**Satellite Calibration and Verification of Remotely Sensed Cloud and
Radiation Properties Using ARM UAV Data**

**Final Technical Report
Interagency Agreement No. DE-IA02-95ER61992
February 28, 1995 - February 28, 1998**

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INTRODUCTION AND SUMMARY

The work proposed under this agreement was designed to validate and improve remote sensing of cloud and radiation properties in the atmosphere for climate studies with special emphasis on the use of satellites for monitoring these parameters to further the goals of the Atmospheric Radiation Measurement (ARM) Program. Specifically, we proposed to

- 1) determine the uncertainty in the broadband radiative fluxes derived from narrowband Geostationary Operational Environmental Satellite (GOES) imager data over the ARM surface site domains;
- 2) develop methods for calibrating the visible (0.65 μm) channels on operational meteorological satellite sensors, including GOES, the Advanced Very High Resolution Radiometer on the NOAA Sun-synchronous satellites, and the Geostationary Meteorological Satellite (GMS), that are used over the ARM surface sites;
- 3) validate and improve the techniques used for remotely sensing surface and cloud properties pertinent to their roles affecting the flow of solar and thermal radiation in the Earth's atmosphere including the impact of reflectance and emittance anisotropy on radiative fluxes;
- 4) evaluate, test, and modify techniques for deriving the radiative flux divergence in the atmosphere and at the surface using remote sensing datasets and to generate specialized datasets combining all relevant ARM Southern Great Plains (SGP) Central Facility data to characterize the constituents of the surface and atmosphere as well as the radiative fluxes from the surface to the top of the atmosphere for the use of the scientific community for testing radiative transfer models used in weather and climate research and operations.

The primary reference data for this research were the proposed measurements from the ARM Unmanned Aerospace Vehicle (UAV) that was to fly several missions during the grant period. Cloud heights from the cloud detection lidar, broadband radiative fluxes from down- and up-looking hemispheric radiometers, and radiances from the high-resolution, infrared and solar Multichannel Pushbroom Imaging Radiometer (MPIR) were to be used to execute many of the proposed tasks. Although four UAV missions were flown, the available data from the radiometric instruments have been delayed because of calibration problems, controversy

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surrounding some of the measurements, and missing channels on the MPIR. To ensure that the goals of the proposed research were addressed, other approaches to the tasks were developed with considerable success. These techniques exploited available satellite, aircraft, and ARM surface measurements to advance our knowledge in each of the four areas of research. Further research is being conducted on each task using new ARM-UAV data as they become available. Other funding supports this follow-on research.

In addition to research, we participated extensively in the planning and execution of the UAV missions as part of the UAV Science Team. The Principal Investigator (PI) provided significant written contributions to the UAV science and mission plans prepared for each field mission. The PI led a group that provided critical real-time satellite and forecast products to the mission science teams in the field and developed an archived high-resolution satellite dataset for each mission. In addition, the PI acted as a scientific liaison between the ARM-UAV and NASA Subsonic Clouds and Contrails Experiment Special Study (SUCCESS) project during the Spring 1996 UAV field mission to ensure maximum benefit for each project when their scientific interests overlapped.

This interagency agreement has fully or partially supported six peer-reviewed articles published or being published in scientific journals, fourteen papers published in conference or meeting proceedings, and eleven other papers presented at scientific meetings or conferences. The results from this research can be found in the papers or are available from the website, www-pm.larc.nasa.gov. Many of the archived satellite data are available in image form at the website or can be obtained in digital formats from the ARM data archive or from the website.

TASK 1: Determination of GOES-based broadband flux uncertainties

The narrowband-to-broadband conversion functions for use with the ARM GOES data were derived from coincident 1986 Earth Radiation Budget Experiment (ERBE) scanner longwave (5–50 μm) and shortwave (0.2–5.0 μm) and GOES-6 infrared window (11 μm) and visible (0.65 μm) data. With the availability of the initial flux data from the broadband shortwave radiometers on the Egrett and Otter aircraft taken during the Fall 1995 ARM Enhanced Shortwave Experiment, it was possible to begin the evaluation of the albedos derived from GOES-8 over the ARM SGP domain with the 1986 conversion functions. The preliminary comparisons showed excellent agreement with the low-altitude, clear-sky Otter-based albedos but some disagreement with the high-altitude Egrett data (C8). Additional data from the Scanner for Radiation Budget (ScaRaB) were used to evaluate the uncertainties in both shortwave albedos and longwave fluxes derived from GOES-7 data during 1994 (M8). Final comparisons with Scarab, the Otter, and ERBE wide-field-of-view fluxes were consistent in showing that the shortwave albedos from GOES-7 and GOES-8 are unbiased on average (C11). The rms differences are less than 10%, a value comparable to a comparison of broadband measurements taken at different angles. The GOES-8 results were biased compared to the Egrett albedos but not during all days. The discrepancies are under further study (C13). The GOES-7 longwave fluxes were found to be within 1–2 Wm^{-2} of the Scarab data, on average, with a 4% rms difference (M8). Thus, the historical narrowband-broadband conversion functions are accurate when applied to later, well-calibrated narrowband data taken over the same areas. A final summary of these results is being prepared for submission to a scientific journal.

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TASK 2: Calibration of satellite narrowband sensors

GOES-7 data were used for ARM SGP radiation and cloud analyses during 1994 and early 1995, while the GOES-8 data have been used since 1995. Although the technical details required for performing aircraft-to-satellite calibrations were satisfied during ARESE flights, the initial calibrations using MODIS Airborne Simulator data were relatively unsatisfactory (C2). A more reliable source for calibration became available during 1996 as greater efforts were used to monitor the calibration of the AVHRR visible channels. Thus, GOES-7 and GOES-8 were calibrated using the AVHRR infrared and visible channels on NOAA-11 and NOAA-14, respectively. The data were matched in time and space over the tropics using data from approximately every third month yielding a linear change in gain for the GOES-8 visible channels and no significant disagreement in the thermal channel calibrations (M9). The methods were extended by using the calibrated GOES-8 as a reference source. These techniques can be quickly used to calibrate other geostationary satellites (C10). The later comparisons show the continued degradation of the GOES-8 sensor in the same linear fashion. The narrowband-broadband validations provide solid evidence of the high accuracy of the calibrations. A journal article is being prepared to document these innovative procedures and provide the calibrations for several GOES satellites, GMS, and NOAA-12 AVHRR.

TASK 3: Validate and improve surface cloud remote sensing methods

A new method for deriving cloud properties from multispectral infrared satellite data was developed for application to the GOES-8 and AVHRR channels for use during night and day (M5, M7). The new method improves the determination of cloud temperature and altitude for thin clouds at night (C6) and can also provide estimates of cloud phase, optical depth, and effective particle size (C1). This new technique can be easily implemented in an automated, semi-operational analysis system that will yield substantial improvements in cloud heights compared to those from previous techniques that use only single-channel infrared data (M10).

To improve the determination and prediction of surface skin temperature over land, clear-sky temperatures were derived from two different satellites viewing the same areas from different angles. Initial results showed that the differences between the observed temperatures were dependent on the time of day and the differences in the relative azimuth angles for several surface types (C7). Similar anisotropy was observed with helicopter data taken over flat, forested terrain. Additional comparisons reveal that the magnitude of the temperature differences depend on the types of vegetation and terrain as well as the magnitude of the observed temperature. The sign of the temperature differences and their relationship to viewing angles is well correlated with the anisotropy of visible-channel bidirectional reflectance (C14). Thus, there may be some modeling techniques that could be used to account for this anisotropy which can produce temperature differences greater than 4°C for a given pair of viewing angles.

A careful analysis of satellite and ARM surface data taken during ARESE revealed a substantial asymmetry in the surface albedo over the SGP facilities (C5). This first determination of the diurnal asymmetry in surface albedo was found to be positively correlated to surface humidity and negatively related to wind speed. The results indicate that the formation and evaporation of dew at the surface causes a more reflective surface early in the morning

compared to the same times relative to local noon during the afternoon (J2). Anisotropy in the visible bidirectional reflectance fields over the SGP area was measured with the MPIR using repeated flights of the ARM-UAV during the Spring and Fall 1996 flight series. Except for slightly more anisotropy, the preliminary results yield reflectance patterns very similar to more general bidirectional reflectance distribution functions (BRDFs) over land (C12). They demonstrate the utility of a UAV with an imager like MPIR for measuring BRDFs for use in remote sensing algorithms. Additional analysis of these data will be conducted for other MPIR channels.

A set of parameterizations of reflectance and emittance for the GOES and AVHRR infrared and solar channels was developed (J5) to facilitate the determination of cloud phase, effective particle size, and optical depth for the both daytime techniques and the multispectral infrared method noted above. A daytime cloud microphysical property retrieval algorithm was developed and applied to AVHRR data over the CART site and compared to the similar optical depths derived from GOES-7 (M1, M6). The results revealed a calibration error in the GOES results prompting the development of the improved AVHRR-GOES calibration method discussed earlier. Additional analyses were compared with liquid water path data taken at the ARM SGP facilities indicating mixed results. The differences were traceable to the occurrence of cirrus clouds over the low-level water clouds (M11). Cloud effective ice crystal sizes, ice water path, and optical depths were compared with in situ and ARM SGP radar analyses to determine the accuracy of the retrievals. Both GOES-8 and AVHRR data were used. The satellite retrievals of effective ice crystal diameter were within $\pm 10\%$ of the in situ data taken in a relatively homogeneous wave cloud (J4). The ice water path and optical depths for a variable cirrus cloud were within a few percent of the same quantities derived from ARM surface radar data (J6). The particle sizes were much smaller than the radar-derived values, but the discrepancies are attributable to differences in the particle size definitions used by the two methods. These findings pave the way for development of a semi-operational analysis program for monitoring cloud microphysical properties over the ARM SGP domain using GOES and AVHRR data.

TASK 4: Evaluate techniques for computing atmospheric radiative flux divergence and provide special datasets on the Internet

A comprehensive dataset describing the atmosphere and surface properties over the ARM SGP Central Facility was developed for April 1994 to allow the testing of various models for computing atmospheric radiative flux divergence, net surface radiation, and top-of-atmosphere radiation (M2, M3). This dataset has been made widely available on the Internet (M4, J1). It includes interactive processing and provides plotted displays of many ARM surface and satellite-derived properties. It has been updated to include the latest calibrations and data taken during ARESE (C4). This effort to provide the community with a valuable, comprehensive database for testing new radiative transfer algorithms and parameterizations will continue with additional periods of interest.

Cloud radiative forcing and anomalous absorption of shortwave radiation by clouds were the foci of both ARESE and the spring 1996 UAV flight series. The GOES satellite radiances were used to produce cloud and clear-sky radiation parameters for both periods. The initial ARESE analyses yielded shortwave absorption approximately 20% greater in cloudy skies than in clear situations (C3). These results are consistent with, but smaller than, anomalous cloud

absorption found in other studies. The results of an analysis of the spring 1996 GOES data (J3) were used to compute the net cloud forcing over the ARM SGP Central Facility. An update of the ARESE results (C9) and the spring 1996 data showed a similar increase in atmospheric absorption when clouds were present. The reason for the apparent anomalous absorption has not yet been determined and is being investigated using a combination of surface radar and radiometer data as well as satellite retrievals of optical depth and particle size (e.g., C15). The successful effort to accurately calibrate both narrowband and broadband fluxes from GOES, however, has essentially eliminated these satellite data as the source of the apparent excess cloud absorption.

CONCLUDING REMARKS

Despite the delays in receiving the ARM-UAV data, the research conducted under this agreement has been extremely successful with significant advances in all of the proposed areas. Additional investigations using forthcoming ARM-UAV data under the sponsorship of the ARM Science Team will build on the research reported here.