NASA's Airborne Terrestrial Applications Sensor (ATLAS): A Customer's Perspective

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Introduction

Research studies of remote sensing applications to agricultural management generally have stringent image acquisition and resolution requirements. To investigate seasonal crop and soil conditions, images must be acquired at critical phenologic stages:

- Prior to planting, to identify soil management units;
- At time of plant emergence, to monitor stand establishment;
- Prior to canopy closure, to determine nitrogen deficiency and plant vigor;
- At plant maturity, to monitor pests, disease, and weed infestations;
- Late in the season prior to harvest, to predict final yield; and
- At senescence, to determine defoliation rates and to schedule harvest.

For most agricultural studies, quick image turnaround (1-7 days) is essential because the crop and soil conditions change rapidly. Furthermore, the spectral information must be obtained with fine to moderate spatial resolution, ranging from 2-20 meters depending on the application. The most desirable spectral wavelengths for agricultural farm management studies are the green, red, near-infrared (NIR), shortwave-infrared (SWIR), and thermal. Finally, considering that spectral information is desired in units of reflectance and temperature (not simply digital number), it is necessary for researchers to deploy calibration instrumentation during flights; thus, the images must be obtained at the precise time and location requested by the on-site ground crew.

This restrictive set of data requirements is rarely met by most aircraft- and satellite-based sensors. An exception is the fleet of NASA aircraft-based sensors, including the Daedalus TM Simulator aboard the ER-2 aircraft and the Airborne Terrestrial Applications Sensor (ATLAS) aboard the Learjet (see Appendix A). A Non-Reimbursable Space Act Agreement was signed between the USDA-ARS U.S. Water Conservation Laboratory (USWCL) and NASA Stennis Space Center (SSC) to investigate the use of ATLAS spectral imagery for farm management applications. Through this agreement, SSC agreed to provide ATLAS imagery of the USWCL field site (Maricopa Agricultural Center, or "MAC") on six dates selected by USWCL scientists to correspond with the cotton and sorghum growing seasons: April 14, June 9, June 23, July 7, August 4, and September 16, 1998. USWCL agreed to provide a critical review of ATLAS image products, provide on-the-job training for SSC personnel in precision agriculture and ground data collection, and present results at the Verification and Validation Symposium at SSC. Preliminary results of this cooperative project are presented herein.

Methods

The ATLAS mission request was designed to best suit agricultural research. It required two days advanced notification of overflight, 2.5 m data resolution, flightline spacing to achieve 20° field of view (FOV) over all MAC, color infrared (CIR) photography to support all flights, and coordination between the USDA ground crew and SSC aircraft crew. This set of specifications resulted in a set of ten parallel, east-west flight lines covering MAC with nearly 75% flightline overlap. The east/west flight direction was chosen to align the sensor's 72° FOV with the principal plane of the sun during the overflights. The extreme image overlap was requested to ensure that every site on the farm was imaged with a FOV of less than 10°. At the end of each overflight, two of the ten flight lines (#1 and #5) were repeated to monitor the effects of changing solar angle on image digital number (*dn*) over the duration of the one-hour flight. Also, the flight was completed with a single flight line along the north/south direction of the farm to further investigate the effects of the wide FOV along a plane orthogonal to the principal plane of the sun.

During each of the six ATLAS overpasses, a standard set of measurements was made on the ground to verify image quality and to document crop and soil conditions:

Tarp Deployment

During each overpass, calibrated reference tarps of 8x8 m dimension were deployed to provide targets of known reflectance for conversion of ATLAS *dn* to units of surface reflectance. Sixteen tarps of four nominal reflectance levels (0.04, 0.08, 0.48, 0.64) were laid on a dirt landing strip in a configuration such that each set of four tarps covered a square of 16x16 m. At the 2.5 m spatial resolution of the ATLAS, this tarp configuration resulted in a box of 6x6 ATLAS pixels covering each set of tarps at four reflectances. Taking into account edge effects due to atmosphere and sensor optics, we assumed that the middle 2x2 set of pixels could be used to determine the *dn*-to-reflectance relation for the ATLAS images.

Radiometer Deployment

To supplement the reflectance information from the tarps, we also made measurements with yoke-based radiometers (4-band Exotech, infrared thermometer, and 8-band Modular Multispectral Radiometer) over two targets - a near-full-cover field of alfalfa and a large packed-earth landing strip. Reflectance and temperature measurements of the landing strip were made from 8:00 a.m. through the time of the overflight to document the changes in this pseudo-invariant object with time and solar zenith angle. The same measurements were made of the alfalfa field during the overflight. A third radiometer was mounted on a boom over a reference $BaSO_4$ panel to monitor sky conditions during the overflight and to allow cross-reference of yoke-based radiometers with a calibrated reference target. An infrared thermometer was used to make surface temperature measurements of the tarps to allow an ATLAS *dn*-to-temperature relation to be derived.

Field Survey

On each overflight date, a three-person crew surveyed the entire farm to document the following information for each border of each field at MAC:

- Crop type
- Crop growth stage
- Percent vegetation cover
- Soil moisture
- Soil roughness
- Crop row direction
- Comments (pests, litter, wilting) and noted anomalies.

This information was input into a spreadsheet and then into a geographic information system (GIS) to produce maps of field-by-field crop and soil information (Figure 1) for eventual interpretation of the ATLAS spectral data.

Bidirectional Reflectance Factors

The ATLAS has a wide field-of-view (72°) that results in views of the surface with forward- and back-scattering configurations in each flight line. With the near 75% flight line overlap at MAC, it was possible to obtain five views of every MAC location with view angles of approximately 26°, 10°, 0°, -10°, and -26° at a solar angle of approximately 20°. To document the variations in target reflectance associated with this wide range of view angles, we measured the bidirectional reflectance of vegetated targets and the packed-earth landing strip using a radiometer mounted on a hinged boom that could measure reflectances of one target at a variety of view angles along a single plane. Measurements made with this apparatus were oriented in three planes: along the principal plane of the sun, at 45° to the principal plane, and orthogonal to the principal plane.

Farm-Wide Hyperspectral and Thermal Measurements

During each overflight, a team of three visited a variety of fields (differing crop types, cover and row direction) and targets (ponds, burned fields, bare soil). In each field, they defined a location with Universal Transverse Mercator (UTM) coordinates and made measurements of surface temperature (8-12 μm) and surface reflectance in 250 wavelength bands in the visible and near-infrared spectrum. These extensive hyperspectral measurements of a wide variety of targets complement the intensive, wide-band measurements described in previous sub-sections.

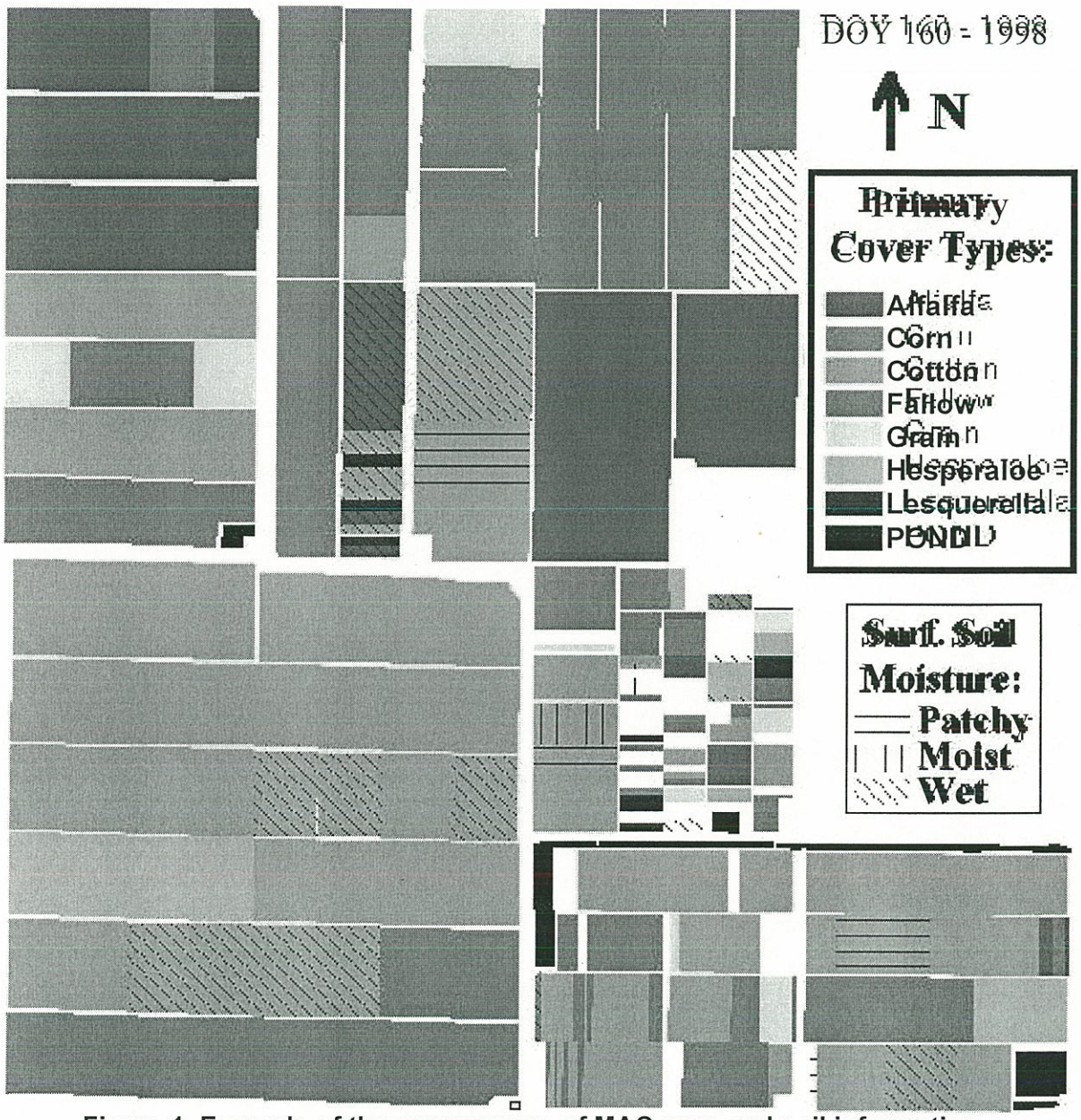


Figure 1. Example of the survey maps of MAC crop and soil information.

NASA MODIS Validation Experiment

In association with the USDA-SSC effort at MAC, a NASA-funded MODIS Instrument Team investigation was designed to acquire a season-long data set of field radiometric measurements and biophysical data. The targets included cotton, alfalfa, and lesquerella at different phenologic stages, and bare soil at a range of sun angles. During each ATLAS overflight, measurements were made of fraction absorbed photosynthetically active radiation (fAPAR), leaf area index (LAI), and above-ground biomass, as well as surface reflectance and temperature. The study objectives were to investigate the relationship between

biophysical measurements and spectral vegetation indices, to study the effects of changing solar and view angles on spectral images, to assess scaling effects, and to evaluate sampling sizes and strategies.

Results

To date, the objective of acquiring timely ATLAS overflights for agricultural study has been met (Table 1). Overflight #1 (May 5) was cloudy, but for all others, the sky was clear and dry. For each overflight, the flight crew called the evening before and the morning of the flight to coordinate the flight with weather, site, and personnel conditions. The flights were executed according to the location and time scheduled in the contract, with deviations made only upon USDA request. The SSC flight crew called the USDA ground crew after each overpass to confirm acquisition. The images, photos, and accompanying reports were delivered to the USDA cooperators within two weeks of acquisition. Data were provided according to the agreed-upon format; that is, images were geometrically corrected but not radiometrically corrected.

Table 1. Status of 1998 USDA/SSC ATLAS flights at MAC.

Flt. # and Date	Weather	Ground Data	Plant Conditions
#1 5 May	Cloudy	Complete	Cotton: Early Emergence
#2 9 June	Clear	Complete	Cotton: 10% cover, vegetative
#3 24 June	Clear	Complete	Cotton: 25% cover, flowering
#4 12 July	Clear	Complete	Cotton: 80% cover, boll formation Sorghum: Pre-emergence
#5 19 August	Clear	Complete	Cotton: 100% cover, boll formation Sorghum: 20% cover, vegetative
#6 16 Sept.	Future Acquisition		

General Image Quality

Since complete MAC coverage was accomplished by ten overlapping flight lines, the first step in our analysis was simply to determine the low, high, and median *dn* of each spectral band for each of 10 flight lines. We also computed the sum of pixel frequencies for the lowest 5 *dn's* and highest 5 *dn's*. With this information, it was possible to assess 1) the appropriateness of the sensor gains and offsets, and 2) the shifts in gain and offset from one flightline to the next.

Regarding gains and offsets, we found that:

- The offset for the visible bands was rather large (about 50-100 *dn*) and all bands had significant saturation at *dn*=255 over agricultural targets;
- Bands 7-8 had very low offsets and minimal saturation at *dn*=255; and
- The thermal bands (ATLAS bands 10-15) saturated over hot targets, and to a lesser degree, over cold targets.

This level of saturation is unacceptable for agricultural research and most operational applications.

Regarding in-flight data stability, the median *dn* should be relatively stable across flight lines, and the trend of all bands across flight lines should be similar (e.g., Figure 2; ATLAS thermal bands). For Flight #2 (June 9), the median *dn* of ATLAS bands 1-3 and 7-8 were as expected; however, the median *dn* of ATLAS bands 4-6 deviated from the trends of all other bands and dropped substantially between flightlines 4 and 5 (Figure 3). From discussions with the flight crew, we determined that the gain of bands 4-6 had been changed in-flight between flight lines 4 and 5 to avoid apparent *dn* saturation.

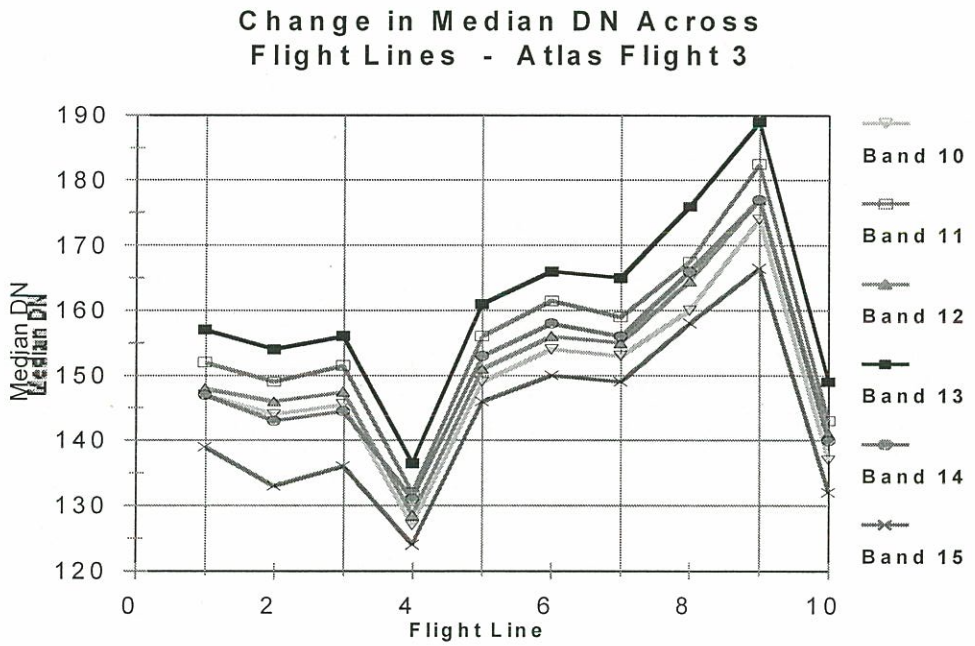


Figure 2. Median *dn* of ATLAS thermal data (bands 10-15) for each flightline of overflight #3 at MAC.

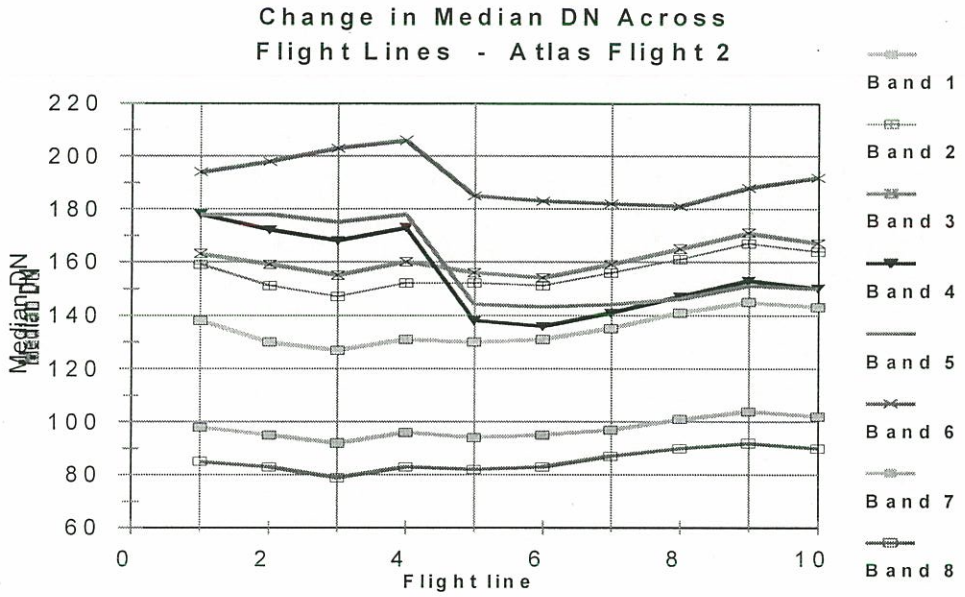


Figure 3. Median *dn* of ATLAS reflective data (bands 1-8) for each flightline of overflight #2 (June 9) at MAC.

Dn-to-Reflectance and *Dn*-to-Temperature Relations

A primary goal of our on-site ground measurements was to produce a linear relation between *dn* and reflectance or temperature that could be applied to data from all flightlines to retrieve reflectance and temperature from image *dn*. At the time of this writing, we have been able to complete this analysis for Flight #2 (June 9) only. *Dn* values were extracted from the center of ATLAS images for areas covering the tarps, vegetation, and landing strip, then were combined with reflectances derived for the calibrated tarps and measured for the vegetation and landing strip to define linear relations for ATLAS bands 2 (green), 4 (red), 6 (NIR), and 14 (temperature) (Figure 4). A linear fit was suitable for these data only when the *dn* did not approach saturation (e.g., *dn*=255). This was the case for ATLAS bands 2, 3, and 14. For ATLAS band 4 (NIR), it is apparent that there is a non-linear sensor response for the high surface reflectance range (Figure 4). This non-linear response is common in most radiometers and can be resolved by setting the gains and offsets to avoid very low and very high *dn* values.

The fit for the thermal calibration was good with the exception of the temperature measurement made over the 0.64 reference tarp. This may have been due to the fact that the temperature measurement was made on the edge of the tarp and the pixel *dn* was extracted from the center. For subsequent overflights, we made temperature measurements in the tarp centers.

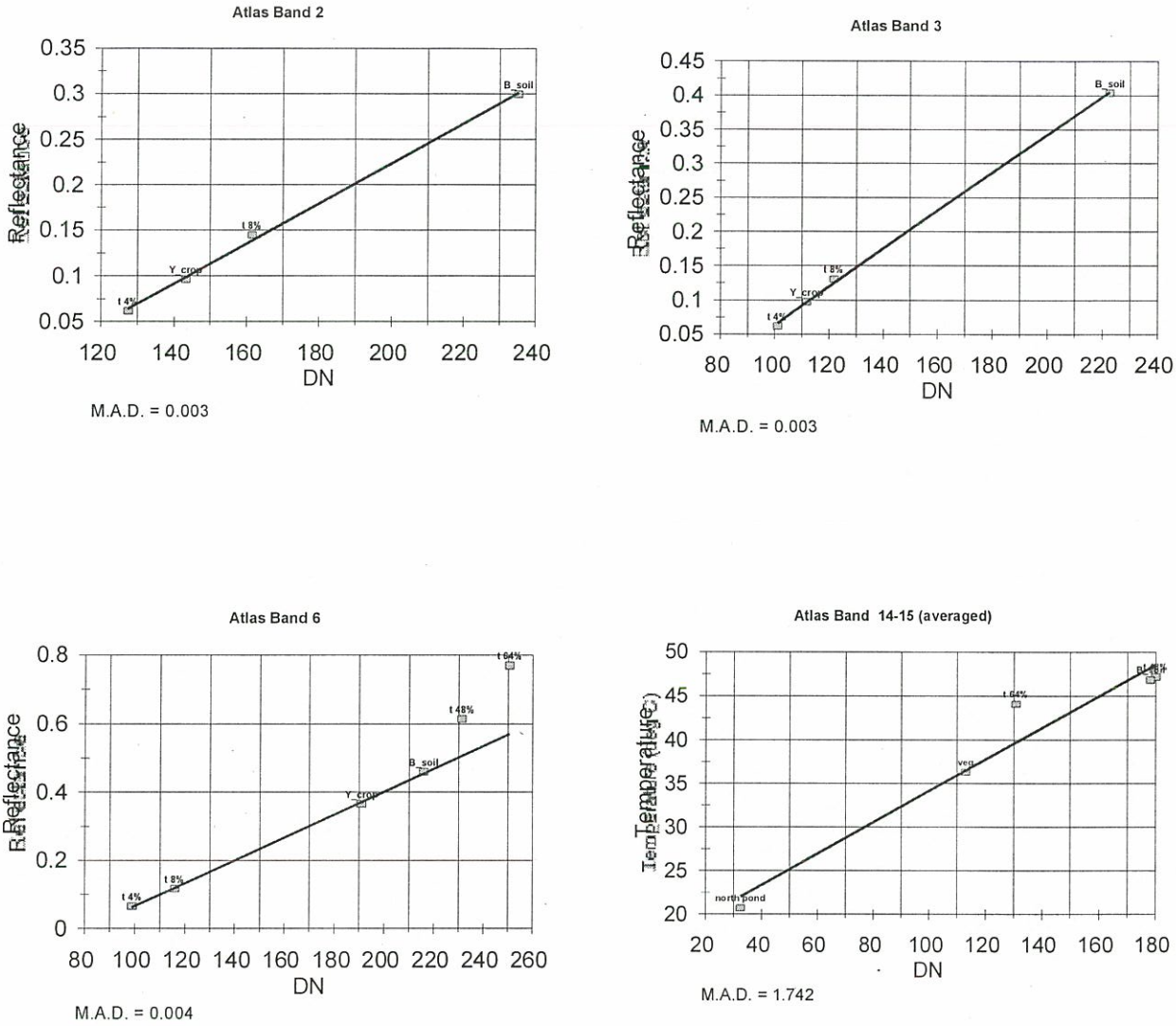


Figure 4. The dn–to–reflectance and dn–to–temperature relations derived for ATLAS Green, Red, NIR, and thermal bands based on ground-based deployment of tarps and radiometers during ATLAS overflight #2 at MAC. The terms "t4%," "t8%," "t48%," and "t64%" refer to tarps of 0.04, 0.08, 0.48, 0.64 reflectances. The terms "Y_crop" or "veg" and "B_soil" refer to measurements of the alfalfa crop and dirt landing strip, respectively. The "north pond" is a shallow fish pond located at MAC. "M.A.D." = Mean Absolute Difference.

View-Angle Induced Variations in Reflectance

The variations induced by off-nadir sensor viewing are readily apparent in the ground-based measurements of surface reflectance over a cotton crop at MAC (Figure 5). Generally, the reflectance is higher in the backscattering direction (negative view angles), reaching a maximum when the view angle equals the solar zenith angle. This trend was most extreme when the measurements were made along the principal plane of the sun and less extreme

when deviating from the principal plane, resulting in minimal effects when the measurements were made in a plane orthogonal to the principal plane.

To assess the view-angle effects of the wide FOV ATLAS imagery, *dn* values for two sites (the landing strip and a vegetated alfalfa field) were extracted from the overlapping sections of five flight lines. Based on the location of the site within the flight line, the sensor view angles (ranging from +26° to -26°) for each measurement were computed. At the time of the ATLAS overflight at MAC, the sun was nearly directly south, resulting in ATLAS sensor views (to the east and west) close to the principal plane of the sun. The trend of ATLAS *dn* with view angle is consistent with expectations: the *dn* was relatively low in the forward-scattering direction and high in the back-scattering direction (Figure 6). The magnitude of the effect was substantial; that is, for both the landing strip and the alfalfa, the measured *dn* could vary by up to 40 counts due simply to the location of the site in the ATLAS flight line.

Concluding Remarks

Based on our experience to date, we have the following suggestions for image acquisition and format.

What Has Worked Well

The minimum two-day *advance notice* of overflight allowed us to mobilize a large field crew for ground-based measurement. The *precision flights* were reliably on time and on target. The SSC flight crew made a *phone call* to the USDA ground crew on the morning of the overflight to adjust the flight time to avoid cloudy weather. The flight *mission design* has been ideal for our agricultural applications; we were able to obtain complete farm coverage with less than 10-degree viewing angle (to avoid bidirectional effects), complete farm coverage with viewing angles as great as 26 degrees (to study bidirectional effects), repeat flightlines for studies of effects of solar angle variations, and spectral (VIS/NIR/SWIR/thermal) and spatial (2.5 m) resolutions suitable for within-field studies. The *rapid turnaround* time for images and the accompanying reports have been very useful for monitoring rapidly changing crop and soil conditions. The *CIR photographs* have been most helpful for interpreting the spectral information in the ATLAS images. The *adherence to the schedule* of flights has allowed us to obtain images corresponding to critical crop phenologic stages.

The *ground-based data* have proven useful for assessing image quality and for documenting crop and soil conditions. The multiple tarps provided a stable ground reference target, but deployment was tedious and particularly difficult with windy conditions. The tarp size and reflectance range was barely suitable for this application; larger tarps and a greater range of reflectance (e.g., 0.16 and 0.32) could have improved our confidence in the results. The complete field surveys we conducted during each overflight have proven valuable for interpreting image anomalies two weeks after image acquisition. The multitude of data acquired by the interdisciplinary team will provide a wealth of information for continuing analysis.

The *visits of SSC personnel* to the MAC field site during several overflights were very useful for both SSC and USDA scientists. The SSC scientists learned the magnitude and limitations of the field effort and the USDA scientists learned more about the image acquisition and processing. This was a very fruitful exchange.

How Things Could Be Improved

The *geometric correction* of the ATLAS imagery was insufficient for automated, within-field analysis of crop and soil spectral responses. The error in image geometric registration was often as large as 100 m and was variable throughout each flight line. The V&V Team at SSC is currently conducting research to develop a better geometric correction process (Scarpace, 1998).

The *radiometric quality* of the imagery appears to be good (see Figure 4); however, the settings of the gains and offsets resulted in substantial image saturation and loss of data. Furthermore, the in-flight adjustments to the gain make flight line-to-flight line and flight-to-flight data analysis of raw *dn* nearly impossible. Considering that the ATLAS sensor is designed with an on-board calibration unit, we suggest that the images be converted to values of radiance or temperature to account for the gain and offset. We also suggest that a means of setting site-appropriate gains and offsets be determined and implemented to avoid saturation.

With more *ground personnel*, it would have been beneficial to obtain ground-based photographs of each field during the overpass. It would also have been helpful to make the ground-based spectral measurements with a hyperspectral instrument covering the VIS/NIR/SWIR/TIR to allow integration of all 14 ATLAS bands. Also, meteorological information from a radiosonde balloon launch would have been useful for thermal atmospheric correction. A permanent ground-based reference target, similar to the target at SSC, would circumvent the four-person task of tarp deployment and would allow limited field personnel to make other important measurements.

Communication could have been improved if a dedicated site liaison had been designated at SSC for this project. In some cases, we found that information from USDA was not received by the person most knowledgeable about the issue, and results from SSC staff efforts were not always passed on to USDA personnel. However, on the whole, we have been pleased with the effort made by all SSC personnel to make this project a success.

Acknowledgments

The work in Arizona has been a cooperative, interdisciplinary effort of a number of scientists, including myself, Ed Barnes, Tom Clarke, Paul Pinter, Jiaguo Qi, and Alfredo Huete; with invaluable assistance by a team of support scientists, technicians, and students, including Mike Baker, Ric Rokey, Suzette Gerszewski, Kathy West, Wanmei Ni, Michael Helfert, Ross Bryant, Chandra Holifield, Pam Nagler, Karim Batchily, and Dan Hymer. Special thanks go to the staff at MAC; our SSC visitors Joe Spruce, Risa Wu, John Foster,

and Steve Tate; to the ever-patient coordinators Jeff Jenner and Rodney McKellip; and to the ATLAS flight crew.

Reference

Scarpace, Frank, 1998. Geometric Correction of Multispectral Airborne Sensor Data, *V&V Symposium '98: NASA Commercial Remote Sensing Verification and Validation Symposium,* CD-ROM, John C. Stennis Space Center, August 4-6.

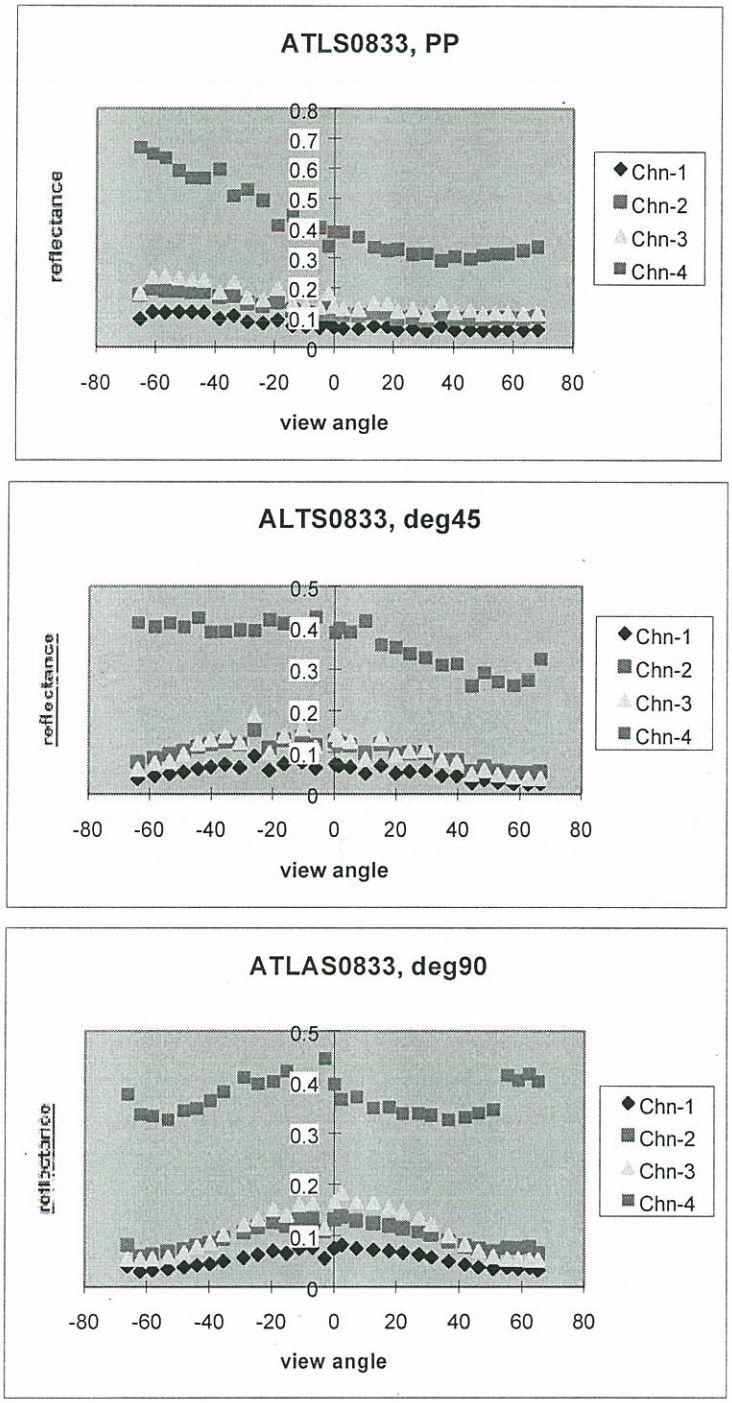
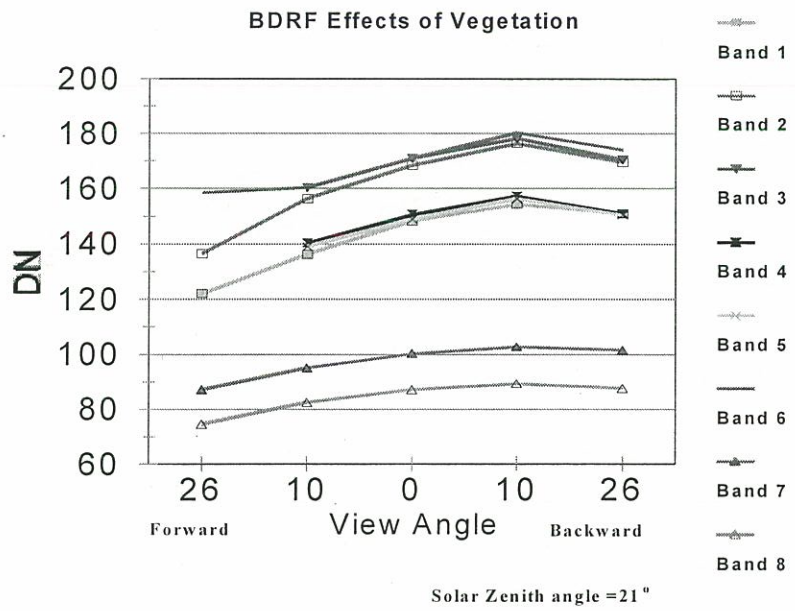


Figure 5. Ground-based measurements of surface bidirectional reflectance of a cotton canopy in blue, green, red, and NIR spectral bands (labeled Channels 1-4) at 8:33 a.m. along three viewing planes: PP≡principal plane of the sun; deg45≡45 degrees off the principal plane; and deg90≡orthogonal to the principal plane.



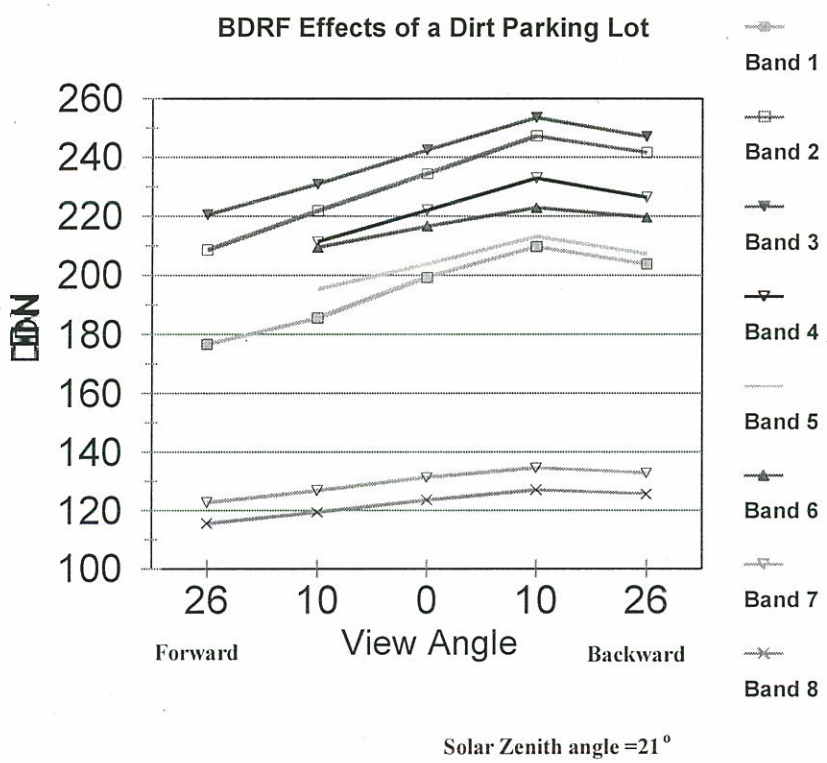


Figure 6. ATLAS measurements of surface bidirectional reflectance of a cotton canopy and a packed-earth landing strip in the eight reflective spectral bands (labeled 1-8) at about 11:00 a.m. along a plane close to the principal plane of the sun. Note that the forward and backward scattering directions are reversed from the presentation format in Figure 5.

Appendix A. Specifications of the ATLAS.

Spectral Coverage (in micrometers):

VISNIR	TIR
Ch. 1: 0.45-0.52	Ch. 10: 8.20-8.60
Ch. 2: 0.52-0.60	Ch. 11: 8.60-9.0
Ch. 3: 0.60-0.63	Ch. 12: 9.0-9.4
Ch. 4: 0.63-0.69	Ch. 13: 9.6-10.2
Ch. 5: 0.69-0.76	Ch. 14: 10.2-11.2
Ch. 6: 0.76-0.90	Ch. 15: 11.2-12.2
SWIR	
Ch. 7: 1.55-1.75	
Ch. 8: 2.08-2.35	

Digitization: 8 bit

Spatial Specifications:

FOV: 72 degrees
IFOV: 2.0 mrads
Pixels/Line: 640 ground scene and 3 calibration source pixels
Scan Speed: 6-50 scans/second
Ground Resolution: 2.5-25 m

Aircraft:

Platform: Learjet 23
Altitude: Up to 41,000' above MSL
Power: 50A @ 28 VDC, max

Geometry:

GPS: Trimble 4000SSE
GPS Accuracy: 1.5m RMS (corrected)
Navigation System: Trimble 2101 (GPS Based)
Gyro Accuracy: 0.4 degrees
Roll Correction: +/- 15 degrees

Calibration:

Thermal: Blackbody
VIS/NIR: Integrating Sphere