2.0 Radiometric Design

2.1 The Radiometric System

The basic building blocks of a general radiometric system for remote sensing are given in Figure 2.1. Unfiltered radiant energy, $L(\lambda)$, which is either emitted from or reflected by objects in the scene, is incident upon the instrument aperture after passing through and being spectrally and spatially altered by the Earth's atmosphere. Upon entering the aperture, the energy is collected and filtered by the spectral response of the instrument, $S(\lambda)$, which includes but is not limited to the effect of filters, and ultimately deposited upon the detecting element. The energy absorbed by the detecting element causes a continuous time varying signal to be produced at its output terminals. The magnitude and type of signal produced are dependent upon the type of detector in the instrument. This signal is then conditioned electronically in order to reduce high-frequency electronic noise and then sampled at regular intervals.

In addition to the desired scene energy which arrives at the detector, background energy may also arrive at the detector from several sources, thereby producing radiometric error. Three possible sources are shown in Figure 2.1. The first source is radiant contamination. No matter how well the optics are designed, detectors will inevitably directly or indirectly view some portion of the mechanical structure of the instrument. This structure in turn radiates energy which may arrive at the detector. It is important that this background scene either be maintained constant or that it vary slowly and predictably such that the related errors in the signal may be characterized and removed.

A second source of noise shown in Figure 2.1, conductive contamination, is of particular importance to thermal detectors. Thermal detectors produce a signal which is directly related to their temperature. Ideally, the detector temperature will only change due to variations in energy arriving from the scene. If the detector is not thermally isolated from the instrument structure, whose thermal state may be varying with time, the detector may produce a false signal having the same temporal frequency. One method used to combat this problem involves utilizing two matched detectors, one active and the other a reference. These detectors are typically placed in a thermally controlled bridge circuit in order to compensate for any common mode changes in the detectors due to thermal transients in the instrument structure.

The final mode of contamination in Figure 2.1 is self-heating. This is an issue only for detectors such as thermistor bolometers and similar devices through which current is passed to measure a resistance. Thermistor bolometers work by having a constant bias voltage applied across their terminals. The electrical resistance of the bolometer material changes with temperature changes provoked by the absorption of varying scene energy. This allows a varying current to pass through the detectors. Some of the energy from the electrical current is dissipated in the detectors by the Joule effect, I^2R, where I is the value of the electrical current in amperes (A), and R is the value of the electrical resistance in ohms (Ω). Although the Joule effect is usually negligible in a well designed thermistor bolometer detector, it must be considered when designing an instrument. This mode of thermal contamination is not compensated for by a bridge circuit arrangement since it would not be a mode common to both detectors.

2.2 Optical Design Considerations

The instrument optical subsystem is designed to determine the spatial (field-of-view) response characteristics of a sensor and to reduce its sensitivity to out-of-field sources. An optimal design must balance several factors, such as the desired field-of-view, aperture size, sampling rate, and rejection of out-of-field energy, and must be assembled in a package which is rugged and easily fabricated. For example, increasing the aperture size for a given field-of-view will result in a stronger signal; however, it will also add more mass and increase the overall size of the instrument. The current discussion focuses on two common systems: a Cassegrain-type co-axial optical and an off-axis mirror system. The commonality of these two designs is that they both contain reflective optics only, thus eliminating the possible effects of ghost fields caused by lens surfaces, and in the case of the Cassegrain design, reducing the possible effects of polarization by implementing the circularly symmetric optics.

2.2.1 Off-axis mirror systems

An example of an off-axis mirror system may be seen in Figure 2.2. In this system, energy is collected by an off-axis paraboloid field mirror which focuses the energy on a precision aperture. Upon passing through the precision aperture, the energy is again collected and refocused onto a detector by an off-axis ellipsoid relay mirror. In this optical design, a filtering element would be placed immediately behind the precision aperture. Advantages of this type of system would be no chromatic aberrations or ghost images from refractive optics, no obscurations which could possibly emit energy in the optical path, the detector view of the baffle is minimized through the use of a field-stop relay mirror, and finally the field mirror provides uniform response over the field-of-view. Two primary disadvantages are associated with this type of system. The first is that the use of aspheric mirrors produces aberrations which are not symmetric, resulting in an optical field-of-view which is neither sharp nor symmetric. The second disadvantage is that this design requires critical alignment of the relay mirror and detector relative to the field stop and field mirror. This can be exceedingly difficult with small part sizes, and small misalignments can produce major losses in sensitivity.

2.2.2 Cassegrain-type optics

An example of a classic Cassegrain system may be seen in Figure 2.3. In this design, scene energy is collected by a primary mirror which reflects it to a secondary mirror. The secondary mirror then directs the energy through a precision aperture located at the focal point and onto a detector located immediately behind the aperture.

The main advantage to this type of optical design is its relative ease of fabrication and ruggedness, there being no critical alignment issues. An additional advantage is that such systems produce a small aberration, or blur circle, and, if spherical mirrors are utilized, the size of the blur circle will remain constant for off-axis radiation, thereby sharpening the optical point spread function [30,34]. The major disadvantage is that the center of the secondary mirror could emit a non-scene-dependent time-varying radiometric signal which would lead to errors in interpreting the data product. This concern can usually be addressed effectively through proper design and sampling criteria, however.

2.3 Radiometric Bandpass Selection

Instrument bandpass selections are designed to match the spectral response characteristics of a sensor to those portions of the reflected or emitted spectrum that are most characteristic of objects of interest within the scene. The two main components of the Earth's radiation budget are naturally separated spectrally by the nature of the distinctly different temperatures of their emission sources. The solar energy which arrives at the Earth contains a spectral distribution which is similar to Planck's blackbody distribution function for a blackbody at a temperature of roughly 5800 K. This means that fully 99 percent of the solar energy arriving at the Earth has a wavelength, λ, of less than 5 μm. In stark contrast to this, the Earth-emitted energy well approximates the spectral distribution of a blackbody at roughly 255 K, resulting in more than 98 percent of its energy being emitted at wavelengths greater than 5 μm.

Although simply measuring the broadband radiances of 0 to 5μm and 5 to >100 μm may satisfy the requirement of measuring the global energy balance, it is not of a sufficiently fine resolution to quantify the energetics of the atmosphere. In order to accomplish this goal, measurements must be made over discrete wavelength intervals which correspond to certain desired information. Fourteen wavelength bands which are of interest to scientists, and their corresponding importance, are given in Table 2.

Although it is easy to identify wavelength intervals that would be beneficial to the scientific community to monitor, it is quite another accomplishment to actually design and fabricate an instrument to monitor them. A significant trade-space exists between what can be measured and the accuracy to which it can be measured. Since the Earth/atmospheric transmittance and reflectance are strong functions of wavelength, there may not be sufficient energy in a specific wavelength interval to be measured by current-generation detectors. Although this can be overcome somewhat by increasing the size and, therefore, energy gathering ability of the optics, it may not be feasible to do so. Another key factor is whether or not it is possible to fabricate bandpass filters with iltering functions sufficiently sharp to adequately measure the wavelength band of interest without significant contamination from sidebands.

A final concern is the placement of these filters in the optical path. Most filters are of the interference type which work by absorbing the energy outside of the passband. By doing so, these filters will themselves heat up and re-emit energy into the optical path, thereby creating radiometric error. Two solutions to this problem are available. The first is to thermally control the filtering elements, but this could add cost, weight, and power consumption to the instrument package and therefore is not feasible in many applications. The second option is to place two filters in the optical path. The first will remove scene energy outside the desired passband, and the second will absorb the out-of-band energy re-emitted by the first. A disadvantage for this system is that if transmission in the passband is low for a single filter, it will be reduced the same amount again by the second filter.

2.4 Radiometric Detectors

Current-generation remote sensing radiometric instruments utilize two types of detectors: thermal detectors and photon counters. Figure 2.4 illustrates the idealized behavior of thermal and photon detectors as a function of the spectral content of the incident energy. The distinction between the two detector types is the energy conversion mechanism. In thermal detectors radiant energy is converted directly to sensible heat, while in photon detectors radiant energy is converted directly into electrical energy.

2.4.1 Thermal detectors

Thermal detectors are simply energy detectors which make use of the heating effect of radiant thermal energy. Their response is dependent upon the amount of radiant power absorbed but, at least in principle, independent of the spectral content of the absorbed radiation.

Thermal detectors contain a thermal mass which undergoes a temperature change when it absorbs radiation. The signal produced by the detector is directly related to the magnitude of this temperature change. In order to obtain large temperature changes per unit of radiant power, small thermal masses and large thermal resistances are necessary. Thus, the sensitive elements of most thermal detectors are physically small and their response rate is governed by the rate of thermal diffusion.

Three examples of thermal detectors are the thermocouple, which operates via the thermoelectric effect; the bolometer, which operates via the change in electrical resistance with temperature [37]; and the pyroelectric detector, which operates via the change in polarization of a crystal when it undergoes a variation in temperature [38,39,40].

2.4.2 Photon counters

Photon counters respond only to incident photons that possess more than a certain minimum energy. Thus, they are selective detectors of optical radiation, responding only to those photons of sufficiently short wavelengths to produce charge carriers. Their response at any wavelength is proportional to the rate at which photons of that wavelength are absorbed. The number of photons per second per watt is directly proportional to the wavelength; thus, the response of a photon detector for equal amounts of radiant power per unit wavelength interval decreases as the wavelength decreases below that corresponding to the minimum energy [40].

Some types of photon detectors are: photoemissive detectors, which are generally used with electron multipliers and are referred to as photo-multiplier tubes; semiconductor photoconductive and photovoltaic detectors; and photographic film. The semiconductor detectors are composed of lead (Pb), silicon (Si), germanium (Ge), and other substances. Various regions of wavelength response may be obtained by doping these materials with other substances [40,41,42].

2.5 Sampling Criteria

2.5.1 Spatial versus temporal sampling rates

The temporal sampling rate, and thus the field-of-view, of an instrument was formerly driven by the ability of spacecraft to transfer large amounts of data to ground-processing stations. Modern electronics have progressed to the point that that is no longer an issue. Today, temporal sampling rates are determined by the desired field-of-view size and detector response time. Science data from the Earth Radiation Budget Experiment indicate that a ground resolution on the order of 20 km is optimal for understanding the impact of clouds on the radiation budget and climate. Resolutions of smaller than 20 km are most likely strongly influenced by three-dimensional radiative transfer in the atmosphere and would not be directly representative of the interaction of the Earth and its space environment.

In order to reduce aliasing errors caused by undersampling, it is desired that there be some overlap in the sampled footprints in both the scanning and orbital directions. Typically, scanning radiometers scan in a direction normal to the satellite ground-track direction in order to maximize their coverage. As a radiometer scans from nadir to the limb, the distance between the centers of the sampled footprints grows rapidly in the scan direction due to the curvature of the Earth. If the spacecraft were not moving, as the radiometer scanned back from the limb to nadir the sampled footprints would exactly overlap. However, the velocity of the spacecraft is nonzero; therefore, as the radiometer scans back from the limb to nadir the footprints are shifted in the spacecraft orbital direction. The distance between the centers of contiguous footprints in the spacecraft orbital direction is small from nadir to limb because of the relatively slow ground velocity of the spacecraft in the orbital direction. This is illustrated in Figure 2.5. The convolution of elevation scan rate and detector response time are used in conjunction with spacecraft orbital velocity and data sampling rate in defining the desired shape of the field-of-view [43].

2.5.2 Sampling errors

When attempting to reconstruct a radiative field from a discreet time series of data points, serious errors may arise due to undersampling. This phenomenon is known as aliasing and can be avoided by application of Shannon's theorem, which states that data must be sampled at a minimum rate of twice the highest frequency component of the input signal in order to avoid aliasing. The effect of aliasing is to introduce false frequencies in the output that were not present in the original signals [43].

An example of aliasing may be seen in Figure 2.6. In the left-hand column the sampling rate is seven times the frequency of the original sine wave, and the waveform recovered is indistinguishable from the original. In the right-hand column the sampling rate is only 7/5 the frequency of the original sine wave, and the resulting waveform recovered now does not resemble the original wave form. In fact, the false signal frequency of the recovered signal is exactly equal to the difference between the original continuous signal and the sample frequency [40].

All natural signals are band-limited by the physical phenomena giving rise to them. However, natural processes do not exhibit ideal band-limited spectra. Therefore the signal must be band-limited before sampling takes place in order to avoid aliasing. Spatial filtering of radiometric signals by matching the optical design with the temporal sampling rate provides for anti-aliasing band-limiting of scene energy by integrating the smaller spatial details within the instantaneous field-of-view.

Blurring is the degradation that occurs in the reconstruction of sampled data because of the loss of small spatial detail when higher frequency components of the radiance field are attenuated by the frequency response of the sensor and signal conditioning electronics. Blurring occurs when the passbands of real filtering networks do not have optimal flatness or when attenuation near the corner frequency is not sharp.

Manalo et al. [44] suggest that the total variance of the difference between the recovered and original radiance field may be written as

$$\sigma_t^2 = \sigma_a^2 + \sigma_b^2 + \sigma_h^2 + \sigma_i^2 \quad , \tag{2.1}$$

where σ_a^2 is the aliasing error, σ_b^2 is the blur error, σ_h^2 is due to small-scale features beyond the sample frequency, and σ_i^2 is the measurement noise. A complete discussion of this theory may be found in references 44-47.

2.6 Signal Conditioning

The conditioning of electronic signals is a requirement of typical remote sensing instruments since the magnitude of the output from the detector is likely to be very small. In order to boost this magnitude to a useful value, it is first necessary to amplify the detector output. This amplification is typically done with low-noise pre-amplifiers.

As a result of using large-magnitude gains, noise picked up from the electronics may be considerable. Fortunately, the electronic noise is typically of a higher frequency content than the desired signal. In order to eliminate aliasing effects resulting from high-frequency electronic noise, it is necessary to introduce a low-pass filter of some sort. Since ringing and overshoot should be avoided when the signal is filtered, the input and output of the filter must both be linear functions of frequency. The net effect of this linear relationship is that all frequency components of a signal transmitted through it are delayed by the same amount of time. Bessel filters are often chosen because of their maximally flat frequency delay characteristics which result in no distortion in the phase of the output signal with respect to the input [48,49].

2.7 Radiometric Calibration

The first step in data processing is to recover a filtered radiance value from the instrument signal response. This step involves conversion of the signal response into physical units of radiance absorbed by the detecting element using calibration data. The proper way to obtain these data is through an absolute calibration. By absolute, it is meant that the radiances of the calibration sources are tied to an accepted temperature scale, such as the International Temperature Scale of 1990 (ITS'90).

2.7.1 Mathematical modeling

The following overview has been obtained from Lee et al. [50] and is intended to analytically describe the calibration approach for a radiometric system which contains reflective optics and a detector with a first-order response mode.

Components of optical systems, such as silvered mirrors and bandpass filters, along with blackening on the detector elements, represent the optical elements of an instrument which reflect, absorb, transmit, and alter the spectral distribution of energy. The nondimensional, theoretical spectral response of the instrument, S(λ), can be represented as

$$S(\lambda) = \tau_f(\lambda)\rho_m^2(\lambda)\alpha_b(\lambda)\,, \tag{2.2}$$

where τ_f is the combined transmittance of the bandpass filters (-), ρ_m is the reflectance of the mirrors (-), and α_b is the effective absorptance of the black paint layer on the bolometer (-). This example assumes two mirrors, a primary and a secondary, in the optical train; thus, the ρ_m term is raised to the second power. The broadband filtered radiance ($Wm^{-2}sr^{-1}$) absorbed by the detector, $\tilde{L}$, can be represented as the integral of the product of the unfiltered radiance ($Wm^{-2}sr^{-1}\mu m^{-1}$) at the instrument aperture, $L_\lambda(\lambda,\Omega)$, the instrument spectral response, S(λ), and the optical point spread function, P(Ω), over the wavelength band of interest and field-of-view, Ω, or

$$\tilde{L} = \frac{\int_\Omega \int_{\lambda_1}^{\lambda_2} P(\Omega) L_\lambda(\lambda,\Omega) S(\lambda)\, d\lambda\, d\Omega}{\int_\Omega P(\Omega)\, d\Omega}\,. \tag{2.3}$$

In Eq. 2.3 Ω represents the field-of-view, and dΩ is the increment of field-of-view solid angle defined as

$$d\Omega = \sin\theta d\theta d\phi \quad , \tag{2.4}$$

where θ is the polar angle with respect to the optical axis and ϕ is the azimuthal angle with respect to the scan direction. These angles are shown in Figure 2.7.

During calibrations unfiltered radiances, $L_\lambda(\lambda,\Omega)$, are emitted from uniform blackbody reference sources which completely fill the optical field-of-view. Use of full-field uniform blackbody sources means the unfiltered radiance, L_λ, is no longer a function of the emission location within the field-of-view defined by Ω and, thus, Eq. 2.3 reduces to

$$\tilde{L} = \int_{\lambda_1}^{\lambda_2} L_\lambda(\lambda) S(\lambda) d\lambda \quad . \tag{2.5}$$

The unfiltered radiances, $L_\lambda(\lambda)$, are calculated as a function of the source temperature using Planck's blackbody radiation distribution function,

$$L_\lambda(\lambda) = \frac{C_1}{\lambda^5 (e^{C_2/\lambda T} - 1)} \quad , \tag{2.6}$$

where C_1 and C_2 are well known constants.

For a linear instrument, the broadband filtered radiance, $\tilde{L}$, is directly proportional to the output of the detector, with the constant of proportionality referred to as the radiometric gain of the instrument. This relationship may be represented as

$$\tilde{L} = G[m - m_s] + \tilde{L}_s \quad , \tag{2.7}$$

where G is the radiometric gain, m is the output signal, m_s is the output signal when the detector views a known source, and $\tilde{L}_s$ is the filtered radiance from the known source. Monitoring the signal relative to a known source is necessary in order to assess any drifts in instrument performance. Operationally this source is usually cold space which has an equivalent blackbody temperature of 2.7 K. Thus, the gain can be expressed as

$$G = \frac{\tilde{L} - \tilde{L}_s}{m - m_s} \quad . \tag{2.8}$$

The gain G is determined experimentally by using Eq. 2.7 in a least-squares analysis to regress known filtered radiances, $\tilde{L}$, absorbed by the detector element, as determined by Eq. 2.5, against the measured responses of the instrument.

2.7.2 Spectral characterization

It is critical to accurately know the end-to-end spectral response of any instrument designed to measure thermal radiant energy. Even though calibrations should always be carried out with absolute radiometric sources, instruments actually measure the magnitude of the average filtered radiance, $\tilde{L}$, absorbed by the detecting element, not the unfiltered radiance incident to the instrument aperture. Failure to take into account the spectral response of the instrument can result in serious errors when trying to predict the radiance of different scenes which have the same spectrally averaged radiance but different spectral weightings, $S(\lambda)$.

The spectral response of an instrument can be determined theoretically based upon component values measured in an absolute way, as shown in Eq. 2.2. However, this method cannot accurately take into account any influence of instrument physical design on the spectral response such as diffuse emission or reflection of energy from instrument components along the optical path. Additionally, an unacceptable expenditure of resources may be required to accurately characterize each component individually. A method which characterizes the end-to-end spectral performance of an instrument is, therefore, desirable.

End-to-end spectral characterization is accomplished by illuminating the instrument with monochromatic radiation at specific wavelengths and normalizing the response of the actual instrument to that of a reference detector which is known to be spectrally flat. Traditionally, it has been difficult to efficiently and accurately generate monochromatic sources over broad wavelength bands. Recent advances in the field of Fourier Transform Spectrometry (FTS) have made inexpensive, accurate, and reliable automated sources for monochromatic energy readily available [51,52].

2.7.3 Longwave radiometric sources

Absolute longwave radiometric sources are typically blackbodies which have been designed with geometrical features to enhance their effective broadband emissivity to achieve values very close to unity. Typical geometric enhancements include concentric grooved circular bodies, or deep cavities. In order to be considered absolute, the emitted radiance of such blackbody sources must be linked to accepted radiometric standards. Currently, this is accomplished by measuring the temperature of the emitting surface with temperature sensors whose calibration is linked to an accepted temperature scale. In the future, it is anticipated that standard radiometric sources will replace the accepted temperature scales, and that T will be based on Planck's blackbody radiation distribution function [51,53].

2.7.4 Shortwave radiometric sources

Generally speaking, absolute shortwave radiometric sources do not exist. Typically, shortwave radiometric sources are lamps whose output is absolutely characterized by transferring the calibration from an absolute longwave source onto it. This is done by using a transfer radiometer, which is typically a cryogenically cooled active cavity radiometer. By comparing the response of the spectrally flat transfer radiometer when it is illuminated by a longwave source to the response when it is illuminated by a shortwave lamp, the emitted radiance of the shortwave source can be said to be known absolutely [54].

2.8 Calculation of Top-Of-Atmosphere (TOA) Flux

Determination of flux at the top of the atmosphere (TOA) involves knowledge of the scene type, the spectral correction algorithm, and an inversion process. The predicted radiances obtained from untreated instrument data product must first be spectrally corrected, or unfiltered, for the optical path of the instrument as well as the scene spectra. This process is described in Section 2.8.1. Upon obtaining the unfiltered radiances, these values must undergo an inversion process by which the TOA fluxes may be determined. This process is described in Section 2.8.2. A complete discussion of this procedure may be found in Smith et al. 1986 [55].

2.8.1 Inversion of filtered radiances to obtain unfiltered radiances

The spectral correction algorithm corrects the radiometric measurements for the imperfect spectral response of the optical path within the instrument. Radiation from the scene is collected and deposited on the detector by the optical components. The radiation passes through the optical front end, impinges on the detector, and causes a signal which is sampled and processed by the electronics, resulting in a filtered measurement. To correct this filtered signal, one needs to know the end-to-end spectral response of the radiometric channels and the spectral nature of the observed scene. The objective for Earth radiation budget studies is to determine the reflected (or shortwave) solar radiation below 5 μm and the Earth-emitted (or longwave) radiation above 5 μm.

In this procedure, the nondimensionalized filtered measurements are modeled as

$$m_f = \int_0^\infty S(\lambda) I(\lambda) d\lambda \quad , \tag{2.9}$$

where λ is wavelength in μm; $S(\lambda)$ is the normalized spectral response of the instrument such that $0 \le S(\lambda) \le 1$ and $I(\lambda)$ is the normalized scene spectral weighting defined by

$$I(\lambda) = \frac{L(\lambda)}{\int_0^\infty L(\lambda) d\lambda} \quad , \tag{2.10}$$

such that

$$\int_0^\infty I(\lambda) d\lambda = 1 \quad , \tag{2.11}$$

where $L(\lambda)$, is the unfiltered radiance at the instrument aperture. It is desired to estimate the "unfiltered" nondimensionalized measurements which are defined

$$m = \int_0^\infty C(\lambda) I(\lambda) d\lambda \quad , \tag{2.12}$$

where $C(\lambda)$ is the ideal instrument response, or

$$C^{SW}(\lambda) = \begin{cases} 1 & 0 \le \lambda \le 5\mu m \\ 0 & \text{otherwise} \end{cases}$$

$$C^{LW}(\lambda) = \begin{cases} 1 & 5 \le \lambda \le 200\ \mu m \\ 0 & \text{otherwise} \end{cases}$$

By taking the ratio of Eq. 2.12 to Eq. 2.9,

$$\lambda_{corr} = \frac{\int_0^\infty C(\lambda) I(\lambda) d\lambda}{\int_0^\infty S(\lambda) I(\lambda) d\lambda} \quad , \tag{2.13}$$

one arrives at a spectral correction factor which is then used to multiply the measured filtered radiance, L, to obtain the spectrally averaged unfiltered radiance, $\tilde{L}$. In addition to variation with scene type, the scene spectral signatures vary with latitude and viewing zenith, solar zenith, and relative azimuth angles due to the shift of the field spectral radiance with viewing geometry. Operationally, the scene spectral signature is not known *a priori*. Green [56] developed a statistically based procedure to implement this process without having to know the spectral signature *a priori* for ERBE.

2.8.2 Conversion of radiance to TOA flux

Both the spectral correction algorithm and the inversion process are a function of the scene that is viewed. For ERBE, the scene types considered consist of four surface types (ocean, land, snow, desert) and one mixed surface type of land and ocean (coastal). These surface types are combined with four cloud conditions (clear, partly cloudy, mostly cloudy, overcast) to give twelve different scene types. For ERBE the instantaneous scene type is identified from the scanner measurements with a maximum likelihood estimation algorithm [57]. The measured filtered radiances are then unfiltered with the spectral correction coefficients for the identified scene and inverted to flux at the TOA by

$$F = \frac{\pi I}{R(\Omega)} \quad , \tag{2.14}$$

where I is the spectrally averaged unfiltered radiance in units of $W/m^{-2}sr^{-1}$, F is the corresponding flux estimate at the TOA in units of W/m^{-2}, and $R(\Omega)$ is the unitless Angular Distribution Model (ADM) that relates radiance to flux for a given scene type [58,59]. The longwave radiance ADM's (limb-darkening models) are a function of viewing zenith while the shortwave radiance ADM's (bi-directional models) are a function of three angles: viewing zenith, solar zenith, and relative azimuth. Thus, the inversion of radiances to fluxes at the TOA involves determining scene type, looking up a value of $R(\Omega)$ for the determined scene type, and applying Eq. 2.14.

2.9 Relevance to Current Effort

The present effort describes the task of completing a numerical toolkit which currently predicts the radiometric performance of the CERES space based scanning thermistor bolometer radiometers. In global terms, the present effort is the conclusion of a multi-year modeling effort whose goal has been to specifically address the issues discussed in this chapter through the creation of a flexible numerical toolbox. It is believed that future instrument designs may be optimized through the use of this design tool.

As the reader will see, the completed end-to-end model addresses these issues by accurately incorporating the basic components of the radiometric system seen in Figure 2.1. In particular it incorporates these components as they apply to the actual CERES flight models. Optical design considerations are addressed with a Monte-Carlo-based ray-tracing technique as discussed in Section 5.5. This ray-tracing technique is extended to assess the influence of wavelength-dependent surface and source characteristics which are important during the radiometric calibration of the completed instrument. A discussion of this extension is presented in Section 5.3 where the results of a simulation of the actual CERES PFM ground calibration are presented. The radiometric detectors are modeled with finite-difference electrical and thermal diffusion models which accurately address the contamination issues presented in Figure 2.1. Sampling criteria and signal conditioning are addressed in Section 5.6 which discusses the numerical prediction of the point response function of the completed radiometric model of the CERES flight instruments. Finally, the results of an effort which endeavors to define the size of the footprint such that the accurate calculation of TOA flux may be completed appears in Sections 5.9 and 5.10.