of the ASTER observation (see Kieffer & Wildey, 1966 for a discussion of the LRM). Because many thousand pixels are summed, the effective signal-to-noise ratio will be very high.

The expected absolute accuracy is limited by the accuracy of the lunar radiance model, whose goal is about 1% one-sigma. Response stablity determination depends only upon the ability of the LRM to model the fractional changes of lunar irradiance due to the variation of lunar libration between EOS observations times, and is expected to be much less than 1%.

Because the apparent size of the Moon is smaller than the integrating spheres used for prelaunch calibration, a correction for the size-of-source effect may be required. The size-of-source response function will be determined by scattered light analysis of the lunar sequence (see below).

4.8.4 Radiometric Linearity

Over the dynamic range of lunar surface brightness (about 0.1 to 0.3 reflectance), the linearity of ASTER response can be tested by cross plot of L1B radiance with LRM radiance for individual points on the Moon. If the PSF is substantial beyond an IFOV, then the lunar radiance model should be convolved by the PSF before doing this comparison.

The uncertainty of this method is TBD; it is currently unknown if the scatter will be small enough to allow a linearity check over the available dynamic range.

4.8.5 Scattered Light Sensitivity

Lunar scans provide an excellent measure of scattered light response because the field radiance is virtually zero off of the Moon; the irradiance from the Moon is a factor of 2 million times brighter than a magnitude 3 star (a typical naked-eye star). The irradiance of the Moon onto a single ASTER VNIR pixel is about that of a magnitude 0.3 star, and significant influence on the radiometric results will be rare. In any event, a map of background celestial objects can be made in a straightforward way from astronomical catalogs.

The level-1A image, averaged down-track to correct for the scan rate, is basically a crude scattered-light response map with 0.5 degree resolution (the size of the lunar source). Development of scattered light response profile is basically a determination of an extended Point Spread Function (PSF), using same form of analysis as for LSF. All image pixels are used to make a PSF response map out to about 1-2 degree from the array center; cross-track extent is limited by the detector array length (unless the Moon passes through an array away from its center), down-track extent is set by the CAM motion rates and recording time. When the Moon is off of the ASTER detector arrays, information on its position relative to the platform Z axis must come from spacecraft attitude information. The AM-1 project is determining how this information can extracted from the spacecraft engineering information and provided to the instrument teams.

4.8.6 Size-of-source effect

The combination of the line spread function and the scattered light sensitivity means that the two-dimensional response function of ASTER can be approximated from analysis of the lunar data. This function can be integrated radially from the center of the IFOV to generate the "encircled energy response", or size-of-source, function out to the angular distance from the Moon to the edge of the lunar scene, about 2.5 degree. Response beyond this should be very small for all ASTER bands, but is subject to change on orbit if there is contamination or degradation of the optical surfaces. Determination of far-off-axis scattered light sensitivity in flight is difficult, and no method has been formally identified. If there is an indication of an extended size-of-source effect, ASTER data could be recorded during the early part of a CAM as the spacecraft Z axis goes past the Earth limb, in effect using the Earth as a large source.

Cross-calibrations with other EOS and non-EOS sensors, as well as measurements of the moon will also be used to determine the validity of the calibration coefficients used for ASTER.

Registered Radiance at Sensor (AST03) - Geometric Japanese Effort

The ASTER system has three subsystems: VNIR, SWIR and TIR. The VNIR subsystem has two telescopes, one at nadir and the other with backward pointing, the other subsystems have a single telescope. This instrument configuration necessitates ground processing to generate a geometrically registered Level-1 data product. Figure 5.1 shows the overall geometric validation activities from the Pre-flight period to the Normal operation period.

Special features to be stressed for ASTER compared to other optical images are; (1) spectral data acquisition with a high spatial resolution of 15 m in visible and near infrared regions, (2) stereoscopic capability in the along track direction, (3) high spectral resolution in short wave infrared region, and (4) high spectral and spatial resolutions in thermal infrared region. These characteristics can be available after the geometric registration. However, there exist many items to be validated, as shown in Figure 5.2.

During the preflight test, the line of sight (LOS) vectors will be evaluated toward Navigation Base Reference (NBR) and the preliminary geometric data base (Ver. 0) will be produced. During the initial checkout period, a fine tune-up process based on acquired image data will be carried out for the preparation of the geometric database (Ver. 1) by the intra-telescope, the inter-telescope registration correction and ground control point (GCP) matching. The interim database (Ver. 0.40) is provided based on the band-to-band registration result at the middle of the initial checkout period. During the normal operation period, the inter-telescope band-to-band registration is to be carried out routinely in the Level-1 processing by the image matching to compensate for the dynamic part of the pointing stability. The geolocation and the intra-telescope registration are evaluated regularly. Thus the geometric database is periodically revised based on the long-term accumulation of data correction information.

5.1 Introduction

5.1.1 Measurement and Science Objective

The objective of the Level-1 algorithm is to generate data products that are radiometrically calibrated and geometrically corrected using the Level-0 data as input. The Level-1 data are the source data for generating the higher-level data products.

5.1.2 Product Description

There are two kinds of the Level-1 data, these are: Level-1A data and the Level-1B data. The Level 1A data are the reconstructed unprocessed instrument data at full resolution, time-referenced, and annotated with ancillary information, including radiometric calibration and geometric correction coefficients and georeferencing parameters computed and appended, but not applied to the Level-0 data.

The Level-1B data are the Level-1A data processed using the radiometric calibration and geometric correction coefficients to registered radiance at sensor. The Level 1B data are typically used as input to the higher level data products.

5.2 Validation Criterion

5.2.1 Overall Approach

The Line of Sight (LOS) vectors toward the Navigation Base Reference (NBR) can be calculated for an arbitrary pointing position using the following two kinds of parameters.

(1) A set of the line of sight (LOS) vectors for the nadir cross-track pointing position toward NBR.

(2) The pointing drive axis vector toward the NBR.

Therefore, these parameters affect the geometric performance and need to be validated.

The intra-telescope and the inter-telescope registrations are carried out with an image matching techniques among the acquired images. The geolocation accuracy depends on the spacecraft knowledge and the instrument boresight stability, and will have to be regularly validated using Ground Control Points (GCPs).

The whole procedures are based on the Level-1 algorithm, that is, the Level-1 modules are used. It is important to note that uncertainties that cannot be corrected by Level-1 procedure must be removed by the validation activity.

5.2.2 Sampling Requirements and Trade-off

Detection of the intra-telescope registration error will be carried out for all bands relative to a reference band in each subsystem, that is, band 2 for VNIR, band 6 for SWIR and band 11 for TIR. The inter-telescope registration error detection will be carried out for band 6 for SWIR and band 11 for TIR relative to the reference band 2. Any scenes obtained can be selected for the band-to-band registration unless there is special maneuver and cloud coverage during the data acquisition. The geolocation error detection will be carried out only for band 2. The geolocation accuracy for other bands may be guaranteed through intra- and inter-bands registration processes, as shown in Figure 5.3. Therefore, the scenes of VNIR band 2 which include the specially prepared GCP chips for the validation purpose of the geolocation accuracy are selected.

5.2.3 Measures of Success

The goal of this validation activity is to accurately estimate the geometric performance of the ASTER instrument and improve the registration accuracy by updating the processing parameters if possible.

The quantitative measure of success is to attain the required accuracy as follows:

Pixel geolocation accuracy : not specifically required but the goal is 100m (nadir direction)
Intra-telescope registration: 0.2 pixels
Inter-telescope registration: 0.3 pixels

The geometric registration accuracy is regularly examined through the quality of Level-1 product and the updated geometric database is validated.

5.3 Pre-launch Algorithm Test/Development Activities

During the subsystem preflight test the LOS vectors will be evaluated against the boresight coordinate frame of each telescope using the collimator. The boresight coordinate frame is right-handed and orthogonal. The Z-axis is coaligned with the boresight vector. The Y-axis is a line normal to the Z-axis and to the pointing drive axis. The X-axis is perpendicular to both the Y-axis and the Z-axis to complete the right hand set. It should be noted that the boresight coordinate frame changes depending on the cross-track pointing position. Therefore, the coordinate transformation is necessary to identify the LOS vectors for an arbitrary pointing position. The evaluation process is as follows.

(1) The cross-track pointing shall be set to the predetermined nadir position, because the boresight changes the direction depending on the cross-track pointing position.

(2) The LOS vectors of selected detectors (number is currently TBD) shall be evaluated toward the body-fixed coordinate system of each subsystem at initial stage.

(3) The boresight vector for each telescope shall be calculated from the evaluated LOS vectors according to the definition of the boresight in which the boresight is an average direction of the all detectors. Then the boresight coordinate frame for the nadir pointing position shall be defined for each telescope.

(4) The exact direction of the pointing drive axis toward the boresight coordinate frame shall also be evaluated.

(5) Then, the measured LOS vectors shall be expressed with the boresight coordinate frame by coordinate transformation from the body-fixed to the boresight coordinates

(6) For SWIR and TIR telescopes the stagger configuration of detectors shall be realigned to the center position between the odd and the even alignment lines.

During the integration and test on the spacecraft the nadir boresight coordinates (the boresight coordinates for the nadir position of the cross-track pointing) for each subsystem is aligned to the Spacecraft Reference Axes (Navigation Base Reference) as exactly as possible except for TIR subsystem, which is rotated by 0.3 degree on Z-axis from the exactly coincided position. For VNIR subsystem the boresight coordinates shall be represented by the nadir telescope. A small alignment error between each subsystem and the spacecraft can be evaluated by using the instrument cube of each subsystem and the spacecraft cube. Then the LOS vectors and the boresight vectors toward Navigation Base Reference (NBR) can be obtained with the coordinate transformation by an alignment error between the two coordinate systems. The boresight shall be as close to the Z-axis of NBR as possible.

The final product during the preflight test is the preliminary geometric database (Ver. 0) which contains a set of the LOS vectors toward the NBR as shown in Figures 5.8. The cross-track pointing axis which is expressed toward the NBR is also a part of the geometric data base.

5.4 Post-launch Activities

5.4.1 Initial Checkout Period

Measurements of the LOS vectors with the collimator during the preflight test may not be sufficiently accurate for precise band-to-band registration. Real image data are essential for precise registration in-flight. However, it is not possible to have focused image data during the preflight test activity on the ground. Therefore, a fine tune-up process based on acquired image data will be necessary for the preparation of the geometric database with an accuracy for operational use. This process shall be carried out during the in-flight initial checkout period, which is scheduled for 105 days just after the launch. The special Level-1B products (path oriented, UTM) shall be used for this purpose.

In addition, there is a strong possibility to enhance the Pixel Geolocation Knowledge (PGK) by evaluating a static error of the pointing information by comparing an acquired image with GCPs. A specified value of PGK is 437 m, which can be evaluated from a position knowledge of 150 m and a boresight pointing knowledge of 120 arcsec. Because these design values of the knowledge for the flight model are much better than the specified values and because the majority of the pointing knowledge is static, a PGK of about 50 m may be anticipated, if the static error is removed.

The initial checkout activity for the geometric database consists of three parts; an intra-telescope registration error correction, an inter-telescope registration error correction and a geolocation error correction. The correction process flow is shown in Figure 5.9

The interim database (Ver.0.40) is provided based on the band-to-band registration result at the middle of the initial checkout period. A fine tune-up process based on acquired image data will be carried out for the preparation of the geometric database (Ver.1) by the intra-telescope, the inter-telescope registration correction and ground control point (GCP) matching. Figure 5.4 shows the main procedures and schedules.

5.4.1.1 Intra-telescope Registration Correction

The intra-telescope registration error detection shall be carried out for all bands relative to the reference band of each subsystem, that is, band 2 for VNIR, band 4 for SWIR and band 11 for TIR. The image matching techniques shall be used for the error detection relative to the reference band. In order to compensate for the parallax error of the SWIR an elevation map of the target subscene is required. Therefore, the scenes, specially prepared for the geolocation correction, will also be used compensate for the parallax error. The correction procedure is as follows (Fig. 5.5). The Level-1B products shall be used for this purpose.

(1) Several subscenes with elevation information are selected in a scene as correlation windows of which sizes are tentatively set to 42 x 42 pixel for VNIR, 21 x 21 pixels of SWIR and 7 x 7 pixels for TIR.

(2) Matching error components in both the along-track (X-axis) and the cross-track (Y-axis) directions are evaluated for each subscene. Subpixel resampling may be carried out if necessary.

(3) For SWIR the parallax error is calculated from the elevation information and subtracted from the image matching error in the along-track direction to evaluate alignment error only.

(4) The error is applied to one closest detector correspond to the center of each subscene.

(5) The LOS vector errors for roll, pitch and yaw components of these selected detectors can be evaluated from these error data and are stored in the off-line database file.

(6) The LOS vectors of other detectors can be evaluated with the linear interpolation method.

This correction will be very small, a few arcseconds at most judging from the accuracy of the preflight measurements. This intra-telescope registration correction will be necessary only for the in-flight initial checkout period, because the detector alignment in the same telescope is considered to be very stable. This stability is specified within ±0.2 pixels during the life of the instrument. In the Level-1 processing, however, because the intra-telescope registration is not performed, this correction must be done precisely to reduce the distortion in the telescope.

5.4.1.2 Inter-telescope Registration Correction

The inter-telescope registration error detection shall be carried out for band 6 for SWIR and band 11 for TIR relative to the reference band 2. Image matching techniques shall be used detect the error relative to the reference band. The parallax error among the reference bands is very small. Therefore, the scenes for this purpose will not be necessarily be the same as those specially prepared for the geolocation correction including GCP information, also these scenes would be preferable to maintain consistency throughout the geometric correction process. The correction procedure is as follows.

(1) Several subscenes for the image matching are selected in a scene as correlation windows of which sizes are tentatively set to 42 x 42 pixel for VNIR, 21 x 21 pixels of SWIR and 7 x 7 pixels for TIR.

(2) Matching error components in both the along-track (X-axis) and the cross-track (Y-axis) directions are evaluated for each subscene. Subpixel resampling may be carried out if necessary.

(3) The error is applied to one closest detector correspond to the center of each subscene.

(4) The LOS vector errors for roll, pitch and yaw components of these selected detectors can be evaluated from these error data.

(5) All LOS vectors of bands 6 and 11 can be evaluated with the linear interpolation method and are stored in the off-line database.

(6) The same LOS vector errors as bands 6 and 11 are applied to all other SWIR and TIR bands.

In the Level-1 processing, the inter-telescope is registered only for the scene center. In this procedure, pixel size adjustment among different telescopes is most important and will be held to the same value during the mission life. The reduction in offset, distortion and rotation that is serious on image matching will guarantee the quality of the product. At the same time, a static component of the misalignment among different telescopes can be evaluated in-flight. Therefore, only the dynamic part of the misalignment, including the pointing knowledge in the cross-track direction, is necessary to be corrected by the image matching during the normal operation phase.

Test scenes in the band-to-band registration are selected by taking account of the quality of the image matching. In most cases, the same scenes are used for both the inter- and intra-telescope registration.

5.4.1.3 Geolocation Correction

The geolocation error detection shall be carried out only for band 2. The geolocation accuracy for other bands may be guaranteed through intra- and inter-bands registration processes. The special GCP file is planned to be prepared for the this geolocation error detection using JERS-1 data with a spatial resolution of 18 m and SPOT data with a spatial resolution of 10 m. About 30 scenes with 10 - 20 GCPs will be prepared throughout the world. At least 30 data sets will be necessary for statistically evaluating the static pointing error. Considering the cloud coverage probability, about 300 GCPs will be prepared for this purpose. The geolocation error detection is performed only for the boresight vector. This procedure corresponds to the determination of the VNIR telescope direction. Only the average value of the registration error over the observed GCP is needed in this process. The size and LOS vectors of all pixels are determined at the next steps (Pixel Size Correction). The correction procedure is as follows (Fig. 5.6).

(1) The scenes of VNIR band 2 which include the specially prepared GCP chips for this purpose are selected.

(2) The band 2 sensor is divided into several clusters which sizes are tentatively set to 42 pixels.

(3) Matching error components with GCP chips in both the along-track (X-axis) and the cross-track (Y-axis) directions are evaluated. The registration errors are accumulated in the GCP matching history file. It should be noted that the effects of latitude and longitude are systematically investigated.

(4) The LOS vector error based on the spacecraft position and the boresight pointing errors can be evaluated from these image matching error data for each scene with GCPs. The registration error is recorded in the off-line database files.

(5) The on-line database is produced. If the database provides better geolocation property, the database is adopted.

(6) The error correction for band 2 shall be applied to all LOS vectors of all bands.

A major purpose of this correction process is to evaluate a static pointing error as a whole including the spacecraft and the instrument. The static error shall be finally determined from a lot of error data during the initial checkout period and will probably be kept in the same value during the mission life. The static error correction shall be applied to all LOS vectors of all bands. It should be noted that the geolocation correction in the Level-1 processing is not intended to correct the terrain errors.

5.4.1.4 Pixel Size Correction

The registration error in the pixel size is detected. This procedure investigates the relation between the pixel alignment and the off-nadir angle (or scale) and corresponds to the determination of the focal length of the VNIR telescope. The error is so small that the pixels at the edge of the linear sensor are used. Therefore, GCPs located 20-30 km from the orbit are needed. Terrain error must be considered in this step.

Next, the registration error in the LOS vector of each pixel is detected. This procedure corresponds to the determination of the distortion and the yaw component of the VNIR telescope. The linear array of pixels is divided to clusters and the registration error for each cluster is obtained. GCPs distributed in a scene are needed to detect the distortion of an image. Thus the accumulation of data is needed for this procedure.

The correction procedure is almost the same as that of the geolocation correction. Matching error components with GCP chips in both the along-track (X-axis) and the cross-track (Y-axis) directions are evaluated for each cluster. The registration errors accumulated in the GCP matching history file are used for this purpose.

5.4.1.5 Stereo-telescope Angle Correction

The registration of stereo-telescope (Band 3B) registration detection shall be carried out especially on the pitch and roll angle. This implies that the correction is done only for the boresight direction. The DEM generation accuracy of band 3B may be guaranteed the registration processes of the pitch angle. The test targets are selected from the GCPs with low elevation. The correction procedure is as follows.

(1) The scenes of VNIR band 3N and 3B which include the precise GCP for this purpose are selected.

(2) The difference of the pitch angle between the two telescopes is by evaluating matching error component with GCP chips in the along-track (X-axis). The terrain error must be considered carefully.

(3) The LOS vector difference based on the spacecraft position and the boresight pointing errors can be evaluated from these image matching error data for each scene with GCPs. The differences in the pitch and roll angles are recorded in the off-line database.

(4) The error correction shall be applied on the LOS vectors of VNIR band 3B.

5.4.1.6 Pointing Axis Correction of Band 2

Once the LOS vectors of nadir pointing are corrected for all bands, the pointing axis is determined. The pointing axis misalignment in the yaw and pitch directions is related to the registration error in the along-track direction. Since the former becomes the odd function against the pointing angle, while the latter the even function, these two parameters are separated. The evaluation is performed only for the boresight vectors of band 2. Two nadir observations and two off-nadir observations (two different views) of GCP sites are planned for this activity.

Since the initial checkout period is limited, the pointing angle must be changed systematically. The pointing axes are determined via two nadir and two off-nadir observations. The accuracy of the encoder is also investigated. The relation of the pointing angle and the displacement of the boresight vector is carefully checked during the normal flight period.

(1) The scenes of VNIR band 2 which include the precise GCP chips for this purpose are selected.

(2) Matching error component with GCP chips in the along-track (X-axis) direction is evaluated for each pointing angle. Terrain error must be considered. The registration errors are accumulated in a GCP matching history file.

(3) The pointing axis error based on the spacecraft position can be evaluated from these image matching error data for each scene with GCPs and is recorded in the off-line database.

5.4.1.7 Pointing Axis Correction of Other Telescopes

The inter-telescope registration is performed to determine the pointing axes of the SWIR and TIR telescopes. This procedure reduces the image distortion caused by pointing and thus decreases the offsets on the inter-telescope image matching. The error correction procedure is as follows.

(1) Inter-telescope registration is carried out. The registration error relative to band 2 at the same pointing angle is recorded in a band-to-band registration history file.

(2) The pointing axes of the SWIR and TIR telescopes are determined from the registration error.

(3) The linearity and repeatability of the TIR telescope are evaluated.

The final product during the in-flight initial checkout period is to prepare the geometric parameters for the normal operational use by tuning up the preliminary data base. The initial data base for the normal operation is named the data base (Ver. 1).

5.4.1.8 Planned Field Activity and Studies

None planned

5.4.1.9 New EOS-targeted Coordinated Field Campaigns

None planned

5.4.1.10 Needs for Other Satellite Data

Landsat, Spot and JERS data will be used to prepare GCPs.

5.4.1.11 Measurement Needs at Calibration/Validation Sites

None planned

5.4.1.12 Needs for Instrument Development(Simulator)

None

5.4.1.13 Geometric Registration Sites

GCPs will be prepared for geometric registration widely throughout the world.

5.4.1.14 Inter-comparison (Multi-instrument)

None planned

5.5 Post-launch Activities-Normal Operation Period

5.5.1.1 Geolocation Validation

As described in the previous section the intra-telescope band-to-band registration will be kept in the same condition throughout the mission life as the initial checkout period. The inter-telescope band-to-band registration is to be carried out routinely in the Level-1 processing by the image matching to compensate a dynamic part of the pointing. Therefore, a special verification activity by the science team will not be necessary for the geometric data base correction regarding the band-to-band registration. Although the products will be routinely evaluated to ensure no problems arise. The accumulation of registration error on the inter-telescope module of Level-1 processing is useful. This value is automatically obtained in the validation procedure.

Although the geolocation knowledge is also considered to be kept in the enhanced value throughout the mission life after a removal of the static pointing error during the initial checkout period, a special verification activity will be important on the geolocation knowledge, because it cannot be done by the usual quality check of the data products. This activity will also be useful to monitor instrument pointing behavior as a whole including both instrument and the spacecraft.

The absolute pixel size and LOS vectors are provided through that of Band 2. However, they will no be sufficiently corrected during the initial checkout period.

This verification activity is planned to be carried out whenever the instrument acquires good image data of the scenes with many GCPs, which are specially prepared for this activity. The GCP file is same as that prepared for the initial checkout activity. Figure 5.10 shows the verification activity flow for the geometric database during the normal operation which is basically same as the geolocation correction part of the initial checkout period. Judgment will be done for the database update if an average pointing error during TBD operation period (tentatively 3 months) exceeds some threshold value.

5.5.1.2 Stereo-telescope Validation

The DEM accuracy is guaranteed through the pitch angle between Band 3N and 3B. The yaw components and pixel size of Band 3B are determined afterwards during the normal operation period. The change in focal length and distortion of sensor alignment due to the launch shift are evaluated.

5.5.1.3 Pointing Axis Validation

Because the initial checkout period is limited, the pointing axis can not be determined precisely. The pointing axis is gradually corrected during the normal operation period. The pointing angle is changed systematically and the yaw and pitch components of pointing axes are determined precisely. The accumulation of registration error on the inter-telescope correction is useful on the registration of the SWIR and TIR telescopes.

5.5.2 MTF Validation

Test sites with a high contrast between the target and background will be used for the evaluation of MTF. Large bridges on the sea will provide the calculation of line spread function (LSF). Roads running parallel to each other will be also good targets. Since the resolutions of each sensor system are different, the targets should be selected for each sensor system. It should be noted that it is difficult to isolate atmospheric adjacency effect, thus lunar observations will be needed, which provide direct estimation of performance. Lunar observation plan is TBD.

5.5.2.1 Planned Field Activity and Studies

None planned

5.5.2.2 New EOS-targeted Coordinated Field Campaigns

None planned

5.5.2.3 Needs for Other Satellite Data

same as 5.4.1.10

5.5.2.4 Measurement Needs at Calibration/Validation Sites

The GPS measurements might be necessary for determination of the precise position information of GCPs. The details are TBD.

5.5.2.5 Needs for Instrument Development (Simulator)

None

5.5.2.6 Geometric Registration Sites

same as 5.4.1.13

5.5.2.7 Inter-comparison (Multi-instrument)

None planned

5.5.3 GCP Preparation Plan

The GCP preparation is planned for the absolute calibration of the line of sight vectors and the pointing axes of each telescope. This calibration activity is important to keep the geolocation accuracy and will have to be carried out intensively during the initial checkout period. Even in the normal operation period the prepared GCPs will be used for routine verification activity of the geolocation accuracy. The geometric data base shall be updated considering the results if necessary. The GCPs are selected considering the deviation (about 20 km) of the orbit from the nominal one. The planned GCPs are shown below.

(1) Standard GCP

Purpose: absolute calibration of the LOS vectors of band 2 (Nadir boresight)

Accuracy: ±15 m or better for X and Y components, ±50 m or better for Z component

Location: within ± 10 km from the nominal orbit

Number: about 300 points at launch for initial checkout activity and TBD points for verification activity during normal operation period.

Position determination : digitized using maps with a scale of 1/24,000 or 1/25,000.

(2) High Quality GCP

Purpose: absolute calibration of the pointing axis direction
absolute calibration of Band 3B
absolute calibration of the Band 2 pixel size

Accuracy: ±1.5 m (TBR) or better for X and Y components, ±2.5 m (TBR) or better for Z component

Location: about 76 ± 10 km away from the nominal orbit (for pointing axis correction)
within ± 10 km from the nominal orbit (for Band 3B correction)
about 20 km from the nominal orbit (for Band 2 pixel size correction)

Number: 20 - 30 points at launch for initial checkout activity and TBD points for verification activity during normal operation period.
Some GCPs located at nadir are needed for the Band 3B correction.
GCPs located about 20 km away from the nominal orbit are needed for the pixel size determination of Band 2.

Position determination : digitized using maps with a scale of 1/2,500 or 1/10,000 (Japan) measured with differential type GPS.

Each GCP data has a following content; GCP ID number, information of place, latitude, longitude, elevation, accuracy and GCP chip. A map is also attached to the data set. These items are used by GCP matching tool, which can handle the image data obtained and the GCP chip. The GCP list file is prepared to control the GCP matching sequence. The GCP matching is performed to provide a registration error both manually and automatically by calculating the correlation value. An off-nadir angle is also calculated to provide the terrain error.

The elevation of the GCP is obtained from maps relative to the mean sea level. The elevation data is converted to the value relative to WGS84 ellipsoid using the geoid data.

The pre-launch GCP chips are created to match the pixel size, the spectral characteristics and the path oriented direction of VNIR band 2. However, because the initial GCP chip was obtained by other satellite, the image matching quality is not so good. When an operator considers the quality of subscene obtained by ASTER is good, the GCP chip will be replaced by new one. Therefore the image matching in the normal operation period will be much more easy. Another consideration must be taken on the seasonal change in the pattern of GCP chips. For such GCPs, several images are stored in the data field and are used by referencing the date of data acquisition. The number of the GCP usage and its matching quality are recorded in the data field, thus GCPs suitable for the geolocation procedure are listed.

Table 5-1 Selected Landsat Scenes for GCP Preparation

Area	Path/Row No	Average Cloud Coverage (%)		
		July	August	September
USA	015/032 - 035	53 - 57	55	47 - 53
	026/033 - 036	34 - 39	39 - 43	39 - 46
Australia	092/084 - 086	34 - 49	32 - 48	21 - 48
	090/089 - 090	56 - 64	57 - 66	61 - 68
France	199/027 - 029	38 - 47	42 - 51	40 - 47
Japan	107/029 - 036	66 - 76	53 - 73	61 - 72
	108/035	68	53	68
	110/035	73	57	72
	112/037	68	56	67
	113/037	68	56	67

Table 5-1 shows the candidate of Landsat scenes to prepare the GCPs, specifically for the initial checkout activity. About 10-20 GCPs will be selected for each scene. The image chips obtained by JERS-1 or SPOT are prepared. Additional GCPs are planned to prepare for verification activity during the normal operation period, although the details are TBD in current stage.

5.5.4 Management of Database Files

During the validation activity, the geometric database files are updated routinely. The database files are classified as three types; on-line database file, off-line database file and validation history file. Tables 5-2 and 5-3 show the contents of these files.

Table 5-2 Contents in Off-line Database and On-line Database

Module	Off-Line Database	On-Line Database
Geolocation	Registration error in boresight vector	LOS vector of Band 2
	Pixel size of Band 2	LOS vector of Band 2
	Registration error in clusters ·DIM A[number of subscene]	LOS vector of Band 2
Inter-telescope	Registration error to reference band ·DIM A[number of subscene]	LOS vector of each Band
Intra-telescope	Registration error to reference band ·DIM A[number of subscene]	LOS vector of each Band
Stereo	Angle between Band 3N and 3B	LOS vector of Band 3B
Pointing	Registration error in pointing axes	Pointing axes of Band 2
	same as band-to-band registration	Pointing axes of each telescope

Table 5-3 Contents of History Data file in Off-line Database

Module	History Data File	Off-Line Database
Geolocation	Registration error for each GCP	Registration error in boresight vector
		Pixel size of Band 2
		Registration error in clusters ·DIM A[number of subscene]
Inter-telescope	Registration error in each subscene	Registration error to reference band ·DIM A[number of subscene]
Intra-telescope	Registration error in each subscene	Registration error to reference band ·DIM A[number of subscene]
Stereo	Registration error for each GCP	Angle between Band 3N and 3B
Pointing	Registration error for each GCP	Registration error in pointing axes
	same as band-to-band registration	same as band-to-band registration

The history data files are parts of off-line database files and are created at each validation procedure, such as GCP matching and band-to-band registration. They are used to generate statistics and accuracy analysis reports. The off-line database files are produced by analyzing the history data files statistically. The on-line database files are composed of the LOS vectors and pointing axis, and used directly in Level-1 data processing. Each updating history and the version of these files must be maintained correctly. It should be noted that each module can update these files separately.

5.6 Implementation of Validation Results in Data Production

5.6.1 Approach (including long term calibration considerations)

All of the validation data will be archived comprehensively at ASTER GDS to provide users. The details plan is TBD.

5.6.2 Role of EOSDIS

N/A

5.6.3 Plans for Archiving of Validation Data

All of the validation data will be archived comprehensively at ASTER GDS to provide users. The details plan is TBD.

5.7 Summary

The geometric validation plan described above includes both pre-launch and post-launch activities. The post-launch activities are divided into two parts, the activities during the initial checkout period and the activities during the normal operation period.

The major geometric validation activities are to evaluate the band-to-band registration and the geolocation accuracy. The results will be used to update the parameters for the processing.

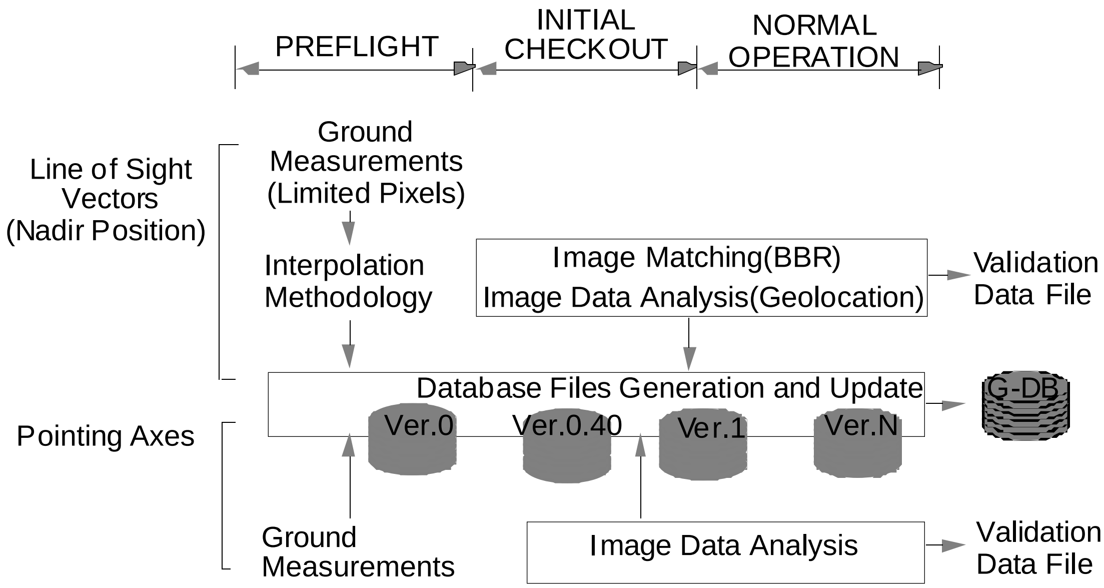


Figure 0-1 Flow of Geometric Validation Activity

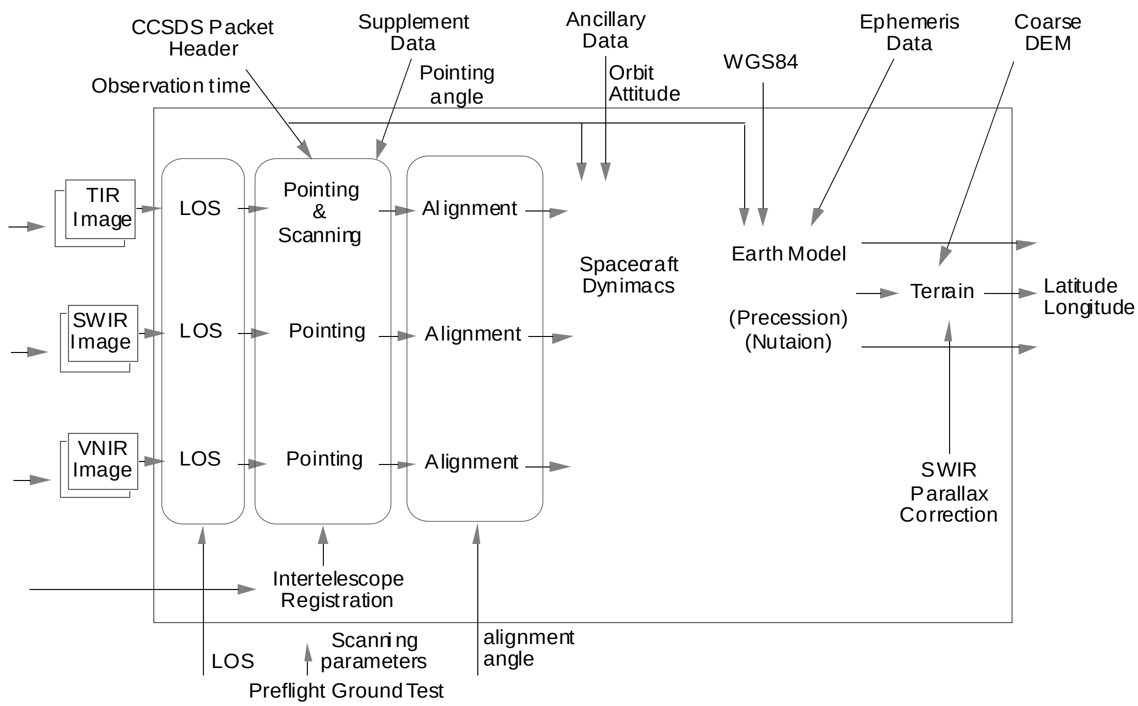


Figure 0-2 Items to be evaluated during the Validation Activities

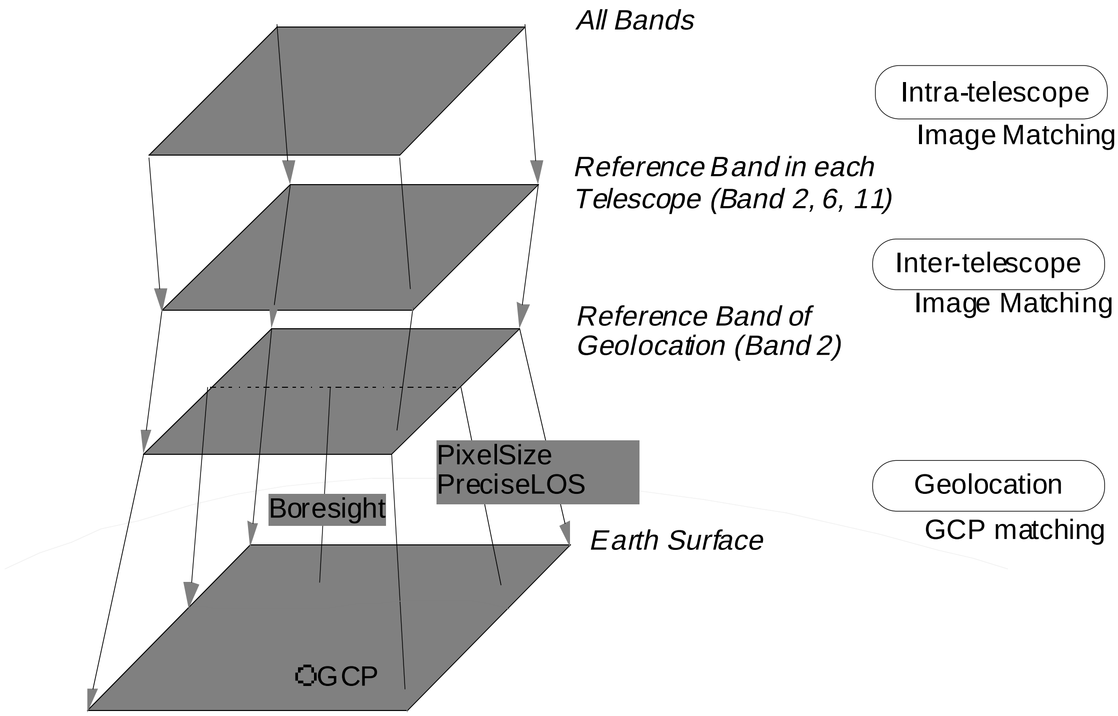


Figure 0-3 Registration Strategy

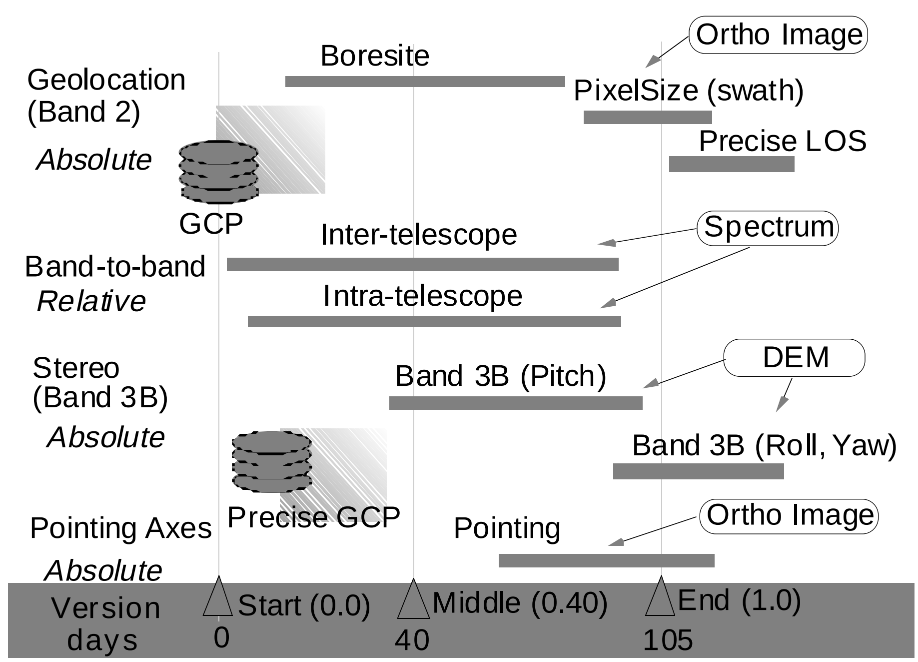


Figure 0-4 The Main Procedures and its Relation with other WGs

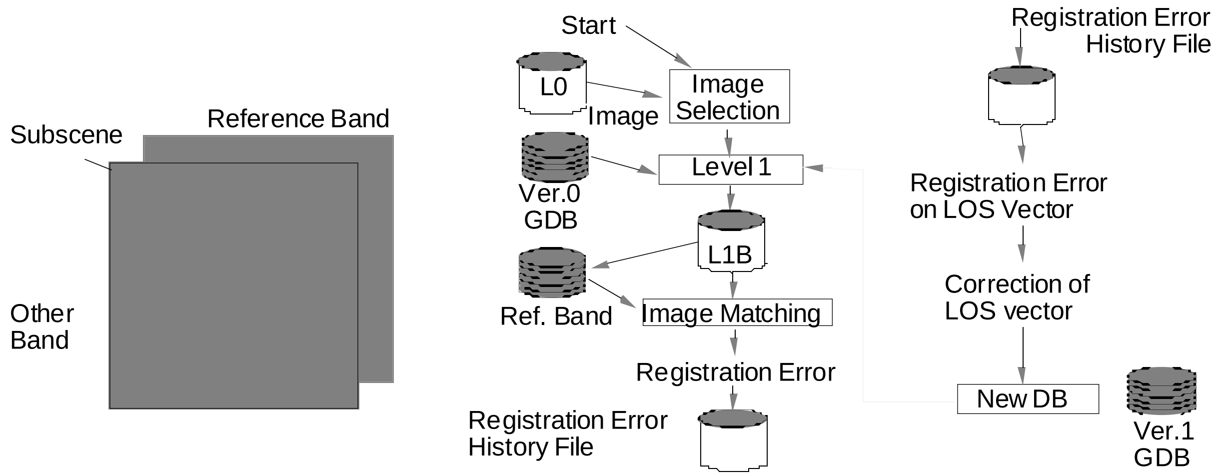


Figure 5.5

Figure 0-5 Flow of the Band-to-band Registration Procedure

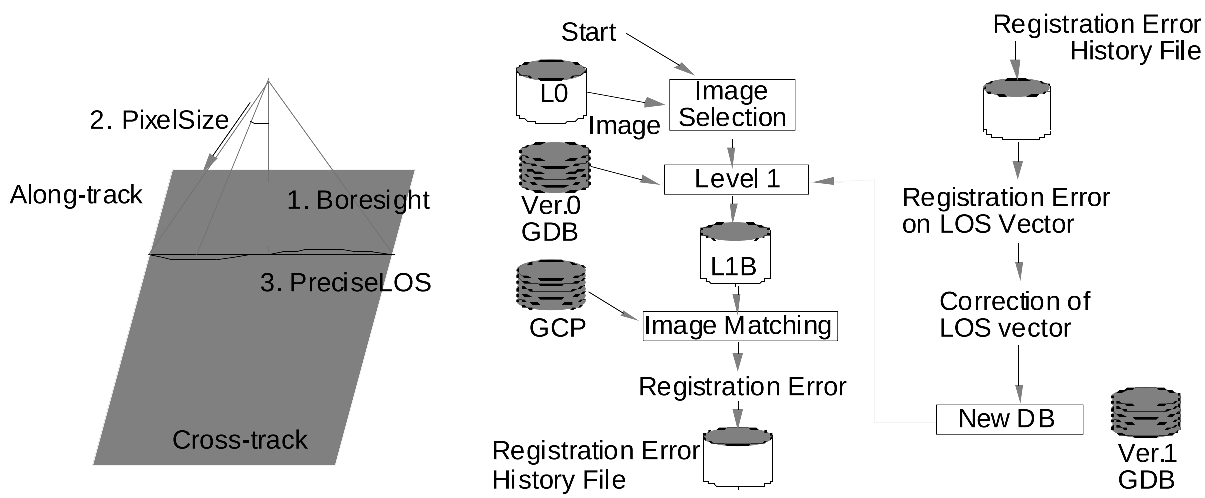


Figure 5.6

Figure 0-6 Flow of the Geolocation Procedure

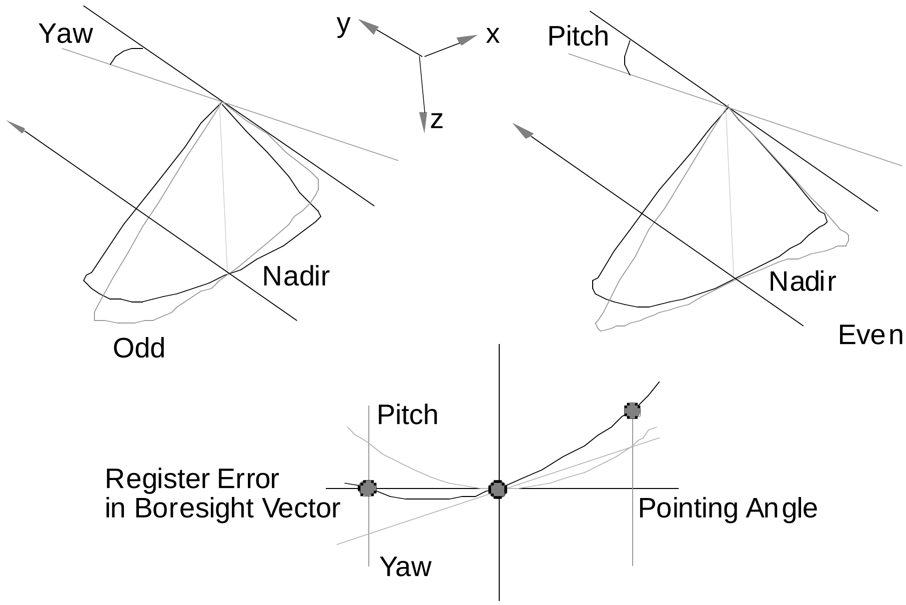


Figure 0-7 Determination of Pointing Axis (Band 2)

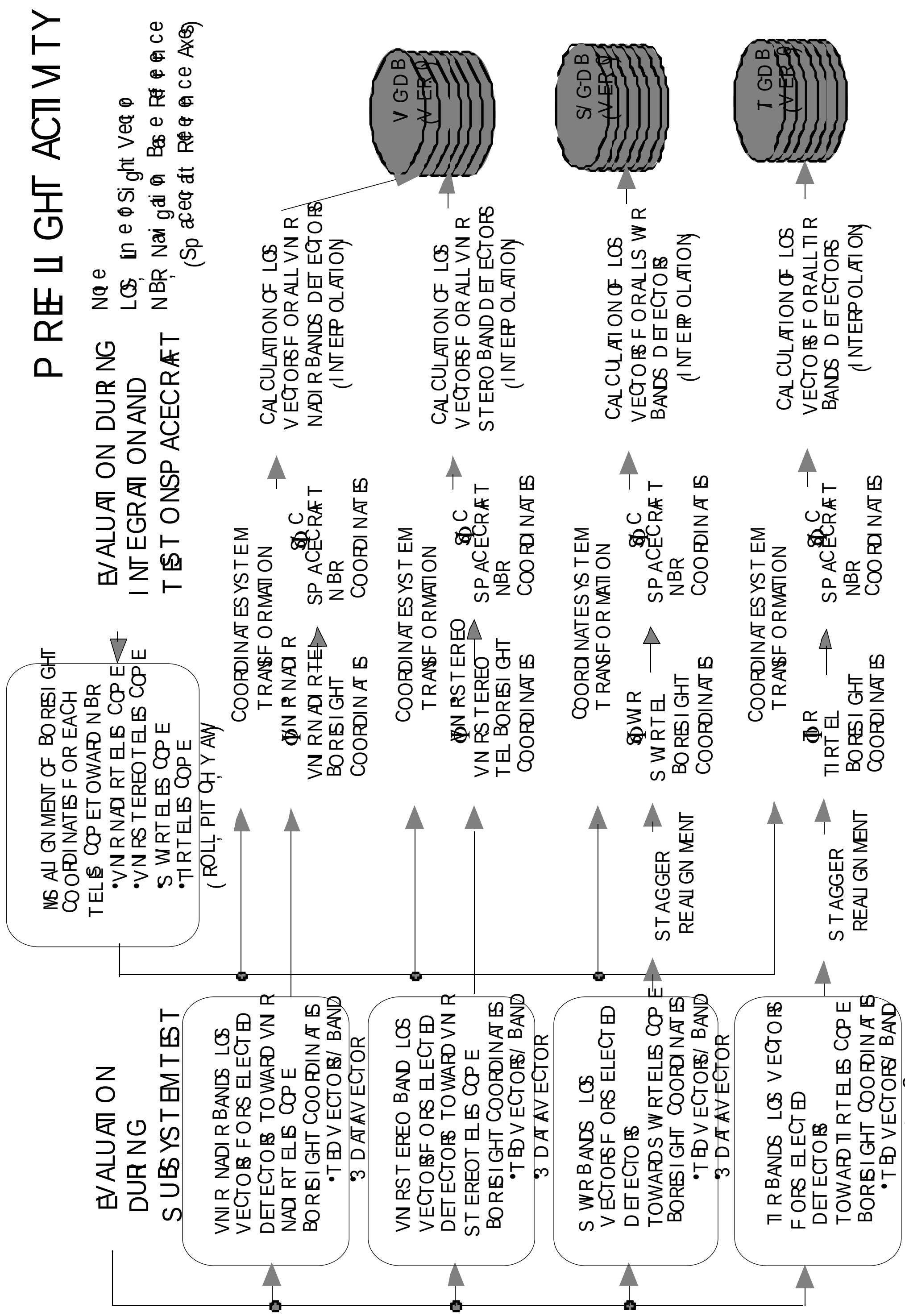


Figure 0-8 Preliminary Geometric Database Preparation during Preflight Test Period

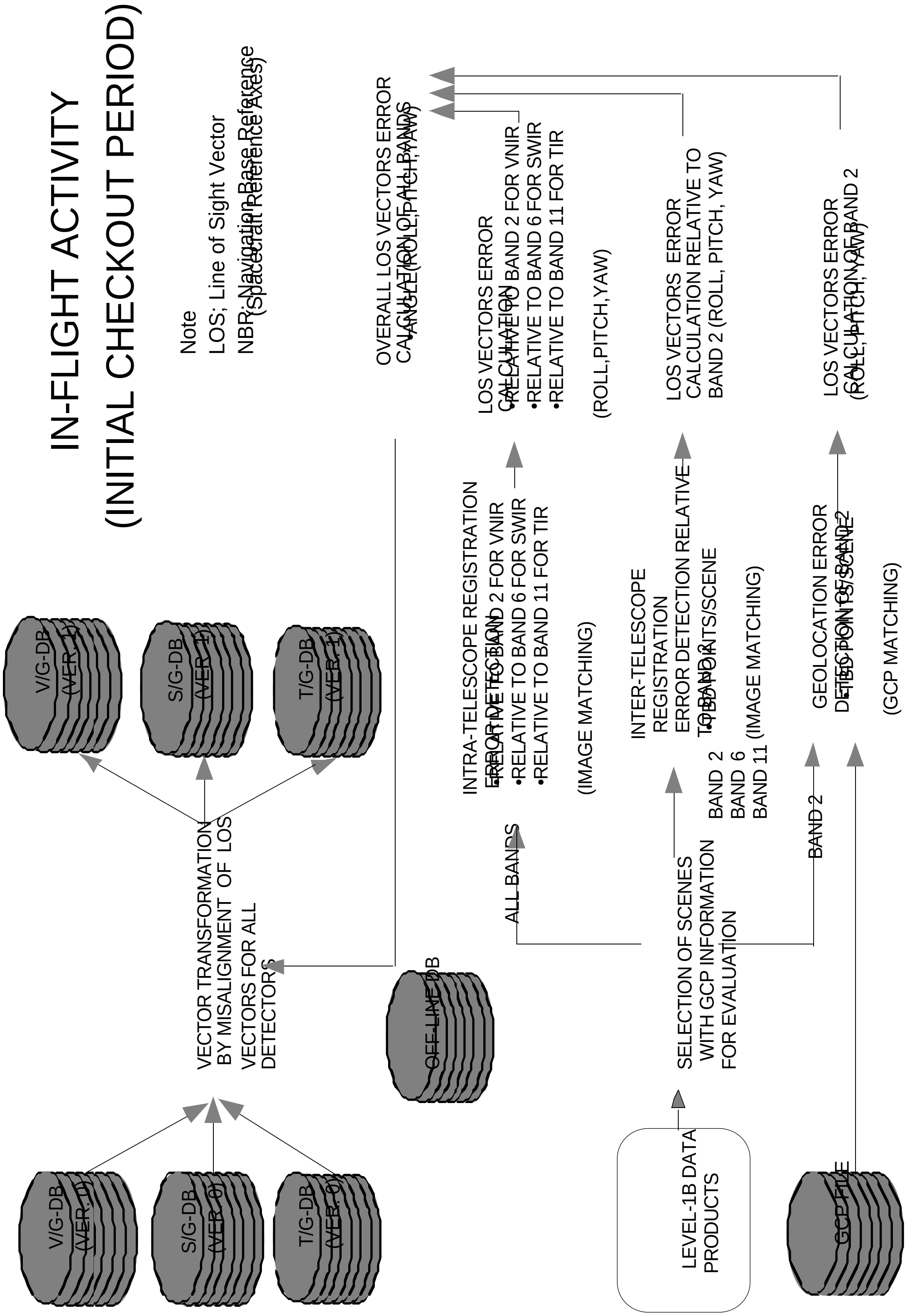


Figure 0-9 Geometric Validation Activity during Initial Checkout Period

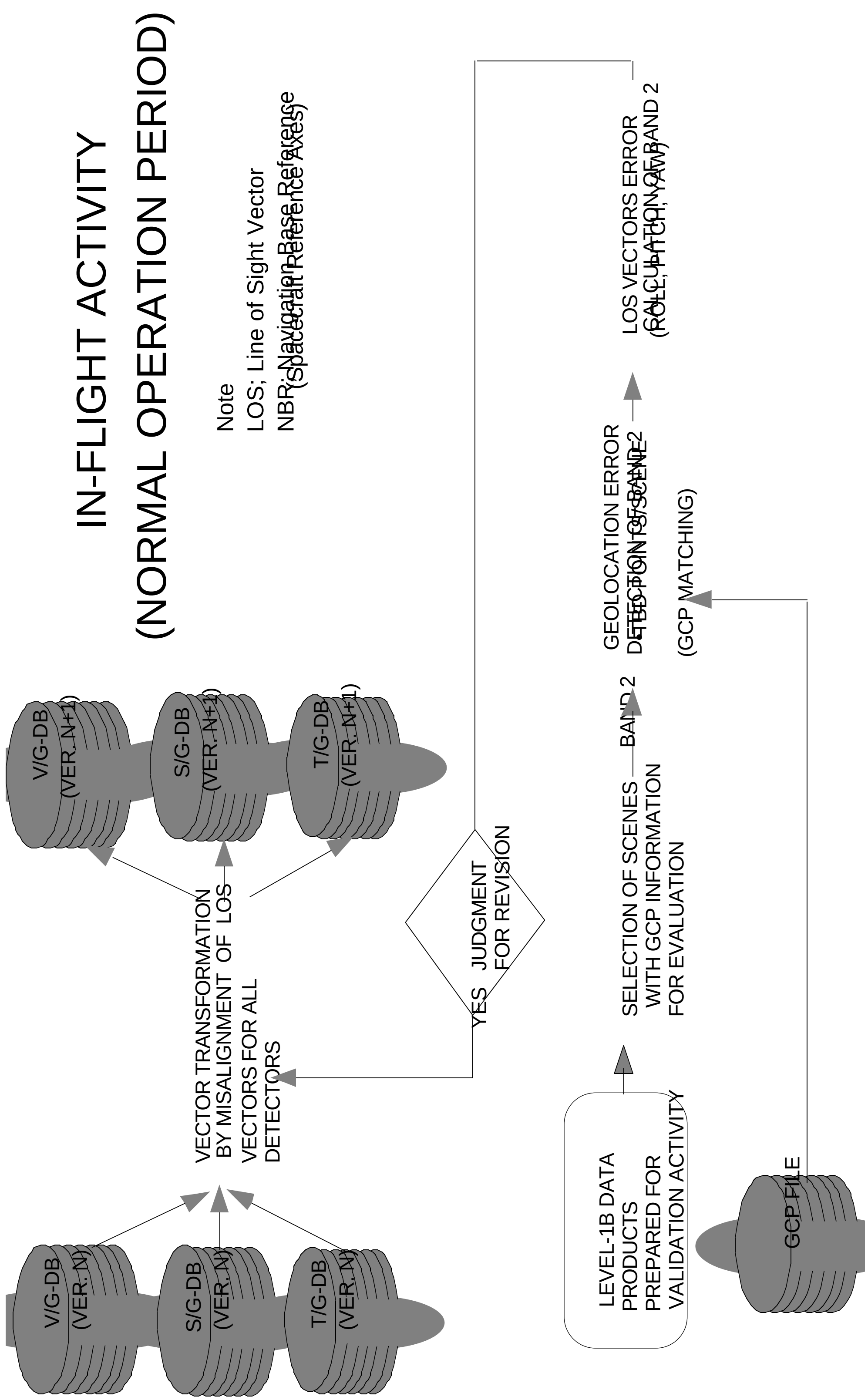


Figure 0-10 Geometric Validation Activity during Normal Operation Period

Decorrelation Stretch (AST06)

6.1 Introduction

6.1.1 Measurement & science objectives

The decorrelation stretch is a process that is used to enhance (stretch) the color differences found in a color image. The method used to do this involves the measurement of inter-channel correlation found in the input data, and removal of this correlation by means of an appropriate color space transformation.

6.1.2 Product Description

The decorrelation stretch product consists of three image planes, assigned as blue, green, and red color planes. Pixels in each plane are one byte in length. The pixels in each output plane are formed by a linear combination of the corresponding pixels in the three selected input channels.

6.2 Validation Criterion

6.2.1 Overall approach

The definition of "validation" adopted by the EOS Panel on Data Quality is that: "[Validation] involves specification of the transformations required to extract estimates of high-level geophysical quantities from calibrated basic instrument measurables and specification of the uncertainties in the high-level geophysical quantities."

The decorrelation stretch is a visualization tool, one to make spectral differences within a scene more apparent to the observer. The result of the decorrelation stretch is not a geophysical quantity, nor is it quantitatively tied to any geophysical quantity. Validation, in the quantitative, geophysical sense as narrowly defined above, is not applicable.

Validation for this product will be limited to testing the software for adherence to the algorithm specified in the theoretical basis document, examining the output data for inter-channel correlation, and visually examining the output.

6.2.2 Sampling requirements and trade-offs

N/A

6.2.3 Measures of success

The quantitative measures of success are that the resulting image channels:

(1) Be uncorrelated (correlation coefficients equal 0.0)
(2) Have a mean value equal to the requested mean

(3) Have a variance from the mean equal to the requested variance for the region of interest (i.e., the area from which statistics were gathered).

6.3 Pre-launch Algorithm Test/Development Activities

6.3.1 Field experiments and studies
No fieldwork is planned expressly for this product. A selected amount of the image data acquired for validation of other ASTER data products will be used to test and exercise the software for this product.

6.3.2 Operational Surface Networks
N/A

6.3.3 Existing satellite/aircraft data
The decorrelation stretch is now being routinely applied to all TIMS aircraft data. The behavior of the algorithm upon this set of data is being monitored.

6.4 Post-launch activities

6.4.1 Planned field activities and studies
No fieldwork is planned expressly for this product. A selected amount of the image data acquired for validation of other ASTER data products will be used to test and exercise the software for this product.

6.4.2 New EOS-targeted coordinated field campaigns
None planned

6.4.3 Needs for other satellite date
None

6.4.4 Measurement needs at calibration/validation sites:
None

6.4.5 Needs for instrument development (simulator)
No specific need. Samples of any simulator data would be welcome for testing and evaluation, but not required for validation.

6.4.6 Geometric registration site
N/A.

6.4.7 Intercomparisons (multi-instrument)
N/A.

6.5 Implementation of Validation Results in Data Production

6.5.1 Approach (including long-term calibration considerations)
If the testing of the algorithm upon other products' validation images indicates the need for a refinement of the algorithm, it will be done as a supplemental software release. Since the algorithm is essentially insensitive to spectral, radiometric, or spatial calibration variations, no changes are needed if these calibrations change over time.

6.5.2 Role of EOSDIS
None

6.5.3 Plans for Archiving of Validation Data
Since no validation data are acquired specifically for this product, there is no additional validation data to be archived.

6.6 Summary

Image data acquired for validation of the other standard products will be used to test the algorithm, but no data will be acquired and no field campaigns will be mounted expressly for this product. "Validation" actually consists of testing the software for its fidelity to the product's ATBD.

Brightness Temperature at Sensor (AST04)

7.1 Introduction

7.1.1 Measurement & science objectives

The purpose of this product is to convert the radiance values that have been observed by the sensors into corresponding brightness temperature values. The brightness temperature product contains essentially the same information as the radiance at sensor (Level 1B) data product, but in a form that is more easily and intuitively understood.

7.1.2 Product Description

The Brightness Temperature at Sensor product consists of five image planes, one for each thermal IR channel. Image pixels are short integer (16 bit), with values expressed in hundredths of degrees Centigrade. For example, a brightness temperature value of 18.3 degrees Centigrade is represented as 1830.

7.2 Validation Criterion

7.2.1 Overall approach

The brightness temperature product is at its core a conversion from radiance to temperature units. For a given wavelength, this relationship is explicitly defined by the Planck function. For an ASTER thermal infrared channel, the Planck function must be integrated with the normalized spectral response function for that channel. Assuming that the spectral response function is known, this computation can be evaluated to be within any practical precision limit, certainly well within the limits of the precision of the input radiance data. Since the dominant sources of imprecision and error are the uncertainty of the input radiance data (Level 1B product) and the uncertainty of the spectral response functions (which are themselves tied to the validation of the Level 1B product), validation of this product is "piggy-backed" to the validation of the Level 1B, radiance at sensor product. It should be noted that the quantity being reported by this product is "at sensor", not "at surface". As such, strict agreement with ground measurements is not an issue, and field experiments are not envisioned.

7.2.2 Sampling requirements and trade-offs

N/A

7.2.3 Measures of success

The success criterion lies solely in the testing that the software uses the Planck function and the spectral response functions properly to calculate the conversion for radiance to temperature (as verified by independent external calculations). Once the uncertainties of the Level 1B product and spectral response function are determined, the uncertainty of this product may be calculated directly.

7.3 Pre-launch Algorithm Test/Development Activities

7.3.1 Field experiments and studies
No fieldwork is planned expressly for this product. The results of the measurement of the sensor spectral response functions will be used to calculate the uncertainty of this product.

7.3.2 Operational surface networks
N/A

7.3.3 Existing Satellite Data
N/A

7.4 Post-launch activities

7.4.1 Planned field activities and studies
No fieldwork is planned expressly for this product. The results of the Level 1B-validation activities will be monitored, and used to calculate the uncertainty related to this product.

7.4.2 New EOS-targeted coordinated field campaigns
None planned

7.4.3 Needs for other satellite date
None

7.4.4 Measurement needs at calibration/validation sites:
None

7.4.5 Needs for instrument development (simulator)
None

7.4.6 Geometric registration site
Not applicable
.
7.4.7 Intercomparisons (multi-instrument)
N/A

7.5 Implementation of Validation Results in Data Production

7.5.1 Approach (including long-term calibration considerations)

The Level 1 validation effort will be monitored. While adjustments to geometric and radiometric parameters (or uncertainties in these parameters) will have no effect on the algorithm for this product, a change in the spectral response calibration would require a change to the software for this product. This would be implemented by the generation of a new lookup table to support the conversion. The new lookup table would be given a separate version number and also identified by its implementation date. The old lookup table would be archived. The validation activities are not likely to result in a change to the spectral response calibration.

7.5.2 Role of EOSDIS
None.

7.5.3 Plans for Archiving of Validation Data
There are no validation data for this product that is appropriate for archival.

7.6 Summary

The Level-1 validation activity will be monitored. If that activity uncovers changes in the spectral response functions for the thermal IR channels, this new information will be used to generate an updated lookup table. No separate activity is planned. No additional fieldwork is needed.

Surface Radiance and Reflectance - VNIR-SWIR (AST09)

8.1 Introduction<u>1.0 Introduction</u>

The Level-2B1 product is surface radiance and the Level-2B5 product is surface reflectance for the VNIR and SWIR telescopes. The algorithms for both are referred to as atmospheric correction. The algorithms are together because they are closely related, require similar input data sets, and use the same look-up table (LUT) approach. The atmospheric correction for the TIR part of the spectrum is discussed in a closely related document.

The atmospheric correction algorithm for the VNIR and SWIR is based upon a LUT approach using results from a Gauss-Seidel iteration radiative transfer code (RTC) (Herman and Browning, 1965). The method has its basis in the reflectance-based, vicarious-calibration approach of the Remote Sensing Group (RSG) at the University of Arizona (Slater et al., 1987). The method currently assumes atmospheric scattering optical depths and aerosol parameters are known from sources other than ASTER data. These sources include other satellite sensor data, ground-based data, or climatology. Using these parameters, a set of piecewise-linear fits are determined from the LUT that relate the measured satellite radiances to surface radiance and surface reflectance.

8.1.1 Measurement & science objectives

The objective of the algorithm is to correct the ASTER TOA radiance for the effects of atmospheric scattering and absorption in the VNIR and SWIR portions of the spectrum. Accurate atmospheric correction can remove the effects of changes in satellite-sun geometry and atmospheric conditions (Teillet, 1992). Atmospherically corrected surface reflectance images improve the accuracy of surface type classification (Fraser et al., 1977, and Kaufman, 1985) and are also a basis for estimating the radiation budget of the Earth (Kimes and Sellers, 1985). Full utilization of satellite imagery for agricultural resource management also requires atmospheric correction (Moran et al., 1990). The sensitivity analysis presented in ATBD-AST-04 showed that this algorithm should retrieve surface reflectance to 0.02, based on preliminary estimates of expected input uncertainties.

8.1.2 Product Description

TBS

8.2 Validation Criterion

8.2.1 Overall approach

The validation approach is similar to past work (Holm et al., 1989) and is based upon the methods developed for the reflectance-based calibration (Slater et al., 1987). The reflectance of a selected target is determined by transporting spectroradiometers across a portion of the target. The radiometers measure the upwelling radiance which is converted to reflectance by comparing this radiance to radiances from a panel of known reflectance. Solar radiometer measurements at the site are converted to atmospheric transmittances (Gellman et al., 1991) and used to determine the aerosol properties and columnar absorber amounts over the site (Biggar et al., 1990, Thome et al., 1992). The results of these measurements are used as input to a Gauss-Seidel iteration RTC to predict the TOA radiance (Herman and Browning, 1965).

The above measurements provide an opportunity to validate both the inputs to the atmospheric correction and the output products. It will be important to determine the uncertainties of the inputs to the atmospheric correction because it is expected that these uncertainties will dominate the overall uncertainty. In the prelaunch phase of the validation, the climatological inputs will be validated. The post-launch work will continue to examine the climatological data sets as well as look at the uncertainties of the MODIS, MISR, and global assimilation model products which will be used in the atmospheric correction. Another reason to determine the input uncertainty effects on the output product is this may allow for a reduction in the number of field campaigns required to validate the atmospheric correction. This is discussed in more detail in section 3.1

8.2.2 Sampling requirements and trade-offs

The bands of interest are the VNIR and SWIR bands of ASTER. The VNIR bands have a ground-spatial resolution of 15 m while the SWIR bands have a resolution of 30 m. Two criteria will be applied to the test targets to minimize the effects of sampling. The first is targets should be homogeneous over at least a 45-m 👇 45-m area. This ensures the pixel we use in the ASTER image will be a "pure" pixel. The second criterion defines what is meant by "homogeneous." The average of the measured reflectance of the target must not vary by more than 0.005 in reflectance units when the sampling by the ground-based spectroradiometer is changed.

8.2.3 Measures of success .3 Measures of success

Successful validation of the algorithm occurs when the retrieved reflectance/radiance from ground-based methods agrees with the value retrieved by the algorithm to within the uncertainties of the two methods. The level of agreement will be site dependent because uncertainties are a function of the surface reflectance of the target and the atmospheric conditions.

8.3 Pre-launch Algorithm Test/Development Activities

Pre-launch activities are divided into two parts, theoretical and experimental. The theoretical validation uses test data sets to check the algorithm's ability for a wide range of simulated atmospheric conditions. These tests will examine effects of input parameter uncertainties and LUT resolution. The test data sets are generated by converting surface reflectance to surface and TOA radiance using the same RTC used to generate the LUT. The experimental validation uses data sets from past field campaigns as well as from planned pre-launch field campaigns. The data sets consist of measured surface reflectance of selected test sites and ground-based solar radiometer measurements.

8.3.1 Field experiments and studies

Theoretical validation: The pre-launch theoretical studies follow the same philosophy as that of the sensitivity and uncertainty analysis shown in the ATBD. This work focuses on understanding what the output uncertainties of the algorithm are for a given input uncertainty. Understanding this effect will allow the output product uncertainty to be determined once the input uncertainties and values are known. This work will also point out the most sensitive cases, which should be the focus of experimental, validation efforts. For example, the ATBD shows TOA radiance from high-reflectance targets is not sensitive to aerosol optical depth for optical depths less than 0.2. This would not be a high priority case to validate, because large uncertainties would not be expected for this situation.

Included in this effort will be a comparison of results obtained by different RTCs to quantify the accuracy of the code used in the LUT generation. The uncertainty/sensitivity analysis will also examine effects from the LUT itself. These effects include parameterizing the aerosols into a format suitable for using the LUT and effects due to the discrete nature of the LUT.

The major difference between the pre-launch, theoretical validation and the sensitivity analysis in the ATBD is the validation work will use test images processed by the atmospheric correction code. These test images will serve to validate the computer code written from the algorithm, as well as validating the algorithm itself.

Experimental validation: Pre-launch validation from an experimental point of view will serve three primary purposes: 1) validation methodology tests; 2) test site evaluation; 3) algorithm testing. Validation methodology tests mean pre-launch field campaigns will be used to practice techniques needed in the post-launch era. Test site evaluation will be used in the pre-launch time frame to help select the one or two primary sites, which will be used for the post-launch algorithm validation. Finally, the pre-launch experiments will be used to determine any major flaws in the algorithm so that it can be changed before the post-launch version is delivered to the DAAC. The experimental approach for pre-launch validation is identical to the approach for the post-launch validation. These methods are described in detail in section 8.4.1.

8.3.2 Operational surface networks

No plans for operational surface networks have been made. The primary reason for this is the lack of surface reflectance data. For example, the DOE ARM CART site is an excellent resource for information regarding the atmospheric composition. It does not have information about the surface reflectance and thus cannot be used to validate this algorithm.

8.3.3 Existing satellite data.

There exist a large number of data sets, which may prove useful for this validation work, such as the FIFE data. These data sets consist of coincident ground-, aircraft-, and satellite-based data that are ideally suited for the pre-launch validation of this algorithm. This work will focus on those portions of the data sets, which have high-spatial resolution VNIR and SWIR data. The preferred satellite data are Landsat-5 Thematic Mapper because it has bands in both the VNIR and SWIR. The key point is this work can use only those images for which ground-based atmospheric and surface reflectance data exist at the time of overpass.

8.4 Post-launch activities .0 Post-launch activities

After launch, validation of this algorithm will occur in a fashion similar to the experimental prelaunch validation experiments. The surface reflectance of a selected test site is measured concurrent with an ASTER overpass. At the same time, ground-based atmospheric data are collected. ASTER data are then atmospherically corrected using two sets of inputs. The first set of inputs are the ground-based atmospheric data. The second are those derived for normal processing of the ASTER scene (MISR data for example).

8.4.1 Planned field activities and studies

The plan described here relies on surface reflectance measurements of selected test targets and measurements of atmospheric properties over these targets. This section describes the method for collecting the surface reflectance and atmospheric data, and the selection of test sites.

Surface Reflectance Determination: The surface reflectance of the site is found by comparing radiometer measurements of the site to those from a panel of known reflectance. This field reference is calibrated at RSG facilities using a pressed polytetrafluoroethylene standard by measuring the reflected radiance from the panel and standard at a variety of wavelengths and illumination angles. We use a value for directional, hemispheric reflectance of the standard provided by the National Institute of Standards and Technology. Polynomial fits are made to the measured data to calculate the reflectance of the barium sulfate for the sun-view geometry and wavelengths for a given set of field measurements (Biggar et al., 1988).

Field measurements are collected by carrying a spectroradiometer across the entire site. The radiometer has bands in both the VNIR and SWIR. The instrument is transported across the site by attaching it to a backpack device, or yoke, which extends the instrument away from the body of the user. The user collects at least 10 reflectance samples along a straight-line path within the area representing an ASTER pixel. Reflectance of the site is determined by comparing measurements of the site to those of the calibrated barium sulfate panel and averaging all of the measurements. Sun-angle changes and the bi-directional reflectance of the reflectance panel are taken into account when determining the reflectance. Global irradiance data are used to determine the significance of changes in diffuse skylight illumination.

Atmospheric composition measurements: The primary instrument used to characterize the atmosphere over the site is the solar radiometer. Data from the radiometer are used in a Langley method retrieval scheme to determine spectral-atmospheric optical depths (Gellman et al., 1991). The radiometer is relatively calibrated immediately prior to, during, or after each field campaign. The optical depth results are used as part of an inversion scheme developed by the RSG to determine ozone optical depth and a Junge aerosol size distribution parameter (Biggar et al., 1990). The size distribution and columnar ozone are used to determine the optical depths at the wavelengths of the ASTER bands in the VNIR and SWIR. Columnar amounts of water vapor are determined using a modified Langley approach (Thome et al., 1992 and Thome et al., 1994). Here, as for the optical depth retrieval, the primary uncertainty in water vapor is the instrument calibration and the system is calibrated prior to, during, or immediately after each campaign. The retrieved columnar water vapor is used in the 5S model (TanrJ et al., 1990) to determine band-integrated transmittances for ASTER wavelengths for the sun-to-surface-to-satellite path.

The ground-based methods described above will be used in two ways. The first will be to use these data as the inputs to the atmospheric correction algorithm. Normally the algorithm will use satellite-derived atmospheric parameters that are expected to be a primary uncertainty source. The ground-based data should be more accurate than the satellite-derived data, thus, the ground-based data should provide a better check on the validity of the atmospheric correction algorithm. The second way the ground-based data will be used is to check the accuracy of the satellite-derived inputs and the effects of the uncertainties in these data. That is, the ground-based data will serve as a validation of the satellite-derived data.

Test target selection: The most difficult aspect of the validation is selecting appropriate test targets. Currently, all test sites used by the RSG are for vicarious calibration. As such, they are sites with high reflectance located in clear atmosphere regions. These sites could be used for the validation of the atmospheric correction of ASTER, but they would not provide much information about the accuracy of the algorithm.

Work is being done to determine more suitable sites for validation of atmospheric correction. The size of the site must be large enough and homogeneous enough so the average reflectance of a "pure" ASTER SWIR pixel can be determined. Ideally, the site would have a high probability of cloudless skies to increase the chance of successful field campaigns, easy access, and proximity to the RSG (to reduce travel costs). The desire for cloudless skies does raise another issue, what conditions are needed to validate the algorithm?

To completely study the problem, requires test sites which satisfy a wide range of surface reflectances, surface relief, horizontally varying surface reflectance, different aerosol types, a range of aerosol concentrations, and varying amounts of absorbing gases. If the extremes are selected, this leads to validation sites which have combinations of

1) Low and high aerosol optical depths
2) Two different aerosol types (marine and continental, for example)
3) Low and high humidities
4) Dark and bright surfaces
5) Flat and highly-sloped surfaces
6) Horizontally-homogeneous surface and one with widely varying reflectance
7) Clear and thin cloud cases

This would lead to a dizzying number of targets and require a large validation budget. Thus, a compromise is required. This compromise is to select targets which first ensure the algorithm operates properly for simplistic cases. Theoretical data are then used to predict cases for which the algorithm might have difficulties and select targets to evaluate these predicted problem areas.

An example of how this might work would be to select a flat, homogeneous, dark target in a turbid atmosphere. If the algorithm is successful in this case, the algorithm is used as part of a sensitivity analysis to determine what conditions are likely to cause problems. For instance, adjacency effects will most likely cause more inaccurate results for targets surrounded by widely different surface reflectance. Then a target would be selected to test this. While this method does not experimentally test all possible cases, it makes good use of the available resources. The number of possible validation sites could still be increased through cooperative data collections with other validation groups.

The primary target should have several areas at least 45 m × 45 m in size with uniform reflectance and each area having a different value of surface reflectance. The target area should have moderate levels of turbidity (aerosol optical depths > 0.30) and preferably a possibility of both continental and marine aerosols. Since it is hoped the site can be within a one-day drive from Tucson, Arizona, the most likely candidates will be along the California coast. At this time, no specific targets have been selected. The prelaunch time frame will be used to evaluate possible targets for post-launch validation. It is hoped a coordinated selection can be made with inputs from other AM-1 platform sensor teams.

Planned field campaigns: Because no particular test site has been selected, no specific field campaign plans have been made. The general plan for the post-launch validation is to focus efforts during the first six months of the sensor's time in orbit. These early efforts must be considered carefully because this is the time during which the sensor is expected to change most rapidly. It would not be productive to plan a validation campaign if the uncertainty in the sensor radiance dominates the retrieval of surface reflectance and surface radiance.

Once the sensor has stabilized to a point where the calibration of the system is not the dominating uncertainty, several validation campaigns will occur. The goal will be to collect three data sets of the same target under similar atmospheric conditions. These data will be processed and used to assess the accuracy of the algorithm. The data will also be used to modify the algorithm. These modifications will not occur until the next delivery of the post-launch code. Thus this first set of validation campaigns will be used primarily to determine algorithm accuracy.

Validation approach: The surface reflectance and atmospheric data described above are collected at the selected test site at the time of an ASTER overpass. The ASTER data are then atmospherically corrected to surface radiance and surface reflectance in two ways. The first is the normal processing path of using satellite-derived inputs. The second will replace the satellite-derived inputs with the results of the ground-based, atmospheric measurements. Both sets of atmospherically corrected surface reflectance/radiance are compared to the ground-based surface reflectance/radiance measurements to determine the level of agreement. The results of the comparisons are then used to evaluate the success or failure of the algorithm and the role of input uncertainties.

Data collected by the RSG during a vicarious calibration at White Sands can be used as an example to illustrate the validation approach. Reflectance data were collected for an area equivalent to 64 Landsat Thematic Mapper pixels on October 8, 1994 using a filtered spectroradiometer. The surface reflectance data were collected over a 40-minute period centered about the TM overpass by referencing to a field reflectance standard as described above. The reflectances computed at the wavelengths of the filtered radiometer were used in a spline fit routine to determine the reflectance for the bands of TM.

Solar radiometer data were collected during this same time period using the RSG's 10-band manual solar radiometer. Atmospheric optical depths were computed from these data for the 10-minute average around the overpass time and used to determine a Junge parameter related to the aerosol size distribution and a columnar ozone amount. These quantities were used to compute the atmospheric optical depths for the TM wavelengths. The optical depths and size distribution were used as inputs to the Gauss-Seidel iteration RTC for surface reflectance values of 0.4 and 0.5. The RTC results give the at-sensor radiance for the altitude of TM for each band.

The DN values for the 64 pixel area, marked in the image by tarpaulins laid at all four corners of the site, were converted to radiance using the calibration coefficients for TM. These radiances were then converted to surface reflectance using the RTC results for the two surface reflectances and assuming a linear relationship between at-sensor radiance and surface reflectance. These RTC-derived results using the TM imagery can be compared to the values measured at the surface. For this case, 3×3 pixel areas of the ground-based and image-based reflectances were averaged for the comparisons. This averaging reduces effects of misregistration of the ground-based data to the imagery. When the 3×3 pixel average reflectances for band 2 of TM were compared, the absolute difference between the image-based and ground-based reflectances differed by less than 0.01. The difference between the average reflectances for all 64 pixels was found to be less 0.002. Of course, this excellent agreement is to be expected since the calibration coefficients for TM were computed using the reflectance-based calibration approach. That is, the same surface reflectance data and radiative transfer code used to determine the sensor radiances were used in the atmospheric correction example. For the validation of ASTER data, an independent calibration will be used. Even though the calibration and validation in this example are not independent, the example still illustrates the approach that will be used.

The ASTER validation will follow the above except for two differences. The first is the image-derived reflectance will be determined from the atmospheric correction code at the DAAC. The second difference is the atmospheric correction code will use both ground-based atmospheric data and satellite-based data. The above example describes only the case of using ground-based data.

8.4.2 New EOS-targeted coordinated field campaigns

Currently, no specific plans exist for coordinated experiments but it is recognized that this is a crucial part of validation.

8.4.3 Needs for other satellite data
There are no needs for other satellite data other than that needed for normal processing by the algorithm. The algorithm requires atmospheric scattering information from MISR or MODIS and absorption information from SAGE III and MODIS. The validation can still be done without these data by relying solely on the ground-based atmospheric information.

8.4.4 Measurement needs
The measurements for the validation approach described here are in three categories: essential, desirable, and optional. There are two essential pieces of information. These are the surface reflectance of a selected test target and the location of this target. Without these data, a validation cannot be done. Desirable data are the characteristics of atmospheric aerosols and columnar amounts of gaseous absorbers. Without any of these data, the validation will rely on climatological values. This is still a useful validation, but is not as important as those including more realistic inputs to the algorithm. There are two pathways with which the aerosol and gaseous absorber information can be obtained, ground-based measurements and satellite-derived values. Both are important to the overall validation plan, but only one is truly needed to perform a single validation. Ideally, both would be available. Optional data consists of additional atmospheric data. These would include sky radiance measurements used to derive scattering phase functions, downwelling diffuse and global irradiance, or surface meteorological data. These data are helpful in this validation work but are not essential.

8.4.5 Needs for instrumental development
The successful collection of data to validate this algorithm would be improved through the development of an ASTER airborne simulator or the increased availability, and decreased cost, of data which can simulate the ASTER bands in the VNIR and SWIR. This is because the 16-day orbit of ASTER decreases the chances of successful validation data sets due to possible poor weather over the selected target site. An airborne simulator would allow the data to be collected when clear weather, or cloudy weather depending on the goals of the validation, is over the validation target.

8.4.6 Geometric registration site
This topic is not applicable to this algorithm. A set of ground control points will always be used to mark the test target by laying tarpaulins at two corners of the site.

8.4.7 Intercomparisons .7 Intercomparisons
This is an important part of this validation plan because of the dependence the algorithm has on outside data inputs. For instance, the algorithm uses aerosol information retrieved from MISR, so it makes sense that the MISR data products used as inputs to this algorithm be validated at the same time that ASTER surface products are validated. The hope is joint-validation campaigns for atmospheric correction of ASTER, MISR, and MODIS will occur. The first step towards developing joint campaigns occurred with a June 1996 campaign used to cross-compare results of vicarious calibration measurements. These measurements are identical to those required for atmospheric correction validation, and, since both ASTER and MISR representatives participated the results can be used as practice for future cross-comparison/joint validation experiments.

8.5 Implementation of Validation Results in Data Production

8.5.1 Approach.1 Approach

The results of the validation campaigns will be used in two ways. The first will be to refine uncertainty estimates reported with the data product. These uncertainties will be developed during the pre-launch phase using the theoretical data sets described above. Once experimental data are obtained, the uncertainties will almost certainly require some changes. This could be in two fashions. The first would be to simply adjust the values of the reported uncertainties. The second is to use the validation results to indicate areas where the algorithm should be revised. As an example, the validation data could indicate the treatment of surface-slope effects causes uncertainties which could be reduced by changing the algorithm. Whether the algorithm is actually modified will depend on the anticipated change in uncertainty, the complexity and computational requirements of the change, and the cost to implement the algorithm change as computer code.

The second way validation results will be used is to determine the primary sources of uncertainty. There are two approaches to validation, the first is to simply see how well the final product is retrieved and assess its uncertainty. This is described in the previous paragraph. The second approach evaluates the input parameters and algorithm. This is the purpose of the ground-based measurement of atmospheric properties. These can be used to evaluate the accuracy of the inputs to the algorithm, in essence validate the inputs. The goal of this portion of the validation will not be to force changes in how the input data are produced. Instead, it is to identify unsuitable inputs, determine which parameterizations of the inputs affect the results, create uncertainty estimates which are a function of input type and value, and evaluate other ways to use input data sets through algorithm modification.

8.5.2 Role of EOSDIS .2 Role of EOSDIS
The primary role of EOSDIS in this validation plan is to supply the data products, which are being validated for the time and location of the experiment. In doing this, EOSDIS will also acquire and process the necessary input data sets to process the ASTER data.

8.5.3 Plans for archival of validation
Archival of the validation data will be done at RSG facilities. The data will be archived in raw and processed format on Sun-based hard disks and 8-mm tapes using UNIX tar commands. Distribution of the data will be through ftp access. A word-wide web site is currently being developed for the RSG. This site will be used to allow others to see a list of available data, samples of the data, and summaries of the results. The site will also instruct users how to retrieve copies of the data from the ftp site.

8.6 Summary

The validation plan described above uses both pre-launch and post-launch work. Pre-launch activities are divided into two parts. The first uses a theoretical approach by creating test data sets for a wide range of simulated atmospheric and surface conditions. These data will be used to examine effects of input uncertainties and LUT resolution. The second uses presently available experimental data and planned pre-launch experiments to test the algorithm in simulated post-launch conditions. This method is similar to Holm et al., 1989 and Moran et al., 1990. The data sets consist of measured surface reflectance of selected test sites and ground-based solar radiometer measurements at the same time as a sensor overpass. The measured surface values of radiance and reflectance are compared to values retrieved from the sensor data.

After launch, validation of this algorithm will occur in a fashion similar to the experimental approach just described. The surface reflectance of a selected test site is measured concurrent with an ASTER overpass. At the same time, ground-based atmospheric data are collected. The ASTER data are then atmospherically corrected using two sets of inputs.

One is based upon the ground-based atmospheric data. The other is the data derived for normal processing of the ASTER scene (MISR data for example).

Two difficulties are anticipated in the validation. The first is site selection. We are presently attempting to determine sites that satisfy the criteria of wide range in reflectance, surface relief, horizontally varying surface reflectance, and site accessibility. The second problem we anticipate is the ability to adequately sample a wide range of surface and atmospheric conditions. We hope to use validation plans of other ASTER Science team members and other instrument teams to increase the number of scenes which can be used for validation. Related to this cooperation will be attempts to conduct field campaigns in conjunction with the MODIS and MISR atmospheric correction groups.

Surface Radiance - TIR (AST09)

The TIR surface radiance product is the surface leaving spectral radiance in the five ASTER Thermal InfraRed (TIR) channels. The radiance leaving the surface is a combination of direct emission by the surface and reflection of radiation incident on the surface from the surroundings, including sky radiation.

9.1 Introduction

9.1.1 Measurement & science objectives

The objectives of the ASTER investigation in the thermal infrared include, among other things, providing estimates of the radiance leaving the land surface. The radiance, which is measured by the ASTER instrument, includes emission, absorption and scattering by the constituents of the earth's atmosphere. The purpose of the atmospheric correction method is to remove these effects of the earth's atmosphere, providing estimates of the radiation emitted and reflected at the surface. Atmospheric corrections are necessary to isolate those features of the observation, which are intrinsic to the surface, from those caused by the atmosphere. Only after accurate atmospheric correction can one proceed to study seasonal and annual surface changes and to attempt the extraction of surface kinetic temperatures and emissivities.

9.1.2 Product Description

The ASTER Standard Data Product AST09, "Level-2 Radiance--TIR, Surface_Leaving", consists of 10 image planes of short integer (16 bit) pixels. For each of the five ASTER TIR channels there is one image plane that specifies the upwelling spectral radiance at the surface, and a second image plane that specifies the downwelling spectral irradiance at the surface. The values in upwelling radiance image planes are expressed in units of Watts per square meter per steradian per micrometer. The downwelling irradiance image planes are in units of Watts per square meter per micrometer. All values are scaled by a factor of 1000 (This is equivalent to units of milliWatts rather than Watts), and rounded to the nearest integer value.

9.2 Validation Criterion

9.2.1 Overall approach

The overall approach to validation for the surface leaving spectral radiance involves comparison of the Level 2 data product with estimates of the same quantity derived from simultaneous *in situ* measurements and equivalent MODIS channels.

9.2.2 Sampling requirements & trade-offs

The uncertainty in the ASTER derived TIR surface leaving spectral radiance has three main sources: 1) the uncertainties in the radiation transfer model (MODTRAN) being used, 2) the uncertainty in the estimates of atmospheric properties used to compute the emission, transmission and scattering of the atmosphere and 3) uncertainty in the on orbit instrument calibration. The sensitivity analysis documented in the Algorithm Theoretical Basis Document (ATBD) for this data product indicates that the expected uncertainty in the atmospheric profiles of moisture and temperature should dominate the overall uncertainty. The purpose of the *in situ* measurements is to insure that sources 1) and 3) above are not dominant and to provide tangible evidence the uncertainty in surface leaving spectral radiance is understood. The comparisons with MODIS will be used to provide a more frequent estimate of the quality of the product being produced and will allow the exploration of a much wider range of atmospheric conditions than will be possible with *in situ* measurements.

9.2.3 Measures of success

The goal of this validation effort is to accurately estimate the magnitude of the uncertainty associated with correcting ASTER Level 1 at sensor radiance estimates for the effect of atmospheric emission, attenuation and scattering under a variety of clear sky atmospheric conditions.

9.3 Pre-launch Algorithm Test/Development Activities

9.3.1 Field experiments and studies

Field experiments have been conducted and are planned at about the rate of two a year, testing aspects of the following approach.:

Radiometric measurements from a boat are used to estimate the kinetic temperature of the radiating surface of water areas the size of several ASTER TIR pixels. An array of continuously recording buoys is used to assist in estimating the space and time variation in water temperature. To reduce geolocation error, 3 x 3 pixel areas will be instrumented. Radiosonde profile measurements are used to determine the atmospheric temperature and moisture profiles for use with the radiation model MODTRAN to estimate the spectral sky irradiance. The ASTER spectral response along with the surface kinetic temperature, the spectral emissivity of water and the spectral sky irradiance are used to compute the channel by channel surface leaving spectral radiance which is to be compared with the same quantity from the algorithm being validated.

Lake Tahoe and the Salton Sea are being evaluated as sites which provide a range of atmospheric conditions (e.g. warm-wet, warm-dry, cold-wet, cold-dry).
Calibration of the equipment used is a major part of this pre-launch activity and several approaches to establishing the calibration of the radiometers being used are being tried. In addition some measurements are being made of land surfaces (playas) to understand if the space/time sampling problems can be well enough understood to take advantage of the high temperatures (>30 C) land surfaces can provide.

9.3.2 Operational surface networks

No Operational surface networks have been identified which would directly support this validation effort with the exception of a network operated by CSIRO in Australia which could be of use in a monitoring role.

9.3.3 Existing satellite data

Field experiments are generally planned around times that satellite data (e.g. Landsat, AVHRR, ATSR) will be available.

9.4 Post-launch activities

9.4.1 Planned field activities and studies

Field activity in the post-launch time period will follow the pattern established pre-launch with increased frequency (up to once a month) during the first 6-8 months following launch.

9.4.2 New EOS-targeted coordinated field campaigns

The two water sites (Lake Tahoe, Nevada and the Salton Sea, California and the land site Railroad valley, Nevada) are large enough to be of use in MODIS validation activities as well as for use with ASTER. In May/June 1996, June 1997 and June 1998 EOS joint validation/calibration field campaigns were conducted and their results solidify support for similar joint activities in the post launch time period.

9.4.3 Needs for other satellite date

Only data from the EOS AM-1 platform is needed for the ASTER validation of the TIR surface leaving spectral radiance. Data from the 60 m thermal channel of Landsat 7 will be useful, especially when aircraft scanner measurements are not available.

9.4.4 Measurement needs (*in situ)* at calibration/validation sites:

The following measurements are needed: Profiles of atmospheric moisture and temperature, estimates of atmospheric aerosol content and column ozone amount, physical and spectral radiometric measurements of well established accuracy of surface temperature over 270 x 270 m areas at the time of EOS AM-1 overflight, spectral emissivity estimates over 270 x 270 areas for non-water targets and good positional location of the surface measurements. In addition it will be useful to have thermal images from aircraft scanners or satellite thermal imagers of the measurement site to provide context information and a qualitative estimate of temperature heterogeneity.

9.4.5 Needs for instrument development (simulator)

A well calibrated thermal scanner with channels closely matched to one or more ASTER channels will be very useful. A proposal from the Jet Propulsion Laboratory and the Ames Research Center to build a close duplicate of the MODIS Airborne Simulator has been written and submitted to the EOS Science Office in March 1996. This proposal was approved and this scanner (currently called the MODIS ASTER simulator (MASTER)) will be available before or near the time of the launch of the EOS AM-1 platform. The MASTER aircraft scanner has been built and is undergoing aircraft testing in the late summer of 1998.

9.4.6 Geometric registration site

Geometric registration validation is a basic Level 1 activity not related to the validation activity discussed here except that the strategy of using measurements over a uniform 3 x 3 area is intended in part to compensate for small (10%) uncertainties in geometric registration.

9.4.7 Intercomparisons (multi-instrument)

Intercomparison with the surface temperature deductions of MODIS for both land and sea surface temperature are a basic part of the plan for the validation of the TIR surface leaving spectral radiance. In principle MODIS measurements will always be available when ASTER data is collected and these intercomparisons will be especially valuable in monitoring the performance of the ASTER algorithm and in exploring atmospheric conditions which may never be seen at the validation sites.

9.5 Implementation of Validation Results in Data Production

9.5.1 Approach

Validation is sufficiently important that a peer-reviewed publication of the initial validation results is planned. Because such publication is likely to involve a delay between completion of the paper and its publication, validation results will be available in text form at the DAAC responsible for processing ASTER data to Level 2 (currently this would be at the Eros Data Center).

9.5.2 Role of EOSDIS

It is expected that the EOSDIS will make available the results of processing ASTER validation scenes to Level 2 in a timely manner and will make available the validation reports of section 4.1 to interested users in electronic form.

9.5.3 Plans for archiving of validation data

Validation data and a description of the processes, procedures and algorithms used will be archived in the ASTER Team Leaders processing facility

9.6 Summary

Taken as a whole the *in situ measurements* and instrument to instrument intercomparisons planned should provide a rich extensive set of validation data permitting an assessment to be made of the uncertainty in the ASTER TIR atmospheric correction algorithm.

Surface Kinetic Temperature (AST08) and Surface Emissivity (AST05)

10.1 Introduction

The Temperature/Emissivity Separation (TES) algorithm that generates the surface temperature and emissivity products is described in detail in the Algorithm and Theoretical Basis Document, ATDB AST-08 and AST-05. A summary of the validation plans for these products is also contained in that document. The validation of both products is described together because they are closely interrelated and must be calculated with a single algorithm. The TES algorithm has been developed by the Temperature Emissivity Working Group (TEWG) which consists of US and Japanese team members.

The TES algorithm is an elaboration of the earlier Alpha residual and MMD algorithms, documented in the ATBD. The key problem in calculating surface temperatures and emissivities is that there are more unknowns than measurements. Even in the simplest situation, there is an unknown emissivity for each image channel, plus a single kinetic temperature. In addition, atmospheric absorptions and emissions contribute additional unknowns. For ocean imaging the emissivity spectrum is well known, and it is sufficient merely to calculate the temperature, provided the atmospheric characteristics have been determined. The TES algorithm is applied to the ASTER standard product AST-09, "Level 2 Radiance--TIR, Land_Leaving." This product has been compensated for atmospheric effects. The challenge for ASTER, designed to look at the land surface for which the emissivities are not known, is to estimate somehow one unknown from independent information. To do this, the Alpha and MMD algorithms use an empirical relationship between contrast and amplitude in the emissivity spectrum: the standard deviation or the min-max difference decreases quasi-linearly as the minimum emissivity increases. TES approximates the measure of spectral contrast by band-ratioing, which removes the effects of temperature, but also emissivity amplitude. Predicting the minimum emissivity from the spectral contrast restores the amplitude information and balances the unknowns and measurements.

The surface temperature product (AST-08) contains a single image plane consisting of short-integer (16-bit) pixels that specify the temperature in 0.1°K quanta. The ASTER NEΔT $\approx$ 0.3°K at 300K. The surface emissivity product (AST-05) contains five image planes consisting of 16-bit pixels specify the emissivity ε in 0.001 quanta. The possible emissivity range of 0-1 is thus encoded as 0 - 1000. ASTER is capable of measuring ε within about $\pm$0.004 (at λ=10 μm and 300K). Current engineering projections of NEΔT=0.2°K correspond to $\pm$0.003 emissivity. Each standard product may have associated with it a 16-bit image plane containing pixel-by-pixel precision and other Quality Control data.

10.1.1 Measurement and science objectives

The objective of the TES algorithm is to calculate the surface temperature and emissivity spectrum. The surface temperature influences heat transport across the surface/air interface and is important in radiation-budget research, and the emissivity spectrum is useful in studies of vegetation (because it helps distinguish substrate from canopy) and change (for example, soil erosion). Changes in surface temperature track phenological changes in vegetation communities and indicate unusual stress in crops, grasslands and forests.

10.2 Validation Criterion

The validation criteria are essentially agreement of the Standard Products calculated by TES with values for the same parameters measured independently for test areas in the field and by other scanners such as MODIS.

10.2.1 Overall approach

Performance characteristics for TES vary with spectral contrast. Although the Earth's surface is complex, for the purposes of TES validation it is necessary to consider only two types of scenes: near-graybodies for which the emissivities are known and homogeneous, and temperatures are known or homogeneous and can be readily measured during overflight; and "colored" surfaces for which emissivity spectra depart from graybody values but which are homogeneous. The first instance corresponds to the important class of scenes covering bodies of water, ice sheets and snowfields, and closed-canopy vegetation. For these scenes, the primary goal is to recover surface temperature since the emissivities are closely known in advance. The second instance corresponds to the class of scenes for which soil and rock are exposed. Surface temperatures cannot be recovered unless emissivities are recovered also, since they are unknowable in advance. This type of scene is common in the arid third of the land surface.

The temperature and emissivity Standard Products will be validated by comparing TES values with simultaneous measurements made: 1) in the field by ground instruments; 2) airborne scanners such as TIMS, MASTER and MAS; 3) MODIS. The goal of quality control efforts will be to see that: 1) TES temperatures recovered for water and snow are accurate and precise within the performance guidelines established by the TEWG; and 2) TES emissivities over water and snow, and also over a limited range of geologic (rock) targets, are likewise within established limits of accuracy and precision.

There is no need to set up special TES sites for tests of water and snow, because these sites are needed primarily for atmospheric correction validation and will be established and managed by the Atmospheric Correction Working Group. The TEWG will help take data at these sites, but under the guidance of the ACWG. Because the emissivities for water and snow are known in advance, the only information the TEWG needs from the water/snow sites is the surface temperature data set, plus the atmospherically corrected aircraft scanner data from the ACWG.

At the "geologic" sites the main problem is measure representative scene emissivities and to assess spatial heterogeneity, in order to define appropriate 90-m scene elements that be imaged by ASTER. Several hundred spectra will be measured until the emissivity at the 90-m scale, estimated from the 10-cm-scale field measurements, is felt to be well determined. Once these are established, before launch, it is not necessary to measure them again. During ASTER or aircraft data takes it is sufficient to measure surface temperatures and atmospheric characteristics, as for the ACWG sites.

The TES algorithm will be validated before launch using ASTER data simulated from airborne scanner images. Field emissivities measured then will be used immediately after launch to re-validate the products using actual ASTER data. Periodically thereafter the validation experiments will be repeated to guard against instrument drift. During the AM-1 mission, validation will include cross-checking with MODIS data, aircraft underflights, and other image data as appropriate.

10.2.2 Sampling requirements and trade-offs

There are two key issues: first, the ideal test site scene must be compositionally homogeneous and isothermal during overflight; and second, the site must be large enough to encompass several ASTER pixels to permit reliable estimates of accuracy and precision. ASTER TIR pixels are 90 m on a side, whereas current field spectral measurements are 10-cm on a side. Both temperatures and emissivities are controlled at all scales down to the mm level, by mineralogical variability and vegetation cover and by surface roughness and texture. Proper random sampling is a practical impossibility. It is therefore important to choose sites carefully such that temperatures change little around the time of overflight, and to minimize the need for a dense sampling grid.

We plan to use sites for which compositional homogeneity can be established without intensive field spectral measurements. For the graybody sites, we will use lakes and snowfields; for the "colored" sites we will use smooth unvegetated bedrock surfaces or sand dunes.

The advantage of melting snowfields is that the temperature is everywhere 0°C, and deviations from known emissivity spectra are small and can be easily measured in the field. On the other hand, accessible snowfields are not available at all seasons.

Lake sites, like snowfields, have known emissivities, but temperatures must be measured by a network of buoys. Lakes are not isothermal at the level of ASTER sensitivity. Accessible lake sites are available at all seasons.

Appropriate "rock" sites are not common. Sand dunes are time-variable and may be moist, changing surface emissivities unpredictably. On the other hand, vegetation is minimal, and the scale of compositional heterogeneity is related to the dune structure (~10 m) so it is relatively easy to assess with field spectra having only 10-cm footprints. Sand dunes are accessible to JPL year-round.

Unvegetated bedrock sites tend to be at high elevation and are inaccessible during the winter. Most low-elevation sites the we know of are pediments (e.g., Cima Dome) and are vegetated. The best sites near JPL are mineralogically homogeneous granitic plutons, smoothed and swept clear of weathering products during the last ice age. Therefore, emissivity spectra can be determined in a reasonable field campaign. Several sites large enough for a grid of 90-m ASTER pixels are known.

10.2.3 Measures of success

The experimental goal is to recover temperatures and emissivities accurately and precisely for the validation sites using both field measurements, ASTER data, and other airborne or spaceborne TIR image data. In order to validate the TES products, the mean recovered ASTER products and the mean field determinations or independent measurements must agree within the specifications given in the ATBD: essentially 1-2°K and 0.01-0.02 emissivity units. Such agreement is a test of product accuracy. Additionally, variability of the standard products at the 90-m ASTER scale, assessed over the grid of "pixels" at the validation sites, must conform to variability predicted by the ATBD from the ASTER NEΔT. Such agreement is a measure of product precision and has similar size to the accuracy requirements.

10.3 Pre-launch Algorithm Test/Development Activities

Pre-launch activities are focused on establishing validation sites, assessing site emissivity characteristics, collecting and interpreting simulated ASTER TIR data, and iteratively refining or tuning the TES algorithm to minimize cost and optimize performance. Activities will include field study, aircraft overflights, ASTER image simulation and calculation of the standard TES products. Work will be conducted collaboratively, especially with the Atmospheric Correction Working Group because the sites and data requirements are strongly overlapping.

10.3.1 Field experiments and activities

Validation sites will be established in the United States and Japan at:

- Lake Tahoe, CA
- Salton Sea, CA
- Mt. Humphreys, CA

- Kelso Dunes, CA (all-weather alternate to Mt. Humphreys)
- Lake Kasumigaura (Japan)
- Tottori Dunes (Japan)

TES validation will be conducted in parallel with other validation tests for reasons of economy. In particular it is planned to work with the Atmospheric Correction sites and data. The two main sites of interest are Lake Tahoe and the Salton Sea. Both are near JPL and accessible year-round. Lake Tahoe is a high-altitude site that includes snowfields part of the year. The Salton Sea is below sea level and atmospheric corrections are bigger than for Lake Tahoe. TES validation at these sites requires only making use of the data collected by the Atmospheric Correction Working Group, although TES personnel will work alongside the ACWG collecting field data, especially spectral data of water and snow. Experimental procedure at these sites is documented in the Validation Plan for ASTER Standard Product AST-09. Japanese testing at the Lake Kasumigaura site will parallel US activities.

ACWG activities include radiometric measurements from boats, deployment of continuously recording buoys to measure temperatures directly, and radiosonde atmospheric profile measurements, reduced with the aid of the radiation model MODTRAN. The ACWG intends to monitor a 3x3-pixel area (270x270 m) to assess geologic variability. Because the water sites have low intrinsic variability, a 3x3-pixel area will probably suffice to estimate accuracy and precision.

The "rock" sites will also be established before launch. The chief activity at Mt. Humphreys will be to verify lithologic homogeneity over a 600x600 m site, sufficient for compiling performance statistics on a 30-pixel image area, and to document field emissivity spectra there. The mineralogic homogeneity, assessed in the field by conventional geologic methods, will be used to establish the minimum sampling density required for the field emissivity spectra. A similar experiment will be conducted at the sand dune sites, both in California and Japan. TIR imaging systems, available at JPL and commercially, will be used in the field to help document site homogeneity at the m to 10-m scale.

Airborne TIR scanner (TIMS) overflights will be conducted of the "rock" sites before launch. These require that temperatures be measured over the sites. This will be done using a hand-held Everest radiometer at pre-selected locations for which field emissivity spectra have been measured. The Everest data will be calibrated against blackbody measurements using a manufactured horn encased in insulation and calibrated using a thermocouple. This device is available at JPL. Because it will take some time to measure temperatures for the whole site, drift will be accounted for by reference to a common base station. Spatial patterns of relative temperatures will be determined by low-altitude airborne imaging. These data will be used in conjunction with the field measurements.

Atmospheric data will be acquired as described in the Validation Plan for ASTER Standard Product AST-09.

Pre-launch experimentation will identify any major algorithm flaws so that a corrected version can be prepared in time for delivery of the post-launch version to the DAAC.

10.3.2 Operational surface networks

No "Operational" surface networks have been identified which would directly support this validation effort with the exception of a network operated by CSIRO in Australia which could be used in addition to or in place of the "rock" sites.

10.3.3 Existing satellite data

Field experiments are generally planned around times when satellite data (e.g., Landsat, AVHRR) will be available. Existing data do not satisfy the multispectral requirements of TES testing and validation.

10.4 Post-launch activities

Post-launch activities will be similar to pre-launch validation exercises. Notably, emissivity spectra will have already been collected, and site heterogeneity already established, simplifying the task. EOS AM-1 and low-altitude aircraft passes over validation sites will be synchronized and will be coordinated with field experiments to characterize temperatures and atmospheric conditions.

10.4.1 Planned field activities and schedules

The plan described here relies on measurements of surface temperatures and atmospheric conditions over at least a subset of the same validation sites explored during the pre-launch activities. With the addition of the ASTER data takes, actual pre- and post-launch activities will be similar. However, it will not be necessary to re-establish site emissivity characteristics during overflight.

It is proposed to drop the "rock" sites after initial post-launch activities have validated the TES algorithm on actual ASTER data; however, it is anticipated that the "water" sites at least will be reoccupied and monitored periodically during the life of the AM-1 platform.

Validation activities will commence immediately after launch. Every effort will be made to conduct at least two experiments over each validation site during the first 6-8 months of the AM-1 mission. Thereafter, at least one "water" site will be revisted less frequently, perhaps annually, for the life of ASTER.

10.4.2 New EOS-targeted coordinated field campaigns

The two US water sites are large enough to be used in MODIS as well as ASTER validation activities. Additionally, a land calibration site at Railroad Valley, Nevada, is large enough for MODIS. Railroad Valley is not a prime TES "rock" site because it is a playa, compositionally varying due to rain and wind. Nevertheless, the prime TES rock sites are too small for MODIS' use, and TES personnel will participate a May/June EOS joint validation/calibration field campaign in anticipation that such activity will help solidify support for similar joint activities in the post-launch time period.

10.4.3 Needs for other satellite data

Landsat-7 60-m TIR data will be useful in a general way in validation activities, especially if Landsat and ASTER data takes can be coordinated. MODIS data will be of use in that they may assist in the atmospheric correction of ASTER data. AVHRR and MODIS data will be useful in helping assess generalized haze and cirrus conditions at the validation sites.

10.4.4 Measurement needs

The following measurements are needed:

> *To characterize atmospheric conditions...* profiles of atmospheric moisture and temperature, estimates of atmospheric aerosol content and column ozone amount, physical and spectral radiometric measurements of surface temperatures at the time of EOS AM-1 overflight, and surface emissivity measurements near the time of overflight, with good location data for the surface measurements. In addition, low-altitude airborne TIR scanner data and spaceborne TIR will be helpful. MODIS and AVHRR images will help assess weather conditions (especially thin cirrus). All the above will be needed for the water sites and will be acquired for the atmospheric correction validation effort.
>
> *To characterize site conditions...* pre-launch emissivity maps (rock sites) and generalized spectra (water sites) will be combined with limited post-launch field measurements made with JPL's Micro-FTIR field emissivity spectrometer. Hand-held radiometric measurements will be made on a predetermined grid of sample locations at the rock sites to characterize temperatures. These will be merged with relative temperature measurements made by TIMS or an equivalent scanner from low-altitude aircraft (1400 m above terrain, or 4.5 m data).

10.4.5 Needs for instrument development

Field TIR imaging systems are required, especially during the pre-launch site-characterization phase, to assess emissivity and temperature heterogeneity scales from 1 cm to 10 m. These data bridge the gap between field spectra (10 cm) and low-altitude scanner data (10 m). JPL currently has constructed a suitable solid-state QWIP imaging system (256x256 pixels, 0.025°K sensitivity at 9.0 µm) that is usable in field settings, and we have experimented with it in the field. This instrument needs little adaptation to function well in the validation experiments, if regular access to it can be secured.

Pre-launch activities will benefit from having a sensitive aircraft scanner that duplicates ASTER's five TIR bands. TIMS is acceptable in general, the match of spectral bands is not ideal.

10.4.6 Geometric registration site
Geometric registration is a basic Level-1 activity not related to the validation plan discussed here. Validation sites will be located on high-resolution aerial photographs first and then located on aircraft or ASTER images by cross-correlation using existing software at UW.

10.4.7 Intercomparisons (multi-instrument)
Intercomparison with surface temperature estimates from MODIS will be an important validation activity. Although the greatest insight will probably be cast on the efficacy of ASTER atmospheric reduction, this is one of the greatest sources of uncertainty in the TES standard Products.

10.5 Implementation of Validation Results in Data Processing

10.5.1 Approach
The validation results will be used to refine the TES algorithm to optimize the accuracy, precision, and cost of the standard products. The accuracy and precision will also be used as part of the QA documentation associated with the header of each ASTER surface-temperature and emissivity image. Finally, the results will be used to assess on a pixel-by-pixel basis the algorithm performance, and resulting precision estimates will be incorporated into a QA data plane associated with each standard product. It is anticipated that precision will vary chiefly with temperature and with the spectral contrast or MMD, and an important role of validation is to characterize the dependency quantitatively.

Validation is of sufficient importance that a peer-reviewed publication of pre-launch results is planned. Results will also be made available in text form at the DAAC responsible for processing ASTER data to Level 2 (currently, this would be at the EROS Data Center).

10.5.2 Role of EOSDIS
The primary role of EOSDIS in this validation plan is to supply the data products, which are being validated for the time and location of the experiment. In doing this, EOSDIS will also acquire and process the necessary input data sets to process the ASTER data.

10.5.3 Plans for archiving of validation data
Validation data and a description of the processes, procedures and algorithms used will be archived in a report at the ASTER Team Leader's processing facility and also at the University of Washington SCF.

10.6 Summary

The validation plan described above uses pre-launch experiments to characterize sites for post-launch validation, to fine-tune and document the TES algorithm, and to prepare initial QA assessments and assessment methodologies for the standard products. Field measurements of temperature, emissivities, and atmospheric conditions will be combined with aircraft and existing satellite TIR scanner data in this effort. Validation sites will be of two types: water and rock sites. Water sites will be used to determine temperature and emissivity recovery for graybodies. Rock sites will be used to test TES for regions of high emissivity contrast. Redundant sites will be maintained in the western US and Japan. An additional site in Australia may be considered. One site (Railroad Valley) may be used specifically to allow for intercomparisons to MODIS.

Post-launch activity will be coordinated with AM-1 overflights and acquisition of ASTER and MODIS data. Collection of emissivity data in the field will be minimal, but temperature and atmospheric data will have to be acquired. Overlap in this activity with the Atmospheric Correction Working Group is anticipated.

Initial post-Launch validation will be concluded at each site within 6-8 months of launch, but continued experiments will be repeated annually for the life of the mission to check for changes in performance. The plan calls for such long-term experiments only at the water sites to maximize economy.

Polar Surface and Cloud Classification (AST13)

11.1 Introduction

11.1.1 Measurement and science objectives

With the growing awareness and debate over the potential changes associated with global climate change, the polar regions are receiving increased attention. Since greenhouse forcings are expected to be amplified in polar regions (Wetherald and Manabe, 1980; Schlesinger and Mitchell, 1987; Steffen and Lewis, 1988), these regions may act as early warning indicators of actual climate shifts.

Global cloud distributions can be expected to be altered by increased greenhouse forcing. In the polar regions, cloud cover changes can be expected to have significant effect on sea ice conditions (Shine and Crane, 1984) and on regional ice-albedo feedbacks (Barry et al., 1984). In particular, polar stratus is very important to the polar heat balance and directly affects surface melting (Parkinson et al., 1987). However, in order to monitor changes in polar surface conditions and polar cloudiness, more accurate procedures have been developed to distinguish between cloud and snow-covered surfaces.

The overriding objective of the ASTER Polar Cloud Mask product is to identify or classify all pixels in imagery obtained poleward of 60N and 60S as cloud or clear. Depending on the type of user, the product can be used to mask out all cloudy pixels for surface studies (e.g., ice process studies) or, conversely, all clear pixels for polar cloud studies. The product will be available on request for both daytime and nighttime imagery; however, a different scheme will be used in each case. The daytime algorithm will utilize visible, shortwave IR, and thermal IR for the feature space. In the nighttime algorithm, only the 5 ASTER thermal IR channels can be used. In the case of daytime imagery (estimated to be 90 percent of the total data obtained from ASTER), as a secondary objective, the underlying surface of thin cloud will be identified as either water, land, snow/ice, or unknown. Also pixels identified as clear will be further classified into one of the 6 subclasses of water, wet/thin ice, ice/snow, shadow on ice/snow, land, and shadow on land.

11.1.2 Product Description

The ASTER Polar Cloud Mask constitutes one, level-2 data product which is a coded pixel map. It will be accompanied by metadata containing statistics for percent occurrence of each class and cloud/clear fraction, in addition to any "pass through" information derived from input streams for radiance/reflectance/temperature. Pass through information will include general quality assurance information such as the presence and location of bad pixels.

11.2 Validation Criterion

11.2.1 Overall approach

Currently Landsat TM data is being used as a surrogate for ASTER in the testing and validation of the daytime algorithm. The two instruments have similar spatial resolution characteristics (i.e., Landsat TM bands 1-5, and 7 at 30m and band 6 at 120m; ASTER Bands 1-3 at 15m, bands 4-9 at 30m, and bands 10-14 at 90m). The spectral resolution capabilities of some of the bands are very similar, but some are significantly different. For example, bands 2, 3, 4, and 5 of Landsat TM are a good match for ASTER bands 1, 2, 3, and 4. However, band 7 in Landsat TM is a broad shortwave IR band covering the 2.1 to 2.4 um region, while ASTER has 5 discrete 50 nm (approximately) bands centered between 2.1 and 2.4 um. In addition, Landsat TM has only one thermal IR band covering the 8-12 um range while ASTER has 5 higher spectral resolution bands within the same region.

Thermal Infrared Multispectral Scanner (TIMS) imagery is being used likewise for the nighttime algorithm. In this case there is a good match between 5 of the 6 TIMS bands and the 5 ASTER thermal IR bands (10-14). However, there is very little coverage of polar regions or snow/ice regimes in the TIMS dataset. In addition, there is no coincident solar wavelength imagery, and accurate identification and labeling of samples are very difficult.

There is a limited amount of high spatial resolution data available from other instruments (such as AVIRIS and MAS), but the primary validation dataset is Landsat TM. In essence, the validation effort to date for the algorithm has been conducted around the Landsat TM dataset.

In validating the operation of the daytime and nighttime algorithms on Landsat TM imagery, three approaches are being used. The first and third are quantitative approaches and the second is more subjective. All three have limitations but, in general, they complement each other. They are described following.

In the first method, the algorithm is applied to a labeled set of samples. To date approximately 3700 contiguous pixel regions (made up of several hundred thousand pixel samples) have been extracted and labeled by a human expert trained in identifying features in polar imagery. For every pixel in every contiguous sample, the classification results from the algorithm are compared to the labeling (test samples), and a "confusion" matrix is generated indicating the percentage of classification for each combination. If the algorithm performs perfectly, the confusion matrix is diagonal in which each diagonal element is 100 percent. This validation method somewhat overestimates the accuracy of the algorithm because the human expert tends to select spectrally homogeneous and unambiguous samples which are generally classified at a higher accuracy rate than for an entire scene. However, it serves to provide an indication of the upper limit of performance and, empirically speaking, indicates within 10 percent the overall scene classification accuracy. This method serves as the basis for validating the accuracy of the algorithm over the life of the product.

The second approach is somewhat objective and involves visual comparison of the classification result with the imagery by a human expert. The expert has access to a tool that allows him to augment his analysis through the use of three-band overlays and various image processing techniques, such as contrast stretching and histogram equalization. When available, more than one expert is used and, generally, their subjective estimates of the accuracy are within 5 percent of each other.

The third approach is an attempt to quantify the overall scene classification accuracy. This is derived from a tool that a human expert uses to label randomly selected regions within sets of Landsat TM imagery. It is very much like the process that an expert uses to extract labeled samples, except the computer randomly selects the region to be labeled as opposed to the expert selecting the region. The random selection of samples by the computer provides for a more objective estimate of classification accuracy when these samples are compared against the results obtained from the classifier.

The results obtained from these methods will also be compared with independent observations from ground-, air-, and other satellite-based observations. Comparisons with these other types of observations will be conducted over an extended period of time for a variety of circumpolar regions.

11.2.2 Sampling requirements and trade-offs

Although current testing and validation of the algorithm is based on approximately 100 Landsat TM quad scenes, due to the limited areal coverage of each quad scene (approximately 100 km by 100 km), the entire circumpolar region is represented at a fraction of a percent. Antarctica is only represented in 24 scenes for 3 months in 1989 and only over coastal areas. The sample set poorly represents the polar regions both in space and time. Currently it is not possible to define the accuracy of the classification, for example, by latitude, ecosystem, season, etc.. However, during post-launch, as ASTER obtains data over various polar regions, representative samples will be extracted and included in the training set for the classifier. Analysis of the distributional nature of important features for classification will be conducted periodically. If warranted, the classifier will be retrained, or if correlative analysis manifests a unique condition by latitude, ecosystem, etc., an additional version of the classifier will be installed to accommodate it.

11.2.3 Measures of success

If the classification accuracy for cloud/clear is greater than 95 percent, when applying the algorithm to all available labeled pixel samples (several hundred thousand to date), the validation will be considered successful. During the prelaunch phase, samples are extracted primarily from Landsat TM and secondarily from AVIRIS and TIMS. During the post-launch phase, labeled samples will be extracted primarily from ASTER and secondarily from Landsat 7 ETM+.

Once confidence has been gained with the cloud masking algorithm, the results will be compared to independent observations. However, there are problems with comparing satellite-derived results with ground-based lidars, radars, and surface-based observations. For example, the relatively small field of view of the lidars and radars, the aspect angle, and time of observation as compared to the satellite sensor are important. Similar problems must be considered for surface observer estimates of cloud cover location. Cloud sides are seen by surface observers and satellites at different observational angles and from opposite sides of the cloud (top vs. bottom). There are two approaches for comparing the independent observations with satellite cloud masks. First is to compare the imager pixels closest to the ground site with temporally averaged (e.g., 10 minutes) lidar or radar data. The second approach is to perform a temporal average of the ground-based data over a period of hours and to compare it with a spatially averaged cloud mask.

11.3 Pre-launch Algorithm Test/Development Activities

11.3.1 Field experiments and studies

The most efficacious approach for algorithm development and testing has been through the use of the existing NASA government archives of Landsat TM data. In terms of both spectral and spatial resolution, and circumpolar region coverage, Landsat TM data serves as the best surrogate for ASTER data. The best quantitative method for validating the algorithm results is through analysis of the cloud mask and testing of the algorithm on labeled samples. The only circumpolar experiment conducted to date that will provide ASTER-like data is SHEBA (summer of 1995). The algorithm will be tested on the MAS and AVIRIS imagery from that experiment when it becomes available. Comparisons will also be made with surface observations obtained from that experiment.

11.3.2 Operational surface networks

It is anticipated that the following products will be used in pre-launch activities:

1. National Weather Service observations (especially in polar regions such as in Fairbanks and Anchorage, AK)
2. Ceilometer network (limited to wintertime conditions at continental U.S. sites)
3. DOE ARM site data from Oklahoma (during wintertime conditions)

11.3.3 Existing satellite data

To the degree affordable, Landsat TM data has been purchased to support the testing and validation of the algorithm. In addition, more Landsat TM data has been obtained at no charge through data sharing agreements. Some aircraft data obtained from AVIRIS, MAS, and TIMS is also being used, especially MAS data taken in the Beaufort Sea area.

11.4 Post-launch activities

11.4.1 Planned field activities and studies

The validation effort for this algorithm will take advantage of any data obtained from field studies conducted pre-launch and post-launch in which polar-like conditions are present. In particular, the following table lists three field experiments, which will acquire data over snow/ice-covered surfaces.

Mission	Dates	Location	Purpose
WINCE	Feb 97	Great Lakes So. Canada	cloud detection and properties over snow-ice covered surfaces
FIRE III-1	Apr-Jun 98	Alaska	Arctic stratus over sea ice
FIRE III-2	Aug-Sep 98	Alaska	Arctic stratus over sea ice

When coincident cloud masking data is available from Landsat 7 (ETM+), comparisons will be made. In the case of reasonable agreement, supporting validation is provided. If they do not, additional analysis will be required.

The validation effort using surface observations will take advantage of the enhanced surface based measurement capabilities located at the DOE ARM sites in Alaska and Oklahoma. The use of the ARM site data from Oklahoma will be limited to wintertime conditions, especially when snow and clouds are present during the time of overpass. An opportunity for validating the algorithm in the detection of thin cirrus will also occur during overpasses of Salt Lake City, UT, using the long range lidar located there (Sassen), and Penn State lidar and radar observations (Ackerman). The following table lists additional polar validation sites.

Polar Validation Sites

Location	Latitude/Longitude	
Barrow, Alaska	71.20N/156.50W	
Ny Alesund, Spitsbergen	79N/12E	
Georg Von Neumayer, Antarctica	70S/08W	
Syowa Base, Antarctica	69S/39E	
Bratt's Lake, Canada	50N/104W	winter
Toravere Observatory, Estonia	58N/26E	

Boulder, CO	40.13N/105.24W	winter
Franz Josef Land, Russia	80N/55E	
Dutch Harbor, Unalaska	55N/167W	
Juneau, Alaska	57W/134W	
Anchorage, Alaska	61.10N/150.01W	
Nome, Alaska	64.30N/165.26W	
Prudhoe Bay, Alaska	70.15N/148.20W	
Aklavik Airport, Canada	68.13N/135.00W	
Alert Airport, Canada	82.31N/62.17W	
Baker Lake Airport, Canada	64.18N/96.05W	
Yellowknife Airport, Canada	62.28N/114.27W	
Godthak, Greenland	64.12N/51.41W	
Kulusuk, Greenland	65.34N/37.07W	
Reykjavik, Iceland	64.08N/21.54W	
Tromso/Langues, Norway	69.41N/18.55E	
Murmansk, Russia	68.58N/33.03E	
Byrd Base, Antarctica	80.01S/119.32W	
McMurdo Base, Antarctica	77.51S/166.40E	
Palmer Base, Antarctica	64.46S/64.05W	
Siple Base, Antarctica	75.55S/83.55W	

11.4.2 New EOS-targeted coordinated field campaigns

With the aforementioned comparison of ground-, air-, and satellite-based observations with the cloud mask, there will still be a deficiency of validation information. It would be beneficial to plan field campaigns in the circumpolar regions, or join already planned field campaigns there to fill in data gaps and augment the validation process.

11.4.3 Needs for other satellite data

Landsat enhanced thematic mapper plus (ETM+) data is needed to augment the transition of the algorithm from Landsat TM to ASTER data. It is also needed for comparison of cloud masking products in the validation process. The Japanese Advanced Earth Observing Satellite (ADEOS) carries two instruments, which can be, used for intercomparison and validation purposes. They are 1) the Advanced Visible and Near-Infrared Radiometer (AVNIR) and 2) the Polarization and Directionality of the Earth's Radiances (POLDER) instruments. AVNIR is a high spatial resolution instrument with similarities to LANDSAT and SPOT. POLDER has a lower spatial resolution of 6 km by 7 km, but has three unique polarization channels in the visible and near-infrared and observes the Earth from 12 directions during a single satellite overpass. POLDER will be especially valuable for the detection of cirrus clouds and aerosols. Note that since AVNIR is operated only on demand, special arrangements must be made to acquire these data.

11.4.4 Measurement needs (in situ) at calibration/validation sites: land, buoys, etc.
Currently, the algorithm is designed to take advantage of ancillary databases, such as coastlines, ecosystems, land character, elevation, etc.; however, the coarse spatial resolution currently available from these datasets makes their use limited. Improved higher spatial resolution surface characterizations are needed.

11.4.5 Needs for instrument development (simulator)
Not applicable.

11.4.6 Geometric registration site
Not applicable.

11.4.7 Intercomparisons (multi-instrument)
The cloud mask obtained from ASTER will be intercompared with that obtained from Landsat 7 ETM+. Other product developers (e.g., MODIS ATMOSPHERES, SNOMAP and ICEMAP, CERES cloud mask) utilizing lower spatial resolution data will be comparing their results with this ASTER derived product.

11.5 Implementation of Validation Results in Data Production

The confusion matrices derived from testing of the algorithm on labeled pixel samples will be included in a product file as an annotation element. There are currently 4 cloud classes and 6 clear classes. The matrix will be 10 by 10 and indicate for each class the percentage of labeled samples classified as each of the 10 classes. This will provide the user with an indication of the relative accuracy of each class, as well as cloud/clear classification accuracy.

11.5.1 Approach (include long-term calibration considerations)
Periodically (approximately every 3 months in the first two years), ASTER scenes obtained over polar regions will be randomly selected for the extraction of new labeled pixel samples. If algorithm testing results indicate degraded performance, the algorithm will be retrained and tested again. If the results are still degraded, the data will be partitioned into the determining condition (e.g., season, ecosystem, elevation) and multiple versions of the algorithm will be implemented at the DAAC. (Note: This does not imply more than one algorithm, only multiple table lookups which the algorithm will select automatically.)

Algorithm performance will continue to be checked against available surface-based, air-based, and satellite-based data when available.

11.5.2 Role of EOSDIS

The product resident within EOSDIS will have a pointer to the developer of the data product. This will provide a feedback mechanism in which users can alert the developer of possible errors or discrepancies. User feedback will provide an additional independent validation of the product and could potentially stimulate investigations into methods for product improvement.

11.5.3 Plans for archival of validation data

The validation results will be archived by the developer at his site. Subsampled versions of the classification masks generated for most of the scenes in the validation process will be maintained at an ftp site. Users will be able to request the full resolution product through the same site. The results from the validation efforts will be published in the peer-reviewed literature.

11.6 Summary

The fundamental basis for development of the ASTER Polar Cloud Mask algorithm is the extraction of labeled pixel samples primarily from Landsat TM data and to a lesser extent from TIMS, AVIRIS, and MAS. These labeled samples are used to train the algorithm and define the distribution of the feature space for each class. They also provide the basis for validation of the algorithm. As long as the classification accuracy of the algorithm on the labeled samples is percentage > 95, the algorithm provides adequate cloud masking results (on the average). Appropriate data sets continue to be acquired and tested during the prelaunch phase and will continue to be acquired during the post-launch phase to ensure the classification accuracy does not drop below 95%. This does not imply that the algorithm always classifies at least 95% of the pixels in each scene correctly for cloud and clear, but that it will do so at an accuracy of approximately 95% on the average. This technique for validating cloud-masking accuracy is augmented by two other methodologies described in 2.1. This product will be derived from the ASTER products for radiance/temperature at the sensor. The assumption is that these inputs are valid (unless otherwise indicated by metadata, in which case the pixel will remain unclassified and passed through as bad/marginal/etc.).

Digital Elevation Models (AST14)

12.1 Introduction

12.1.1 Measurement and Science Objectives

The shape of the surface of the planet Earth (topography of the land and bathymetry of the oceans) is a fundamental geophysical parameter required for quantitative research in nearly all disciplines of earth science. Land topographic data and derived measurements of slope and aspect are also required for quantitative correction of most space-acquired radiometric measurements of the land surface, including those of MODIS and ASTER.

The ASTER instrument includes an along-track stereo imager that will be capable of acquiring coherent, digital, cloud-free global coverage of the Earth's land surface during the 6 year mission. The system is configured to acquire data with a base/height ratio of 0.6 at 15 m spatial resolution; it is capable of acquiring 771, 60 km X 60 km stereo pairs per day. These data will be used to produce digital elevation models (DEMs) using commercial off-the-shelf software that run digital stereo correlation algorithms to calculate parallax differences. Developed during the late 1970's and early 1980's using digital satellite data, and based on over 60 years experience in the field of aircraft photogrammetry, these algorithms have been thoroughly documented, tested and validated in the peer reviewed literature.

The specific objectives of the ASTER stereo experiment are: 1) to acquire cloud free stereo coverage of 80% of the land surface between 85° N and 85° S; and 2) to produce, with commercial software, standard product DEMs at a rate of one-per-day starting at launch. Specifications of the DEM data product are provided in Table 1. According to these specifications, ASTER DEMs can meet 1:50,000 scale map accuracy standards, and provide slope determinations with accuracies of better than 5° over measurement lengths of 100 m or greater.

12.1.2 Product Description

Data consist of a regular array of elevations (in meters, recorded in byte) referenced to either the lowest elevation in the scene (relative DEM) or to mean sea level (absolute DEM) and projected in UTM referenced to WGS84. Posting is 30 m; coverage is one, 60 X 60 km, ASTER band 3N scene.

12.2 Validation Criterion

12.2.1 Overall Approach

The overall approach to validating the ASTER DEM standard data product is to confirm that the DEMs meet RMSEz and RMSExy specifications shown in Table 1.

Eleven validation sites have been established by the ASTER DEM Working Group (ADEMWG). These are: Huntsville, Alabama; Drum Mountains, Utah; Lake Okoboji, Iowa; Mount Etna, Italy; Taxco/Iguala, Mexico; and Mount Aso, Mount Fuji, Mount Kiso-Komagatake, Mount Tsukuba, Mount Unzen, and Saga Plain, Japan. Over each validation site, we will subtract z values from highly accurate DEMs, obtained from other sources, from z values from ASTER DEMs covering the same area, on a pixel-by-pixel basis. RMSEz values will be calculated from the resulting difference data under the conservative assumption that the highly accurate DEM values are correct. In order to validate planimetric accuracy, over each validation site we will measure x-y displacements of distinct topographic features on elevation profiles derived from ASTER DEMs with respect to the same features on the same lines of profile derived from the highly accurate DEMs. Also, the locations and elevations of GCPs withheld from the DEM generation process will be compared with their locations and elevations on the DEM. RMSExyz values will be calculated from the resulting difference data, again under the conservative assumption that the highly accurate DEM values are correct.

Comparison of these RMSEz and RMSExy results to the specifications shown in Table 1 will confirm that the standard data product meets specifications. RMSEz and RMSExy will be measured over each validation site at least once per year in this way in order to monitor system stability over the 6 year mission. A Lead Scientist from the ADEMWG has been designated for each validation site and will be responsible for: acquiring appropriate (either or both SPOT or JERS-1) digital stereo data to simulate ASTER stereo data for pre-launch system testing, providing appropriate ground control point (GCP) data and DEM data from other sources that meet or exceed 1:25,000 mapping accuracy standards, selecting topographic profiles, and assessing validation results.

12.2.2 Sampling Requirements and Trade-offs

The 11 validation sites (see 12.2.1 above) were selected by the ADEMWG to be representative of the range of stereo scene-types that will be observed by the ASTER stereo system during the mission. These validation results should therefore be representative of ASTER DEM data obtained from other sites.

12.2.3 Measures of Success

See items 12.1.1 and 12.2.1 above.

12.3 Pre-Launch Algorithm Test/Development Activities

12.3.1 Field Experiments and Studies

No field experiments are required or planned. All validation site data are already in the possession of the Lead Scientists and will be provided after the commercial system is selected through an RFP process. These include SPOT and/or JERS-1 digital stereo datasets (ASTER simulation data), GCP data and DEMs from other sources. Simulation data sets and GCPs for two sites were provided as part of the RFP package for use by proposers to demonstrate their system's capability. An RFP for acquiring the commercial system has been released and a system testing plan has been prepared. The system is scheduled for installation at the Land DAAC by the end of FY'97.

12.3.2 Operational Surface Networks
None required or planned.

12.3.3 Existing Satellite Data
See items 12.2.1 and 12.3.1 above.

12.4 Post-launch activities

12.4.1 Planned Field Activities and Studies
No field activities or studies are required or planned. See section12.2.

12.4.2 New EOS-Targeted Coordinated Field Campaigns
No field campaigns are required or planned. See section 12.2.

12.4.3 Needs For Other Satellite Data
No other satellite data are required. See items 12.2.1 and 12.3.1 above.

12.4.4 Measurement Needs at Validation Sites
No measurements are needed or planned. See section 12.2.

12.4.5 Needs For Instrument Development
No instrument development is required or planned.

12.4.6 Geometric Registration Site
Not relevant.

12.4.7 Intercomparisons (Multi-instrument)
Not applicable.

12.5 Implementation of Validation Results in Data Production

12.5.1 Approach

The specification sheet (Table 1), available on-line in the ATBD throughout the mission, will provide the latest validation data to users. These specifications will be updated, throughout the mission, based on the most recent validation results.

12.5.2 Role of EOSDIS
No role, because a commercial system will be used. See section 12.2 and item 12.3.1 above.

12.5.3 Plans for Archival of Validation Data
All validation data will be archived at the Eros Data Center.

12.6 Summary

Quantitative validation of the ASTER DEM standard data product is a straight forward problem that has been resolved by the ADEMWG using simple differencing procedures that will demonstrate that the product meets RMSExyz specifications.

Summary Charts

Table 1. Specifications for ASTER DEM data product (AST-14).

UNIT OF COVERAGE: 60 km x 60 km ASTER scene

FORMAT: Data consist of a regular array of elevations (in meters) referenced to either the lowest elevation in the scene ("relative DEM") or to mean sea level ("absolute DEM") and projected in the Universal Transverse Mercator (UTM) coordinate system.

RESOLUTION:
1. x-y; 30 or 60 m (posting)
2. z; 1 m (smallest increment)

PRODUCT NAME	# OF GCPs (MINIMUM)	GCP (RMSExyz) ACCURACY	DEM (RMSExyz) ACCURACY
Relative DEM	0	N/A	10 - 30 m*
Absolute DEM	1	15 - 30 m	15 - 50 m**
Absolute DEM	4	5 - 15 m	7 - 30 m**

* Z values referred to local vertical datum

** Z values referred to absolute vertical datum (mean sea level)

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