1.0 Introduction

1.1 The Earth Radiation Budget

The ability of man to influence his surroundings on a global scale is a phenomenon unique to the twentieth century. With the advent of industrialization has come the consequence of releasing vast quantities of pollutants into the atmosphere. As a result, atmospheric composition has become dynamic, with climatic consequences that are not yet well understood. Measurement of the radiative exchange between the planet Earth and its space environment represents one of the fundamental activities for understanding the driving mechanisms of our planet's weather and climate.

The Earth radiation budget, or the energy balance of the Earth-atmosphere-ocean system, is defined as the difference between the absorbed solar radiation and the radiation emitted from the Earth and its atmosphere which is lost to space. Contributions to the Earth's radiation budget are shown in Figure 1.1. Since solar and Earth-emitted energy originate from sources having large temperature differences, the spectral content of the two components is drastically different as well. The Earth has an equivalent blackbody temperature on the order of 300 K and so 98 percent of its energy is emitted beyond 5 μm. The sun, on the other hand, emits at an equivalent blackbody temperature of approximately 5800 K, resulting in 99 percent of its energy being emitted below 5 μm. In fact, the solar energy spectrum peaks in the visible range. This vast difference in the spectral domains allows for the relatively easy monitoring of the two components of the Earth radiation budget.

The global yearly average of solar radiation incident to the Earth is roughly 340 Wm^{-2}. Of this, approximately 30 percent, or 100 Wm^{-2}, is reflected back to space by clouds, atmospheric scattering, or the Earth's surface. This results in a net absorption by the Earth and its atmosphere of about 240 Wm^{-2} of solar radiation. Under equilibrium conditions this should be equal to the Earth/atmosphere emitted longwave energy[1].

It is suggested by Houghton [2] that the effect of doubling the current concentration of the greenhouse gas CO_2 in the atmosphere would be a reduction in the Earth-emitted longwave energy of four Wm^{-2}, or about 1.7 percent due to the increased greenhouse effect. This radiative imbalance would induce a time-dependent climate change, ultimately resulting in a new equilibrium climate.

This conjecture clearly shows the need to be able to measure the Earth radiation budget to better than one-percent accuracy for a yearly global average. A complete discussion of our planet's dynamic climate system is provided in references 1, 3 and 4.

1.2 Earth Radiation Budget Measurements

The following historical overview follows those of Hunt et al. [5], and House et al. [6].

The first serious attempts at estimating the Earth radiation budget components on the basis of measurements were not made until well into the nineteenth century. Pouillet obtained an estimate of the solar constant of 1211 Wm^{-2} in 1837. However, it was not until the first decade of the twentieth century that the initial attempt to determine the components of the Earth radiation budget, on the basis of observational data, were made. These early efforts suffered from severe limitations in geographical sampling of climatic observations.

During the 1920's, Simpson was the first to recognize the importance of the spectral distribution of water vapor absorption and to calculate the distribution of incoming and outgoing radiation as a function of latitude and season, making use of observed cloud distributions.

The 1940's and 50's marked a time of significant developments in atmospheric physics that led to increased knowledge of the Earth radiation budget. Aircraft studies during this period provided much-needed data on cloud physics.

With the onset of the 60's, man was about to enter the Space Age, and with it the era of satellite meteorology. The first spacecraft dedicated to the determination of the Earth radiation budget was Explorer 7, launched on October 13, 1959. The radiometers on Explorer 7 consisted of black and white hemispheres containing thermistor bolometers attached to rectangular mirrors on the equator of the spacecraft. The reflected image of each hemisphere in the mirrors made the radiometers behave as spheres in space.

The first imaging system to be carried into space was launched on April 1, 1960, on board the TIROS-1 spacecraft, the first in a series of seven spacecraft. The Television Infrared Observation Satellite (TIROS) mission provided four years of Earth radiation budget data and included the first such spacecraft to provide a continuous record of data for one year, TIROS-7.

The most successful of the early observational systems were the NIMBUS-6 and NIMBUS-7 spacecraft. These spacecraft were launched in 1975 and 1978, respectively, and together provided more than a decade of continuous Earth radiation budget data [6].

Advancements which have influenced the evolution of Earth radiation budget instrumentation may be broken down into four broad categories: (1) spacecraft power budgets, on-board data storage, spacecraft stabilization, and attitude control; (2) viewing angles of nonscanning medium field-of-view and wide field-of-view radiometers and scanning medium and high-resolution radiometers; (3) spectral isolation of the wavelength bands of interest; and (4) onboard calibration standards for both longwave and shortwave detectors.

The Earth Radiation Budget Experiment (ERBE) was the first program to incorporate all of these advancements.

1.3 The Earth Radiation Budget Experiment (ERBE)

The Earth Radiation Budget Experiment (ERBE) was begun by the National Aeronautics and Space Administration (NASA) in 1979 in order to quantify the radiative interaction between the Earth and its space environment. The radiation from the sun, which is absorbed by the Earth and eventually re-emitted, is the energy source which drives the motions of the Earth's atmosphere and oceans and which determines our weather and climate. The goal of ERBE was to monitor this interaction over a long time scale and over specific geographical regions [7].

The ERBE mission consisted of three spacecraft. The first ERBE instruments were launched on October 5, 1984, aboard the National Aeronautics and Space Administrations Earth Radiation Budget Satellite (ERBS). The remaining radiometric instruments were launched on December 5, 1984, and September 17, 1986, aboard the National Oceanic and Atmospheric Administration's NOAA-9 and NOAA-10 spacecraft. Each radiometric package contained four Earth-viewing nonscanning active-cavity radiometers, three scanning thermistor bolometer radiometers, and a solar monitor. Inflight stability of all radiometric channels was monitored by internal calibration sources. Combined, these radiometers quantitatively described the spectral and spatial distribution of the Earth's radiative field.

The suite of ERBE instruments, both nonscanning active cavity and scanning thermistor bolometer radiometers, are described in detail elsewhere [8,9,10].

ERBE has established the benchmark by which the success of future Earth radiation budget measurement missions will be judged. Definitive answers to several important scientific questions were obtained throughout the mission. Two such questions answered are the net cooling effect which clouds and volcanic activity produce on our climate system [11-14], and the correlation of solar activity to global-average atmospheric temperature change [15,16].

1.4 The Clouds and the Earth's Radiant Energy System (CERES) Mission

The Clouds and the Earth's Radiant Energy System (CERES) mission is an investigation to examine the interactive role of cloud and radiation feedback in the Earth's climate system. The CERES broadband scanning radiometers are an improved version of the Earth Radiation Budget Experiment (ERBE) scanning thermistor bolometer radiometers and are discussed in detail in Chapter 3. The CERES instruments will fly on several National Aeronautics and Space Administration (NASA) spacecraft beginning in 1997 with the Proto-Flight Model (PFM) instrument on the Tropical Rainfall Measuring Mission (TRMM) spacecraft which will be launched on 1 November, 1997. Future instruments will fly aboard the NASA Earth Observing System (EOS) AM and PM platforms to be launched in June, 1998, and December, 2000, respectively. A complete description of these planned missions and their orbital parameters may be seen in Table 1. The CERES science investigations will provide data to extend the 13-year climate record of top-of-atmosphere shortwave (SW) and longwave (LW) radiative fluxes collected by ERBE. Additionally, CERES will combine simultaneous cloud property data derived using EOS narrowband imagers to provide a consistent set of cloud/radiation data, including SW and LW radiative fluxes at the surface and at several selected levels within the atmosphere. CERES datasets are expected to provide top-of-atmosphere (TOA) radiative fluxes with a factor of two to three less error than ERBE data. Estimates of radiative fluxes at the surface and within the atmosphere will be a significant challenge, but should show significant improvements over current capabilities. A complete description of the CERES mission may be found elsewhere [17,18,19].

1.5 The Thermal Radiation Group

Under the direction of Professor J. R. Mahan, graduate students in the Mechanical Engineering Department at Virginia Polytechnic Institute and State University have been studying the dynamic electrothermal properties of instruments designed to measure the Earth radiation budget since the early 1970’s. The Thermal Radiation Group originally studied the theoretical radiative characteristics of spherical balloon-type detectors [20-22]. However, with the development of more powerful computers in the early eighties the group turned their focus towards applied numerical modeling of more complex radiative enclosures. Eskin [23] was the first student in the group to utilize a Monte-Carlo-based ray-trace method. Eskin’s work modeled the radiative exchange inside a conical cavity such as those in the ERBE active cavity radiometers. Gardiner [24] studied the operation of ERBE-type active cavity radiometers at cryogenic temperatures. Tira [25,26] was the first to utilize the Monte-Carlo ray-trace method in onjunction with a finite-element model of an active-cavity radiometer to determine the electrical response of a detector to varying radiative inputs

The recent focus of the Thermal Radiation Group has been the completion of high-level dynamic electrothermal end-to-end numerical models for space-based radiometric channels. These models usually begin with a radiative and optical analysis of the instrument in question using a Monte-Carlo ray-trace technique. The results from the ray trace are then implemented into either a finite-element or finite-difference thermal and electrical diffusion code which characterizes the electrothermal behavior of the instrument to various radiative inputs. Once validated by successfully duplicating actual flight instrument data product [27], these models may be used to investigate the sources of any anomalous behavior of the actual instruments. The first complete end-to-end model for the Earth Radiation Budget Experiment Earth-viewing nonscanning active cavity radiometers was assembled in its final form by the current author. A thorough discussion of this effort may be seen in reference 28.

The fabrication of an end-to-end model for the Clouds and the Earth's Radiant Energy System scanning thermistor bolometer radiometers was begun by Meekins [29]. This effort consisted of an optical and radiative analysis of the Earth Radiation Budget Experiment scanning thermistor bolometer radiometer design. This work was later expanded by Bongiovi [30] to include the final CERES design geometry. Concurrent with Bongiovi's work, Haeffelin [31] completed a study of spatial equivalence in ERBE- and CERES-type thermistor bolometer detector assemblies. Savransky [32] completed a transient finite element thermal conduction model of the CERES instrument structure to analyze the potential effects of radiative noise due to time-varying thermal gradients in the instrument structure.

Other recent areas of research by members of the Thermal Radiation Group have been in the areas of atmospheric and optical modeling, as well as the design and analysis of new thermal detectors. Villeneuve [33] completed a study to assess the sensitivity of Angular Directional Models (ADM's) to variations in cloud parameters. This effort also created a tool with which to create realistic Earth scenes which can be scanned and analyzed by the end-to-end models. Walkup [34] completed a Monte-Carlo-based virtual optical workbench to aid in the optical design of future radiometric instruments. The latest thrust of the Thermal Radiation Group has been the design of the next generation of detectors for remote sensing of the Earth and its atmosphere [35].

1.6 Motivation and Goals

Over the course of the author's graduate studies he has been fortunate to work closely in both the engineering and scientific sides of the remote sensing arena. The engineering side of the arena is composed of the engineers and technicians who design, fabricate, and characterize remote sensing instruments. The scientific side of the arena consists of the scientists and engineers who analyze the on-orbit instrument data product in order to make assessments of the health of the Earth-atmosphere-ocean system. There currently exists cultural differences between these two groups which lead to the possibility of misinterpretations in the analysis of data product.

For the previous two years, the author has monitored the assembly and radiometric characterization of three flight models for the Clouds and the Earth's Radiant Energy System project at NASA's Langley Research Center. In this period of time, the author has acted as the liaison between the instrument science team and project engineers. This role has allowed him to become intimately familiar with the design, assembly and characterization of the CERES flight instruments. As a result, he has come to believe strongly that only through a thorough understanding of the design, fabrication, and test history of an instrument can all of the subtle details be understood concerning its performance once it is operational. This belief is supported by the work of Maschoff et al. [36]. Additionally, by taking this intimate knowledge and using it in conjunction with rigorous first-principle numerical models, unique insights into an instrument's performance may be realized. This results in an understanding of behavior which previously could only be obtained empirically. It is this philosophy which has motivated the current effort.

The goals of the current effort are

1. To complete an end-to-end model of the Clouds and the Earth's Radiant Energy System scanning thermistor bolometer radiometers. This would be the culmination of a multi-year effort by various members of the Thermal Radiation Group at Virginia Tech.
2. To validate the model against actual data from the testing and characterization of the CERES flight instruments.
3. To analyze anomalous flight instrument behavior and provide a rigorous explanation of its cause.
4. To conduct a series of studies to enhance the understanding and data retrieval capability of the as-built CERES instruments.

1.7 Organization

This dissertation is organized into three sections. The first section gives a general discussion of the trade-offs encountered in the design of a radiometric instrument such as the CERES scanning thermistor bolometer radiometers. This section culminates with an in-depth discussion of the as-built CERES flight instruments in Chapter 3. The second section presents in detail the first-principle end-to-end numerical model of the CERES instruments which was developed over a period of years by members of the Thermal Radiation Group at Virginia Tech. The final section presents the results of utilizing the completed end-to-end model to complete the goals outlined above are presented.