Semi-annual EOS Contract Report
Period: July 1 - December 31, 1998
Remote Sensing Group (RSG), Optical Sciences Center (OSC) at the University of Arizona
Principal Investigator: K. Thome
Contract Number: NAS5-31717

Summary: During this six-month period, Remote Sensing Group personnel attended meetings related to MODIS and ASTER, including the MODIS Science Team meeting in December and a meeting related to a calibration round robin at Ames Research Center. A cross-calibration software package was completed and tested using a SPOT HRV-Landsat TM pair of images of White Sands and a SPOT HRV-AVHRR pair from Railroad Valley. Evaluation of the diffuse-to-global instrument continued as did work on the BRDF camera. Several field campaigns were made to Ivanpah Playa for characterization of the MASTER sensor and testing of an airborne radiometer took place at Railroad Valley and Lake Tahoe. Automation of the group's blacklab measurements is nearly complete and a study of the distance dependency of irradiance from standards of spectral irradiance was finalized.

Introduction: This report contains eight sections. The first seven sections present different aspects of work performed under our contract. If appropriate, each section covers five areas; task objective, work accomplished, data/analysis/interpretations, anticipated future actions, and problems/corrective actions. The first seven sections are: 1) Science team support activities; 2) Cross-calibration radiometers; 3) Bi-directional reflectance distribution function (BRDF) meter; 4) Diffuse-to-global meter; 5) Calibration laboratory; 6) Algorithm and code development; and 7) Field experiments and equipment. The eighth section contains information related to faculty, staff, and students.

Science Team Support Activities: This section refers to all work performed in support of MODIS and ASTER team activities as well as work performed for other sensor teams. Over the past six months this included the attendance at team and other related meetings and completing assigned action items.

S. Biggar and K. Thome attended the MODIS Science Team Meeting held in College Park December 15 and 16. Thome attended the Land Discipline meeting December 17 and Biggar attended the Ocean Discipline meeting held on the same day. Both Biggar and Thome also attended a briefing held by MCST on December 14 describing the characterization and correction of the response-versus-scan-angle problem in the TIR bands of MODIS.

J. Smith and P. Nandy attended the IGARSS conference in Seattle in July. Smith presented a poster on her paper entitled "Field evaluation of a diffuse-to-global irradiance meter for vicarious calibration," and Nandy presented a talk on the paper entitled "An Instrument for BRDF Retrieval for Vicarious Calibration." Thome and E. Zalewski attended the SPIE Conference in July in San Diego where Thome presented a paper on the calibration of Vegetation using vicarious methods and Zalewski presented a paper on the on-board calibration system for a visible to infrared multispectral imaging sensor. Thome traveled to Irvine, California to attend a meeting of the Committee on Earth Studies of the National Academy of Science on November 4 where he presented a summary of vicarious calibration techniques. He also attended a workshop sponsored by the Goddard Institute for Space Sciences on solar photometry held August 11-13 and the first meeting of the Global Aerosol Science Team held at the same location from November 18-20.

Cross-Calibration Radiometers: This section describes work related to a set of cross-calibration radiometers (CCRs) that cover the wavelength region from 400 to 2500 nm. We have constructed two radiometers to accomplish this with each radiometer optimized for a specific portion of the spectrum. Both use interference filters for spectral selection and have low stray light and polarization responses, exhibit sharp, and well-defined fields of view and spectral response profiles. The radiometers are ultrastable with respect to temperature and time and have been used to provide an important independent calibration and cross-calibration of the calibration facilities used for the preflight calibration of EOS sensors.

The VNIR CCR covers the 400- to 900-nm spectral range and is compared directly to NIST-calibrated and NIST-traceable standards of spectral irradiance. Biggar designed the radiometer with three silicon detectors in a "trap" configuration and two precision apertures determine the field of view. The SWIR CCR operates in the 1000- to 2500-nm spectral range and is compared to NIST-calibrated and NIST-traceable standards of spectral irradiance and pressed PTFE (Algoflon) targets. The system is designed around a chopped, lock-in amplified InSb detector and the field of view is defined by a cryogenically-cooled baffle system.

Biggar traveled to San Francisco October 26-27 for a meeting at Ames Research Center (ARC) with J. Butler of GSFC, C. Johnson and S. Brown of NIST, and the ARC personnel responsible for the calibration of MAS and MASTER. The group discussed methods for cross-calibrating the 30-inch spherical integrating source (SIS) and two smaller hemispherical sources used by ARC for preflight calibration of MAS and MASTER. Also included in the discussion were improvements needed to the ARC facility prior to a calibration round-robin experiment. Current plans are to hold this round-robin at ARC in February1999 using both the SWIR and VNIR CCRs in conjunction with the NIST transfer radiometers.

Biggar worked in the RSG's blacklab to understand temporal changes in the response of the SWIR CCR over the course of a day seen while testing the new equipment in the blacklab. The cause appears to be poor vacuum pumping of the radiometer's dewar allowing the detector to warm slightly with time. E. Nelson ordered new vacuum valve plugs and O-rings for the vacuum pump used to pump down the dewar. Biggar checked past data from the SWIR for problems, but operation of the radiometer in round-robin experiments included frequent filling of the dewar, so this effect was not a problem.

Biggar and J. LaMarr began investigating the possibility of performing solar-radiation based calibrations of both radiometers. Past results with the VNIR CCR have shown good agreement with results from G. Thuillier. By mounting our Spectralon panel vertically, we can then collect data with both the VNIR and SWIR CCRs. The horizontal operation of the SWIR CCR will prevent spillage of the liquid nitrogen from the radiometer's dewar. A major outcome of such an experiment is that it will allow a direct link between the laboratory standards used to calibrate EOS sensors and the solar irradiance standards used in many radiative transfer codes and Level 2 processing algorithms.

Biggar also modified software to control the VNIR CCR to correct communication problems between the computer and data collection hardware caused by an upgrade in the controlling computer. P. Nandy used the VNIR CCR to begin characterizing the spatial uniformity of our 40-inch spherical integrating source (SIS). Figure 1 shows a plot of the relative output of the SIS as a function of position. The results clearly shows a variability in SIS output at the 1% level showing the importance of such a data set for the calibration of the BRDF camera system.

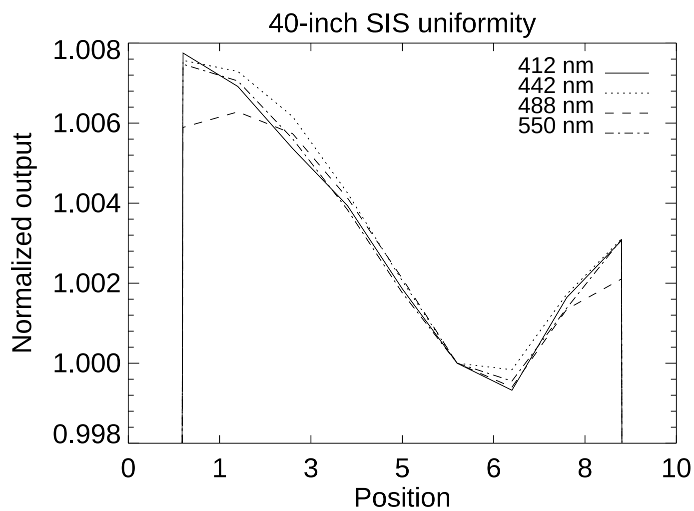

Figure 1. VNIR CCR data showing spatial uniformity of 40-inch SIS.

<u>BRDF Meter:</u> The objective for this task is to design and construct a device, and develop software for measuring the directional reflectance and inferring the bi-directional reflectance distribution function of the ground. The basic design incorporates a fisheye lens, a CCD-array detector, and interference filters for spectral selection.

Nandy processed BRF data collected during the May Railroad Valley campaign using previously-developed, batch-processing routines. Figure 2 shows a set of measurements from this campaign corrected for the relative angular response of the camera. The solid curve shows the full-spatial resolution data for a single azimuthal direction corresponding to the predicted cross-track direction of EOS AM-1 for a sun angle typical of this site for the spring and fall for the predicted overpass time of AM-1. The broken curves are 15-degree running averages of the full resolution data for two spectral bands corresponding to Thematic Mapper bands 1 and 3. The full resolution data clearly shows the problems with surface homogeneity that must be addressed for this approach to work. The results shown, as well as other data collected during this campaign, indicate that the BRF of the playa is within 10% of lambertian for view angles out to almost 60-degrees. Further evaluation of these data are underway to determine the feasibility of modeling the BRF of the playa. Data from the June campaign described below are being evaluated to determine if there are effects due to spatial location, surface moisture, and other effects. These data are being examined in conjunction with further development of data processing software.

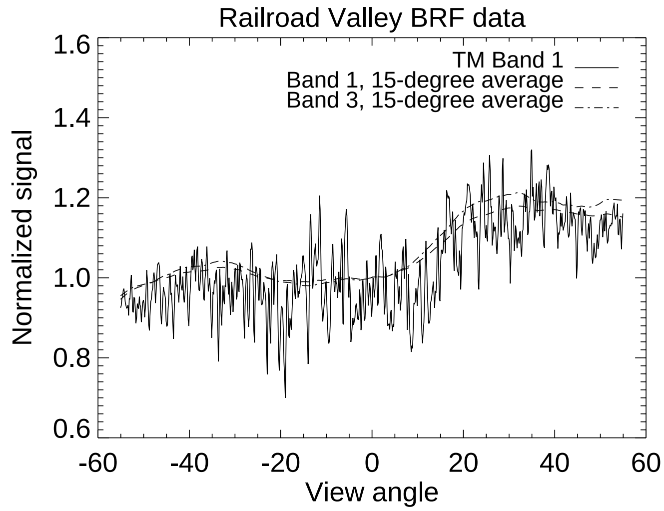

Figure 2. BRF camera data collected at Railroad Valley Playa for the cross-track scan direction of EOS AM-1 for a sun angle similar to that expected for EOS AM-1.

Nandy shipped the BRDF camera system to Photometrics for its yearly maintenance. A frayed instrument cable was replaced and a shutter mechanism damaged during the cleaning process was also removed and replaced. New molded plastic cables were ordered to replace the original cables and these cables will be more flexible in cold weather, simplifying operation. Nandy began modifying the chiller for the camera to a more portable version to allow the system to be moved more easily to allow spatial sampling of the surface BRF. Nandy began the gain/offset calibration of the BRDF camera system. Biggar and Nandy developed an experiment to characterize the CCD using the 6-inch SIS and a pinhole to produce a uniform light on the array. Nandy used a nodal-slide to determine the position of the fisheye lens' rear nodal point to determine the axis of rotation for the full-system calibration using the 40-inch SIS.

Diffuse-to-global meter: The objective of this task is to design and build an instrument to collect diffuse-to-global irradiance data. By comparing the diffuse downwelling irradiance to the global (direct plus diffuse), an improvement to the atmospheric correction may be made which reduces the uncertainty of the reflectance-based method. The diffuse-to-global meter will collect these data automatically and more repeatable than in the past.

Smith completed development of the graphical user interface wrapper for processing of diffuse-to-global data. The processing software and interface are complete and she has begun work on an evaluation module to track historical intercept values and allow the user to view this information and make appropriate processing selections.

Smith completed processing of the data collected at the Pinal Air Park in March to compare results from the diffuse-to-global meter to several multi-filter, rotating shadowband radiometers (MFRSR) operated by S. Schiller of South Dakota State University. Figure 3 shows retrieved optical thickness results for several days for several of the MFRSRs and the diffuse-to-global meter for the 500-nm band. The results shown in this figure clearly show that there can be large differences in the retrieved optical depths from instruments. On the best days shown, the differences are 0.04 in optical depth, peak to peak.

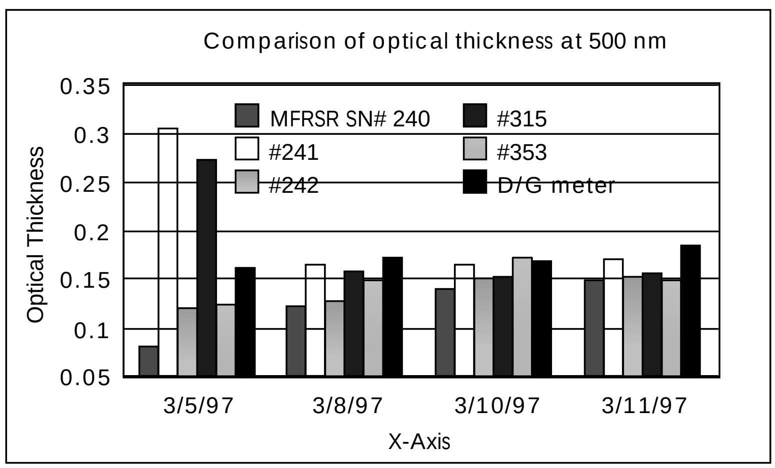

Figure 3. Retrieved optical depths at 500 nm for four days at Pinal Airpark near Tucson.

Figure 4 shows the retrieved diffuse-to-global ratio for one day of the comparison for three of the MFRSRs and the diffuse-to-global meter. It is clear from the figure, that the MFRSR data are noisier than that from the diffuse-to-global. Discussions with personnel from Yankee Environmental

Systems (manufacturer of the MFRSR) indicate that much of this noise is due to uncertainties in laboratory calibration of the angular response of the diffuse collector of the MFRSR. It is also clear that the instruments retrieve significantly different ratios, especially at large airmass with differences as much as 20%. Smith is currently evaluating the effect of such differences in the irradiance-based calibration.

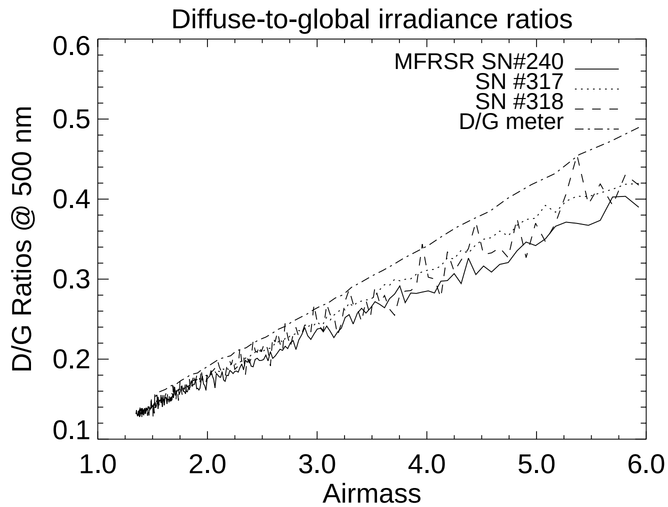

Figure 4. Diffuse-to-global ratios for several instruments from March 11, 1997 at Pinal Airpark near Tucson.

<u>Calibration Laboratory:</u> The objective of this project is to develop a calibration laboratory that will provide the necessary high-radiometric-accuracy standards and characterization set-ups for 1) the cross-calibration radiometers and 2) the field and aircraft radiometers needed for preflight algorithm and code validation and the actual in-flight calibration of the EOS multispectral imaging sensors beyond 1998.

Biggar, C. Burkhart, and E. Nelson made significant progress in the blacklab towards automating BRF measurements. A new room divider with chopper and shutter was installed to allow us to automate our dark current measurements and to improve signal-to-noise by chopping the source. A. Ahmad worked on software to control the chopper but has encountered problems getting it to respond to commands, possibly due to a difficulty in finding the home position. Biggar and M. Mienko integrated software to remotely operate a new filter wheel, including a shutter. Biggar and Nelson installed a new amplifier developed by Nelson. Biggar wrote software to electronically control the amplifier's gain. Problems were encountered when the amplifier saturated in the output stage and further tests of the amplifier showed it to be susceptible to thermal effects. Nelson has fixed both problems. While evaluating the system, Biggar discovered that the output of an aging lamp in the blacklab was unstable. This problem indicates a need for an automatic monitoring of the lamp and Biggar has implemented this. After the blacklab improvements, it now takes about 50 minutes to measure the BRF of a sample for a single view direction, nine bands, and 14 incident angles. This is a reduction in time by nearly a factor of three. Test data show negligible differences between those collected manually and in an automated fashion.

Biggar modified blacklab software to improve flexibility of the code's GPIB connection. We received and installed a new GPIB-ENET to replace a failed unit. Biggar worked with C. Burkhart on a mount in the blacklab for the Data Acquisition unit, the GPIB-ENET, and the EG&G lock-in. Ethernet wires were also installed in the laboratory. A. Ahmad and Biggar continued upgrading the Optronic monochromator to include the use of linear stages for improved measurements of spectral transmittance.

Biggar measured the BRF of our field reflectance panels, as well as the NIST-supplied reflectance standard. He processed the data from these measurements and found that they agreed well with those made prior to the trip. Biggar and J. Chowdhury began BRF measurements using techniques similar to those used by NIST. This will allow us to compare more directly results of our measurements of the NIST panel to those made by NIST. Biggar measured the NIST-reference panel one more time for the purpose of comparison with our newly received 10" Spectralon panel from Labsphere. Biggar also measured the BRF of two Spectralon panels supplied by Landsat-7 Science Team Member, S. Moran of the USDA ARS group in Tucson. An interesting result from these measurements was that one of the panels has a larger than normal retro-reflection caused by the method in which the panel is shipped. The panel is shipped in a plastic bag and then placed in a wooden box. The panel can freely move inside the wooden box allowing it to be rubbed by the plastic and this in effect polishes the surface of the panel making it more specular.

Biggar also continued improving the IDL-based software used to process the blacklab data. Ahmad worked on inserting our blacklab results into a database. This included examining several databases before selecting and installing mySQL. He designed the table structure for the data and loaded a sample data set into the database. Several test queries on the data indicate that the database is operating properly. Ahmad has also begun developing C-code to convert the historical archive of blacklab data into a format suitable for the database.

Biggar worked from September 25-29 with B. Steward and C. Cattrall from K. Carder's group at the University of South Florida. The purpose of the work was to characterize Carder's reference panels and portable field radiometers. Biggar measured the BRF of four grey and two 99% Spectralon panels. He also used our 40-inch SIS to evaluate the linearity of four of the group's spectrometers. Biggar sent results of the measurements to B. Stewart.

Biggar completed a paper on the $1/r^2$ dependence of spectral irradiance and submitted this to *Engineering and Lab Notes.* The paper describes the uncertainty that is caused by operating NIST standards of spectral irradiance at distances other than the prescribed 50 cm measured from the base of the lamp. Typically, when a source is operated at a non-standard distance, the distance is measured from the base of the source and the ratio of the square of this distance to the square of the 50-cm distance is used to adjust the irradiance. Using the VNIR CCR mounted to a precision linear stage, Biggar found that this approach causes uncertainties, as shown by the D=0.0 curve in Figure 5. By taking into account the offset between the actual source (the tungsten filament) and the base of the lamp, a distance of 0.272 cm, Biggar obtained much better agreement with a $1/r^2$ dependence in spectral irradiance (D=0.272 curve in Figure 5).

Algorithm and Code Development: Currently, several algorithms exist to perform our calibration work. The RSG has applied these algorithms as FORTRAN programs which are neither user friendly nor efficiently linked together into a single package. The task objective is to convert these existing codes into ANSI standard C in a user-friendly package with rules-based decision making in the package. The group is now also involved in the atmospheric correction of ASTER data in the solar-reflective portion of the spectrum

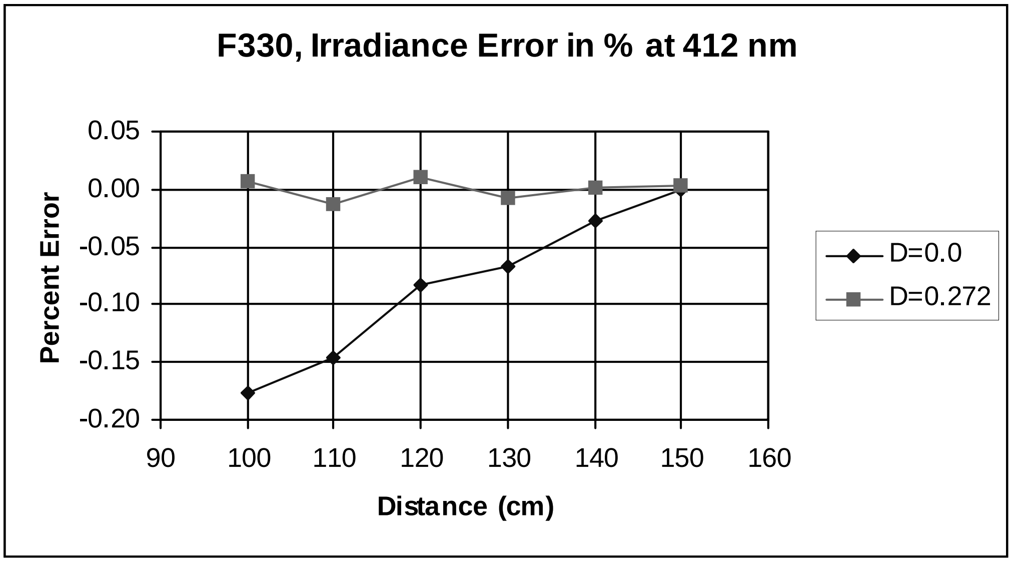

Figure 5. Results of $1/r^2$ test of FEL lamp showing percent error in irradiance from measuring the distance from the base of the lamp (D=0.0) to that when measuring from the center of the lamp filament (D-0.272)

K. Scott completed development of the cross-calibration program and is now making minor changes as part of testing she is currently doing. Atmospheric, aerosol, and miscellaneous other information were gathered in preparation for cross-calibrations using pairs of image data from a SPOT HRV/Landsat TM 1994 calibration at White Sands and an AVHRR/SPOT HRV 1995 calibration at Railroad Valley. The software includes an error analysis based on multiple runs using input parameters that are varied randomly based on their estimated uncertainties.

Smith developed several IDL widget-based processing tools for airmass calculation based on date, location, and input times; time computation for a given airmass, location, and date; and band-averaging of input solar irradiance and reflectance. J. LaMarr developed an atmospheric correction validation set based on surface and atmospheric data from the BOREAS campaign and AVIRIS imagery. He obtained the aerosol optical depth data collected during the campaign and used these data to determine best fit Junge size distributions. The surface reflectance and radiosonde data for the validation set were obtained from F. Hall of GSFC. LaMarr wrote software to implement an atmospheric correction to account for spectrally-flat cirrus based on the method developed by B. C. Gao and he began investigating the level of error introduced by assuming no spectral dependence.

Field Experiments and Equipment: The objectives of the field experiments are to test new equipment, determine needed improvements, test retrieval algorithms and code, and monitor existing satellites in much the same way as we shall for EOS sensors.

Biggar and R. Clemens began a detailed characterization of our ASD FieldSpec FRs. Measurements with the new version of the FR that has better thermal stabilization of the VNIR detector showed changes of <1% during the first hour of operation. Burkhart machined a dark cover for the 8-degree field of view foreoptic for more accurate dark correction adjustment. Biggar and Clemens collected data with the FR and the VNIR CCR viewing the 40-inch SIS at several lamp levels to evaluate the FR's linearity. An interesting outcome of the test was that the two determined that the sphere requires about two hours to warm up and stabilize and at least thirty minutes to stabilize after changing lamp levels. The two also ran the FR with covered optics in a dark room for several hours and the instrument's dark current stabilized after 90 minutes.

The new airborne radiometer (ABR) was performance tested by Clemens and Zalewski in both the laboratory and the field. This radiometer consists of a cassegrainian telescope with a group of nine optical fibers at the focal plane; one of which is the input to the FR and the rest are linked to spectrally filtered silicon photodiodes. The silicon photodiode outputs are recorded with a HP34970A, eight channel data logger. For the initial tests only four of the eight channels were used. The signal levels recorded over the Railroad Valley site were not as high as anticipated, prompting a re-design of the fiber-filter-detector configuration.

Burkhardt machined a new mount for the SWIR CCR that allows for the ABR to be mounted for laboratory testing. Biggar and Clemens used this mount to perform an approximate calibration of the ABR with the VNIR CCR and the 40-inch SIS. They first used the optical fiber-spectral filter configuration from the first field test over Railroad Valley during the June cross-calibration exercise. They also tested it with a new set of fiber-filter holders designed by Zalewski and machined by Burkhardt. The improvement was a factor of thirty in signal level using the new configuration. Zalewski also included in the design of the filter-fiber mount a simple means to incorporate a commercially available lens to further improve the signal levels. Clemens refined Zalewski's calculations with the ZEMAX program and also examined a two-lens configuration that promises to yield even greater signal levels. The appropriate lenses have been purchased for future improvement in the SNRs of the ABR's narrow-band channels. Clemens and Zalewski measured the field of view of the ABR to have a half-angle of 0.1 degrees where the signal level drops to 0.0005 of the maximum. Burkhardt machined four telescope covers to protect the ABR during take-off and landing. Two of the covers have clear plexiglass windows. He also designed and fabricated a +/- 20 degree tilt mechanism so the ABR can be used at non-nadir same view angles.

For the stabilized source project J. Chowdhury constructed a second, hard-wired version of the radiance feedback control circuit. Chowdhury and Zalewski discovered that large AC signals appear at the outputs of the OP07 operational amplifiers used throughout the circuit. These AC signals caused variable DC offsets at various critical points in the circuit. Capacitor filters were installed to dampen the AC noise. The hard-wired circuit still appeared to not have achieved the same performance level as the bread-board version of the circuit.

After the June field trip to Reno and Railroad Valley, Clemens and Chowdhury began developing code to process the ABR narrow-band data and FR data. Clemens developed IDL software to read and view the aircraft's flightline based on the GPS data. Clemens also determined a method for viewing the GPS data in Auto_CAD by converting the data to dxf-format files. The first goal is to show both the FR and narrow-band data as a function of time to correlate the two data sets. Clemens wrote instrument instructions for field campaigns with the ABR and a manual for the telescope, HP Data Logger, ASD and video camera. She also documented the aircraft setup for future campaigns.

Several test flights of the ABR were attempted in September. A flight over San Carlos Lake was hampered by cloudy weather as was a flight of the Wilcox Playa. A successful flight was made over the Gulf of California coincident with a SeaWiFS overpass. These data are still being evaluated. The ABR was also used during a field campaign to Lake Tahoe that included Clemens and Zalewski operating the airborne radiometer and W. Barber and LaMarr collecting ground-based data in conjunction with B. Stewart of MODIS Science Team member, K. Carder's group. Weather conditions for the campaign were partly cloudy, but successful data were collected with the ABR but a malfunction of the ASD FieldSpec FR prevented correlative spectra from being collected. Biggar determined that the problems with the FR spectrometer were due to the use of new controlling software without properly resetting the configuration files required for the new program to work with the cooled VNIR option. With an updated file, the system operates correctly. Biggar later contacted ASD and determined that unfortunately, much of the VNIR data cannot be salvaged from the campaign and it is uncertain whether the SWIR data could be salvaged reliably.

Barber, J. Smith, and E. Whittington traveled to Ivanpah Playa from August 10-13 to collect data in support of an evaluation flight of the MASTER sensor. Thome processed the data from this campaign and supplied the results to S. Hook of JPL and M. Fitzgerald of Ames. Unfortunately, the TIR and VNIR portions of the sensor did not operate properly. Biggar, LaMarr, B. Magi, and M. Mienko collected data at Ivanpah Playa for a calibration flight of MASTER on the B200 aircraft. The overflight took place December 2 and Thome processed the data from this campaign and supplied the results to ARC and S. Hook. Barber, Nandy, and Whittington collected data on December 10 for a test flight of MASTER and MAS on the ER-2. Unfortunately, MASTER did not operate properly. Thome still processed the data from the campaign for the purpose of comparing results with MAS radiances.

In assorted field-related activities, LaMarr met with J. Murphy of the Pima County Fairgrounds to investigate the possibility of paving and painting an area for the purpose of calibrating small-footprint sensors. LaMarr began to investigate the cost and feasibility of such a project. Thome processed data from the January campaign to Railroad Valley at the request of M. Dinguirard of CERT. The processing of this data set required Thome to develop software to correct surface reflectance data for changing atmospheric conditions using the constant panel data. The use of the constant panel data changed the retrieved reflectance by as much as 25% at some wavelengths. Much of this change is due to the fact that the site was snow covered, thus panel measurements with partial cloud covered were being confused with site measurements under full sun conditions.

R. Kingston worked with personnel from S. Moran’s group to develop data collection software for PolyCorder/Exotech instrumentation. The software includes improvements to monitor a single input signal while data logging occurs and logging text with each record that reports the current Exotech gains. Burkhart designed, constructed, and installed a tip-tilt mount for the clinometer that will be mounted inside one of our Exotech radiometers to measure the tilt of the radiometer during surface reflectance measurements.

Multiple members of the RSG collected solar radiometer on the roof of the Optical Sciences Center to characterize our automated radiometers. A portion of the data collections also included an automated solar radiometer and a MicroTops solar radiometer from the JPL-ASTER group. Thome processed all of the data to obtain calibrations of the radiometers for all ten bands, including the water band. He retrieved total optical thickness data and columnar water vapor from the automated solar radiometers. The results were sent to S. Hook of JPL along with the data from the MicroTops radiometer, and radiosondes launched daily at Tucson International Airport for evaluation of the water vapor retrieval.

Faculty, staff, and students: The personnel presently associated with the RSG are as follows: Faculty: Biggar, Slater, Thome, and Zalewski. Staff: Barber, Burkhart, Dancer, Kingston, Nelson, and Recker. Students: Ahmad (MS), Andersen, LaMarr* (Ph.D.), Mienko (MS), Nandy*(Ph.D.), and Whittington (Ph. D.). Those with an asterisk following their names have passed the Ph.D. Preliminary Examination and are mainly working on their Ph.D. research. Anderson is an undergraduate in the Optical Engineering program at the University of Arizona, Magi recently graduated with a BS degree in Physics and will continue working with the group until August 1999. Lopez and Smith successfully defended their MS research and will continue with the until finding work outside the University. Scott successfully defended her PhD dissertation entitled "Radiometric calibration of on-orbit satellite sensors using an improved cross-calibration method" and Walker successfully his dissertation entitled "Models and validation measurements of bidrectional reflectance factor for diffuse reflecting materials." Both completed their research in absentia.

Papers and publications

Two papers appeared in peer-reviewed journals and three papers were presented at conferences related to activities funded by this contract during the six-month reporting period. These are listed below along with their abstracts.

Thome, K., K. Arai, S. Hook, H. Kieffer, H. Lang, T. Matsunaga, A. Ono, F. Palluconi, H. Sakuma, P. Slater, T. Takashima, H. Tonooka, S. Tsuchida, R. Welch, E. Zalewski, "ASTER preflight and in-flight calibration and the validation of Level 2 products," *IEEE Trans. On Geos. and Rem. Sens.*, **36**, pp. 1161-1172, 1998.

Abstract: This paper describes the preflight and in-flight calibration approaches used for the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER). The system is a multispectral, high-spatial-resolution sensor on the Earth Observing System's (EOS) AM-1 Platform. Preflight calibration of ASTER uses well-characterized sources to provide calibration and preflight, round-robin exercises to understand biases between the calibration sources of ASTER and other EOS sensors. These round-robins rely on well-characterized, ultra-stable radiometers. An experiment held in Yokohama Japan showed that the output from the source used for the VNIR sub-system of ASTER may be underestimated by 1.5% but this is still within the 4% specification for the absolute, radiometric calibration of these bands. In-flight calibration will rely on vicarious techniques and on-board blackbodies and lamps. Vicarious techniques include ground-reference methods using desert and water sites. A recent joint field campaign gives confidence that these methods currently provide absolute calibration to better than 5% and indications are that uncertainties less than the required 4% should be achievable at launch. The AM-1 platform will also provide a spacecraft maneuver that will allow ASTER to see the moon allowing further characterization of the sensor. A method for combining the results of these independent calibration results is presented. The paper also describes the plans for validating the Level 2 data products from ASTER. These plans rely heavily upon field campaigns using methods similar to those used for the ground-reference, vicarious calibration methods.

Thome, K. J., F. P. Palluconi, T. Takashima, K. Masuda "Atmospheric correction of ASTER," *IEEE Trans. On Geos. and Rem. Sens.*, **36**, pp. 1199-1211, 1998.

Abstract: An atmospheric correction algorithm for use in an operational mode for the high-spatial resolution sensor ASTER is presented. The correction is a straightforward approach relying on inputs from other satellite sensors to determine the atmospheric characteristics of the scene to be corrected. Methods for the solar reflective and thermal infrared are presented separately. The solar reflective approach uses a look-up table based on the output from a Gauss-Seidel iteration radiative transfer code. A proposed method to handle adjacency effects is included. This approach relies on model output from a code that assumes the surface to be a checkerboard-type terrain. An example of a numerical simulation shows the effect of a land surface on the radiance over the ocean is stronger just off the coastal zone and decreases exponentially with increasing distance from the land. A typical numerical simulation is performed over the Tsukuba lake area in Japan. The TIR approach relies on the radiative transfer code MODTRAN that is run for a given set of atmospheric conditions

for several different locations in the scene for several representative elevations. Pixel-by-pixel radiances are then found using spatial interpolation. Sensitivity analysis of the methods indicate that the results of the atmospheric correction will be limited by the accuracies of the input parameters.

Nandy, P., K. Thome, S. Biggar, "Instrument for retrieval of BRDF data for vicarious calibration," *International Geoscience and Remote Sensing Symposium*, Seattle, Washington, pp. 562-564, 1998.

Abstract: The University of Arizona's Remote Sensing Group has performed vicarious calibrations of satellite and airborne sensors since the mid-1980s. Improvements of the accuracy of these techniques requires that the bidirectional reflectance of the test sites be characterized. The Remote Sensing Group has developed a four-band, imaging radiometer based on a two-dimensional CCD array and 8-mm fisheye lens for the retrieval of bidirectional reflectance. This paper describes the design of this radiometer and the methods used to calibrate the system. The calibration is based upon measurements of a 40-inch spherical integrating source and we describe a method to separate the spatial inhomogeneity of the source from that of the CCD array. Early data collected with this instrument of test sites at White Sands Missile Range and Lunar Lake Playa are presented and show good agreement with previous data collected at these or similar sites.

Smith, J., K. Thome, B. Crowther, S. Biggar, "Field evaluation of a diffuse-to-global irradiance meter for vicarious calibration," *International Geoscience and Remote Sensing Symposium*, Seattle, Washington, pp. 562-564, 1998.

Abstract: Vicarious calibration methods have been developed to calibrate radiometric sensors in-flight. One such method, the irradiance-based method, requires the measurement of the diffuse-to-global (diffuse-total) irradiance ratio. A diffuse-to-global irradiance meter has recently been developed by the Remote Sensing Group at the University of Arizona. The instrument uses a baffled integrating sphere as its collector and an occulting disc to block the sun for diffuse-irradiance measurements. Data are collected at 10-nm intervals from 350-1100 nm. In this paper, two methods are used to evaluate this instrument. The first relies on the well-known Langley method to determine atmospheric optical thickness from measurements of the direct solar irradiance derived from the difference between the global and diffuse irradiances. Secondly, the diffuse-to-global ratio was used to predict the radiance at the top of the atmosphere. These radiance results are compared to those from the reflectance-based method as well as those derived from data collected by the AVIRIS sensor. Data were collected at Lunar Lake Nevada June 23, 24, 25 1997 and White Sands Missile Range on October 31 and November 1, 1997. Comparison of optical thickness obtained from data collected by a well-understood solar radiometer show differences in optical thickness ranging from 0.003 minimum to 0.018 maximum. These results are encouraging as they indicate that there are no major effects due to inhomogeneities in the spherical collector.

Thome, K., J. LaMarr, K. Scott, and C. Gustafson-Bold, "Methods for the calibration of SPOT-4 HRVIR and Vegetation," *Proceedings SPIE #3439,* San Diego, California, pp. 439-449, 1998.

Abstract: The Remote Sensing Group at the University of Arizona has provided vicarious calibration results for all three SPOT-series satellites carrying the HRV cameras. The HRVs are high spatial-resolution sensors that are well-suited to the reflectance-, irradiance-, and radiance-based methods. The SPOT-4 platform has a similar sensor, the HRVIR camera, that now includes a band at approximately 1630 nm. The SPOT-4 platform also has a new sensor, Vegetation, that has much lower spatial resolution than the HRVIR sensor, and thus poses a challenge for vicarious calibration. This work presents the modifications that must be made to reflectance-, irradiance-, and radiance-based approaches in order to use them for the Vegetation sensor. Since both HRVIR and Vegetation are on the same platform, it is possible to use HRVIR to calibrate Vegetation. This paper also describes a proposed procedure for such a calibration along with an uncertainty analysis due to spectral mismatch and spatial misregistration. The work also shows how such cross-calibration can be done using a cross-calibration between Landsat-5 TM and SPOT-3 HRV using White Sands Missile Range. The results show TM can be cross-calibrated using HRV to provide calibration coefficients which are within 1% of those obtained from a reflectance-based approach.

Zalewski, E., W. Rappoport, F. Sileo, J. Stein, G. Huse S. Bender and P. Thacher, "On-board Calibration System for a Visible to Thermal Infrared Multispectral Imaging Sensor," SPIE Symposium, San Diego, June 1998.

Abstract: An on-board radiometric calibration system has been designed to maintain the accuracy of the laboratory calibration of a multi-spectral imaging sensor through launch and during its mission lifetime. Separate sub-systems which include somewhat redundant yet complementary measurements serve to maintain visible through thermal infrared calibration accuracy. Thermal infrared accuracy is maintained by a unique blackbody source built into the front door and forward baffle structure of the telescope assembly in order to assure end-to-end stability. A pair of smaller blackbody sources mounted on a turret close to the focal plane are complementary to the blackbody at the front of the telescope and fully redundant to each other. In a similar fashion there are complementary and somewhat redundant calibration subsystems for the visible to near infrared spectral bands. The front door of the telescope is designed to expose a white diffuser panel by unfolding and forming a plane at 45 degrees with respect to the optical axis of the telescope. Orientation of the space craft to enable light from the sun to irradiate this surface provides a source of known radiance for end-to-end calibration maintenance. The stability of the reflectance of the diffuser is monitored by a multi-band radiometer which compares the reflected to the direct sunlight. An incandescent source assembly mounted on the turret near the focal plane is complementary and somewhat redundant to that of the diffusely reflected solar radiation.