GROUND-LOOK RADIOMETRIC CALIBRATION APPROACHES FOR REMOTE SENSING IMAGERS IN THE SOLAR REFLECTIVE

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ABSTRACT:

Since the early 1990s, the availability of remote sensing imagery in the solar reflective (400 to 2500 nm) has seen a dramatic increase. Airborne- and satellite-based sensors now cover this spectral range with a variety of spectral resolutions (from the multispectral to hyperspectral) and spatial resolutions ranging from better than 0.3 m for some airborne systems (and better than 1 m for satellite-based sensors) to 1 km. A critical component to the successful use of data from these systems is the pre-flight and in-flight radiometric calibration of the sensors. This paper provides an overview of currently-used calibration approaches for the inflight calibration using terrestrially-based sites. These methods are colloquially known as vicarious calibration and, alternatively referred to as radiance validations. This discussion focuses on reflectance-based and cross-comparison approaches that can be used at a range of spatial and spectral resolutions. An example of the application of the in-flight and pre-flight calibrations is demonstrated showing results from ALI, ASTER, Hyperion, ETM+, Ikonos, and MODIS.

1. INTRODUCTION

The longest continuous data set of high-spatial-resolution imagery dates back to the launch of Landsat 1 in 1972 through the current data sets from both the Thematic Mapper (TM) on Landsat 5 and the Enhanced Thematic Mapper Plus (ETM+) on Landsat 7. A key element to the use of the Landsat data is the knowledge of the radiometric calibration of the sensors, both due to preflight efforts in the laboratory and postlaunch data (Thome et al., 1997). The radiometric calibration of these systems not only helps characterize the operation of the sensors, but, more importantly, this calibration allows the full Landsat data set to be used in a quantitative sense for such applications as land use and land cover change.

One of the reasons for the successful postlaunch radiometric characterization of Landsat sensors has been the fact that the calibration has relied on multiple approaches including onboard calibrators and vicarious approaches. Here the term onboard calibrator refers to any device that is on the platform or part of the sensor that supplies a known output for the sensor. Vicarious calibration refers to any approach that does not rely on an onboard calibrator. Landsat-7 ETM+ provides an excellent example of a multiple-approach philosophy with three separate onboard calibrators. The first two are based on designs from previous Landsat sensors and are based on a direct solar look and a lamp-based source. The third on-board calibrator is a full-aperture, full optical path solar diffuser approach that is new to Landsat (Barker, et al., 1999). Incidentally, ETM+ marked the first implementation of a spaceborne diffuser for absolute radiometric calibration of a high-spatial-resolution sensor, though lower spatial resolution sensors, such as the Sea Viewing Wide Field of View Sensor (SeaWiFS), have used this approach previously with good success (Barnes et al. 1999).

The primary advantage to on-board calibrators in the past has been that the calibration could be performed with high temporal frequency. For the whiskbroom designed sensors of Landsat, this meant calibration information as frequently as every scan line. The use of lamp-based approaches for pushbroom sensors, such as the Haute Resolute Visible (HRV and now HRVIR) cameras that are part of the System Pour l'Observation de la Terra (SPOT) program does not allow calibrations as frequently as a whiskbroom sensor, but there are still sufficient data sets to allow an accurate trend analysis (Gellman et al., 1993). In theory, the use of an onboard lamp in a pushbroom sensor allows calibration to occur prior to every data collection, but this must be weighed against the loss of data that is incurred while the sensor is viewing the lamp rather than the surface of the earth.

The partial aperture solar calibrator and full aperture diffuser on ETM+ can provide data once per orbit, however the full-aperture solar calibrator on ETM+ is used only approximately once per month to prevent degradation of the diffuser. Thus, these more recent approaches imply that calibration data are provided less frequently than the older approach of lamp-based calibrators coupled with scanning systems. While this lack of frequency is not desirable, the onboard systems still have good precision.

This high precision is an outcome of the fact that the stability of lamps and diffusers over several days is quite small. In the case of the IC for Landsat, the lamps are stable enough to allow examination of within scene variability of detectors. This short-term stability means that the precision of the onboard calibration approaches is quite good. However, one thing that must be kept in mind regarding the on-board calibrators, is that they cannot provide a calibration that is of higher accuracy than the preflight, laboratory calibrations. That is, the accuracy of the in-flight, absolute calibration must be worse than the preflight calibration, since the preflight calibration source is often used to calibrate the on-board calibrators or the onboard calibrators suffer from unknown degradation as a function of time.

Thus, there is a good justification for including calibration approaches that are independent of the preflight calibration. Many methods have been proposed and used for the in-flight radiometric calibration of satellite sensors using vicarious approaches. Hovis et al. (1985) made one of earliest attempts at vicarious calibration by measuring radiances above a ground target from a high-altitude aircraft to verify the degradation of the response of the Coastal Zone Color Scanner's shorter wavelength bands.

Since this early work, many types of vicarious calibration have been developed that do not require such in situ measurements. Kaufman and Holben (1993) developed a method using large-view angles and molecular scatter to characterize the short-wave, visible channels of the Advanced Very High Resolution Radiometer. Vermote et al. (1992) used a similar approach to calibrate the short-wavelength channels of SPOT-1 HRV sensor where the contributions from aerosols and sea-surface reflection were determined from data at longer wavelengths. Cosnefroy et al. (1996) assumed that test sites in desertic regions are invariant targets and thus provide a well-understood ground target of known radiance. If absolute accuracy is not a requirement, but only interband relative calibration is critical, then approaches using clouds and sun glint have been shown to be successful (Kaufman and Vermote, 1995, Hagolle et al., 1996). In all of these approaches, a calibration of the sensor can be determined without the need for any ground-based or ocean-based measurements in conjunction with the sensor overpass. Because the above approaches rely on assumptions based on climatology, the results of these methods can suffer from larger uncertainties than those using in-situ measurements. On the otherhand, the lack of requirement of in-situ data means that the methods can be applied at much greater frequency and this can serve to reduce the effect of outlying data points. A more recent approach using no in-situ measurements, to the chagrin of some scientists, are lunar-based calibrations. Several sensors are now using the moon in a relative sense for calibration and will soon move towards using it as an absolute standard (Barnes et al., 1999, Kieffer and Wildey, 1996)

In the late-1980s, the Remote Sensing Group (RSG) at the University of Arizona developed three vicarious techniques of absolute calibration that rely on in-situ measurements. These methods are referred to as the reflectance-, irradiance-, and radiance-based techniques (Slater et al., 1987, Biggar et al., 1990). The advantage of these approaches is they can supply an absolute radiometric calibration independent of the preflight and onboard calibrations. In the past, these methods have suffered to a degree from a lack of precision as well as low frequency of data collections. More recent work by the RSG which is summarized here has shown that it is feasible to produce results at a frequency that often rivals that of the solar diffuser approaches and with precision that is approaching 2% in some bands and cases.

This work describes the current approach by the RSG for reflectance-based and cross-comparison calibrations. The approaches described here are suitable for both large spatial footprint sensors (such as the 1-km scale of MODIS) and the higher spatial resolution sensors such as Ikonos. The methods are also suitable for both multispectral and hyperspectral sensors. The paper begins with a description of the reflectance-based approach followed by the cross-comparison method. Desired test site characteristics are given next and a set of minimum recommended measurements is included based on past work by the RSG. Finally, examples of recent results for several sensors are given demonstrating the current status of in-situ vicarious calibration approaches.

2. REFLECTANCE-BASED APPROACH

This section gives details of the reflectance-based method currently used by the RSG. The four subsections describe the basic parts of this approach. Essentially, the approach relies on measurements of the surface reflectance of a test site at the time of sensor overpass. Concurrent with the reflectance measurements are atmospheric measurements and the results of both the surface and atmospheric characterization are used as input to a radiative transfer code to predict at-sensor radiance. The at-sensor radiance is then compared to the sensor output to provide the calibration.

2.1 Surface reflectance retrieval

The reflectance-based approach relies on ground-based, surface reflectance measurements of a selected site. For ETM+ this site is a rectangular area that is 480 m × 120 m with the long side of the site oriented approximately in the along-track direction of Landsat-7. This ensures that all 16 detectors are sampled for ETM+ and gives four samples for each detector (a total of 64 pixels). For pushbroom sensors the site is orthogonal to the "Landsat" site and is 300 m × 80 m. The smaller size of the pushbroom site (colloquially known in the RSG as the SPOT/ASTER site) dates to the original work for the HRV cameras on SPOTs 1-3 with 20 m spatial resolution of the multispectral camera. The original size was selected to give a similar 64 pixels, but was reduced by 20 m to better match the 15-m resolution of the VNIR bands of the Advanced Spaceborne Thermal Emission and Reflection radiometer (ASTER). This pushbroom site is also used for more recent "hyperspatial" sensors such as Space Imaging's Ikonos sensor. In addition, the RSG has begun measurements of 1 km^2 areas for use with large footprint sensors. The size of the site and ground-sampling within it is a compromise between sampling a large enough area of the ground to provide adequate data for a sufficient number of detectors yet small enough that the site can be covered in a reasonable amount of time. Time periods in excess of one hour tend to suffer from changes in atmospheric illumination, solar angle effects, user fatigue, and instrument power limitations.

To obtain the reflectance of the test site, a spectroradiometer is transported across the entire site. The primary instrument for the surface-reflectance collection is a commercially-available spectrometer that gives 1.4-nm spectral resolution from 350 to 1000 nm and 10-nm resolution for the 1000-nm to 2500-nm spectral range. The output is interpolated within the data collection software to report results at a 1-nm spacing across the entire spectral range. The instrument is transported across the site using a backpack device that extends the instrument away from the body of the user and raises the foreoptics to a height of as much as 2 m above the ground. An 8-degree field of view is used for the measurements giving a circular sample on the ground of approximately 0.3 m diameter. A larger field of view gives better spatial sampling but is more susceptible to surface bi-directional reflectance effects. A smaller field of view forces a longer integration time, and thus longer time to measure the test site.

The user in the case of the Landsat and ASTER sites walks a path parallel to the cross-track direction of the sensor through the center of the four cross-track pixels. In the RSG's approach, the user collects data continuously while walking with the foreoptic pointed in the nadir direction. This means the data are susceptible to movement of the foreoptic, both vertically and in angle, but also allows for further spatial sampling. This approach is done for all of the cross-track paths. In the case of the Landsat site, this approach samples 2.5% of the site. For the 1 km^2 site a different sampling strategy is employed in which a plus sign is walked within the area giving a total of eight 500 m paths with the paths in similar directions separated by 100 m. For this type of site, only 0.12% of the surface area is measured. The time to measure each site is 30-65 minutes.

The critical aspect to this approach is that the surface measurements are not made in an absolute mode, but rather are made with reference to a panel of known reflectance. Measurements of the reference are made at the start and end of the data collection, as well as after every 8 pixels for the smaller sites (approximately every 5-8 minutes) and after every 1 km walked for the large-footprint site (approximately every 15 minutes). This level of sampling reduces the level of uncertainty due to changes in instrument response with time and changing atmospheric conditions, while keeping the data collection time to a reasonable level. Knowing the bi-directional reflectance of the reference allows the reflectance of each sample to be computed taking into account effects due to sun-angle changes and reflectance panel bi-directional reflectance.

It should be clear that a critical part of this reflectance retrieval is the characterization of the reference panel in the laboratory. The calibration of this panel is done with reference to a standard made from pressed polytetrafluoroethylene based on a prescribed approach defined by National Institute of Standards and Technology (NIST) (Biggar et al., 1988). 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 field standard for the sun-view geometry and wavelengths for a given set of field measurements (Biggar et al., 1988). Ignoring the BRDF effects of the reference can cause as much as a 5% error in the calibration of the satellite sensor (Thome et al., 1998).

2.2 Atmospheric Characterization

Atmospheric characterization data are collected at the same time as the surface reflectance measurements. This characterization relies on solar extinction measurements from a ten-band solar radiometer. Data are used in a Langley method retrieval scheme to determine spectral atmospheric optical depths. The optical depth results are inverted to determine ozone optical depth and a Junge aerosol size distribution parameter. 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 is derived using a modified Langley approach.

2.3 Radiative Transfer Code

The atmospheric and surface data are used in a radiative transfer code that computes hyperspectral, at-sensor radiances (Thome et al., 1996). The code is based on a Gauss-Seidel iteration radiative transfer code to predict the top-of-the-atmosphere radiance taking into account weak ozone absorption. Strong gaseous absorption effects due to water vapor are determined using MODTRAN3.5 to compute transmittance for the sun-to-surface-to-satellite path. This sun-to-ground-to-sensor transmittance is multiplied by the at-sensor radiance from the radiative transfer code to correct for strong absorption.

The relative radiances that are the output of the radiative transfer code are converted to absolute radiances by multiplying by a supplied solar irradiance curve corrected for changes in earth-sun distance. Two solar irradiance standards are currently employed by the RSG. The first is from the World Radiation Council selected for NASA's Earth Observing System (EOS) project. The second is based on the Chance/Kurucz model that is part of MODTRAN4.0. These two solar models have significant differences between them that will have to be understood at some time (Thome et al., 2001). In all cases, the RSG takes care to ensure that a solar model consistent with the calibration team of each sensor is used. As long as users take care to do the same and convert data to reflectance, comparisons between sensors should be consistent. Once the at-sensor, hyperspectral, absolute radiances are determined, they are band-averaged across the sensor spectral response.

2.4 Determination of Calibration Coefficient

The final step needed to determine the sensor gain is to compare the digital number (DN) output from the sensor to the predicted radiances. The DN output is determined by averaging the output for all pixels coinciding with the ground measurements. The test site is located through the use of inexpensive, commercially available blue tarpaulins that are placed in at least one corner of the site. In the case of the 1 km^2 area, registration of the imagery to a high resolution image is used to locate the most likely location of the test site. The results from the sensor are then compared to the predicted radiance to determine the calbration of the sensor.

3. CROSS-COMPARISON APPROACH

The cross-comparison approach currently used by the RSG is effectively the same as the reflectance-based. The goal is to derive the surface reflectance for a 1 km^2 area and using this reflectance as an input to a radiative transfer code, along with the coincident atmospheric data, allows a prediction of the at-sensor radiance. The key difference is that rather than basing the surface reflectance on ground-based measurements, the surface reflectance is derived from data from a well-understood sensor. The first step is to select the test site common to the two sensors to be compared. Ideally, the data from both sensors would be coincident in time with identical view and solar geometries. The sensors being studied by the RSG at this time have near-coincidence in view geometry and only 40 minutes being the largest separation in time between any two sensors. The test site is then located in the reference image and the at-sensor radiance is determined for all bands using the best known calibration information.

An atmospheric correction is applied to the data to determine a surface reflectance for the 1-km^2 area. The correction relies on data from ground-based solar radiometer measurements operated at the time of the overpass of the reference sensor and a simple linear assumption between at-sensor radiance and surface reflectance. Bands affected by strong gaseous absorption due to water vapor are corrected based on column-water vapor derived from the solar radiometer data and the radiative transfer code MODTRAN. If it is assumed that the relationship between reflectance and at-sensor radiance is linear over the surface reflectance range shown, then knowing the at-sensor radiance allows the surface reflectance to be determined by linear interpolation.

The surface reflectance derived from the atmospheric correction are curve fit using the results of ground-based measurements of surface reflectance described above. The curve fit assumes that the shape of the surface reflectance for the 1 km^2 area matches identically that of the ground-based measurements and only the absolute value of the reflectance is not known due to the fact that the ground-based measurements do not coincide with the imagery. The curve fit relies on a multiplicative factor that is altered until the least squares sum of the difference is minimized

At this stage in the process, a hyperspectral reflectance of the 1-km^2 area of the playa is known. Ideally, this reflectance would then be further modified to predict the reflectance for the sun-sensor geometry of each individual sensor using the bi-directional reflectance distribution function (BRDF). Since the test sites used by the RSG are within 2% of lambertian out to view angles as large as 30 degrees, the surface reflectance is assumed constant for all sensors. This reflectance is used as input to the radiative transfer code to predict at-sensor radiance for each sensor in an identical fashion as described above in the reflectance-based approach. This takes into account changes in atmospheric conditions, changes in atmospheric effects due to the specific sun-sensor geometry of each individual sensor, as well as effects due to the changing angle of the incident solar irradiance.

4. TEST SITE CHARACTERISTICS

One of the most critical parts of the RSG approaches is the selection of the test site. This includes both the overall region as well as the specific ground locations being used. For the RSG's work there are several critical characteristics of an ideal test site and in brief, these are (Scott, 1996):

1) A high-reflectance to reduce the impact of atmospheric errors
2) Higher elevation reduces the amount of atmospheric aerosols
3) High spatial uniformity over a large area minimizes the effects of scaling the reflectance data to the size of the full test site
4) Changes with season should be minimal.
5) The site should be nearly lambertian to decrease uncertainties due to changing solar and view geometry.
6) Spectral uniformity of the site is considered important over as wide a spectral region as possible.
7) Accessibility of the site
8) Knowledge of the site based on past work at the site

There is no ideal calibration site that satisfies all of these conditions, but in the Southwestern US 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. The three most widely used of these test sites are given below.

The White Sands Missile Range test site in New Mexico has been in use for vicarious calibration since the mid-1980s. It is located in the desert southwest of the United States in a region of low aerosol loading and an elevation of 1.2 km. The test site used here for ETM+ is commonly referred to as Chuck Site and is located in the alkali flats region. The coordinates of the test site are 32.919 degrees north latitude and 106.351 degrees west longitude. The site is relatively devoid of vegetation, though the area near the site includes regions of greater vegetation and large gypsum dunes. 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. The level of reflectance varies with season with the lowest reflectance values occurring during the winter months when portions of the missile range are either underwater or wet from the higher water table. Highest reflectance values are typically seen in late fall after the surface has dried after summer-season rains. The size of the White Sands area is the largest of the test sites with an overall size of about 50 km.

Railroad Valley Playa is a dry lakebed in Nevada with a composition dominated by clay. The coordinates of this test site are 38.504 degrees north latitude and 115.692 degrees west longitude and it site is located at 1.3 km above sea level between the cities of Ely and Tonopah, Nevada. It is a desert site with no vegetation and aerosol loading is typically low. Railroad Valley Playa is the largest of the playa test sites used by the RSG, but is still about one-fourth of the area of White Sands. While the spectral reflectance of the playa sites is typically lower than that of White Sands, especially in the blue part of the spectrum, the spectral reflectance is reasonably flat throughout the spectral range of ETM+. This site also has its lowest reflectance in the winter months due to a rising water table. The site is also more susceptible to cloudiness than the White Sands site with peak cloudiness in the winter and late summer months.

The Ivanpah Playa test site is at an elevation of 0.8 km located near the California-Nevada border along Interstate 15, which is the major highway between Los Angeles, California and Las Vegas, Nevada. The coordinates of the test site are 35.550 degrees north latitude and 115.388 degrees west longitude. This playa is immediately south of another playa, Roach Lake Playa, that is also used by the RSG. The size of Roach Lake is approximately 3 km × 3 km. This is somewhat smaller than the Ivanpah Playa, which is approximately 3 km × 7 km, hence Ivanpah is the preferred site for the RSG. The spectral reflectance of Ivanpah Playa has a similar spectral shape as that of Railroad Valley, but is significantly brighter than Railroad Valley while darker than White Sands in the visible and near infrared. The reflectance of this playa is quite stable with time except for the few days following heavy rainfall. Ivanpah is more uniform spatially then both White Sands and Railroad Valley. It is also the most easily accessed of the sites being only 15 minutes from nearby hotels. Lunar Lake Playa is an additional site used by the RSG being very similar to Ivanpah except more uniform and brighter. It is only 3 km × 3 km in size and is located a short distance from Railroad Valley. Besides its smaller size, its primary difficulty is that it is frequently underwater during winter months for extended periods.

5. MEASUREMENTS REQUIRED

Experience by the RSG over the past five years has indicated that there are several key factors that will lead to continued improvements in the results of in-situ-based vicarious calibration. Paramount of these is a consistency of a basis set of measurements. This basis set is described here with the purpose of ultimately creating a protocol that can be followed by all groups. This would allow consistent comparisons between results from different groups as well as point to probable bias causes. However, it should be emphasized that the author is not implying that no deviations from these approaches, improvements to equipment, nor inclusion of additional measurements should be avoided. To the contrary, it is these very topics that prevent vicarious data collections from becoming simply routine and leads to improvements.

It cannot be emphasized enough, though, that due to the lack of precision that can affect vicarious calibration and the vagaries of instrumental effects, it is critical that each measurement campaign keep a set of measurements that are consistent from campaign to campaign. Thus, the first recommendation is that groups that are currently collecting vicarious calibration data sets, radiance validation data sets, or validation data in general, should continue to collect data in the manner that they are most familiar. It is also critical that groups maintain this consistency in terms of equipment, processing schemes, and test sites. When any of the three are modified (and they should be from time to time to ensure improvement), there should be a transition period to understand the effects of the changes and, more importantly, provide traceability to the past data sets.

Eventually, groups should migrate to an approach similar to that described above for the reflectance-based approach. While this may appear self-serving, this conclusion and the approach used by the RSG have not been reached lightly. Rather, they are based on nearly 20 years of field data measurements, of which the author has participated in more than 12 years. It has included improvements in field reference standards and equipment, changes in test sites, new satellite sensor technology, and most importantly continual attempts to improve the field measurements of the RSG and processing schemes. Early attempts to improve the measurements served to dramatically improve the accuracy of the data (from uncertainties >5% to values that can hopefully be shown some day to approach 2%) but for which a price has been paid in that older data sets are now obsolete and exist only in the literature in a useful form.

To summarize, the basic measurement set consists of:

1) Surface reflectance characterization referenced to a panel of known reflectance. While sampling strategies are important, work by the RSG has shown that if the sampling creates uncertainties approaching 1%, an alternate site should be selected. That is, site selection is more important than surface reflectance sampling.
2) Solar extinction measurements including bands to allow for ozone and water vapor characterization and sufficient bands to allow retrieval of aerosol optical depth at 550 nm (or some other reference wavelength) and an Angstrom turbidity coefficient. The frequency of the data collection, accuracy of calibration, and specific bands of the radiometer, while important, are again of secondary importance if an appropriately bright site can be located. Surface reflectance in excess of 0.3 will ensure this to be the case for aerosol loadings giving aerosol optical depths at 550 nm less than 0.15.
3) Use of a radiative transfer code including multiple scattering and a method for taking into account ozone and water vapor absorption. It is strongly recommended that users select a radiative transfer code for which they are familiar and understand the codes limitations. This is far more important than selecting the most complicated and accurate code. In other words, an accurate code that is run improperly is far worse than a code with slightly lower accuracy but used properly. In addition, if the site has reflectance greater than 0.3, the selection of radiative transfer code becomes less important.

If the above three requirements are met, the data set collected should be of sufficient quality to allow it to be compared with results from other groups. This is important in that it will increase the level of data sets available, thus increasing the power of vicarious methods. However, if the data sets are of questionable heritage, the results are not useful even if they are extremely accurate.

6. CURRENT STATUS

On the following page is shown three graphs to indicate the current level of vicarious calibration in both accuracy and precision. The first graph shows a time series of the percent difference between the vicarious calibration and preflight calibration of ETM+. The key elements to draw from Figure 1 are that there are no visible trends in the differences between the vicarious and preflight. This lack of a trend has also been verified by the onboard calibrator for ETM+ and other bands show similar results. A second point to notice is that there appears to be a bias between the vicarious and the preflight. Evaluation of atmospheric errors indicates that this cannot be the source of the bias. Rather, it must either be a real bias in the reflectance measurements or in the calibration of the sensor itself. Finally, the last point to note is that while the RSG has prided itself in the past several years on its careful collection approaches, there are still data sets that defy explanation as to why they disagree to a larger extent from the other data sets.

Figure 2 summarizes the results of Figure 1 for all bands plus showing similar results for ASTER and MODIS. Here, all of the results have been averaged and a standard deviation computed. The graph shows the ratio of the reported radiance from the sensor to that predicted by the vicarious results. The results clearly indicate that the bias between the RSG and ETM+ discussed above. In addition, MODIS has a very similar appearing bias. On the otherhand, ASTER appears radically different from the other two sensors. This difference is still under study, but because the standard deviation of the RSG's measurements is in the 2-3% range, it is felt that there are real differences between ASTER and the other two. Note, that no conclusion can be drawn regarding which is correct, only that ASTER differs from the others.

Figure 3 shows the results of comparing the reflectance derived from ETM+ to those from ALI, Hyperion, Ikonos, and MODIS. This figure shows the power of coordinated platforms as well as having a well-understood and stable sensor in orbit. While further work is underway to verify the excellent agreement between the sensors, all of which are within the uncertainties of each separate sensor, the approach clearly has merit and should be useful in attempting to create consistent data sets across platforms and sensors over time.

7. CONCLUSIONS

Recent work by the RSG has indicated that the precision of vicarious calibration by experienced groups can approach 2% at the current time. This level of precision can only be achieved if the users take care to collect a consistent basis set of data for each collection. It is further felt that this precision can be improved through additional field instrument characterization, higher frequency of collections, and separation of results by test site and users. At this level of precision, it will soon be possible to use vicarious approaches for trending purposes as well as for absolute calibration. This will become critical in future years as the trend towards smaller spacecraft will force engineers to begin to explore the possibilities of removing onboard calibration from the sensor and platform.

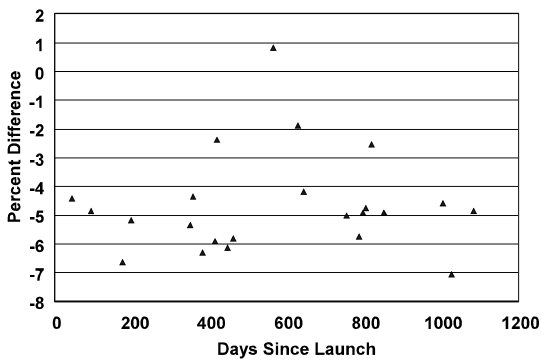


Figure 1. Percent difference between vicarious and preflight results for Band 1 of ETM+ for all data sets collected by RSG.

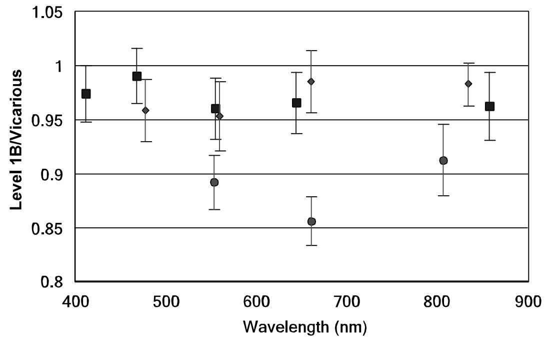
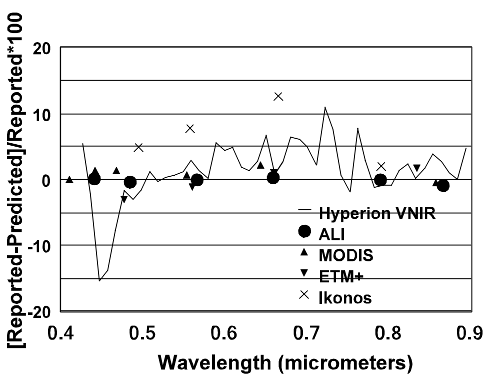


Figure 2. Summary of ASTER (circles), ETM+ (squares), and MODIS (diamonds) results



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