CERES Validation Plan Overview

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1. Introduction

The purpose of the present document is to provide a relatively brief overview of the strategy for validation of the CERES (Clouds and the Earth's Radiative Energy System) cloud and radiative flux data products. Figure 1 shows a data flow diagram of the CERES data products. The circles in this diagram represent analysis algorithms (subsystems), while the boxes represent input or output data products. The CERES Algorithm Theoretical Basis Documents (ATBDs) present the algorithms, and this overview is an introduction to the documents that present the corresponding validation plan for each data product. There is generally one output data product per subsystem or algorithm, so that there is a one to one correspondence between the ATBDs and the validation plan chapters. The ATBDs and Validation Plans for each subsystem can be found at http://asd-www.larc.nasa.gov/ceres/docs.html. Similar to the ATBDs, because of the size of the documentation, it was felt to be useful to provide a shorter overview to allow an interested reader to begin with the big picture, and then focus on a particular data product of interest. Data products can be obtained from the NASA Langley Distributed Active Archive Center (DAAC) using a web-based data ordering tool (http://eosweb.larc.nasa.gov/~latisweb/.).

For each CERES data product, there is a Data Quality Summary document which can be accessed from either the DAAC ordering web page or the CERES home page (http://asd-www.larc.nasa.gov/ceres/new_ASDceres.html). This document summarizes the key validation results to date for each archived and validated data product. It also has links to ongoing validation web sites maintained by the CERES working groups, and to journal and conference papers as they are published. As of August, 2000 for example, Data Quality Summaries are available for the following data products available from the LaRC DAAC:

- *Edition 2 CERES TRMM calibrated/navigated radiances (BDS),*
- *Edition 2 CERES TRMM ERBE-Like ES-8, instantaneous TOA fluxes*
- *Edition 2 CERES TRMM ERBE-Like ES-4 and ES-9 gridded monthly TOA fluxes*
- *Beta versions of Terra CERES BDS, ES-4, ES-8, and ES-9 data*
  (Beta is an early version that is not yet validated or ready for scientific publication but is intended to give the science community rapid access to the early data.

By October 2000 the Edition 1 validated TRMM SSF data product and data quality summary will be available. This data product includes instantaneous cloud physical properties from the VIRS cloud imager matched with each CERES broadband radiance field of view. Edition 1 of Terra ERBE-Like TOA fluxes are also expected in October after its approval at the CERES science team meeting in September, 2000. All data products are reviewed by the CERES science team before release as a validated Edition 1 version. These Data Quality Summaries are short (several pages) and are meant to be the minimum set of information necessary to understand the strengths and weaknesses of the data products. The more complete reports of validation results are typically published in the peer reviewed scientific literature, but take much longer to make available to the science community. The Data Quality Summary was a concept developed and

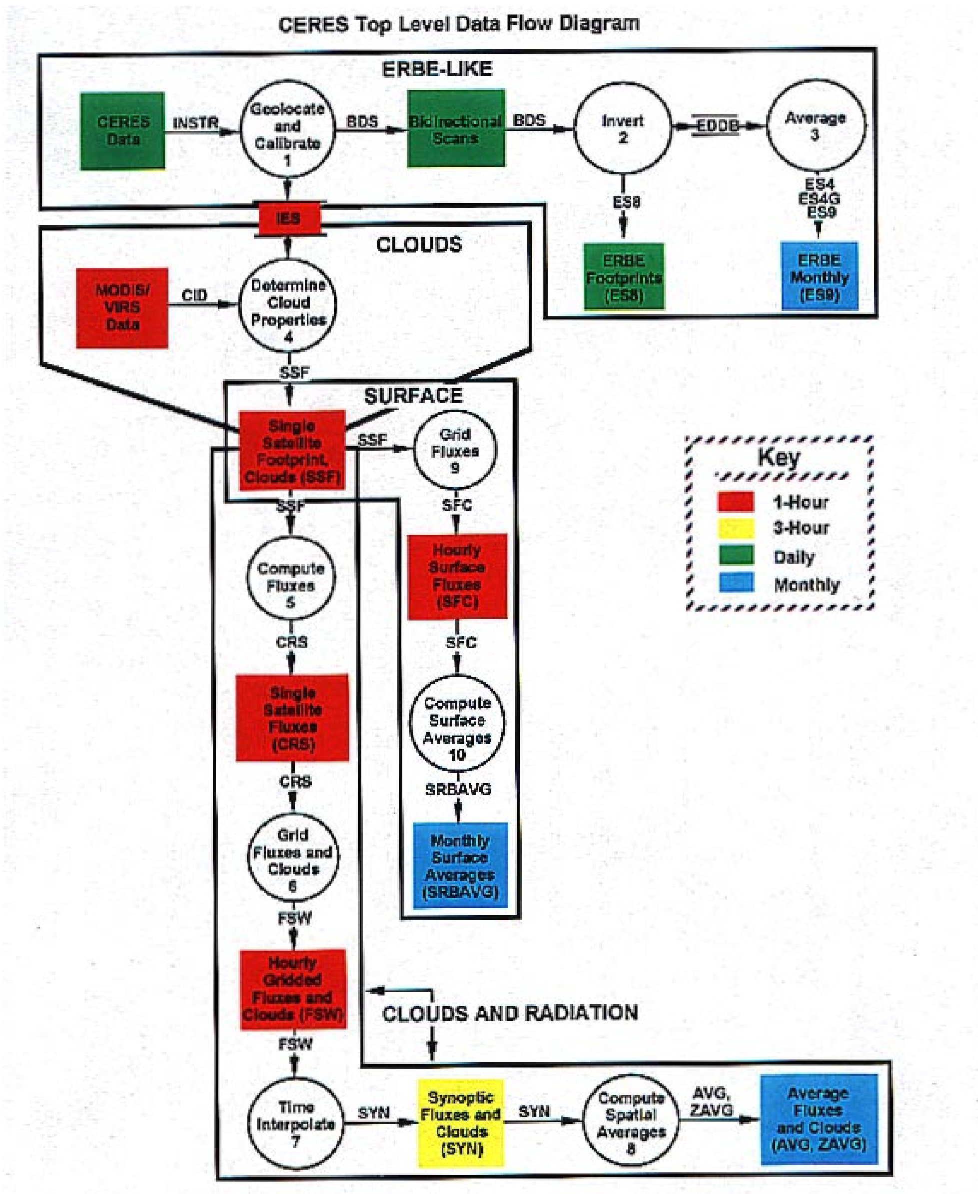


Figure 1. CERES Data Flow Diagram. Boxes represent data products. Circles show the algorithm subsystems that convert input to output data products.

implemented by the CERES team to facilitate more rapid and rigorous scientific use of the data products for climate research.

The present validation plan overview is divided into four sections: Axioms, Strategy, Issues, and Conclusions. An unfortunate aspect of large interdisciplinary science efforts is the plethora of acronyms. In a validation plan such as this they are a necessary shorthand. In order to avoid the cumbersome delay as the typical reader wades through the definition of these acronyms, they have been compiled in a list at the end of this overview. Readers not familiar with these acronyms are advised to print out a copy of the list and keep it close at hand.

There are three journal publications which summarize the overall clouds and radiation science strategy (Wielicki et al., 1995), the CERES experiment (Wielicki et al., 1996), and the CERES analysis algorithms (Wielicki et al., 1998).

2. Axioms

Before launching into a discussion of the actual CERES validation strategy, it is useful to provide a context and vision for the validation effort. This is done in the present section as an informal discussion of a set of axioms which describe the overall validation problem for cloud properties and radiative fluxes remotely sensed from space. This section summarizes the philosophy of CERES validation.

2.1 *In the beginning there is radiometric calibration.*

Since remote sensing of the environment from space typically begins with a measurement of photons impinging on detectors, the question of absolute calibration is essential to all products derived using the instrument's estimated radiance values. For climate measurements, changes of only a few percent in geophysical parameters are of critical interest. In this sense, absolute radiometric calibration (including stability over time) become the Holy Grail of remote sensing. The strength of most conclusions rests on the ability to perform that calibration. At the same time, obtaining absolute accuracy in radiometric calibration of better than 2-5% is extremely difficult, especially for solar spectral wavelengths. Several redundant strategies are needed to assure confidence in absolute radiometric calibration, or design a remote sensing algorithm that only relies on relative calibration and stability. Most of the CERES cloud and radiative flux products require well understood absolute calibration, especially the radiative fluxes, cloud optical depth, and cloud height/temperature.

2.2 *Radiation budget is an 8-dimensional sampling problem.*

At the same time we desire radiative fluxes accurate for time averaged data to 1% or better, solar and thermal infrared radiative fields vary by an order of magnitude as a function of 8 different dimensions:

- *wavelength*
- *latitude*
- *longitude*
- *altitude*
- *time*
- *solar zenith angle*
- *viewing zenith angle*
- *viewing azimuth angle*

In principle, after solving the calibration problem, we only have to accurately sample all 8 of these dimensional spaces to solve the radiation measurement problem. Rather than blackening the sky with instruments and satellites, the CERES approach to solving these sampling problems includes:

	Dimension	Sampling Solution
-	wavelength	*Broadband detector instrument*
-	latitude	*20 km fov, crosstrack scanning instrument*
-	longtitude	*20 km fov, crosstrack scanning instrument*
-	altitude	*Cloud properties using simultaneous imager and 4-D assimilation for T(z), q(z)*
-	time	*Diurnal sampling orbits: morning, afternoon, precessing plus geostationary 3-hourly data when 3 satellites not available*
-	solar zenith angle	*Rotating Azimuth Plane scanner plus imager (i.e. new CERES angular dependence models)*
-	viewing zenith angle	*Rotating Azimuth Plane scanner plus imager*
-	viewing azimuth angle	*Rotating Azimuth Plane scanner plus imager*

While most researchers are familiar with the first 5 of these dimensions, the last three dimensions (solar and viewing angle) are especially critical to determination of accurate radiative fluxes. In essence, each satellite radiance measurement taken from a particular view angle must be converted to an estimate of the radiative energy reflected or emitted over all angles of the hemisphere. In order to achieve the next advance in this sampling, a CERES rotating azimuth plane (RAP) scanner (Fig. 2) is flown once in each orbit (i.e. EOS-AM/PM/TRMM). The reason for this is that the orbit determines the solar zenith angles sampled at each latitude or climate region. The CERES RAP scanner data are then combined instantaneously with space and time matched imager cloud and surface properties to provide a measure of the anisotropy of the radiation field as a function of surface and cloud condition (e.g. cloud optical depth) over a large ensemble of cases (Wielicki et al., 1998; Loeb et al., 1999b). Finally, the data are reprocessed using the imager data to classify each CERES broadband crosstrack scanner measurement to select the proper anisotropic correction for conversion of the radiance measurement into a flux estimate (Wielicki et al., 1998). A discussion of the relative expected error for each of these dimensions can be found in Wielicki et al., 1995 for radiative fluxes at the top of the atmosphere. In principle, such an analysis is needed in the long term for any geophysical variable estimated using remote sensing satellite data. For example, the MISR and POLDER science teams are developing improved narrowband spectral surface ADMs for use in studies of land surfaces and vegetation.

Not all variables are sensitive to all 8 sampling dimensions. Nevertheless, throughout the CERES validation plan, or any other EOS validation plan, there will be frequent references concerned with how to deal with sampling difficulties in one or more of these dimensions. The five dimensions most critical for CERES measurements are usually the angle sampling, time sampling, and altitude.

Figure 2. CERES Crosstrack and Rotating Azimuth Plane (RAP) Scan Patterns simulated for the Terra spacecraft orbit passing over South America. RAP views entire hemisphere of radiation (but with spatial gaps), crosstrack provides continous spatial coverage with limited view angles.

2.3 *Cloud and radiation budget errors are strong functions of the time and space scale of the data product.*

This is true of any geophysical quantity remotely sensed from space. In general, but not always, errors are largest at the smallest time and space scales, and the errors decrease with averaging interval. An example of the errors for TOA fluxes at a range of space and time scales can be found in Wielicki et al., 1995, including both the ERBE error estimates and the expected CERES improvements.

2.4 *Validation of satellite remotely sensed data against surface, aircraft, or balloon in-situ data is greatly complicated by the 8-dimensional sampling problem.*

The problem is that the space and time scales of the in-situ data and the satellite data are rarely directly comparable. An excellent example of this problem is the comparison of satellite volume rainfall rate estimates against surface based rain gauges (Morrissey and Wang, 1995). Typically, there is insufficient in-situ measurements to cover a satellite field of view, whether the field of view is 250 meters (MODIS), or 20 km (CERES). In this case, even a perfect remote sensing measurement will be expected to differ from an in-situ verification measurement because of the inability to match the observations in time or space. For CERES, a common example will be comparing a surface flux radiometer to a satellite based estimate for a CERES field of view.

The matching error can be reduced (but not eliminated) by increasing the number of surface observations within a field of view (level 2 data) or grid box (level 3 data). This error can also be minimized by using very large ensembles of matched data.

2.5 *Validation is in essence an error analysis. But putting confidence bounds on error estimates is complicated by the difficulty of specifying the true degrees of freedom in the validation data.*

Atmospheric fields of temperature, cloud height, TOA radiative fluxes, and other variables are not white noise, nor are they necessarily Gaussian distributed. In general atmospheric time series or spatial series produce “red” spectra: large space and time scales have more spectral energy than small space and time scales (e.g. Leith, 1973). This complicates comparisons with in-situ measurements which are invariably taken at small space and time scales, while a satellite overpass is a few second snapshot of a large area. Leith 1973 proposed using the 1/e point of the auto-correlation function as a reasonable measure of the time or space scale representative of independent samples. For surface observer cloud fraction (roughly a 30 km field of view), this independence scale is estimated as 350 km (Jones, 1992). The auto-correlation 1/e scale for surface measured rainfall rate is roughly 200 km (Morrissey and Wang, 1995). Further work is needed in this area, but we can draw some basic conclusions from the relatively large independence scale.

i) Validation against a single case study (satellite overpass of an in-situ measurement) can serve to invalidate an approach, but it cannot put any confidence bounds on the rejection, nor can it put any confidence bounds on acceptance of a remote sensing measurement if the in-situ and satellite estimates happen to agree.

ii) For cloud advecting over an ARM (Atmospheric Radiation Measurement) surface site at 10 m/sec, it takes 9.7 hours for 300 km of atmosphere to advect by the site and present an “independent” test of cloud fraction at the site. Obtaining the large number of samples required for validation of a complete range of climate regions /atmospheric states will require long time series of surface site data matched each day with satellite-based estimates. The ARM sites, BSRN (Baseline Surface Radiation Network) surface sites, and other long-term sites are considered the best strategy for CERES validation of cloud and radiation data.

iii) Field campaigns are best for process studies and hypothesis formation. They provide the most complete case study data, but provide very limited statistical significance.

2.6 *Climate studies will require validation of both the bias and random error components. Validation in some cases will also be required for higher order statistical moments. (e.g. Chambers et al., 1996 for distributions of cloud optical depth)*

Study of climate variations typically requires accuracy of a few percent or better. Such accuracy is rarely achieved instantaneously for any satellite remotely sensed data. Instead, a large ensemble of observations is required. While the instantaneous error in a single field of view is important to know, the bias of a large ensemble of observations is even more important. Especially critical is the behavior of this bias as a function of variation in related geophysical parameters. For example: studies of the role of clouds in climate will be interested in the dependence of cloud albedo on cloud liquid water path or ice water path. This is one of the fundamental partial derivatives that will affect cloud feedbacks in the climate system. If the bias error in CERES derived shortwave albedo is a function of cloud IWP, then spurious results will be obtained for studies of cloud feedback mechanisms in the climate system, or for validation of cloud physical models. This fact indicates that validation efforts will be forced to use very large ensembles of data to eliminate such concerns.

2.7 *Knowledge of the accuracy of the satellite remote sensed radiative fluxes and cloud properties will improve as longer time series of validation data become available: the limit will be the degrees of freedom in the validation data, and the accuracy of the validation data.*

There will be no magic moment that we can declare the CERES data product "validated". Instead, we will be able to declare confidence bounds on the validation of each CERES data product. These confidence bounds will narrow with time as greater numbers of independent samples are used in validation from the surface sites such as ARM and BSRN. The confidence bounds will also narrow as the validation data itself is better understood and quantified. This is particularly true for cloud physical and optical properties derived using lidar, radar, and radiometer data at the DOE ARM surface sites in Oklahoma, the Western Tropical Pacific Ocean, and the North Slope of Alaska. These ground-based validation data are themselves now being tested using field experiment in-situ aircraft data, as well as testing the consistency of independent measurement approaches for the same cloud property. Initial ARM cloud data is primarily for single layered cloud systems, but work is undeway to extend this to multi-layered and mixed phase clouds. Different science studies will require different levels of accuracy to be useful. The studies with the highest accuracy requirements will be required to wait until a substantial time record of validation data has been analyzed, or until improved validation data becomes available. Nevertheless, CERES has a nominal validation schedule for attaining accuracies deemed useful by a broad range of science community users. The data products are phased in order of accuracy and time in order to provide the science community with data as soon as possible.

2.8 *Since clouds are the major modulator of the radiation fields at most wavelengths used by the EOS instruments, all of the instruments provide at least some information on cloud properties.*
Intercomparison of different remote sensing approaches (both alternative algorithms and measurements) for remote sensing of cloud and radiation will be a critical part of discovering both coding and logical errors in EOS algorithms. Observations beyond EOS, such as ISCCP are also needed to verify time sampling errors.

Good examples of other spaceborne instruments that will help CERES validate its algorithms and final data include ASTER, MISR, AMSR, AIRS, and POLDER. POLDER data is being used to verify CERES strategies to develop angular models (Loeb, 1999), ASTER data will be used to verify the dependence of imager derived cloud properties on field of view size, AIRS will provide more complete spectral cloud emissivity in the thermal infrared, and MISR will provide very high spatial resolution multi-angle data to verify angular model strategies using coarser spatial resolution CERES RAP data. Each of these instruments takes a different slice of the rather daunting 8-dimensional space we referred to in section 2.2. Since clouds often exhibit strong systematic diurnal cycles, time sampling error analyses will use ISCCP geostationary radiance and cloud data sets to verify errors in monthly mean data products.

The most critical satellite component for CERES validation, however, will come from the recently selected PICASSO and Cloudsat missions which will fly cloud lidar and cloud radar in formation with the EOS Aqua mission. The Aqua platform will include CERES, MODIS, AIRS/AMSU/MHB, and AMSR. The French POLDER-2 multi-angle instrument is also planned to fly in this formation. The cloud lidar and radar will provide the first multi-layer cloud data and will be the ideal cloud fraction/cloud altitude validation source for passive remotely sensed cloud properties.

2.9 *The challenges involved in validating each of the CERES cloud and radiation data products are often quite different.*

This is one of the motivations for having validation plans for each data product. These diverse challenges are also discussed further in section 4 of this overview entitled “issues”. In particular, the strategies for validation of CERES radiance calibration, TOA radiative fluxes, surface radiative fluxes, cloud properties, and atmospheric radiative fluxes are all very different.

2.10 *Field Campaigns alone will never get sufficient statistical sampling for global validation. They do, however, provide unique physical process tests and discover new problems because of their unusually complete data sets. They will also provide the bulk of the in-situ cloud microphysical validation of surface remote sensing of clouds, such as for tropical clouds from FACE in 2002 and CRYSTAL in 2003.*

The sampling problems mentioned earlier indicate that any given field experiment conducted over several weeks to a month will obtain at best some 5 to 20 of degrees of freedom for cloud systems. On the other hand, these same experiments often contain the most complete data sets from surface to above the atmosphere. They can provide definitive cases to demonstrate inconsistencies in current approaches, and they can suggest new hypothesis for improvements. But they cannot obtain sufficient statistical significance to generate confidence in the new hypotheses: that must come from larger sample data.

An example of CERES field campaign validation efforts is the measurement of spectral albedo and spectral angular dependence across the complete solar spectrum for a wide range of IGBP surface types. This validation effort is dictated by the need to understand broadband solar radiation at the surface of the earth, and by the limited availability of spectral albedo or angular dependence measurements beyond 1 μm wavelength for surfaces representative of the broad

IGBP surface classes. Efforts in this area began with helicopter flights over eastern Virginia forest and the ARM Oklahoma site, and will continue by advancing to a low flying aircraft fitted with solar and infrared spectrometers which can obtain both hemispheric and angular measurements near the surface. These spectral and angular solar reflectance measurements will be statistically sampled similar to the CERES RAP scan mode from space. Statistical ensembles sorted by IGBP surface class and at key surface sites such as the DOE Oklahoma site and the Fort Peck SURFRAD site will be taken as a consistency check of CERES surface solar flux algorithms. These measurements should also be useful to other EOS teams such as MISR and MODIS studying the spectral anisotropy of land surfaces.

As is noted in the next section, however, a critical application of field experiments is obtaining in-situ cloud microphysical data. A good example is recent collection of such data in the SHEBA/FIRE arctic campaign over the arctic ocean and over the Pt. Barrow ARM site. The next major opportunity will be the FACE and CRYSTAL tropical cloud experiments in 2002/3 planned for Florida and for the warm pool region of the western Pacific near the ARM sites. The collection of this in-situ data is very expensive, and requires coordination of both NASA and DOE efforts. CERES unfortunately has no planned funding to support such efforts, so efforts by existing and future NASA EOS Validation NRAs and the DOE ARM program are critically needed.

Finally, there are some parameters such as cloud ice water path (IWP) which are exceedingly difficult to measure, yet are critically needed by cloud modelers. Currently, we only have passive microwave measurements from surface, aircraft, and space to estimate cloud liquid water path (LWP). New instruments using the far-infrared/sub-mm wave regions have been developed for IWP and column average particle size. These technologies need further testing in ice cloud experiments such as FACE and CRYSTAL. These will add a further independent constraint on the validation of ARM lidar/radar/radiometer vertical profiles of cloud microphysics.

2.11 *A better sampling option for validation is long term surface sites (multiple years) at a minimum of about 7 sites to cover major climatological regimes (measuring clouds, radiation, aerosols, atmosphere) and a minimum of 30 sites (measuring surface radiation and aerosols) to cover varying anthropogenic aerosol emissions.*

The ARM sites (W. Pacific tropical ocean, Oklahoma midlatitude land, Pt. Barrow Alaska polar land) will provide three of these climate regions. Missing climate regions include midlatitude and high latitude open ocean, subtropical ocean, desert, and tropical land. Each of these regions is characterized by greatly differing atmospheric states, especially in the boundary layer. The difficulty for aerosol/radiation sites is finding sites where both aerosol and radiation measurements are taken at the same site. Note that obtaining long-term accurate validation data for these surface sites is not simply a matter of buying an instrument and cleaning it once a week. Calibration, validation and analysis efforts for “climate quality” surface data are substantial. The Department of Energy ARM sites, the Baseline Surface Radiation Network (BSRN), and SURFRAD are all making the effort to provide such long-term accurate surface-based data. In the longer term, other climate regions must also be addressed. Because of the expense of adding ARM sites, CERES will augment existing capabilities to improve measurements in these missing climate regimes. Examples are the addition of micropulse cloud/aerosol lidars at BSRN sites at Bermuda (midlatitude ocean), Saudi Arabia (desert), and a tropical land site, probably in northern Australia, Brazil, or Africa. Fortunately, there is a new NASA and international effort to set up a network of micropulse lidars patterned after the successful AERONET effort. CERES is providing 3 micropulse lidars previously purchased to this lidar network: the first of these will be put in at the Solar Village BSRN site in Saudi Arabia (J. Spihnirne, Aug 2000 personal communication). Second, because even Bermuda is an island, CERES will run a BSRN level surface radiation site on the existing Coast Guard "Chesapeake Light" lighthouse platform 25 km off the coast of Virginia. This site will be used for tests of algorithms against a more uniform ocean background. In the long run, a mobile ARM site should be a serious consideration in the future to obtain at least 1-2 years of data in each of the other mentioned climate regimes. The ideal scenario would be permanent installation of ARM-like cloud/radiation instrumentation on the NOAA Ron Brown for global ocean measurements. ARM is working on a mobile site, but completion is not expected until 2002 (T. Ackerman, personal communication, July, 2000).

2.12 *For some cloud properties, the best sampling will come from new active and passive remote sensing technologies as part of the future ESSP and other international programs. Examples are improved measurements of cloud cover, cloud layer heights, and cloud layer overlap using PICASSO cloud lidar and Cloudsat cloud radar, as well as improved measurements of ice cloud properties. These measurements will often be taken at nadir only, but will provide an entirely new level of global validation data.*

Fortunately, the NASA ESSP program has recently selected the PICASSO-CENA and Cloudsat missions. PICASSO will fly a cloud and aerosol profiling lidar, infrared camera, and visible camera on a spacecraft flying in formation with the EOS Aqua platform. The Cloudsat mission will add a cloud profiling radar. Cloudsat and PICASSO will fly in formation viewing the same cloud within less than a minute, while both satellites will fly within <+/- 6 minutes of Aqua at all times during its nominal 3 year mission lifetime. The mission will drift across the Aqua spacecraft crosstrack scanning swath of MODIS/CERES/AIRS/AMSR so that observations will be available to validate cloud, aerosol, and radiation measurements for a full range of viewing conditions appropriate to the Aqua and Terra missions. Based on an earlier space shuttle lidar experiment named LITE, the PICASSO-CENA lidar is expected to penetrate at least to the top of the boundary layer cloud 80% of the time. The cloud radar will detect almost all of the additional thicker cloud layers. Thin cirrus missed by the radar will be detected by the lidar. This combination will greatly advance the validation of CERES cloud and radiation data, as well as provide in combination with CERES the best constraint available on the entire vertical profile of radiative fluxes from the surface to the top of the atmosphere. The active instruments are especially critical for improvement of the accuracy of downward longwave fluxes at the surface, and for polar clouds which have poor contrast with the background snow and ice surface in passive radiometer data. Aqua is currently planned for launch in May, 2000 with a 5 to 6 year lifetime on orbit. PICASSO and Cloudsat are planned for launch in March, 2003 with a 2 to 3 year lifetime on orbit.

At this point, we switch from a discussion of axioms to an overview of the specific CERES strategies for validation of the radiative flux and cloud products shown in Figure 1. All of the concepts raised in the section on axioms help to shape the overall CERES validation strategy. This plan is based not only on CERES investigations to date, but also on extensive experience gained by the CERES investigators as part of the ERBE, FIRE, and ARM programs.

3. Strategy

3.1 Validation Data Sources and Applicable Validation Techniques

The data products shown in Figure 1 require the validation of 5 basic types of measurements.

-	Instrument broadband radiances	(SW, LW, 8-12μmWindow)
-	Top of atmosphere radiative fluxes	(SW, LW)
-	Surface radiative fluxes	(SW, LW, up, down, net)
-	Radiative fluxes within the atmosphere	(SW, LW, up, down, net)
-	Cloud properties	(amount, height, temperature, optical depth, emissivity, particle phase and size)

The last four of these five measurements occur in data products with time and space scales that include:

- CERES instantaneous field of view (20 km at nadir for Aqua/Terra, 10 km for TRMM)
- Instantaneous satellite swath 1 degree latitude/longitude spatial grid
- Synoptic 3-hourly 1 degree grid
- Monthly average 1 degree grid
- Zonal and Global average

In turn, there are seven major techniques or "tools" that will be employed as part of the validation process:

	Technique	**Example**
i)	On board calibration	(ground and in-orbit)
ii)	Theoretical sensitivity	(radiative transfer theory simulations)
iii)	Pre-launch satellite surrogate data	(ERBE/AHVRR/HIRS on NOAA-9)
iv)	Internal consistency checks	(viewing zenith angle dependence)
v)	Surface site data	
	a. Current surface sites	(ARM, BSRN, SURFRAD, AERONET)
	b. EOS-enhanced sites	(Chesapeake Light, Micropulse Lidar Network)
vi)	Field campaigns	(FIRE, SHEBA, ARESE, GCIP, CRYSTAL)

vii) Other satellite data (POLDER,ASTER, MISR, GLAS, PICASSO, Cloudsat, ScaRaB, ERBS non-scanner)

The usefulness of these seven validation tools varies greatly with data product. Surface site data is of primary importance for validation of surface radiative fluxes, but of little use for TOA Fluxes. For high spatial resolution imagers such as Landsat and ASTER, surface site data is useful in validating the radiance calibration. For CERES 20 km fields of view, however, and for calibration at the 1 to 2 % level, the surface data has little or no utility.

Table 1 summarizes the utility of each of the 7 different validation strategies to the 5 types of CERES data for instantaneous CERES fields of view as found in the IES, SSF, and CRS data products.

Table 1 **Data Product / Validation Strategy Matrix**
(1 = critical, 2 = important, 3 = useful)

Validation Technique	Radiance	TOA Flux	SFC Flux	Atmosphere Flux	Cloud Prop.
Onboard calibration	1	1	1	1	1
Theoretical sensitivity studies	2	3	3	2	2
Pre-launch satellite data surrogate	3	2	2	3	2
Internal consistency check	2	1	3	2	2
Surface Sites					
- ARM,BSRN,SURFRAD			1	1	1
- EOS enhanced sites			1	1	1
Other EOS-ERA satellite data	3	2	1	1	1
Field campaigns			2	2	2

For the synoptic and time averaged CERES data products, other satellite data become critical in evaluating the time sampling errors (e.g. current geostationary satellite data such as GOES-8 and future data such as the Geostationary Earth Radiation Budget (GERB) experiment planned for flight on Meteosat Second Generation in 2002).

In the following sections, brief examples of the validation approaches are given for each of the 5 major data types. These are meant to illustrate the overall approach and to include key references to the appropriate literature. The reader interested in further detail is directed the specific validation plans for each individual CERES data product (http://asd-www.larc.nasa.gov/valid/valid.html). Note that TOA fluxes appear in two data products: ERBE-Like fluxes in ES-8, and the improved CERES TOA fluxes in SSF. Surface radiative fluxes also appear in two distinct data products: SFC for flux estimates with minimal dependence on radiative modeling, and CRS (pixel level) and FSW(1 degree gridded) for surface flux estimates which use a strong modeling component as part of the estimation. Further information on the distinction of these data products can be found in the CERES ATBD Overview document (http://asd-www/larc/nasa/gov/ATBD/ATBD.html). There is also a CERES Data Product Catalog (http://asd-www.larc.nasa.gov/DPC/DPC.html).

3.2 *Broadband Radiance Calibration*

There are four fundamental CERES broadband radiances to calibrate:

- SW radiance: solar reflected (~ 0.3 - 5μm),
- TOT radiance: solar and thermal infrared earth emitted (~ 0.3 - > 100μm)
- LW radiance: thermal infrared earth emitted (~5 - > 100μm)
- Window radiance: (8 – 12 μm)

The CERES instrument measures SW, TOT, and Window directly, and infers LW as the difference between TOT and SW during daylight observations and directly from the TOT channel at night (Lee et al., 1996). The key to robust calibration is independent redundant calibration checks, especially for the reflected solar component, which is the most difficult to calibrate. Calibration traceability begins pre-launch in a specially designed calibration vacuum chamber (Figure 2), and is completed using four in-orbit calibration systems: on-board variable temperature blackbodies to verify gain of the TOTAL and Window channels, multiple-level tungsten lamps to monitor stability of the SW channel, a solar diffuser mirror (Mirror Attenuator Mosaic or MAM) to monitor SW channel stability using the sun, and deep space scans to verify the instrument scan position dependent offsets. The onboard calibration sources are used to monitor the stability of the instrument gains while in orbit, not to determine the absolute calibration.

Key elements of the complete calibration and instrument characterization include a) instrument theory, b) ground calibration, c) on board calibration stability, d) in-orbit offset determination using deep space scans, e) internal consistency checks of the data, especially the consistency of the Window, SW, and Total measurements. Validation results for the TRMM CERES instrument can be found in Priestley et al., 2000.

3.2.1 *Instrument Theory*

- Complete instrument thermal, optical, and electrical models were developed for the CERES instrument, including a detailed finite element model of the complete detector/telescope system. These models are used to predict and verify instrument performance both pre- and post-launch. Part of the theoretical understanding of the instrument includes measurement of the spectral reflectance, transmittance, and absorptance of all detector, optics telescope and calibration materials, as well as measurement of detector time response (Priestley et al., 1997; Haeffelin et. al., 1997; Lee et al., 1998). Key improvements demonstrated over the ERBE measurements include:
- flatter spectral response of the CERES scan mirrors which eliminate the spectral response dip from the aluminum mirrors used in ERBE and ScaRaB (Lee et al., 1998),
- factor of two smaller angular field of view than ERBE,
- improved characterization of instrument spectral response from 0.3μm to 100 μm (Lee et al., 1998).

3.2.2 *Ground Calibration*

The TRW vacuum chamber calibration facility (Fig.3) simulates the complete range of in-space observations from space look through earth views. Because the absorption properties of atmospheric gases vary greatly with wavelength at atmospheric pressures, it is considered critical to calibrate the CERES broadband radiometer in vacuum conditions. The vacuum chamber is designed to characterize a) instrument channel gain, b) elevation dependent zero-radiance offsets, c) point response function, d) response to sources outside the sensor field of view. Platinum resistance thermistors traceable to the International Temperature Scale of 1990 (ITS-1990) are used to tie the Narrow and Wide Field of View Blackbodies to ITS-1990 thermistors, with a NFOV blackbody calculated emittance of .999952 (Jarecke et al., 1993). A cryogenically cooled cold space reference, and constant radiance reference is used in the vacuum chamber for

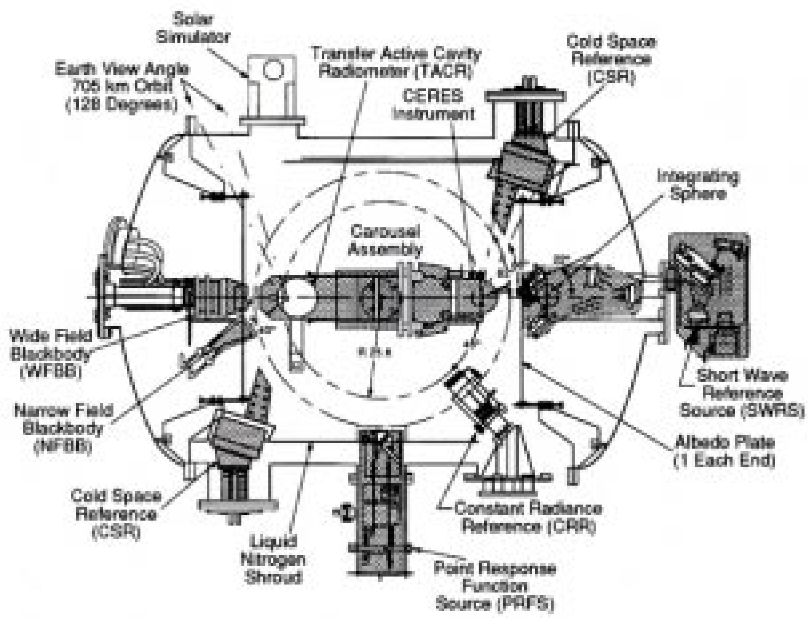


Figure 3. CERES Ground Vacuum Calibration Chamber.

verification of instrument scan dependent offsets. In addition to the CERES instrument, the vacuum chamber also contains a cryogenically cooled (4K) Transfer Active Cavity Radiometer (TACR): used to transfer calibration from the NFOV blackbody (infrared) to the integrating sphere (solar). This solar integrating sphere is calibrated using the TACR in 17 spectral intervals from less than 0.3 to greater than 3.5 μm. The CERES SW channel is then calibrated against the integrating sphere. In this way, the TACR is used to transfer the fundamental blackbody calibration to a shortwave energy calibration. The key to success is the existence of a spectrally flat absorbing thermal cavity radiometer, which is provided by the TACR. Finally, the CERES instrument field of view (point spread function) is verified by scanning across a slit source in the calibration chamber. The CERES ground calibration results are given for the TRMM and EOS-AM CERES instruments in Lee et al., 1998. Estimated absolute accuracy of the ground calibration is better than 0.5% for the TOTAL channel and better than 1% for the SW and Window channels.

3.2.3 *In-Orbit Calibration Stability*

Variable temperature (ambient to 320K) on-board blackbodies with platinum resistance thermometers are used to monitor stability of the longwave window channel and the longwave part of the total-wave channel. Experience with TRMM and Terra in-orbit data has shown agreement with ground determined gains for SW and LW channels to better than 0.5% (Lee et al., 1998). Even more importantly, the TRMM TOT channel gain has shown no statistically significant gain change in 18 months of in orbit calibrations with a 95% confidence level of < 0.15%. For longwave flux at the top of the atmosphere, this is equivalent to roughly a stability of better than 0.3 W/m^2. The Window channel has shown no statistically significant change in gain with a 95% confidence level of < 0.2%. For the window channel flux at the top of the atmosphere, this is equivalent to a stability of less than 0.15 Wm^{-2}.

Stability of the SW channel gain and the SW part of the TOTAL channel gain is determined using two independent methods:

i. A SWICS (Shortwave Internal Calibration Source) tungsten lamp capable of operation at four intensity levels from 0 to 400 W m^{-2} sr^{-1} for monitoring the gain of the shortwave channel and shortwave part of the total-wave channel. This lamp calibration indicates a 1% change over the 18 months of CERES TRMM data. This 1% change, however, is not larger than the expected uncertainty in the stability of the tungsten lamp source itself.

ii. A Mirror Attenuator Mosaic (MAM). The MAM is a solar diffuser plate which allows stability checks using the solar disk as a source for the shortwave and total-wave channels. The MAM eliminates the uncertainty of lamp output. Since it is a reflective surface, it also eliminates the uncertainty of degradation in space of transmissive diffusers. Bi-weekly solar calibrations of the SW channel using the MAM has shown no change in SW channel gain over the first 10 months to a 95% confidence level of < 0.2%. This equates to a stability in SW flux at the top of the atmosphere of better than 0.2 Wm^{-2}. While the lamp and MAM results differ by 1%, the MAM is considered to be a much more accurate measure of calibration stability.

Stability of the broadband channels on both Terra CERES instruments show performance similar to the TRMM instrument and is shown in Fig. 4 over the first 6 months of data. Agreement of in-orbit and ground calibration was also within 0.5% for all channels.

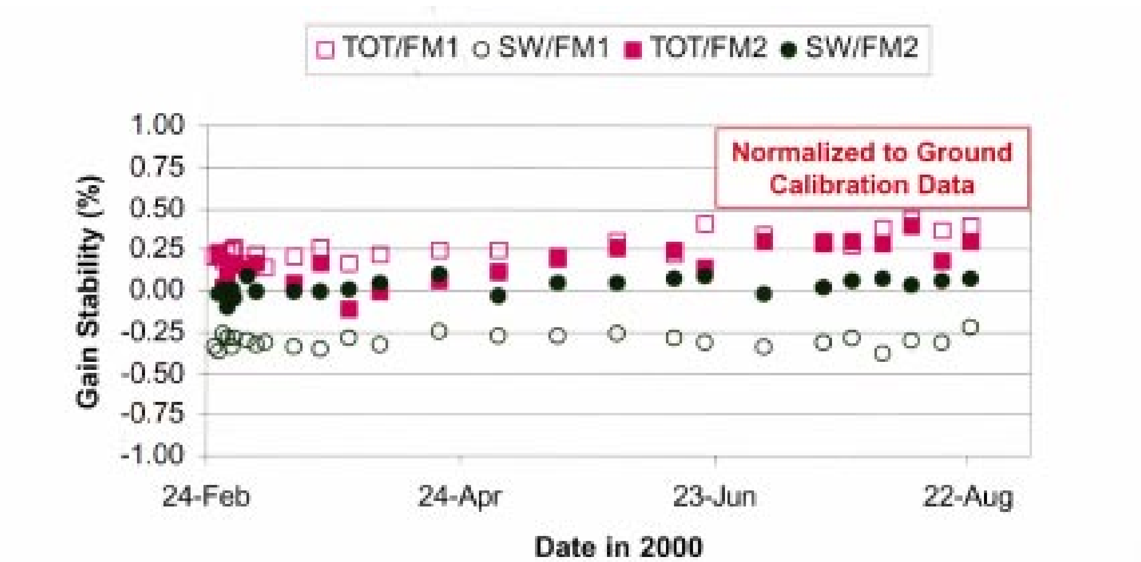


Figure 4. The in-orbit Terra CERES gain determinations using the on-board calibration sources over the first 6-months. Gains are relative to the ground determined values pre-launch and show consistency to better than 0.5% for the Total and SW broadband channels on both instruments. No statistically significant gain changes over the first six months on orbit. Calibration stability will be monitored approximately every 2 weeks on orbit.

3.2.4 *Navigation Accuracy*

Navigation of the CERES instrument on TRMM has been checked using scans across coastlines for both the CERES and VIRS cloud imager. Navigation accuracy using this coastline check shows a 1 σ uncertainty in the location for both CERES and VIRS fields of view of 1 km or better. Coastline checks of navigation for both CERES instruments on Terra show a similar accuracy.

3.2.5 *Scan Position Dependent Instrument Offsets (Zero-Level)*

One of the major challenges for the ERBE instrument was a problem with electronic noise induced instrument offsets (zero radiance level) which depended on elevation and azimuth scan position of the instrument. The CERES electronics design has reduced this variation in offset by an order of magnitude so that the CERES scan dependent offsets for TRMM and Terra instruments are typically 1 digital count or less (equivalent to ~ 0.6 Wm^{-2} in TOA flux) but can occasionally reach levels of 2 counts. Because these offsets cannot be predicted in principle from the instrument theoretical model, they must be measured first during ground calibration and then verified after launch by scans of deep space. These deep space scans were performed for the CERES TRMM instrument near the beginning of the TRMM mission in January, 1998. The scans are performed for each of the CERES operational scanning modes (crosstrack, rotating azimuth plane, short scan) and are of sufficient length to average instrument noise at each scan position to determine a scan dependent offset to an accuracy of 0.1 to 0.2 digital counts (roughly 0.1 Wm^{-2} in TOA flux). The reason that these checks must be performed in orbit is that the instrument experiences shipping, mounting on the spacecraft, spacecraft level environmental testing, and finally launch. In addition, for the CERES Terra instruments launched in December, 1999, the offsets were measured in late 1996. Since this time period the CERES Terra FM-2 instrument has had rework performed for the 'watch dog timer reset' anomaly and both Terra CERES instruments have had their voltage converters changed to avoid any repeat of the voltage converter anomaly on the TRMM CERES instrument. The TRMM CERES voltage converter anomaly limited TRMM CERES data collection to January through Aug 1998, some short periods of time in support of field experiments and intercalibration with ScaRaB-2, and operation throughout March/April 2000 to obtain overlapping observations with the CERES instruments on Terra. The TRMM CERES instrument offsets determined using the deep space scans agreed with the ground determined offsets to within 0.5 to 0.75 digital counts, or a correction of less than 0.4 Wm^{-2}. However, since the desired knowledge of the offsets is to 0.25 Wm^{-2}, these changes to the Total channel offsets are considered significant for climate time series measurements, especially when comparing data between two CERES instruments. Note that only the CERES Total channel offsets varied significantly between ground and space: the window and shortwave channel offsets varied by less than 0.2 counts. We plan to perform deep space scans at the beginning of both the Terra and Aqua missions. We also plan to check the stability of these offsets in orbit after a few years. If experience with these 5 instruments confirms that the offsets are stable in space (as expected) and in general agree to within less than 0.4 counts with ground determined values, then these deep space scans can be eliminated with future flights of the CERES instrument design, such as for the NPOESS system planned for launch in 2009.

3.2.6 *Intercalibration of CERES instruments on TRMM, Terra, and Aqua spacecraft, as well as with ScaRaB on the Resurs spacecraft, and GERB on Meteosat Next Generation.*

Because of the excellent stability of the CERES instrument gains demonstrated in the first year of TRMM data, and because climate system anomalies in the next decade are expected to be roughly 2 to 4 Wm^{-2}, obtaining a 10:1 signal to noise ratio requires understanding the radiative flux record at a level of roughly 0.25 Wm^{-2} (Hansen et al., 1992). The CERES instruments appear to be capable of achieving and demonstrating this level of stability and characterization, but validation of this requires a deep space scan for validation of scan dependent offsets as well as overlapping calibration of CERES sensors on different spacecraft. The need for overlapping gain calibration is that the absolute accuracy of the CERES broadband data is estimated to be 0.5% for the total channel and 1% for the Window and SW channel: i.e. roughly 1 Wm^{-2} in TOA fluxes for all three channels. Achievement of 0.25 Wm^{-2} consistency requires overlapping measurements. Note that this is analogous to the solar constant measurement with active cavity radiometers: overlapping observations are required to obtain the long-term record accuracy required for climate applications. Intercalibrations of all 5 CERES instruments on TRMM, Terra, and Aqua will be performed by using time/space/angle matched observations. For instruments on the same spacecraft (EOS-Terra and Aqua) this intercalibration will be performed using both scanners in crosstrack scan mode to co-locate the data in space, time, and angle of view. For intercomparison between satellites, the scan planes will be rotated to account for differences in orbit plane inclination.

CERES broadband data will also be inter-calibrated with ScaRaB-2 and GERB broadband data in order to place all three data sets on the same radiometric scale. CERES/ScaRaB-2 inter-calibrations were performed in January and March of 1999 by selecting periods when the TRMM precessing orbit is in nearly the same local time sampling at the equator as ScaRaB on Resurs. During this period, the CERES scan plan was rotated to account for the difference in orbit inclination between TRMM (35 degrees) and Resurs (98 degrees) and thereby align the CERES and ScaRaB scan planes. This greatly increased (by an order of magnitude) the number of time/space/angle matched radiance data for CERES and ScaRaB. The first such calibration manuever was carried out January 20-22, 1999, and additional intercalibrations were performed in March 1999 until the Resurs satellite communication system failed.

The same technique was then used in March and April of 2000 to intercalibrate the TRMM and Terra CERES instruments. Consistency of the TRMM and Terra SW, Total, and Window channel radiances was found to be within 0.5% with a 95% confidence bound of 0.1% for Total and Window channels, and 0.5% for SW channels. Confidence bounds are noise limited by the inability to perfectly match CERES fields of view in time, space, and angle of view. The CERES Window channel on the Terra FM-2 instrument was the only exception to these results. This channel showed a gain change from ground calibration of 0.5% (as measured by on-board blackbodies), as well as a difference of 1% with the TRMM and Terra FM-1 window channels. Further examination of ground calibration data showed that this window channel detector showed about a 10% increase in gain during the 16 days of vacuum testing in the calibration chamber. Other CERES detectors only showed a 1% increase over 16 days. It appears that this FM-2 window channel detector continued to slightly change during longer exposure to vacuum in space and had not completely stabilized during ground calibration.

The GERB (Geostationary Earth Radiation Budget) instrument will use a 1-dimensional broadband detector array to scan the earth from west to east. Roughly 250 detectors are used. Validation of the calibration of GERB and CERES requires in principle time/space/angle matched radiance data for each GERB detector. Fortunately, this can be achieved with 30 samples per 6 month period by using the Terra or Aqua CERES Rotating Azimuth Plane (RAP) scanner. Unlike a crosstrack scanner in low earth orbit, the CERES RAP scanner is capable of matching view angles with all GERB detectors. While this activity will primarily be a validation of the GERB calibration, the high time resolution (30 minute or better) of the GERB data will in turn provide CERES with the first broadband geostationary data set to use in validating CERES time sampling algorithms using the combination of low earth orbit CERES broadband data and narrowband ISCCP geostationary radiance data. In essence, CERES uses the narrowband radiometer data to provide a second order diurnal cycle correction to the basic broadband radiation fields.

3.2.7 *Internal Consistency Check: 3 Channel Checks*

One of the advantages of an instrument with SW, Total, and Window channels is the ability to verify the internal consistency of the calibration of all three channels. This is accomplished by utilizing optically thick deep convective clouds with a

Window channel brightness temperature of 205K or less. These are cloud tops at 15 km altitude or higher, and therefore the majority of the atmospheric absorption and emission has been eliminated. With the exception of a small amount of ozone and CO_2 absorption: the spectrum of radiation from a deep convective cloud at 205K is very close to a blackbody. In this case, using night-time data we can verify the relationship between the Window channel and TOT Channel broadband longwave radiance. This relationship has been compared to line-by-line radiative transfer calculations and shows excellent agreement, as well as very little dependence on ozone, water vapor, or temperature variations in the stratosphere. This allows the use of the Window channel radiance in the daytime to predict the broadband longwave radiance very accurately for these deep convective cloud cases. Then this broadband longwave radiance is compared to the estimate using the TOT channel minus the SW channel. The difference between these two predictions of daytime longwave radiance is then determined as a function of SW radiance from 0 to 1000 Wm^{-2}. This intercomparison has been performed for each of the first 8 months of TRMM CERES data and verified agreement to within 0.2%, with no detectable change over time. This 0.2% difference can arise from either an error in the absolute accuracy of the SW channel gain or from the SW part of the Total channel. The sign of this inconsistency is such that longwave radiances during the daytime are too large by 0.2% of the SW radiance. On average, this can cause a daytime bias of about 0.4 Wm^{-2} .

3.2.8 *Consistency of nadir radiances between ERBE and CERES*

A consistency check will be performed between the nadir longwave daytime and night-time radiances averaged over the oceanic regions from 20S to 20N latitude. Oceans are selected to minimize the sensitivity to diurnal cycles in longwave fluxes.   Day and night are separately examined to allow comparisons of TOT channel (night) and TOT - SW channel (day) estimates of broadband longwave radiances. Overall, these checks for TRMM are consistent with the results of 3.2.7 for deep convective clouds.

3.3 Instantaneous Top of Atmosphere Radiative Fluxes

Like the instrument validation, this area has extensive experience from the ERBE and Nimbus 7 experiments. The major challenge is conversion of a spacecraft measured radiance at one viewing angle to an estimate of the hemisphere averaged radiative flux. This correction depends on solar zenith angle, as well as the satellite viewing zenith and viewing azimuth angles. Error studies of the ERBE data indicated that angular sampling errors are one of the largest sources of uncertainty in the ERBE TOA flux data (Suttles et al., 1992; Wielicki et al., 1995). Estimates for ERBE-Like flux instantaneous error (1 sigma) are 36 Wm^{-2} for SW fluxes with an insolation of 1000 Wm^{-2}, and 12 Wm^{-2} for instantaneous LW TOA fluxes. For large ensembles of data (e.g. monthly regional means or zonal means) the errors due to angular sampling are greatly reduced. For monthly regional means, the accuracy is estimated to be 3.5 Wm^{-2} for SW fluxes and 1.5 Wm^{-2} for LW fluxes (Wielicki et al, 1995, Suttles et al., 1992).

As a result of the importance of angular sampling errors, CERES has added a Rotating Azimuth Plane Scanner (Figure 3) to fly once in each orbit (Terra morning sunsychronous, Aqua afternoon sunsynchronous, and TRMM variable time of day precessing orbits). The purpose of this instrument is to provide complete sampling of the anisotropy of radiation as a function of cloud and surface properties. The cloud and surface properties are identified by co-located cloud imager data (MODIS on Terra and Aqua, and VIRS on TRMM). This new angular sampling capability is used to develop new angular dependence models (ADMs) for conversion of measured CERES broadband radiances into estimates of hemispheric average radiative fluxes. They will be derived as functions of surface type (ocean, land vegetation type, snow, ice) and as a function of cloud properties including cloud amount, optical depth, particle phase/size, and cloud altitude). The pre-launch estimate is for roughly 100 to 200 ADM classes (ERBE used 12 classes). These new ADMs are expected to reduce angular sampling errors by a factor of 2 to 4 over those encountered by ERBE.

Note that for CERES, there are two data products with TOA fluxes: the ERBE-Like ES-8 data product which uses the historical ERBE ADMs and analysis methods for climatological continuity with the earlier ERBE data, and the new CERES TOA fluxes which use the new CERES ADMs along with scene classification by co-located cloud imager data for each CERES field of view. The validation plan assumes that each of these TOA flux estimates is tested for error. The CERES RAP data (along with MISR) provides a better validation test of even the ERBE-Like data that has been available previously. POLDER data from ADEOS-I and later from ADEOS-II also provide an excellent data set to test broadband concepts on a narrowband data set. To date, simulations of the CERES ADM strategy have been carried out using 3 months of POLDER data over ocean. Using these narrowband data to simulate the CERES broadband SW data, the predicted reduction of TOA flux error of a factor of 3 appears achievable, perhaps with well less than 200 scene types (Loeb et al., 1999).

Since there are no “truth” data for TOA fluxes (we cannot effectively match aircraft data with the large 20km CERES field of view in time and space), validation of the ADMs and therefore the TOA fluxes is accomplished using the following internal consistency checks:

3.3.1 *Sorting into Angular Bin (SAB) fluxes versus fluxes derived using Angular Dependence Models (ADMs): bias errors in TOA fluxes*

Analyze monthly average fluxes using the sorting into angular bins method (SAB) developed by Arking and Vemury (1984) on the CERES RAP data. This is in essence a "direct integration" of radiance to flux, but can only produce monthly average flux estimates and cannot be used for instantaneous data. This SAB method is, however, very useful as an independent consistency test of the CERES method of converting each radiance to a flux. The SAB analysis will be used to compare to the TOA fluxes derived from application of CERES and ERBE ADMs for both CERES cross-track and CERES RAP data. This will be a more accurate version of the test applied by Suttles et al. 1992 using the ERBE ADMs and the Nimbus 7 data. For CERES, this SAB test can be applied not only for grid box monthly mean data, but to test the dependence of TOA flux derivation with cloud fraction, optical depth, and cloud phase.

3.3.2 *Dependence of TOA fluxes on viewing zenith angle: bias errors in TOA fluxes*

A second important test is to determine the dependence of CERES TOA fluxes on viewing zenith angle. Ideally, there would be no dependence on viewing angle if a perfect conversion of radiance to flux is made for all viewing geometries. For ERBE ADMs, a 10% change in SW flux and a 2-3% change in LW flux with viewing zenith angle was found (Suttles et al., 1992). When climate data are averaged over viewing zenith angle, however, it was shown that overall biases were approximately 1% or less. For the new CERES ADMs, the dependence on viewing zenith angle should be greatly reduced from that found with the ERBE ADMs. Again, a factor of 2-4 improvement is expected.

3.3.3 *Dependence of TOA fluxes on viewing azimuth angle: bias errors in TOA fluxes*

Because CERES has both crosstrack and rotating azimuth plane data, we can test the consistency of the TOA fluxes between these two different scan modes, and thereby test for biases with viewing azimuth angle in the time averaged climatological fluxes. If the angular models work correctly, there should be no difference in large ensemble average fluxes from crosstrack or RAP scan data. For CERES on TRMM, the instrument operated in a three day cycle: one day in RAP mode and two days in crosstrack scan. This was selected as the best compromise between ideal spatial sampling (crosstrack) and angular sampling (rotating azimuth plane) which could be achieved using a single CERES instrument on TRMM. The Terra and Aqua missions will allow one CERES instrument on each platform to devote full time to acquiring data for development of improved angular models. Because of the more limited sampling, the angular models developed for TRMM will not be as accurate as those for Terra or Aqua.

To test ERBE-Like TOA fluxes, the first six months of CERES TRMM data were analyzed separately for mean SW and LW fluxes from 40S to 40N latitude using all data (crosstrack and RAP) and crosstrack only data. The SW and LW TOA flux differences between these two analysis methods agreed to within less than 0.1 Wm^{-2} for both total sky fluxes as well as clear-sky fluxes. This limits the difference between crosstrack and RAP TOA flux data to less than roughly 0.3 Wm^{-2}. Note that the increase from 0.1 to 0.3 is because the RAP data is only 1/3 of the combined TRMM crosstrack + RAP. On Terra and Aqua, direct RAP versus crosstrack data comparisons will be possible, allowing an error analysis of regional fluxes in addition to the 40S to 40N.

3.3.4 *Instantaneous TOA Flux Uncertainty : random errors in TOA fluxes*

For instantaneous TOA flux errors, flux estimates made from multiple viewing angles at the same time and for the same 1 degree grid box are compared. This test is accomplished using overflight of a grid box by two CERES scanners: either two on the same spacecraft (Terra and Aqua with one scanner in crosstrack and one fixed in a different azimuth plane), or two instruments on different spacecraft (TRMM, Terra, Aqua). This provides an estimate of the instantaneous uncertainty of grid box TOA flux estimates when made from differing viewing zenith and azimuth angle views of the same target. Note that grid box values are used in order to minimize the spatial sampling noise caused by mismatches in spatial alignment of CERES fields of view at different viewing angles. As mentioned earlier, for ERBE, this type of intercomparison gave 1 sigma values of 36 Wm^{-2} for SW fluxes (~ 12% relative uncertainty for a typical SW insolation of 1000 Wm^{-2}) and 12 Wm^{-2} or 4% for LW fluxes (Wielicki et al., 1995).

A second method to examine instantaneous flux errors for SW fluxes is to use MISR or POLDER multi-angle (7) views of along-track narrow-band data. These data have sufficiently high spatial resolution that they can be spatially matched or gridded at scales similar to the CERES field of view scale of roughly 10 - 50 km. A difficulty of this comparison will be the necessity to model narrow-band to broadband conversion between MISR or POLDER and CERES radiances. In general, the strategy will be to use the algorithm for development of CERES ADMs, apply it to POLDER or MISR data, and then test the narrow-band flux consistency. POLDER will be optimal for this test because of its ability to view all azimuth angles, at least out to a viewing zenith angle of 60 degrees. MISR has better spatial resolution than POLDER (200m versus 8 km) and will obtain data for a wider range of viewing zenith angles (out to 75 degrees). MISR, however, will see a limited range of azimuth angles. Initial tests of this type have been performed using POLDER data from ADEOS I and have so far confirmed the viability of the planned CERES ADM approach (Loeb et al. 1999a,b; Loeb et al 2000). Adding cloud optical depth dependence to the ERBE cloud amount dependence, early indicate instantaneous SW flux errors are reduced by a factor of 4 to roughly 4%.

For errors typical of monthly mean regional values, Fig, 5 uses POLDER data to estimate the predicted capability of the new CERES SW angular models for regional monthly mean fluxes. When averaged over all solar zenith angles, relative errors are reduced to less than 0.15% for bias, and to 1.5% for 1 sigma variations. These values are a factor of 10 and 4 better than the equivalent ERBE angular model performance (Suttles et al., 1992, Loeb et al., 2000). Further details can be found in the Subsystem 4.5 CERES validation plan on the web.

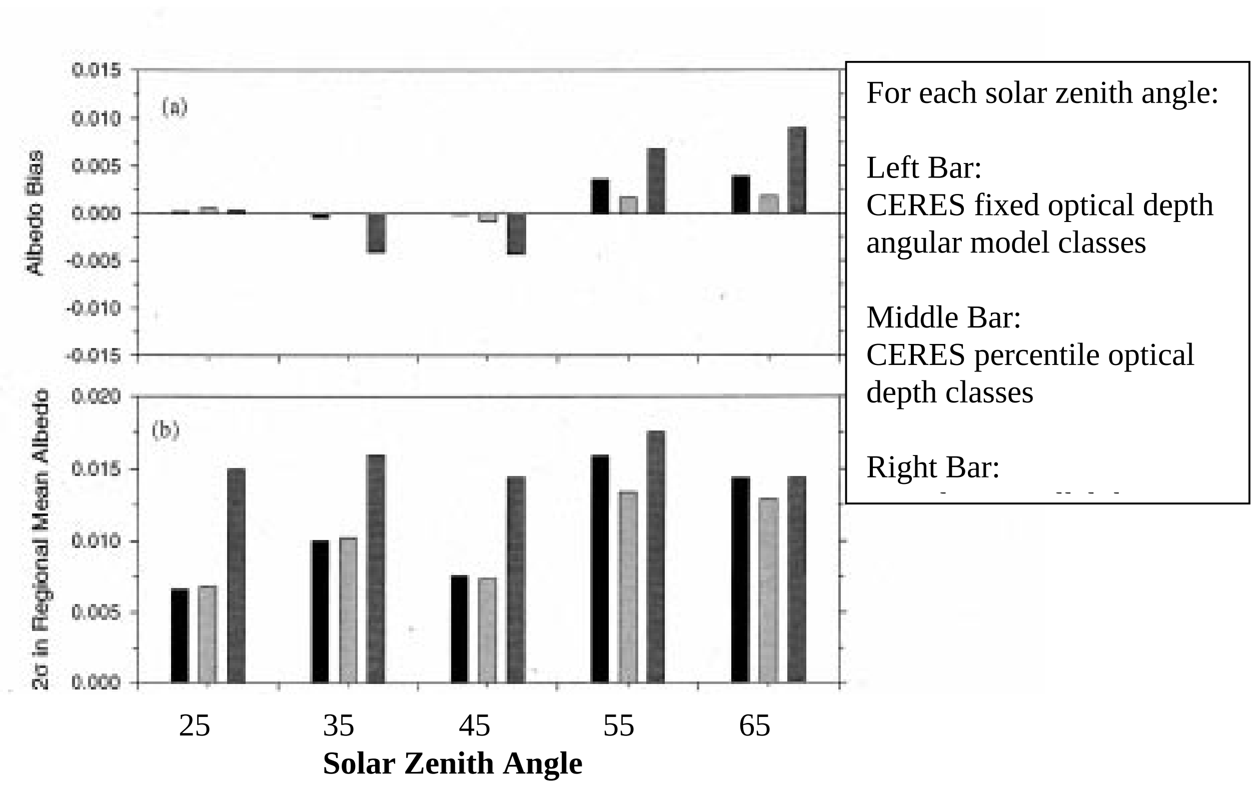


Figure 5. Angular sampling errors estimated using POLDER data for two months, 60S to 60N. Errors are determined by comparison to the direct integration of hemispheric radiance as the time-averaged reference. Regions are 1000km by 1000km to reduce random noise in the direct integration reference. Largest errors are for 1-D theory. Smallest errors use CERES percentile classes of cloud optical depth to eliminate systematic biases in imager-derived tau.

3.3.5 *Consistency with historical ERBE and ScaRaB broadband TOA flux data.*

Comparisons are also performed of climatological SW and LW fluxes and oceanic nadir radiances between CERES, ERBE, and ScaRaB. For ERBE, these intercomparisons will include not only the ERBE scanner data from 1984 to 1989, but also the non-scanning active cavity radiometer ERBS data which has provided wide-field-of-view SW and LW fluxes continuously from 1984 through 1999. Comparisons of tropical mean (20S to 20N latitude zone) fluxes for ERBS nonscanner data in January through August of 1998 with CERES scanner fluxes showed results very similar (within 1 Wm^{-2}) to results found between the ERBS scanner and ERBS nonscanner instruments in 1984 through 1990. Both CERES and the ERBS WFOV show anomalies relative to the 1985-1990 ERBE baseline period of up to 8 Wm^{-2} at the peak of the 97/98 ENSO event in February 1998, reducing to about 3.5 Wm^{-2} in July and August of 1998 when the ENSO index has returned to near zero (Wielicki et al., 1999). Overall, the data appear to show a remarkable increase in tropical mean outgoing longwave radiation between the late 1980s and late 1990s. The ERBS nonscanner data record indicates that this change began in 1990, well before the Pinatubo volcanic eruption. The anomaly has reduced to about 3.5 Wm^{-2} in March and April of 2000 as seen by both TRMM and Terra CERES instruments. Note that Terra

CERES ERBE-Like TOA flux data is currently available as a "beta" data product for early use. This is not a validated, publishable data product, but is intended to allow early use of the data by the science community before the first validated Edition 1 is made available after approval by the CERES Science Team expected at the September, 2000 Science Team Meeting.

3.3.6 *Theoretical Simulations of ADM models*

A very useful complement to the data analysis methods mentioned above is the use of 1-dimensional, 2-dimesional, and 3-dimensional radiative transfer models to test concepts for ADM development and to predict their accuracy theoretically. These studies have been used to set nominal initial cloud classes for the ADMs (e.g. optical depth classes and cloud fraction classes) and to examine the accuracy expected theoretically for different approaches to conversion of radiance to flux. Examples of these studies can be found in Chambers, 1999 and Loeb et al., 1999b. The validation effort strives to obtain consistency in the measurements and theoretical predictions of ADMs for a reasonable number of cloud types. Initial pre-launch results have focused on broken and stratiform water cloud, and deep convective clouds (Hu et al., 1999).

3.4 ***Surface Radiative Fluxes***

Surface radiative fluxes are an extension beyond the previous ERBE capability. In many cases, we expect a fairly close relationship between TOA and surface fluxes (shortwave, and clear-sky longwave), but for cloudy sky longwave fluxes, we expect little or no relationship between surface and TOA. As a result of the added difficulties, CERES is using two separate approaches to estimation of surface fluxes. These approaches are described in the CERES ATBDs. One method emphasizes an algorithm based on radiative transfer modeling (CRS data product), while the second method emphasizes direct relationships between surface and TOA fluxes wherever possible (SFC data product). Both methods produce estimates of surface SW and LW fluxes separately for both clear-sky and cloudy sky conditions.

3.4.1 *Downward SW and LW broadband fluxes at the surface: ARM, BSRN, and SURFRAD*

While the estimation problem is more difficult, an advantage for surface flux estimates is the availability of direct measurements at the surface which can be used for validation. Like many other geophysical fields, however, the region of the earth viewed by a satellite observation rarely matches exactly that viewed by the surface radiometer. Recourse must be made to statistical intercomparisons in order to reduce the sampling noise induced by the different space and time sampling characteristics of satellite and surface data (e.g. Morrissey and Wang 1995 for an example using precipitation validation). Studies carried out by the WCRP Surface Radiation Budget program have shown that even for 280 km grid box monthly mean, the space/time sampling error dominates comparisons of satellite-derived surface SW downward flux to estimates from a single surface radiometer (Darnell et al., 1992, Bishop and Rossow, 1991). The error is greatly reduced when an array of surface radiometers is used. The ideal sites in this regard are the DOE ARM sites, where arrays of solar radiometers are used. These will be the most important validation sites for the CERES surface flux estimates. A second strategy is to composite many sites form similar climatological regions: thereby obtaining a regional average with less error than any single grid box or site. Finally, surface radiometers typically view an area of 5-50km in diameter, a scale which depends on cloud base altitude. CERES will test a procedure to match individual CERES fields of view (20 km at nadir) to surface site data locations and thereby reduce the spatial sampling noise caused by attempting to represent a large 280 km region by a single point measurement. In this way the combination of multiple surface sites and smaller CERES fields of view will allow a thorough examination of the spatial sampling issues for validation of solar insolation at the surface.

The DOE ARM sites, however, only cover three climate regimes: tropical ocean, midlatitude land, and polar land. Additional sites are needed to cover other climate regimes including tropical land, subtropical, midlatitude and high latitude ocean, and desert. For surface radiation, these other sites are obtained using the WCRP Baseline Surface Radiation Network (BSRN), supplemented with the U.S. SURFRAD and CMDL sites which include both surface radiation and aerosol data. While there is a much larger GEBA solar surface radiation data set, the BSRN, SURFRAD, and CMDL sites include both SW and LW fluxes, and are quality controlled to higher standards. An example of the status of data in the BSRN archive as of January 1999 is given in Table 2. This table presented two concerns for CERES validation. First, the only oceanic island sites operating are Bermuda (midlatitude) and Kwajalein (tropical). There are several polar sites (Barrow, Ny Alesun in the Arctic, and Neumayer, Syowa, and South Pole in the Antarctic. Florianopolis is a midlatitude land site in S. America. The remaining stations are U.S. and European midlatitude land sites, with the exception of Tateno in Japan.

The CERES team is working with both Els Dutton (science lead for BSRN and CMDL) and De Luisi (science lead for SURFRAD) to optimize CERES validation efforts using these sites and to work to augment these sites where necessary. According to Dutton (personal communication, 9/18/00) there are several sites that in the last 18 months have been certified and are now delivering data to BSRN, including:

Solar Village Saudi Arabia
Sede Boger, Israel
Alice Springs, Australia
Toravere, Estonia
De Aar, South Africa
Tamanrasset, Algeria

So that desert sites are now reasonably represented. The DOE ARM tropical western pacific island sites (Manus, Nauru) are expected to start delivering data soon. Australia is planning two further sites, one near Darwin and another in the Cocos Islands in the Indian Ocean. For CERES we have also been using Maldives Islands site in the Indian Ocean which has been maintained as part of the recent INDOEX experiment. For most BSRN sites, data archive lags about 1 to 2 years from data acquisition, but this is expected to improve in the near future with improved hardware and software at the BSRN archive site. More information on the BSRN program can be found at http://bsrn.ethz.ch/.

While these are critical sites for future climate studies, funding for such "routine" observations is often lacking internationally, and will be a continuing challenge and fundamental limit on our ability to validate CERES surface flux estimates in a complete range of climatological conditions as well as for a statistically robust set of cases. The most critical needs are for tropical sites over land, and for all oceanic observations.

Table 2. BSRN Sites and Data Status as of January, 1999.

Number of monthly files sent to the WRMC and inserted into the BSRN/WRMC database as of January, 1999

YEAR ➔

STATION	1992	1993	1994	1995	1996	1997	1998	Total
Ny Alesun	5	12	12	12	12	12	2	67
Barrow	12	12	12	12	12	1	-	61
Lindenberg	*	*	3	12	10	-	-	25
Regina	*	*	*	*	3	-	-	3
Payerne	3	12	12	12	12	12	8	71
Carpentras	*	*	*	*	4	12	2	18
Boulder	12	12	12	12	12	1	-	61
Billings	*	*	*	12	12	12	-	36
Tateno	*	*	*	*	12	12	12	36
Bermuda	12	12	12	12	12	1	-	61
Kwajalein	9	12	12	12	12	1	-	58
Ilorin	4	12	9	-	-	-	-	25
Florianopolis	*	*	6	12	12	12	11	53
Syowa	*	*	12	12	-	-	-	24
Georg von Neumayer	9	12	12	12	12	12	1	70
South Pole	12	12	12	12	12	1	-	61
Total	78	108	126	144	149	89	36	730

BSRN archive status courtesy Dr. Hermann Hegner, BSRN data manager, Swiss Federal Institute of Technology, Department of Geography, Winterthurerstr.

It should be noted that recent experience in the ARM Southern Great Plains site indicates that further work is needed to define the absolute calibration accuracy of surface flux measurements, especially the SW diffuse. This is needed not only for specific experiment periods, but especially to produce consistent long-term data sets which can provide the statistical sampling necessary to validation CERES surface flux estimates for a complete range of clear and cloudy conditions. Currently there are two types of SW broadband measurements that appear to be capable of high accuracy (better than 1-2%: BSRN and the Valero flux radiometers. BSRN bases its solar calibration on active cavity direct beam measurements to calibrate direct-beam measuring phyrheliometers, and separately measures the diffuse field using a shaded pyranometer. All instruments are on a solar tracker table. The Valero radiometers characterize in the laboratory the solar zenith and azimuth dependence of the direct beam response for each individual radiometer, and then account for non-cosine response during data analysis. Ideally, both radiometers (BSRN and Valero) are desired and should be available at the 3 ARM sites. A blind intercomparison of the BSRN and Valero radiometers in tests in Boulder, Colorado and San Diego, California showed good agreement overall between the two sets of SW radiometers. LW fluxes are measured using pyrgeometers for BSRN and Valero LW flux radiometers. Given the importance of surface radiative fluxes to the climate system, further development of robust highly accurate SW and LW radiometers is desired.

Studies of the effect of changing thermal emission from the filter domes of Epply SW pyranometers by adding thermistors to monitor dome temperature have shown that fluxes can be underestimated by 2 to 10 Wm^{-2} depending on the thermal conditions and the radiometer (Haeffelin, 2000). Efforts are underway to reduce these errors at BSRN and other surface sites. Note that this effect reduces, but does not totally eliminate some of the observed discrepancies between observed and calculated atmospheric solar absorption.

CAGEX (CERES/ARM/GEWEX) is the prototype for CERES validation efforts using the ARM CART sites. Examples of initial tests can be found on the web at (http://snowdog.larc.nasa.gov:8081/cagex.html). As mentioned in the introduction, it is expected that the error bounds will tighten as longer time series of validation data are analyzed and algorithms improve. A key improvement will come about 3 years after Terra launch when CERES has gathered sufficient data to construct new anisotropic models for correction of radiance to flux. This is expected to greatly reduce instantaneous field of view TOA flux errors, and therefore surface flux errors which use the TOA fluxes as an instantaneous constraint.

While CAGEX focuses on specific ARM Intensive Observation Periods or IOPs, these short periods of time are insufficient to statistically test the algorithms in a complete range of climatological conditions even at the ARM sites. Therefore CAVE (CERES/ARM Validation Experiment) will extend the model of CAGEX to continuous time series validation of CERES surface fluxes. CAVE will not have as complete a set of measurements as CAGEX, but will offer greatly improved statistical sampling for validation. Following the ARM sites, the CAVE validation approach will be extended to key BSRN and SURFRAD sites. The selection of additional sites will depend on when data is available in the archive, and on obtaining data from climate regimes not covered by the initial three ARM sites. Examples of early results for comparisons of CERES and BSRN surface fluxes can be found in the validation documents on the web for subsystems 4.6 and 5.0. These early results, however, are not representative of final results because they are forced to constrain surface radiative flux estimates against the ERBE-Like TOA fluxes. The improved CERES angular models (section 3.3) are required to improve the SW TOA flux accuracy and thereby more accurately constrain estimates of SW downward fluxes at the surface. For TRMM, the new CERES angular models are expected to be developed and validated by late spring/early summer of 2001.

Since downward LW fluxes depend critically on cloud base altitude, it is also critical to improve cloud base altitude measurements in conjunction with BSRN class surface LW radiation measurements for climatological regions not covered by the three ARM sites. As an initial step in this direction, CERES has acquired 3 Micropulse Lidars for extended deployment at BSRN sites. NASA is now starting an international network of near-continuous surface based lidar sites (J. Spinhirne, GSFC, 2000, personal communication). This network is being modeled on the AERONET network for aerosol measurements. CERES will contribute its 3 lidars to this effort. The first deployment is expected at the Saudi Solar Village BSRN site. Additional deployments are expected at the Bermuda BSRN site, and at a tropical land site in Africa, South America, or Australia. These lidar will allow accurate cloud base measurements to augment BSRN sites in midlatitude ocean, desert, and tropical land climate regions.

3.4.2 *CERES Chesapeake Lighthouse Ocean Platform: an Ocean Background BSRN Site.*

While BSRN includes a few island based tropical and midlatitude ocean sites, there are no BSRN quality sites available on platforms which would allow surface fluxes to be measured directly over an ocean background for satellite algorithm validation. In order to provide such a site, CERES has obtained permission from the U.S. Coast Guard to place a BSRN quality station on the Chesapeake Light ocean platform. This platform is located roughly 25km off the coast of Virginia, east of Norfolk. The platform is far enough from land that entire CERES fields of view can be located without land within the field of view.

Figure 6. Chesapeake Light platform 25km off the coast of Virginia. CERES has developed and supported this as an ocean background BSRN and AERONET site.

The Chesapeake Light platform has both uplooking and downlooking BSRN quality direct and diffuse SW flux measurements (downlooking at the two southern corners of the platform to minimize shading effects), LW flux measurements (pyrgeometer), along with both Cimel and MFRSR aerosol measurements. Routine data collection began in August, 1999. The data is routinely archived as part of the BSRN surface radiation archive as well as the AERONET aerosol archive. The platform also has NOAA instruments that routinely measure surface meteorology, wave height, and water temperature. The CERES instruments are solar powered, so that there are no sources of anthropogenic aerosol on the platform. This site will provide the most uniform background for satellite detection of aerosols and thin clouds and will be used to test in particular the optically thin atmospheric cases. This site is formally called COVE (Chesapeake Light Ocean Validation Experiment) and will also be used in a field experiment jointly carried out by the CERES, MODIS, and MISR teams to perform a shortwave flux closure experiment, including verification of satellite aerosol retrieval. This experiment is described later in this plan.

3.4.3 *Upward SW and LW fluxes at the surface*

In order to understand the net radiative energy flux at the surface of the earth, not only downward, but upward SW and LW fluxes are also required. For oceanic regions, the thermal emission of the ocean surface is well understood, including the dependence of ocean surface emissivity on direction and wind speed. For ocean albedo, the situation is somewhat less clear, but is still fairly well understood. For land, the spectral albedo, broadband albedo, spectral infrared emissivity, and broadband emissivity are much less well known, and are highly variable in space as a function of soil type, land cover, and snow/ice cover. POLDER and MISR will provide improved observations of the anisotropy and spectral albedo of land surfaces from about 0.4 to 1.0 μm, once atmospheric corrections have been made, but only for limited solar zenith angles (limited by a 10:30am sunsynchronous orbit). MODIS will add information at wavelengths beyond 1 μm, but only for limited viewing and solar angles. Modeling will be required to extrapolate these results to other wavelengths, solar zenith angles, and viewing angles to obtain the final results required for time and space integrated surface reflected and emitted fluxes. Note that recent results show that even the thermal infrared shows viewing zenith and viewing azimuth dependences in thermal emission which are analogous to the patterns seen for solar reflectance. The similarity is not thought to be accidental: sunlit and shaded sides of standing vegetation exhibit higher/lower temperatures, and therefore an angle dependent thermal emission. This effect can reach levels of 5 to 10 K in brightness temperature (Smith et al., 1999).

Accurate estimation of surface broadband reflectance and thermal emission will require not only accurate satellite measurements at the top of the atmosphere from POLDER, MISR, MODIS, and CERES, but also surface and aircraft measured data to validate these global satellite approaches. Unfortunately, the spatial scale at which we can typically measure spectral surface properties tends to be much closer in scale to Landsat 30m data than to CERES 20 km data. In addition, there is a severe problem of extrapolating results from small "fields" to global inhomogeneous land conditions. The MISR, POLDER, and MODIS land teams are concentrating on deriving global spectral albedo and anisotropy maps at high spatial resolution for the spectral region from 0.4 to 1.0 μm. CERES is planning to extend these validation efforts beyond 1 μm for both spectral albedo as a function of solar zenith angle and spectral anisotropy. The strategy for this validation effort is similar to what the CERES instruments will do at the top of the atmosphere. A spectral radiometer (covering continuously 0.4 to 2.5 μm) will be scanned in elevation and azimuth much like the CERES RAP scan, while a second spectral radiometer will obtain a hemispheric upward flux measurement, and a third spectral radiometer will obtain a downward spectral flux measurement. The instruments will be mounted on a small low altitude OV-10 twin engine aircraft, and flown over long flight legs near the surface to minimize atmospheric correction. The flights will be used to statistically characterize IGBP surface types and will be used to check the ability to predict the narrowband and broadband surface albedo from the global satellite observations. This strategy was demonstrated first in August, 1998 during an ARM/CERES shortwave IOP at the Oklahoma ARM site. Instead of the OV-10, a helicopter was used, and the spectrometer only scanned in elevation, while the helicopter flew rosette patterns to sample solar azimuth angles. While these flights established the basic measurement strategy, and tested the basic instrumentation, it could not provide large statistical sampling as is possible with the OV-10 and a bidirectionally scanning spectrometer.

By spring, 2000 the instrumentation was converted from the helicopter to the OV-10 platform, and engineering flights began. The initial OV-10 instrument payload includes up and downlooking broadband SW and LW fluxes, as well as up and down-looking spectral SW fluxes from 0.4 to 2.5um. GPS navigation is included for all data collection. Because of funding cuts in FY99 and FY00, the bidirectional scanning spectrometer will be delayed until Fall, 2001.

Flight schedule for the OV-10 will begin with flights over the Chesapeake Light site to simplify logistics and obtain rapid experience with the platform. Note that the OV-10 aircraft is owned by NASA Langley and was selected for use in these missions because of its low cost, low altitude capability (50 to 100m minimum altitude) and easy availability and accessability at NASA Langley. Since this is a relatively modest budget activity, effort will focus in the first year of flights (Fall 2000 through Fall 2001) on Ches Light ocean spectral albedo in conjunction with the Ches Light BSRN/Aeronet measurements. Ocean spectral albedo will be characterized as a function of solar zenith angle and wind speed. This will require flights in both summer and winter clear-sky cases. The following year, flights will switch to cover other IGBP surface types. The intent is to cover seasonal an solar zenith angle dependence for each IGBP type with a statistical sample over long flight legs, as opposed to characterization of individual "postage stamp" crop or grassland surfaces as traditionally done. Forest, grassland, and shrub desert would be three of the highest priority surface types to characterize. Current schedule of flights includes:

OV-10 Spectral Albedo/Emissivity flights begin in Fall, 2000.

- Spring/Summer 2000: Engineering Flights

Engineering flights to measure ocean spectral albedo near the Chesapeake Light station. These flights began during March, 2000. Electronic noise problems were found in the amplifiers for the broadband instruments and were resolved by August, 2000. Spectral up and down looking fluxes did not have the electronic noise problem.

- Fall 2000 through Spring 2001: Ocean near Chesapeake Light

20 flights for a wide range of solar zenith angle, wind speed, and aerosol. Because this data would be useful to other teams, flights will be coordinated with Terra overpasses on clear days where possible.

- Summer/Fall 2001: Flights in support of the CLAMS field experiment

CLAMS is a clear-sky shortwave "closure" experiment with an ocean background and will be carried out near the Ches Light site. CLAMS will also be used to verify satellite aerosol retrieval methods.

- Spring 2002 through Winter 2002: IGBP forest *flights over mixed forest of eastern Virginia: IGBP mixed forest class. Obtain seasonal and solar zenith angle dependence of spectral albedo, 0.4 to 2.5 μm.*

- 2003 Shrubland and Desert

Spring 2003: DOE ARM site in Oklahoma during the "green season"
Summer 2003: Shrubland EOS validation site, and desert.
Winter 2003: Fort Peck Montana snow measurements.

Flights beyond 2003 will depend on experience in the first two years of flights. CERES is interested in working as closely as practical with the EOS land community in organizing these surface characterization flights. The list of flights above is nominal and can be modified to help other parts of the EOS program. The sampling strategy for these flights will emphasize long flight legs to obtain stable statistics on characteristic IGBP land types. The OV-10 flights near BSRN or ARM sites will also be used to horizontally "map" spectral albedo near the surface site in order to help with SW "closure" experiments carried out at the scale of CERES fields of few (10-30 km) such as the SW IOP in August, 1998.

3.5 *Atmospheric Radiative Fluxes*

There are three different ways to approach atmospheric fluxes:

i) atmospheric column average: Net fluxes at TOA - Net fluxes at the surface

ii) atmospheric layer/level average: e.g. net fluxes for a 2 km layer containing stratus cloud

iii) atmospheric fluxes at a single level, location, and time.

These are listed roughly by priority to understanding the impact of changes in radiation on climate. Fortunately, the list is also ordered from easiest to most difficult to validate. CERES will begin with validation of column average (e.g. early CAGEX and CAVE results: see section 3.4.1). Levels ii and iii will take longer, and will depend critically on future success of NASA and DOE field experiments such as an ARESE II, CRYSTAL, etc.

We note that there are three critical unresolved scientific issues that the CERES validation effort will be involved in that are basically related to atmospheric radiative fluxes:

i) How much solar radiation does the clear-sky atmosphere absorb?

ii) How much solar radiation does the cloudy-sky atmosphere absorb?

iii) How does the often complex vertical layering of clouds affect LW atmospheric heating rates? Can we determine this layering sufficiently accurately from space with passive instruments (optical plus microwave) or must we have active lidar and radar instruments to understand this heating globally?

In the sections below it will become clear that these scientific questions will be critical to guiding the validation of CERES atmospheric radiative flux estimates.

3.5.1 *Atmospheric Column average net radiative flux*

Validation of column average radiative divergence (i.e. SW and LW heating/cooling rates) will be studied by matching in time and space the CERES TOA fluxes with surface based fluxes using long time series. The CAVE data mentioned in section 3.4.1 will be ideal for this study and will allow separate study of both clear and cloudy conditions. Cloudy conditions can be further subdivided into single layer water cloud and ice cloud, as well as broken versus stratiform cloud. However, subdivision into these important physical classes will only occur as longer time series of matched CERES TOA and surface ARM, BSRN, and SURFRAD data become available. In particular, the new CERES angular dependence models will be required to greatly increase the accuracy of TOA fluxes as a function of cloud conditions, and to more rigorously constrain the estimates of column radiative fluxes. In a sense, this validation is a fairly straightforward combination of the separate validation efforts for TOA fluxes and Surface fluxes. Accuracy in the net atmospheric fluxes will be linked directly to accuracy in TOA and surface fluxes. It is expected that the spatial variability of radiative fluxes at the TOA and surface will cause instantaneous uncertainties in column average SW fluxes of between 20 and 50 Wm^{-2}. To average out this spatial sampling noise to a level of 2 Wm^{-2} will require averaging a single surface radiation site over 100 - 600 satellite overpasses. For the combination of Terra and TRMM, or Terra and Aqua, this averaging would require between 2 and 6 months of data. As a result, we expect the results of this study will require analyzing at least 10 different surface sites for at least 2 to 3 year periods. Verification of the spatial sampling errors will be accomplished by using the arrays of surface radiometers available at the ARM sites. These sites will be especially important for validation of results as a function of cloud type. These long time series should provide the best data for verification of total column atmospheric absorption of solar radiation in clear-sky and cloudy-sky conditions. Note that one of the limits on accuracy of net SW fluxes at the surface (even in cloudy conditions) is knowledge of the spectral surface albedo near the surface radiometer site. This concern is behind both the development of the Chesapeake Light ocean platform site for BSRN radiative flux data, as well as the use of the OV-10 aircraft data to characterize surface albedos near several surface sites (see sections 3.4.2 and 3.4.3).

Column heating for longwave fluxes presents a somewhat different problem. The emphasis shifts from horizontal inhomogeneity to vertical inhomogeneity. Here the primary uncertainty is in the definition of cloud layering boundaries, and in the optical thickness of each cloud layer. While passive optical satellite radiometers at visible through infrared wavelengths are very effective at determination of optically thin cloud and the uppermost optically thick cloud layer, multiple cloud layers often confound such approaches. There is some hope, however for two multiple cloud layer cases: optically thin cirrus over lower level stratus (Baum et al., 1995) and stratiform oceanic water cloud beneath optically thin or thick ice cloud. (Lin et al., 1998a,b). It is unknown what fraction of multi-layered cloud these passive methods can effectively treat, or which what accuracy. From surface observers, roughly half of all cloud systems are multi-layered, mostly two-layered systems. Fortunately, in addition to the ARM, BSRN, and

SURFRAD LW fluxes at the surface, the NASA ESSP program has recently selected the PICASSO-CENA and Cloudsat missions to carry spaceborne cloud/aerosol lidar and cloud radar to fly in formation with Aqua starting in Spring 2003. From the Lidar In space Technology Experiment (LITE) lidar flown on the space shuttle, it is estimated that 80% of the time, the PICASSO-CENA lidar will observe all cloud layers down to the top of any boundary layer clouds (or the surface if no cloud). The active sensors on Cloudsat and PICASSO will greatly assist in extending the understanding of LW fluxes at the surface and in the atmosphere beyond the limited surface site locations. This is especially important since very few of these surface radiometric sites are oceanic, where boundary layer clouds are almost always present, unlike conditions over land. Since low cloud can greatly alter downward longwave flux at the surface, the combination of the Cloudsat/PICASSO-CENA profiles of cloud layers in combination with the CERES TOA fluxes will provide the most accurate test of CERES LW atmospheric fluxes at the surface and within the atmosphere. Note that the lidar will not, however observe all multi-layer clouds: about 20% of the time (40% of multi-layered cases) will be too thick for the lidar to penetrate. Most of these thicker cases will be identified using the Cloudsat 94 GHz radar. The radar is optimal for all clouds with large particles, and for moderate to thick clouds with small particles (e.g. 5 to 10 micron radius water droplets). The need for a complement of lidar and radar is typical of all cloud physical property measurements: the thinnest clouds are better studied with optical systems, while the thickest clouds are best studied with microwave or far-infrared. Note that the nominal orbit of PICASSO-CENA will be to fly within +/- 6 minutes of Aqua at all times (this requires an orbit adjust roughly twice per year, and once in orbit it may be relatively straightforward to tighten this to +/- 1 or 2 minutes with monthly or bi-monthly orbit adjusts by PICASSO-CENA). Cloudsat will then track within less than 1 minute of PICASSO. The orbit inclinations for PICASSO and Cloudsat have been selected so that they will slowly precess across the Aqua scan swath of MODIS, AIRS, CERES, and AMSR so that cloud and aerosol layering validation results will be achieved for all viewing angle conditions typical of a sun-synchronous satellite mission. These results will therefore also be applicable to future NPOESS morning and afternoon orbits. Another advantage of the combination of lidar and radar is the ability to probe the cloud microphysics structure by using the different scattering moments of cloud particles (r^2 Mie scattering for the lidar, and r^6 Ralyleigh scattering for the 94 Ghz cloud radar).

3.5.2 *Atmospheric Layer average net radiative flux*

Shortwave atmospheric layer and atmospheric level radiative fluxes are by far the most difficult to validate, at least for cloudy sky conditions. At the scale of aircraft radiative flux measurements, the large horizontal variability in cloud optical properties causes large local variations in radiative fluxes, especially for downward fluxes. This problem is most simply visualized by considering a hole in a status deck: for the 500m of aircraft track in the clear area (only 5 seconds of data) solar insolation will exceed the clear-sky value (full direct sun plus diffuse radiation from the surrounding cloud), and then upon entering the cloud, the solar radiation will drop to levels below that predicted for a uniform stratus deck with even accurately known cloud optical depth (radiation leakage out the cloud side). So only long averages of aircraft track data (typically 100km or more) can hope to average this variability to levels adequate to test modeling. Very few such studies have been done to date, and the best recent example is the DOE ARM ARESE experiment in Oklahoma (e.g. Cess et al., 1999). The ARESE experiment used aircraft above and below the cloud, and uplooking/downlooking broadband and narrowband flux radiometers to verify that sufficient horizontal sampling had been achieved on 3 different days: one with stratiform water cloud and two with varying amounts of broken low cloud. The amount of absorption inferred depended critically on the solar radiation instruments used: large absorption was inferred using current state of the art broadband radiometers (Valero et al., 1997), but a flux spectrometer gave very different results. From first principles, the absolute calibration of broadband solar radiometers is expected to be more accurate than calibration of a solar spectrometer , but in the ARESE case, these more accurate data give a more surprising scientific result. Since scientific scrutiny is proportional to surprise, the ARESE data are suggestive of problems in modeling absorption of solar radiation in clouds but also suggests the need for further measurements. A follow-on experiment, ARESE-II was carried out in Spring, 2000 at the Oklahoma ARM CART site. One of the limitations of ARESE was the lack of cloud microphysics and liquid water path data along the aircraft tracks. ARESE-II concentrated on flights over the ARM CART site with uplooking surface based microwave radiometer and cloud radar for LWP and microphysics measurements. CERES will participate in analyses of these cases to assist in validation of the CERES atmospheric fluxes.

Layer average net LW fluxes are more straightforward, and primarily rely on multiple level aircraft flux measurements, combined with accurate temperature, humidity, and cloud profiles. The major issue is again cloud layering, and this is dealt with most straightforwardly at the ARM sites (lidar/radar/radiometer cloud vertical profiles) and then extended to global conditions using the PICASSO-CENA and CloudSat ESSP data flying in formation with Aqua. Since the nominal launch of PICASSO-CENA/Cloudsat is in Spring 2003, initial validation of cloud layering will rely on the ARM site vertical cloud profiles.

3.5.3 *Atmospheric fluxes at a single level, location, and time.*

This is basically the instantaneous vertical level flux profile for a single CERES field of view. The ensemble mean behavior of these fluxes can be validated as in section 3.5.2. Validation of instantaneous values is much more difficult and requires validation of aircraft radiative flux measurements at short time and space scales. For SW fluxes, this will be the worst case to attempt to deal with horizontal inhomogeneity in the cloud field. Testing the accuracy of such fluxes in principle requires a full 3-dimensional distribution of cloud macrophysics and microphysics. Such data will not be available for validation until ARM radar/lidar/radiometer cloud data are extended to scan either perpendicular to the local wind, and thereby map out a three-dimensional cloud structure as the cloud field advects past the site, or to scan cloud volumes. While such scanning capabilities are in the early phase of demonstration with individual lidars and radars, the entire complement of lidar, cloud radar, and radiometer volume or area scans is not currently available. In the long run, however, validation of radiative models at the smallest time and space scales will require such observations. The strategy then would be to first use these 3-D ARM cloud profiles to validate radiative transfer models (monte carlo or other multi-dimensional radiative transfer). Then the combination of the ARM volume cloud profile data with these validated detailed radiative transfer models would be used to validate the CERES radiative flux profiles at the scale of CERES fields of view for a large statistical sample of cases, analogous to the boot strapping approach planned to validate CERES cloud physical properties discussed in section 3.6. This type of validation will not be practical for 3-5 years, and fortunately, for climate research it is not as critical as the understanding of the large ensemble fluxes as validated in 3.5.1 and 3.5.2 above.

3.6 *Cloud Properties*

To date, there has been no satisfactory source of cloud validation data for global satellite remote sensing. There are primarily four reasons for this difficulty.

First, the climatological sources of data such as surface observer cloud fraction (subjective, with day/night biases) and celiometer cloud base height (only clouds below 4 km altitude) do not adequately constrain the satellite cloud retrievals to accuracies needed for climate research, nor do they include critical cloud parameters like cloud optical depth, emissivity, or particle size/phase.

Second, the cases of highly accurate validation data (e.g. ER-2 aircraft lidar cloud top/base during FIRE field experiments) suffer from an inadequate number of samples for robust validation statistics. Further complicating the number of samples is that the typical horizontal distance between independent cloud samples is measured not in tens of km but rather in 100's of km.

Third, the accuracy of microphysical properties derived using aircraft probes has been inadequate (somewhat for water droplets, but especially for ice crystals). This situation has improved greatly over the last decade, as FIRE and other field program studies have clearly demonstrated the existing problems. As a result new instrumentation (especially for small ice particles) has been developed and recently deployed in field experiments such as the joint FIRE/SHEBA arctic cloud experiment (ACE). Initial ACE data, however, indicates that there still may be a factor of 2 difference in some of the probes, suggesting that further intercomparisons in controlled laboratory environments and similar mounting positions on the aircraft will be necessary to rigorously understand the results.

Fourth, any attempt to validate the remote sensing of cloud particle size has been greatly complicated by the large and systematic vertical variation of particle size in both water and ice clouds. Particle size commonly varies by a factor of 2 to 3 in water cloud and a factor of 5 or more in ice clouds. Therefore, any rigorous validation of microphysical remote sensing retrievals requires vertical profiles of particle size and number, not just an aircraft penetration at a single level in the cloud.

A new strategy is required to finally obtain objective “cloud truth” of both sufficient accuracy, and sufficient sampling. Such a strategy is possible for the first time by using long time series of cloud observations from the DOE ARM sites. This strategy is basically a bootstrapping effort to use aircraft in-situ data to validate point estimates of remotely sensed (lidar/radar/radiometer) vertical profiles of cloud properties derived over the ARM sites, followed by long time series of these vertical cloud profiles available at 1000’s of satellite overpasses to obtain statistical robustness. Even in this case it must be admitted that a significant risk remains: the new methods to use lidar/radar/radiometer data to derive vertical profiles of cloud boundaries and microphysics are very promising but still under development. Therefore, the first step must be validation of this new surface remote sensing capability, before it will be useful to validate satellite remote sensing.

3.6.1 *Aircraft => ARM Cloud => Satellite Cloud*

The new cloud validation strategy can be summarized as

Aircraft In-situ => ARM Vertical Cloud Profiles => Satellite Cloud Properties.

This new strategy starts with aircraft in-situ microphysical data used to validate ARM or other lidar/radar/radiometer remote sensing vertical profiles of cloud microphysics and cloud boundaries. In this case, the aircraft flight track is typically spiraled around or stepped vertically through the ARM vertical cloud profile information. Validation of the ARM vertical cloud profile data is done for data matched horizontally, vertically, and in time.

Next, the long continuous time series of this ARM cloud profile data is used during thousands of satellite overpasses. For example, 3 ARM sites with 4 satellite overpasses/day for 365 days/yr for 3 yrs = roughly 13,000 validation cases.

Such a validation will represent the first objective test of satellite-based cloud retrieval methods sufficient to unambiguously test the accuracy of these methods as a function of cloud type (water, ice, single/multi-layer, thin/thick, large/small cloud particles) and satellite viewing condition (view angle, sun angle), with sufficient statistical sampling to provide a robust analysis for both random and bias errors in cloud properties.

As the time series of matched ARM/satellite cloud validation data grows longer, the knowledge of the remote sensing accuracy as a function of cloud/atmosphere/satellite viewing states increases, and the constraints on global or regional cloud modeling tighten.

A careful analysis of long time series of cloud properties will also allow rigorous determination of the degrees of freedom in the validation data set, a critical part of the rigorous error analysis needed. Studies of auto-correlation time series or spatial series of cloud data for cloud fraction, cloud height, and cloud optical depth all suggest that independence scales for clouds vary from 100 to 500km, depending on cloud type and cloud physical property. It is thought that the shortest independence scale is for cloud optical depth or cloud liquid/ice water path, and the longest independence scale is for cloud layering. Note that any rigorous analysis of satellite retrieval errors must address the issue of degrees of freedom and therefore this independence scale in the cloud systems.

Considering a distance of 200km between independent cloud samples, and a typical cloud system motion of 10m/s, we conclude that independent cloud measurements at an ARM site will occur roughly every 5 hours. So each ARM site is capable in a year of taking ~ 1000 independent cloud observations. Given that typical instantaneous uncertainties in satellite cloud property retrievals are likely to be of order 20%, then obtaining sufficient cases to validate systematic biases in retrievals to an accuracy of 2% will require 100 independent cases. Consider further that there is a desire to validate results as a function of critical cloud and observational variables:

- cloud thickness
- water/ice cloud phase
- cloud particle size
- satellite viewing zenith angle
- solar zenith angle

If we require validation of 3 distinct ranges for each of these parameters (e.g. low, moderate, and large solar zenith angles), we require validation of $3^5 = 240$ observing cases, with 100 independent samples per case, or roughly 24,000 independent validation measurements! This would take 8 years of data at 3 ARM sites if all cases were evenly distributed. Clearly, we cannot wait 8 years to validate our satellite cloud observations. Instead, we will have to initially be satisfied with much less accuracy and less discrimination of cloud/viewing condition. With 2 years of data we can roughly achieve 4% accuracy in retrieval bias tests. As longer time series of matched ARM/satellite observations become available, and if other research groups add sites similar to the ARM capability for cloud profiling, then the knowledge of retrieval accuracy can be improved with time. Note that this large number of degrees of freedom in the validation data also serves a second purpose: it eliminates the ability to "tune" 10 or 20 retrieval parameters as might be done with a few case studies from traditional field experiments.

In addition to the bootstrapping approach for *aircraft => ARM => CERES* mentioned above, there are a range of internal consistency checks required for validating cloud remote sensing algorithms. These internal consistency checks are important because even this new strategy to advance the state of the art in validation of satellite remote sensing of cloud properties will have limitations. Only a few climate regions will initially be tested. Cloud remote sensing instrumentation similar to ARM will be required for 3-5 year measurements at desert, midlatitude ocean, tropical land, high-latitude ocean, and mountain sites, just as for the surface radiation data discussed earlier. Currently there are no such sites available. One possibility to help in this regard for the future would be to provide a "roving ARM site". There is discussion of instrumenting the NOAA Ron Brown oceanographic research vessel in this regard. This would be a major step forward for oceanic regions. The CERES team strongly endorses the need for such oceanic measurements of cloud profiles and will use this data to extend the ARM validation if it is made available.

Figure 7 gives results for comparisons of the CERES cloud property validation using the TRMM VIRS imager data compared to the Oklahoma ARM site. Results are shown for nearly simultaneous measurements from VIRS and ARM for particle size, optical depth, and LWP.

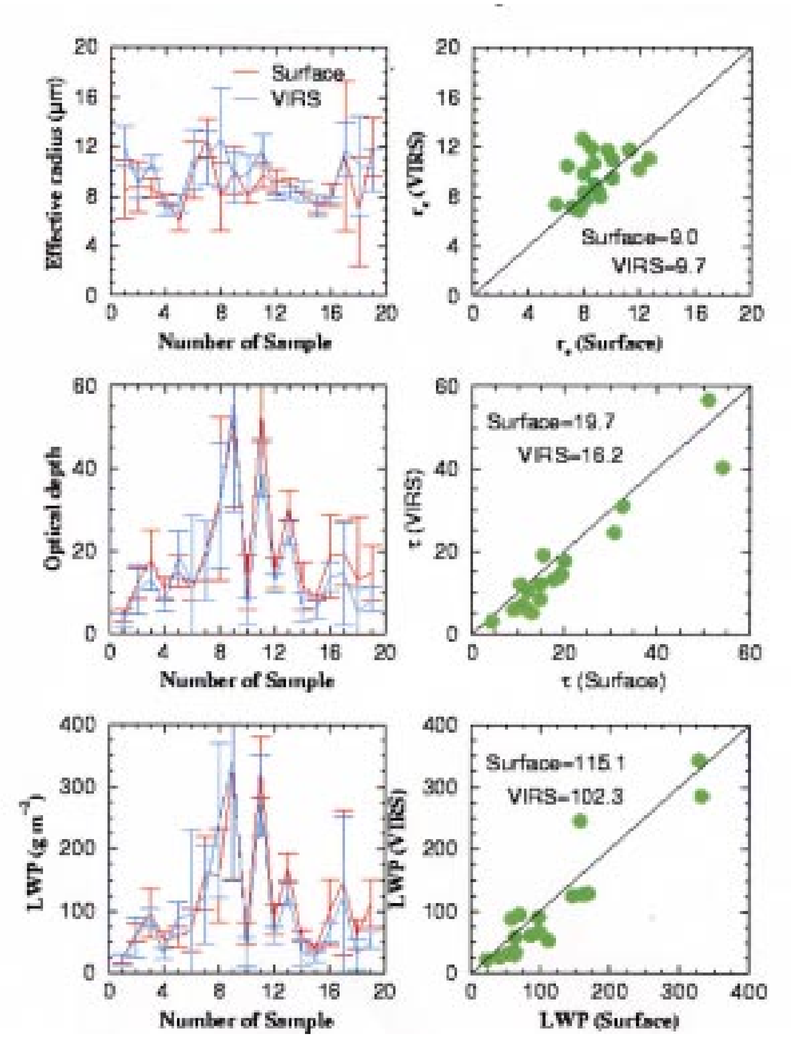


Figure 7. CERES cloud properties derived using the VIRS imager on TRMM compared to the DOE ARM CART site observations for single level water cloud in Oklahoma during January through August 1998.

The comparisons are encouraging, but many more such matches are needed for final validation. Note that the 20 cases shown are all the cases that satisfied both the ARM radar/radiometer algorithm requirement for single level water cloud, and nearly simultaneous daytime observations by TRMM. This confirms the conclusions earlier that years of such intercomparisons will be required to cover a complete range of cloud types and conditions. For this reason, the additional VIRS data on TRMM will be processed through the CERES cloud algorithm over the entire TRMM data set, not just the 10 months of CERES broadband data. This will allow at least a factor of 4 increase in sampling over the results shown in Figs 7 and 8.

One of the more difficult aspects of cloud retrieval using the VIRS data is the lack of any CO2 sounding channels to more accurately estimate cloud altitude of non-black high cloud at night. The ISCCP analysis, for example, must assume clouds are black in the infrared at night. The availability of 3.7, 11, and 12 micron window channels on VIRS, however, allows for a better estimate of cloud altitude at night, even for thin cirrus. Figure 8 shows early validation results of the CERES night-time algorithm analysis clouds during overpasses of the ARM CART site. The cases include thin cirrus as well as thick high and low clouds. Comparisons are again to the time- and space-matched ARM lidar/radar cloud altitude data. Further details can be found in the CERES cloud subsystem validation chapters on the web (Subsystems 4.1 through 4.3).

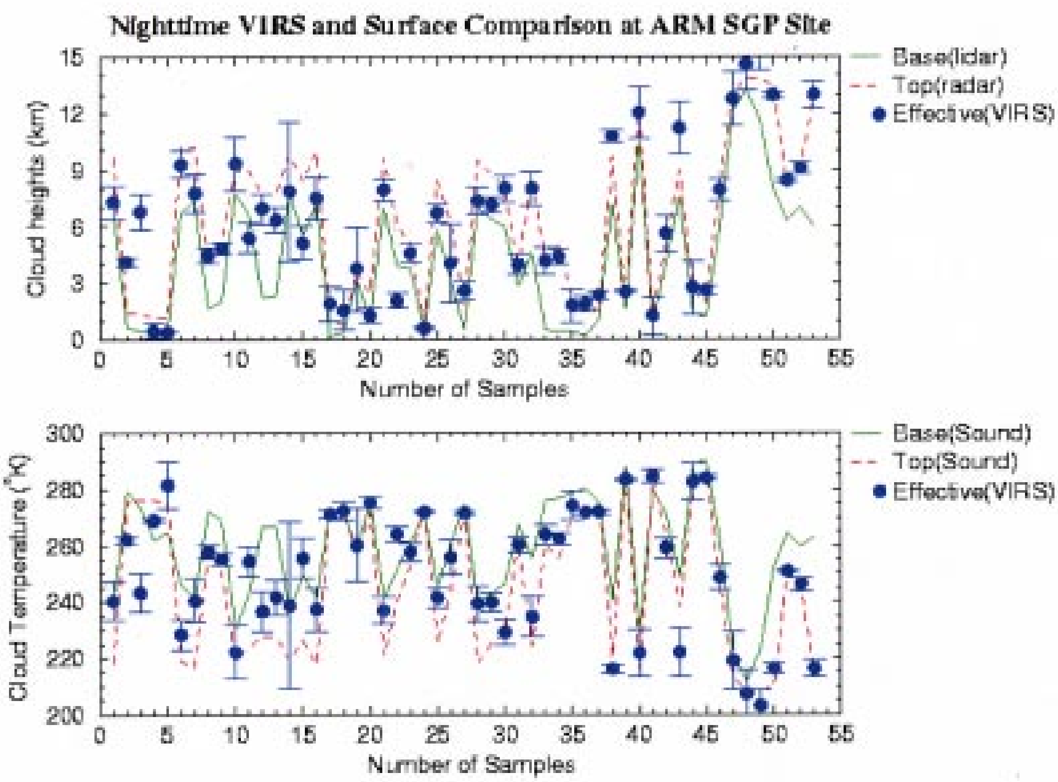


Figure 8. CERES night-time cloud altitude determination for the ARM Southern Great Planes (SGP) site in Oklahoma. VIRS is the effective radiating altitude or temperature of the cloud layer: this is near cloud top for thick clouds, and near cloud center for optically thin clouds.

3.6.2 *Aircraft => ARM Cloud => PICASSO/CloudSat Cloud => Passive Satellite Cloud*

For cloud fraction and cloud layering, the selection of the PICASSO-CENA lidar and Cloudsat radar missions will help greatly with validation of CERES cloud properties. This mission will provide global validation of these properties for all MODIS viewing zenith angles, from forward to back scatter, and over all climatological regions, equator to pole. Unfortunately, the high spectral resolution A-band spectrometer planned for PICASSO-CENA and Cloudsat has recently been descoped from these missions. The A-band was planned for use in studies of ice crystal scattering asymmetry parameter, and for 3-D cloud effects on radiation. The French space agency, however, is planning to add a small spacecraft with a POLDER-2 multi-angle polarization imager flying in formation with PICASSO/Cloudsat/Aqua. This multi-angle polarization measurement may allow recovery of some of the information planned for the A-band spectrometer. In addition, the CloudSat team plans to combine the 94GHz cloud radar with the PICASSO-CENA lidar to estimate vertical profiles of cloud microphysics using the difference in backscattering dependence on particle size: r^2 for lidar versus the r^6 for radar. This method has the potential to work for clouds with optical depths up to about 3 to 5 after which the space-based lidar signal is too strongly attenuated. For thicker clouds, Cloudsat will be testing the use of passive optical or microwave instruments on Aqua to combine with the active radar data. This would provide a very exciting first global view of all cloud layers, especially in the polar regions where little is known about cloud properties or our ability to estimate them from space.

The addition of active lidar and radar in space brings a global dimension to the validation activity which becomes:

Aircraft =>ARM Cloud Profiles => PICASSO/CloudSat Cloud Profiles => Aqua Cloud

The PICASSO-CENA and Cloudsat missions are slated for launch in spring of 2003, and will fly in formation with Aqua as discussed earlier. The Aqua and PICASSO data will also be used to provide a more accurate SW and LW vertical profile of atmospheric radiative fluxes along the PICASSO-CENA ground track. This will supplement the global observations provided using CERES and Aqua. Validation of this enhanced data will be done as part of the PICASSO mission.

Even before the launch of PICASSO-CENA and Cloudsat, there will be an opportunity in 2002 to use the IceSat lidar to get an early sample of some of the capabilities available with the matched Aqua/PICASSO-CENA data. In particular IceSat will be in formation (within +/- 6 minutes) roughly 10% of the time for 40 days each year, or roughly 4 days worth of matched orbits per year. This data will provide an early sample of the capability available with Aqua//PICASSO, and will allow some examination of clouds at other local times of day because of the precessing orbit (i.e. changing local time of day) of the IceSat mission: Icesat will also be in formation with Terra and ADEOS-II for a 40 day period very similar to that for Aqua, but shifted by 3 months. Because the ice sheet orbit restricts the orbit precession repeat to almost exactly 2 years, the same month of the year will be matched between the IceSat lidar and Aqua or Terra each year. Unfortunately, for long-term cloud measurements this orbit aliases the cloud diurnal cycle into the seasonal cycle. Nevertheless, this mission will be useful to assist in cloud validation prior to the launch of PICASSO and Cloudsat. Icesat will also observe clouds at times of day not seen by the sunsynchronous PICASSO/Cloudsat/Aqua 1:30pm orbit.

3.6.3 *Consistency Studies: Theory, and Related Satellite Sensors such as ASTER*

For our understanding of cloud remote sensing to be accurate and well based, there are some necessary conditions that have to be met which go beyond the Aircraft => Surface => Satellite paradigm discussed in sections 3.6.2 and 3.6.3.

In particular, theoretical sensitivity studies are used to test and understand the sensitivity of the satellite passive radiometer retrievals of cloud properties. For example: what is the effect on cloud optical depth of calibration errors in the visible channel of VIRS or MODIS? In early CERES results on TRMM this was a major issue, and the calibration knowledge of the visible channel on TRMM has been examined extensively. One method that has helped greatly was to use the convolution of imager satellite radiances into the CERES broadband field of view for all CERES data. This matched VIRS narrowband and CERES broadband data was analyzed over the entire globe for all VIRS and CERES channels. The analysis clearly showed when artifacts in the VIRS calibration occurred, and these have since been resolved, in particular for the visible channel.

The ASTER satellite will be used to verify the sensitivity of the CERES cloud algorithms to spatial resolution. This satellite has most of the MODIS and VIRS cloud remote sensing channels: the major omission being a 3.7 μm channel. Microphysics effects can be studied, however, using the 1.6 and 2.1 μm channels in place of 3.7 μm. ASTER will allow a much more thorough analysis of these effects with more statistical rigor than was possible with pre-launch Landsat data (e.g. Wielicki and Parker, 1992 and subsystem 4.0 of the CERES ATBDs.). CERES has worked with the ASTER team on Terra to select key climatological regimes which will be used to collect scenes over ocean and land backgrounds for these validation studies. These studies will also be useful in setting spatial resolution requirements for future cloud/radiation satellite missions. A list of the selection of ASTER "star" validation sites is given in Appendix A.

Studies will also be made of the consistency of the cloud property retreivals as a function of viewing zenith angle as well as azimuth angle. The VIRS and MODIS data sets will be used directly for viewing zenith and two azimuths, while studies at a more complete range of angles for cloud optical depth will be examined using POLDER and/or MISR data (Loeb et al., 1999a)

For cloud liquid water path, independent estimates of this quantity from space are available using TMI and VIRS on TRMM, as well as AMSR and MODIS on Aqua. These differences will be examined to verify the performance of the cloud remote sensing algorithms.

3.6.4 *Summary of key remote sensing challenges for cloud properties*

Key problems to be addressed for cloud remote sensing when compared to this new validation data are expected to include (roughly in order of expected importance):

- Multi-layer cloud (expected 50% of the time)
- Polar cloud (snow/ice background)
- Horizontal inhomogeneity (e.g. non-plane parallel effects)
- Vertical inhomogeneity (especially particle microphysics)
- Beam filling for sensors with spatial resolution coarser than 250m

- Cloud masking for highly variable backgrounds
- Distinction of aerosol form cloud at very low optical depth (less than 0.5)

3.6.5 ***S'COOL:*** *Education Outreach and Cloud Validation*

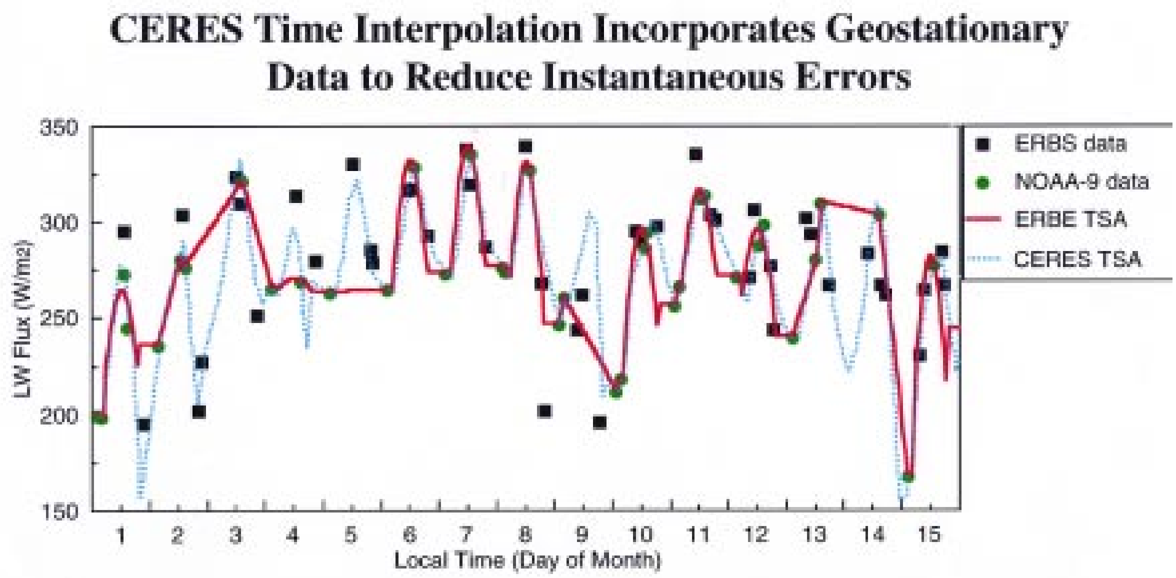
One of the more exciting new initiatives started by Lin Chambers and Dave Young of the CERES team is to involve elementary and high school children in the CERES cloud validation program. The basic concept is that schools sign on to the program, obtain basic training in performing surface cloud observations (sky cover, type, altitude), they log onto the CERES web site to get predicted satellite overpass times, the class conducts cloud observations at the time of the TRMM, Terra or Aqua satellite overpass, and then they either fax or use the web to submit their observations to the CERES S'COOL program (Students Cloud Observations OnLine). This program already has over 600 schools participating in 45 different countries, on all continents. This effort will continue to expand in the future, and provide not only educational outreach, but also surface observations that CERES will compare to our satellite based retrievals. These are expected to be particularily useful for clear-sky determination.

3.7 Time Interpolation and Spatial Averaging

Time interpolation and spatial gridding is used to achieve the final climate data sets on the 1 degree equal-angle grid (larger steps in longitude are taken at higher latitudes: changes take place in steps of two as explained in the spatial gridding ATBD, Subsystem 6). The most difficult part of this task is the time interpolation: handling the time dependent diurnal cycles of surface temperature, solar zenith angle albedo dependence, and cloud property diurnal cycles. For cloud and surface fluxes, the ARM and BSRN sites are used as high time-resolution validation data sets. For TOA fluxes, 3-hourly geostationary radiance data is used to augment the CERES low earth orbit observations. Extensive pre-launch studies have been done by simulating the broadband radiation fields using hourly GOES narrowband data, and then subsampling appropriate to the satellite orbital sampling of TRMM and/or Terra and/or Aqua spacecraft (Young et al., 1998). In general, CERES uses the low-earth orbit broadband data to define the basic radiation field, and then treats the diurnal cycle of these fields as a second order correction to the mean field. In this case, the calibration of the geostationary narrowband data is not a major issue (it is tied regularly to CERES) and the dependence of narrowband/broadband relationships are allowed to change with region of the earth and scene condition (clear or cloud).

Figure 9 shows an example of the combination of broadband and geostationary data using NOAA-9 and ERBS spacecraft ERBE data. NOAA-9 afternoon sunsynchronous broadband data plus 3-hourly geostationary narrowband data (ISCCP-B1 radiance data) were used as inputs. The precessing ERBS orbit (varying local times of day) was then used to test the accuracy of predicted broadband fluxes at other times of day using the proposed CERES Time/Space Averaging algorithm (TSA) as shown in blue. The line in red shows the ERBE-Like TSA algorithm without the GOES data to aid in time interpolation. Even these early tests show a

Figure 9. Example of a 1-month regional time series comparing CERES and ERBE time



interpolation approaches. These results have been run for the entire GOES disk view in July, 1985 and show a factor of 2 improvement for the new approach.

factor of 2 reduction in time sampling error. Studies are underway to evaluate the contributions of separate error sources in the monthly mean using this approach. For example: given the broadband measurement constraint, what is the sensitivity to variability or drift in the geostationary sensor gains.

Future validation studies will examine the utility of converting geostationary radiances to cloud properties for use in time interpolation of cloud, surface, and atmosphere radiative fluxes. The key issues here will be the dependence of these properties on differing calibration between VIRS, MODIS, and the geostationary instruments. For this reason, a routine monitoring of matched time/space/view angle geostationary/VIRS and geostationary/MODIS data will be performed. The input geostationary data is obtained from the ISCCP B1 archive. If successful, the ability to merge highly calibrated broadband data with high time resolution geostationary data will allow future radiation budget measurements (e.g. NPOESS starting in 2009) to be made with a single broadband instrument. NPOESS is planning to implement this strategy by flying a CERES-like broadband instrument on its 1:30pm sunsynchronous platform (same orbit as Aqua).

3.8 Meteorology Ozone and Aerosols (MOA) Testing

CERES inputs meteorology fields including temperature profile, water vapor profile, winds, ozone, and aerosols for a variety of uses in CERES processing. Current sources of these products include:

- ECMWF for temperature, humidity, winds at 0.5 deg resolution and 50 vertical levels with 6 hourly time resolution in the atmosphere and 3-hourly at the surface.
- NOAA satellite based ozone data from their SMOBA data product
- Aerosols for TRMM are currently retrieved in the CERES algorithm using the VIRS imager data and an advanced 2-channel (0.6μm and 1.6μm) version of the AVHRR Pathfinder algorithm (Larry Stowe). Aerosols for Terra and Aqua will be taken from the standard MODIS aerosol data product.

Since these products are primarily provided from non-CERES sources, the CERES validation plan only tests these products for accuracy in ways specific to CERES use of the data. Below we list each of the major uses of these inputs in the CERES algorithms and the CERES validation tests on these input data.

3.8.1 Land Surface Skin Temperature

The CERES cloud algorithm uses cloud imager derived land skin temperature for cloud retrieval where it is available, but uses the ECWMF skin temperature when it is not available. Extensive testing was done shortly after the launch of TRMM (spring and summer 1998) to determine the effect of skin temperature accuracy on the cloud retrieval algorithm for NCEP, DAO GEOS-2, and ECMWF. Hourly GOES retrievals and ARM site data were used to test the products, and ECMWF was shown to be the most accurate, and to meet the CERES cloud retrieval needs. Diurnal cycles of skin temperature as well as seasonal biases were considered.

3.8.2 Temperature/Humidity Profiles

The major concern for CERES is to verify the performance of the humidity profiles for LW flux calculations within the atmosphere, and of temperature inversions for conversion of satellite determined cloud temperature into cloud height. Clear-sky CERES measured broadband longwave and window (8-12μm) channel radiances were compared to calculations using ECMWF, DAO, and NCEP temperature and humidity profiles over land and ocean along with the MODTRAN radiative transfer model . The CERES window channel responds primarily to surface skin temperature and column water vapor (dominated by the boundary layer water vapor). The CERES broadband channel, however, responds strongly to the upper tropospheric water vapor which controls about half of the broadband emitted energy for clear-sky longwave radiance: that coming from wavelengths longer than 15 μm. These comparisons also confirmed that in early 1998, that ECMWF gave the best performance for skin temperature, column water vapor, and upper tropospheric humidity. Tests were also made of the boundary layer temperature inversions. Unfortunately none of the models performed well here (errors in cloud height of 1km or more), and so CERES decided that for marine boundary layer clouds, a constant lapse rate from surface to cloud top would be assumed for any clouds with cloud temperatures warmer than the ECMWF profile temperature at 750 hPa. The lapse rate assumed is 7.1K/km based on field experiment radiosonde profiles.

3.8.3 Aerosols and Ozone

For aerosols on Terra and Aqua spacecraft, the CERES algorithms will input the MODIS and MISR data products, and rely on the MODIS and MISR team validations. For TRMM, there was no available aerosol product, and so Larry Stowe on the CERES Science Team modified the AVHRR pathfinder algorithm to take advantage of the VIRS 0.6 and 1.6μm channel imager data whenever the CERES cloud mask algorithm indicated "strong clear". This algorithms performance is tested using TRMM overpasses of the AERONET aerosol sites to verify aerosol optical depth. Dependence of the aerosol properties on viewing angle and solar zenith angle were also examined. Performance in the Edition 1 SSF data product is similar in accuracy to the AVHRR Pathfinder algorithm. CERES relies on NOAA for validation of the ozone profiles. The ozone profiles are used in the SARB atmospheric flux calculations. They are also used to make a relatively small correction for ozone absorption in the visible wavelength imager channels for the cloud retrieval algorithms.

*3.8.4 Future 4-D Assimilation Data Sourc*es: *ECMWF, DAO GEOS 3.3, and NCEP*

The final objective for CERES is to obtain a source of 4-D assimilation data for temperature, humidity, and winds that will be processes consistently from the beginning of the TRMM mission in January 1998, through the end of the CERES data. During the early validation phase, ECMWF data has been used, and some changes in this 4-D analysis system have occurred, and will continue to occur. The GSFC DAO group is nearing completion of the GEOS 3.3 system, which we anticipate will achieve similar accuracy to the ECWMF results but at 1 degree resolution instead of 0.5 degree. We have continued to coordinate this activity with the DAO staff. Man-Li Wu at NASA GSFC is the DAO representative to the CERES team and attends the CERES science team meetings. The DAO has agreed to provide a fixed 4-D analysis system starting in December 1997, for use in CERES climate data sets and feels they can meet our requirements with GEOS 3.3. CERES testing of GEOS 3.3 products will begin in Jan/Feb of 2001 and will include the tests mentioned above for skin temperature (3.8.1) and temp/humidity profiles (3.8.2). Analysis will use two complete months of January 1998 and July 1998 for skin temperature testing to allow tests of seasonal and diurnal cycles using the same data in the earlier testing. One of the considerations in the skin temperature test will be whether the 0.5 deg ECWMF spatial resolution is a significant improvement over the 1 degree resolution of GEOS 3.3. In addition, several days in the early Terra data for spring 2000 will be used in the 3.8.2 temperature/humidity test and will be examined globally. A decision will then be made for future use of GOES 3.3 and ECMWF. Beyond this time frame, it may also be feasible to consider the ERA-40 re-analysis product, which is also planned for use in a fixed continuity analysis of past and future data. It is unclear at this time, however, when ERA-40 will be available, although late 2001 looks likely.

3.9 CLAMS: Chesapeake Lighthouse and Aircraft Measurements for Satellites: Summer/Fall of 2001.

CLAMS is an aircraft field campaign that is planned for summer 2001 at the CERES Ocean Validation Experiment (COVE) site – a rigid sea platform 20 km east of Virginia Beach. CLAMS is a clear-sky, shortwave (SW) radiation closure campaign sponsored by CERES, MISR, MODIS-Atmospheres, and GACP. It seeks more accurate:

i) *Broadband and spectral fluxes at the sea surface and within atmosphere;*
ii) *Space-time variability of spectral BRDF of the sea surface;*
iii) *Retrievals of aerosols and radiative impacts with satellites.*

CLAMS flights seek clear conditions (cloud-free but not aerosol-free). CERES, MISR (Terra), MODIS-Atmospheres, and GACP sponsor CLAMS. Besides the continuous, long-term COVE measurements, CLAMS is planning for flights by

- NASA ER-2 carrying the Air MISR multi-angle spectral radiometer, the MODIS Airborne Simulator (MAS), and a Cloud Lidar (CPL).
- Langley low-level OV-10 carrying broadband and spectral flux measurements (0.4 to 2.5um) both up and downlooking.
- CV-580 from the University of Washington CV-580 is probable and would provide measurements of in situ aerosols and chemistry, along with the CAR radiometer for surface BDRF.
- The French are considering deployment of the M-20 aircraft with an airborne version of POLDER and the LEANDRE Lidar.

CLAMS is needed to fill gaps in CERES surface and atmospheric radiative flux validation using COVE. There are two main limitations to the observations of broadband upwelling radiation at COVE. First, the platform obstructs some of the view of the ocean surface. Second, there are uncertainties in how well the ocean directly beneath the platform represents the sea in general. On the larger 20 km scale of a broadband CERES footprint, there are certainly systematic variations in spectral albedo at COVE, which is 20 km off Virginia Beach. MODIS pixels will be used to scale the COVE sea optics to the larger CERES footprint. Does the sea bottom directly under the platform permit COVE measurements to adequately represent the sea within 1 km (the scale of an imager pixel like MODIS)?

The two issues can be resolved by a survey of broadband flux (up and down for SW and LW), downwelling spectral irradiance, and upwelling spectral irradiance and directional radiance with the CERES Fixed wing Airborne Radiometer (C-FAR) on the low-level OV-10 aircraft. In the months leading up to CLAMS, COVE will measure the broadband upwelling fluxes (BSRN) and selected SW spectral radiances (SP1-A spectral-photometer) to establish the variations of albedo and BRDF for a wide range of conditions. CLAMS will provide the needed offsets (due to platform obstruction) of those relationships. And by exhaustively covering a few MODIS pixels, CLAMS will permit us to securely “scale-up” MODIS-based sea optics to the larger CERES footprint. MISR Validation has similar concerns about scene variability within its instrument’s FOVs (i.e., Kahn et al., 2000) and plans to use AirMISR spectral radiances on the ER-2, as well as C-FAR spectral fluxes on the OV-10.

The variation the spectral SW radiance between imager pixels (MODIS, MISR, or AVHRR) nearby COVE under clear conditions is influenced by the spatial variability of both the sea and the aerosols above it; CLAMS will target both in order to allow separation of these two effects. A particular imager pixel centered on 1 km**2 may be adequately surveyed near the sea surface by the OV-10, but because the imager views at an angle, aerosols at horizontal distances much greater than 1 km will affect the radiance to the satellite. An accurate “atmospheric correction” to a SeaWifs retrieval, for example, depends on aerosols spread over a larger area than just a single pixel projected to the sea surface. A separation of the spatial variation of aerosol loading from that due to ocean optics is needed to validate accurate retrievals of both quantities. This is especially the case if one seeks to retrieve the low “backround” loading of aerosols that force global climate. The CPL on the ER-2 will be the principal tool in CLAMS for determining the vertical and horizontal variation of aerosols. Thin vertical “pencil” slices by CPL will be interpreted by MAS and AirMISR images from the ER-2. They will also serve as a test-bed for developing algorithms of the PICASSO-CENA satellite lidar mission planned for 2003.

In-situ aerosol and chemistry measurements by the CV-580 would provide CLAMS with an even higher level of closure for aerosol optical properties. When combined with the CPL on ER-2 and the COVE surface-based instruments, there would be thorough description of the aerosol; sufficient for rigorous testing of the physical assumptions on aerosols behind the retrievals of MODIS, MISR, GACP and CERES (including the broadband angular dependence model). The vertical profiles of SW flux retrieved by CERES-SARB are strongly influenced by the profiles of aerosol absorption, which can be measured by the CV-580. Aerosol absorption is the principle source of de-coupling between aerosol forcing at TOA and at the surface. INDOEX found that surface and TOA forcing differed by roughly a factor of three; as hypothetical aerosol forcing may be vanishing at TOA but even exceed the forcing of greenhouse gases to the atmosphere itself, this has enormous implications for the global hydrological cycle. CLAMS should be an excellent database for studies of aerosol assimilation (i.e., Collins and Rasch).

A second CLAMS campaign in fall 2001 may be needed to meet special needs of CERES and MISR, and to extend the application of COVE data to AIRS (on the Aqua spacecraft planned for launch in summer, 2000). MISR requires especially stringent cloud free conditions (which may not coincide with the MISR week-long viewing cycle) and prefers low aerosol loadings for validation. The mean aerosol optical depth at COVE in July is about 0.3, which is suitable for MODIS validation. But the conditions required by MISR for coincidence of ER-2 (with AirMISR) and Terra may not be obtained in a single month (i.e., July 2001).

Table 3 gives the expected aerosol optical depth from COVE AERONET measurements, the frequency of totally clear-sky conditions from the Hahn et al surface observer seasonal cloud climatology, and the frequency of contrails from surface observers at nearby Langley Air Force Base.

Table 3. Selected atmospheric properties at the COVE site.

Month	***Aerosol Optical Depth***	***Freq. Of Clear-Sky***	***Contrail Freq.***
May	0.19	15%	27%
June	0.27	13%	16%
July	0.35	13%	9%

Aug	0.30	13%	11%
September	0.17	18%	11%
October	0.12	18%	22%

A second component of CLAMS in fall 2001 would permit CERES to validate the retrieval of the vertical profile of LW surface/atmosphere fluxes by collaborating with AIRS in checking the vertical profile of water vapor (especially UTH) with an M-AERI spectrometer at the COVE platform, NAST-I and NAST-MTS on Proteus, and possibly an airborne LASE DIAL water vapor profile measurement. The LASE DIAL is probably the most accurate instrument for the measurement of UTH, which is the critical variable in the computation of the LW SARB profile. NAST-I radiances on Proteus, which can operate efficiently at a wide range of altitude, would allow a spectral validation of the broadband LW SARB vertical profiles. In a second CLAMS, CERES OV-10 flights would measure the spatial variations SW sea optics for MISR and spatial variations of ocean skin temperature for AIRS. Such observations of ocean skin temperature and the humidity profiles would provide an ideal input for a theoretical simulation of CERES LW TOA radiances and fluxes under clear conditions. Comparably accurate input data would be much more difficult to obtain over land, where surface LW emission varies greatly in space due to canopy orientation, soil moiture and type, and viewing angle relative to the sun (Minnis et al, 2000 and Lin et al. 2000). A CLAMS web-site can be found at http://www-cave.larc.nasa.gov/cave/cave2.0/CLAMS.dir/index.html. Further information on CLAMS objectives relative to CERES can also be found in the subsystem 5.0 CERES SARB validation plan on the web.

4. Key CERES Validation Issues

The CERES validation strategy for clouds and radiation was to save resources by bootstrapping results from existing programs: ARM, BSRN, FIRE, SURFRAD, etc. This strategy is highly cost effective, but does entail risks if these programs are not successful. In particular, both ARM and FIRE programs have taken roughly factor of 2 funding cuts since the CERES program plan assumed their data availability. It has taken longer than anticipated to validate the ARM vertical cloud profiles using aircraft data, and longer than anticipated to bring the 3 climatological ARM sites on line. The Barrow and Western Pacific sites have only routinely started providing data in the last year. Further, we are just arriving at the point of getting routine daily ARM retrievals of radar/lidar/radiometer cloud data. It does appear, however, that at least for several cloud types, these data will be routinely produced at the ARM sites starting this year. This delay affects primarily the schedule for TRMM cloud validation, although EOS-AM might be affected if there are additional delays and budget cuts. CERES has also taken annual budget cuts, and as a result the current validation plan for TRMM is roughly 6 months behind schedule. Note that to help in this regard, the EOS Validation program has been funding a few key efforts to improve the ARM data analysis: especially those investigations by Mace, Intieri, and Heymsfield. CERES is working with these individuals to maximize the benefit to CERES validation efforts. The key problem is obtaining sufficient cases of aircraft in-situ data validating the ARM vertical profiling cloud data. *Field experiments like ACE (arctic)* *and CRYSTAL (tropical ocean) will help greatly but must focus aircraft data increasingly on validation of the surface remote sensing data. FACE and CRYSTAL tropical cirrus experiments in particular will be critical in light of the almost total lack of microphysical observation at altitudes above 12 km in the tropics. Fortunately early drafts of the CRYSTAL program included efforts to focus on support of the Aircraft => ARM => Satellite strategy.*

BSRN has not received the level of funding and support from the international community that was envisioned in the early 1990s. The leaders of this program have put tremendous individual effort into it, but with little financial support. Again, the EOS validation program has tried to help with funding for Dutton, Deluisi, and NREL to assure some basic level of data is available to validate EOS. CERES is also contributing directly to these efforts by supporting the BSRN/AERONET site at Chesapeake Light, as well as purchase and deployment of micropulse lidars at 3 BSRN sites in climate regions not covered by ARM.

As is evident from the discussions of the individual sections, it is still not clear how we obtain ARM-like validation data in climate regions not currently covered by ARM: desert, tropical land, subtropical ocean, midlatitude ocean, high latitude ocean, and antarctica, One promising possibility is that NOAA will outfit the Ron Brown oceanographic research vessel to routinely take BSRN and lidar/radar/radiometer cloud and aerosol data during ship cruises. This type of "roving" oceanic ARM site would be a major step forward. It will not, however, solve the problem of the tropical land and desert climate regions. ARM is considering deployment of a mobile ARM site for 1 to 2 year deployments, but plans are still under development (T. Ackerman, personal communication 7/00)

Finally, while the focus of the CERES validation effort is on a long time series of observations to achieve statistical robustness, we must not forget that the most complete set of parameter measurements will always be from field experiments such as ACE, SAFARI-2000, and CRYSTAL/FACE. FACE and CRYSTAL will be the only short term programs to measure in-situ tropical cloud microphysics, and SAFARI-2000 may be the only opportunity to measure IGBP tropical land spectral albedos, ADMs, and emissivities. These are critical especially for tropical forest and savannah. CERES will work with these programs to assist in the validation effort, especially for the use of aircraft in-situ data to validate the ARM vertical cloud profiling data.

5. Validation Organization, Management, and Co-ordination

It is clear from the discussion in the earlier sections, that carrying out the CERES validation involves a wide range of activities. Coordination of these activities is handled through the organizational structure of the CERES science team. B. Wielicki is the scientific lead for the overall validation activity, while the CERES Working Group Chairs lead the specific validation efforts. The CERES Science Team serves as a review team representing the user community and reviews the validation results for each data product before it is approved to move from a developmental "beta" quality to final validated "Edition 1" data products. Note that the validation plans, like the ATBDs are put through a formal written review process by the EOS Project. So for any given data product, the process is:
Working Group Validation => Science Team Review => Data Quality Summary => Production, Distribution and Archive => Research/Publication. Notice that early "beta" versions of data

products are usually available prior to final validation in order to encourage early access by the science community. But these early "beta" data products have been given very minimal validation and are NOT to be used in scientific publications. For example, the CERES instruments on the Terra spacecraft began taking data in March, 2000. The initial "beta" quality global data products (level 1 radiances through level 3 gridded TOA fluxes) were made available starting in May, 2000. The CERES Science Team approved Edition 1 of the Terra ERBE-Like BDS, ES-8, ES-4 and ES-9 data products in September, 2000. Data Quality Sumaries were completed in October, 2000, and production of Edition 1 data products is planned to begin near the end of October, 2000.

The CERES Working Groups are organized to be as consistent as possible with the data products in the data flow diagram (Fig. 1). The chairs of each working group are in charge of leading the validation activities for their data product(s). For example the working groups and chairs are:

Working Group	**Chair**	**Data Products**
Instrument	Kory Priestley	BDS (radiances)
Cloud Working Group	Pat Minnis	SSF (cloud properties)
TOA Fluxes/Angular Models	Norman Loeb	ES-8 (ERBE-Like TOA fluxes) New angular models for SSF product SSF (TOA Fluxes only)
Surface Products	Dave Kratz	SFC
Surface and Atmosphere Radiation Fluxes (SARB)	Tom Charlock	CRS
Time Interpolation and Spatial Averaging (TISA)	Dave Young	FSW, SYN, AVG, ZAVG, SRBAVG

In this way, the validation activity is organized along the same lines of communication as the development of the algorithms and production analysis software. Many of the CERES science team members are also active within the working groups in supporting validation activities.

Finally, because of the strong dependence of CERES validation on activities by ARM and BSRN, there is a need to coordinate with these other science activities. This coordination is handled through telecons, email, and participation at CERES science teams, including invited presentations to the CERES team. Key contacts that CERES coordinates with are:

Validation Data Source	*Contacts*
ARM	Tom Ackerman (ARM Project Scientist) Jay Mace and X. Dong at Univ of Utah Taneil Uttal at NOAA ETL
BSRN	Els Dutton at NOAA CMDL
SURFRAD	Deluisi at NOAA CMDL
AERONET	Brent Holben, NASA GSFC
Future ground lidar network	Jim Spinhirne, NASA GSFC

6. Validation Schedules

More detailed validation plans are given in each of the subsystem validation plans (see http://asd-www.larc.nasa.gov/ceres/docs.html), while the current document is an overview of the entire plan. Below is the overall schedule for validation of each CERES major level 1, 2, and 3 data products. The "validation date" gives the predicted time that a data product would complete validation and pass review by the CERES science team. At this point the CERES Data Quality Summary for the data product would be ready, and the data product would start production of Edition 1 data, including reprocessing of earlier versions such as the "beta" quality data.

Nominal CERES Validation Schedule

Product	Name	Validation Date
Level 1 Radiance Calibrate/Navigate	**BDS**	**Launch + 6 months**
Level 2 ERBE-Like TOA Fluxes	**ES-8/4/9**	**Launch + 9 months**
Level 2 Cloud Properties: validate	**SSF**	**Launch + 18 months**
Level 2 Cloud: Reprocess/archive	**SSF**	**Launch + 24 months**
Level 2 New angular models (ADMS) (based on reprocessed cloud archive+radiances)		**Launch + 30 months**
Level 2 Surface/Atmosphere Fluxes	**CRS**	**Launch + 36 months**
Level 3 Gridded/Time Avged Cloud/Flux	**Several**	**Launch + 42 months**

To date, this schedule has been met successfully for validation of the level 1 instrument radiance (BDS) and levels 2/3 ERBE-Like TOA Fluxes (ES-8, ES-4, and ES-9) on both TRMM and Terra missions with CERES instruments. Aqua is currently expected to launch in summer, 2000. The combination of Terra and Aqua CERES data will be used to provide more accurate diurnal cycles of the radiation fields. The CERES instrument on TRMM operated from Jan 98 to August 98, for selected field experiments such as INDOEX in March/April of 1999, and for an overlap period with Terra of March/April of 2000. Unfortunately, a faulty voltage converter degraded over time, and has precluded an useful data from CERES/TRMM after June, 2000. The fault was traced to a design problem in the voltage converters, and these components were replaced on all of the Terra and Aqua CERES instruments. The TRMM SSF Edition 1 data product was approved by the science team September, 2000 and will enter production near the end of October, 2000. This early version of SSF will be used to generate the new CERES angular models for TRMM, so that it contains cloud and aerosol physical properties for each CERES field of view, but TOA fluxes only for clear-sky fields of view. After the new angular models are produced, then the Edition 2 SSF with TOA fluxes for all fields of view will be available. The delays in TRMM SSF validation were caused by delays in getting calibrated VIRS data, delays in getting ARM cloud profile data, and validation budget cuts.

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Appendix A: ASTER STAR Sites for CERES and MODIS

Note: Daytime acquisitions include all 14 VNIR, SWIR and TIR channels
Nighttime acquisitions include all 5 TIR channels

In Priority Order:

I. ***ARM sites***: 5 sites, **1200 total scenes** over 5 years, (58% during daytime)

Purpose is to help validate retrievals of cloud properties, radiative fluxes and aerosol properties. The sampling strategy is dependent upon how rapidly the surface properties and clouds change. The Oklahoma ARM site is the most variable for land and cloud both in terms of season and day-to-day. ARM sites have the best characterization of the atmosphere anywhere in the world, and these are the highest priority CERES and MODIS acquisitions. The tropical ocean and polar ARM sites experience slower and fewer changes in cloud type and surface conditions with season; therefore, they require fewer acquisitions.

Site	Lat/Long	Requirement
ARM, Oklahoma	40.03/-105.27	4 daytime/mo * 60 mo = 240 2 night/mo * 60 mo = 120
ARM, Manus Island	-2.06/147.43	2 daytime/mo * 60 mo = 120 2 night/mo * 60 mo = 120
ARM, Nauru Island	-0.53/166.92	2 daytime/mo * 60 mo = 120 2 night/mo * 60 mo = 120
ARM, Kiritimati Is. (Christmas Is)	1.87/-157.33	2 daytime/mo * 60 mo = 120 2 night/mo * 60 mo = 120
ARM, Barrow*	71.27/-156.83	1 daytime/mo * 60 mo = 60 1 night/mo * 60 mo = 60

*Note that the polar scenes will be 2 daytime per month (polar day) plus 2 nighttime per month (polar night).

I. ***BSRN sites*** (Baseline Surface Radiation Network): Purpose is to obtain verification of surface radiation and cloud properties in climatic regimes not covered by the ARM sites. These sites have the world's most accurate surface radiation measurements. Each site requires 1 daytime and 1 nighttime acquisition per month for each of the 60 months of the mission, or 120 acquisitions per site. 14 sites * 120 acquisitions/site = **1680 total scenes**.

BSRN Site	Lat/Long
Alice Springs, Australia	-23.70/133.87

Aswan, Egypt	24.00/33.00
Bermuda	32.37/-64.70
Bondville, Illinois	40.05/-88.37
Boulder, Colorado	40.03/-105.30
Carpentras, France	44.05/5.05
Florianopolis, Brazil	-27.58/-48.52
Fort Peck, Montana	48.00/-105.00
Georg von Neumayer, Antarctica*	-70.65/-8.25
Goodwin Creek, Mississippi	34.00/-90.00
Ny Alesund, Spitsbergen, Norway*	78.93/11.93
Ping Chuan, China	28.00/102.00
Syowa base, Japan, Antarctica*	-69.00/39.35
Toravere Obs/Estonia	58.33/26.73

II. ***<u>SURFRAD and AERONET sites</u>***: These sites are primarily to characterize different aerosol types around the world. <u>Daytime sampling only</u>. 1 daytime acquistion per month for each of the 60 months, or 60 acquisitions per site. 20 sites * 60 acquistions/site = **1200 total scenes.**

Site	**Lat/Long**	
Sable Island, Nova Scotia	43.93/-60.01	Perturbed Marine
K'puszta, Keszcemet, Hungary	46.97/19.55	Perturbed Continental
Cheeka Peak, Washington	48.30/-124.62	Clean Marine
Tucson, Arizona	32.23/-110.95	Desert
GSFC, Maryland	39.03/-76.88	Urban
Bondoukoui	11.85/-3.75	West Africa
Ouagadougou	12.20/-1.40	West Africa
Catalina Island, California	34.00/-119.00	Urban
Cuiaba	-15.50/-56.00	Biomass Burning
Dry Tortugas	24.60/-82.80	Florida
Bermuda	32.37/-64.70	Atlantic
Capo Verde	16.73/-22.94	W. Coast Africa
Ascension Island	-7.98/-14.41	Atlantic
Barbados	13.00/-60.00	Caribbean
La Reunion	-20.00/55.50	S. Indian Ocean
Mongu	-15.50/23.00	S. Central Africa
Male	5.00/74.00	S. India, ocean
Tromelin	-16.00/54.50	Biomass Burning
Okinawa	25.50/128.00	S. China Sea
Crete	35.00/25.00	Mediterranean

III. ***<u>Polar sites</u>***: These sites are in addition to the ARM and BSRN sites listed above. They are to cover major types of snow/ice/cloud conditions in the polar regions. Note that the polar scenes will be 2 daytime per month (during polar day) plus 2 nighttime per month (during polar night). Average 1 acquisition/month * 60 months (=60 acquisitions/site) * 9 sites = **540 total scenes.**

Polar Site	**Lat/Long**
Alert Airport, Canada	82.31/-62.17
Baker Lake Airport, Canada	64.18/-96.05
Upernavik, Greenland	72.47/-56.10
Norilsk, Russia	69.20/88.06
Franz Josef Land, Russia	80.00/55.00
McMurdo, Antarctica	-77.51/166.40
Palmer, Antarctica	-64.46/-64.05
Casey, Antarctica	-66.01/111.05
Brockton, Antarctica	-78.48/-174.40

V. ***Ocean sites***: These sites are chosen to characterize the Scherr Global Cloud Climate regions not covered by the existing land and island site data listed above. Specific ocean locations are listed rather than strips, since clouds will not be independent in adjacent 60 km ASTER scenes along an orbit track. 1 daytime and 1 nighttime acquisition per month is requested for each site * 60 months (= 60 acquisitions/site) * 16 sites = **960 total scenes**.

Lat/Long
53.00/-150.00
43.00/-153.00
37.00/-123.00
30.00/-119.00
20.00/-133.00
15.00/-103.00
7.00/-90.00
-7.00/-137.00
-10.00/65.00
-20.00/-75.00
-28.00/37.00
-30.00/-75.00
-33.00/-142.00
-40.00/150.00
-45.00/-145.00
-55.00/-147.00

IV. ***Special MODIS sites:*** These sites have been selected by the MODIS team. The Tibetan Plateau is expected to be an especially difficult region for cloud masking. Two others sites are in and out of the monsoon region, one in the middle of India and one that is often cloud covered, in Borneo. 1 daytime and 1 nighttime acquisition is requested for each of the three sites/mo * 60 months = 120 scenes/site. **Total 360 scenes** over 60 months.

Site	**Lat/Long**
Tibetan Plateau	33.00/90.00
India	17.00/77.50
Borneo	00.00/115.00

Summary of Scenes:

I.	1200
II.	1680
III.	1200
IV.	540
V.	960
VI.	360
Total	5940