# Chapter 1. Introduction

Compelling evidence of changes in the Earth's climate has intensified the already widespread concern among scientists about the need for a better understanding of the Earth's ocean-atmosphere system. This concern has led to efforts directed towards defining and modeling the Earth's climate and understanding its changes. Particular emphasis has been placed on the possible role of anthropogenic influences on the Earth's climate. The Earth's radiation budget (ERB) lies at the heart of these issues. Several major studies have been commissioned aimed at obtaining a better understanding of the ERB in order to define strategies for mitigation of the consequences of human and natural activities and to improve the reaction to natural disasters. These programs have led to the development of new instruments and technologies to measure various characteristics of the Earth's ocean-atmosphere system. High-level modeling and analysis of these instruments are essential to the understanding of their behavior. This dissertation is intended to contribute to the understanding of the results obtained from numerical models of the instruments used in this effort. Specifically, a rigorous statistical protocol is defined and demonstrated for establishing the uncertainty and related confidence interval in results obtained from Monte Carlo ray-trace models of radiometric instruments. The resulting protocol is shown to be equally useful in the general radiation heat transfer modeling environment.

## 1.1 The Earth's radiation budget and its measurements

Monitoring the ERB represents one approach to quantifying issues such as the greenhouse effect and regional and global changes suffered by the Earth's ocean-atmosphere system. A descriptive model of the global energy balance is illustrated in Figure 1.1. The top of the atmosphere receives an average of 340 W/m$^2$ from the sun.
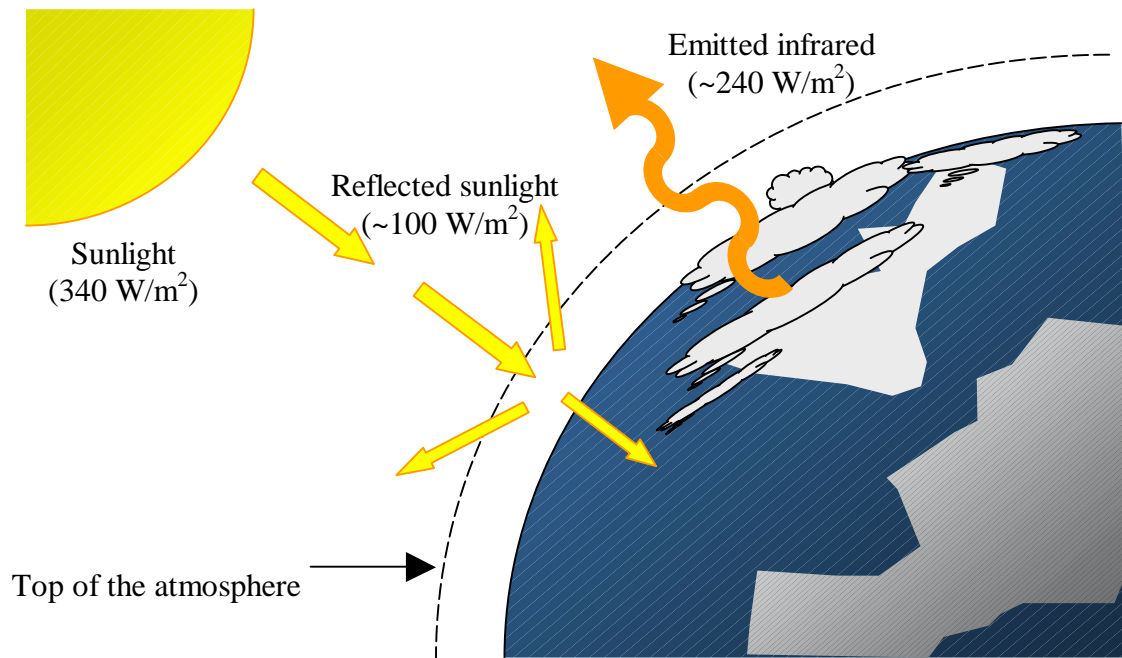
**Figure 1.1** Illustration of the global energy balance at the top of the Earth's atmosphere

About thirty percent of this radiation is reflected back into space, with the atmosphere or the Earth's surface absorbing the remaining seventy percent. Incident radiation has a spectral distribution determined by the sun's chromosphere, which has an equivalent blackbody temperature of about 6000 K [Lenoble, 1993]. Solar radiation reflected from the Earth has a similar spectral distribution, with some variation due to selectively stronger absorption in some bands. Earth-emitted radiation has a spectral distribution corresponding somewhat to a blackbody at a temperature of around 300 K [Wolfe, 1996]. Figure 1.2 shows the shape and relative level of the curves that represent the spectral distribution of solar heat flux reflected from the Earth and the Earth-emitted heat flux, both incident to a plane surface in a low orbit around the Earth.

In order to maintain equilibrium, the Earth must re-emit a flux equal to that absorbed. When this equilibrium is perturbed by a phenomenon such as the greenhouse effect, the Earth will effectively heat up or cool down in order to try to reach a new radiative balance [Wielecki, 1995]. Then the ERB is the difference between the radiation incident to the Earth from the sun, $P_{sun}$ (W), and the radiation leaving the Earth into space. Thus, under steady-state conditions (ERB = 0)

$$P_{\text{sun inc}} = P_{\text{earth refl}} + P_{\text{earth emit}} \tag{1}$$

where $P_{\text{sun inc}}$ is the solar power incident to the Earth, $P_{\text{earth refl}}$ is the short wavelength (0 to ~5 μm) part of the radiation leaving the Earth and its atmosphere, and $P_{\text{earth emit}}$ is the long wavelength (~5 μm to ~100 μm) radiation emitted by the surface and the atmosphere of the Earth.
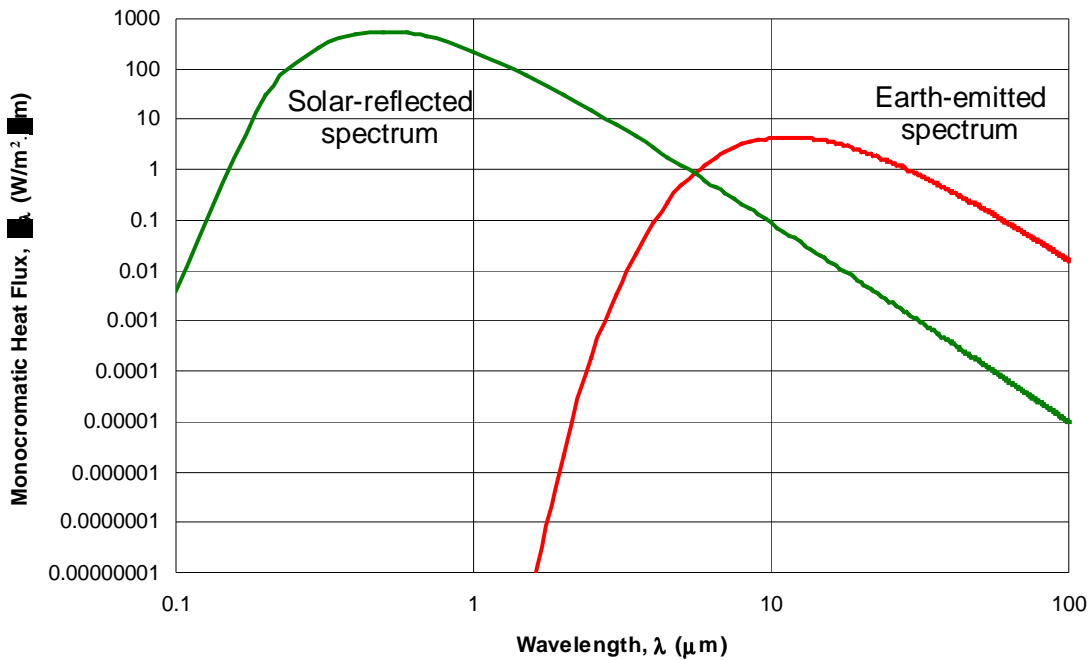
**Figure 1.2** Comparison of solar-reflected and Earth-emitted flux spectra as viewed from a satellite in low Earth orbit

Several measurement programs have sought to obtain sufficient data to quantify the regional and global emission and reflection of radiation by the Earth. Before satellite observations of the ERB were possible, scientists used highly imaginative approaches to determine the radiation budget components.

According to Hunt [1986] the first estimate of the solar constant[1] was made by Pouillet 160 years ago, and Abbot and Fowle made the first attempt to determine the

---

[1] The solar constant is defined as the solar flux incident to an imaginary spherical shell with the Sun at its center and having a radius equal to the mean Sun-Earth distance.

components of the Earth radiation budget at the beginning of this century. Hunt also describes the effort of Very in 1912 and of Danjon in 1936, both of whom used the ratio of the relative sunlit and Earth-lit brightnesses of the lunar disk to obtain estimates of the Earth's albedo. In the 1940's advances in laboratory spectroscopic technology provided more complete observations of atmospheric components, such as water vapor, ozone, and carbon dioxide, and by the end of that decade the first space-borne observations of weather were obtained from cameras on sub-orbital rockets.

On February 17, 1959, Explorer 6 produced the first photographic images of the Earth's cloud cover, thereby announcing the first of three generations of Earth radiation budget satellite missions between 1959 and 1984 [House, 1986]. In this first generation of satellite-based ERB observations, satellites such as Explorer 7, TIROS 2, and TIROS 7 featured orbital inclination angles reaching mid-latitude regions of the Earth. The principal problem faced by these satellites was their limited or even nonexistent data storage capacities. During the second-generation missions (1960-1981) daily global coverage of the Earth was possible due to satellites such as Research/ESSA (1960), Nimbus 3 (April 14, 1969) and the NOAA series beginning on December 11, 1970. These satellites also extended the duration of spacecraft measurements to several years. The third-generation missions began with the Earth Radiation Budget Experiment (ERBE). The ERBE program was created as a response to the need for sufficient data to cover the sampling requirements for each component of the ERB: direct solar irradiance, reflected short wavelength radiation, and emitted long wavelength radiation [Barkstrom, 1982]. The first of the three ERBE satellites was launched from the space shuttle *Challenger* (Mission 41-G) on October 5, 1984 [Kopia, 1986]. Additional ERBE instruments were placed in orbit on the National Oceanographic and Atmospheric Administration NOAA-9 satellite, which operated between February 25, 1985, and November 7, 1988; and on the NOAA-10 satellite that operated from December 17, 1986, to September 16, 1991. Presently, NOAA has NOAA-12, launched in May 1991, and NOAA-14, launched in December 1994, both operating in polar orbits that provide visible and infrared radiometric data, radiation measurements, and ozone levels in the atmosphere [Anon., 2002].

Measurements of the interannual variations of the ERB made from sun-synchronous, polar orbiting spacecraft face the problem of unknown errors resulting from the different equator crossing times of each spacecraft. Data from geostationary satellites such as the American Geostationary Operational Environmental Satellite (GOES) and the European Meteorological Satellite (METEOSTAT) provide a regular sample of the atmospheric diurnal cycle. This information provides a better understanding of the temporal and spatial sampling errors inherent with sun-synchronous, polar-orbiting spacecraft and promotes further investigation of spatial scales and meteorological conditions. Currently, the United States is operating GOES-8 (or GOES-East), launched on April 13, 1994, and GOES-10  (or GOES-West), launched on April 25, 1997. GOES-11 was launched on May 3, 2000 and is being stored in orbit as a fully functioning replacement for GOES-8 or GOES-10 upon their eventual failure [Anon., 2000].

The National Aeronautics and Space Administration (NASA) of the United States is an integral part of the American effort to understand the Earth's ocean-atmosphere system. In addition to the GOES program, NASA is also presently using data from the Upper Atmosphere Research Program (UARS) [Anon., 2001*a*], whose principal purpose is to provide information about the upper atmosphere that can lead to a better understanding of the effects of human activity. UARS was launched on September 12, 1991, from the Space Shuttle *Discovery* (STS-48). Data are collected from a near-circular Earth orbit of about 585 km altitude and having a 57-deg inclination.

NASA's Clouds and Earth's Radiant Energy System (CERES) program is one of the major contributors of data for Earth Radiation Budget studies. As part of the Earth Observing System (EOS) program CERES was planned to provide continuity with the type of monitoring that the Earth Radiation Budget Experiment (ERBE) provided [Barkstrom, 1990].

The first CERES instrument was launched aboard the Tropical Rainfall Measuring Mission (TRMM) in November 1997, and a second and third instruments were launched on the EOS Terra satellite in December 1999. Clouds and radiative fluxes vary throughout the day, making necessary multiple measurements to achieve adequate temporal sampling. The CERES FM3 and FM4 instruments were launched in early May 2002 on the EOS Aqua spacecraft.

## 1.2     The Thermal Radiation Group

For almost three decades, the Thermal Radiation Group (TRG), led by Dr. J. Robert Mahan of the Department of Mechanical Engineering at Virginia Polytechnic Institute and State University, has been involved in the optical and radiation heat transfer modeling of radiometric channels in support of the ERB programs. The Group's earliest work was the design and execution of experiments to test the detector concept proposed for the Long-Term, Zonal Earth Energy Budget Experiment (LZEEBE). LZEEBE was intended to obtain continuous zonal and regional measurements of albedo and Earth-emitted radiation over the entire globe [Fanney, 1975]. Fanney, in the same contribution, reports the results of a test of a prototype in a thermal-vacuum chamber. Rasnic [1975] developed a thermal and kinetic model of an opaque, thin-wall spherical satellite of the type intended to be used in LZEEBE and used in other spherical shell satellites such as Explorers IX, XIX, XXIV, and XXXIX. Passwaters [1976] integrated Rasnic's model with an Earth radiative scene model developed at Colorado State University based on 172 Nimbus III measurements. This effort permitted a detailed simulation of the interaction of radiative heat fluxes from the Earth with a thin-walled spherical shell in low Earth orbit.

More recently, the Thermal Radiation Group has provided support to NASA's ERBE and CERES projects. Eskin [1981] presents the first optical model of a diffuse-specular radiometer cavity using the Monte Carlo ray-trace (MCRT) method. This effort is also described by Mahan and Eskin [1981, 1984]. Five years later Gardiner [1986] combined the finite-element method and the Monte Carlo ray-trace method to formulate a thermal model describing the dynamic response of the active sensing element of a cavity radiometer. The model was then used to analyze the steady-state and transient response of a hypothetical version of the instrument operating at cryogenic temperatures. For his master's thesis Tira [1987] created a dynamic electrothermal model to study the effects of the thermal and electrical time delays of the total Earth-viewing channel of ERBE. Later in 1989 and 1990 he and his co-workers presented improved models of the ERBE nonscanning radiometer and new results for the simulation of the solar observations. Later in his doctoral dissertation Tira [1991] modified the aperture geometry to better

represent the optical path followed by the radiation incident to the instrument. In the same study, Tira used the improved model to analyze the transfer function of ERBE's wide field-of-view (WFOV) channel and proposed a series of in-flight scenarios that permit this transfer function to be obtained during solar calibration. Finally, he used the MCRT method to compute the point spread function of the ERBE scanning instrument. Meanwhile, Mahan *et al.* [1987] developed a finite-element model to study the conduction and radiation heat transfer within a generic active-cavity radiometer. Kowsary [1989] in his doctoral dissertation investigates the radiative behavior of spherical cavities whose walls are completely or partially specular. Meekins [1990] developed a detailed optical model of the scanning radiometers of both ERBE and CERES using the MCRT method, and Bongiovi [1993] modified and improved Meekins' model for the ERBE and CERES scanning instruments and added a radiative analysis to the existing optical analysis. In a closely related work, Haeffelin [1993] integrated a three-dimensional transient diffusion model of the active element of the scanning thermistor bolometer detector with a dynamic electronic analysis of its signal conditioning circuit, and later combined this with the optical radiative model developed by Meekins and Bongiovi to create a pseudo-end-to-end channel model. Haeffelin *et al.*, 1993, presents a more detailed discussion of the ERBE nonscanning and scanning channels. Priestley [1993] followed up on Haeffelin's work in his own master's thesis and later [Priestley *et al.*, 1995] reports the results of an investigation to estimate the level of vulnerability of thermistor bolometer radiometers to signals produced by undesired fluctuations of the temperature in the substrate to which the detector is bonded. Nguyen [1994] formulated a thermal model to optimize the design of the Mirror Attenuator Mosaic (MAM) used to calibrate the CERES instruments in Earth orbit.

In 1996, Walkup consolidated the expertise accumulated by the Thermal Radiation Group to create a design tool for optical systems intended for radiometric imaging. Combining the field of optical engineering and radiation analysis, Walkup developed software that allows a designer to evaluate one- and two-mirror telescope configurations using the MCRT method to perform both the optical analysis and the radiation heat transfer calculations. Later, Haeffelin [1996, 1997] finalized years of effort by the Thermal Radiation Group by integrating the optical/radiative model with the

dynamic electrothermal module of CERES-like radiometric channels. Also in 1996, Savranski carried out a study that concludes that the thermal noise in the CERES telescope structure is sufficiently small to be neglected. Integrating the active and reference detector models into a model of the complete detector assembly, Priestley [1995, 1997] completed the end-to-end model of the CERES scanning thermistor bolometer radiometers. He also used an Atmospheric Radiation Model created by Villeneuve [1996] to provide a realistic simulation of the heat fluxes at the top of the atmosphere as an input to his model. He also used his model to simulate and verify the CERES instrument calibration protocols.

In the last five years members of the Thermal Radiation Group have focused their efforts on the design of next-generation instruments for the remote sensing of the Earth and its atmosphere. Weckmann [1997] developed a dynamic electrothermal model of a sputtered thermopile thermal radiation detector to define an optimal design of and to study the feasibility of such detectors for future-generation space-borne radiometers. In her 1998 master's thesis the current author used the MCRT method to develop a thermal radiative model for the same design studied by Weckmann [Sánchez, 1998]. The model permits calculation of quantities characterizing the optical cross-talk among pixels of the detector to facilitate the decision-making process relative to an optimal design of the detector. Later with her co-workers she developed the theoretical foundation for the protocol defined and demonstrated in this doctoral dissertation [Sánchez, *et al.*, 1999, 2000, 2001]. In 1998, Barreto designed an experimental procedure for the estimation of electro-thermophysical properties of the different materials used to fabricate the thermopile thermal radiation detector. Also in 1998 Coffey explored methods for modeling the diffraction of light in the MCRT environment. She also used an MCRT model of the CERES optical system to study the feasibility of partitioning the current telescope so that it serves several detectors. This was accomplished by an MCRT-based model in which the spherical mirrors were replaced with hyperbolic mirrors to achieve acceptable uniformity of radiation flux across the telescope focal plane. She also used a new Monte Carlo ray-trace environment (a precursor of FELIX[1]) for the conceptual

---

[1] FELIX is the Functional Environment for Longwave Infrared eXchange, a commercial MCRT environment created by Félix J. Nevárez of the Thermal Radiation Group.

design of a next-generation radiometer for monitoring atmospheric energetics from space [Coffey *et al.*, 1999]. Finally, Sorensen [1998] integrated the optical model for the thermopile thermal radiation detector developed by the author with the electrothermal model developed by Weckmann to obtain an end-to-end model of a linear-array detector. He also developed a protocol based on discrete Green's functions for removing optical cross-talk from among elements of the final instrument output. In 1999, he used generic algorithms and numerical models to design and analyze thermopile detectors [Sorensen *et al.*, 1999]. Finally in 2000, he carried out a numerical study of sources of uncertainty in the calibration of radiometric instruments [Sorensen, *et al.*, 2000]

In other related areas of thermal modeling research, Smith [1999] studied the utility and accuracy of an ALGOR$^{®}$ finite element model for understanding thermal contamination in a pyranometer and, in a separate contribution, presented a protocol for correcting measured short wavelength irradiance for variable thermal radiation effects [Smith, 1999]. Smith *et al.* [2001] also created an MCRT model of a pyranometer to be integrated with the existing FEM model to study the sensitivity of the signal to external conditions such as wind and air temperature. Barry [1999] analyzed the effect on the performance of a thermal radiation detector with hypothetical contact resistance between the layers of the detector. Using the random walk method he also showed that the interfacial roughness effect does not explain the thin-film effect. Dobarco-Otero [2000] developed an alternative method of modeling the absorption of incident radiation in a multi-layered detector. In his model, the incident radiation is treated as volumetric heat generation that is attenuated by passage through the absorbing layer. He also contributed to the development and demonstration of the design of an optically flat absorber layer [Mahan, *et al.*, 2001]. Carnicero [1999], as a requirement for his degree in the *Centro Politécnico Superior* of the University of Zaragoza, modeled an aureolometer to detect the radiation coming from the solar aureole, and presented a preliminary design of the main parts of the aureolometer. For his master's thesis, he described and characterized the thermal offset in a Precision Spectral Pyranometer and demostrated that this offset can be corrected by small modifications of the instrument [Carnicero, 2001]. Finally Santamaría [2001] used the MCRT method to develop a radiative model for the vertical distribution of the absorption rate of solar radiation by tropospheric aerosols.

## 1.3      Motivation and goals

Application of Monte Carlo ray-trace (MCRT) method to heat transfer problems has grown rapidly since its use was first reported in the 1960's. In what appears to be the first publication describing the Monte Carlo approach to radiation heat transfer, J. R. Howell and M. Perlumutter [1964] describe a method to calculate the heat transfer and temperature distribution between infinite parallel gray plates at different temperatures separated by an absorbing and emitting gray gas with or without a uniform heat source in the gas. Later in 1966 Corlett used the Monte Carlo method to develop a program intended for engineering calculation of thermal radiation in real enclosures. In the same year, Sparrow and Cess briefly discussed the application of Monte Carlo methods in thermal radiation problems. The MCRT method has subsequently proven to be very useful in the estimation of the *radiation distribution factor*, $D_{ij}$ [Mahan and Eskin, 1981, 1984], in various instrument models. Mahan [2002] presents a formal structure for the experimental design of MCRT algorithms in his textbook.

The increasing use of the MCRT method in thermal radiation and optical modeling has created a general awareness in the scientific community of the need for a well-founded common statistical basis for citing precision and accuracy. In particular, the Thermal Radiation Group has at its disposal a robust Windows-based MCRT environment, FELIX, developed by another member of the Group, Félix Névarez-Ayala [2002]. With this program the user can import CAD-based geometries, perform an MCRT analysis, and export the resulting distribution factors as an image or as a data file. Although FELIX is still under development, a beta version has been used in the current investigation. A student version of FELIX is packaged with Mahan's radiation heat transfer textbook [2002].

The ultimate objective of the research reported in this dissertation is to develop a protocol to predict, to a specified level of confidence, the uncertainty of the results obtained by MCRT models. The vehicles for demonstrating the protocol are radiometric instrument models. A relatively simple radiometric cavity from an instrument developed earlier by the TRG is used initially, followed by application of the procedure to a more

complicated geometry. In order to achieve the overall goal, several related objectives must be met:

- study the sensitivity of the distribution factors calculated by the MCRT method to variations in the optical properties, such as the reflectivity and its specular component, of simple enclosures

- study the variation of the distribution factors with different types of simple enclosures and consisting of different numbers of surfaces for a fixed set of surface optical properties

- develop a method to predict the uncertainty in the distribution factors, to a stated level of confidence, of simple enclosures based on variations in their geometric, optical, and radiative properties

- apply the statistical principles developed to bound the uncertainties in distribution factors and net heat flux for generic enclosures (experimental design of MCRT models)

- extend this method to a more complex MCRT model, specifically to the model of CERES instrument.

After discussion of the principles of the Monte Carlo ray-trace method in Chapter 2, the pursuit of these objectives is described in Chapter 3. The theory developed in Chapter 3 is then validated by means of numerical experiments in Chapter 4. The statistical approach is applied in Chapter 5 to a more complex geometry, and finally conclusions and recommendations are presented in Chapter 6.