

2.0 EFFORTS TO MONITOR GLOBAL CLIMATE CHANGE

2.1 The Earth radiation budget

Averaged over the entire Earth and over the span of a year, the sun delivers approximately 340 W/m^2 of shortwave radiation. Approximately 99 percent of this energy is below $3.8 \text{ }\mu\text{m}$, with one percent below $0.3 \text{ }\mu\text{m}$. Of the arriving solar energy, about 30 percent, or 100 W/m^2 , is reflected back into space. This reflected energy is called the Earth's albedo. The solar energy which is not reflected back into space (240 W/m^2) is absorbed by the Earth/atmosphere, which heats up and emits longwave radiation. The Earth's temperatures currently range between approximately 240-300 K with 99 percent of its emitted energy at wavelengths longer than $4.6 \text{ }\mu\text{m}$ and only two percent above $60\text{-}70 \text{ }\mu\text{m}$ [Lenoble, 1993]. Ahrens [1992] explains that "Earth's temperature" can mean a variety of things. For instance, the Earth's observed average surface temperature is about 288 K. On the other hand, if Earth is viewed as behaving as a blackbody, where it absorbs solar radiation and emits infrared radiation at equal rates, its radiative equilibrium temperature is approximately 255 K. Thus care should be taken when reporting and interpreting changes in the "Earth's temperature".

Since the solar and terrestrial radiation are present in wavelength bands which barely overlap, the two can be measured separately. By subtracting the total emitted and total reflected energy from the solar contribution, the net radiation budget, or the net amount absorbed by the Earth at a given time and location can be computed. If the net amount at a given time and location is positive that particular area of the Earth tends to warm, whereas if the net is negative that area cools. This spatial variation in temperature is what drives the weather of our planet. If this difference is averaged temporally and spatially, the net radiation budget is approximately zero. However, if some disturbance (due to human activity or to natural events) were to occur which disturbed this equilibrium, a time-dependent climate change would occur, and the temperature of the Earth would change (increase or decrease) until radiative balance was once again established. One of the goals of Earth-observing instruments is to determine whether this sort of imbalance is occurring, and if so, to identify its causes. One of the steps in this process is to measure the parameters necessary to derive the global net radiation energy budget.

2.2 Earth-observing instruments

The use of satellites is an especially effective measurement method in the quest for the answers to the fundamental question of whether the temperatures of the Earth are changing, as they can provide global coverage and thus make measurements used to derive the global TOA (Top-of-the-Atmosphere) radiant energy budget. Satellite-based observation began in the early 1960's with the onset of the Space Age, and has continued ever since.

As the generations of Earth-observing instruments have developed, they have served in the continued gathering of data initiated by previous instruments, in making increasingly advanced measurements and in using increasingly sophisticated algorithms in data reduction. As with most improvements there are trade-offs, as these upgrades do not come without a price. In the process of replacing one instrument with another having greater capability, the organization leading the investigation risks the disturbance of the

collection of continuous science data. Detected changes in measurements which may be due to the transition in instruments could be misinterpreted as changes in the Earth's energy budget. This risk is minimized as much as possible, and instruments are replaced as the motivations for improvement outweigh the risks. To help minimize risk, new-generation and past-generation instruments' missions are made to overlap so that calibrations can be transferred, if at all possible. Instrument improvement is achieved by using the lessons learned from previous missions, and the progressive state of knowledge about the Earth/atmosphere system that reveals data products which may be more useful. Change is also motivated by the organization's desire to stay atop the latest technology. In the case of the National Aeronautics and Space Administration, change is often driven by the fact that "NASA Headquarters and Administration appear to want to view NASA as technology developers rather than scientific leaders" [Barkstrom, 1998]. So for various reasons, the push is on to conduct successful experiments using state-of-the-art technology and to gather useful information that can be used to advance our knowledge about the Earth/atmosphere system while planning constantly for the future generations of instruments to be used to monitor our planet. At the same time, Earth-observing experiments must continue to gather a complementary set of data throughout the generations of instruments so that the studies are sufficiently long-term to monitor change over the decades.

2.3 Earth-observing instruments leading to the current research effort

2.3.1 ERBE

In 1979, the National Aeronautics and Space Administration began ERBE (the Earth Radiation Budget Experiment), a mission that was to measure the most basic parameters in monitoring the Earth's climate. ERBE was launched aboard the NASA ERBS (Earth Radiation Budget Satellite) in 1984, and aboard NOAA-9 and NOAA-10 in 1984 and 1986. The ERBE instrument is a scanning thermistor bolometer radiometer consisting of three channels sensitive in the short (0.2-5.0 μm), the long (5.0-50 μm) and the total (0.2-100 μm) wavelength bands. The principal goals of this mission were to measure broadband radiances at the Top-of-the-Atmosphere (TOA), to convert these anisotropic

radiances to TOA fluxes using Angular Distribution Models (ADMs) and the Maximum Likelihood Estimation (MLE) technique [Wielicki and Green, 1989], and to derive the global TOA radiation energy budget. ERBE collected thirteen years of data, and provided what NASA calls the most accurate data of the Earth's outgoing longwave and solar reflected shortwave radiation ever obtained, as well as answers to some long-standing questions about climate forcing and feedback mechanisms in the Earth/atmosphere system. Among these important findings, ERBE data showed that the annual average effect of clouds is to cool the current climate system. This did not, however, end the debate as to whether clouds act to decrease global warming. "A common misconception is that because clouds cool the present climate, they will likewise act to moderate global warming. What is actually important is the change in the net cloud radiative forcing, associated with a change in climate, that governs cloud feedback" [Wielicki *et al.*, 1995]. In the process of answering questions, these answers prompted further questions and the next generation of instruments evolved. The insight into the influence of clouds gained by ERBE data served as a basis for naming the monitoring of clouds and their influence on the Earth's radiant energy system as a top priority in the next generation of instruments, CERES.

2.3.2 CERES

The Clouds and the Earth's Radiant Energy System (CERES) is a suite of broadband scanning radiometers based on the ERBE instrument, but featuring many improvements [Wielicki, 1996; Bongiovi, 1993; Haeffelin, 1996; Priestley, 1997; Smith, 1998]. The CERES instrument incorporates full two-dimensional directional sampling by scanning in both elevation and in azimuth angle. It includes the same short and total wavelength channels of ERBE, but the longwave channel was replaced by a "window" channel, sensitive in the region of 8.0-12.0 μm . The first CERES instrument, the PFM (Proto-Flight Model), was launched in late 1997 aboard TRMM (Tropical Rainfall Measuring Mission), as part of NASA's Earth Observing System (EOS). Two more CERES instruments are scheduled to be launched aboard the spacecraft EOS-AM and EOS-PM in the late 1990's and the beginning of the 21st century, and these and follow-on instruments will extend measurements for a total of fifteen years. CERES data will serve to extend

the thirteen years of ERBE data by measuring broadband radiances at the top of the atmosphere which will be converted to TOA fluxes. The CERES Pathfinder Project was organized to analyze CERES data products and to “bridge the gap” between ERBE and CERES missions. In addition to TOA fluxes, more sophisticated parameters are being determined. The CERES instruments fly on satellites containing cloud imagers that make simultaneous measurements of the same scene being viewed by CERES. CERES data are being used with this cloud imager data to infer surface fluxes and to provide the vertical profile of radiative divergence. Data collected during CERES azimuthal rotations is being used to build angular distribution models (ADMs), striving to meet the mission goals to reduce the ADM errors by a factor of four over ERBE. CERES is expected to provide TOA fluxes that are two to three times more accurate than those of ERBE data [Wielicki *et al.*, 1996]. Over the course of the development and launch of CERES, and with the use of CERES science data, NASA has identified the desirable features of the next generation of instruments. In summer, 1998, NASA outlined these features and named this potential future instrument, PERSEPHONE.

2.3.3 PERSEPHONE

NASA developed the preliminary conceptual design of PERSEPHONE under the criterion that the next-generation instrument be smaller, less resource intensive, less costly, and requires less build time. In the spirit of these requirements, and in the continued quest for the understanding of climate forcing and feedback mechanisms, NASA has identified increased spectral partitioning of radiance as the principal feature of this potential next-generation instrument. This partitioning will involve dividing the measured energy into a larger number of spectral bands rather than simply measuring in the shortwave, total, and window channels as in ERBE and CERES. Since radiant energy is spectrally and spatially altered as it passes through the Earth/atmosphere system before arriving at the detector, and since most atmospheric constituents and surface properties are selective absorbers (i.e. they strongly affect radiation in limited spectral regions), measurement of energy in these narrower spectral bands will yield a deeper understanding of our Earth’s climate system [Barkstrom, *et al.*, 1998].

In order to achieve the goal of refined spectral partitioning while keeping cost at a minimum, NASA has proposed that the current CERES telescope be modified to serve several detectors. Each detector would measure energy in a different spectral band by placing the desired filters in its optical path. While expanding the capability of the current CERES telescope, NASA wishes to improve the calibration accuracy and spatial and angular sampling capability while maintaining the current envelope of size, mass, and electrical power. In addition, NASA wishes to maintain the same (or better) quality of the Optical Point Spread Function (OPSF) on all detectors as that of the current CERES telescope. The OPSF describes the radiation throughput to the detector as a function of the angle at which collimated radiation enters into the instrument. These concepts will be described more thoroughly in Chapter 5.0.

Modification of the CERES telescope to meet the criterion outlined above creates new challenges that will require the state-of-the-art in technology to overcome. Barkstrom, *et al.* [1998] identify the three most serious challenges that must be overcome in order for this redesign to succeed. The first issue involves the need for an increase of detector sensitivity by more than an order of magnitude over the current CERES detector since the redesign calls for the division of energy into smaller spectral intervals. The other two issues involve the need to isolate the different spectral bands without loss of calibration accuracy, and the need for calibration sources for the narrower spectral intervals.

In addition to these issues, a redesign of the optics may be required in order to achieve an approximately uniform radiative flux over all detectors. One of the topics of research for the current master's thesis involves the determination of whether a redesign is required, and if so, further study of a potential optical prescription that will yield acceptable performance.

2.4 The Thermal Radiation Group

The Thermal Radiation Group of the Mechanical Engineering Department at Virginia Tech has been involved in the numerical modeling of Earth-observing instruments since

the early 1970's, in addition to other research projects. Much of this work was funded under NASA grants, in support of the work done by the Radiation Sciences Branch, Atmospheric Sciences Division of NASA Langley Research Center. Under the direction of Dr. J. R. Mahan, master's and Ph.D. students of the Thermal Radiation Group have worked to develop high-level, dynamic, electrothermal, end-to-end numerical models of both ERBE and CERES instruments. These models are capable of simulating the response of these instruments to simulated Earth scenes [Haeffelin, *et al.*, 1997]. The end-to-end models include an optical/thermal-radiative module and a thermistor bolometer dynamic electrothermal module. The optical/thermal-radiative module is used to model the optics of the instrument using the Monte-Carlo ray-trace (MCRT) method as it applies to radiation heat transfer. The output from this module is then used as input to the second electrothermal module, a finite-difference or finite-element code characterizing the electrothermal behavior of the detector to various inputs.

In addition to this work, over the course of the past few years a Ph.D. student in the Thermal Radiation Group, Félix Nevárez, has been developing a flexible, ray-trace-based numerical tool that can be used to build the radiative model of any instrument. In the past, students have built a highly specific code for the instrument at hand, such as those described for the CERES and ERBE instruments. This new tool brings with it the capability to build in a matter of weeks what could have taken up to several years using previous capabilities. The optical prescription for the PERSEPHONE instrument has been studied using this tool.

In addition to this topic of investigation, the author has investigated an entirely separate issue, the proper modeling of diffraction of radiant energy as it enters an instrument as treated in the Monte-Carlo ray-trace environment. This issue is important in many of the computer modeling efforts conducted by the Thermal Radiation Group, but has been neglected in the past. It is believed that a higher level of sophistication in the modeling of diffraction will benefit modeling efforts by future generations of students of the Thermal Radiation Group.

2.5 Goals of the current research

The goals of the current research effort are to:

1. Develop a radiative model of the CERES instrument using the new ray-trace tool being developed in the Thermal Radiation Group. This model will be used to:
 - serve as validation of the new ray-trace tool by comparing results to results from a previous radiative model and experimental results.
 - study the current CERES telescope to determine whether changes will be required for the successful implementation of the multiple detector concept for potential next-generation instruments.
 - investigate a new optical prescription which may better serve the needs of the proposed next-generation instrument concepts.
2. Investigate the importance of the modeling of diffraction of radiant energy as it enters instruments of the type modeled by the Thermal Radiation Group.
3. Investigate, develop, and test means of numerically modeling diffraction in the Monte-Carlo ray-trace environment.