AN ATMOSPHERIC CORRECTION METHOD FOR ASTER THERMAL RADIOMETRY OVER LAND

ASTER Standard Data Product AST09, “Level-2 Radiance--TIR, Land_Leaving”

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1. Introduction

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, described in this document, is to remove these effects 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.

The position of the Thermal InfraRed (TIR) surface leaving radiance in the ASTER data product flow is shown at the middle right of Diagram 1. This product and its associated uncertainty are the primary inputs for the separation of surface kinetic temperature and spectral emissivity for the ASTER thermal infrared channels.

2. Overview

ASTER will provide thermal infrared, multichannel (5), high spatial resolution (90 m) images of most of the earth’s land surface. Previous imaging instruments notably AVHRR, the Landsat Thematic Mappers (TMs) and the Heat Capacity Mapping Mission (HCMM) either possessed lower spatial resolution (AVHRR, HCMM) or provided a single channel of thermal data (TM, HCMM). For these instruments, the data has usually been provided to the user without atmospheric correction.

The noise equivalent delta temperature performance of the ASTER thermal infrared (TIR) channels is to be 0.3 K or better. Results presented from testing of the flight model in June of 1996 indicated the laboratory performance of the TIR subsystem is 0.2 K or better. At the instrument, the accuracy of measurement expressed as a brightness temperature, is to be 1 K or better in the range 270 to 340 K. The goal of the atmospheric correction procedure is to keep the residual error due to uncompensated effects as low as possible. In most circumstances we would like the residual error to be under 1 K.

2.1 Approach

The approach proposed here for atmospheric correction in the thermal infrared involves two fundamental elements: 1) the use of a radiation transfer model capable of estimating the magnitude of atmospheric emission, absorption and scattering and 2) the acquisition of all the necessary atmospheric parameters (e.g. temperature, water vapor, ozone, aerosol profiles) at the time and location of the measurement to be corrected.

The radiance leaving the surface, L_{sur}, (which is a combination of both emission and reflection) is related to the radiance derived from the sensor, L_{sen}, the transmission of the atmosphere, T_r, and the atmospheric path radiance, L_{path}, (which arises from both atmospheric emission and scattering) by the following equation:

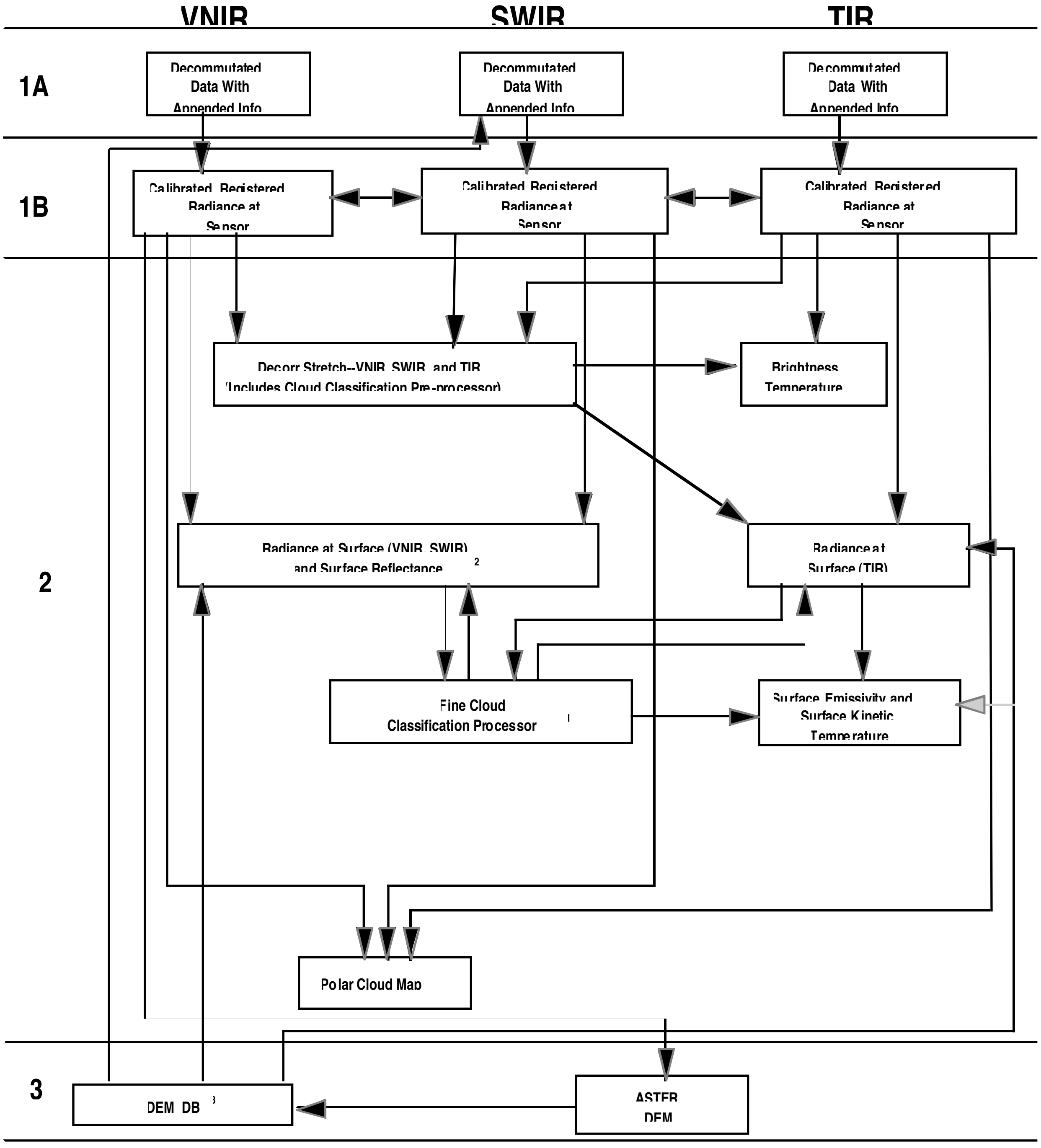
$$L_{sat} = L_{sur} * T_r + L_{path}$$

The radiation transfer model is used to calculate the atmospheric transmission and path radiance allowing the surface radiance to be determined.

The surface leaving radiance is a combination of radiation emitted by the surface and sky irradiance reflected by the surface. If the spectral emissivity of the surface is known these two components can be separated. For this reason the Level 2 TIR atmospheric correction product will include the band integrated sky irradiance for each pixel of the five ASTER TIR channels.

Diagram 1

ASTER Product Inter-Dependencies



[1] Produces a cloud mask that is incorporated into other products

[2] Computed simultaneously with Radiance at Surface

[3] Refers to a database of DEM data regardless of the source

Alternatives to this approach do exist, such as the "empirical" methods, which have been successfully used for obtaining sea surface temperature estimates (Hilland et al., 1985). These alternates use "split window" or multichannel measurements to derive the sea surface temperature (Prabhakara et al., 1975, McMillin, 1975, Deschamps and Phulpin, 1980). This method is based on establishing an empirical relationship between water temperatures measured at the sea surface and the brightness temperatures measured in two or more strategically chosen spectral channels. The difference between the brightness temperatures in several channels can be used to estimate and remove the atmospheric influence. When such approaches have been used over land, they have produced mixed results (Price, 1984). They are not proposed here for three reasons: 1) the ASTER thermal infrared channels have been placed in the clearer regions of the atmospheric 8-13 µm window region providing less "leverage" on atmospheric effects, 2) in general the spectral emissivity of the land surface is not known as it is for water and it is highly variable depending on many factors including composition, fractional vegetation cover and surface moisture content and 3) the multichannel method, depending as it does on channel-to-channel temperature differences, is very sensitive to the measurement noise inherent in the instrument and the absolute accuracy of the radiance for each channel.

The effect of emissivity variations on two-channel (split-window) methods has been examined in detail by Becker (1987) showing the method requires both an absolute knowledge of the mean emissivity of the channels used and their difference in emissivity. For AVHRR channels 4 and 5 the mean emissivity must be known to 0.005 and the difference in emissivity to 7×10^{-4} for the error in the surface temperature derived to be of order 0.5 K from this effect. In general the emissivity of the land surface is not known to this accuracy and precision.

The effect of brightness temperature inaccuracies on multichannel sea surface temperature (MCSST) methods has been investigated by Wan and Dozier (1996). These authors show, (using MCSST formulas for AVHRR channels 3, 4 and 5) with a simple error analysis, that errors in channel brightness temperature are multiplied by 6 for the two channel case and by 3 for the three channel case when converted to uncertainty in sea surface temperature. This places a limitation on the noise and accuracy, which is acceptable for the systems to be used with the multichannel method.

For the reasons given above we have not proposed a multichannel atmospheric correction approach for the derivation of land surface temperature. However, this approach does have the very strong advantage that it uses measurements from the time and place of interest and thus inherently attempts to account for the atmosphere on a pixel by pixel basis. It is fortunate that Wan and Dozier (1996) propose such an approach for the derivation of land surface temperature from MODIS. The MODIS channels were selected in part with such a method in mind and the longer integration time available to MODIS provides for a considerably lower system noise than is possible with ASTER. Comparison of ASTER and MODIS results will perhaps lead to a better understanding of the relative power of the two methods for land surfaces.

The method proposed here for atmospheric correction of the ASTER thermal infrared data is a "clear sky" method in that it does not attempt to correct for the presence of intervening clouds. Clouds have a strong impact on thermal radiation reaching the sensor. As originally proposed the ASTER data product AST10, "Scene Classification", parameter #3804 was to be available at the scale of an ASTER thermal infrared pixel to assist the user in identifying cloud locations. Now AST10 "Scene Classification" will not be produced as a standard product but will be available for internal use in the generation of other ASTER standard products. Information on the cloud content of individual ASTER pixels will be provided by using cloud information from the scene classification and incorporating this information in a "Quality Assessment" array which will accompany the atmospheric correction data product. Although many of theTerra platform instrument teams including ASTER's will attempt determination of cloud properties, which could be used to calculate their effect on thermal radiation, we find the uncertainties in such corrections would be difficult to estimate and even more difficult to validate. For these reasons we will not attempt to correct those portions of the image where a cloud exists between the surface and the sensor.

2.2 ASTER Thermal Infrared (TIR) Subsystem Characteristics

ASTER continues the trend to higher spatial resolution surface imaging begun with the Landsat Thematic Mapper and by SPOT. In addition, ASTER increases the number of channels (14 versus the 7 of the Thematic Mapper and 4 of SPOT). Also, ASTER will provide same-orbit stereo capability by using nadir and aft looking telescopes. It will provide multispectral thermal emission measurements (5 channels) in the atmospheric window region from 8 to 12 μm. ASTER consists of three imaging subassemblies (the visible includes two telescopes), one in each spectral region: The visible and near infrared (VNIR), the short wave infrared (SWIR) and the thermal infrared (TIR). The nominal size of the instantaneous field-of-view at the earth's surface is 15, 30 and 90 meters in the VNIR, SWIR and TIR respectively with a cross-track swath width of 60 km for all channels and the instrument has been assigned a data volume equivalent to an 8% duty cycle.

The TIR subsystem (Fujisada and Ono, 1991) uses a Newtonian catadioptric system with aspheric primary mirror and lenses for aberration correction. The telescope of the TIR subsystem is fixed to the platform and pointing and scanning is done with a single mirror. The line of sight can be pointed anywhere in the range plus or minus 8.54° in the cross-track direction of nadir, allowing coverage of any point on earth over the platform's 16 day repeat cycle. Each channel uses 10 mercury cadmium telluride (HgCdTe) detectors in a staggered array with optical bandpass filters over each detector element to define the spectral response. Each detector has its own pre- and post- amplifier for a total of 50. The detectors are to be operated at 80 K using a mechanical split-cycle Stirling cooler.

In the scanning mode the mirror oscillates at about 7 Hz with data collection occurring over half the cycle. The scanning mirror is capable of rotating 180˚ from the nadir position to view an internal full-aperture reference surface, which can be heated to 340 K. The scanning/pointing mirror and telescope design precludes a view of space, so at any one time only a one-point temperature calibration can be obtained. A temperature controlled and monitored chopper is used to remove low-frequency drift. In flight, a single point calibration is planned before and after each observation and is to be used to control measurement drift (offset). On a less frequent basis (roughly once every two weeks), the temperature of the reference target will be adjusted to several different temperatures and a multi-temperature calibration set will be recorded to permit both gain and drift to be estimated.

For the TIR subsystem it is convenient to establish the subsystem noise requirement in terms of a noise equivalent delta temperature (NEΔT). The subsystem requirement is that the NEΔT be less than 0.3 K for a 300 K target. The accuracy requirement on the TIR subsystem is given for each of several brightness temperature ranges as follows: 200-240 K, 3 K; 240-270 K, 2 K; 270-340 K, 1 K; and 340-370 K, 2 K. Twelve bits are used in the collection and recording of TIR data. These instrument accuracy requirements are to be met through a combination of careful design and pre-flight calibration. They are to be maintained through in-flight calibration.

The full-width-at-half-maximum (FWHM) spectral response of the five TIR channels are given in Table 1.

Table 1 TIR Channel Full-Width-At-Half Maximum Spectral Response (μm)

Channel	10	11	13	14	15
Width (FWHM)	8.125-8.475	8.475-8.825	8.925-9.275	10.25-10.95	10.95-11.65

3. Algorithm Description

Among the issues that must be dealt with in pursuing the correction scheme are: 1) selection of an adequate atmospheric radiative transfer model for calculating path transmission and radiance, 2) finding sources of information about atmospheric parameter to be used in the transfer model and 3) preparation of parameter sets compatible with the transfer model by merging and interpolation from the various sources.

3.1 Choice of the Atmospheric Radiative Transfer Model

In selecting a radiative transfer model we looked for the following properties: 1) the code should be of sufficient tested accuracy to meet the goals of the experiment, 2) it should be widely and easily available, 3) it should possess an originator or custodian interested in making improvements, 4) it should be in use for the purpose of making atmospheric corrections in the thermal infrared and 5) it should be fast enough to be used with high spatial resolution imaging data. We have selected MODTRAN (Moderate Resolution Atmospheric Radiance and Transmittance Model, the launch version is 3.5) because it possesses the properties listed above and because we have used it, in its several versions, for more than ten years and are familiar with its properties.

MODTRAN (Abreu et al., 1991, Anderson et al., 1993) traces its heritage back through the several versions of LOWTRAN (Berk et al., 1989, Kneizys et al., 1988, Kneizys et al.,1983, Kneizys et al., 1980, Selby et al., 1978, Selby and McClatchey, 1975, Selby and McClatchey, 1972). The version of MODTRAN to be used at launch is MODTRAN 3.5. Our practice following launch will be to incorporate an entire version or features from a new version of MODTRAN when there is a computational or accuracy advantage to be gained from such incorporation.

MODTRAN 3.5 includes all the functional capabilities of LOWTRAN 7 (Kneizys et al., 1988) but uses a more accurate and higher resolution molecular band model with 2 cm^{-1} resolution based on the HITRAN molecular data base (Rothman et al., 1992) significantly improving on the 20 cm^{-1} resolution of LOWTRAN 7. MODTRAN 3.5 provides sufficient spectral resolution to be used with the narrowest ASTER thermal infrared channels (0.35 μm FWHM).

The MODTRAN band model uses a stored spectral data base for 12 (H_2O, CO_2, O_3, N_2O, CO, CH_4, O_2, NO, SO_2, NO_2, NH_3, and HNO_3) of the 13 (N_2 is handled more simply) molecules included, with band model parameters calculated for 1 cm^{-1} spectral bins at 5 temperatures between 200 to 300 K (Berk et al., 1989). The MODTRAN transfer model includes the effect of scattering (Rayleigh, Mie, single and multiple) and allows user specification for profiles of temperature, water vapor density, ozone, aerosols (in three regions, boundary layer, troposphere and stratosphere) and any of the other gasses which may vary with time (e.g. CO_2).

The higher spectral resolution of MODTRAN compared to LOWTRAN 7 and its more accurate representation of the effect of temperature and pressure on molecular absorptivity, provide MODTRAN with significantly more accuracy than LOWTRAN 7. Transmittance comparisons for horizontal paths have been made with the radiative transfer model FASCODE3P (Clough et al., 1988) and radiance comparisons have been made with an upward looking interferometer using good atmospheric parameter measurements (Anderson et al., 1993). These comparisons seem to establish agreement to better than 2%. More work needs to be done involving comparisons between MODTRAN and transfer models of established accuracy in the mode in which the model is to be used for ASTER atmospheric correction (i.e., looking vertically through the entire atmosphere). A comparison of this type was conducted by Wan and Dozier (1992) in comparing MODTRAN, LOWTRAN 6 and LOWTRAN 7 with ATRAD an accurate multiple scattering radiative transfer model they have used in previous studies. Wan and Dozier attempted to isolate the factors in MODTRAN that contributed to the differences between MODTRAN and ATRAD and concluded that the MODTRAN approximations were accurate in the 0.5 to 2% range for broad thermal bands.

These limited attempts at establishing the accuracy of MODTRAN indicate it may be suitable for use, but further work using the ASTER band passes is needed to establish the accuracy, which can be expected. (A 2% radiance error corresponds roughly to a 1-1.6 K brightness error in the ASTER channels.)

3.2 Sources for Atmospheric Parameters

The second element of the atmospheric correction approach involves identifying sources for all the necessary input atmospheric parameters that are either as accurate as necessary to meet the overall accuracy goal or are the best available. Most of these parameters will be obtained from the TERRA platform instruments MODIS and MISR. Information on these parameters was obtained from the EOS Data Products List (Version 1.0, prepared 10/29/93) distributed to the instrument teams with a letter from Michael King dated 12 November 1993.

3.2.1 Temperature and Water Vapor Profiles

The most important factors in determining the broad band atmospheric transmission and path radiance for the five ASTER TIR channels are atmospheric water vapor and temperature. Three MODIS clear atmosphere data products are prime candidates: MOD30(#3726) Temperature Profile (20 levels, 5 Km spatial resolution); MOD30(#3727) Water Vapor Profile (15 levels, 5 Km spatial resolution) and MOD38(#3725) Water Vapor Atmospheric (Thermal IR). The two profile products will use Environmental Modeling Center (EMC) forecast data assimilation model profiles as a base and will modify the assimilation model profiles so that the derived profiles are consistent with the radiances measured by MODIS. The column abundance data product MOD38 provides an overall estimate of the amount of water in the column and is listed with an uncertainty of >20% or 5 mm. Since MODIS will always collect data in the region observed by ASTER, these products should in general be available for use.

As a backup we propose interpolating the assimilation model data directly into the ASTER scene. There are two such assimilation systems that will be available: the EMC global (or-for the appropriate areas of North America-the regional) assimilation forecast system (Kalnay et al., 1990) and the NASA Goddard EOS (GEOS-1) assimilation system (Schubert et al., 1993). These two systems differ in objective in that the EMC system is an operational weather forecast system from which profiles could be obtained essentially coincident with the receipt of the raw data from ASTER. The GEOS-1 assimilation system does not have an operational forecast requirement and will be able to wait for all the data needed for assimilation to arrive. Since the processing of ASTER data at Level 2 will be conducted on a demand basis both of these models could be of use in the absence of profile data from MODIS.

3.2.2 Ozone

Because of the placement of the five ASTER TIR channels, ozone is not a significant factor in atmospheric correction except for channels 11 and 12, which are the closest channels to the ozone band between 9 and 10 µm. If profile information is available from SAGE (Stratospheric Aerosol and Gas Experiment) during the late 90's it would be our first choice. Since SAGE II or its replacement may not be available at the start of the TERRA mission we will use the MODIS product MOD07(#1333) O_3 Total Burden (5 Km spatial resolution) with a profile based on climatology. We could also use ozone estimates from TOMS (Total Ozone Measurement System) although they would not be coincident in space and time with the ASTER measurements as is the ozone amount determined from MODIS measurements. In addition, NOAA EMC regularly produces a stratospheric ozone profile product, which could be used. As a backup, if no ozone estimates are available from the same time period as the ASTER measurements, we will use a climatology based on the extensive record from TOMS, SBUV and SAGE.

3.2.3 Aerosols

Like ozone, aerosols will not often limit the accuracy of the atmospheric correction. However, during episodes of high volcanic aerosol loading, they will have an important impact on the radiometry. Both MODIS and MISR plan an extensive set of aerosol data products. We plan to use the MISR data product MIS05(#2299) Aerosol Optical Depth (17.6 km spatial resolution) to establish the amount of aerosol present. The aerosol composition and particle size distribution will be obtained from the values used by MISR to estimate the optical depth or from the MODTRAN model based on the geographic location of the ASTER scene. The MODIS data product MOD04(#2293) Aerosol Optical Depth, Spectral, is a backup available over some land areas and the oceans. In the absence of the MISR or MODIS product over land we will develop a compendium of profiles as a function of time of year and geographic location.

3.3 Adaptation of the Input Parameters to MODTRAN

All the primary atmospheric information needed for the calculation of the atmospheric correction with MODTRAN, including surface elevation, will be available only at a resolution lower than the ASTER TIR's 90 m pixel (although ASTER itself will produce elevations on a finer scale, they will not in general be available in time for the use in the atmospheric correction calculation, so that other, lower resolution elevation sources must be used instead). Although we intend to try several approaches, our current thinking is to interpolate the atmospheric information to a uniform grid (for example, 15 km grid point spacing) across an ASTER scene (60 x 60 Km). The atmospheric correction would then be calculated for each grid point for several elevations representative of the surrounding terrain. The correction appropriate for each pixel will be obtained by a space interpolation from the surrounding grid points. The selection of the grid spacing will be based on keeping the interpolation error to an acceptable level without requiring an excessive number of MODTRAN executions.

The primary sources of the input data used for each ASTER scene will be identified with metadata entries so the user will be able to obtain a record of the sources along with the atmospherically corrected ASTER data itself.

3.4 The Sensitivity of the Derived Radiance to Error in the Input Parameters

3.4.1 Profiles for Temperature, Water Vapor, Ozone and Aerosols

The accuracy of the atmospheric correction method proposed depends on the accuracy with which the primary input variables can be determined and the sensitivity of the correction to the uncertainty in these input variables. The primary input variables are atmospheric profiles for temperature, water vapor, ozone and aerosols. The sensitivity of the atmospheric correction to uncertainties in the input variables depends on both wavelength (channel integrated values) and the base value for the input variables.

Estimates for this sensitivity were developed using the LOWTRAN 7 radiative transfer model and three of the atmospheres included with LOWTRAN 7 (Kneizys et al., 1988). The atmospheres used were Midlatitude Summer (air temperature at the surface 297.2 K, 2.35 g cm^{-1} column water amount, 0.332 atm cm total ozone and a “visibility” of 25 km); Tropical (air temperature at the surface 302.7 K, 3.32 g cm^{-1} column water amount, 0.277 atm cm total ozone and a “visibility” of 25 km) and Subarctic Winter (air temperature at the surface 257.2 K, 0.33 g cm^{-1} column water amount, 0.376 atm cm total ozone and a “visibility” of 25 km). The sensitivity for each variable, model atmosphere and wavelength was determined by entering a small change in the base value of each of the four primary variables, one at a time, and noting the corresponding change in the calculated radiance. The sensitivity in each of the ASTER channels was obtained by weighting the wavelength dependent sensitivities with an estimate of the expected spectral profile for each ASTER channel.

To illustrate the relationship between uncertainty in the input parameters and the uncertainty in the derived radiance (or its equivalent in brightness temperature) the following uncertainties will be used: 1. Water vapor, 20%, a number near the upper limit accuracy estimate for the MODIS column water vapor abundance determined from thermal infrared measurements (MOD38, #3725, P. W. Menzel); 2. Atmospheric temperature, 0.5% (i.e. ~1.5 K), the largest number associated with MODIS atmospheric temperature profile (MOD30, #3726, P. W. Menzel) which is in the range estimated for northern hemisphere numerical forecasts of order 1-2 K (Kalnay et al., 1990); 3.&4. For ozone and aerosols (expressed as visibility, which is one way aerosol amount is expressed in the LOWTRAN 7 model) the uncertainty was taken as 50% to illustrate the low sensitivity to these variables. The results for three of the five ASTER channels in both radiance and brightness temperature are given in Table 2 for the two most sensitive atmospheres.

Because of strong water vapor absorption below 8 µm, ASTER channel 10 is about twice as sensitive to uncertainties in both atmospheric water vapor and temperature as any of the other four channels. Channel 12 is the most sensitive to uncertainties in ozone because of the presence of part of the 8.5 to 10 µm complex of ozone bands in this channel. Gross errors (25% in column abundance) in ozone will lead to errors of significance (greater than the instrument's NEΔT) for channel 12. Aerosols have some impact on all five channels. The 50% uncertainty used here for visibility could be exceeded if it is necessary to use a climatology based estimate for aerosols. For example, this could happen if a version of SAGE were not in operation and the stratospheric aerosol amount increased due to a volcanic eruption. Increases in tropospheric aerosols will be measured by MISR. The difference between a vertical distribution and an aerosol abundance is not of major importance since the corrected radiance is relatively insensitive to tropospheric aerosols.

Table 2 Percent Change in Derived Radiance as a Function of Percent Change in Input Parameter

Input Parameter	% Change in Input Parameter	% Change in Derived Radiance* for Tropical Atmosphere			% Change in Derived Radiance* for Midlatitude Summer Atmosphere		
		Channel 10	Channel 12	Channel 13	Channel 10	Channel 12	Channel 13
Water Vapor	20	4.4 (2.2)	1.8 (1.0)	2.2 (1.5)	2.3 (1.5)	0.9 (0.5)	0.9 (0.6)
Atmospheric Temperature	0.5	-3.5 (-1.8)	-1.5 (-0.9)	-1.7 (-1.1)	-2.3 (-1.2)	-0.9 (-0.5)	-0.9 (-0.6)
Ozone	50	0.2 (0.1)	1.1 (0.6)	0.1 (0.1)	0.1 (0.1)	1.1 (0.6)	0.1 (0.1)
Visibility (Aerosols)	50	0.2 (0.1)	0.4 (0.2)	0.4 (0.3)	0.1 (0.1)	0.5 (0.3)	0.4 (0.3)

* Numbers in parenthesis ( ) are the changes in derived brightness temperature (K) which are equivalent to the percent change in derived radiance.

The simple sensitivity analysis presented here deals with errors that are biased consistently in one direction throughout the profile. As such, they should produce the largest error in radiance for a given assumed percentage error in one of the input variables. In practice the error may vary with altitude, assume either sign within a given profile and the error from one source may partially balance that from another source. Note in Table 2 that overestimates of atmospheric water vapor and temperature result in errors with opposite signs. The large number of parameters, in excess of 150, which are necessary to set up an atmospheric model in MODTRAN are correlated or anticorrelated to varying degrees in ways that are difficult to unravel. It may be that "standard" errors will be considerably less than the 'maximum" errors that result from adding everything with the same sign.

Keeping the surface radiance error associated with error in the estimated water vapor and temperature profiles below the 1 K accuracy of the ASTER instrument itself will difficult for warm humid atmospheres.

3.4.2 Elevation

Elevation errors contribute to the error in atmospheric correction. Here, we define the elevation error as the difference between the average elevation of the pixel of interest and the elevation used for that pixel in computing the atmospheric correction. An elevation error can occur either because there is a vertical or horizontal error in the elevation model being used or because the pixel of interest is incorrectly located with respect to the elevation model.

The magnitude of the resulting error in the atmospheric correction depends on the atmospheric profile (e.g. the amount of water vapor in the profile), the elevation of the surface, the surface temperature and the ASTER channel being corrected.

To obtain examples of the magnitude of the atmospheric correction error in relation to the size of the altitude error, the atmospheric correction error was calculated for: five representative atmospheric profiles, all five ASTER TIR channels, every hundred meters from sea level to 5.8 kilometers assuming in each case the altitude error was 100 meters. The maximum error occurs in the shortest wavelength ASTER TIR channel, channel 10 and is 0.28 K in brightness temperature. The maximum error in the least sensitive channels (12 and 13) is 0.08 K. Although the atmospheric correction error is not strictly linear with elevation error, (the maximum error is about 0.3 K per 100 meters of elevation) the linear assumption is reasonably close for elevation errors up to several hundred meters.

Currently the only global digital elevation model (DEM) which is available is ETOPO5 (Gesch, 1994) which has elevations posted every 5 arc minutes (approximately 10 kilometers). This spacing is too coarse to be used with 90 meter ASTER TIR pixels. The EOS Project has developed a plan to provide, by 1998 (and this product is now available for general distribution by the EDC), a near-global DEM with 30 arc second (approximately 1 kilometer) postings based on the Digital Chart of the World (DCW) and other sources (Gesch, 1994) and is examining providing data at 3 arc second (approximately 90 meters) postings based on the Defense Mapping Agency's (DMA) Digital Terrain Elevation Data (DTED) (Gesch, 1994). Through the Land Processes DAAC (LPDAAC) at the Eros Data Center, where ASTER Level 2 data products will be created in the United States, an arrangement with DMA is being explored which would allow atmospheric correction to be conducted using DTED where it is available. In examining the effect of elevation errors on atmospheric correction, the properties of the DCW and DTED will be used as these elevation models will likely provide the core of the elevation data available for use at least at the start of the TERRA platform mission.

The properties of the DCW and DTED of interest are some measure of the size of uncertainty both horizontally and vertically. Information on these quantities can be found in Gesch, 1994. The stated horizontal accuracy for the DCW is 2,000 meters circular error at 90% confidence and the vertical accuracy is _650 meters linear error at 90% confidence. Where these accuracies have been checked against other sources of topographic data (e.g. the DTED) the horizontal accuracy was about 600 meters and the vertical accuracy about 100 meters at 90% confidence (Gesch, 1994). For the DTED the corresponding accuracies at 90% confidence are horizontally 130 meters and vertically 30 meters. Both the DCW and the DTED contain artifacts that can appear as artificially steep slopes.

In addition to the horizontal and vertical errors in the elevation models, the horizontal uncertainty in the location of an ASTER pixel also contributes to the error in the estimate of the pixel's elevation. This error can almost entirely be removed (to the level of a fraction of a pixel) by using ground control points, but current estimates of the number and coverage of ground control points available, indicate only a small fraction of ASTER scenes will be able to use such control. Without ground control the pixel geolocation knowledge is estimated as 342 meters 3 sigma with almost all the of this uncertainty associated with the 90 arcseconds of pointing knowledge uncertainty.

In terms of atmospheric correction errors, the DCW is dominated by the vertical error (650 meters) if the stated errors are accepted and the induced horizontal error (about 600 meters) if the comparisons are accepted. For ASTER channel 10, the most sensitive channel, an elevation error of 650 meters would translate into the equivalent of a brightness error of 1.8 K for the most sensitive atmospheric profile examined. The associated brightness temperature error for a horizontal error of 600 meters depends on the slope of the terrain with a slope of 30 degrees leading to an a brightness temperature error of 0.8 K. For the DTED the atmospheric correction error is dominated by the uncertainty in the location of an ASTER pixel relative to the elevation data. The associated brightness temperature error for a horizontal error of 342 meters in channel 10 with the most sensitive atmospheric profile examined on a 45 degree slope is 0.5 K.

Because the tests conducted with the DCW indicate the vertical accuracy may be closer to 100 meters that the stated accuracy of 650 meters, the horizontal error either in the elevation data or the location of an ASTER pixel may be dominant in determining the vertical error both for the DCW and the DTED. In this case the question concerns the slope distribution for the land area of the earth at the scale of and ASTER pixel. Such information is not yet available for complete continents. Some studies of smaller areas have been conducted which provide some insight into the slope distribution at spatial scales appropriate to ASTER TIR measurements. Recently a study of the Tibetan plateau (an area nearly 3500 by 1500 km) using DTED elevation information has been conducted which includes slope information (Fielding et al., 1994). Slope information was calculated across this area using 4 X 4 point windows that were fitted to a plane using a least squares procedure. The long dimension (North/South) of these planes is about 280 meters. A least squares fitting was used involving 16 elevation samples to minimize the impact of topographic artifacts in the resulting distribution. For the Tibet slope sample about 0.5% of the area has slopes are greater than 45 degrees and for 6.8% of the area the slopes are greater than 30 degrees (Fielding, 1995. personal communication). The DTED has also been used to assess the performance of satellite laser altimetry for a 200 meter footprint (Harding et al., 1994). Nine different terrain types were examined for areas 1 degree by 1 degree in latitude and longitude using a 3 X 3 point window and a least squares procedure providing a scale length of about 186 meters. For the highest relief area (“convergent mountain front”) examined, about 8% of the surface exhibited slopes greater than 30 degrees in the North-South direction with similar values for the East-West direction. (Harding et al., 1994). At the scale length (90 meters) of ASTER thermal measurements steeper slopes will be more prominent.

For the majority of the earth’s surface the existing sources of topographic information (i.e. DCW and DTED) should result in elevation related atmospheric correction errors which are less than a few tenths of a degree Kelvin for the most sensitive ASTER Channel and atmospheric profile (e.g. for the Tibetan region, 50% of the area has slopes less than about 3 degrees (Fielding, 1994)) . In steep terrain (slopes greater than about 30 degrees) it is likely the positional accuracy of both the elevation model and the ASTER pixels will determine the size of the atmospheric correction error and this error could be more than a degree Kelvin in unfavorable cases. Two additional points are also inherent in using an atmospheric profile based atmospheric correction algorithm. First, this method is sensitive to artifacts in the topographic model used. Since global topographic data sets are necessarily large and have been compiled from a variety of sources artifacts are inevitable. It is important to understand and remove these artifacts, where possible, as they will impose systematic position based errors on the atmospherically corrected brightness temperatures. Second, topographic errors are not spectrally neutral across the five ASTER thermal channels. Methods which use the spectral contrast across these channels to extract additional information should, at a minimum, take into consideration the systematic effect topographic error will have on atmospherically corrected ASTER thermal data.

3.5 Calibration and Validation

3.5.1 Pre Launch

The pre launch validation of the ASTER TIR atmospheric correction algorithm involves three major elements: The atmospheric radiative transfer model, the input data and their interpolation within an ASTER scene, and the production algorithm and its operation at the Land Processes DAAC (LPDAAC).

The radiation model selected, MODTRAN, is widely available and used and has an active group supporting improvements (MODTRAN3 final has recently been released). We will maintain communication with the MODTRAN developers and pay attention to discussion on its use in papers, meetings and reports. We plan no substantial theoretical or experimental test of its validity. We do plan end-to-end tests of the atmospheric correction algorithm but our understanding of the accuracy of the radiometers we will use to generate this test data, and the accuracy with which we can characterize the atmosphere are sufficiently poor that they cannot fairly be considered a rigorous test of the radiation model itself.

The development of a production version of the atmospheric correction algorithm will be implemented through a series of increasingly complete steps (a beta version and versions 1 and 2). The beta version was delivered to the LPDAAC at the beginning of 1996 with the following versions delivered at roughly yearly intervals. Each of these deliveries will be accompanied by a set of test data that is to be used to verify the algorithm runs properly at the DAAC. Each delivered version will be more complete with respect to the number of input data sets it can accommodate. Spatial and temporal interpolation within the input data sets (e.g. elevation, profiles of atmospheric temperature, water content, ozone and aerosols) will be conducted so as to minimize the resulting interpolation error in the correction, consistent with placing realistic limits on the number of computations required.

In addition to the generation of synthetic data sets to test the algorithm we will also acquire and use samples of all the input data sets in order to better understand the error and artifacts they may contain. We will also acquire aircraft scanner data and make the necessary atmosphere and surface measurements to conduct end-to-end tests of the correction algorithm. We plan to use the NASA Thermal Infrared Multispectral Scanner (TIMS) for this purpose and hope to be able to use data from the scanners and spectrometers to be used in the MODIS, TES and AIRS algorithm development. A joint field exercise at Railroad Valley and Lunar Lake Nevada was conducted in June 1996 with members of the ASTER, MODIS and MISR teams involving the aircraft scanners TIMS, MODIS Airborne Simulator (MAS) and the ASTER Airborne Simulator (AAS).

3.5.2 Post Launch

The inflight calibration of the ASTER TIR subsystem and the validation of the atmospheric correction algorithm are intimately connected in that correction for the atmospheric transmission and path radiance is necessary before surface or near surface radiance measurements can be compared to those at the sensor. The instrument calibration activity will be a joint effort involving members of the Japanese and American science team. Water targets will form an important part of the instrument calibration effort as the emissivity of water is known, the temperature of large areas, compared to an individual ASTER pixel, can be determined with a minimum number of measurements and the temperature changes slowly enough that the measurements can be completed before the water temperature has significantly changed. High altitude sites will be used to minimize the size and error associated with the atmospheric correction. Land surface targets may be used to estimate the high and low temperature calibration of the instrument along with cloud top temperature estimates and comparisons with thermal measurements from MODIS. The emissivity of land surface targets will be determined with a field portable spectrometer and both broad band and ASTER bandpass radiometers will be used to established the surface brightness temperature and radiance. If we are successful in establishing the accuracy of the inflight calibration of the NASA aircraft scanner TIMS (Thermal Infrared Multispectral Scanner), we will use a radiance calibration method in which the only correction for the atmosphere that is necessary is for the atmosphere above the aircraft.

Once the calibration and calibration uncertainty has been established the same basic measurements used to establish the instrument calibration will be used to validate the operational version of the atmospheric correction algorithm. In addition, water targets spanning a range of latitude and season will be used to establish the quality of the correction method across a range of atmospheric temperature and water vapor profiles. Multiple radiosonde launches will be used to provide control for the atmospheric temperature and water vapor profiles and sun photometer measurements will be used to provide aerosol optical depth information and total column water abundance as a check on the radiosonde water vapor profiles. The measured and calculated brightness temperatures (or radiances) will be compared and the field measured atmospheric parameters will be compared with those used in the operational algorithm calculation to understand differences between the field and ASTER derived brightness temperatures. On a regular basis, as a part of data quality control, the spectral brightness temperature of non-instrumented water targets will be examined along with the corresponding atmospheric profiles to look for spectral biases between channels and regular comparisons over the same targets will be made with MODIS thermal measurements.

3.5.3 Formal Validation Plan

For the previous revision of this Algorithm Theoretical Basis Document (Revision 2, 16 August 1996) the EOS Validation Scientist requested the document contain an expanded validation plan following a prescribed outline. Section 3.5.3 is that plan for the TIR land leaving surface radiance product. This validation plan has three components: 1) *In situ* measurements of water targets by the algorithm developers, 2) Cross comparisons with equivalent MODIS channels across a wide range of atmospheric conditions as a consistency check and 3) Using *in situ* measurements from non-ASTER investigators. The overall validation objective is to 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.

Following completion of the second revision of all the ASTER ATBDs, the individual data product validation plans were collected in a single document to form the ASTER Validation Plan (see http://asterweb.jpl.nasa.gov for a copy). As a result this section (3.5.3) is somewhat redundant with material already presented.

3.5.3.1.1 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.

3.5.3.1.2 Missions

ASTER is scheduled to fly on the TERRA platform with a launch in the summer of 1999. ASTER will not fly on any of the subsequent AM or PM platforms. The design life of the instrument on orbit is five years but the design is such that, with attention to life limiting elements, ASTER should be able to produce data for the six year life of the Terra platform.

3.5.3.1.3 Science data products

The Level 2 science data product to be validated is the surface leaving spectral radiance in the five ASTER 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.

3.5.3.2.0 Validation criterion

3.5.3.2.1 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.

3.5.3.2.2 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.

3.5.3.2.3 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.

3.5.3.3.0 Pre-launch algorithm test/development activities

3.5.3.3.1 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.

3.5.3.3.2 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.

3.5.3.3.3 Existing satellite data

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

3.5.3.4.0 Post-launch activities

3.5.3.4.1 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.

3.5.3.4.2 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 June 1996 an EOS joint validation/calibration field campaign was conducted and its results may solidify support for related joint activities in the post-launch time period.

For ASTER the critical component for validation is estimating the kinetic or radiating temperature of an area of 3 x 3 ASTER pixels (270 x 270 m). It is likely that only ASTER team members would be willing to undertake such an activity lowering the value of coordinated campaigns.

3.5.3.4.3 Needs for other satellite date

Only data from the TERRA 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.

3.5.3.4.4 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

TERRA 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.

3.5.3.4.5 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. If approved, this scanner, currently called the MODIS ASTER simulator (MASTER), would be available before or near the time of the launch of the TERRA platform.

3.5.3.4.6 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.

3.5.3.4.7 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.

3.5.3.5.0 Implementation of validation results in data production

3.5.3.5.1 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).

3.5.3.5.2 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 5.1 to interested users in electronic form.

3.5.3.5.3 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

3.5.3.6.0 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.

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