EVALUATION OF THE USE OF DARK AND BRIGHT TARGETS FOR THE IN-FLIGHT CALIBRATION OF AVIRIS

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1. INTRODUCTION

One of the goals of NASA's Mission to Planet Earth (MTPE) is to create a set of long-term observations for the study of global change using multiple sensors on multiple platforms (Asrar and Dozier, 1994; Slater et al., 1996; Barnes and Holmes, 1993). These sensors will monitor environmental changes on a global scale for both terrestrial and aquatic targets (Hooker et al., 1993). For instance, the Earth Observing System's AM-1 platform has five sensors with each sensor having its own calibration team. Critical to the success of MTPE is ensuring the accuracy of the radiometric measurements over the lifetime of each platform and traceability between platforms. This can only be accomplished for the 18-year MTPE program through vicarious calibration (Slater and Biggar, 1996).

Vicarious calibration refers to methods of in-flight calibration that do not rely on onboard calibrators. Hovis et al. (1985) made one of the earliest vicarious calibrations by measuring the radiance above a ground target from a high-altitude aircraft to verify the degradation of the Coastal Zone Color Scanner's shorter wavelength bands. Since then, many types of vicarious calibration have been developed. For example, Kaufman and Holben (1993) propose 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) propose a similar approach for Systeme Pour l'Observation de la Terre-1 (SPOT), Haute Resolution Visible (HRV) cameras but used data at longer wavelengths to determine contributions from aerosols and sea-surface reflection.

The two methods used in this work rely on in-situ measurements to improve accuracy and are referred to as the reflectance- and radiance-based techniques (Slater et al., 1987). The reflectance-based method relies on ground-based measurements of the surface reflectance and atmospheric extinction at a selected site to predict top-of-the-atmosphere radiance at the time of satellite overpass. The radiance-based approach refers to methods such as that of Hovis et al. (1985) where the radiance from the target is measured by a well-characterized and well-calibrated radiometer at the same time the sensor to be calibrated views the target. The advantage of this technique is that the radiometer can be carried in an aircraft above most of the influence of the atmosphere, greatly reducing uncertainties from the atmospheric characterization. These two techniques have been used successfully for the SPOT HRV (Gellman et al., 1993), Landsat-5 Thematic Mapper (TM) (Slater et al., 1987, Thome et al., 1993), a Daedalus scanner (Balick et al., 1993), and the Airborne Visible and Infrared Spectrometer (AVIRIS) (Vane et al., 1993). The test sites for this past work have all been high-reflectance, land targets.

Included in MTPE are sensors designed for ocean-color studies. These sensors have high sensitivity and will saturate over the high-reflectance sites typically used for vicarious calibration. Thus, the vicarious calibration of these sensors requires low reflectance targets. The use of water sites is a natural choice since the operational conditions of the sensor is more closely reproduced. Using low-reflectance targets adds complexities to vicarious calibration due to the fact that the atmosphere contributes a much higher portion of the radiance at the sensor. In order to achieve the same calibration uncertainty levels, the atmospheric characterization must be

better than is necessary when using high-reflectance targets. The use of water targets also requires developing more sophisticated radiative transfer codes to account for the specular reflection of the air-water interface as well as factors such as the surface's wave-slope distribution, the diffuse water and foam reflectances, and the coupling of radiance between water and atmosphere.

The AVIRIS sensor is a natural choice to evaluate the use of both bright and dark targets for vicarious calibration of satellite sensors. The hyperspectral nature of the sensor allows the bands of the MTPE sensors to be synthesized, allowing uncertainties of the vicarious calibration to be determined for the specific sensor bands. AVIRIS is also capable of flying at high altitude, thus closely simulating the atmospheric path seen by satellite sensors. In addition, the preflight calibration and characterization of AVIRIS, coupled with the reliability of AVIRIS makes it a good choice for testing vicarious calibration.

In this work we present the reflectance-based and radiance-based results from two campaigns. The first was to Lake Tahoe in June 1995 and marked the first attempt by the Remote Sensing Group (RSG) at the University of Arizona (UA) to use a dark, water surface for vicarious calibration. Radiance data from a low-altitude aircraft, surface measurements of water reflectance, and atmospheric characterization were used to predict the radiance at the altitude of the AVIRIS sensor. The vicariously-derived calibration coefficients are compared to those obtained from a preflight calibration of AVIRIS. The reflectance-based method, agrees at the 0.3-7.7% level with the preflight coefficients and the radiance-based method, differs from the preflight results by 1.0-17.5%. The second campaign was a joint vicarious campaign held in June 1997 to evaluate the accuracy of reflectance-based, vicarious calibrations. Six groups participated in this campaign and made independent measurements of surface reflectance and atmospheric transmittance on five different days. The results of this campaign, using a high-reflectance playa, were compared to those of the AVIRIS sensor to look for biases in the reflectance-based approach. Results from this campaign showed that the radiance at AVIRIS could be predicted to better than 5% for most bands not affected by atmospheric absorption.

2. METHODS

2.1 Reflectance-based Method

The reflectance-based method relies on characterizing the surface of, and the atmosphere over, a test site at the time of a sensor overpass. The results of the measurements are used as input to a radiative transfer code to predict a normalized radiance at the sensor that is converted to absolute radiances via an assumed solar irradiance curve. The atmospheric characterization typically relies on solar extinction measurements and these data are converted to spectral optical depths that are used to describe aerosol parameters and columnar amounts of gaseous absorbers (Gellman et al., 1991; Biggar et al., 1990; King et al., 1978; Flittner et al., 1993; Thome et al., 1992). Surface characterization typically consists of measuring the upwelling signal from the test site and ratioing to data collected while viewing a panel of known reflectance to obtain the surface reflectance of the site (Biggar et al., 1988). Past work shows the uncertainties expected from the reflectance-based approach are better than 5% for regions in the VNIR not affected strong absorption and that the primary source of uncertainty in aerosol parameters such as refractive index and size distribution (Biggar et al., 1994). Uncertainties in the surface reflectance are also a significant error source. Biggar et al. (1994) also show that reasonable improvements in equipment and data collection methods should bring these uncertainties to less than 3.5%.

For low reflectance targets, uncertainties in the predicted radiance due to atmospheric uncertainties are higher due to the relative importance of atmospheric signal contributions. The successive orders of scattering ((SOS) radiative transfer code has been used for the Lake Tahoe data (Deuzé. et al., 1989). The primary advantage of using the SOS transfer code is its ability to handle a rough ocean surface and polarization of the radiance field. Gaseous absorption is computed separately using the Second Simulation of the Satellite Signal in the Solar Spectrum (6S) transfer code (Vermote et al., 1995). Band integrated transmittance values for ozone and water vapor are computed using columnar measurements while absorption from oxygen and other molecular gases are computed using standard atmospheric models. The Lunar Lake data set is processed using a hyperspectral

version of a Gauss-Seidel iteration radiative transfer code and MODTRAN3 to determine the exo-atmospheric solar irradiance and gaseous transmittance (Thome et al., 1996).

2.3. Radiance-based Method

The radiance-based method uses aircraft-based measurements of the spectral radiances over a calibration site at sensor overpass. An atmospheric correction is made for the effects between the aircraft and sensor being calibrated using the atmospheric and surface reflectance data collected for the reflectance-based approach. As with the reflectance-based method, the RSG uses the SOS code for radiance-based calibrations over water targets and the 6S code to compute gaseous absorption. Over bright land targets, the hyperspectral Gauss-Seidel iteration code is used. These codes are used to transfer the aircraft-level radiances to sensor level. Past work shows the uncertainties expected from the radiance-based approach are better than 3% for regions in the VNIR not affected strong absorption and that the primary source of uncertainty is the calibration of the radiometer in the aircraft (Biggar et al., 1994). Biggar et al. (1994) also show that reasonable improvements in equipment and data collection methods should bring these uncertainties to less than 2.0%.

3. CALIBRATION AT LAKE TAHOE

3.1 Test Site Description

Data were collected for a vicarious calibration of AVIRIS on June 22, 1995. This field campaign was a joint effort between the RSG, the Marine Research Group of the University of South Florida, the Naval Research Laboratory, and the Jet Propulsion Laboratory (JPL). Lake Tahoe is a deep graben fault lake located on the California-Nevada border (39.1° N, 120.0° W) at an elevation of about 1.9 km above mean sea level (MSL). At this elevation, the aerosol loading is low. Since aerosol signal contributions constitute one of the largest sources of uncertainty in the vicarious calibration process, low aerosol loading is a desirable feature for any prospective site. Other benefits from the use of this lake include its large size (approximately 19 km by 32 km), the high probability of cloud-free conditions, the presence of a high contrast shore line to facilitate image registration, and the relatively clear water. Disadvantages of this location include the low upwelled signal levels (due to the smaller optical depths between the site and sensor), and the need to make assessments of adjacency effects from the vegetation surrounding the lake.

During the calibration period, the aerosol loading was low (aerosol optical thickness of 0.051 at 560 nm) and only a few scattered cumulus clouds were present. Winds were light, averaging around 0.75 m/s throughout the morning. Image data were acquired by AVIRIS at approximately 18:19 Universal Coordinated Time (UTC). The viewing geometry for the portion of the lake where reflectance data were collected was at a nadir angle of 1.7 degrees and azimuth of 186.1 degrees. An average of 48 pixels was used to compute the mean, dark-corrected band readings corresponding to the portion of the lake that where surface reflectance measurements were made.

3.2 Radiance-based Vicarious Calibration

The radiometer used in the radiance-based approach was a seven-band system that essentially simulates the solar-reflective bands of TM with an additional band in the shortwave IR. For this work, only the first four bands were used corresponding to center wavelengths of 0.49, 0.56, 0.66, and 0.83 μm. The radiometer was mounted in a Cessna-180 airplane and flown at an altitude of 3.9 km above sea level . Simultaneous video was collected to aid in the registration of the low-altitude data to the AVIRIS data. Three passes of the test site were made around the time of the AVIRIS overflights. The atmospheric and lake reflectance data collected in conjunction with the reflectance-based method were also used for the radiance-based calibration process. Calibration coefficients for the seven-band radiometer were obtained using a solar-radiation-based technique (Biggar et al., 1993). The resulting calibration coefficients determined for AVIRIS from the radiance-based approach are given in Table 1.

The differences st the two shorter bands are quite small, 1-4% and get much larger at the two longer-wavelength bands. This is somewhat as expected since the radiance decreases at these longer wavelengths due to reduced scattering and thus there is lower signal to noise. Uncertainties in the calibration of the MMR are relatively insensitve with wavelength with a value of 3.0% for band 1 and 2.5% for band 4. The largest source of uncertainty in the measured radiance by the MMR is the pointing error of the radiometer. For the case

Table 1				
Results of June 22, 1995 AVIRIS calibrations. Calibration coefficients are quoted in units of $(W\ m^{-2}sr^{-1}\mu m^{-1})$ / DN for Barnes MMR band centers.				
Method	Band 1	Band 2	Band 3	Band 4
Preflight	0.2344	0.1785	0.1603	0.1113
Reflectance-based	0.2525	0.1791	0.1627	0.1121
Radiance-based	0.2440	0.1768	0.1388	0.0918

shown in this work, a 2° pointing uncertainty gives changes in radiance of 5.2% for band 1 to near 50% for band 4. This is primarily due to the larger relative importance of specularly reflected sunlight at the longer wavelengths.

3.3 Reflectance-based results

Surface measurements of the water properties at the time of the AVIRIS overflight were made from a research vessel on the lake. An anemometer was used to measure wind speed around the time of sensor overpass. Diffuse water reflectance was measured using a hand-held spectroradiometer designed and built by the group from the University of South Florida. Due to the relatively calm state of the water, foam contributions are assumed to be negligible. The resulting calibration coefficients determined from the reflectance-based method for the four MMR bands are presented in Table 1. The differences between the AVIRIS results and the reflectance-based values range from 0.3% for band 2 to 7.7% for band 1.

This is remarkably good agreement for a first attempt at this type of calibration. The larger differences at the shorter wavelengths are expected because of the larger signal due to scattering. Thus, any uncertainties in characterizing the atmosphere will lead to larger uncertainties in the predicted radiance at shorter wavelengths. Modeling of the reflectance uncertainty shows that largest uncertainties in predicted radiance will occur at longer wavelengths. This is true both for effects due to wave-slope uncertainties as well as the measuring the diffuse reflectance. Thus, the differences seen here are most likely dominated by atmospheric uncertainties.

4. CALIBRATION AT LUNAR LAKE

4.1 Test Site Description

The purpose of the Lunar Lake campaign was to have several groups collect data for reflectance-based calibrations for comparison. Lunar Lake was selected because its high reflectance and the low aerosol in the region reduce uncertainties due to atmospheric effects. The area is spatially uniform with portions of the playa varying by less than 0.5% of the reflectance over $10^4\ m^2$ areas and this reduces uncertainties in determining the surface reflectance. The playa is slightly smaller than an ideal site, being approximately 3 km by 5 km in size, but this should not be a factor in any comparisons between groups. The surface of the playa is also very hard and resistant to change from people walking on it. This makes the site suitable for an experiment where several groups would be walking on the site for several days with multiple collections each day. The primary area used for the work described here was a 360-m by 120-m representative area of the playa assumed to approximate 48, 30-m pixels. This area was located at approximately 38 degrees 23 minutes North and 115 degrees 59 minutes West and was laid out in an east-west orientation.

While several groups participated in the campaign, including groups from Japan and Canada, results from only three of the groups are discussed here. These three groups are from the UA, JPL, and South Dakota State University (SDSU). The field work consisted of several data collections per day for several days. The

times were selected to correspond approximately to the time of the EOS-AM1 platform overpass. All groups essentially used the same approach for collecting surface reflectance data using ASD FieldSpec FRs for the measurements and referencing playa data to measurements of Spectralon® panels to convert to reflectance. Atmospheric measurements were primarily made using solar radiometers constructed in the UA's Electrical and Computing Engineering Department. The JPL and SDSU groups used automated versions of these solar radiometers while the UA group operated a manual version. The JPL and SDSU groups also collected measurements of downwelling global and diffuse irradiance using multi-filter, shadow-band radiometers and the UA group made similar measurements with an occulting disk system.

4.2 Reflectance-based results

The primary purpose of the campaign was to compare the results of vicarious calibrations that will be similar to those used for the vicarious calibration of EOS AM-1 sensors. From a previous campaign, it was known that a primary cause of differences between vicarious results is in the retrieval of surface reflectance (Thome et al., 1998). For this campaign, efforts were made to more closely examine retrieved surface reflectance. Table 2 gives an example of some of the results obtained for measurements of the playa surface for several bands from the ASTER, ETM+, and MISR sensors. As can be seen, the retrieved reflectances agree very well. Similarly good results were obtained for predicted radiances for the several data sets that were collected for looking at predicted radiances at the top of the atmosphere with differences less than 5% for most bands and less than 12% for all bands. Further evaluation of the entire set of results is currently underway in an attempt to understand the causes of differences.

Two overflights of the AVIRIS sensor were scheduled during the campaign. The overpass on June 27 occurred during cloudy skies and no ground data were collected coincident with the overflight. The other overflight took place on June 23. In this work, we present the results from the UA group only, since the focus of this paper is to look at differences in using bright and dark targets for vicarious calibration. Future work will include more detailed discussions of the AVIRIS results in reference to the results from all of the groups at the Lunar Lake campaign. The output from the UA radiative transfer code for atmospheric scattering and ozone absorption is at one-nm intervals. The results are based upon inputs derived from inversion of solar radiometer data. Atmospheric transmittance was determined using MODTRAN3 based on input columnar water vapor from solar radiometer data. The data were then band-averaged over 10-nm intervals to derive radiances that could be directly compared to those from AVIRIS. Figure 1a shows the radiances derived from AVIRIS and those based on the field data for the VNIR portion of the spectrum and Figure 1b shows results for the SWIR. Figure 2b shows the percent difference between the reflectance-based radiances and those from AVIRIS.

There are several notable features to note in Figures 1 and 2. First is that the percent difference is large in regions of strong water vapor absorption. This is due to poor surface reflectance retrievals in these bands due to low signal. To avoid this problem, it is possible to curve fit the spectral reflectance in regions of strong atmospheric absorption. This is currently underway and should improve the comparisons in these spectral regions. Also noticeable is the larger discrepancies at shorter wavelengths. There are several possible causes for this. The first is that the spectral reflectance of the Lunar Lake Playa is rapidly changing with wavelength at the short end of the spectrum. Shifting the input surface reflectances by 4 nm gave much better agreement at these

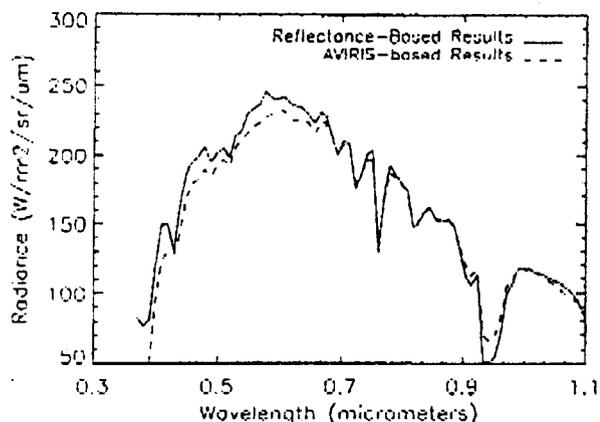| Table 2 Retrieved surface reflectances of Lunar Lake Playa from June 24, 1998 for sensor bands given									
	MISR 1	MISR 2	MISR 3	MISR 4	ASTER 2	ASTER 4	ASTER 5	ETM+ 1	ETM+ 5	ETM +7
UA	0.268	0.411	0.488	0.521	0.483	0.523	0.482	0.303	0.523	0.467
JPL	0.292	0.411	0.480	0.516	0.480	0.531	0.482	0.324	0.523	0.472
SDSU	0.267	0.410	0.492	0.526	0.488	0.532	0.491	0.303	0.532	0.475

Figure 1a At-sensor radiances in the VNIR at AVIRIS from measurements and reflectance-based predictions.
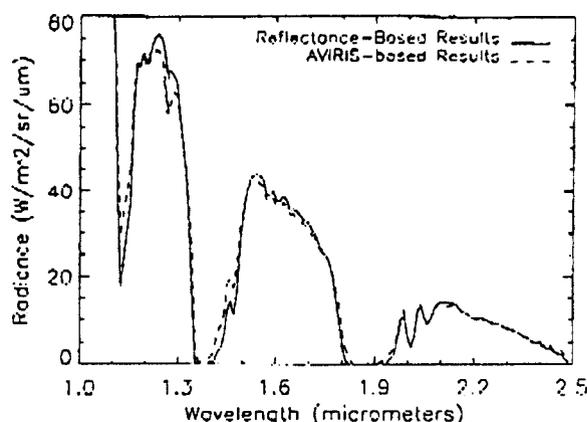
Figure 1b At-sensor radiances in the SWIR at AVIRIS from measurements and reflectance-based predictions.

wavelengths. Studies of the surface reflectance data are currently underway to determine if this shift is feasible. Another explanation is that laboratory calibrations of radiometer's are typically less accurate at shorter wavelengths due to the low output of laboratory sources. However, it is doubtful that the large differences at these wavelengths could be entirely due to this effect. Finally, the effects of the atmosphere are more important at short wavelengths due to greater scattering. If the aerosols are improperly characterized, then this would be more noticeable at shorter wavelengths. Even with these large differences, the agreement between the reflectance-based results and those from AVIRIS is quite good.
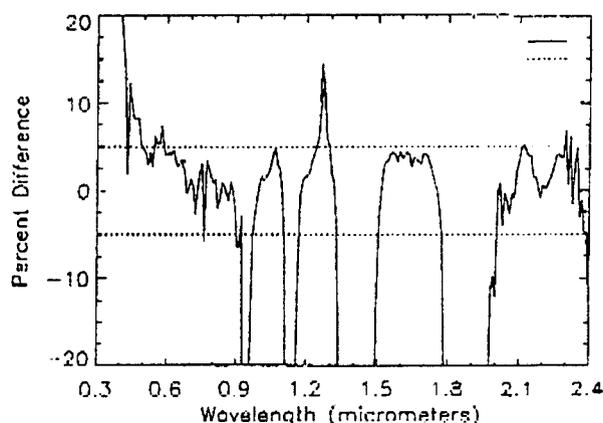

Figure 2 Percent difference between reflectance-based predictions of at-sensor radiance and the measured AVIRIS radiances

5. CONCLUSIONS

During a field campaign at Lake Tahoe on June 22, 1995, calibrations of AVIRIS were attempted using both the reflectance-based and radiance-based methods. This experiment shows that the use of dark, water targets to calibrate radiometric sensors can result in meaningful sensor characterization. In particular, the reflectance-based method shows promise towards meeting the desired 2-3% uncertainty levels for ocean color sensors since experimental agreement of better than 1.5% is found for the Lake Tahoe AVIRIS experiment. Similarly promising results were found from reflectance-based calibrations at Lunar Lake with large portions of the spectrum having less than a 5% difference between the reflectance-based predictions and the measured AVIRIS radiances. These results are still in the preliminary stage and it is likely that further study of this data set will lead to even better agreement. The results of the radiance-based calibration at Lake Tahoe are quite good at the shorter wavelengths where atmospheric scattering leads to larger signals and smaller effects of specularly reflected solar energy. The results also showed the sensitivity to radiometer pointing when using water targets for vicarious calibration.

6. ACKNOWLEDGEMENTS

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