FIRST-PRINCIPLE DYNAMIC ELECTRO-THERMAL NUMERICAL MODEL OF A SCANNING RADIOMETER FOR EARTH RADIATION BUDGET APPLICATIONS

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***Abstract*—Low Earth Observing instruments that are used to monitor the incoming solar and outgoing longwave radiation have been a crucial part of studying the Earth's radiation budget for the past three decades. These instruments go through several robust design phases followed by vigorous ground calibration campaigns to set their baseline characterization spectrally, spatially, temporally and radiometrically. The knowledge from building and calibrating these instruments has aided in technology advancements and the need for developing more accurate instruments has increased. In order to understand the on-ground instrument performance, NASA Langley Research Center has partnered with the Thermal Radiation Group of Virginia Tech to develop a first-principle, dynamic, electro-thermal, numerical model of a scanning radiometer that can be used to enhance the interpretation of an Earth radiation budget-like instrument on orbit. This paper will summarize the current efforts of developing this high-fidelity end-to-end model and also highlight how it can be applied to an Earth radiation budget instrument.**

Keywords*— Earth radiation budget, MCRT, modeling, RBI, CERES

I. INTRODUCTION

The radiation budget for the Earth is a balance between the energy the Earth receives from the Sun and the energy that is radiated back into space. The four radiation components that contribute to this balance are solar incident, solar reflected, earth absorbed, and earth emitted energy. In order to maintain an energy balance, the earth must emit, over the course of time, the same amount of energy as it absorbs from the sun. Such a balance ensures that the temperature of the Earth will remain constant thereby resulting in a stabilized global climate over a long period of time.

For the past three decades, the science and the engineering community at NASA Langley Research Center (LaRC) has been involved with designing, building, calibrating, flying, collecting and processing the data for instruments involved in making the observations for our earth radiation budget. These instruments, which are often manifested as Low Earth Observing (LEO) payloads, go through extensive design phases followed by vigorous calibration protocols to set the baseline requirments spectrally, spacitaly, temporally and radiometrically. Over the years, the science community has made considerable advancements in making these measurements more accurate with the help of modeling tools that allow for on-ground parametric analysis of these instruments. In order to better understand the performance on ground, NASA LaRC has partnered with the Thermal Radiation Group (TRG) of Virginia Tech to develop a high-fidelity, first-principle, dynamic, electro-thermal, numerical model of a scanning radiometer that can be used to enhance the interpretation of an Earth radiation budget-like instrument in orbit. An effort such as this helps the science community in supporting and validating the engineering design and fabrication phase for the instrument, and also helps with quantifying various anomalous effects and uncertainties in knowledge of system parameters.

The objective of this effort is to model the complete end-to-end science signal chain which starts from photons arriving at the entrance apperture of the instrument to reading the data out as digital counts. Fig. 1 shows a block diagram for a sample instrument signal chain. This end-to-end model will help understand the science data stream output for an Earth radiation instrument with any viewing scenes such as calibration targets, earth scene or any other user-defined radiance.

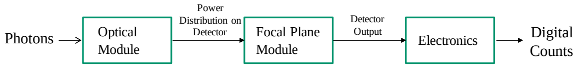

Fig. 1. Flow of signal chain for an instrument. Photons converted to digital counts.

II. GENERAL INSTRUMENT MODEL FLOW FOR AN EARTH RADIATION BUDGET INSTRUMENT

The end-to-end radiometric model consists of several subcomponents including: external sources, optical train, detector module, and electronics. The framework of this model begins with radiance from an external source, which is typically a calibration target or geo-scene. The input radiance is carried through the optical train, where a radiative and optical analysis is performed using a Monte-Carlo Ray Trace (MCRT) technique. The results from the ray trace are then implemented into a finite-element thermal diffusion or a finite-difference electro-thermal diffusion detector module. Lastly, the output is carried through the electronics signal chain to produce the digital counts for the radiative input.

Several numerical modeling platforms or techniques can be used to complete an end-to-end system characterization of an instrument. These include, but are not limited to, MCRT techniques, finite-difference electro-thermal model, electric circuit model, and other off-the-shelf software tools such as Zemax Optical Design Software and Thermal Desktop. For a complete description of MCRT and finite-difference techniques, the reader can refer to [1, 2]. The remainder of this paper will talk about applying the tools and techniques of the afformentioned end-to-end model characterization to NASA LaRC's Radiation Budet Instrument.

III. OVERVIEW OF THE RADIATION BUDGET INSTRUMENT

The next generation Radiation Budget Instrument (RBI), successor to the Clouds and the Earth's Radiant Energy System (CERES) instruments [3,4], will measure the Earth's reflected sunlight and emitted thermal radiation at the top of atmosphere (TOA) and ensure continuity with long-standing data records maintained by the Earth Radiation Budget (ERB) programs. RBI is scheduled to fly on the Joint Polar Satellite System 2 (JPSS-2) spacecraft, a polar-orbiting, sun-synchronous satellite in low earth orbit. The goal of this mission is to continue and extend the unique global climate measurements of the Earth's radiation budget provided by CERES since 1998. RBI will contain three scanning radiometers that measure three spectral bands at TOA: a total band from 0.3 to > 50+um, a shortwave band from 0.3 to 5.0 um, and a longwave band from 5.0 to 50+um. Radiometric calibration is essential to the RBI mission, therefore, the instrument itself will contain three on-board calibration targets to provide and hold the calibration stable over the full RBI spectral range and throughout the mission lifetime. RBI along with its internal modular view highlighting three on-board calibration targets and the sensor and focal plane module can be seen in Fig. 2.

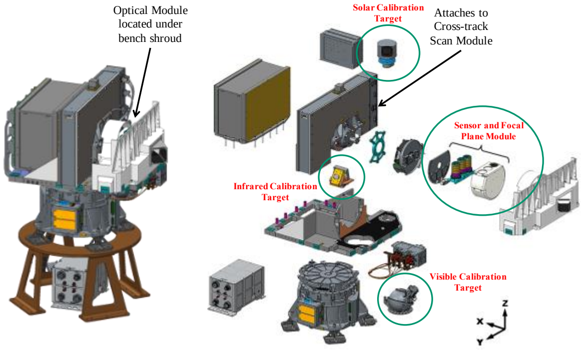

Fig. 2. Modular view of the RBI highlighting the three on-board calibration targets, and the sensor and focal plane module.

In order to assess the accurate performance of RBI during its design and build phase and to evaluate the impact of instrument performance on science data, an end-to-end characterization of the instrument is necessary. The end-to-end radiometric system model consists of the RBI components that are directly involved with radiometric performance and calibration, and a realistic earth model that is based on real scene observations. The model is broken into subcomponents that consists of scenes and targets, the optical sensor module, the focal plane module that houses the on-board thermopile detectors, and finally the signal conditioning electronics that output science digital counts. This effort will allow us to simulate the entire science data stream output, photons in to bits out, and give us the flexibility to input various scenes that might be comprised of calibration targets or Earth scenes. The framework of this effort is shown in Fig. 3.

IV. RBI END-TO-END MODELING SUBCOMPONENTS

The following sections will highlight the different subcomponents that are currently being developed to complete the end-to-end modeling effort for RBI. These sections are: A. on-board calibration targets, B. the sensor module, C. the focal plane module, D. signal conditioning electronics, and E. the Earth model.

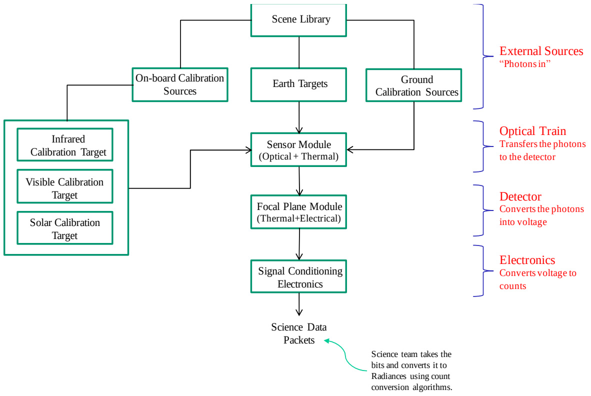

Fig. 3. Modeling framework of the RBI instrument model

A. *On-board Calibration Targets*

RBI consists of three on-board calibration targets: the Infrared Calibration Target (ICT) used to calibrate the total and longwave channel, the Visible Calibration Target (VCT) used to calibrate the total and shortwave channel, and the Solar Calibration Target (SCT) used to calibrate the shortwave and total channel. The geometry and surface properties for all of the targets were used and modeled using the MCRT technique mentioned previously. The thermal analysis in conjunction with MCRT analysis provides the complete description of power leaving the calibration targets and arriving at the entrance aperture of the sensor module. Preliminary results from all three of the calibration targets have been completed.

B. *Sensor Module*

The sensor module of this model consists of the fore baffles, the telescope primary and secondary baffles, the spectral filters for the longwave and shortwave channel and finally the focal plane, where the energy is absorbed. Similar to the on-board calibration targets, MCRT techniques were used to model the geometry and surface properties of this module. The output of this module is a time-series of radiation arriving at the focal plane. A transient thermal analysis of this module has also been performed in parallel to assess background infrared (IR) signal noise.

C. *Focal Plane Module*

This module consists of two thermopile detectors housed on a Molybdenum baseplate. A finite difference technique was used to model the electro-thermal diffusion behavior of this module. With given knowledge of the geometry and detector properties, this module takes the time-series of radiation from the sensor module and converts it into a voltage time series signal. The voltage is produced due to the temperature difference across the thermopile detectors, a change that is detected due to the heat sink of the detector and the arriving radiation. The time-series of voltages from this module is then carried through to the next phase.

D. *Signal Conditioning Electronics*

The signal conditioning electronics module for RBI is composed of three sub-modules: A Focal plane module, which consists of the thermopile detectors and the preamplifier, a detector electronics board, which consists of the programmable gain and the delta sigma modulator, and finally a Field Programmable Gate Array (FPGA) which also includes the Bessel filter. Data received from the thermal diffusion model is processed and amplified on the focal plane module. This analog signal is then passed to and processed by the detector electronics board and converted to a digital signal using an A/D converter. Finally, the digital signal is then processed through a Bessel filter to provide the science output of digital counts. The model accepts the (time series) signal voltage and provides 20-bit science data at one hundred samples per second.

E. *Earth Model*

In addition to developing a complete end-to-end signal chain model of RBI, the science team at LaRC is also developing Earth scenes to be used in conjunction with the aforementioned end-to-end modeling tool. These realistic Earth scenes, based on real observations from previous Earth radiation budget programs and imager instruments, will include spatial, spectral, and temporal variations in different scene types to provide the most realistic concept of operations for an instrument on-orbit. This effort will require multiple auxiliary datasets and various algorithms working together to define a synthetic orbit in terms of geo type and atmospheric state, scene viewing geometry, and sun illumination geometry. This combined information will provide a complete description of a radiation field that the instrument will capture as it is scanning in a sample orbit.

V. CURRENT STATUS AND FUTURE WORK

The efforts described in this paper are currently underway. A complete high-fidelity independent model of the ICT, VCT, sensor module, and the electronics signal chain is complete. A first-order model of the SCT and the focal plane module is also complete. The team is currently working on the interfaces between the different subcomponents to simulate the complete end-to-end signal chain. Short-term studies, such as stray light behavior, filter heating and re-emission, temperature variations in the sensor module and the instrument point spread function have been completed, and on-going sensitivity and parametric analyses are also underway.

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