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HISTORY OF EARTH RADIATION BUDGET AT LANGLEY RESEARCH CENTER

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1. Introduction

In 1917 it had become apparent that the United States was far behind the European countries in the development and use of aircraft. Even though the Wright brothers had been the first to fly, their achievement had been ignored in the U.S. The U. S. Congress created the National Advisory Committee of Aeronautics (NACA), with the charter of developing practical solutions to the problems of flight. The first step of the Committee was to establish a laboratory where these problems could be studied and solutions developed. This laboratory, located in Hampton, Virginia, became the Langley Research Centre.. The charter of the NACA did not include research into the atmosphere, which was regarded as the purview of other organizations, for example, the Weather Bureau.

In October 1957 the Soviet Union placed the first artificial satellite into orbit: Sputnik 1. Again it was catch-up time. In 1958 Congress created the National Aeronautics and Space Administration. All of the assets of the NACA and some other research facilities were incorporated into the new agency, whose charter included “the exploration and application of space for peaceful purposes.” LaRC initiated the manned space flight program as Project Mercury, which was moved to Houston, Texas as the Manned Space Flight Center. The advantages of satellites for Earth observation were obvious and the Goddard Space Flight Center, created by the National Space Act of 1958 and located at Greenbelt, Maryland, began the development of meteorological satellites. LaRC was first and foremost an aeronautical center and that remained its core mission.

Nevertheless, by 1960 several research divisions at the NASA Langley Research Center were involved in the study of materials in space, instrumented rocket payloads, satellite experiments, and reentry vehicles. These research space flight programs made important contributions to the design of the Apollo heat shield, the lunar orbital rendezvous concept, and lunar landing simulations. Other major space projects in which Langley played a major role in the late 1960’s and 1970’s included the Mars Viking mission. Beyond managing a major portion of the Viking project from Earth lift-off to landing on Mars, Langley researchers performed interplanetary trajectory analyses, designed and tested the Mars entry and landing vehicle as well as provided support for instruments, electronics and systems engineering. The experiences gained in these projects were valuable later in the development of the Earth radiation budget projects at the NASA Langley Research Center. In the mid-1960’s the Apollo Program was moving forward; man would set foot on the Moon before the end of the decade. Within LaRC research was being done to send a man to Mars and return. Research was being done for the design of the heat shield which would protect the men returning from Mars. There were teams in two different organizations of LaRC studying the heating problem. After the successful missions to the Moon, the American public was no longer interested in space exploration. In the early 1970’s the Nation’s interest turned inward and the demand became Relevance. At this time, public concern about the environment began to grow. The teams studying reentry from planetary return began looking for ways in which their capabilities could be used for problems on Earth.

2. Beginning Earth Radiation Work at LaRC

By 1959, in the Pilotless Aircraft Research Division, engineers were concentrating on various Earth unmanned satellites. A team under the leadership of William O’Sullivan developed the technology to place balloons in orbit and inflate them there. The first balloon had a 100 foot diameter and was used to bounce a message from President Eisenhower from Earth to the balloon and back to Earth. This was the first communication satellite.

During the 1960’s more balloons, but much smaller (12 foot diameter), were placed into orbit to explore the upper atmosphere. One of the researchers in this team, George Sweet, pondered what other ways could these balloon be used. The engineers at LaRC knew that the temperatures of the balloons depended on the sunlight and Earth-emitted radiation and the colors of the balloons’ surfaces. George Sweet reasoned “Let’s put three balloons together with three different coatings and measure their temperatures. From this we can measure the direct sunlight, the sunlight reflected from the Earth and the earth-emitted radiation.” This approach applied the concept used by Vern Suomi for the first Earth radiation budget experiment, which was flown on the Explorer VII in 1959.

Dr. Vern Suomi of the University of Wisconsin designed an instrument which consisted of two pairs of flat plates that were mounted on opposite sides of the spinning spacecraft. One pair was painted black, the other was white. The black pair absorbed sun-light, both direct and

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that reflected from the Earth, and Earth-emitted radiation. The white pair reflected most sun-light but absorbed Earth-emitted radiation. The temperatures of these hemispheres were transmitted to Earth. Using these temperatures and thermal balance equations for the hemispheres, researchers could calculate the amount of sun-light and Earth-emitted radiation on the device. In early spacecraft, moving parts were avoided as much as possible. This experiment provided the first crude measurements of the Earth's radiation balance.

Dr. Suomi was appointed as Director of the Weather Bureau, where he advocated the development of satellite instruments and the application of these measurements to weather forecasting. Dr. Suomi later led the development of the spin-scan instruments and their use on the Geostationary GOES satellites for continuously observing the weather over the U.S, and the camera which was used on the Viking Lander to give pictures of the surface of Mars in 1976. He returned to the University of Wisconsin, where he founded the Space Science and Engineering Center. As a dominant figure in satellite meteorology, his support for any project to measure Earth radiation budget was vital.

In the early 1970s a team of engineers from various divisions of LaRC was willingly recruited by George Sweet to help develop his concept of using balloons to measure Earth radiation budget. First, the hardware must be designed to achieve the goals of accuracy and longevity. Next, methods had to be developed to analyze the data to produce scientifically useful results.

While the rest of the Langley Team was working to complete the radiation budget satellite concept, George Sweet began to develop the scientific rationale for measuring Earth Radiation Budget and the requirements for the measurements. George recruited Lou Smith and the two visited a number of researchers at the National Centre for Atmospheric Research, Colorado State University, University of Wisconsin and University of Maryland. Their questions were: what would be done with the data when it became available, that is, what scientific questions would it answer, and what were the accuracy and time and space scales required?

The first question: Why is Earth radiation balance important? The Sun radiation heats the Earth, making the Tropics hotter than the higher latitudes. These temperature differences cause the atmosphere and oceans to circulate, carrying heat to the cooler regions. The Earth emits heat as radiation. This balance of incoming and outgoing radiation governs or climate. By measuring this balance of radiation over the Earth, we can learn about the climate and the processes which determine the climate. These data would provide insight into interannual changes of weather and climate.

In the early 1970s, William Bandeen, one of the foundation stones of Goddard Space Flight Centre, brought in Dr. Thomas Vonder Haar, a student of Dr. Suomi, and Dr. Ehrhardt Raschke from the University of Cologne to work with himself and Musa Pasternack with data from the Medium Resolution Infrared Radiometer, which had flown aboard the Nimbus-3 research satellite. (The Nimbus satellite series, of which there were seven, was a very successful program by NASA for developing and demonstrating instruments for observing the Earth, its atmosphere, oceans and ice/snow cover.) Their work demonstrated the ability of satellite instruments to measure the radiation balance of the Earth and the application of this information to studies of the Earth's climate.

At that time, climate models were in their infancy. The prevailing viewpoint was that radiation was important only for times scales of a month or longer. For time scales for weather, the effects of radiation were unimportant and the flow of the atmosphere was dominated by its dynamics. This belief had come about because the computer power until then was too limited to include radiation heating and cooling of the atmosphere and the surface. Models of the atmospheric circulation had been developed which excluded radiation and provided reasonable results. The requirement for the time scale for Earth radiation budget data was established as one month. Corresponding to the one month time scale, the spatial scale was also large. The requirement for the spatial scale for the Langley experiment was thus taken to be 10-degree zonal averages. The results of the three balloon design would provide information with zonal resolution, that is, for latitudinal bands, and would operate for a long time because it had no moving parts to fail. For this reason, the concept was named the Long-term Zonal Earth Energy Budget Experiment (LZEEBE).

In order to get a new start, the project would have to have the backing of the Meteorological Program Office, which was headed by Harry Press. This office was a headquarters function but was located at Goddard Space Flight Center. Funding for NASA, university and industry studies and instrument development came through this Office. The Head of MPO was Harry Press. He had come from LaRC where he had worked on the Thunderstorm Project in the late 1940s. Later he moved to GSFC, and served as head of the Nimbus Project. As head of MPO, Harry made certain that if there was a proposal for a new start for an Earth radiation budget project, it would succeed. The Langley team would periodically go to MPO and present their work. Harry Press would provide his critique and point out the direction in which the team should proceed. He provided the Langley group with a sparring partner to assure that there were no major problem areas or weaknesses.

3. Competition

Interest in Earth Radiation Budget was increasing. Vern Suomi had followed his Explorer VII radiation budget measurements with similar radiometers on the ESSA 5 through -9 spacecraft. These spacecraft were also spin-stabilized, with their spin axes perpendicular to their orbits. Professor Suomi proposed to repeat this experiment, but with faster radiometers which would make measurements as they rotated to be horizontal, thus providing a better measurement of flux. Because there were no mechanisms with moving parts to fail, this instrument would operate for a long time, providing a long data record. As director of the Space Science and Engineering Centre at the University of Wisconsin, he submitted a proposal to NASA to develop further his concept.

Dr. Tom Vonder Haar, now at the Colorado State University, submitted to NASA a proposal to develop a scanning radiometer to measure Earth radiation budget. This proposal included participation by Ball Brothers Space Division to develop the engineering aspects of the instrument.

The Suomi and Vonder Haar proposals were funded by NASA through the Meteorology Program Office, which assigned the management of these grants to Langley Research Centre. By managing these grants, the Langley team became familiar with each concept and its advantages and disadvantages.

While this work was being done by Langley researchers and by grants and contracts with universities and industry, an Earth radiation budget instrument was being flown by NOAA. Dr. Jay Winston was head of the Meteorological Satellite Laboratory of NOAA. He had brought Dr. William L. Smith, a recent graduate of the University of Wisconsin and a student of Dr. Suomi, into the MSL. Bill had developed techniques for using sounding measurements from scanning radiometers to compute temperature and humidity profiles in the atmosphere. Now Bill was developing the Earth Radiation Budget (ERB) instrument, which would fly on the Nimbus 6 and -7 spacecraft. The ERB included a scanning radiometer with eight channels and flat plate radiometers. The scanning radiometer scanned in both the nadir angle and in azimuth, so as to provide measurements from which the distribution of radiation in direction as it leaves the Earth's atmosphere could be determined. The flat plate radiometers measured solar radiation reflected from the Earth, the radiation emitted by the Earth and the radiation directly from the Sun.

After the launch of Nimbus 6 in 1975, Dr. Smith went on sabbatical to Australia to make ground measurements to validate ERB results. Dr. Herb Jacobowitz took over the ERB instrument. Unfortunately, the scanning radiometer of the ERB aboard the Nimbus 6 spacecraft only operated for about a month before a cable failure rendered it useless. However, the wide field-of-view radiometers provided good measurements of the Earth's radiation budget for several years. This early failure of the scanning radiometer added weight to Dr. Suomi's argument that long-term data sets required non-scanning radiometers.

With the Nimbus 7 spacecraft being prepared for launch, NASA began the Science Team concept. Previously, a Principle Investigator had the responsibility of assuring that the instrument met its scientific objectives and of using the data for scientific investigations. Under the Science Team approach, an Experiment Scientist led a team of scientists in these tasks, which greatly expanded the use of the data for research. NASA sent out an Announcement of Opportunity for participation in the science team for the ERB instrument. The Langley team submitted a proposal for participation in the ERB Science Team, which was accepted. Experience in the ERB Science Team greatly extended the scientific understanding and capability of Langley's team to carry out a project for Earth radiation budget.

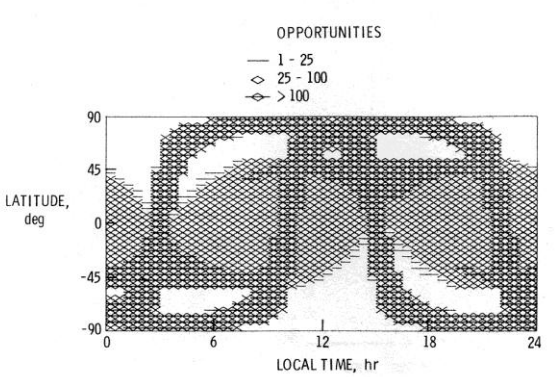
The determination of the Earth's radiation budget requires several steps, the first of which is to make the measurements. These measurements are then used to compute the flux "at the top of the atmosphere" at the time of measurement, which requires a model of the distribution of the radiation in all directions. For reflected solar radiation these models are called "bidirectional reflectance distribution functions" because the direction of the incoming and outgoing rays must be included in the computation. Data from the ERB project would be used to generate these models. The measurements must cover the entire Earth in order to establish the balance of radiation into and away from the Earth. Finally, the flux must also be known for all times of day so as to compute the total energy during the day, which also requires a model. Measurements of radiation at all times of day were needed to produce these models of diurnal variation.

The Langley team first addressed some key areas for radiation budget measurements required by the scientific community. In particular, new and improved data analysis techniques and better time and space sampling approaches were explored and developed. Since space and time sampling was also a key issue, computer simulations were performed to determine the geographical and temporal coverage of various satellite orbits for Earth radiation measurements.

Edwin F. Harrison and Gary G. Gibson were experts in mission analysis, i.e. design of orbits for specific purposes. They examined the problem of diurnal variation and the measurements required to produce them. A satellite must be placed in an orbit which would pass over the Earth at all times of day during a "reasonable" time. They showed that a satellite placed in an orbit by the space shuttle would precess through all times of day during a 72-day period, which would provide the data needed to generate the diurnal variation models. This orbit would cover the Earth between 57^{o}N and 57^{o}S. To cover the rest of the Earth and to provide additional coverage during the day, instruments should be placed on the NOAA-9 and -10 spacecraft.

Various radiometers were studied by Robert Babcock and project management approaches were set up by Charles Woerner and Jack Cooper. This work placed the Langley team into a position where they understood many of the problems of measuring the radiation budget and analyzing it.

The study grants for the concepts of the University of Wisconsin and Colorado State University and the



This figure by Harrison and Gibson shows the local times (horizontal axis) of observation by a precessing satellite and by the NOAA 9 and -10 operational spacecraft for all latitudes (vertical axis).

Langley LZEEBE proposal were completed and submitted to NASA Headquarters. Dr. Morris Tepper, Program Scientist for meteorology at NASA Headquarters, was in a dilemma as to what path to take for Earth radiation budget measurements. Professor Suomi, “Father of Satellite Meteorology”, insisted that long term measurements of Earth radiation budget could only be accomplished by use of flat plate radiometers, which would give a resolution of 10 degrees on the Earth. Because Earth radiation budget is a climate topic, it was necessary to have the support of NOAA before the project would be approved. As head of the Satellite Meteorological Satellite Laboratory, Dr. Jay Winston gave the requirement that any Earth radiation budget program must provide monthly mean maps with 2.5 degree resolution. This requirement could be met only with a scanning radiometer. The Langley team had stepped into this arena of conflicting requirements and competing organizations. One of our mid-level managers noted that the Langley team was strong technically and inept politically.

A number of reviews were held of the various concepts, culminating in a review by a panel of the National Academy of Sciences. The Langley team including of George Sweet, Edwin Harrison, Lou Smith, Charles Woerner, and Jack Cooper, as well as Robert Curran of Goddard made presentations After hearing the debate of scientific requirements, resolution and length of time record, the panel concluded that there were two categories of measurements required: one was for a long-term data set which would have a resolution of 10 degrees or smaller, and another was for 2.5 degree resolution data set. The panel endorsed both sets of requirements. Their conclusion was to fly both scanning and flat plate radiometers. The panel further recommended to NASA that “Langley be asked to analyze the data for the next Earth radiation budget experiments.” The National Academy Sciences report was a major factor contributing to the decision to assign experiment management responsibility for the NASA Earth Satellite System to the Langley Research Center.

With the direction provided by the NAS, the Langley team gave up the LZEEBE concept and put together a proposal to fly scanning radiometers as proposed by CSU and also non-scanning radiometer packages. These would fly on the NOAA 9 and -10 spacecraft and a dedicated Earth Radiation Budget Satellite, which would be placed into orbit by a space shuttle. Although the LZEEBE concept was supplanted by this new approach, it had served the purpose of establishing the science requirements and had resulted in a team which would carry the new project to fruition. This proposal was forwarded by the Meteorological Program Office with its approval to NASA Headquarters. In addition to the report by the National Academy of Sciences recommending that the Langley Team have the responsibility for the Earth Radiation budget project, Dr. Paul F. Holloway, Director for Space at LaRC at that time, had attended key reviews and assured NASA Headquarters that the project would have the support of LaRC to make it a success. The project was named the Earth Radiation Budget Experiment (ERBE), to show continuity with the ERB project, and included in the NASA budget. Congress funded the new ERBE project in the FY78 budget and also gave NASA the responsibility of conducting research in Earth radiation budget. The team of retreaded engineers now had the responsibility of carrying out this project.

There were three events of major significance to Earth radiation budget and climate research in 1978. The Nimbus 7 spacecraft was placed into orbit, with several instruments which were prototypes to prove the capabilities of the next generation of spacecraft instruments, including the Earth Radiation Budget instrument. Second, the ERBE project got its new start. Third, Jules Charney convened a workshop of scientists who were concerned about the effects of trace gases such as carbon dioxide on the radiation balance of the Earth. These scientists were the nucleus of research into Global Warming. In two decades these effects would become a major issue after measurements showed that the global mean temperature was in fact increasing as predicted.

4. The Earth Radiation Budget Experiment Becomes a Project

The budget for FY78 included funding for a new start for the Earth Radiation Budget Experiment Project. The ERBE Project would design, build, calibrate and fly scanning and non-scanning instruments on each of three spacecraft, collect and process the data, generate data products and use them for scientific investigations. The Langley Research Center was given the responsibility for the instruments and the scientific leadership of the project. Goddard Space Flight Center had the responsibility for the spacecraft on which the ERBE instruments would fly. At LaRC the project was now organized with the design and building of the instruments in the Projects Division and the scientific functions in the Atmospheric and Environmental Sciences Division (AESD) of Langley Research Centre. The scientific functions included collaborating with the engineering team in the Projects Division to specify details of the instrument which affected the measurements and the calibration of the instrument, development of software which would be used for the computations required to process the measurements from electronic signals to useful scientific products, and the use of these products for scientific investigations. Close collaboration is needed between the engineering and scientific teams to assure an instrument which will operate to generate good data for scientific research. For ERBE, the years of working together to win the project had made the group a closely-knit team, which provided the closeness for the collaboration.

Within the Projects Division, Cal Broom was selected as Project Manager. He was completing his service as Project Manager for the Viking Project, which had orbited a spacecraft around Mars and then sent a craft to land on the Red Planet and to make the first scientific measurements from the surface of Mars. Charlie Woerner was assigned as Assistant Project Manager and Jack Cooper was designated as Instrument Engineer. Mike Luther, who had done much work with the LZEEBE concept, was assigned to be Instrument Engineer for the non-scanning package and Leonard Kopia became Instrument Engineer for the scanner. The first task for the engineering team was to write a Statement of Work, which would be the major part of a Request for Proposals. Several companies responded to this request and the winning bid was by the TRW Space Division, in Redondo Beach, California.

The Radiation Sciences Branch was formed in AESD which included the in-house scientists, with Ed Harrison as the head. The Data Management Group was formed with the responsibility of producing the software required and using it to process the measurements from the electronic signals from the spacecraft to generate scientifically useful information. Jim Kibler was selected as head of this group. Jim had worked from the beginning of the formulation of the project to define the requirements for the data processing.

The first item task in AESD was to select an Experiment Scientist, who would have the responsibility for getting the greatest scientific return possible from the project. He would lead the Science Team which would be selected, coordinate with the engineering team in the design of the instruments, manage the development of the software to process the data, and defend the budget for the science work in the Byzantine politics of a major project. Dr. Bruce Barkstrom, a professor with George Washington University and an expert in radiative transfer theory, was hired for this job. His first task was to work with the team in AESD to specify requirements for the instruments to go into the Statement of Work being prepared by the engineering team. Next, he had to write the requirements for the Announcement of Opportunity for participation in the ERBE Science Team. From the researchers responding to this announcement, an international team was selected of scientists in the universities and research laboratories across the United States and in Europe. Table 1 lists these people and their affiliations. Along with each person listed were often several other researchers, so that many people were involved with the preparation for the project and the application of the data for scientific investigations.

The Science Team was organized into four working groups, with responsibilities for the instrument, the computation of fluxes at the "top of the atmosphere," the averaging of the fluxes at the times of measurement to produce daily mean fluxes, and finally to define the data products needed by the scientists. In-house scientists had been working already in the first three areas and continued this work throughout the project. Lee Avis worked on many details of the instrument requirements, to use in the Statement of Work. Richard Green and Lou Smith worked on methods of retrieving the "top of atmosphere" fluxes from the measurements from the scanning and non-scanning radiometers. For the scanning radiometer, the approach was that used by Raschke, Vonder Haar et al. Richard Green and Lou Smith developed new methods of retrieving TOA fluxes from the non-scanner measurements. Tim Suttles used data from the ERB instrument and radiative transfer theory to create the bidirectional reflectance functions which were needed for retrieving the TOA fluxes. These models would be used for the ERBE, ScaRaB and CERES projects and would only be superseded more than two decades later by the models developed using CERES data. Ed Harrison and Dave Brooks worked on the problem of using the instantaneous measurements to compute daily-mean fluxes.

As the work load built up in preparation for launch of the Earth Radiation Budget Satellite (ERBS) and the NOAA 9 spacecraft, Tom Charlock, Pat Minnis and Bruce Wielicki, recent Ph. D.'s, were brought into the team to help. Minnis and Harrison used GOES data to establish the half-sine shape for the diurnal variation of the outgoing longwave radiation. Bruce Wielicki and Richard Green developed the scene identification algorithm for selecting the bidirectional reflectance distribution functions for retrieving TOA fluxes from the measured radiances. Soon after launch of the first set of ERB instruments Robert B. Lee III joined the tem and was soon leading the Instrument Working Group .

In order to measure the Earth's radiation budget for all hours of the day, Edwin Harrison and Gary Gibson had shown that a minimum of three spacecraft would be needed. ERBE instruments would fly on two of the operational spacecraft that NOAA uses to observe and measure the atmosphere and oceans. The third spacecraft was built primarily to carry ERBE instruments, and was called the Earth Radiation Budget Satellite (ERBS). It also carried as a "guest instrument" a SAGE (Stratospheric Aerosol and Gas Experiment). Figure 2 is a drawing of the ERBS, showing the ERBE scanning and nonscanning instruments, the SAGE instrument and the major parts of the spacecraft. The spacecraft was built by Ball Aerospace Systems Division. It was boosted into orbit by the Space Shuttle Challenger in October, 1984 and deployed by astronaut Sally Ride, who was Mission Specialist for Flight 41-G.

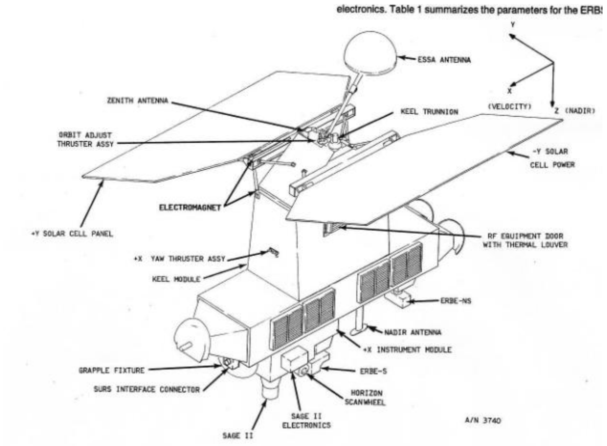


Figure 2: Earth radiation Budget Satellite ERBS, showing instruments and major spacecraft components.

To deploy the spacecraft required gripping the spacecraft by the Shuttle arm (Remote Manipulator System), release the spacecraft from its cradle in the Shuttle bay and move it out in to space. The solar cell arrays provide electrical power to all systems of the spacecraft and are folded in order to fit into the Shuttle bay. Before releasing the spacecraft these arrays must be unfolded and locked into place. Initially, the arrays were stuck and would not unfold. If they did not unfold, the mission would be a failure. Dr. Ride used the procedures that had been prescribed for this contingency. First she shook the spacecraft. No luck. Last chance was to wait until the Shuttle had been in the shadow of the of the night side of Earth and everything cooled down in the darkness of space, and when the Shuttle emerged into daylight and the Sun warmed all of the parts, shake well. This worked. (standard practice of any auto mechanic to break loose a recalcitrant bolt: heat it then turn it.) The solar arrays opened and locked into place, to the relief of all involved. All spacecraft and instrument systems were checked out and operated well. ERBS was now ready to fly. Figure 3 shows the Earth Radiation Budget Satellite held by the Shuttle arm just before release into space.

Challenger placed the ERBS into orbit above the Earth. ERBS fired its own rocket motor to boost itself into an orbit 620 km above Earth, where it would begin observing the Earth's radiation budget and stratospheric ozone and aerosols. A month was allowed for the gases from the rocket engine and any other contaminants from the spacecraft to disperse completely, then the contamination covers to the instruments were opened and the measurements of the Earth's radiation budget began. The scanning radiometer had been designed with a goal of two years of operation. It provided measurements for five years. The nonscanning radiometer measured the Earth's and Sun's radiation for fifteen years. October 1999, there was a problem in which the detectors did not return to their correct position after a calibration check, but stuck in a tilted position. They continued to provide data for another five years, for a total of twenty years of measurements. It was necessary to leave sufficient spacecraft capacity to maintain control until it is deboosted from orbit, to eliminate space debris. In October 2004, the instruments were turned off and the spacecraft was idled.

Figure 3: ERBS held by Remote Manipulator Arm of Challenger before release into space.

5. ERBE Accomplishments

Over 200 peer-reviewed journal articles have been written which use ERBE data. These papers include the effects of clouds on the balance of Earth's energy, the effects of a volcanic eruption on the climate, the variation of energy absorbed from the Sun and given off by the Earth during the day, and the energy given off by the Sun over a 15-year period.

The most important achievement of the Earth Radiation Budget Experiment was the first measurements to show that clouds cool the Earth. There is no way for the Earth to respond to the energy arriving as light from the Sun which is absorbed - except by reemitting light to the coldness of outer space. Hot surfaces, like the Sahara Desert or Death Valley, CA, emit a lot of heat. Cold surfaces, like Antarctica or a snow field, emit relatively little heat. The Earth's temperature is established by balancing the energy absorbed from the Sun against the energy the Earth emits back to space. ERBE results demonstrated that the effects of clouds on the radiation balance of Earth were the greatest uncertainty in global climate models.

Before ERBE, scientists were not sure whether the increased reflection from clouds would offset the effect that clouds have in trapping the emitted heat. By

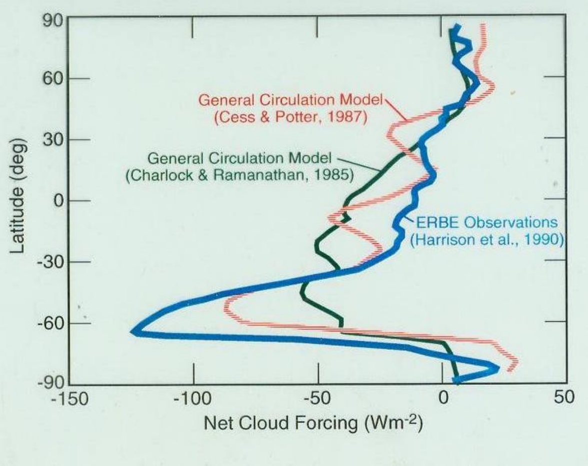


Figure 4: Effects of clouds on radiation budget as measured by ERBE and as computed by two circulation models.

increasing the amount of energy reflected back to space, clouds decrease the energy absorbed from the Sun. However, clouds also trap the energy emitted by the Earth's surface. High clouds are particularly effective at trapping emitted heat.

The ERBE instruments were able to measure the radiation budget of both clear areas and cloudy ones. The scientists on the ERBE science team were able to show that low clouds reflect more energy than high clouds trap. In other words, clouds cool the present climate.

Figure 4 shows comparisons of ERBE results with those from General Circulation Models. This study led to further comparisons of GCM results shown by figure 5. These comparisons demonstrated the need for extensive research to improve the characterization of clouds in circulation models.

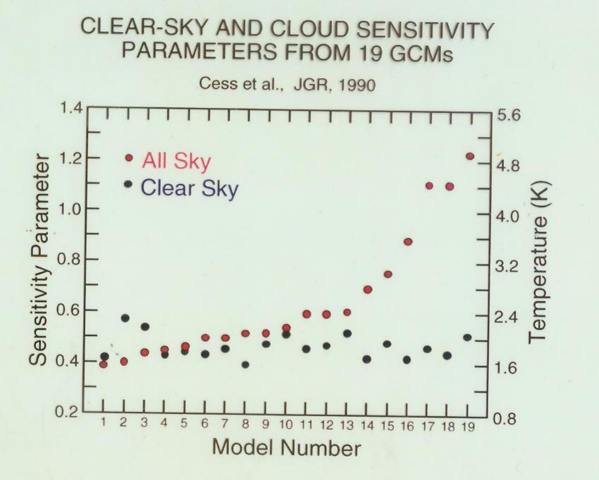


Figure 5: Clear sky and cloud sensitivity parameters from 19 General Circulation models, by Cess et al., 1990.

The fact that clouds act to cool the current climate does not mean that we understand how clouds will respond if the climate changes. For example, if carbon dioxide increases trap more emitted heat, climate changes might increase the amount of high cloud and thereby enhance the greenhouse effect. Such an enhancement is called a positive feedback. The ERBE measurements did not provide enough information to identify how clouds will respond to other climate changes. The answers to this and other such questions require a more complex project, which would follow the ERBE project..

In addition to this fundamental measurement of the impact of clouds, ERBE was also able to show that stratospheric aerosols from the eruption of Mount Pinatubo reflect enough sunlight to cool the Earth. Figure 4 shows Mount Pinatubo continuing to erupt after the initial eruption, which blasted tons of material into the stratosphere. The tiny stratospheric droplets in this aerosol form from volcanic gases sent into the stratosphere when the volcano erupted. Sunlight changes the gas to tiny droplets of sulfuric acid that we see as the red color of twilight. The droplets grow by absorbing water from the stratosphere and then settle into the lower layers of the atmosphere over about a two year period after the eruption. The ERBE instruments were able to measure the increase in reflected sunlight and the drop in emitted heat to space caused by the slight drop in the temperature of the Earth. Figure 7 shows this change over the first few months after the eruption.

Figure 6: Eruption of Mount Pinatubo in 1991 threw vast amounts of aerosols into the stratosphere.

The ERBE instruments also measured the amount of energy the Sun sends to the Earth. Interestingly, this solar output increases a tiny bit when there are sunspots and decreases during periods when there are few sunspots. Because the ERBE solar instruments on the Earth Radiation Budget Satellite (ERBS) have lasted over fifteen years, ERBE has helped reduce the uncertainty about whether the differences between its measurements and those of other instruments were caused by the Sun or by instrument calibrations.

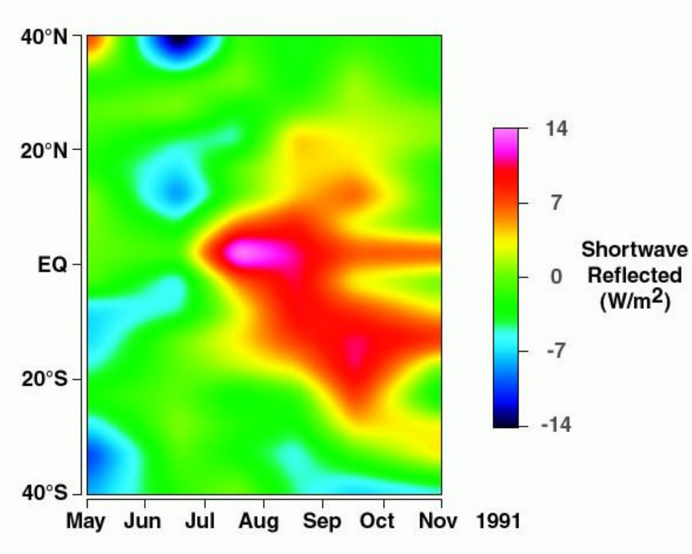


Figure 7: Increase of reflected solar radiation by aerosols from eruption of Mount Pinatubo. Vertical axis is latitude, horizontal axis is time.

The major reason for having a spacecraft in a precessing orbit was to measure the variation of the Earth-emitted radiation during the day, as the surface and the air heat up and cool down and the clouds form and disperse. Figure 8 shows the range of the change of Earth-emitted radiation.

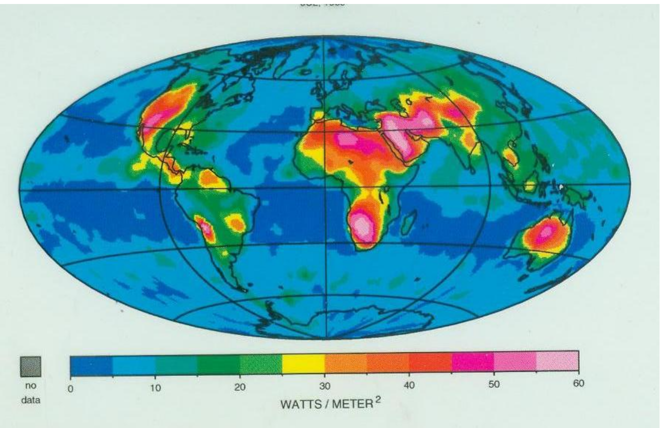


Figure 7: Range of change of Earth-emitted radiation during the day.

In summary, the major results of ERBE were to

- Provide the radiation standard for validating and improving General Circulation Models for climate sensitivity studies.
- Derive the first accurate diurnal variations of regional radiative parameters over the globe for climate studies.
- Observe large longwave and shortwave radiative anomalies during the 1987 El Nino as well as the El Nino starting in 1990 that continued through 1993, which represents the longest El Nino period in the past 50 years.

The above discoveries led to the declaration of understanding the role of clouds as the top scientific priority of the U.S. Global Change Research Program.

Since the 1980's, NASA LaRC has frequently had external Peer Review Panels to evaluate their research programs in atmospheric science. One Peer Review panel stated in 1987 that "The Radiation Sciences Branch achievements are exceptional; demonstrating its world-recognized prowess and scientific products in terms of data for the general research community and significant publications is remarkable, considering the (small) size of the branch." In another Peer Review of the Radiation Science Branch noted that "The branch programs' impact on international science has been immense and is truly world class." A third Panel wrote the following comment: "The Panel overall impression of the Radiation Sciences Branch's personnel is that they constitute an exceptionally harmonious group that is characterized by a high degree of interaction among scientists, both internally and externally. "

6. The Beginning of CERES

As the decade of the 1980's came to a close, the scanning ERBE instruments aboard the NOAA-9 and -10 spacecraft had each met its requirement of operating for two years and stopped. All three nonscanning instruments and the scanning instrument aboard the ERBS continued to perform with no problem. The ERBE Data Processing System was now generating data products from the measurements and these products were being used by researchers to learn about the relations between radiation and climate. With the value of radiation budget data demonstrated, it was time to initiate a project as a successor to ERBE.

Bruce Barkstrom proposed a project which would build on the successes of ERBE and go far beyond. For this project he selected the name Clouds and Earth Radiant Energy System CERES. This was the name of the Roman goddess of agriculture, home, family and stability. A gilded statue of CERES stands atop the commodities market building in Chicago. One of the early hopes of radiation budget research was to understand interannual variations of climate well enough to make seasonal forecasts which would benefit agriculture.

The CERES project would go beyond ERBE in three ways. First, the data record would be much more accurate than ERBE. There are three sources of error in the final data products: the instrument, the retrieval of fluxes from the measurements, and the averaging over the day from the limited measurements available. CERES would attack all three sources of error. The new project would use experience with the ERBE instrument to reduce measurement errors by a factor of two. Also the field of view would be reduced by a factor of two, thus giving more uniform fields for which bidirectional reflectance functions BDRFs would be used. To reduce the errors in the retrieval of fluxes from the radiance measurements required improve BDRFs, which in turn required more measurements from which to develop the models. The models for ERBE were developed using 218 days of measurements from the ERB instrument aboard the Nimbus 7 spacecraft. The CERES project would have one instrument aboard a spacecraft operating in cross-track scan so as to map the geographic variation of the radiance and another instrument would rotate in azimuth and nadir angle to measure radiation in all directions so that with more data better BDRFs could be created. These improved descriptions would reduce the error of the fluxes retrieved from the measured radiances. Finally, to reduce the errors in computing the daily average radiation fluxes, a pair of instruments would fly on a morning and an afternoon spacecraft as for ERBE, and also data from the geostationary meteorological satellites would be brought in to define changes in radiation between the times of CERES measurements.

CERES would also expand the objectives of measuring the radiation from the "top of the atmosphere" to include the radiation flux from the Earth's surface and from the atmosphere. These new data products would require cloud information from imaging instruments aboard the spacecraft in which the CERES instruments would fly and from the geostationary meteorological satellites. Also, meteorological data would have to be brought in to compute the radiation within the atmosphere.

The CERES project would require bringing in and processing massive amounts of data, which was a forbidding undertaking in 1990. However, Dr. Barkstrom's avocation was computers and he foresaw the evolution of computers and the capacity to transfer data so that by the time the instrument was in orbit, this work could be done with reasonable resources. Without this great evolution of computers and data transfer capability, the new objectives of extracting the surface radiation budget and the radiation absorbed and emitted by the atmosphere would be impossible. It was a daring move. In the late 1980's and early 1990's, Dr. Barkstrom was instrumental in formulating and promoting the development of an organization for bringing the massive amounts of data, processing and storing it, and then disseminate the data to scientific, educational and policy-making communities. These organizations were known initially as Distributed Active Archive Centres and would be located at major satellite research centres. At LaRC this organization is known today as the Atmospheric Science Data Center (ASDC).

A proposal was prepared to build, calibrate and fly six CERES instruments. This proposal was submitted by Barkstrom to NASA Headquarters. In the contingency that this instrument proposal resulted in an Announcement of Opportunity for other organizations to submit proposals and win the competition, a proposal was submitted to use the data for scientific investigations, with Bruce Wielicki as the Principal Investigator. The Langley Team had proven itself, the need for radiation budget data had been demonstrated and the new proposal was a major step forward. Both proposals were accepted, and the CERES project was funded for a new start. This new start was accomplished with one stroke; there was no extended struggle as there had been for ERBE.

An Announcement of Opportunity was released by NASA Headquarters and researchers were selected for the Science Team. The members are listed in Table 2. The LaRC people, the Science Team and the support contractors were divided into working groups. The Instrument Group was led by Robert B. Lee, III. Bob had demonstrated his ability for this job by his work with the ERBE instruments. Lou Smith would support the Instrument Working Group with analyses to address various questions. Also, Professor Robert Mahan of VPI&SU received grants to develop computer models to complement this work. Richard Green had led the Inversion Group for ERBE and would lead this work for CERES. Because of the time consumed by his duties as Branch Head and the expanded data requirements for the Time Averaging part of the data processing, Ed Harrison handed over the leadership of the Time Averaging Group to Dave Young. Two new working groups were formed. Pat Minnis led the development of algorithms for the computation of cloud properties, which would be of fundamental importance for the CERES objectives. Thomas P. Charlock led the working group for Surface and Atmospheric Radiation Budget (SARB), which in addition to the surface radiation budget would retrieve the radiative heating of the atmosphere from satellite measurements. For the development of Bidirectional Reflectance Functions, Norman Loeb, a recent Ph. D., was brought in. Later, Kory J. Priestley joined the Instrument Working Group. The Science part of CERES was in place.

On the Project side of CERES, which had the responsibility of overseeing designing, building and calibrating the instruments and having them integrated with the spacecraft, there was also an experienced team from ERBE. Charley Woerner had become head of the Projects Directorate. Jack Cooper was appointed Project Manager for CERES.

Statements of Work were prepared by Jack Cooper, with heavy input from Bruce Barkstrom; each was supported by their teams. Requests for Proposals were sent out by NASA Headquarters and TRW won the competition. A major factor in their selection was their including the Radiation Calibration Facility in their proposal. Upgrades to the thermal-vacuum tank which had been used for the ERBE instruments would be designed and built in parallel with the instrument. Steve Carman, who had been Calibration Engineer for ERBE, was named as the Project Manager for CERES for TRW. Tom Evert would again be the Chief Engineer. The contract called for six CERES instruments to be built and calibrated.

The next issue was on what spacecraft would the CERES instruments fly? At Goddard Space Flight Centre, Dr. Joanne Simpson, the First Lady of Meteorology, was leading a team to develop a concept which would become the Tropical Rainfall Measuring Mission. This project was a collaborative effort between NASA and the Japanese Space Exploration Agency

(JAXA). The spacecraft was built by Goddard Space Flight Centre and the Precipitation Radar was built by JAXA. The remaining instruments, including the Proto-Flight Model of CERES, were supplied by NASA. The TRMM spacecraft was placed into orbit by JAXA using an H-2 booster in November 1997. The CERES PFM began operating a month later. Initially, the instrument operation matched expectations. Unfortunately, an electronic component began to deteriorate and the instrument was turned off in order to save its remaining life for later.

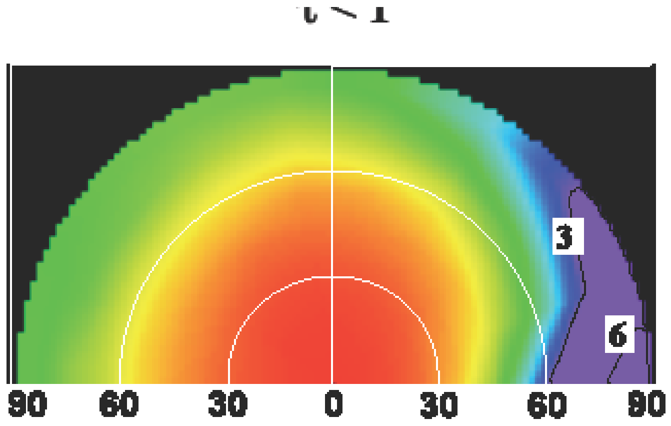
At the time that CERES was being considered for a new start, there was intense discussion as to the type of spacecraft which would carry the next generation of instruments for Earth observation. This discussion led to the Terra and Aqua spacecraft as the primary spacecraft. Later, other smaller spacecraft such as Calipso and CloudSat would complement the Aqua by flying in formation with it. This set of spacecraft is denoted the “A Train.”

The Terra and Aqua spacecraft would each carry two CERES instruments. One CERES would operate in cross-track scan so as to map the geographical distribution of radiation. The other CERES would operate in a biaxial mode to make measurements from which the amount of radiation in each direction as it leaves the atmosphere can be computed. Flight Models 1 and 2 were mounted on the Terra spacecraft, which was placed into orbit on 18 December 1999 by an Atlas 2C launch vehicle. At this point, the Torch had been passed to the New Generation.

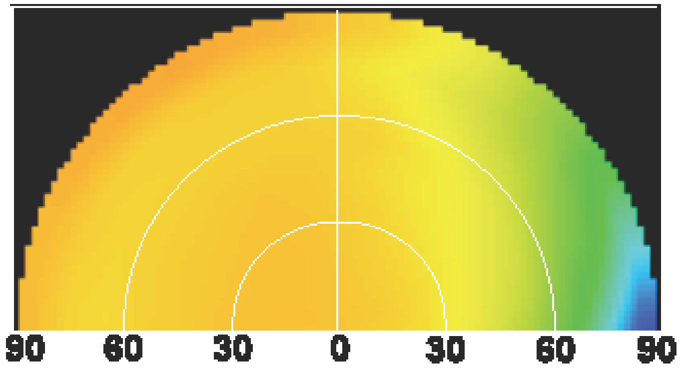
In the 2007 External Peer Review Report of the Langley Radiation and Climate Sciences Branch, it is stated that “The Panel was universally impressed with the high quality and relevance of the science being performed by the branch. The program has demonstrated unprecedented leadership in space-borne earth radiation budget studies which are having major impacts upon scientific research outside of NASA.”…… “The CERES work is first rate and first class. The care and precision associated with calibration of the instrument and maintaining the data record are to be commended. Dr. Bruce Wielicki and the rest of the CERES investigators have clearly thought through the issue of providing outstanding and usable extended period climate records. The fusion of the data from other instruments, combined with models, to produce outstanding measurements of radiative fluxes serves as a benchmark for the community.”

7. CERES Results

One important result from CERES measurements is the set of bidirectional reflectance models, or anisotropy factors, which are needed to retrieve flux from a radiance measurement. Figure 9 shows an example of these models. These models supercede those which were developed for ERBE by use of Nimbus 7 ERB measuremens. The new anisotropy factors provide greater accuracy for the fluxes computed using CERES data.



a. Optical depth less than 1 (optically thin)



b. Optical depth greater than 50 (optically thick)

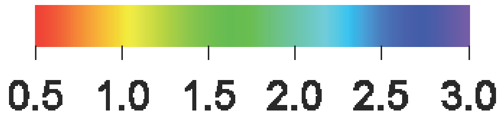


Figure 9: Bidirectional reflectance Function for taking into account dependence of reflected pattern of reflected solar radiation for overcast ice clouds for Sun between 60 and 70 degrees from zenith (Loeb et al., 2002)..

The new data products from CERES include maps of surface radiation budget components: shortwave down, shortwave up, longwave down and longwave up at the surface. Figure 10 shows a global map of longwave down flux at the surface for March 2003. Other products include photosynthetically active radiation PAR and ultraviolet radiation, total, UVA and UVB. Figure 11 shows the monthly-mean diffuse component of PAR over the coterminous U. S. for June 2005. Figure 12 shows a similar map for the ultraviolet index. In addition, the difference between the fluxes at the surface and at 500 mb and between 500 mb and 250 mb are generated.

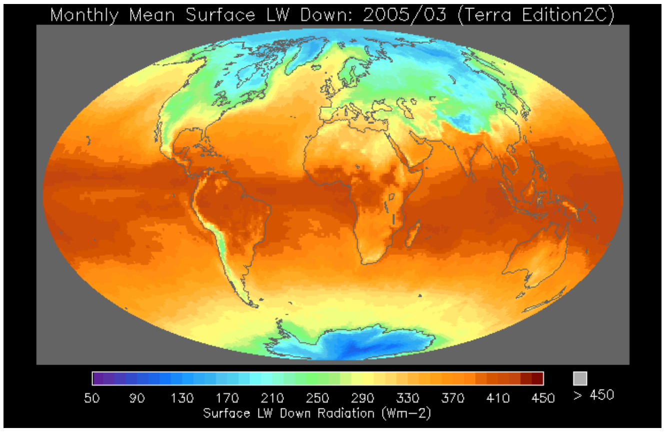


Figure 10: Longwave down radiation flux at the surface for March 2005.

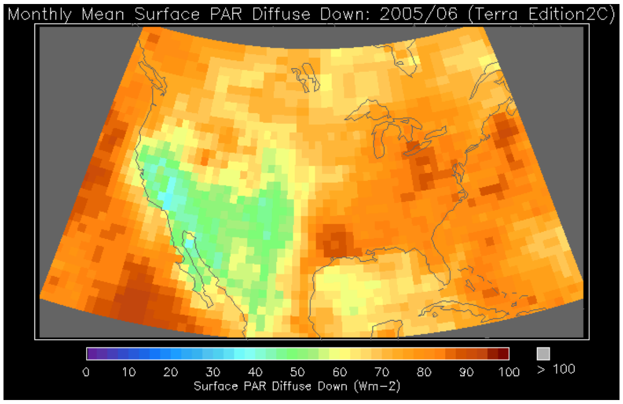


Figure 10: Monthly–mean diffuse component of Photosynthetically active radiation over coterminous U. S. for June 2005.

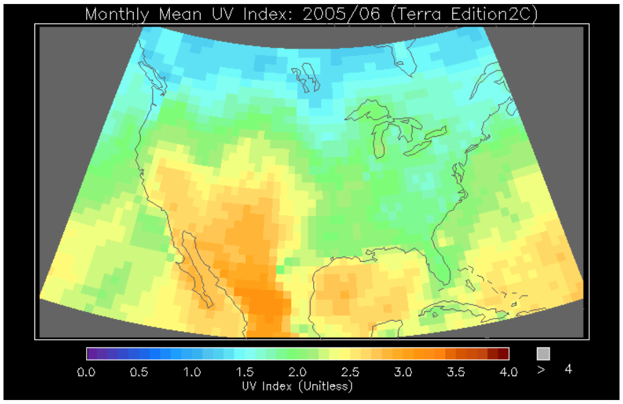


Figure 11: Monthly-mean map of ultraviolet index for coterminous U. S. for June 2005.

8. CERES FM-5 on the NPP spacecraft

Continuation of the Earth Radiation Budget (ERB) Climate Data Record (CDR) has been identified as critical in the 20 07 NRC Decadal Survey. Also, the World Climate Research Program in its report “The Global Climate Observing System” reiterated the need for ongoing Earth radiation budget data. Following an assessment titled “Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals[3]”, NASA HQ authorized multi-phase analysis and engineering design studies in 2007 to assess feasibility of adding CERES back on NPP, which were completed in September, 2007. These studies showed that CERES could be accommodated without impacting the September 2009 Launch Readiness Date. The studies identified instrument, spacecraft and ground system modifications but found no technical or schedule barriers. NASA, NOAA and NPOESS agreed in early 2008 to fly the final existing CERES FM-5 on the NPP spacecraft, which presently has a launch readiness date in 2011. This mission will continue the critical Climate Data Record begun by the Earth Radiation Budget Experiment (ERBE) instruments in the mid 1980’s and continued by the CERES instruments currently flying on the Earth Observation System (EOS) Terra and Aqua spacecraft. The CERES FM-5 pre-flight radiometric characterization program has benefited from the operational experience of the CERES EOS sensors. Improvements to the pre-flight program included increased sampling under vacuum conditions and additional tests to characterize the primary and transfer standards in the calibration facility. Ground calibrations have been completed for FM-5 and the instrument has been delivered and integrated to the spacecraft. Rigorous ground calibration is performed on each CERES unit to achieve an accuracy goal of 1% for SW flux and 0.5% for outgoing LW flux. Any ground to flight or in-flight changes in radiometer response are monitored using a protocol employing both onboard and vicarious calibration sources and experiments. Recent studies of FM-1 through FM-4 data have shown that the SW response of space based broadband radiometers can change dramatically due to optical contamination. With these changes having most impact on optical response to blue-to UV radiance, where tungsten lamps are largely devoid of output, such changes are hard to monitor accurately using existing on-board sources. This paper discusses the ERB CDR, describes the CERES FM-5 on NPP, then outlines the lessons learned on the existing CERES sensors from 30+ years of flight experience and presents a radiometric protocol to be implemented on the FM-5 instrument to ensure that its performance exceeds the stated calibration and stability goals.

9. Beyond FM-5

Sufficient quantities of Spare parts were procured during the original CERES/EOS build such that a seventh CERES Flight Instrument (FM-6) can be assembled and flown on the NPOESS C1 platform in the 2014 timeframe. With the operational scenario of flying FM-6 in a single 1330 orbit with no other sufficient on-orbit assets to intercompare/validate the radiance measurements, specific upgrades to onboard calibration subsystems are necessary to verify that the FM-6 radiance measurements meet the stated requirements of the CERES/EOS program. Specific upgrades to increse the spectral range of the Shortwave Internal Calibration Source (SWICS), as well as providing reference detectors to monitor degradation of the CERES solar diffusers have been proposed, yet have not yet been funded, and are not in the current CERES FM-6 baseline design. The baseline design will incorporate new coatings for the solar diffusers, as well as a functional reference detector to monitor the SWICS lamp output. In addition the narrowband 8 to 12 micron atmospheric window channel will be replaced by a broadband (nominally 5 to 50 microns) longwave channel. These modest changes will help to maintain better in-orbit calibration of FM-5 over the legacy flight units.

For another operational meteorological spacecraft to be launched in 2018 and future missions, a new version of CERES will be designed and built. The present CERES was designed in the early 1990's with 1980's technology and many of the key components, such as processors, RAM or the detectors, are no longer available or feasible to produce. Thus, building another copy of the current CERES instrument is not a viable option. Conceptual design of the CERES II instrument has now started for use on the NPOESS C2 platform and for future missions.

10. Reflections on Radiation Budget Research at Langley Research Center

- The Work started with the Recognition of Need for Measurements leading to Scientific Data Products and the Areas requiring Work.
- A Team was formed to address these Areas. The Team Approach has been continued through ERBE and CERES.
- The Science Teams' Research gave excellent returns on the Investments in these Projects.

Table: Principle Investigators on ERBE Science Team

Investigator	Institution	Investigator	Institution
Bruce Barkstrom	LaRC	Herb Jacobowitz	NOAA/NESDIS
Andre Berrior	CNES	Bob Kandel	Ecole Polytechnique
Robert Cess	SUNY/Stoneybrook	V. Ramanathan	U. Chicago
Charlie Duncan	GSFC	Ehrhard Raschke	U. Koeln
Ed Harrison	LaRC	Bob Schiffer	NASA HQ
Dennis Hartmann	U. Washington	Lou Smith	LaRC
Fred House	Drexel University	Tim Suttles	LaRC
Gary Hunt	University College	Tom Vonder Haar	Colorado State U.

11. An Annotated Bibliography

Although Vern Suomi demonstrated the use of non-scanning radiometers to make measurementss of the Earth's radiation budget, the use of scanning radiometer data to compute the Earth's radiation balance was shown by this paper:

Raschke, E., T. H. Vonder Haar, W. R. Bandeen, and M. Pasternak, 1973: The annual radiation balance of the earth-atmosphere system during 1969 - 1970 from Nimbus 3 measurements, J. Atmos. Sci., 30, no. 3, Apr., pp 341 - 364.

The ERB instrument and the applicatiion of the measurements from the ERB intrument which flew aboard the Nimbus 7 are described by

Smith, W. L., J. Hickey, H. B. Howell, H. Jacobowitz, D. T. Hilleary and A. J. Drummond, 1977: Nimbus 6 Earth radiation budget experiment, Appl. Opt., 16, pp 306 - 318.

Jacobowitz, H., H. V. Soule, H. L. Kyle, F. B. House and the Nimbus-7 ERB experiment team, 1984: The earth radiation budget (ERB) experiment : An overview, J. Geophys. Res., 89, pp 5021 - 5038.

Accurate measurements of Earth radiation budget muse include measurements over all times of day. The design of the orbits of a system of spacecraft was defined by

Harrison, E. F., P. Minnis, and G. G. Gibson, 1983: Orbital and cloud cover sampling analyses for multi-satellite Earth radiation budget experiments, J. Spacecraft and Rockets, 20, 491-495.

A series of papers was written to explain the ERBE project and the processing methods of the data. This collection was published in Reviews of Geophysics in 1986. The overall project and the scientific purposes were described by

Barkstrom, B. R. and G. L. Smith, 1986: The Earth Radiation Budget Experiment: Science and Implementation, Rev. of Geophys., 24, 379-390.

The knowledge of Earth radiation budget before satellite measuremwents and with satellite measurements before ERBE were explained by

Hunt, G., R. Kandel and A. T. Mecherikunnel, 1986: A history of presatellite investigations of the Earth's radiation budget, Rev. Geophys., 24, 351-356.

House, F. B., A. Gruber, G. E. Hunt and A. T. Mecheriunnel, 1986: History of satellite missions and measurements of the Earth radiation budget (1957-1984), Rev. Geophys., 24, 357-377.

The scanning radiometer and the non-scanning radiometers were described by

Kopia, L. P., 1986: Earth Radiation Budget Experiment scanner instrument, Rev. Geophys., 24, 400-406

Luther, M. R., J. E. Cooper and G. R. Taylor, 1986: The Earth Radiation Budget Experiment non-scanning instrument, Rev. of Geophys., 24, 391-399.

The computation of the flux at the top of the atmosphere and the averaging over tiime required algorithms which are explained by

Smith, G. L., R. N. Green, E. Raschke, L. M. Avis, J. T. Suttles, B. A. Wielicki and R. Davies, 1986: Inversion methods for satellite studies of the Earth's radiation budget: Development of algorithms for the ERBE mission, Rev. Geophys, 24, 407-421.

Brooks, D. R., E. F. Harrison, P. Minnis, J. T. Suttles and R. S. Kandel, 1986: Development of algorithms for understanding the temporal and spatial variability of Earth radiation balance, Rev. Geophys., 24, 422-438.

The bidirectioal reflectance distribution models which were used to account for the directionality of the reflected solar and emitted longwave radiation are described by

Suttles, J. T., R. N. Green, P. Minnis, G. L. Smith, W. F. Staylor, B. A. Wielicki, I. J. Walker, D. E. Young, V. R. Taylorand L. L. Stowe, 1988: Angular Radiation Models for the Earth-Atmosphere System. Vol. I: Shortwave Models. NASA Ref. Pub. 1184.

Suttles, J. T., R. N. Green, G. L. Smith, B. A. Wielicki, I. J. Walker, V. R. Taylor, and L. L. Stowe: Angular radiation models for earth-atmosphere system, Vol. II - Longwave radiation,NASA RP-1184, 1989.

These models were used not only by ERBE, but also by CERES for the first edition of data products and by the ScaRab and GERB projects. They were superceded by the models which were developed using CERES measurements:

Loeb, N.G., N.M. Smith, S. Kato, W.F. Miller, S.K. Gupta, P. Minnis, and B.A. Wielicki, 2002: Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System instrument on the Tropical Rainfall Measuring Mission Satellite. Part I: Methodology, J. Appl. Meteor.

Loeb, N.G., K. Loukachine, N.M. Smith, B.A. Wielicki, and D.F. Young, 2002: Angular distribution models for top-of-atmosphere radiative flux estimation from the Clouds and the Earth's Radiant Energy System instrument on the Tropical Rainfall Measuring Mission Satellite. Part II: Validation, J. Appl. Meteor..

Although efforts are underway to improve these models, the same CERES measurements are being used. There are no plans to create another data set such as was done by CERES.

Some of the scientific results of ERBE are published in these journals:

Harrison, E. F., D. R. Brooks, P. Minnis, B. A. Wielicki, W. F. Staylor, G. G. Gibson, D. F. Young and F. M. Denn, 1988: First estimates of the diurnal variation of longwave radiation from the multiple-satellite Earth Radiation Budget Experiment (ERBE). Bull. Amer. Met. Soc., 69, 1144-1151.

Minnis, P., E.F. Harrison, L.L. Stowe, G.G. Gibson, F.M. Denn, D.R. Doelling and W.L. Smith, Jr.: Radiative climate forcing by the Mt. Pinatubo eruption, submitted to Science (1992).

Barkstrom, B. R., E. F. Harrison, G. L. Smith, R. N. Green, J.F. Kibler, R. Cess and the ERBE Science Team, 1989: Earth Radiation Budget Experiment

(ERBE) archival and April 1985 results, Bull. Amer. Met. Soc., 70, 1254-1262.

Ramanathan, V., R.D. Cess, E.F. Harrison, P. Minnis, B.R. Barkstrom, E. Ahmed and D. Hartmann: Cloud-radiative forcing and climate: Results from the Earth radiation Budget Experiment, Science, 243, 57-63 (1989).

Ramanathan, V., 1987: The role of Earth radiation budget studies in climate and general circulation research, J. Geophys. Res., 92, 4075-4095.

Ramanathan, V., E. F. Harrison and B. R. Barkstrom, 1989: Climate and the Earth's radiation budget, Physics Today, 42, 22-33.