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Non-imaging Airborne Spectroscopy for Calibrating Satellite Imagery

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Abstract

Accurate analyses of satellite-detected data require calibration to ground-surface reflectance to remove effects of atmospheric scatter and absorption. Calibration requires pairing satellite data with reflectance measured near the ground. A non-imaging spectrometer flown aboard a light aircraft is a solution that enables application of the empirical line calibration technique. Collecting spectra by aircraft requires that the data contain geoposition information with the aircraft flown sufficiently low to pair the spectrometer data with the size of the satellite-generated data pixels while minimizing the atmospheric path length between the sensor and the ground—hence, generating quasi-ground level reflectance. Several additional factors must be solved for accurate spectrometer application. These include (i) changes to the aircraft to enable nadir view of the ground, accomplished with simple engineering and installation through the plane's belly, (ii) on-the-fly calibration for changing light quality during the flight, solved by an uplooking Teflon membrane, accessed by fiber optic and a port through the cabin and upper wing section; (iii) spectrometer aiming, a factor of aircraft attitude during data collection that can be solved empirically or mathematically, and (iv) spatial uncertainty for the spectrometer aim point due to uncontrolled aircraft pitch and roll, solved by identification of areas of low variability on the satellite image to be paired with spectrometer data. Although measurement of quasi-ground-level reflectance using this system may be performed at times other than satellite overpass, a crucial consideration is the ephemeral nature of the phenomena that are being investigated.

Acknowledgements

The Owens Dry Lake, in eastern central California, is the single greatest source of fugitive dust in North America and is the subject of a massive control effort. The analyses contained in this paper were performed to ensure accurate measurement for compliance of surface wetting that is the main dust control measure. We thank the Great Basin Unified Air Pollution Control District, in Bishop California and the City of Los Angeles Department of Water and Power for their support in this research and especially Mr. Ted Schade, Air Pollution Control Officer and his capable staff for their continued interest, encouragement and support.

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1. Introduction

For accurate analyses, multispectral and hyperspectral satellite data must be calibrated to apparent reflectance. A crucial step for calculating reflectance is accounting for atmospheric effects on the data. There are multiple methods to do this, all with pros and (often significant) cons. One method, commonly used for multispectral data, is dark object subtraction, "DOS" (Chavez 1996). DOS is image based and requires no field work, but the implementation is subjective, inconsistent, and may in some cases introduce more error than the atmosphere itself (Moran et al., 1992). Another method, often used on hyperspectral imagery, is radiative transfer modeling (Gao et al., 1993). Some examples of modeling programs are ACORN, ATREM and FLAASH. This approach also does not require field work, but may result in poor quality spectra due to mismatch between modeled airmass light-scattering conditions and actual conditions affecting the measurements. A ground truth based empirical line correction (ELC; Smith and Milton, 1999) is the method with which we have had the best results. ELC uses field spectra of large homogeneous ground targets to develop equations that are used to correct raw digital numbers (DNs) to apparent reflectance. ELC gives the best quality image spectra, but, prior to development of these airborne techniques, required field access to large homogeneous light and dark field targets (Clark et al., 1995). This paper describes our efforts to develop an airborne system for application of ELC using an Analytical Spectral Devices (ASD) spectrometer.

For our applications, we have found that the airborne ELC method provides superior results for calibration because it can be rapidly deployed over large areas of the satellite image and provides multiple ELC points to pair and crosscheck the proper calibration for any combination of visible-to-SWIR satellite bands since the ASD spectrometer obtains a continuous spectrum from 350 to 2500 nm.

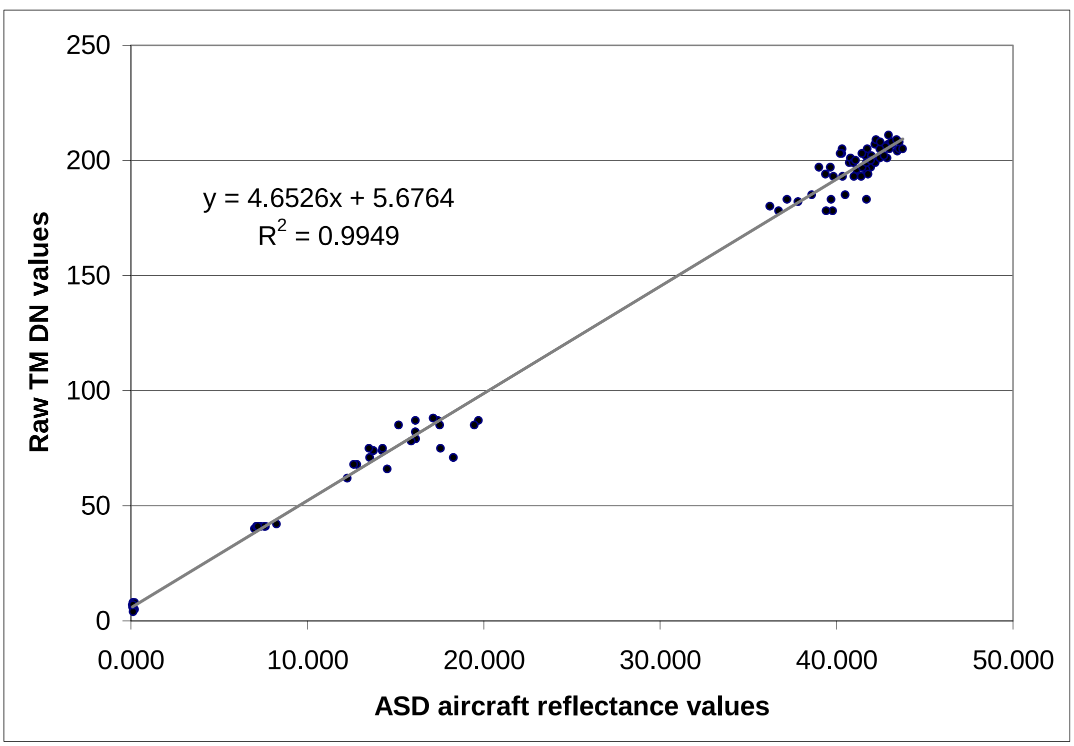
A major challenge to the traditional ground-based method for collecting the field spectra necessary for using the empirical line correction is identifying and then accessing appropriate sites. An effective method for overcoming spatial uncertainty is to select sites within areas of spectral homogeneity with a scale of multiple pixels. Often such homogeneous areas are difficult to find within potentially large regions of satellite imagery and, in some cases impossible to identify, a priori, from the satellite imagery, or while "in the field". Correctly paired spectra and satellite pixels are also highly dependent upon the rate at which the target phenomena change (e.g., a clear water body becoming turbid).

To streamline acquisition of target spectra in the field, we have adapted a non-imaging field spectrometer to take spectra from a specially-equipped light aircraft. This platform allows rapid access to nearly all regions in the satellite image. Spatial uncertainty with geocorrection of satellite imagery combined with the spatial uncertainty induced by aircraft pitch and roll also required development of special image processing techniques to ensure the proper pairing of targets between airborne spectra and corresponding satellite-generated pixels.

While airborne hyperspectral imagers are available, they are far more expensive to mobilize than utilizing ground-truth corrected satellite data. We have found that for environmental monitoring, even with relatively large pixels and multi-spectral limitation, satellite data fvrom existing sources still tends to perform well. Compared to airborne hyperspectral imagery, satellite data requires less computer resources for manipulation, less time for geocorrection and, given the long-term library of potential images (e.g., the over 20-year record provided by Landsat TM), offers the potential for historic evaluation if calibration questions can be solved.

ELC assumes a linear relationship between reflectance at the satellite and on the ground (Smith and Milton, 1999). This is the technique that we advocate using with aerial spectrometry because the resulting data sets offer excellent opportunity to pair areas of homogeneity on the satellite image with points acquired by the spectrometer. Since the spectrometer may be flown relatively close to the ground (say 500 to 1000 ft altitude), under most conditions, the path length through the atmosphere is negligible. Figure 1 presents an empirical data plot that shows that the assumed empirical line is truly a line (Baugh and Groeneveld, paper in preparation). Because of the well-behaved linear relationship, a single good match between spectrally homogeneous locations on the satellite image can provide the relationship needed for calibration. It must be remembered though, that an area that is homogeneous in one spectral region may not be so in another.

Figure 1. Empirical proof of the empirical line obtained for TM band 5 (TMB5) over Owens Lake, California. The satellite data are from 04-08-06 and the ASD TMB5-equivalent spectra were acquired a day later.



We regard our airborne system and aspects of its design, characterization, and application, as a developing science. Thus, the procedures that we describe here are subject to change and upgrade as we learn more.

Finally, we apologize for the blatant mix of units that we use here. This interdisciplinary subject, however, requires such a mix since aircraft are flown in knots (a knot is equivalent to 1.15 mph), at an altitude in feet, acquiring data for comparison to satellite data whose pixels are measured in meters.

2. Brief Description of the Airborne Spectrometer System

The HydroBio airborne spectral platform is a Cessna 185 – a high wing, single-engine conventional-geared aircraft capable of hauling heavy loads for operation in and out of remote unimproved landing strips (Figure 2).

Figure 2. Cessna 185 equipped to fly non-imaging spectrometry. Activities include removing the cap from the uplooking Teflon-covered port (wing), mounting the downlooking foreoptic (belly), and securing the spectrometer in place (through door).

Figure 2.A. Internal view of the down-looking port with the fiber optic in place (seat rail and track in background). When not in use, this port is plugged by a machine screw to prevent dirt and debris from entering and potentially clogging the port.

Figure 2.B. External view of the down-looking port covered by a knurled screw-on cap that covers and protects the nipple through the belly skin.

Figure 2C. Downlooking port with the ASD 1^{o} foreoptic in place. The tab formed by the hose clamp around the barrel of the foreoptic provides a clockwise (tightening) force from the slipstream to secure the foreoptic to the nipple in flight.

The choice of our aircraft resulted from significant attention to versatility. Besides its heavy-hauling and rugged-outback-operations capabilities, the airframe of the Cessna 185 has a large wing that is very stable in flight, resisting pitch and roll, while achieving a range of over 100 miles per hour between stall and maximum true airspeeds. There are no controls or wiring within the airframe through the forward cabin positions where easy passenger-access and horizontal positioning during flight make desirable locations for up-looking and down-looking ports. For the Cessna 185, minimal engineering was required to fit the ports into the air frame.

The hardware installed for both up-looking and down-looking ports, was designed specifically for this aircraft, and was installed with FAA-designated engineering approval. The installation is characterized by minimal-sized holes through the aluminum skin of the aircraft, with sheet aluminum doublers for reinforcement to ensure equivalent or better strength of the airframe.

The down-looking port is located near the center of the aircraft mass, accessible from the front passenger (right) seat. Inside the aircraft, the port is machined from aluminum to bridge between the floor of the aircraft and the outside skin. The ASD fiber optic cable is pushed into the port to snap into a ball-bearing detent that provides friction and positive feedback to the operator that the tip is locked into place (Figure 2.A.). A threaded nipple projects through the belly skin outside the aircraft to accept ASD optical lenses (Figure 2.B.,2.C.).

Although we considered a gyroscopic mechanism for maintaining nadir-looking foreoptic alignment in all flight attitudes, this system was rejected in favor of engineering simplicity and the convention of flying in level attitude for data collection. Constraining operation to straight and level over the target eliminated the need for the considerable additional engineering, testing and development necessary to apply gyroscopic correction.

Each spectrometry mission requires a pilot (left seat) and a spectrometer operator (right seat) with the pilot calling for equipment “on” to begin data collection; thereafter maintaining the aircraft in level-flight attitude until the spectrometer data collection is complete. We view maintaining separate crew members for aircraft and spectrometer operation as absolutely essential for safety: both piloting and spectrometer operations are jobs that require full attention.

An inexpensive hand-held GPS is used to provide geoposition data during the flight (Figure 3.A.). So far, we have found that GPS equipment more accurate than a simple hand-held unit is not warranted because any increased accuracy would be overshadowed by larger spatial uncertainty associated with spectral collection and comparison (i.e., from movement of the aiming point of the foreoptic due to turbulence-induced pitch and roll and the spatial uncertainty arising from geocorrection of satellite data). The spectrometer is secured behind the passenger seat during the data collection mission (Figure 3.B.). The operator controls the equipment with a laptop computer from the passenger seat connected to both the spectrometer and the GPS by external umbilical (Figure 3.C.).

A challenge for collecting reflectance data with our aircraft/spectrometer system is properly measuring the light striking the target (irradiance) during data acquisition, especially if the target area is remote from our ground operations (where we obtain Spectralon reference measurements before and after the flight), or the mission greatly exceeds 20 minutes (which is typical). Our solution is to use an up-looking Teflon-membrane-equipped port through the top of the aircraft (Figures 4), and relate readings through this port to Spectralon measurements on the ground. This up-looking port remains covered when not in use to protect it from the elements and particles that may adhere electrostatically to the membrane surface. The membrane was machined out of a solid block of Teflon, with a circular region about 2-mm thick lit by solar radiation. The fiber optic tip is recessed to allow a field of view (FOV) of about 1.5 cm of the membrane surface. Like the down-looking port, the up-looking port is equipped with a ball bearing detent that provides positive feedback to the operator that the fiber-optic tip is correctly pushed into position.

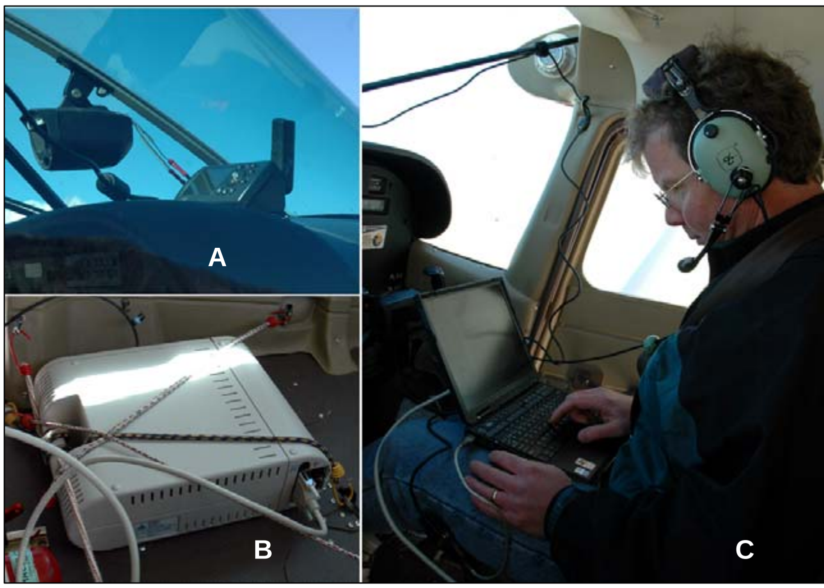


Figure 3.A. Viewed through the windshield, a hand-held GPS is carried mounted with Velcro on the dashboard forward of the instrument panel and connects to the laptop via a serial port.

Figure 3.B. An ASD Spectrometer safely secured behind the passenger seat for the data acquisition mission.

Figure 3.C. Operator

Figure 4. Uplooking Teflon port viewed from inside the cabin with the fiber optic tip ready for insertion. The tip fits into ball bearing detents for both up- and down-looking ports. The inset shows the port as it appears on the outside of the skin. This port measures about 4 cm across. The annular space of metal and raised design prevent the port from receiving reflected light.

3. Overview for Use of Airborne Non-imaging Spectrometry

A major influence upon passively-sensed satellite data is atmospheric haze consisting of smoke, pollen, water vapor and other atmospheric gasses (Leprieur et al., 1995**)**. Haze may affect the signal received by the satellite by attenuation or skewing that may result in loss of accuracy for the index chosen for measurement. The two-way passage of light, both incident and reflected, alters the signal at the satellite. Calibration to reflectance, i.e., the ratio signal-to-incident light, removes this effect upon the data. By providing an accurate measure of reflectance with the effect of atmospheric scattering and absorption removed, spectrometry provides the most detailed and accurate calibration data sets, often over a wide range of the spectrum (Green et al., 1998).

There are three problems that need to be overcome when using an airborne spectral system for calibrating satellite data. These are:

1. Accurately determining the geoposition of the spectral acquisitions;
2. Overcoming spatial uncertainty to pair spectral data with satellite pixels; and
3. Calibration to reflectance.

Geopositioning with image data is relatively straightforward because points on the image can be selected and matched with corresponding locations on a map coordinate system. The location of non-image spectrometric data is provided by GPS that reads position information into the data of spectral snapshots taken over the ground with the software that runs the data collection. Geoposition error may arise because of lag time in the feedback provided by the GPS, inherent error associated with the GPS and with the pointing of the foreoptic. Spatial uncertainty further arises because of the pitch and roll of the aircraft platform during flight. The actual geoposition relative to the position provided by the GPS must be determined empirically in one of two ways. One way is to repeatedly fly over targets, noting the position relative to the known position of target transitions—such “aiming” calibration should be performed during relaively ideal conditions of low turbulence and minimal aircraft load (but will, to some extent, also contain some spatial uncertainty due to minor pitch and roll movement of the aircraft). The second method is a statistical technique: both methods are described in this paper.

As a separate consideration, the spatial uncertainty induced by the aiming of a fixed foreoptic relative to nadir is a complex problem. Such spatial uncertainty is induced non-systematically by pitch and roll of the aircraft and systematically by factors that affect the nose-up trim of the aircraft: these include natural flight characteristics of each aircraft, density altitude, outside air temperature, aircraft cargo loading and power settings. Density-altitude, a term to describe atmospheric conditions relative to the International Standard Atmosphere, is a direct indicator of aircraft performance. As density altitude increases, lift and engine power output decrease and, to compensate, the plane must fly at a higher angle of attack at a given power setting. Over a target and at the same barometric pressure, density altitude may vary about 4,000 feet between a cold winter day and a hot summer day. Thus, flying over a target at the same elevation above sea level can experience a wide latitude of conditions that affect the aiming point. Thus, the aiming point should be determined for each mission or bounded appropriately during the data analyses.

Calibration to yield reliable and accurate reflectance with a non-imaging airborne system requires additional consideration. For measurement of target reflectance, the spectrometer must first be calibrated against the radiance of a Spectralon standard that is highly reflectant throughout the passive-light spectrum. At each point along the spectral curve the level of light from the standard is used as the denominator to ratio against the light reflected from the target, thus automatically adjusting for the quality of the light impinging upon the target. While making ground-based field measurements, recalibration of the spectrometer is performed frequently to adjust for changing light conditions with time of day and the effect of drifting atmospheric air masses that may contain variable amounts of haze and high thin clouds.

Because the path length through the atmosphere tends to be ratiometrically small compared to the entire column of the atmosphere, airborne spectra are nearly equivalent to ground-based spectra if they are acquired sufficiently close to the ground—we generally choose an altitude above ground level of 1000 feet, or less.

If the spectral mission is relatively short and proximal to the landing strip, acceptable calibration to reflectance can be achieved by measurements of the standard on the ground before and after the flight and using linear interpolation for correction if there is a significant time difference between the two points in time. If the target is a large distance away, the increased travel time, plus the potential that the airmass content of light-affecting aerosols and particles over the target will be different, require use of a system for on-board calibration during flight (as described in Section 5).

4. Geopositioning of the Spectrometer Aiming Point

As the plane is flown along a line, the onboard GPS system provides positions that indicate where the data were collected. These are not the correct positions of the points because the pitch attitude of the aircraft affects the fixed aiming point, possibly multiple tens of meters from the indicated position given by the GPS.

We developed two ways to solve the aiming-point problem. The first requires a series of dedicated passes over land-water boundaries (or other sharp contrast surface conditions) during the mission. The second involves statistical study of the data, but requires no additional overflights. Although we believe that the latter, statistically based technique is superior, we advocate that both techniques be applied as water-land overpass analyses are valuable to determine whether there is any bias right or left of track: something that the statistical analysis cannot determine. Once programming is completed for the statistical approach, application can then be made for each overpass.

4.1. Problem and Purpose

In order to precisely locate the spectral sample on the ground, several problems must first be solved. These are:

1. Define the timing relationship between the GPS and spectral sampling;
2. Understand the pointing characteristics of the spectrometer optics as mounted on the aircraft; and
3. Perform post-processing to interpolate the geoposition of each acquisition between the GPS reporting points.

During operation, the location of a spectral acquisition is mapped by GPS, recorded by ASD software, and stored both in the spectral record and a separate log file. The system uses a GPS unit that is connected to a laptop computer via a USB port. Every 2 seconds the GPS sends a position update to the computer. This 2 second update cycle is adequate for stationary spectral acquisitions, but in an aircraft typically traveling at between 52 and 93 m/s (100 and 160 kts), the elapsed time represents an unacceptable ground track of 104 to 154 meters. At its fastest acquisition rate, the ASD spectrometer records about 5 spectra in 2 seconds. When traveling at 130 kts, the resulting oval-shaped integrated FOV is 2.7 meters wide and 16.1 meters long when using the 1^{o} lens at 500 feet (152 meters) above ground level (AGL). We generally try to operate our aircraft during acquisition with throttle settings to achieve a true airspeed of about 110 kts (though groundspeed is variable due to winds aloft). This speed facilitates aircraft handling, safety and economy, maximizes along-track density of data acquisition and optimizes the size of the along-track footprint (about ½ TM pixel).

4.2. Approach

We performed several experiments to empirically determine the relationship between the reported positions from the GPS and the actual position of the spectrometer's instantaneous field of view (IFOV). These experiments consisted of flying over distinct land-water boundaries (beaches/shores), plotting GPS locations on high resolution aerial photographs, interpolating the position of the spectral samples that occur between the 2 second GPS updates, and finally measuring the difference between reported positions and land-water spectral response. Following these empirical experiments, we developed statistical methods to address some inherent variability.

Testing was done with an ASD 1^{o} FOV lens. At 500 feet AGL the IFOV is 2.7 meters wide. Forward motion during the time of the spectral acquisition (about 0.2 seconds) results in an oval-shaped pixel 13.8 meters long (distance traveled + 2 times the IFOV radius). This small footprint helps in precisely defining the pointing characteristics of the lens mounting system. Apparent positioning of the "footprint" every other second was made by a Garmin GPS, designed for handheld usage, that is mounted above the instrument panel in view of the sky (through the Plexiglas canopy; Figure 3A). GPS position data are stored in a log file, along with the file names of each of the 0.2 second spectral acquisitions, and other ephemeris data. With storage/processing time, this means that 4 to 5 samples are recorded for each position record from the GPS.

Numerous (about 18) passes were flown over an isthmus between two water bodies in northern New Mexico, remote from human habitation and structure. The angle of approach was varied intentionally from perpendicular to parallel in order to provide a variety of perspectives. Data acquisition started when the aircraft was flying level on the intended heading and when the land/water boundary was several seconds away. About 40 spectral samples were taken for each pass (about 10 seconds duration). A nadir-looking aerial photograph was taken at the time of data acquisition and geocorrected to a USGS digital orthophoto-quad in ArcGIS. This and other photos were used to confirm water level within the target lakes since their levels fluctuate and the orthophoto quad may not indicate an accurate position for the land water boundary (Figure 5).

During post-processing, positional interpolations were computed and spectral averaging was done to simplify the analysis. As discussed previously, about 4 spectral samples are acquired between each GPS position update. A program was written that interpolates the intermediate locations between GPS updates. The only assumptions are that the speed and direction of the aircraft are constant (reasonable at this timescale). The program inspects the GPS time stamps in the ASD GPS log file to locate breaks between complete flight lines and segments that need interpolating. It then keeps the GPS update points and interpolates any number of intermediate samples that lie between them. The result is a new log file with interpolated GPS locations as well as original GPS locations for reference.

For this analysis we chose to resample the spectrometer's data to Landsat band 5 equivalence since this band is particularly sensitive to water. This resampling yields a single index number for each sampling location that is sufficiently sensitive to identify water, land, or a spatial mix of the two.

The interpolated GPS log was converted to ESRI shape file format, and the resampled spectral data were joined to the shape file. The result is a vector point file that can be viewed in ArcGIS, and displayed over high resolution imagery of the water bodies. A threshold was chosen by inspection to separate water (low reflection) from soil (higher reflection), and each point was colored uniquely for water, soil, or mixture. Each flight line was inspected first visually and then with the software's measurement tools to determine the pointing and timing characteristics of the airborne spectrometer system.

4.3. Results

Flown at the same power setting throughout the mission (ca. 60% power), at 7,000 feet altitude, on a cool (10^o C) day and at about standard atmospheric pressure (30.02 in.Hg measured at a nearby airport), the 1^o lens mounted on the down-looking acquisition port has a small forward offset from nadir, while the side to side error is small and balanced. Flight conditions during data acquisition were light turbulence, often called "chop" by pilots. The lag of the aiming point was about 19 meters forward from nadir, with a standard deviation of 6.75 meters (number of samples = 24). At the higher power setting, this displacement was primarily due to time lags in GPS integration and location reporting, and very secondarily due to aircraft angle of attack.

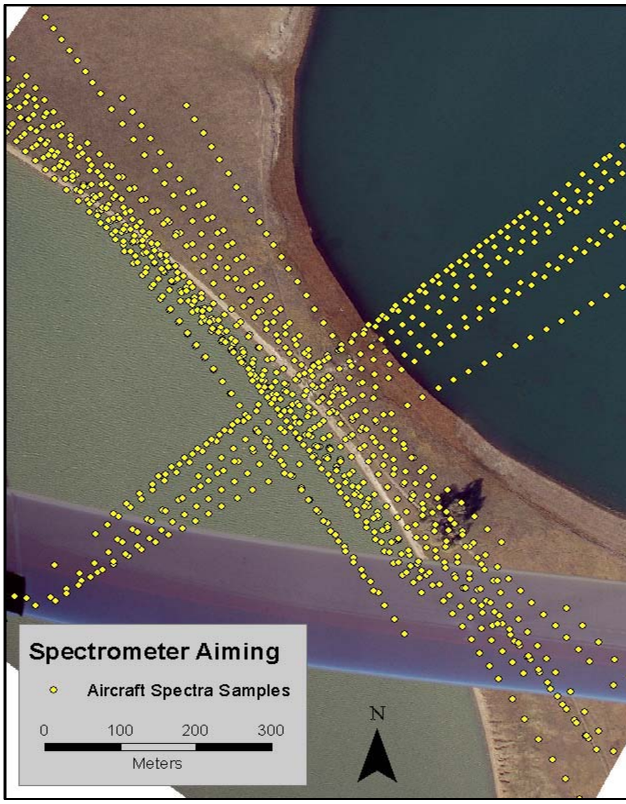


Figure 5. Data acquisition points crossing an isthmus between two Northern New Mexico reservoirs plotted atop a near nadir look air photograph taken during the mission. The photo was taken out the side of the aircraft in "near" nadir position and later geocorrected on an orthophoto base. The photo represents real time conditions for water position and was used to establish the interface between water and land. The position of the data indicating a cross from water-to-land, and vice versa was checked in relation to its physical position to determine the aiming point of the spectrometer relative to the indicated geoposition.

The flightlines that parallel the water's edge, though more difficult to collect (target hidden from pilot's view), show small side to side offsets that are balanced. Average offsets to the right are 8.8 meters, and to the left 11.5 meters. The number of samples averaged for right offsets is 9, while there were only 2 samples for the left side. Since the left and right offsets are fairly balanced, though the number of samples to the left was limited, we interpret that optical aiming in this vertical plane is nearly nadir, and side to side errors of about 9 meters are due to aircraft roll. This greater roll than pitch rate reflects the effects of turbulence since the vertical micro-wind shears in turbulence have more profound effect on the large surfaces of the wings than on the relatively small surface presented by the horizontal stabilizer.

Under the light turbulence conditions that this mission was flown, the shape of the region for aiming uncertainty was an oval whose center was located 19 meters forward of nadir that was about 20.7 meters wide and 27.3 meters long [2.7 IFOV + (2 * 9) wide and 13.8 IFOV + (2 * 6.75) long]: just fitting inside one TM pixel. For other flight conditions with greater turbulence, the area of uncertainty will increase.

Since forward offset is a constant during a mission flown at the same power setting, this is corrected by our purpose-written processing software. Once this forward offset is made for all data points, to overcome issues with geopositional uncertainty, we have developed methods for finding low variance regions of the satellite image, and this enables constraining the pairing of pixels for ELC to those ground areas large enough to contain the uncertainty in data positioning due to aircraft pitch and roll after correction for the forward lag. This processing is described in Section 6.

4.4 Alternative (Preferred) Statistical Technique for Determining Forward Lag

Operational analyses of mission data showed that a 19 meter forward lag would not fit for all conditions but varies depending upon density altitude and air temperature, even without varying the aircraft's power settings. At higher density altitudes and temperatures, more of the aircraft's thrust is used to maintain level flight and for level flight, the aircraft will increase angle of attack to compensate: thus, the aiming point will correspondingly move forward. Realizing that every mission can be expected to have different conditions, we developed a statistical technique to determine the aiming point.

We have found that it is best to fly an entire mission at the same power setting for data consistency. With consistent data sets, it is then possible to determine the forward lag of the aiming point by statistical analysis. Figure 6 graphically shows a spectrometer mission for ELC calibration of TM band 5 (TMB5) over Owens Lake California. Although the points are plotted in their location as indicated by interpolation of the GPS coordinates, the amount of forward lag, and thus actual positions for these raw data are unknown. This mission was purposely flown at a lower power setting (ca. 40% power) than the previous data set over the reservoir isthmus (Figure 5).

For evaluation of the forward lag, geocorrected TM band 5 data from the Owens Lake mission of 04-08-06 were plotted against aircraft ASD spectra for forward lags of 0 to 80 meters in 5 meter steps (5228 spectral sample points). The ASD spectra were resampled to TMB5 equivalence and regressed against the appropriate extracted pixel values, with the squared regression coefficient (r^2) retained as an indication of the best fit. The relationship (Figure 7) clearly illustrates a 40 meter forward lag that shows the highest r^2 value. Inspection of aircraft spectra over discrete features, such as perpendicular road crossings, confirmed that 40 meters is the best offset for this mission. Finer detail than the nearest 5 meters is unnecessary within the context of the spatial uncertainty induced by turbulence and aircraft handling during the flight.

Because forward lag is a property of the conditions present during each flight—aircraft load, density altitude, air temperature and power settings—these conditions can be recorded for future reference. the same forward lag can be used with equivalent aircraft and atmospheric conditions. Records kept for missions where the properties are varied can be used to define curves for forward offset. Although this is required for close tolerance work, a degree of uncertainty in forward position can also be bounded by choosing target pixel regions of low spectral variability for pairing with spectrometric data as described in section 6. However, for using spectra to calibrate TM data with pixels of 28.5m, and with lag distances of 40 meters (1.4 pixel widths), forward lag is a crucial property to know.

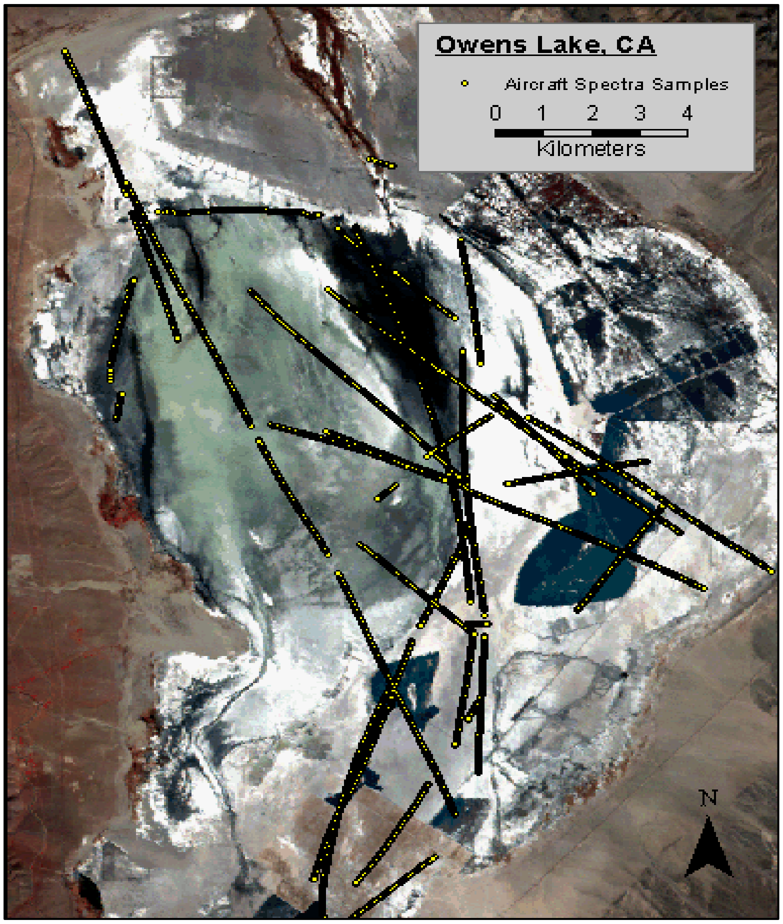
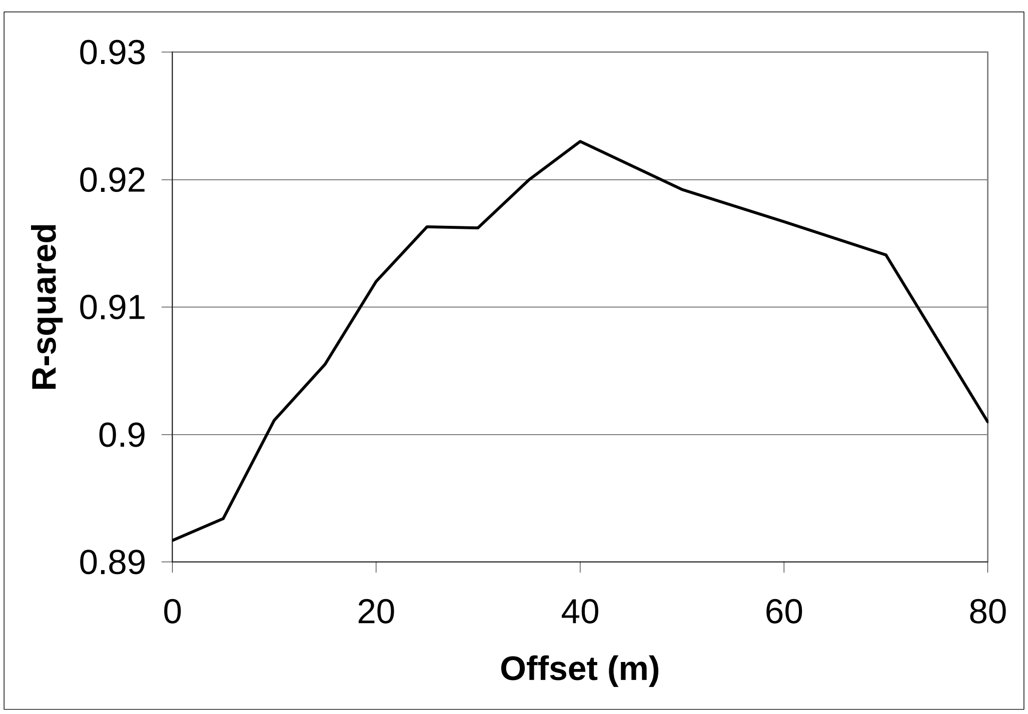


Figure 6. TM false color image of Owens Lake 04-08-06 with spectrometer data that were obtained a day later displayed over it. AT Owens Lake, TM band 5 (TMB5) is being used to identify whether the flooded cells are kept wet enough to be compliant to air quality regulations. Since it is important that these determinations are correct, the spectrometer is being used for determination of and cross checking of ELC calibration. Close-tolerance calibration is important because TMB5 may be affected by high-thin clouds or smoke that are, otherwise, not visible on the TM scene.

Figure 7. Plot of regression values for TMB5-equivalent ASD spectra (1% foreoptic) against TMB5 pixels (converted to reflectance with accompanying header data) paired from the flightlines shown in Figure 5. The forward lag for geoposition of the data was 40 meters .



5. Calibration to Spectralon Reflectance On-the-fly

5.1. Purpose

Remotely-sensed data are commonly converted to reflectance before analysis. Reflectance is the ratio of the amount of light leaving a target to the amount of light striking the target. It is a property of the material being observed and, thus, should be equivalent under different illumination conditions. Radiance is what the sensor measures directly, and is a function of illumination intensity and geometry, and atmospheric conditions. A standard method for converting radiance measured in the field to reflectance uses a Spectralon panel, which serves as a reference that reflects nearly 100% of all the light striking it in the range of wavelengths of interest for this work (350 to 2500 nm). Typically, the Spectralon panel is scanned by the spectrometer every 10-20 minutes during field work, or as changing atmospheric conditions warrant.

In this experiment we develop a ratio that describes the relationship between the radiance detected through the uplooking port and radiance from a Spectralon panel. We also describe a simple post-processing statistical method to reduce the effect of aircraft pitch and roll when collecting uplooking (calibration) data.

5.2. Approach

Spectralon measurements were made before and after all flights. Because the aircraft fuselage casts a shadow, it was not possible to take a Spectralon measurement through the downlooking port with it mounted to the aircraft. The 1^o lens was removed from the aircraft and attached directly to the ASD fiber optic cable. Measurements were made adjacent to the aircraft in radiance mode with care taken to shield the Spectralon panel from light reflected off the polished sides of the aircraft. The same Spectralon procedure was followed immediately after concluding each flight.

Because of changing solar conditions during the flight, the pre-and post- flight Spectralon measurements differed. During post-processing a set of intermediate Spectralon spectra were interpolated between the pre-and post- Spectralon measurements. One interpolated spectrum was created to correspond with each of the spectra collected during the flight. It is assumed here that the changing values are due to solar conditions and not to atmosphere-induced scatter or absorption.

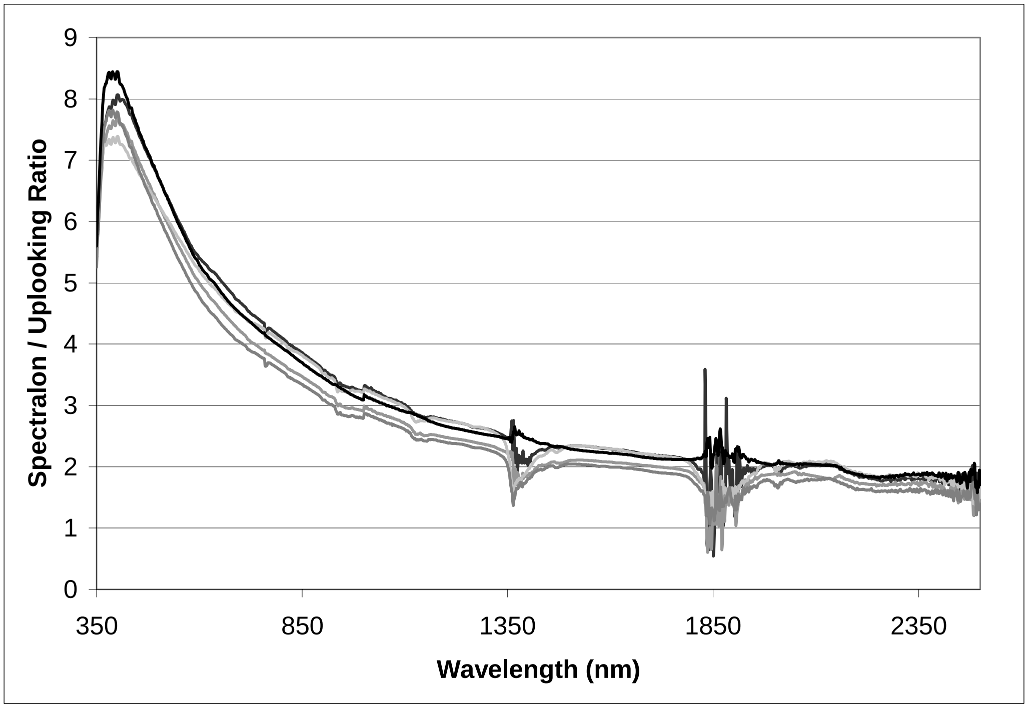
During flights, the ASD fiber optic was inserted into the uplooking port, and the instrument settings were left unchanged from the Spectralon measurement. The spectrometer was set to take 20 (uplooking) spectra with no averaging. Continuous collection in this mode was done during straight and level flight after leaving the airport and on return to the airport.

During post processing, we calculated a ratio (or factor) to relate uplooking readings to Spectralon measurements in the following equation:

$\text{Ratio} = \text{Spectralon}_{\text{interpolated}} / \text{uplooking}$

A ratio for each band in the 2151-band spectra was taken (spectralon/Teflon uplooking) to produce a continuous relationship. Five sets were averaged to produce a generalized relationship between the Spectralon and uplooking measurements. The initial ratios for the five uplooking and the average relationship are shown in Figures 8 and 9.

Figure 8. Ratios of ASD spectra taken through the Teflon membraned in the air to ground-based measurements. The variability of the measurements reflect changing solar radiation between when the two sets measurements were taken.



5.3. Results

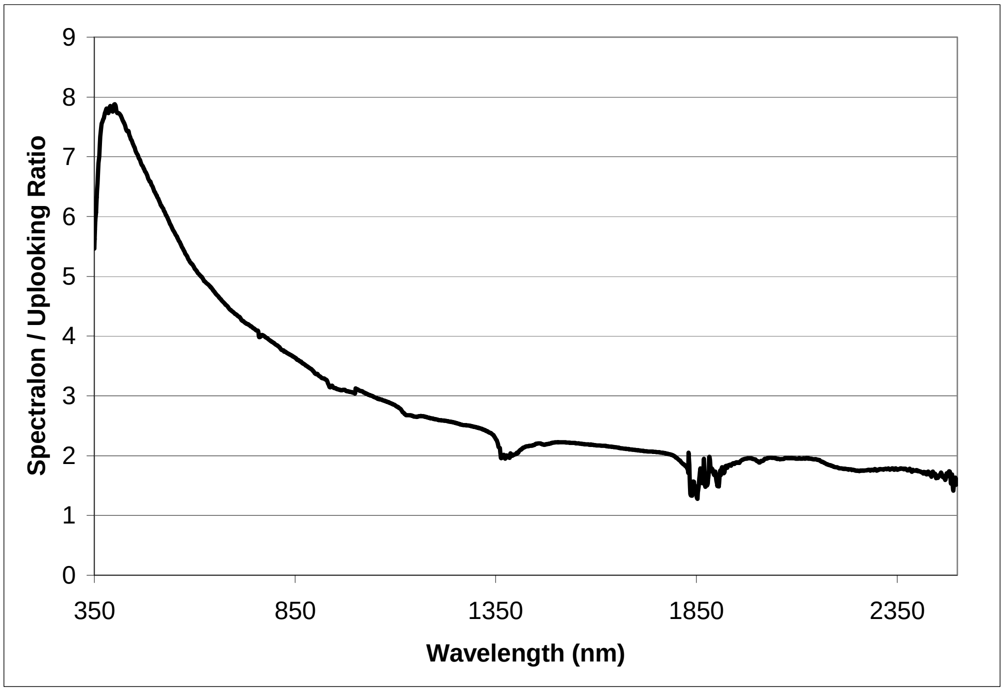
The ratio relationship between Spectralon and uplooking measurements (through Teflon), shown in Figure 9, is specific to the 1^{o} lens used in its development. Because of the difference in the amount of light collated by each lens, use of a different angular FOV lens would require that this experiment be repeated. This ratio is used to calculate reflectance from downlooking spectra in the following equation:

Reflectance = downlooking radiance / (recent uplooking reading * ratio) * 100

The method for collecting spectral measurements using our customized platform is:

1. Prepare ASD spectrometer with 1^{o} lens, set to radiance mode, and optimize spectrometer over Spectralon panel.
2. Take uplooking measurement in straight and level flight before collecting downlooking spectra, retake uplooking spectra every 20 minutes during flight.
3. Take downlooking measurements.
4. Apply reflectance equation in post processing.

Figure 9. An average curve defined from the spectra shown in Figure 8.



6. Post-Processing for Position Uncertainty from Aircraft Pitch and Roll

Uncontrolled pitch and roll of the aircraft is caused by turbulent air. These motions lead to changes in the aiming point, and thus, induce positional uncertainty. We chose to evaluate this as a thought problem rather than by obtaining measurements.

From the New Mexico experiment in light turbulence (Section 4), aircraft pitch and roll was minor (at most 3-5 meters) and at 500 feet AGL this caused displacement of up to about 13 meters. (Our tests in light turbulence during the light turbulence showed an average of about 9 meters of side to side displacement.) During moderate turbulence this may increase to about 10 degrees. At 500 feet AGL this results in displacement to about 27 meters (equivalent to a TM pixel). Thus, the state of turbulence during the flight must be recorded in the mission notes, and be considered in post processing. Turbulence greater than moderate is (thankfully) grounds for canceling a spectrometer mission due to the induced positional inaccuracy.

To overcome pitch- and roll-induced errors, we developed a method to find relatively homogeneous areas in the imagery. Only the spectral data that lie in these homogeneous regions are then considered for further analyses. A program was written that passes a 3x3 filter kernel through all pixels in the satellite image of interest. and returns the standard deviation, coefficient of variation (CV), and mean of all the pixels in the 9-pixel kernel to the centroid pixel, and a new 3-band image is made in which all pixels contain these values. Coefficient of variation is a measure of the standard deviation normalized by the mean (100 * standard deviation / mean). This allows direct comparison of areas with high reflectance and low reflectance.

To reduce the effect of spatial uncertainty from the airborne data, aircraft spectra that fall within regions of low-CV pixels in the image matrix are selected for the analyses. Note that this technique is highly specific to the spectral region of interest because what may be homogeneous in, say, the blue region of the spectrum may not be in the NIR region. Thus, foreknowledge of the system and spectral region of interest is required for correct application of this crucial step. When paired correctly, strongly linear plots such as Figure 1 result.

7. Considerations for Elapsed Time in the Acquisition of Spectra to be Paired with Satellite Data

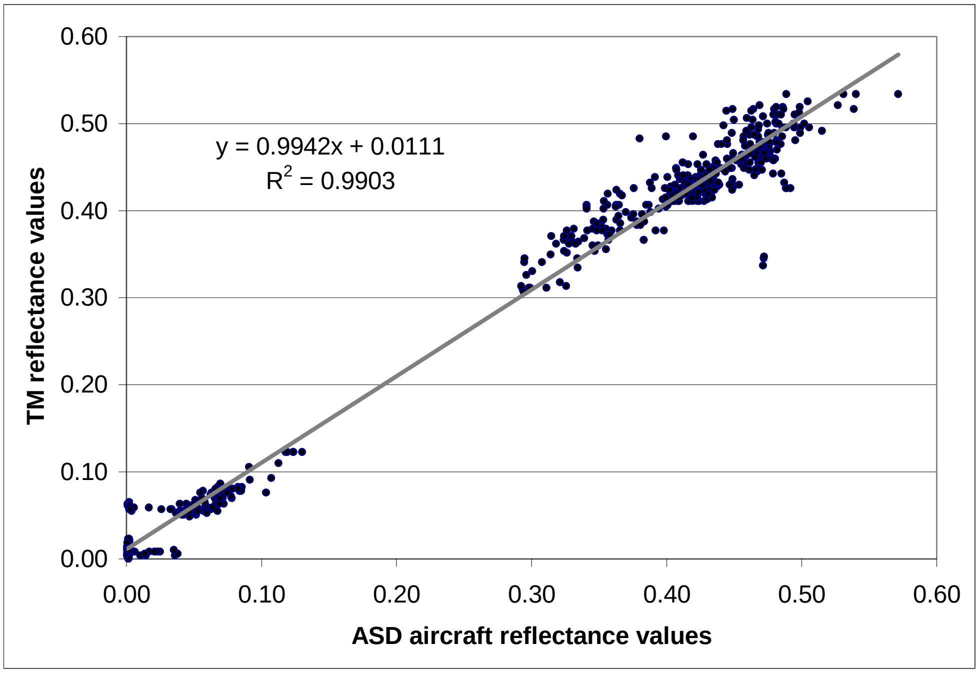
One final and probably obvious aspect for calibrating satellite data to airborne data is how rapidly the system under study is changing. Acquiring spectra during the time of overpass is ideal, however, this is not always possible. Thus, it is imperative to have an understanding of the rate at which the phenomena under study may change. As an example, Figure 10 A-C shows TM reflectance values versus corresponding ASD reflectance values for 3 time gaps between satellite overpass and aircraft acquisition. There was a one day difference for data sets acquired April 8 and 9, 2006 (Figure 10 A); a 3 day difference for data sets acquired February 11 and 14, 2006 (Figure 10 B); and an 11 day difference for data sets acquired February 03 and 14, 2006 (Figure 10 C). Note that not only is the square of the regression coefficient (r^2) of the comparison less for the larger time separation, but also the slope of the regression line is increasingly less than 1:1 with increasing time separation. This drift is expected for the Owens Lake especially during Springtime, because the system is drying after a period of mid-winter storms (this is a strongly Mediterranean climate) and as the evaporative demand increases with longer and hotter days.

The closeness of the required timing for aircraft overflight relative to satellite overpass may vary greatly depending upon the target. Targets whose measured properties may change rapidly require shorter elapsed periods. Here are a few examples:

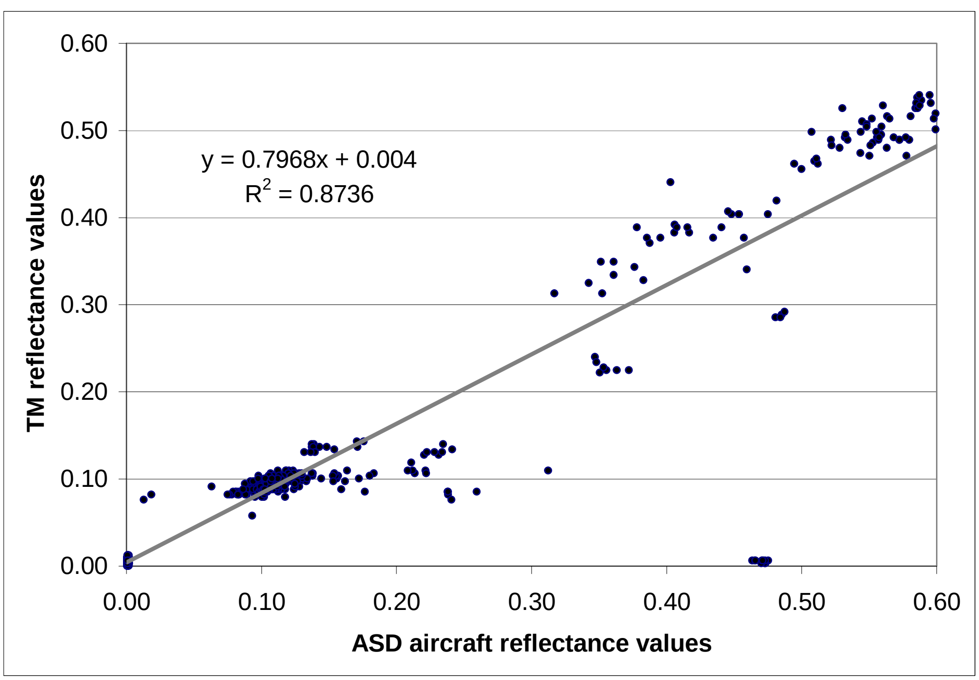
Target	Timing Relative to Overpass—Within:
River	minutes to hours
Lake	hours
Drying lakebed (e.g., Owens Lake)	1-2 days
Cultivated Crops and forest canopies (variable timing)	1-2 days during Spring 1-2 weeks in mid-Summer
Geologic features (without vegetation cover)	non-specific, best if same solar angle (due to shadows)

Figure 10. Paired ASD TMB5-equivalent and Landsat TMB5 data from Owens Lake with regression relationships calculated. A. Paired data from April 08 (Landsat 5) vs April 09 (ASD), a 1 day separation. B. Paired data from February 11 (Landsat 7) vs February 14 (ASD), a 3 day separation. C. Paired data from February 03 (Landsat 5) vs February 14 (ASD), an 11 day separation.

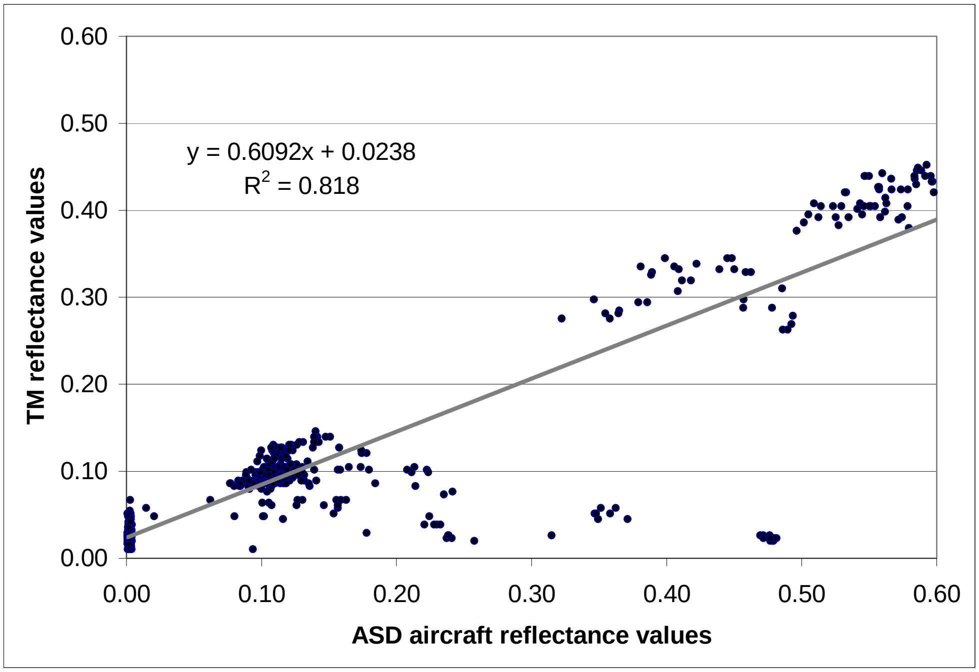
A.



B.



C.



8. Conclusion

A non-imaging spectrometer can be mounted for aerial data collection once the challenges inherent to using a small aircraft platform are solved. The solutions for this work are non-trivial and require a considerable and focused effort that includes engineering and testing the system, and writing software to apply the results.

By pairing contemporaneous airborne non-imaging spectrometry point values with above-the-atmosphere pixel reflectance values, empirical line calibration can be generated and applied. This form of calibration is particularly useful for monitoring areas with dynamic surface conditions where stable dark and light surfaces are not available to produce a two point empirical line.

The ability of the specially-equipped aircraft to cover large areas quickly and to collect thousands of data points covering a wide spectrum during a mission of an hour or less, make this system attractive for many remote sensing-based applications. Although the development of this system requires considerable effort, we believe that once the system is in place, it can consistently perform at a fraction of the cost of alternatives.

9. References

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