Validation of CERES/TERRA data

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ABSTRACT

There are 2 CERES scanning radiometer instruments aboard the TERRA spacecraft, one for mapping the solar radiation reflected from the Earth and the outgoing longwave radiation and the other for measuring the anisotropy of the radiation. Each CERES instrument has on-board calibration devices, which have demonstrated that from ground to orbit the broadband total and shortwave sensor responses maintained their ties to the International Temperature Scale of 1990 at precisions approaching radiances have been validated in orbit to ±0.3 % (0.3 W $m^{-2}sr^{-1}$). Top of atmosphere fluxes are produced by use of the CERES data alone. By including data from other instruments, surface radiation fluxes and radiant fluxes within the atmosphere and at its top, shortwave and longwave, for both up and down components, are derived. Validation of these data products requires ground and aircraft measurements of fluxes and of cloud properties.

keywords: CERES, TERRA, Radiometry, validation.

1. INTRODUCTION

The climate of Earth depends upon its radiation balance between the absorbed solar radiation and the outgoing longwave radiation. For this reason, a long term data set of these quantities is required in order investigate climate variability at time scales from interannual to interdecadal[1,2]. Also, many large scale atmospheric experiments need radiant fluxes at the top of the atmosphere as those fluxes are quite important for the energy balance at large scales[3]. In order to provide an accurate data set of broadband radiation measurements, the Clouds and Earth Energy System (CERES) instrument was developed[4,5,6]. This instrument has 3 channels: a shortwave channel for reflected solar (.2-5.0μ) and a total channel (.2-100μ). The total channel minus the shortwave channel gives the outgoing longwave radiance. The CERES scanning radiometers also have a third channel, which measures radiances in the 8 to 12 micron window of the Earth's atmosphere. This channel will provide information about the extent to which this spectral region is obscured by traces gases. The Proto-flight model CERES instrument flew aboard the Tropical Rainfall Measuring Mission in 1997. The TERRA spacecraft was launched 18 December 1999 and carries 2 CERES instruments, Flight Models 1 and 2 (FM1 and -2), which are identical in construction but perform totally different functions. One instrument scans in a cross-track pattern in order to map the Earth's outgoing longwave radiation and the solar radiation reflected from the Earth. The other instrument scans in azimuth and elevation simultaneously so as to measure radiances in all directions, thereby providing data about the anisotropy of the radiation field. Another mode provides for along-track scanning, which produces especially useful data for directionality of radiances and other aspects of radiant flux measurement. These data are required to develop improved bidirectional reflectance models of the upwelling radiation which are needed to compute radiant fluxes more accurately from measured radiances. Both instruments began making measurements of the Earth on 24 February, 2000. In addition to the radiative flux at the "top of the atmosphere" which is provided by CERES alone, data from the MODIS instrument and other ancillary data are used to compute the upward and downward components of longwave and shortwave radiative fluxes at the surface and through the atmosphere and at its top. The retrieved radiative fluxes through the atmosphere are a new type of data product and require extensive validation. Clouds play a major role in radiative fluxes and their properties, both large scale (cloud fraction, height) and microphysics (phase, particle sizes) must be taken into account.

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This paper discusses the validation of the CERES/TERRA measurements and of some of the data products.The CERES instrument and on-orbit validation of the calibration is described. The use of the measurements to generate data products is briefly discussed. In order to validate the radiation products at the surface and through the atmosphere, measurement programs at the surface are required. These programs include ground and aircraft campaigns and are also briefly described.

2. CERES IN-FLIGHT CALIBRATION

Each of the 3 channels of a CERES instrument consists of a thermistor bolometer with a telescope to gather radiation. All three channels are mounted on a beam which scans in elevation[7]. In addition, each instrument carries an Internal Calibration System (ICS) and a Mirror Attenuator Mosaic (MAM)[8]. The ICS has 2 black bodies, one for the longwave part of the total channel and one for the 8-12μ window channel. Each scan of the radiometer begins with a view of space as shown in fig. 1 to establish the near-zero radiance level. The ICS also has a Shortwave Internal Calibration Source, a tungsten lamp monitored by a silicon photodiode, which is used to check the calibration of the shortwave channel. The radiometer scans across the Earth at a rate of 67 degrees/sec. (the standard rate) to a second space look, and then scans to look inside the instrument at the ICS. At selected times, when the Sun is in the proper position relative to the instrument, the instrument rotates in azimuth so that the Sun shines into the MAM[9] and the radiometer scans in elevation to look with the total and shortwave channels at the reflection of the solar radiation from the MAM. The FM1 instrument and its ICS were calibrated in the TRW Radiation Calibration Facility in October 1996 and the FM2 in February 1997 by use of black bodies with platinum resistance thermometers which tied the calibration to the International Temperature Scale of 1990. The MAM is not an absolute radiometric reference, but provides a check on changes in response of the instrument by using the Sun as a source[10]. The Sun is stable to better than 1% and monitors on other spacecraft give values of the solar irradiance accurate to a fraction of 1%. The MAM has been shown to have a precision of 0.5%.

The on-orbit calibration results for the FM1 and FM2 instruments are reported by Lee et al. (2000)[11]. The sensor response change as derived from measurements of the ICM blackbody for the total channel of the FM1 is shown in fig. 2. (note that the scale on the right side of the figure is from -1% to +1%.) The FM1 total channel response is 0.3% higher than that measured on the ground. The precision is 0.05%. Figure 3 shows the FM1 shortwave sensor response change as determined from the ICS lamp; the on-orbit value is -0.3% lower than the ground computed value. Again, the results are precise to 0.05%. The FM1 window channel response as calibrated on-orbit by the ICS blackbody is shown by fig. 4 to be +0.4% higher than the ground response and the noise is at the ±0.4 % level. The percentage increase for this channel is higher because the level of the signal in the relatively narrow channel is much lower.

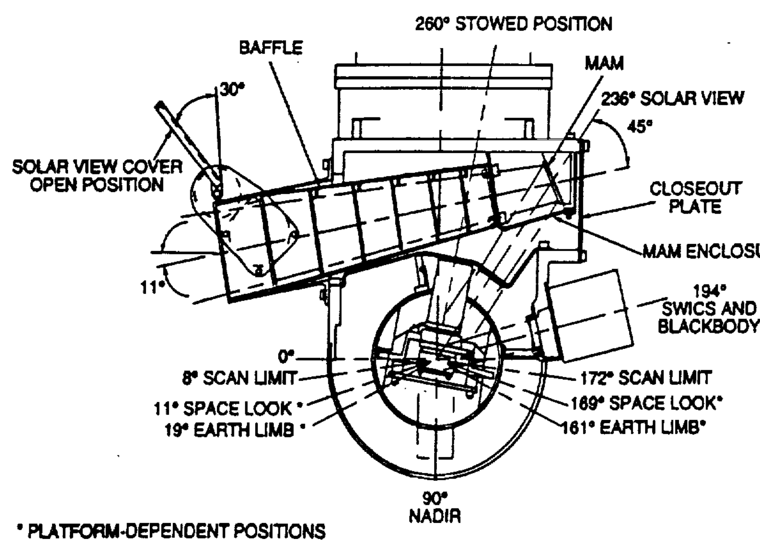

Figure 1. Cross section of CERES instrument, showing location of Internal Calibration System and Mirror Attenuated Mosaic and scan positions.

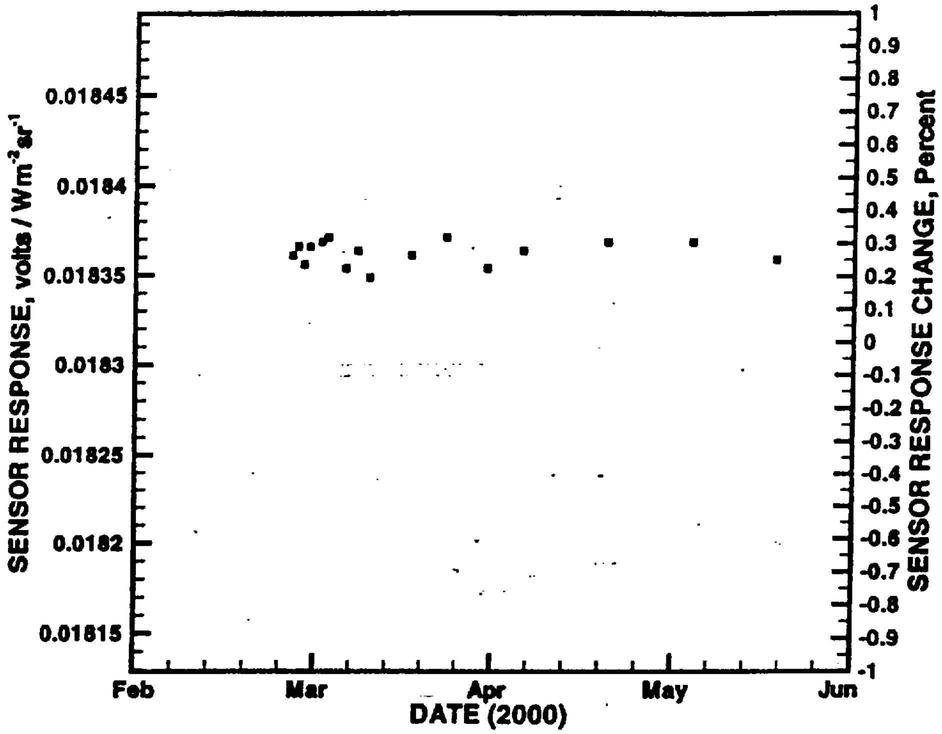

Figure 2. On-orbit CERES FM1 total channel response changes as derived from measurements of internal blackbody radiances.

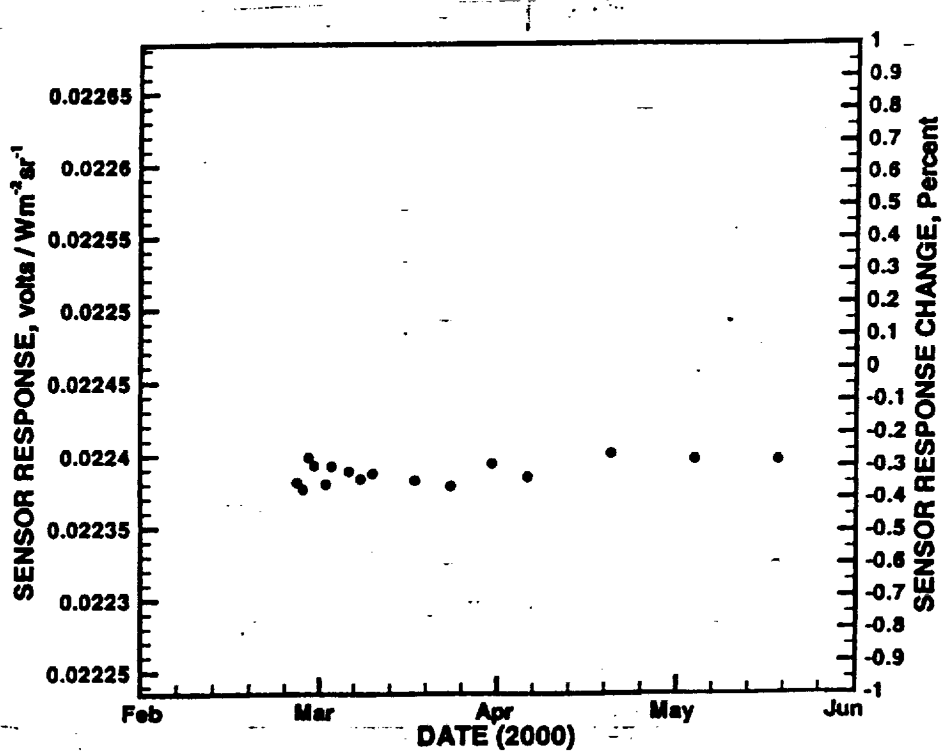

Figure 3. On-orbit CERES FM1 shortwave channel response changes as derived from measurements of Internal Calibration System lamp radiances.

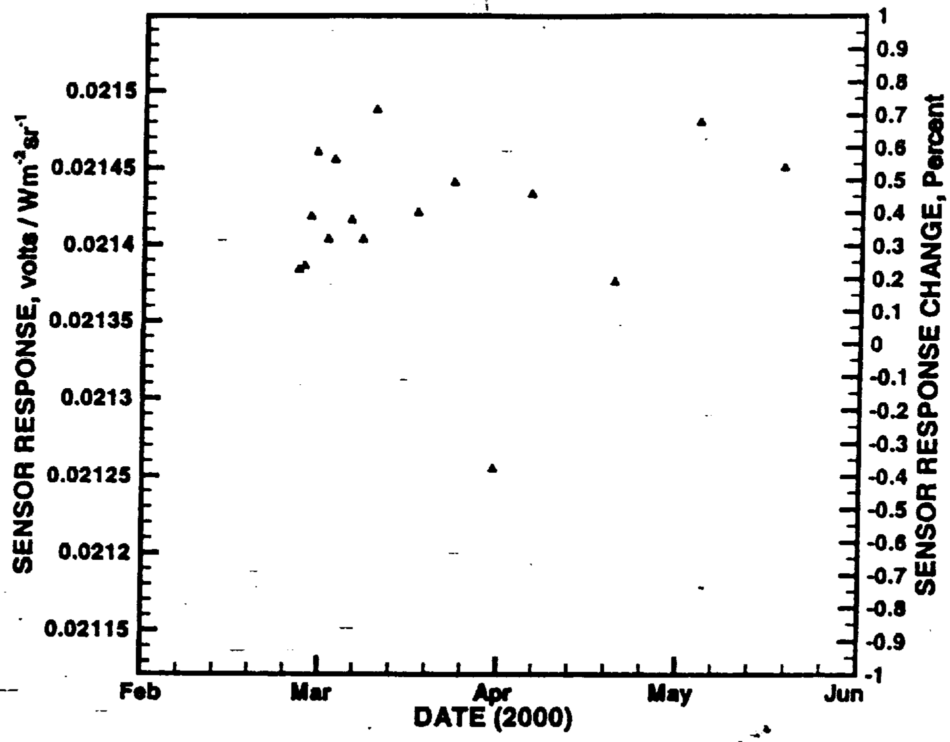

Figure 4. On-orbit CERES FM1 window channel response changes as derived from measurements of internal blackbody radiances.

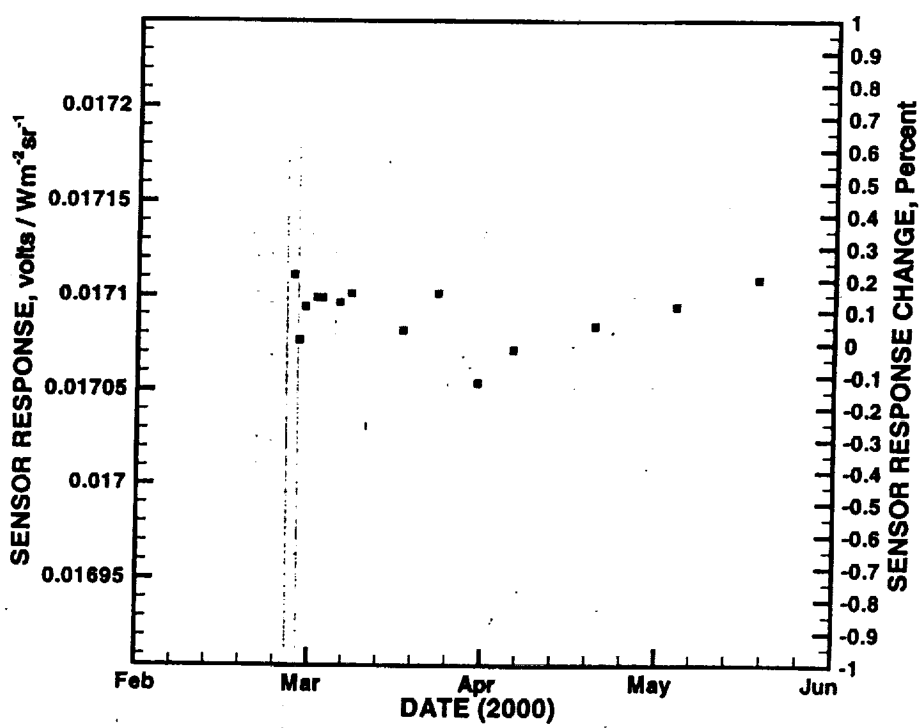

Figure 5. On-orbit CERES FM2 total channel response changes as derived from measurements of internal blackbody radiances.

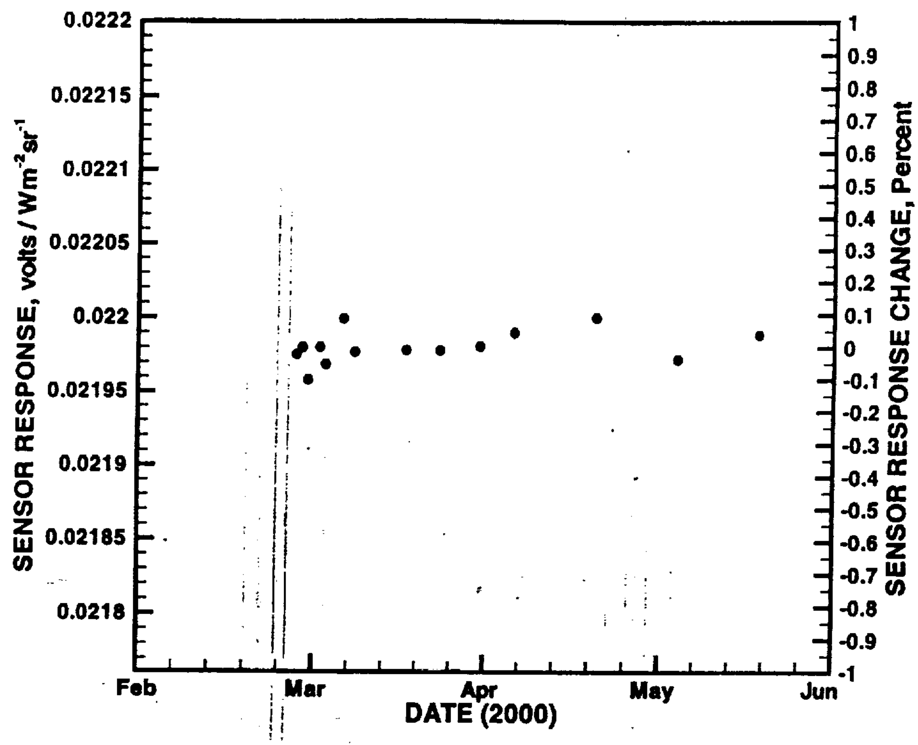

Figure 6. On-orbit CERES FM2 shortwave channel response changes as derived from measurements of Internal Calibration System lamp radiances.

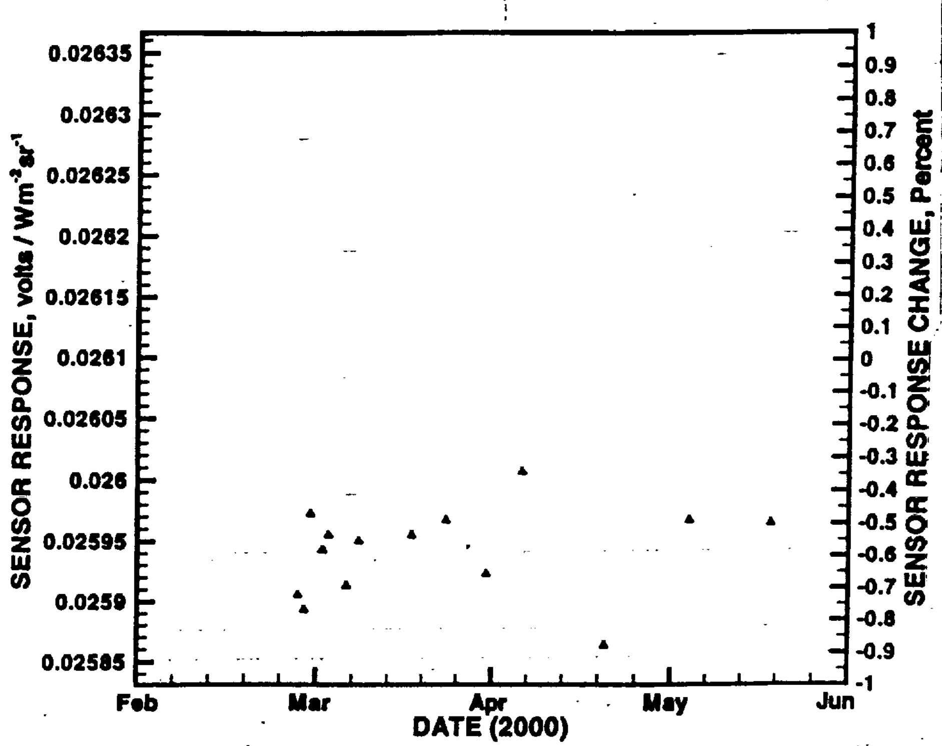

Figure 7. On-orbit CERES FM2 window channel response changes as derived from measurements of internal blackbody radiances.

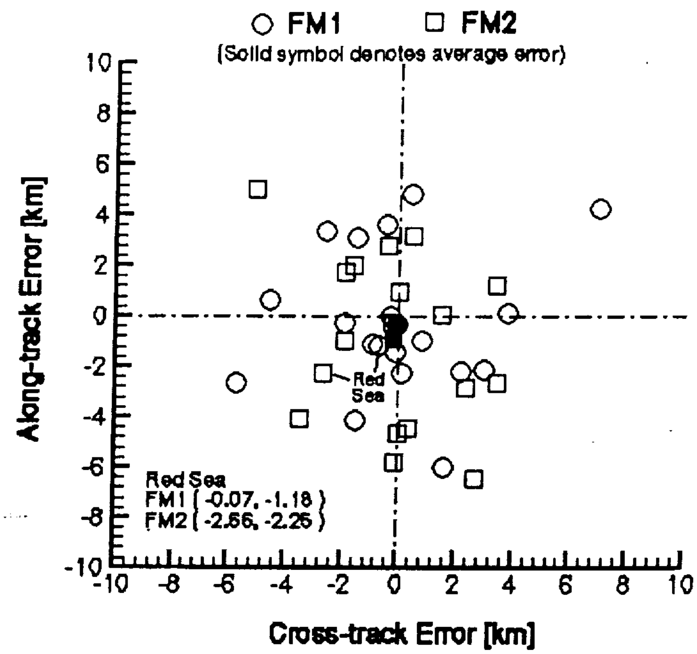

Figure 8. Cross-track and along-track errors for CERES/TERRA FM1 and 2 as determined by coastline detection technique.

Figure 5 through 7 show the results for on-orbit calibrations compared to the ground calibrations for the FM2 channels using its ICS. The FM2 total channel on-orbit responses is 0.1% higher than the response determined on the ground and is stable to ±0.1 %. The FM2 shortwave channel on-orbit calibration results agree with the ground results within ±0.05 % and the precision of the on-orbit calibration is ±0.1 %. The FM2 window channel is -0.6% lower than the ground value and has noise at the ±0.2 % level. These results are compatible with the ±0.2 % stability demonstrated for the 3 channels of the CERES/TRMM instrument[35].

3. VALIDATION OF GEOPHYSICAL QUANTITIES

In addition to the gains, there are a number of other facets of the measurements which must be validated[12]. Some applications of the CERES measurements require knowledge of the point spread function (PSF) of the instrument. Thus, the PSF was computed theoretically[13] and was measured for each channel of each instrument[14]. A spurious slow mode was detected during ground calibrations and a numerical filter was designed to attenuate the effects of that mode[15]. In-flight results showed that the effects of the slow mode were eliminated. Also, because MODIS pixels must be located precisely relative to the CERES PSF, it is necessary to validate the location of the CERES pixels precisely. This was done using the method of Curry et al.[16], which estimates the inflection point of the response of the instrument at a sharp edge i.e. a coastline with high contrast between land and ocean temperature or reflectivity, and accounts for the displacement between the inflection point and the centroid of the pixel. Typical results are shown by figure 8 for FM1 and -2. At the TERRA altitude of 705 km, the pixel size for the CERES is 20 km near nadir and the technique shows that any biases of cross-track and along-track error are each less than 1 km.

The spectral responses of the channels are not flat, but have structures which vary with wavelength[17]. To use the measurement to compute accurately the radiance entering the instrument, it is necessary to account for the spectral response of the instrument and the spectrum of the incoming radiance. As a validation check of the algorithm for accounting for the spectral response, the spectral radiance of outgoing longwave radiation from deep convective

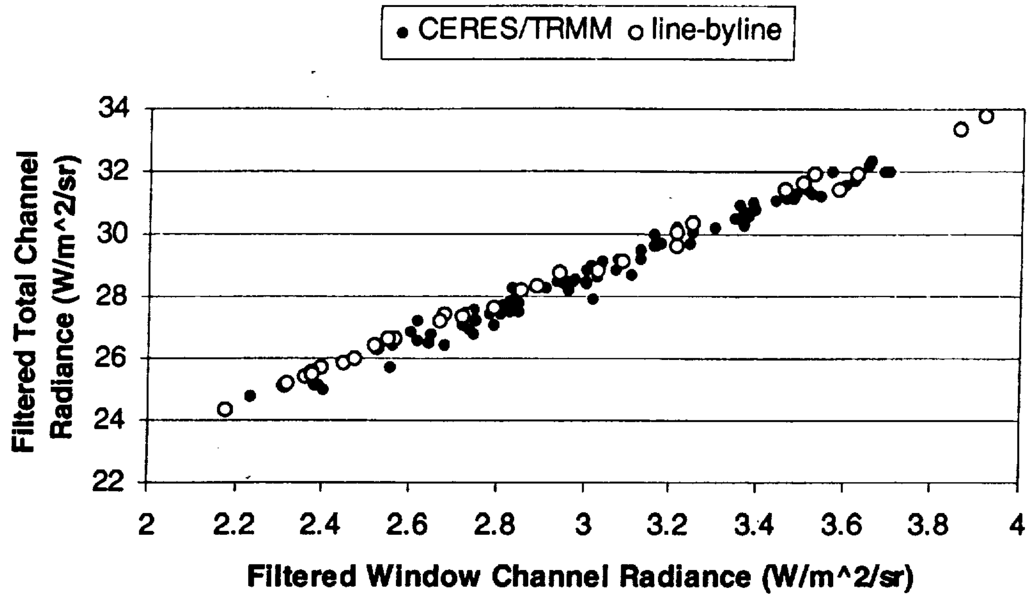

Figure 9. Filtered total channel radiances as a function of 8-12μ window channel radiances for deep convective clouds at night, comparing measurements for CERES/TRMM with line-by-line radiative transfer computations.

clouds were computed as a function of cloud top height using a line-by-line radiative transfer code. By use of these spectral radiances and the spectral response of the instrument, the spectral radiances absorbed by the detectors for the total and window channel were computed and integrated to give the quantities measured by each channel, which are referred to as "filtered radiances." Deep convective clouds were used because they are opaque in the longwave and the water vapor above them is small, reducing uncertainties in the spectral radiances due to uncertainties in water vapor. Figure 9 shows the results of the theoretical computation compared with measurements from the total and window channels of the CERES /TRMM instrument taken at night, to eliminate reflected solar radiation[18]. Similar comparisons will be done for the FM1 and -2 instruments. The shortwave channels of the CERES/TRMM can be compared with those of the FM1 and FM2 by use of deep convective clouds which have a large horizontal extent. Such clouds have an average reflectance of approximately 72%. On the basis of these measurements no statistical differences can be seen between the PFM, FM1 and FM2.

In order to compare the radiances of the FM! and FM2 aboard the TERRA spacecraft with those from the CERES/ TRMM, the CERES/TRMM instrument was rotated in azimuth so that at the point where the orbits overlapped, the CERES/TRMM scanned in the same directions relative to the ground as the cross-track scanning FM1 aboard the TERRA spacecraft. For a given scene near the orbit overlap point, the CERES/TRMM and the FM1 will both have the same view zenith angle and relative solar zenith angle and will be measuring the same radiances. These results showed that the instruments aboard both spacecraft agree within 0.4% for the shortwave radiances and 0.5% for the longwave radiances[19]. The CERES/TRMM measurements in turn have been compared to the Earth Radiation Budget Experiment (ERBE) Wide Field-of-View Radiometer on the dedicated Earth Radiation Budget Satellite[20], which has established a 15-year data set of Earth radiation measurements and has served as an intercomparison basis for the ERBE scanning radiometers and the ScaRaB also[21].

Figure 10 shows the data flow for the CERES products. After applying the calibrations to derive filtered radiances and geolocating the pixels, the data stream splits into an "ERBE-like" stream (horizontal in the diagram) and a stream for surface and atmospheric fluxes (vertical in the diagram). In the ERBE-like stream, bidirectional reflectance functions are used to account for anisotropy of the radiances in order to compute outgoing longwave fluxes and reflected solar fluxes for each pixel. These fluxes are then spatially averaged to produce regional means at TOA and temporally averaged to produce monthly-mean regional-mean fluxes. These ERBE-like data products are currently available for the

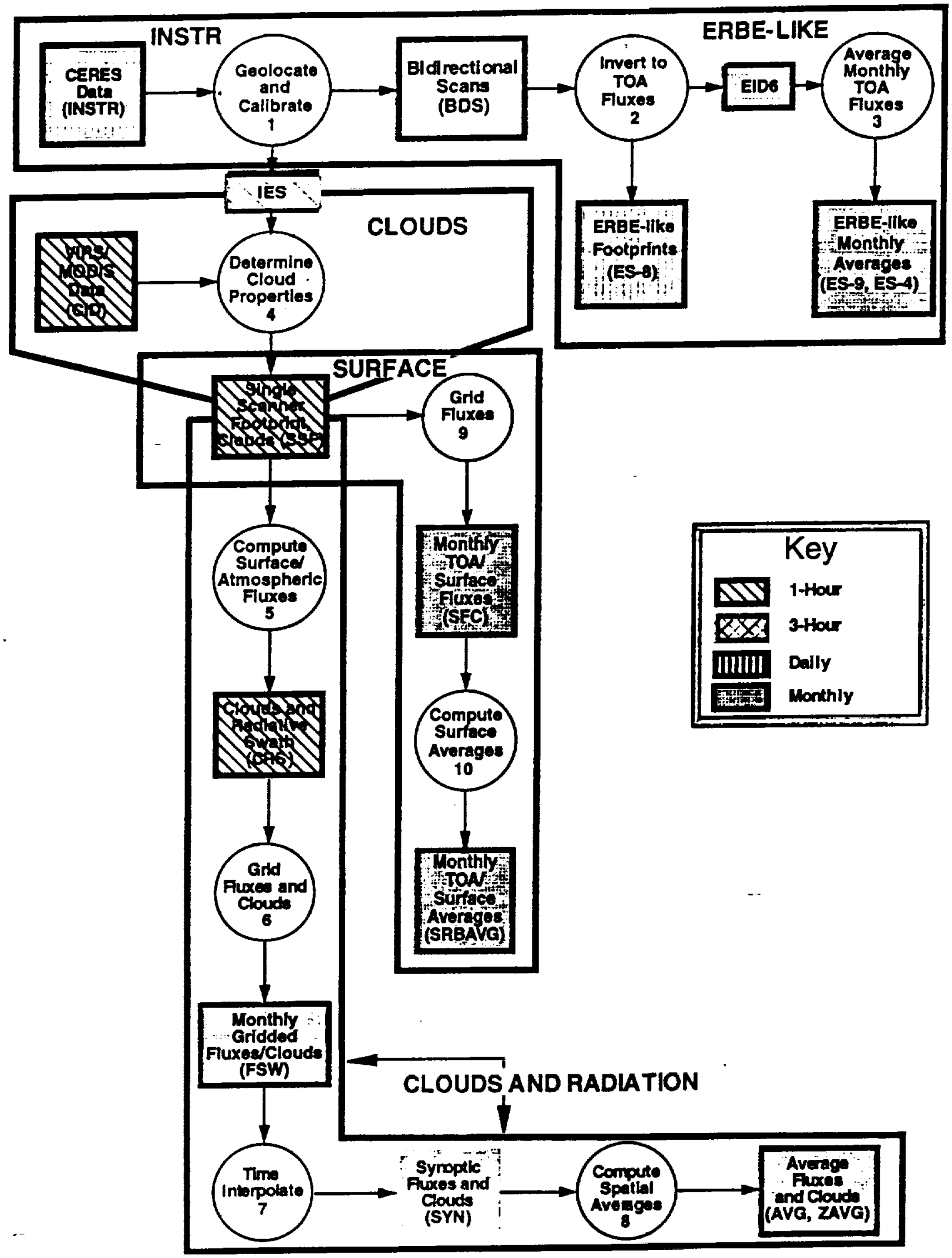

Figure 10. CERES top-level data flow diagram.

CERES/TRMM. Validation of these products for the CERES/TERRA is nearly complete and these products should be available in a matter of months.

One major item remains to be done for the validation of the CERES radiances. The zero radiance counts may vary with scan position and movement due to electronic noise and strains on the thermistor-bolometer detectors (these devices act like strain gauges). Although great care was given in the design and construction of these instruments to minimize these effects, ground tests showed that they exist at the 1 to 2 count level[22]. Also, for the ground tests, only scanning with the scan axis vertical could be done, as any other orientation would introduce zero shifts due to gravity induced stresses. The only way to validate that the zero-radiance value does not change with scan position or motion for the FM1 and FM2 is to have a Calibration Attitude Maneuver by the TERRA spacecraft, in which the spacecraft turns such that the side which usually faces Earth is facing away from the Earth on the night side, so that the instruments can scan deep space as a near-zero radiance source. The TRMM spacecraft performed such a maneuver and the results were very useful to a several of the instruments aboard for determining zero offsets, noise and similar instrument characteristics.

4. SURFACE AND ATMOSPHERIC RADIATION BUDGET

Previous Earth radiation budget experiments have dealt with the radiation components at the top of the atmosphere TOA. Other programs have developed surface radiation data sets[23]. The CERES program will use the CERES measurements together with data from the Visible and InfraRed Spectrometer (VIRS) aboard the TRMM spacecraft and from the Moderate Resolution Imaging Spectrometer (MODIS) aboard the TERRA spacecraft and other ancillary data to compute the surface radiation and also the radiative fluxes through the atmosphere[6]. These additional data products must be validated.

In the vertical stream of fig. 10, VIRS data (on TRMM) and MODIS data (on TERRA and AQUA) are used to compute cloud properties for each CERES footprint (pixel). From these results, surface fluxes are computed using a fast algorithm for only surface fluxes[6], which are spatially gridded and averaged to produce regional-mean fluxes, then temporally averaged to produce monthly-mean regional surface fluxes. Also, the cloud information is used with a more comprehensive radiative transfer code to compute the fluxes at the surface (a second estimate) and at selected levels through the atmosphere, including the top (again, a second estimate), for each footprint consistent with the CERES radiance measurements at TOA[24]. These footprint fluxes are gridded and spatially averaged to produce instantaneous regional-mean fluxes, which are interpolated to synoptic times for use with circulation model results and radiosonde measurements and finally temporal averaged to produce monthly products. The methods used in generating these products are new; thus much validation is required and additional time is needed before their release.

A major goal of the Global Energy and Water Cycle Experiment (GEWEX) is to improve techniques of deriving surface and atmospheric radiation from satellite measurements. Surface measurements of radiation were made in cooperation with the Atmospheric Radiation Measurement (ARM) program of the Department of Energy. Before launch, a pilot project, the CERES-ARM-GEWEX Experiment (CAGEX)[25] was used to distribute on-line records of input data for radiative transfer codes, computed and measured fluxes. These data were useful in validating the methods and radiative transfer code[26, 27] used for computation of surface and atmospheric fluxes. In particular, this project emphasized the need for improvements in standard instruments for surface flux measurements[36]. Directional data were also collected for spectral radiances using a helicopter-borne radiometer[28] for development of surface bidirectional reflectance functions[29]. Measurements of radiation at the surface are collected for validation of CERES from over 30 sites worldwide. The sites include many from the Baseline Surface Radiation Network (BSRN)[30, 31] and sites of the Climate Monitoring and Diagnostic Laboratory of NOAA. AERONET[32] data are used for validation of derived aerosol properties.

In addition to these sites, which are all on land, the Chesapeake Lighthouse, located 25 km off the coast of Virginia, has BSRN instrumentation for making radiometric measurements: upward and downward broadband fluxes and spectral radiances and sun photometers, looking upwards for measuring aerosols and downwards for measuring bidirectional reflectance distribution functions. Also, a NOAA lidar aimed downward will provide a record of wave spectra, so that the effects of waves on spectral reflectance can be determined. This station is unique in providing long-term continuous radiation measurements over water. The site is uniform over a large area and is well-suited for comparisons with CERES measurements for the CERES Oceanic Validation Experiment (COVE). The CERES-ARM Validation Experiment (CAVE) is a data base similar to CAGEX but is an ongoing compilation of data consisting of CERES radiances collocated with surface broadband flux measurements from the earlier described data sources including COVE.

In order to characterize surface solar reflectance across most of solar spectrum (0.4 through 2.5 μ) for a range of surface types (forest, mixed crop, ocean, scrub desert, etc.) within the U.S., a small aircraft (OV-10) is being outfitted with the scanning spectral radiometer[28] and will make flights to make additional measurements from which spectral albedo and bidirectional reflectance distribution functions can be derived. This aircraft will operate in the neighborhood of ground sites, including the Chesapeake Lighthouse, during TERRA and AQUA over-flights. In-situ measurements of cloud microphysical parameters and radiant fluxes by instruments aboard the ER-2 to validate these quantities computed from CERES and MODIS measurements.

Because clouds are the major modulator of Earth radiation, cloud properties must be available as input to the surface and atmospheric flux computation. Cloud properties, both large scale (cloud fraction, height of top) and microphysical (phase, particle size) will be derived from MODIS measurements on TERRA and VIRS on TRMM[33]. In order to validate the cloud properties, field test programs with ground-based radar and lidar and aircraft flights with cloud physics instrumentation are required. During the ARM program in 1998, measurements by lidars, radars and microwave radiometers were used to derive cloud properties which were compared with results from the Visible-Infrared Scanner (VIRS) aboard the TRMM spacecraft[34]. These results were used to upgrade the techniques for retrieving cloud properties from the satellite sensors. Additional field missions and aircraft flights are planned for gathering cloud properties during TERRA overpasses.

5. CONCLUSIONS

On-orbit calibration of the FM1 gains have demonstrated that the FM1 total and shortwave channels have maintained their ties with the ground calibration to 0.3% and the window channel to 0.4%. The FM2 total and shortwave channels are consistent with ground calibration within 0.1% and the window channel to 0.6%. The pixel locations have been shown to be accurate to 1 km for cross-track and along-track components near nadir. Comparisons of the 3 channels by use of deep convective clouds and other terrestrial targets indicate that the 3 channels agree to better than 1%. The major unresolved issue is the verification that the zero-radiance offsets as measured on the ground for restricted azimuth angles are adequate for all azimuth angles.

Data from the Atmospheric Radiation Measurement Program, the Baseline Surface Radiation Network and AERONET provide ground truth for validating algorithms and the derived surface and atmospheric radiation fluxes. Also, the Chesapeake Lighthouse has been equipped with BSRN radiometers and AERONET solar photometers to provide continuing surface radiation and aerosol data over an ocean site.

6. ACKNOWLEDGEMENTS

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