1. Introduction

It is the nature of mankind to seek an understanding of the world around him, to explain natural phenomena. The Earth's climate system presents a real challenge from both an observational and a theoretical perspective. By understanding the effects of global climate change its consequences can be anticipated and mitigated.

Processes that have the potential to change the climate system, such as global warming due to the "greenhouse effect," are of major concern. For many years we have known that burning fossil fuels increases the concentration of carbon dioxide (CO_2) within the atmosphere and that this change increases the atmospheric greenhouse effect. Recently, we have discovered that greenhouse gases other than CO_2, such as methane (CH_4) and nitrous oxide (N_2O), can also play a significant role in greenhouse warming.

Despite the increase in greenhouse gas concentrations, the magnitude of any resulting climate change is still not understood. This is due to the complex nature of feedback within the climate system. For example water vapor, which is the most active greenhouse gas, is believed to represent a positive feedback to global warming. However, increased amounts of water vapor due to a warming of the Earth's surface may correlate with increased cloud amounts. Clouds are known to have a net cooling effect on the atmosphere. Thus, the responses of water vapor and clouds to changes in the Earth-atmosphere system, whether anthropogenic (fossil fuel burning, deforestation) or natural (volcanic), play a key role in determining climate change.

Thus, to increase our understanding of the long-term consequences of human activities on the global environment and also to improve our capabilities for long-range weather and climate forecasting, the international scientific community has combined its research efforts to address these scientific issues. A program of observation of variables that govern global climate change, including the radiation budget, has been undertaken. The motivation for the work described in this thesis is to adapt sputtered thermopile technology to the fabrication of detector elements in radiometers for monitoring the Earth radiation budget from space. The present effort is aimed at providing the next generation of scanning radiometers for the ongoing Cloud and Earth's Radiant Energy System (CERES) experiment and at providing the Geostationary Earth Radiation Budget (GERB) experiment with a radiation detector.

1.1 The Earth Radiation Budget

The global energy balance at the top of the atmosphere (TOA) can be expressed as an equilibrium between the incident solar radiation, the shortwave radiation reflected by the Earth and its atmosphere, and the longwave radiation emitted by the Earth and its atmosphere. The hypothesis on the radiative energy budget to be tested may be expressed symbolically as

$$\mathrm{P_i - P_r = P_e} \, , \tag{1.1}$$

where $\mathrm{P_i}$ (W) is the incident solar energy, $\mathrm{P_r}$ (W) is the reflected solar energy and $\mathrm{P_e}$ (W) is the thermal energy emitted by the Earth-atmosphere system.

In terms of heat fluxes, ϕ (W/m^2), this balance can be written as

$$\int_t \int_s (\phi_i - \phi_r)\, dt\, ds = \int_t \int_s \phi_e \, dt\, ds \, , \tag{1.2}$$

where the integral over s is formed over an imaginary surface at the TOA and the integral over time, t, is formed over a sufficiently long time period.

Under equilibrium conditions, the climate system is such that the Earth absorbs as much shortwave energy as it emits in the longwave bands. If we consider the Earth in the energy balance we have another equation,

$$P_a = P_e = P_i - P_r \,, \tag{1.3}$$

where P_a (W) is the part of the incoming radiation absorbed by the Earth and the atmosphere. A simple model of the global energy balance at the top of the atmosphere and at the surface of the Earth is illustrated in Figure 1.1.

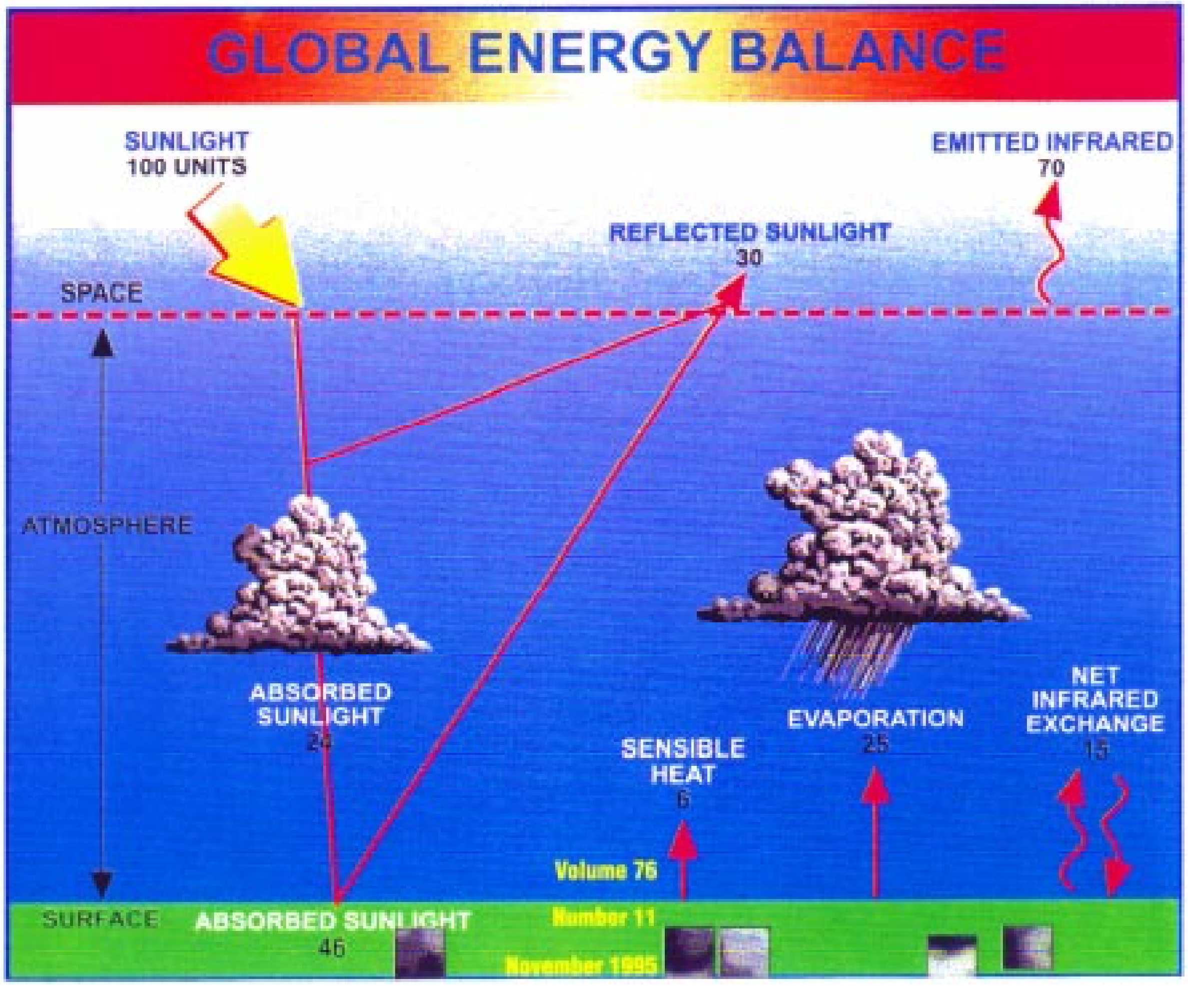

Figure 1.1. Illustration of the global energy balance at the top of the atmosphere and at surface of the Earth [Bulletin of the American Meteorological Society (cover), Volume 76, 1995]

On average, the incoming solar heat flux at the top of the atmosphere is 340 W/m^2. Of this amount roughly 30 percent (about 100 W/m^2) is reflected back into space so that 240 W/m^2 is absorbed by the Earth-atmosphere system and thus, under equilibrium conditions, 240 W/m^2 is re-emitted by the Earth and the atmosphere into space. Perturbing this equilibrium, for instance by admitting a change in the chemical composition of the atmosphere such as increasing the amount of a greenhouse gas, will affect the emitted radiation. To compensate for such imbalances, the Earth will heat up until a new radiative balance is achieved [Wielicki, 1995]; hence the term "global warming."

Global warming is also influenced by cloud feedback. The introduction of clouds enhances shortwave reflection, cooling the Earth-atmosphere system; but it also decreases the emitted long-wave radiation, warming the Earth-atmosphere system. The net result of clouds on the climate, called the net cloud radiative forcing, is a cooling effect [Ramanathan, 1989]. While this net cooling effect has been confirmed, the role of cloud feedback on the energy balance is not fully understood and remains an area of ongoing research.

Do human activities produce perturbations to the extent that the climatic equilibrium is modified? Do climate models accurately portray the influence of clouds on climate? How does the cloud feedback mechanism influence the climate? Further investigations have to be carried out to answer these questions. The Earth radiation budget and cloud properties must be observed and improvements in detection of radiative flux at the TOA must be obtained.

The goal of EOS, the Earth Observing System, is to obtain data on the emitted and reflected components of the radiation coming from the Earth; EOS is NASA's contribution to the international Mission to Planet Earth. This program consists of space-based remote sensing platforms on Earth-orbiting satellites which provide critical global observations of the Earth's radiation. The main aim of EOS is to understand the climate evolution over a long period of time [Anon., 1993].

1.2 A Brief History of Earth Radiation Measurements

In 1959 Explorer 6 made the first satellite-based Earth radiation budget measurement, and with this first attempt began an era of three generations of Earth radiation budget satellite missions between 1960 and 1984 [House, 1986]. In 1979, twenty years after Explorer 6, the United States Congress created the Earth Radiation Budget Experiment (ERBE) as a NASA program. This was the first satellite mission dedicated to measuring the Earth radiation budget using multiple satellites in order to obtain sufficient spatial and temporal coverage [Barkstrom, 1984].

The ERBE goal was to achieve spatial resolution and temporal sampling adequate to define diurnal, or daily, variations of the Earth radiation budget components [Lee, 1990]. The first ERBE satellite was launched by the space shuttle Challenger on October 8, 1984. On December 12, 1984, and September 17, 1986, two additional satellites that included ERBE instrumentation, called National Oceanic and Atmospheric Administration (NOAA) 9 and 10, were launched. Each of these satellites carried three scanning radiometers with a narrow field-of-view covering a 0.2-to-5-μm wavelength interval (shortwave), a 5-to-50-μm wavelength interval (longwave), and a 0.2-to-100-μm "total" interval. They also carried four nonscanning radiometers. These nonscanning radiometers include two unfiltered total and two filtered shortwave wide and medium field-of-view (WFOV and MFOV) channels, respectively, which stare at the Earth. The nonscanning detectors are active cavity radiometers which supply electrical heat to the instrument cavity in just the amount required to compensate for the variation of incident radiation [Tira, 1987].

The results of the ERBE program are widely reported, but the 1989 article in **Science** by Ramanathan is perhaps the best summary. Briefly, these results validate the essential physics of the greenhouse effect. They confirm that water vapor is a major source of positive feedback in the climate and that clouds have a net cooling effect. It was also established that low-level clouds cool the climate through reflection of shortwave solar radiation, whereas high-level clouds cause heating through absorption and reflection of longwave radiation emitted by the Earth's surface.

Though the question of the general effect of clouds on the Earth's climate has been answered, the ERBE scanning radiometers were too short-lived to provide data on the cloud feedback effect.

Viewing these encouraging results and taking into account the progress made in technology, NASA planned the CERES program. CERES is a component of the EOS program that intends to maintain the same type of monitoring as ERBE. Planned EOS instrument launches can be found in Table 1.1.

CERES scanning radiometers are of the same genre as those utilized on ERBE but with improved resolution and greater accuracy. Like ERBE, CERES has three scanning radiometric channels with the longwave channel limited to a narrower band (8 to 12 μm) in order to measure water vapor. But unlike ERBE, CERES will not carry nonscanning channels. In the case where two CERES instrument packages are used on the same platform, they will operate in two modes: the cross-track mode, which provides continuity with ERBE data, and a biaxial rotating mode in which the scanning plane is rotated from the reference cross-track plane. This second mode will provide angular radiance data that will be used to refine the bidirectional reflectance function.

The first of the CERES instrument packages will be launched in November of 1997 aboard the Tropical Rainfall Measuring Mission (TRMM) satellite. The mission periods of the planned CERES host spacecraft to be launched may be seen in Table 1.2.

Table 1.1. Planned EOS instrument launches [Wiekicki, 1995].

Satellite	Sponsor	Launch	Measurements
TRMM[1]	Japan/US	1 November1997	radiative fluxes and cloud properties
EOS-AM[2]	US/Japan	June 1998	radiative fluxes and cloud properties
EOS-PM[3]	US/ESA[4]	December 2000	radiative fluxes and cloud properties
METOP[5]	EUMETSAT[6]	2000	cloud properties: complements EOS-AM
EOS-ALT[7]	US	2002	lidar cloud height

---

[1] Tropical Rainfall Measuring Mission

[2] Earth Observing System-AM (morning equatorial crossing time)

[3] Earth Observing System-PM (afternoon equatorial crossing time)

[4] European Space Agency

[5] Meteorological Operational Satellite

[6] European Meteorological Satellite

[7] Earth Observing System Altimetry Mission

Table 1.2. Planned CERES Host Spacecraft [Barkstrom, 1990]

Spacecraft	Sponsor	Number of CERES Instruments	Mission Period
TRMM	NASA/ NASDA[8]	1	1997-2000
EOS-AM-1	NASA	2	1998-2003
EOS-PM-2	NASA	2	2001-2005

---

[8] National Space Development Agency (Japan)

1.3 Signal Processing

In order to assess the Earth radiation budget from orbit, the radiation field measurements must be converted into electronic signals. These signals are then transmitted to Earth and translated, or “inverted,” from the satellite altitude to the top of the atmosphere. The continuous signal obtained, a voltage as a function of time, is sampled so as to have a succession of values (V) for each pixel scanned. Those values are then transformed into radiance (W/m^2/sr) using the calibration conversion function. Bidirectional Reflectivity Distribution Functions (BRDF), called also Angular Dependence Model (ADM), are used to convert the radiance into instantaneous flux at the TOA. The flux values at the TOA are then averaged over time and space to obtain a measurement of the Earth radiation budget. Figure 1.2 shows the logic flow of the data processing procedure. These data are used to develop models that determine the average monthly radiation budget and its variability on regional, zonal, and global scales.

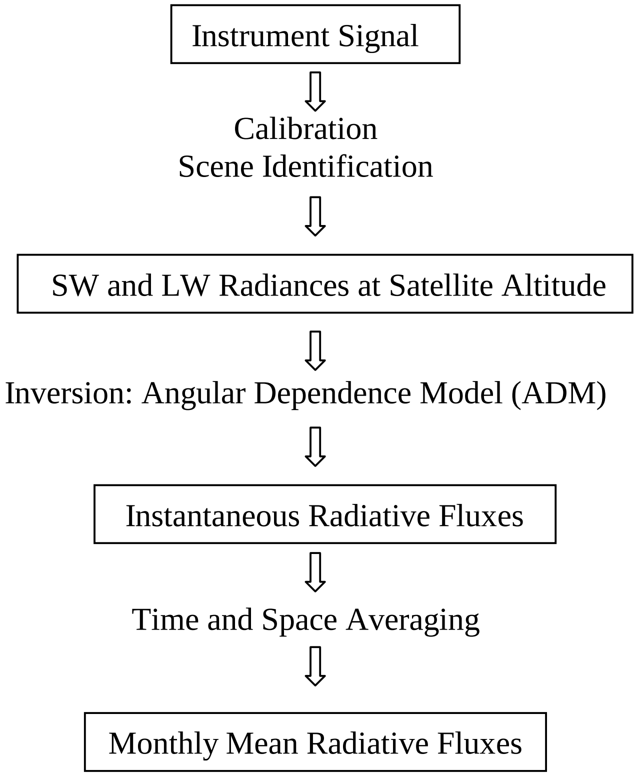

Figure 1.2. Data processing [Haeffelin, 1997]

1.4 Description of the Sputtered Thermopile Thermal Radiation Detector

A new detector concept for Earth radiation budget radiometry applications has been proposed by a team led by Prof. J. R. Mahan from the Department of Mechanical Engineering at Virginia Tech and Mr. L. W. Langley, president of Vatell Corporation [Mahan, 1996]. The intended application of the detector was the Geostationary Earth Radiation Budget (GERB) instrument. The GERB experiment was proposed by a European-American consortium lead by the United Kingdom. The GERB instrument is to be carried on a geostationary satellite with each detector pixel having a 30-by-30-km field-of-view on the Earth's surface. The satellite rotation on its axis would produce a series of scans of a linear array across the disk of the Earth. The GERB instrument is scheduled to fly on ESA's Meteosat Second Generation Satellite (MSG) and to be launched in the year 2000. The GERB-related effort has evolved into an effort to develop a next-generation detector for CERES. All of the preliminary detector design is based on the GERB instrument specifications.

The proposed detector consists of a linear array of blackened single-junction-pair thermocouples, shown in Figure 1.3. The linear array consists of 256 pixels. The 60-by-60-μm pixels are separated from each other by a 3-μm gap etched by a laser. Each pixel contains the active and reference junction of the thermocouple. The elements of a junction pair are electrically connected through leads attached to platinum pads at one end of the pixel (the reference junction). The output voltage is measured at the other end of the pixel (active junction). Each pixel is electrically and thermally independent.

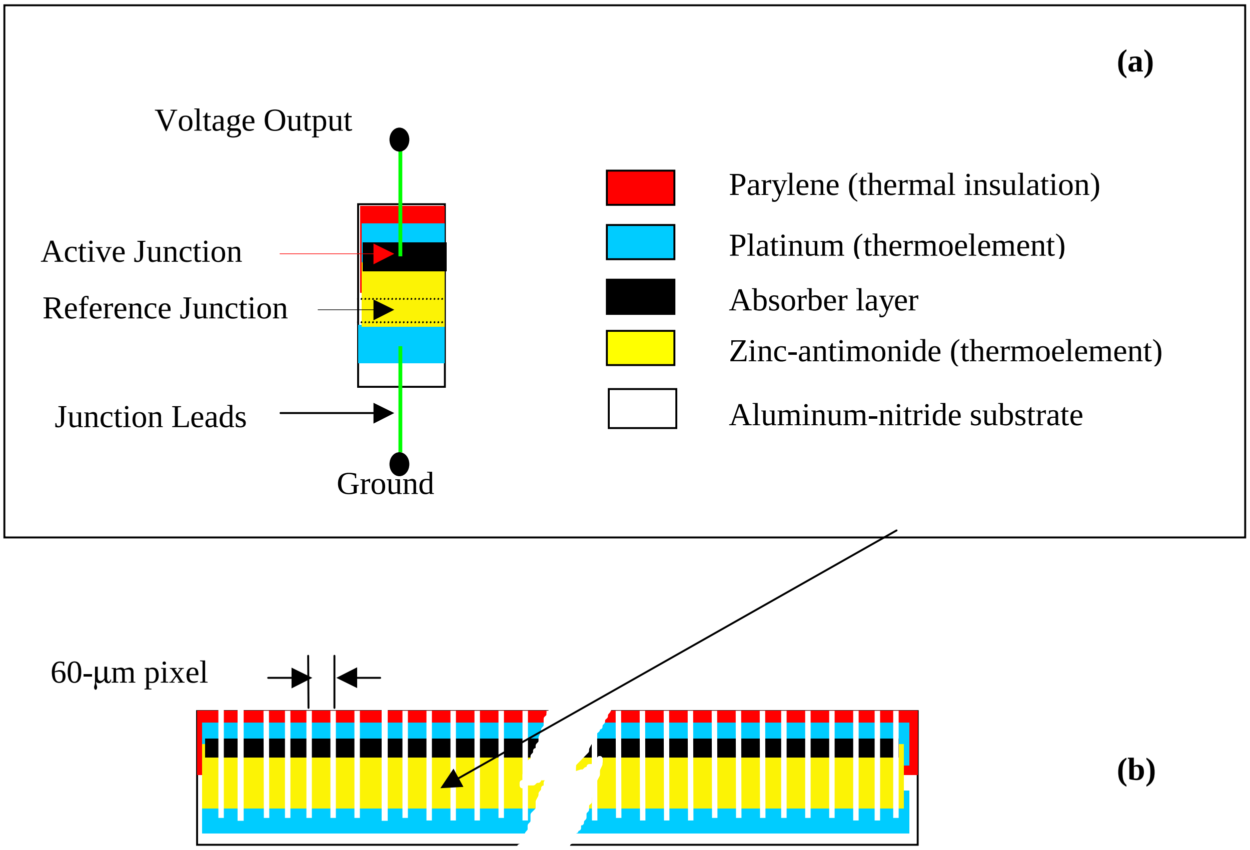

Figure 1.4. (a) Detail of a single pixel and (b) the thermopile linear array and connection leads [adapted from Mahan, 1997]

This design could be slightly changed for alternative future applications of the device, such as CERES next-generation instruments, by increasing the size of a pixel so that it contains two or more thermocouple junction pairs electrically connected in series, i.e. a thermopile. The sensitivity of the device would increase proportional to the number of thermocouple junction pairs in the thermopile.

In the proposed GERB configuration the linear array is mounted on one wall of a wedge-shaped cavity, as shown in Figure 1.5.

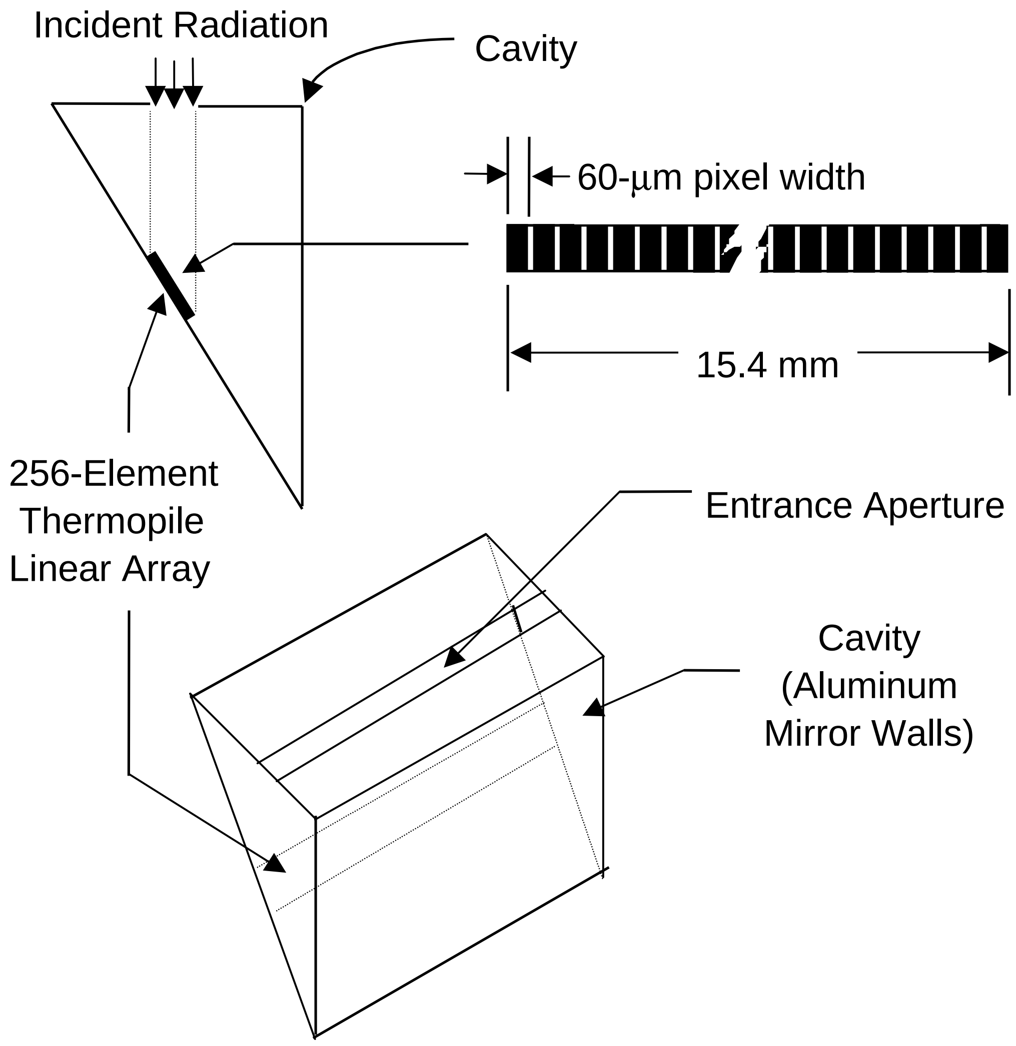

Figure 1.5. The thermopile linear array and its cavity [Mahan, 1997]

Incident radiation enters the instrument aperture through a 60-µm entrance slit. The design of the cavity ensures that the active junctions are directly exposed to incident scene radiation, while the reference junctions are shielded by the opposite cavity mirror wall.

The active junction is coated with a high-emissivity, specularly reflecting paint. This black absorber is sufficiently thick to absorb the incoming radiation, yet sufficiently thin to respond quickly to varying radiation heat fluxes. Both the active and reference junctions are mounted on an aluminum-nitride heat sink. The reference junctions are in direct thermal contact with the heat sink, whereas the active junctions are separated from the heat sink by a thin film of polymer which acts as a thermal impedance. This thermal impedance allows the active junctions to obtain a higher temperature than the reference junctions when exposed to thermal radiation.

The detector concept is innovative in that the thermocouple junctions are made of a zinc-antimonide (ZnSb) and platinum (Pt) couple. This combination of an amorphous semiconductor and a pure metal has a very high Seebeck coefficient, or thermoelectric efficiency. The sensitivity of such a combination is increased by a factor of several hundred compared to traditional metal-metal thermocouple junctions.

In the current design the walls of the cavity and the heat sink are maintained at a constant temperature of 311 K by an actively controlled heater in order to reduce thermal noise due to variations in heating of the satellite.

1.5 Goals and Motivations

The Thermal Radiation Group, a laboratory in the Department of Mechanical Engineering at Virginia Polytechnic Institute and State University, has been working on instruments that measure the Earth radiation budget under the direction of Dr. J. Robert Mahan for more than 25 years. The group has provided a unique ability to combine optical, radiative, thermal conduction, and electronic models in order to produce end-to-end dynamic electrothermal models of the ERBE and CERES instruments. In the last two years the group has widened its field of study by exploring a new detector technology: sputtered thermopile thermal radiation detectors. The objective is to study the feasibility of such detectors for future-generation space-borne radiometers. The current thermistor bolometer sensor on CERES may be replaced by a thermoelectric device in the next generation of Earth radiation budget radiometers. The feasibility study is being conducted through of two interrelated efforts:

(1) development and use of numerical models of the detector and cavity with the overall objective of defining an optimal design, and
(2) fabrication of prototypes which reflect the optimized design.

The goal of the effort described in this thesis is limited to the development of a dynamic electrothermal model of the thermoelectric device using the finite element method. This numerical modeling effort will allow us to predict the performance of the sensor in its final structure (the cavity) and implement design strategies to predict the optimal sensor thermoelectric properties. These stated goals will be achieved through meeting specific objectives. First a study of the base-line design of a thermocouple junction pair and its limiting case is to be conducted. Then a parametric study will be performed. The thermocouple sensitivity to critical parts of the base-line design geometry will be determined by studying the effect of changing these parameters and exercising different boundary conditions