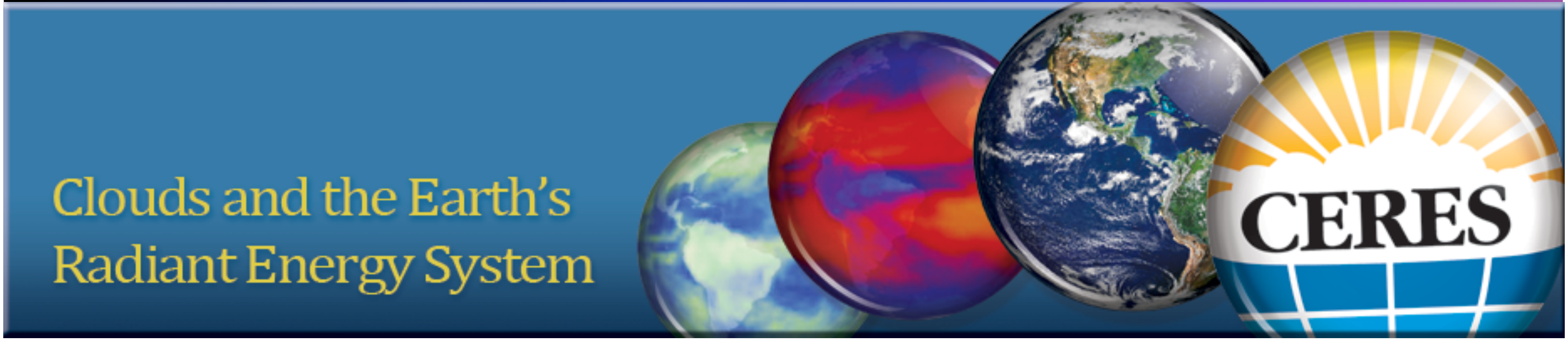

Enabling Continuity in the Earth Radiation Budget Observations by Application of a Rigorous Calibration and Validation Protocol to the Observations of the Clouds and the Earth’s Radiant Energy System (CERES) Instruments

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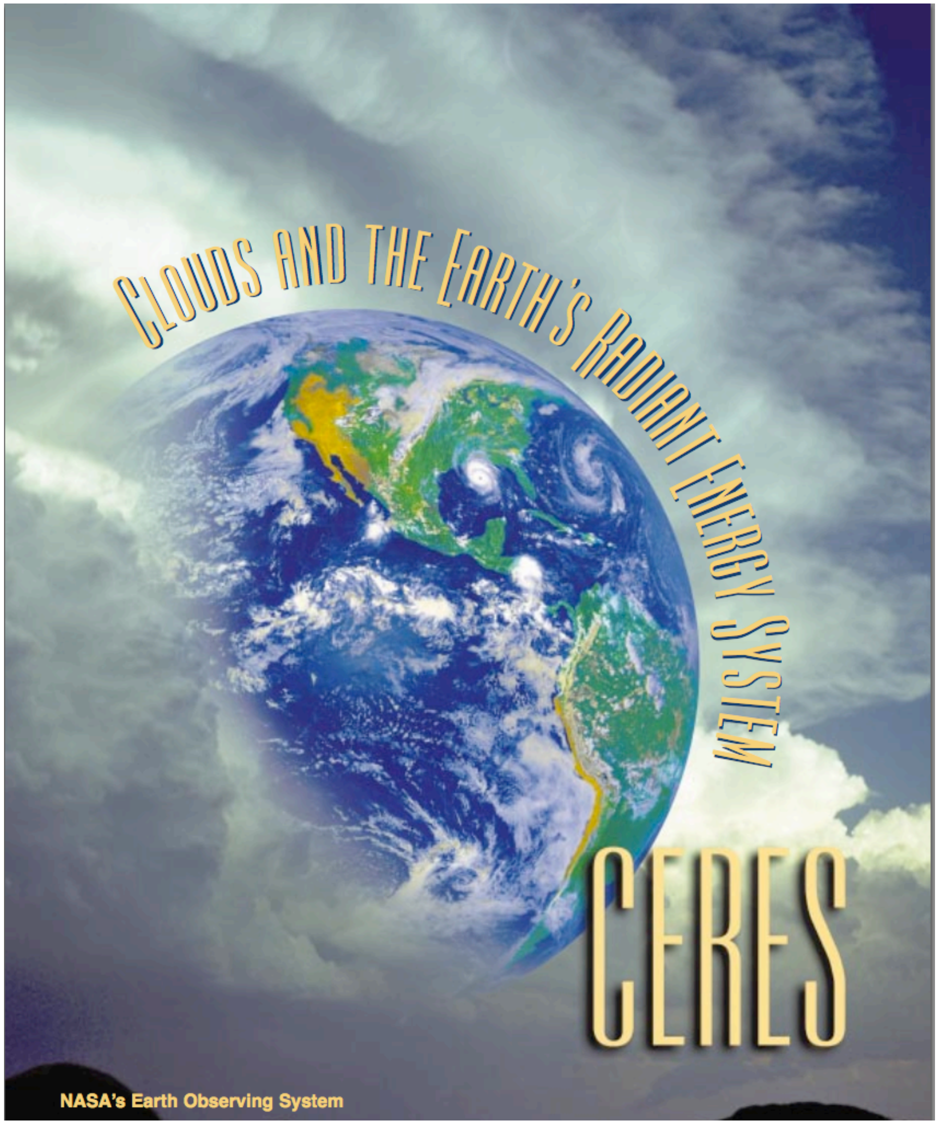
[1]NASA Langley Research Center, [2]Science Systems and Applications Inc

CalCon 2013
Utah State University
August 19, 2013

Discussion Topics



- **CERES Overview**
  - Measurement objectives
  - Instrument description
  - Flight history
- **Radiometry**
  - Performance Requirements
- **Cal/Val Implementation**
  - Pre-Launch Calibration
  - Post-Launch Protocol
  - Data Product Release Strategy
- **Lessons Learned**

Climate Data Records

- **What are they?**
  - Long term data records whose span and accuracy allow definitive and rigorous conclusions with regard to key climate questions.
  - Phenomena in question typically have decadal + time scales
  - Signals <1% of mean value and 2-3 times less than the natural variability
- **What are their typical characteristics?**
  - Climate quality typically not achieved until 2-3 years after initial measurements
  - Quality obtained through multiple reprocessings
  - Rigorous configuration control
    - Different quality editions
    - Rigorous archival system
- **What Climate Data Record does CERES produce?**
  - Earth Radiation Budget (ERB)
- **ERB Identified as a critical Climate Data Record:**
  - *2007 Global Climate Observing System WCRP Report*
  - *2007 NRC Decadal Survey*
  - *'Impacts of NPOESS Nunn-McCurdy Certification on Joint NASA-NOAA Climate Goals', January 2007*

Spatial and Temporal characteristics

What is the *temporal span* of the phenomena being observed?

- **Process studies**
- **Coverage of field campaigns**
- **Seasonal Cycles**
- **Inter-annual variability**
- **Decadal change**

What is the *spatial extent* of the phenomena being observed?

- **Global Mean**
- **Zonal**
- **Regional**
- **Cloud forcing**
- **Cloud radiative effect**

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Measurement to CDR

- **Does CERES measure Climate Data Records directly?**
  - No, CERES measures instantaneous TOA broadband radiances
    - SW channel - Reflected Solar
    - TOT channel - Reflected Solar + Emitted Thermal
    - LW channel - Emitted Thermal
- **How do we get CDR's from instantaneous Radiance measurements?**

Thermal Energy → Electrical Signal → Radiance → TOA flux → Surface and Atmospheric Flux → Gridding → Spatially Averaged → Temporal Interpolation → Temporal Averaging

- **In addition to CERES instrument data, this process requires:**
  - Cloud Imager Data
  - Aerosol Optical Depth
  - Atmospheric State Data
  - Surface Temperatures
  - Geostationary imager data for diurnal interpolation

High level of data fusion; up to 11 instruments on 7 spacecraft all integrated to obtain climate accuracy in TOA to surface fluxes ~8-dimensional radiative assimilation

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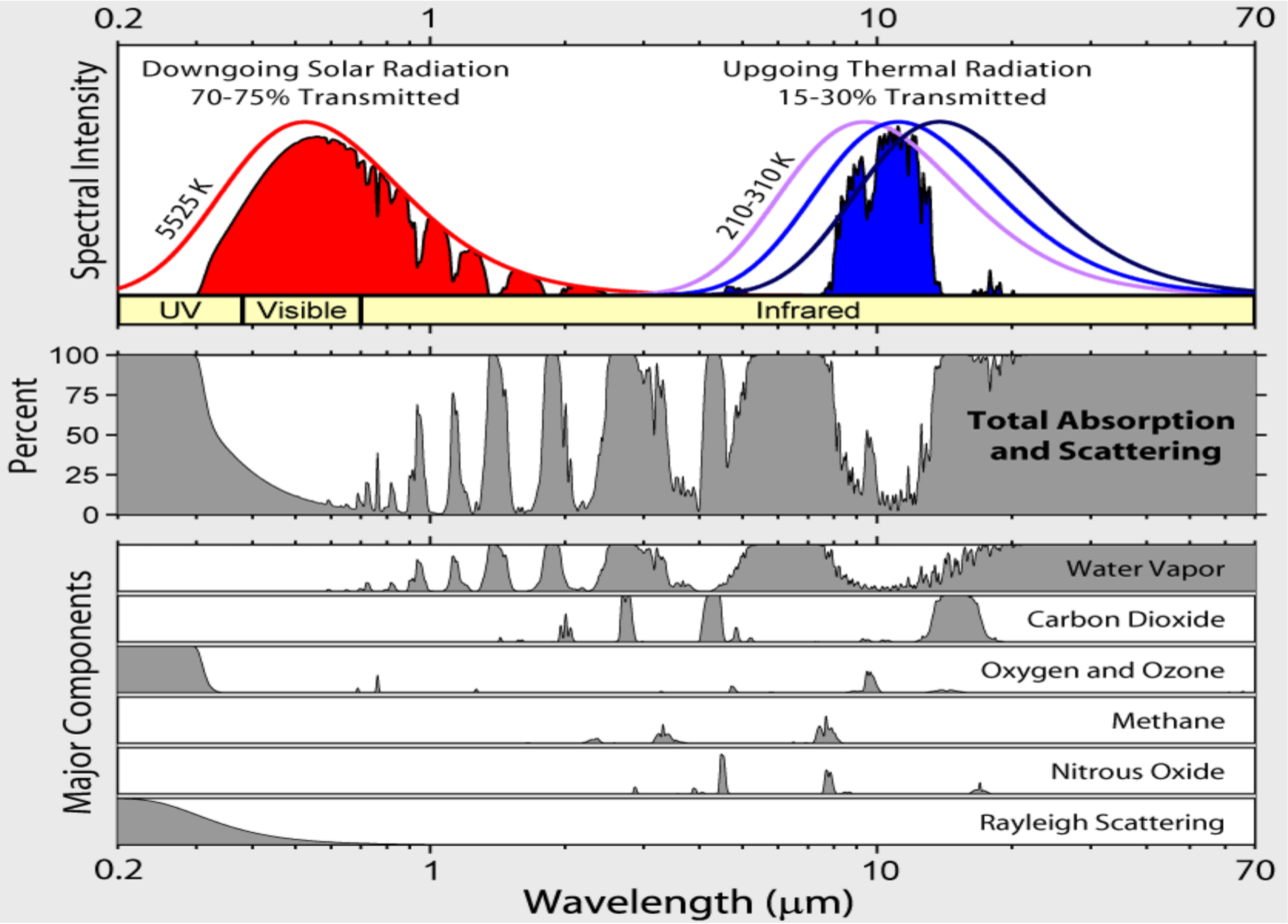
Radiation & Earth’s Atmosphere

Clouds and the Earth’s Radiant Energy System



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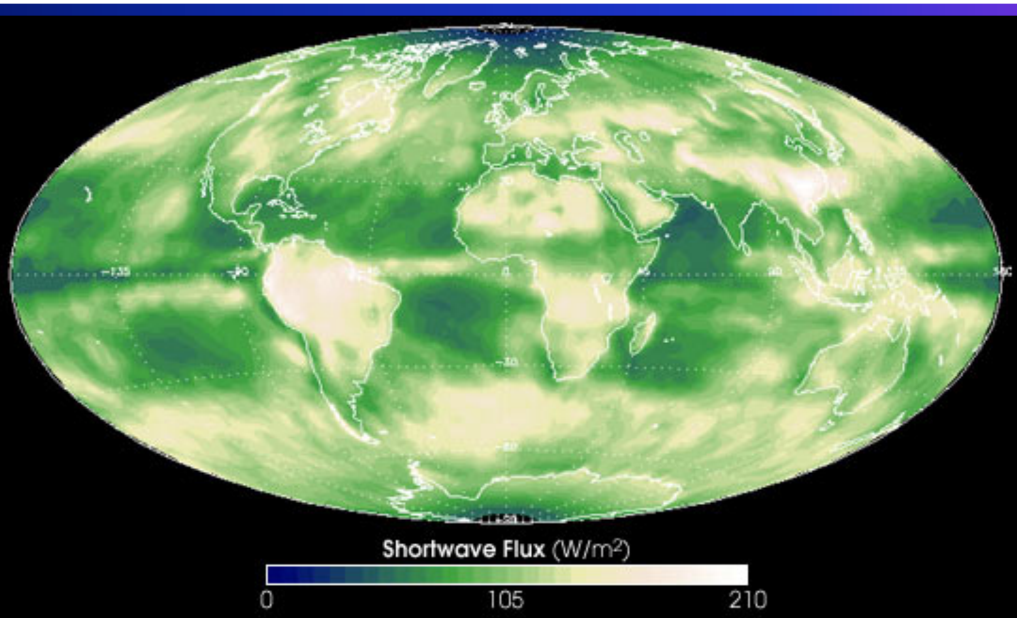
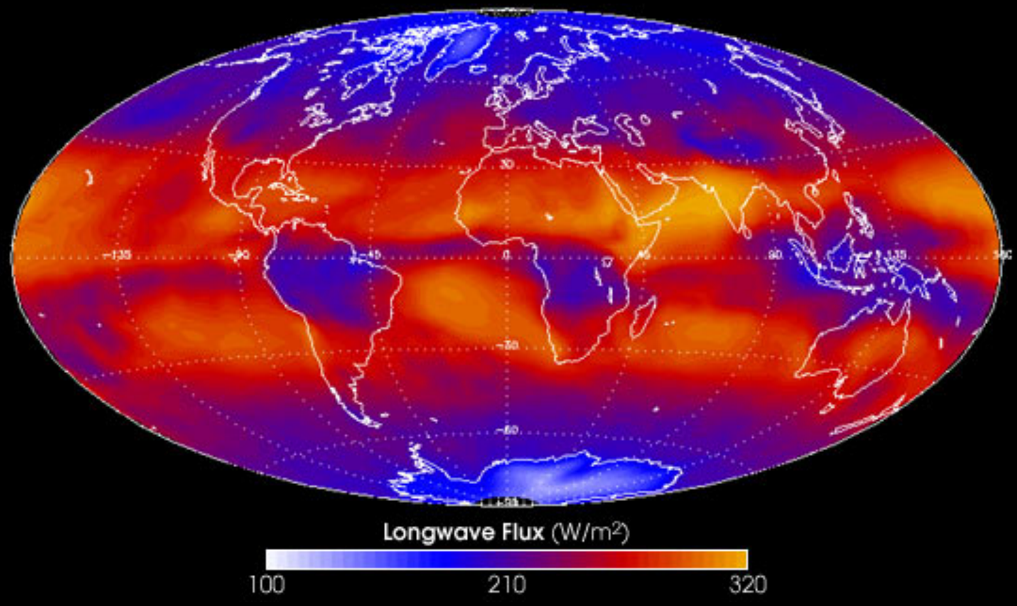
Primary CERES Climate Data Records

Reflected Solar Energy

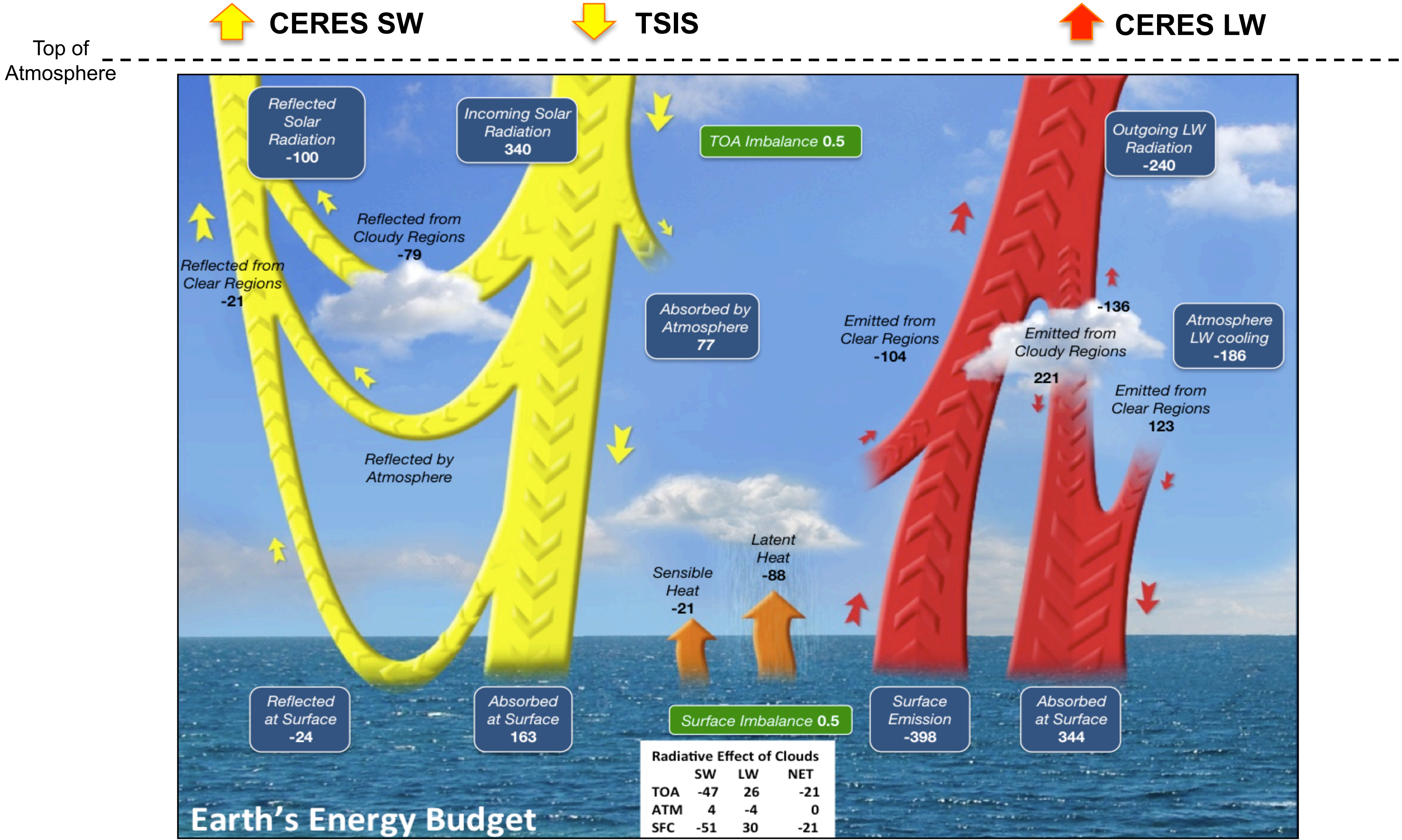


Emitted Thermal Energy



Earth's Energy Budget

Clouds and the Earth's Radiant Energy System



Radiative Effect of Clouds

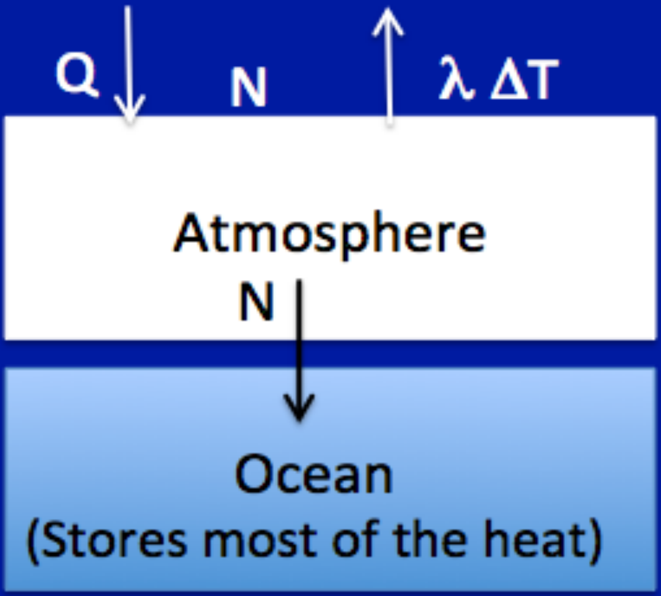
	SW	LW	NET
TOA	-47	26	-21
ATM	4	-4	0
SFC	-51	30	-21

The radiative imbalance between the surface and atmosphere determines how much energy is available to drive the hydrological cycle and the exchange of sensible heat between the surface and atmosphere.

Earth’s Energy Imbalance, Climate Forcing, Climate Feedback

$$N = S_o/4 - (F^{SW} + F^{LW}) \approx Q - \lambda\Delta T + \varepsilon$$

- Earth’s energy imbalance (N) provides a measure of the net climate forcing acting on Earth.
- If λ (climate feedback parameter) were known, the ratio N/λ would provide an estimate of the warming “in the pipeline”, even if climate forcings remain fixed at present-day levels.
- Uncertainty in λ responsible for spread in climate sensitivity amongst climate models: Global average surface warming following a doubling of CO_2: 2°C to 4.5°C.
- Largest uncertainty in Q from aerosols (direct & indirect effects)



Q

N

λ ΔT

Atmosphere

N

Ocean

(Stores most of the heat)

N = Earth Energy Imbalance (net heat flux into climate system)

Q = Forcing (LLGHG, aerosols, sun)

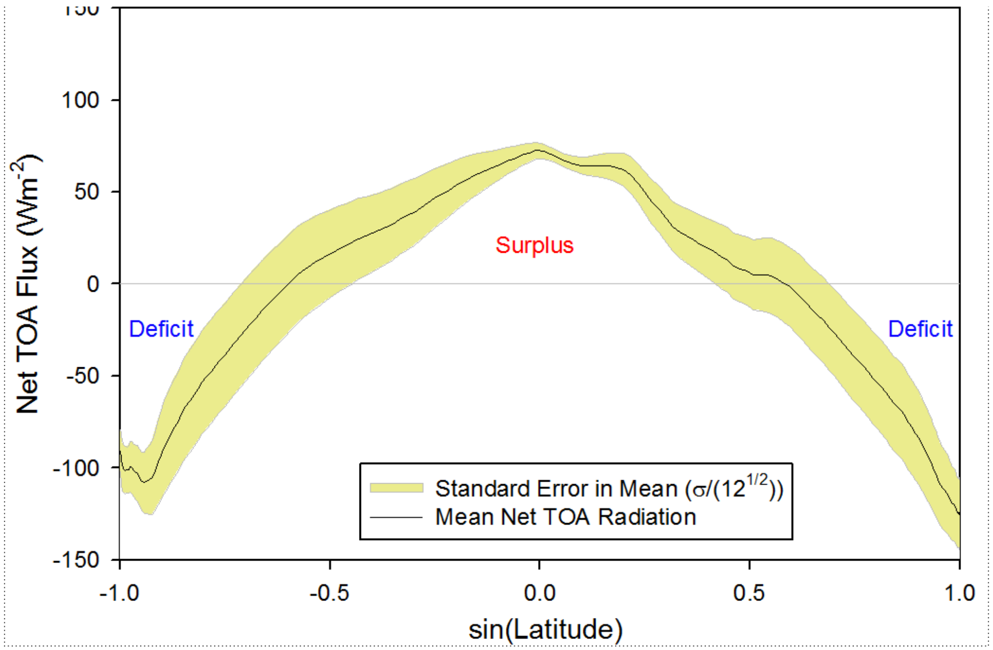
ΔT = Temperature change

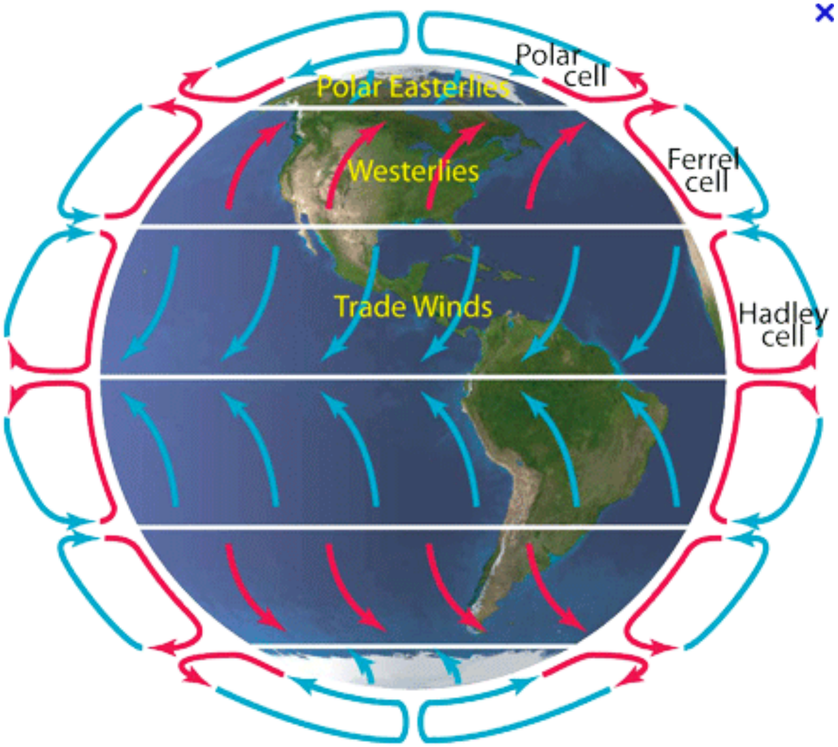
λ = Climate Feedback Parameter

ε = Internal variability of system not related to surface temperature.

Earth Radiation Budget Science

Net TOA Radiation
(Climatology: March 2000-June 2011)





- Radiation imbalance between low and high latitudes is balanced by equator-to-pole heat transported by the atmosphere and oceans.
- The regional pattern of net radiation drives the atmospheric and oceanic circulations.

Earth Radiation Budget Science Needs

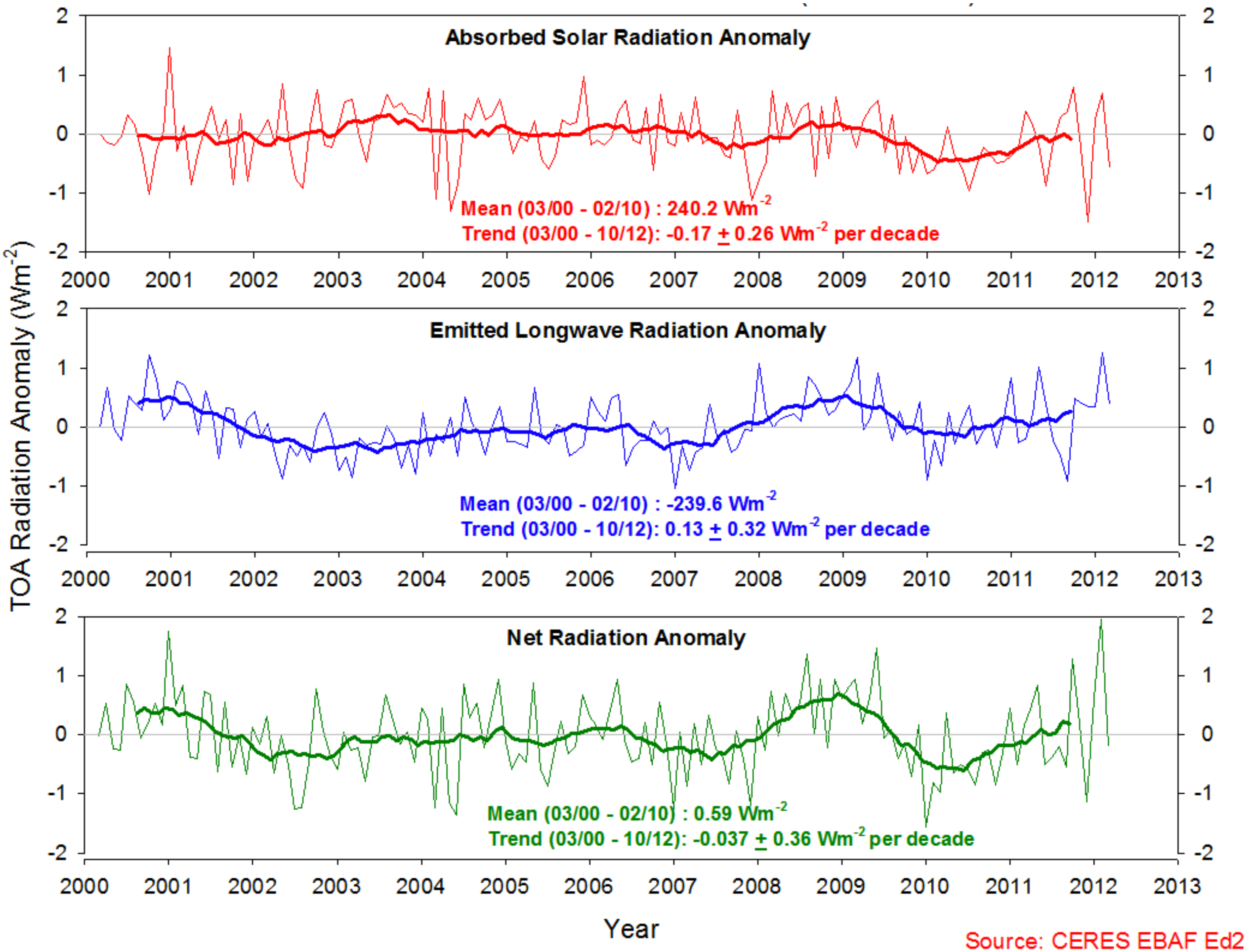
- ***Accurate*** **observation-based data products for climate model evaluation and improvement.**

- ***Precise*** **observations to enable improved understanding of the variability in Earth's radiation budget over multiple decades.**

- ***Continuous*** **long-term global Earth radiation budget observations at the top-of-atmosphere, within-atmosphere and surface together with coincident cloud, aerosol and meteorological data.**

Global Top-of-Atmosphere Radiation Anomalies

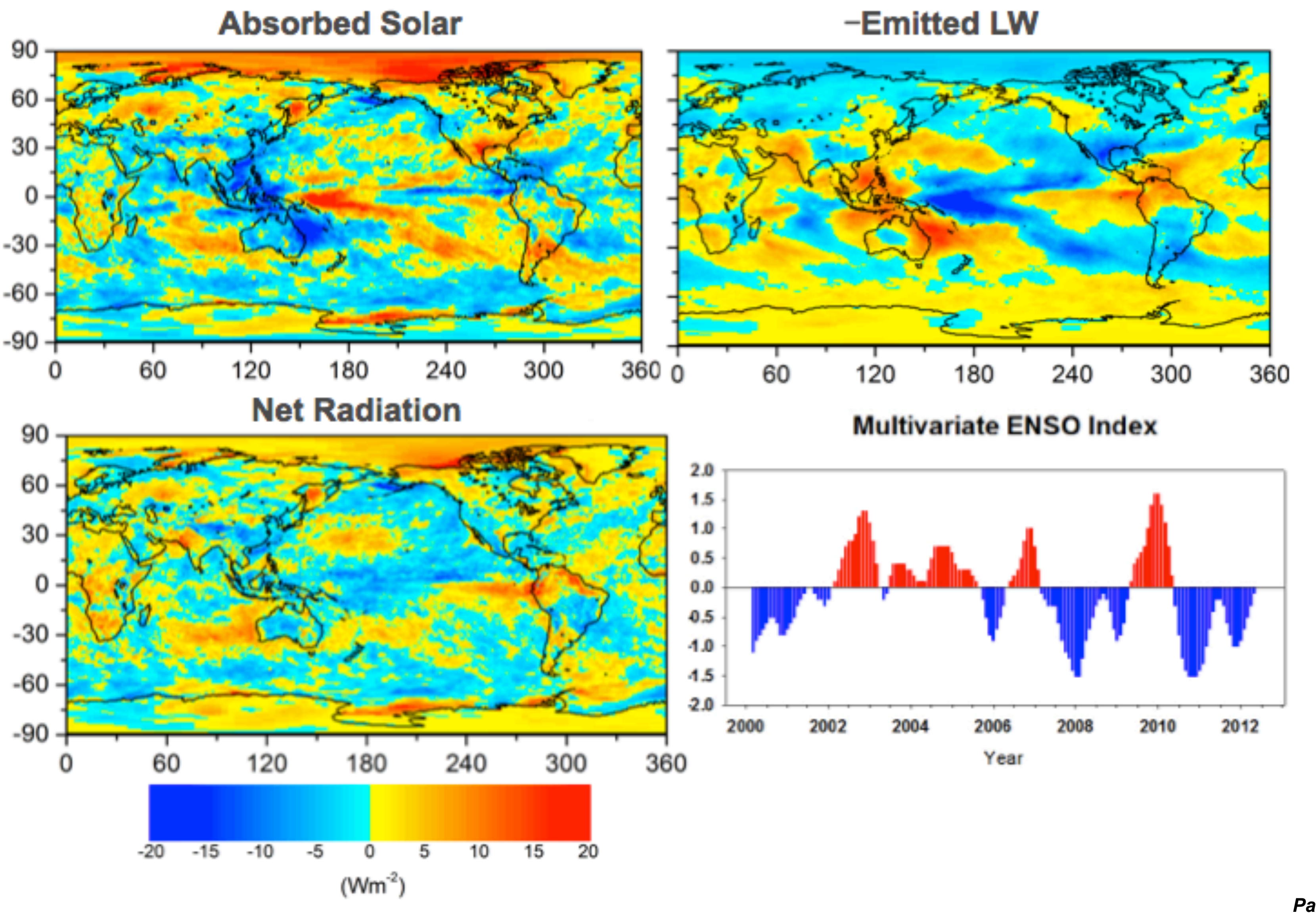
Clouds and the Earth's Radiant Energy System



Source: CERES EBAF Ed2.7

Earth Radiation Budget Science

Clouds and the Earth's Radiant Energy System



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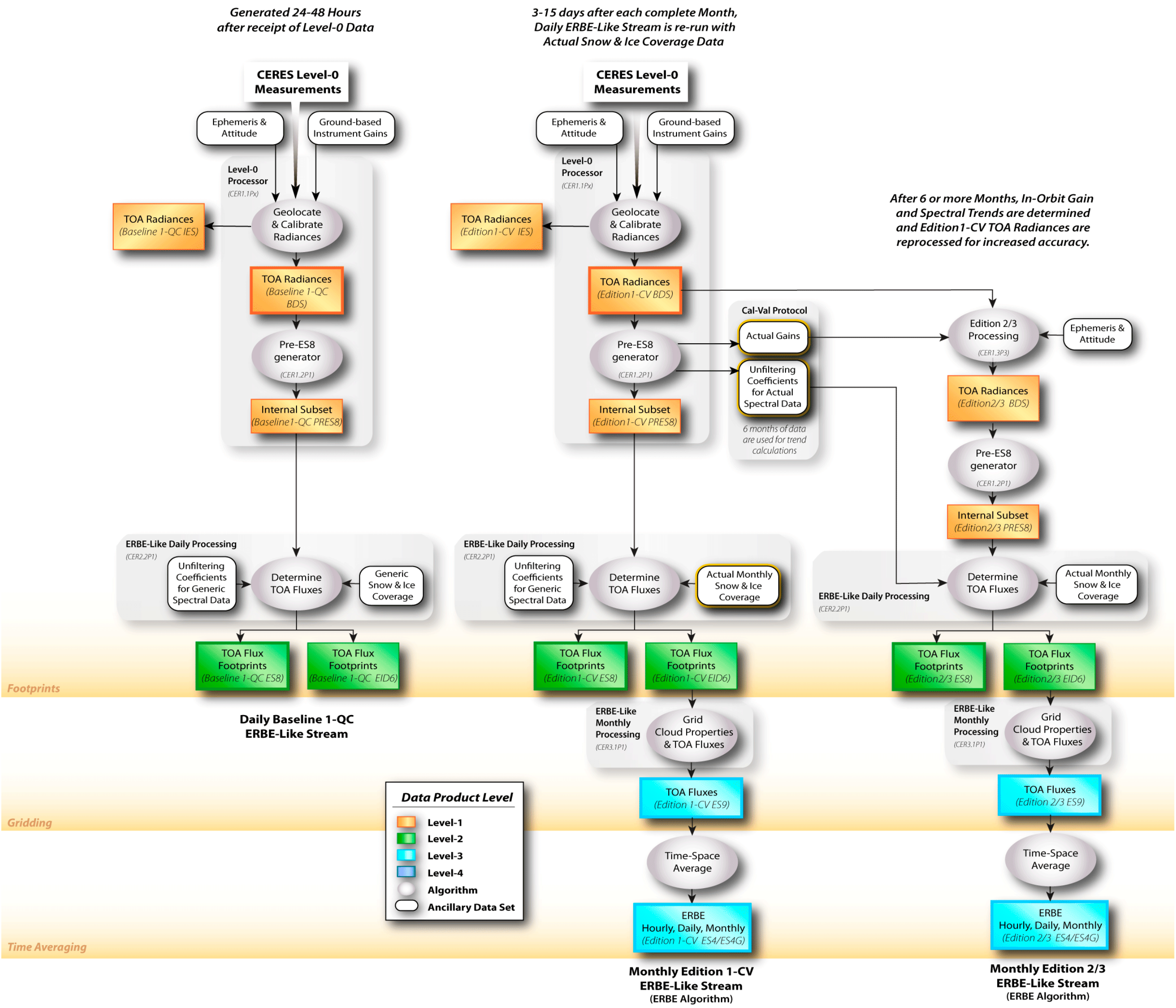
CERES IWG Processing Flow

Clouds and the Earth's Radiant Energy System



Generated 24-48 Hours after receipt of Level-0 Data

CERES Level-0 Measurements

Ephemeris & Attitude

Ground-based Instrument Gains

Level-0 Processor (CER1.1Px)

Geolocate & Calibrate Radiances

TOA Radiances (Baseline 1-QC IES)

TOA Radiances (Baseline 1-QC BDS)

Pre-ES8 generator (CER1.2P1)

Internal Subset (Baseline1-QC PRES8)

ERBE-Like Daily Processing (CER2.2P1)

Unfiltering Coefficients for Generic Spectral Data

Determine TOA Fluxes

Generic Snow & Ice Coverage

TOA Flux Footprints (Baseline 1-QC ES8)

TOA Flux Footprints (Baseline 1-QC EID6)

Daily Baseline 1-QC ERBE-Like Stream

3-15 days after each complete Month, Daily ERBE-Like Stream is re-run with Actual Snow & Ice Coverage Data

CERES Level-0 Measurements

Ephemeris & Attitude

Ground-based Instrument Gains

Level-0 Processor (CER1.1Px)

Geolocate & Calibrate Radiances

TOA Radiances (Edition1-CV IES)

TOA Radiances (Edition1-CV BDS)

Pre-ES8 generator (CER1.2P1)

Internal Subset (Edition1-CV PRES8)

Cal-Val Protocol

Actual Gains

Unfiltering Coefficients for Actual Spectral Data

6 months of data are used for trend calculations

ERBE-Like Daily Processing (CER2.2P1)

Unfiltering Coefficients for Generic Spectral Data

Determine TOA Fluxes

Actual Monthly Snow & Ice Coverage

TOA Flux Footprints (Edition1-CV ES8)

TOA Flux Footprints (Edition1-CV EID6)

ERBE-Like Monthly Processing (CER3.1P1)

Grid Cloud Properties & TOA Fluxes

TOA Fluxes (Edition 1-CV ES9)

Time-Space Average

ERBE Hourly, Daily, Monthly (Edition 1-CV ES4/ES4G)

Monthly Edition 1-CV ERBE-Like Stream
(ERBE Algorithm)

After 6 or more Months, In-Orbit Gain and Spectral Trends are determined and Edition1-CV TOA Radiances are reprocessed for increased accuracy.

Edition 2/3 Processing (CER1.3P3)

Ephemeris & Attitude

TOA Radiances (Edition2/3 BDS)

Pre-ES8 generator (CER1.2P1)

Internal Subset (Edition2/3 PRES8)

ERBE-Like Daily Processing (CER2.2P1)

Determine TOA Fluxes

Actual Monthly Snow & Ice Coverage

TOA Flux Footprints (Edition2/3 ES8)

TOA Flux Footprints (Edition2/3 EID6)

ERBE-Like Monthly Processing (CER3.1P1)

Grid Cloud Properties & TOA Fluxes

TOA Fluxes (Edition 2/3 ES9)

Time-Space Average

ERBE Hourly, Daily, Monthly (Edition 2/3 ES4/ES4G)

Monthly Edition 2/3 ERBE-Like Stream
(ERBE Algorithm)

Footprints

Gridding

Time Averaging

Data Product Level

- **Level-1**
- **Level-2**
- **Level-3**
- **Level-4**
- **Algorithm**
- **Ancillary Data Set**

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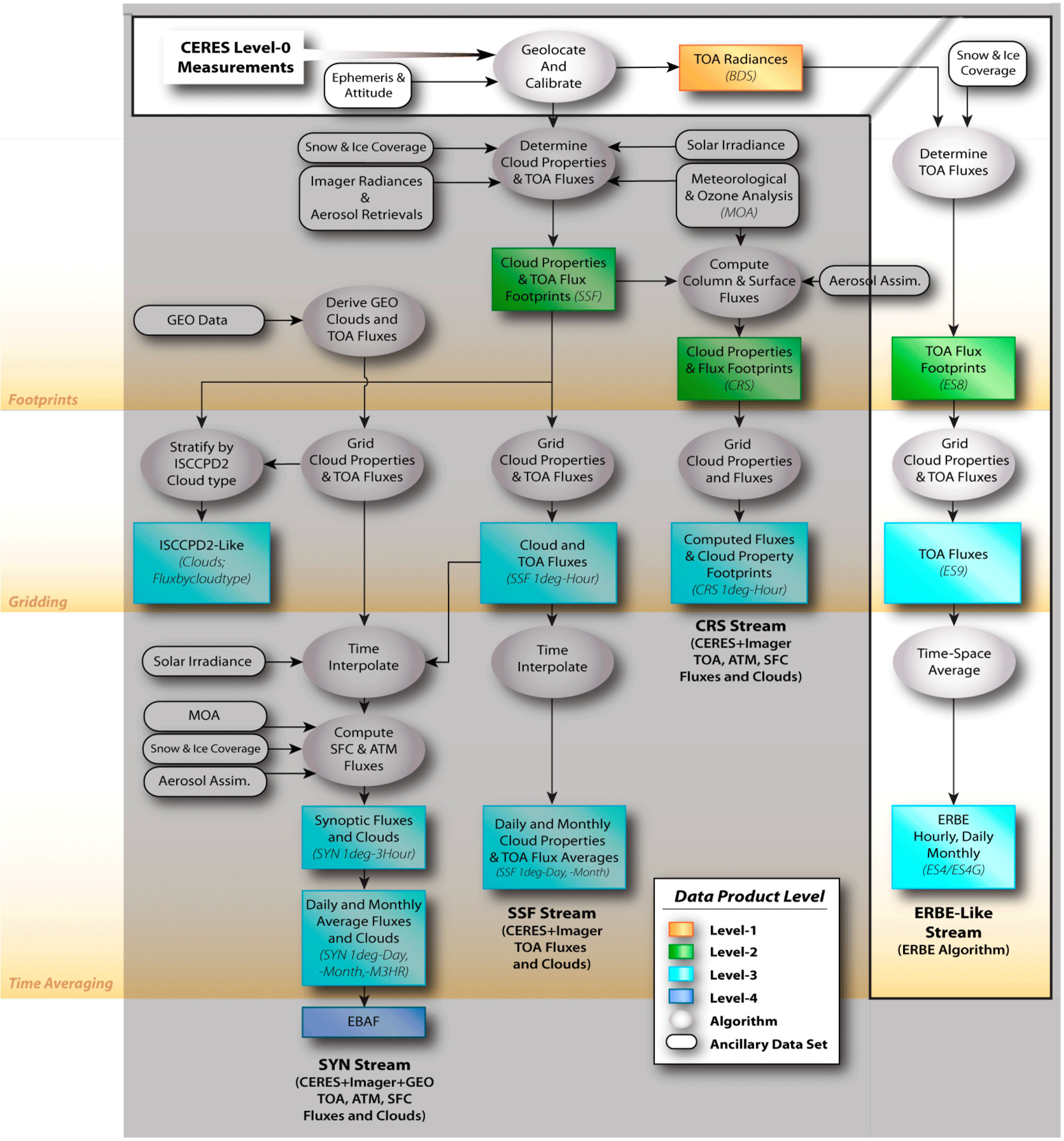
CERES Processing Stream

Clouds and the Earth's Radiant Energy System



CERES Level-0 Measurements
Ephemeris & Attitude
Geolocate And Calibrate
TOA Radiances (BDS)
Snow & Ice Coverage
Determine TOA Fluxes

Snow & Ice Coverage
Imager Radiances & Aerosol Retrievals
Determine Cloud Properties & TOA Fluxes
Solar Irradiance
Meteorological & Ozone Analysis (MOA)
Cloud Properties & TOA Flux Footprints (SSF)
Compute Column & Surface Fluxes
Aerosol Assim.
GEO Data
Derive GEO Clouds and TOA Fluxes
Cloud Properties & Flux Footprints (CRS)
TOA Flux Footprints (ES8)

Footprints

Stratify by ISCCPD2 Cloud type
Grid Cloud Properties & TOA Fluxes
Grid Cloud Properties & TOA Fluxes
Grid Cloud Properties and Fluxes
Grid Cloud Properties & TOA Fluxes
ISCCPD2-Like (Clouds; Fluxbycloudtype)
Cloud and TOA Fluxes (SSF 1deg-Hour)
Computed Fluxes & Cloud Property Footprints (CRS 1deg-Hour)
TOA Fluxes (ES9)

Gridding

CRS Stream
(CERES+Imager TOA, ATM, SFC Fluxes and Clouds)

Solar Irradiance
Time Interpolate
Time Interpolate
Time-Space Average
MOA
Snow & Ice Coverage
Aerosol Assim.
Compute SFC & ATM Fluxes
Synoptic Fluxes and Clouds (SYN 1deg-3Hour)
Daily and Monthly Cloud Properties & TOA Flux Averages (SSF 1deg-Day, -Month)
ERBE Hourly, Daily Monthly (ES4/ES4G)
Daily and Monthly Average Fluxes and Clouds (SYN 1deg-Day, -Month,-M3HR)

SSF Stream
(CERES+Imager TOA Fluxes and Clouds)

ERBE-Like Stream
(ERBE Algorithm)

Time Averaging

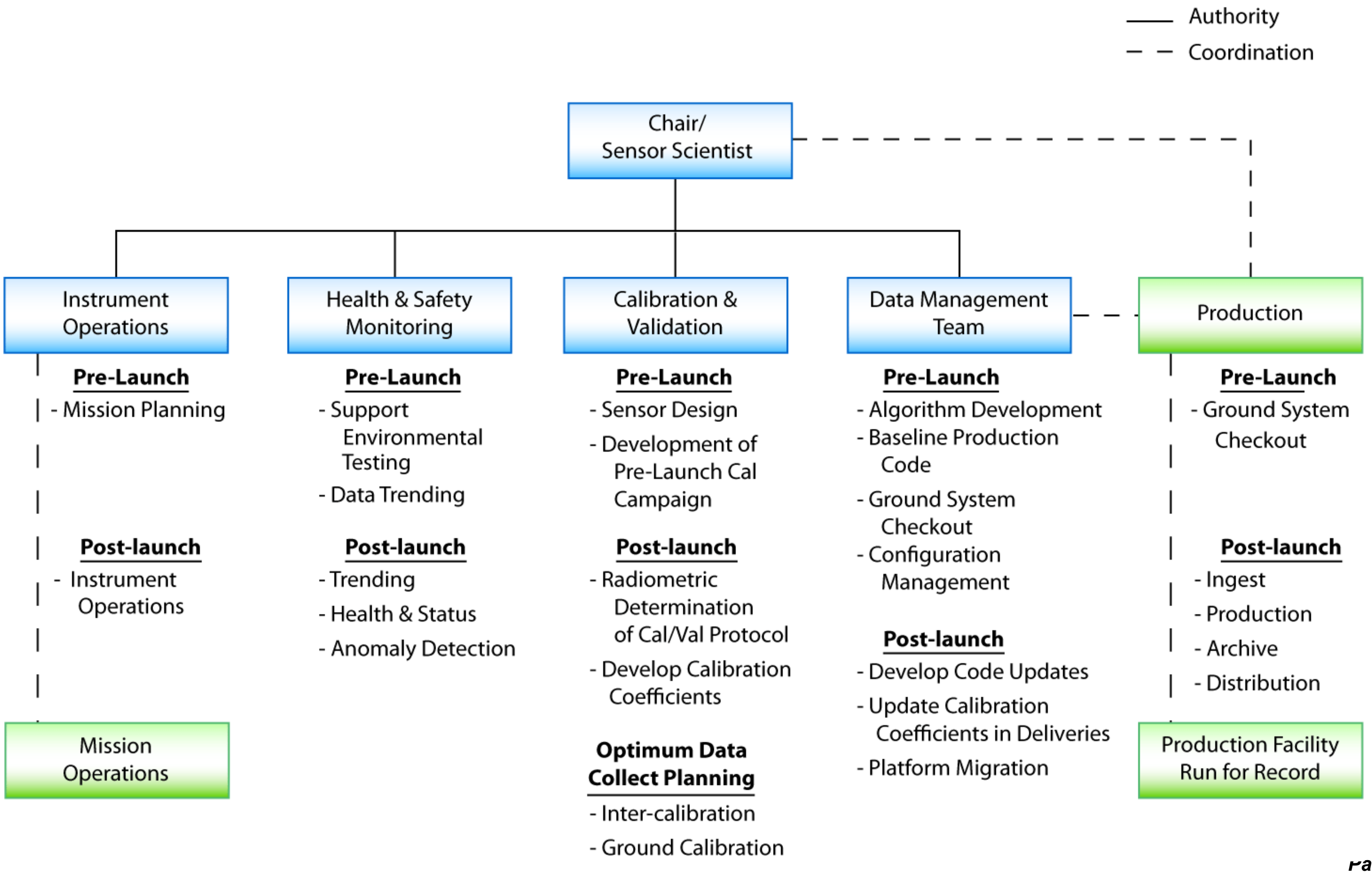
EBAF

SYN Stream
(CERES+Imager+GEO TOA, ATM, SFC Fluxes and Clouds)

Data Product Level
- 🟧 **Level-1**
- 🟩 **Level-2**
- 🟦 **Level-3**
- ▨ **Level-4**
- ○ **Algorithm**
- ▭ **Ancillary Data Set**

CERES
Instrument Working Group

CERES Science Team
Instrument Working Group



—— Authority

– – Coordination

Chair/
Sensor Scientist

Instrument Operations

Pre-Launch
- Mission Planning

Post-launch
- Instrument Operations

Mission Operations

Health & Safety Monitoring

Pre-Launch
- Support Environmental Testing
- Data Trending

Post-launch
- Trending
- Health & Status
- Anomaly Detection

Calibration & Validation

Pre-Launch
- Sensor Design
- Development of Pre-Launch Cal Campaign

Post-launch
- Radiometric Determination of Cal/Val Protocol
- Develop Calibration Coefficients

Optimum Data Collect Planning
- Inter-calibration
- Ground Calibration

Data Management Team

Pre-Launch
- Algorithm Development
- Baseline Production Code
- Ground System Checkout
- Configuration Management

Post-launch
- Develop Code Updates
- Update Calibration Coefficients in Deliveries
- Platform Migration

Production

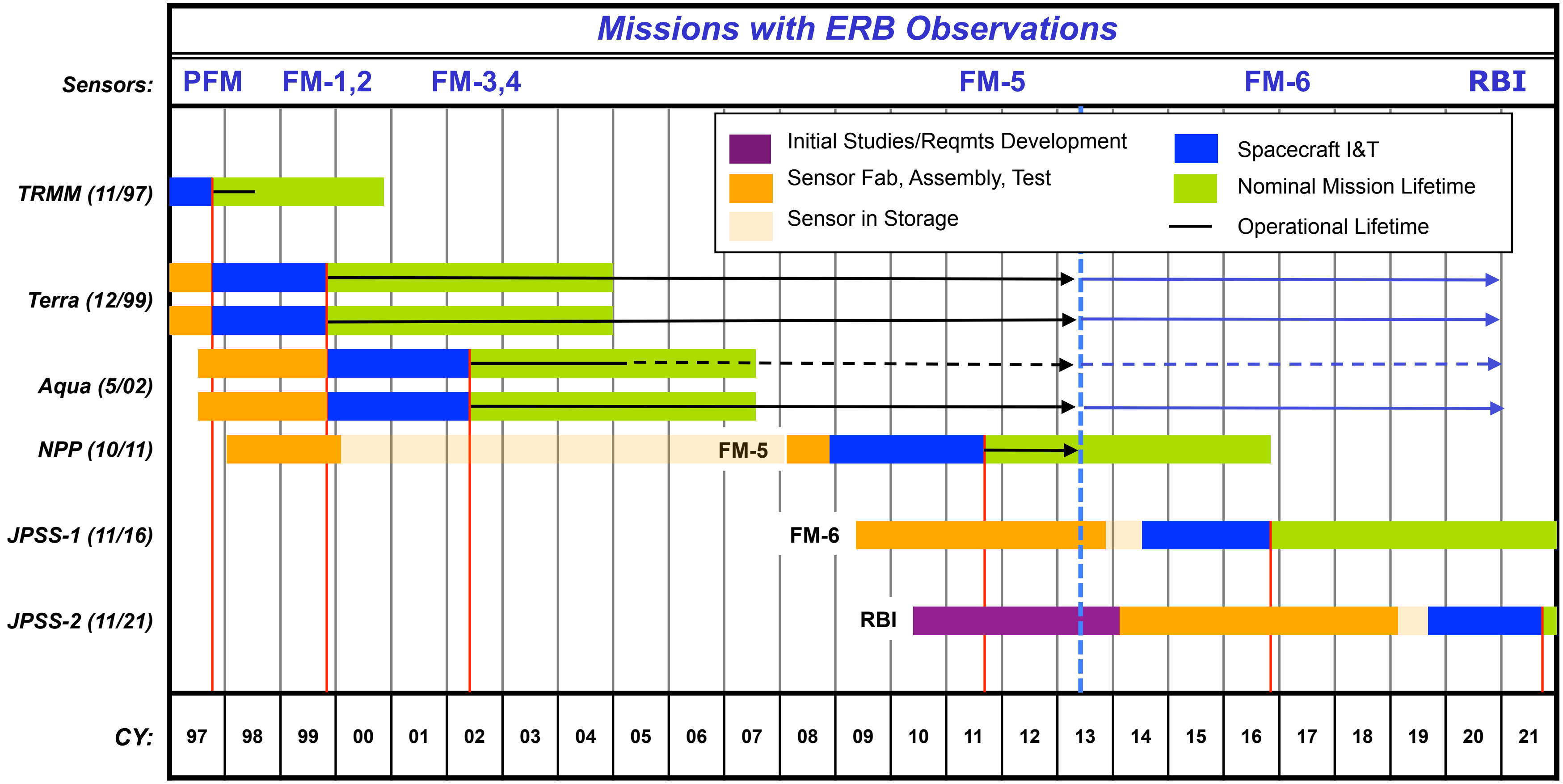
Pre-Launch
- Ground System Checkout

Post-launch
- Ingest
- Production
- Archive
- Distribution

Production Facility Run for Record

Enabling Climate Data Record Continuity

CERES Flight Schedule



We now have over 51 years of flight experience with the CERES instruments and simulators

Agency Roles and Responsibilities

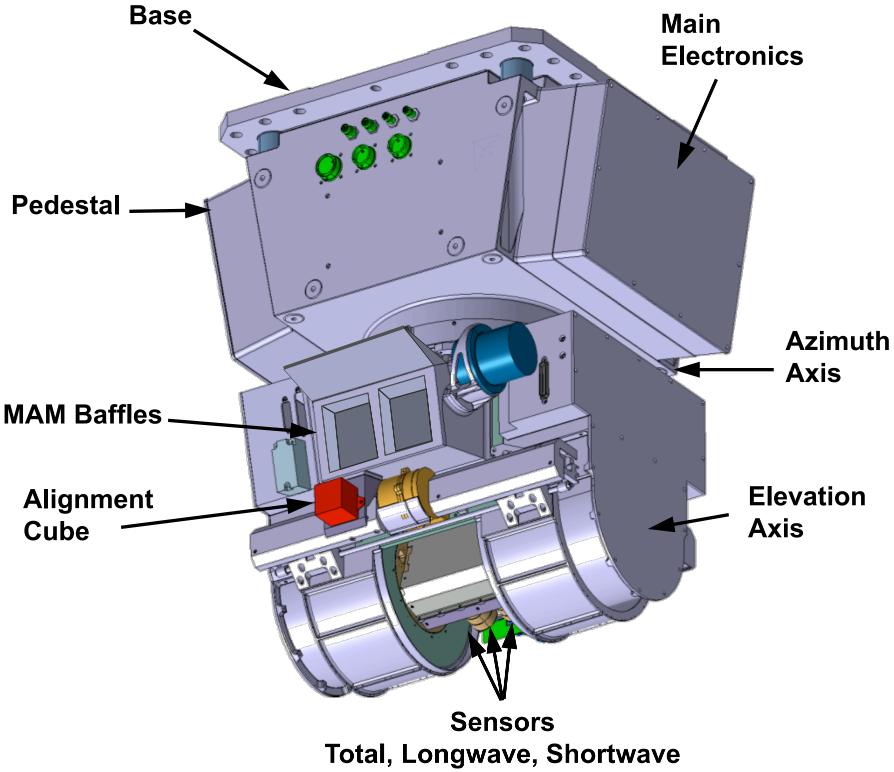
Mission	Instruments	Responsible Agency ($$ in budget)		Implementation	
		Hardware	*Science, Data Processing*	*Hardware*	*Science, Data Processing*
EOS	PFM-FM4	NASA	NASA	NASA Procurement	NASA Science Team
NPP	FM5	NASA/***NOAA***	NASA	NASA Procurement	NASA Science Team
JPSS-1	FM6	***NOAA***	***??***	NASA Procurement	***??***
JPSS-2	RBI	***??***	***??***	NASA Procurement	***??***

CERES Instrument

Clouds and the Earth's Radiant Energy System

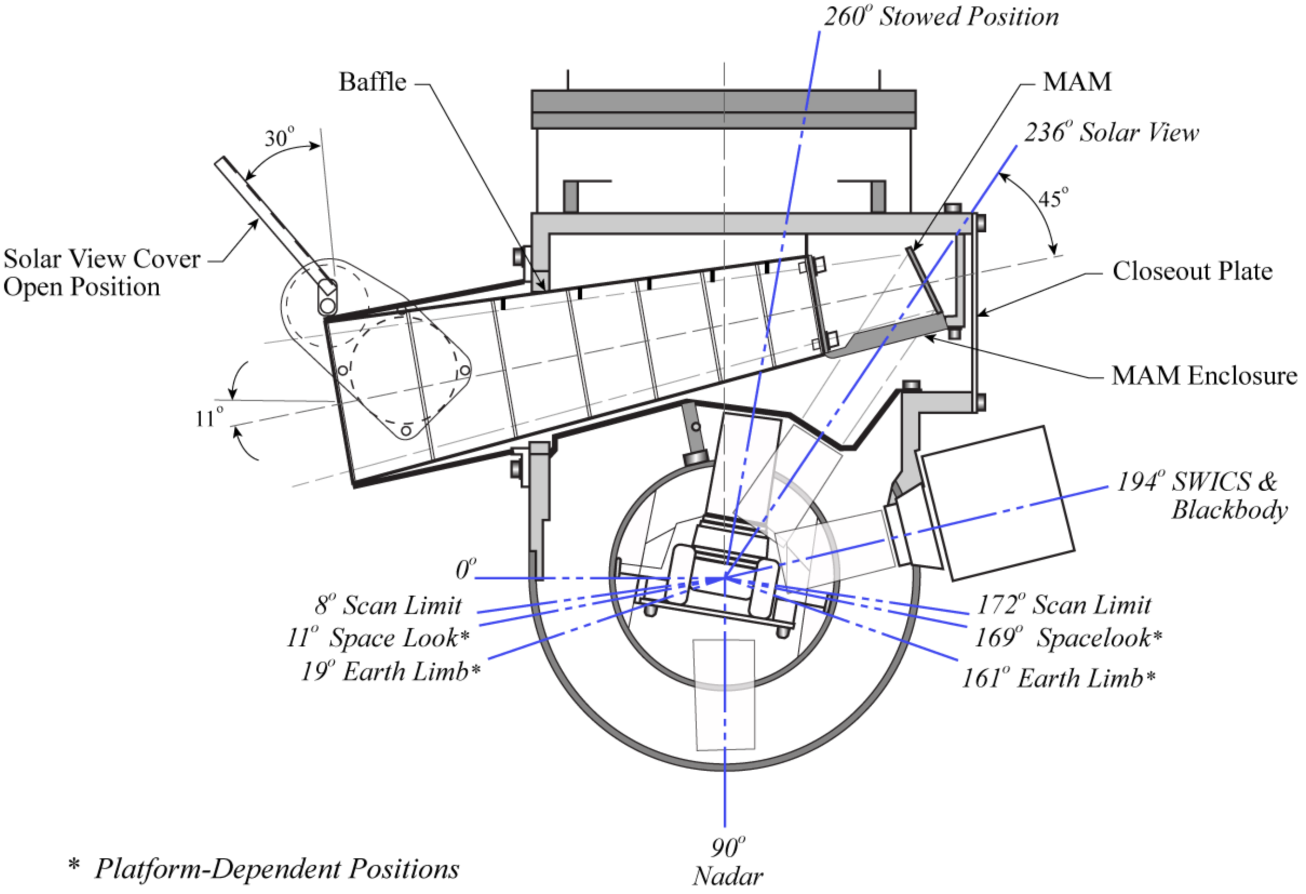
- **Designed, manufactured and tested by TRW, Redondo Beach, CA (currently Northrop Grumman Aerospace Systems)**
- **Contains three sensor assemblies with cassegrain optics and thermistor bolometer detectors**
- **Sensors measure thermal radiation in the near-visible through far-infrared spectral region**
- **Sensor channels are coaligned and mounted on a spindle that rotates about the elevation axis**
- **Hemispherical sampling obtained with an azimuthal axis drive system**

Orbits	705 km altitude, 10:30 a.m. descending node (Terra) or 1:30 p.m. ascending node (PM-1), sun-synchronous, near-polar; 350 km altitude, 35° inclination (TRMM)
Spectral Channels	Solar Reflected Radiation (Shortwave): 0.3 - 5.0 μm Window: 8 - 12 μm Total: 0.3 to > 100 μm
Swath Dimensions	Limb to limb
Angular Sampling	Cross-track scan and 360° azimuth biaxial scan
Spatial Resolution	20 km at nadir (10 km for TRMM)
Mass	45 kg
Duty Cycle	100%
Power	45 W
Data Rate	10 kbps
Size	60 x 60 x 70 cm (deployed)
Design Life	6 years



CERES View Angles

Clouds and the Earth's Radiant Energy System

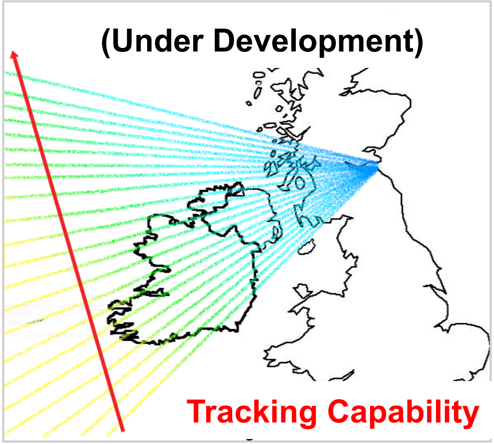


* *Platform-Dependent Positions*

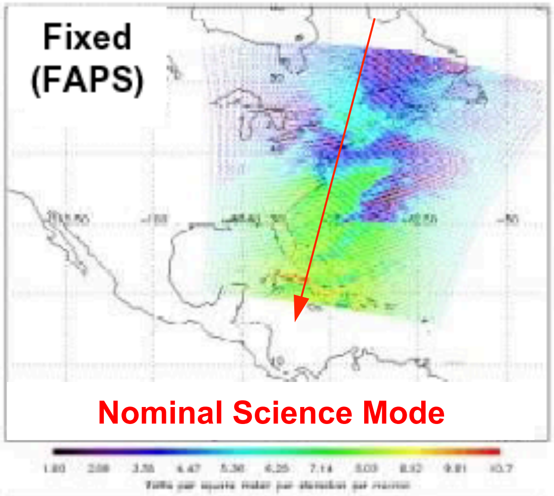
In 6.6 Seconds, CERES completes a single elevation scan, which comprises a single packet of data.

Operational Scanning Capabilities

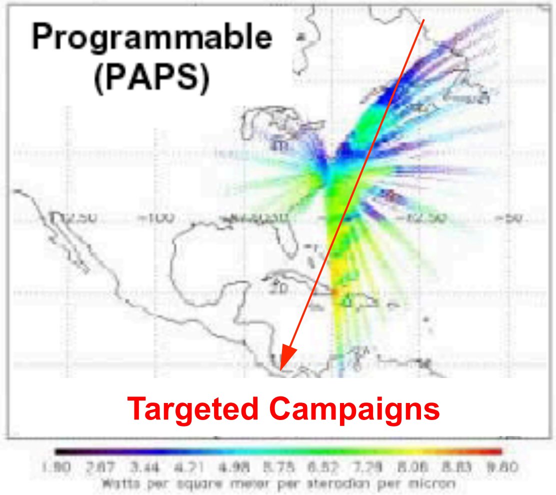
Clouds and the Earth's Radiant Energy System


(Under Development)

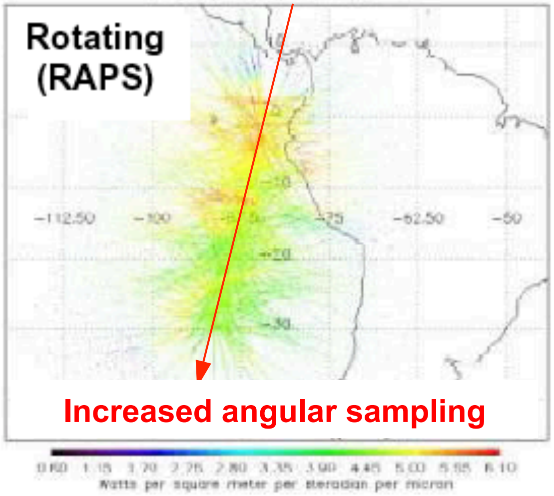
Tracking Capability


Fixed (FAPS)

Nominal Science Mode


Programmable (PAPS)

Targeted Campaigns


Rotating (RAPS)

Increased angular sampling

Radiometric Performance Requirements

CERES is defined as a class 'B' Instrument

5-year design Lifetime

Spectral Regions	**Reflected Solar**		**Emitted Thermal**		**Atmospheric Window**
Wavelengths	0.3 - 5.0 μm		5.0 - 200 μm		8 - 12 μm
Scene levels	<100 w/m^2-sr	>100 w/m^2-sr	<100 w/m^2-sr	>100 w/m^2-sr	All Levels
Accuracy Requirements	0.8 w/m^2-sr	1.0 %	0.8 w/m^2-sr	0.5 %	0.3 w/m^2-sr
SOW Stability Requirements		< 0.14%/yr		< 0.1%/yr	
Climate Stability Goals		< 0.6 w/m^2/dec < 0.03 %/yr		< 0.2 w/m^2/dec < 0.02%/yr	

- **Requirements for CERES are more stringent than ERBE's by a factor of 2**
- **Requirements per Ohring et. al. are more stringent than CERES by a factor of 3-5**

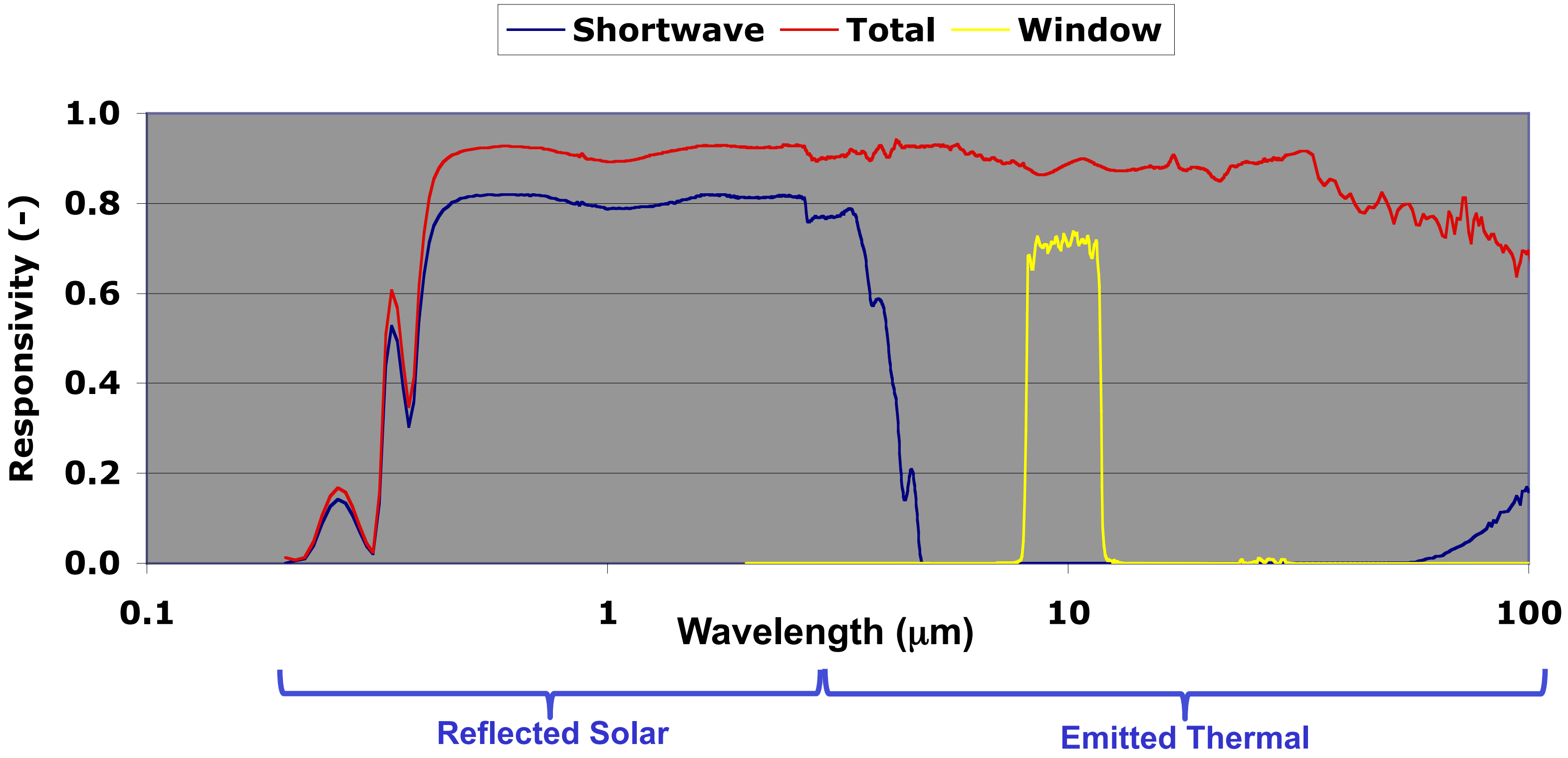
Calibrate, Calibrate, Calibrate….

Evolve Observational Strategies via FSW Modifications

CERES PFM-FM5 Radiometric Channels

Clouds and the Earth's Radiant Energy System

Proto-Flight Model Sample
Spectral Response Function



Note: LW_{DAY} = Total - Shortwave

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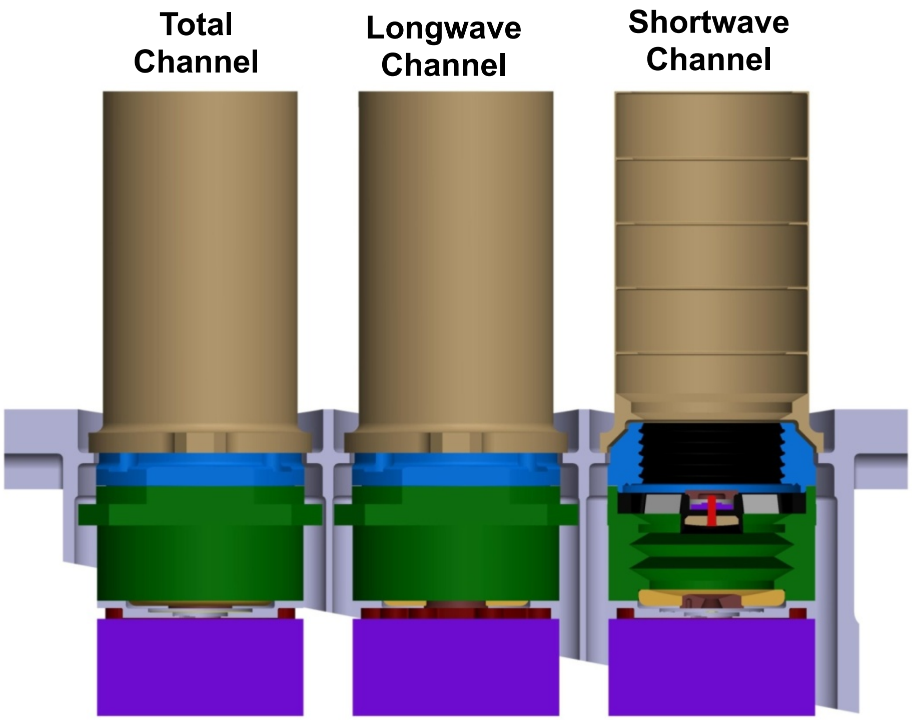
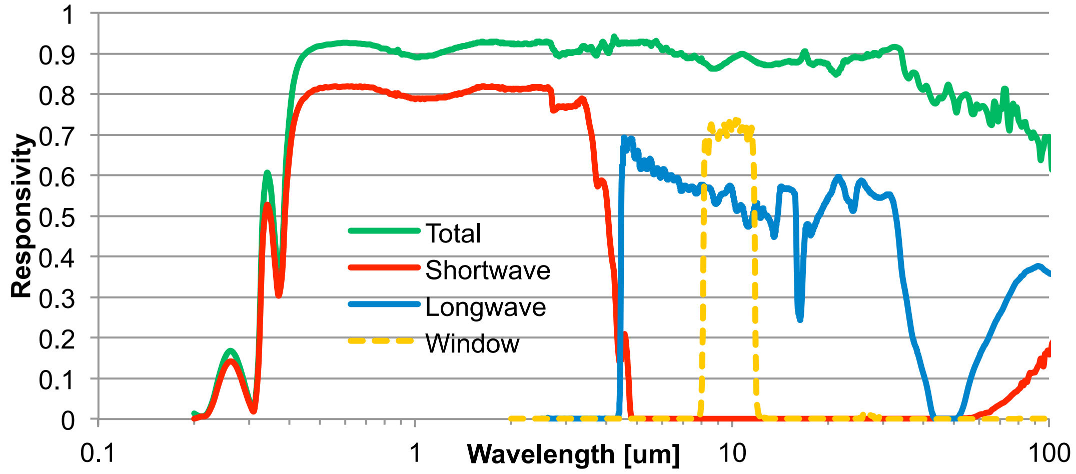
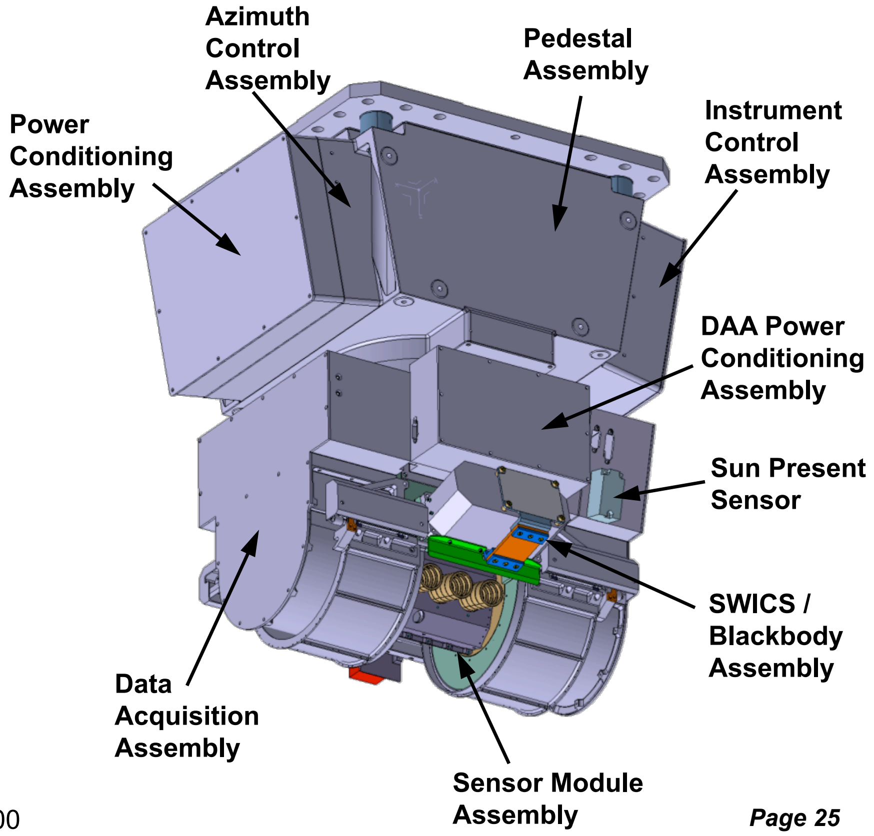
CERES Sensor Module Assembly



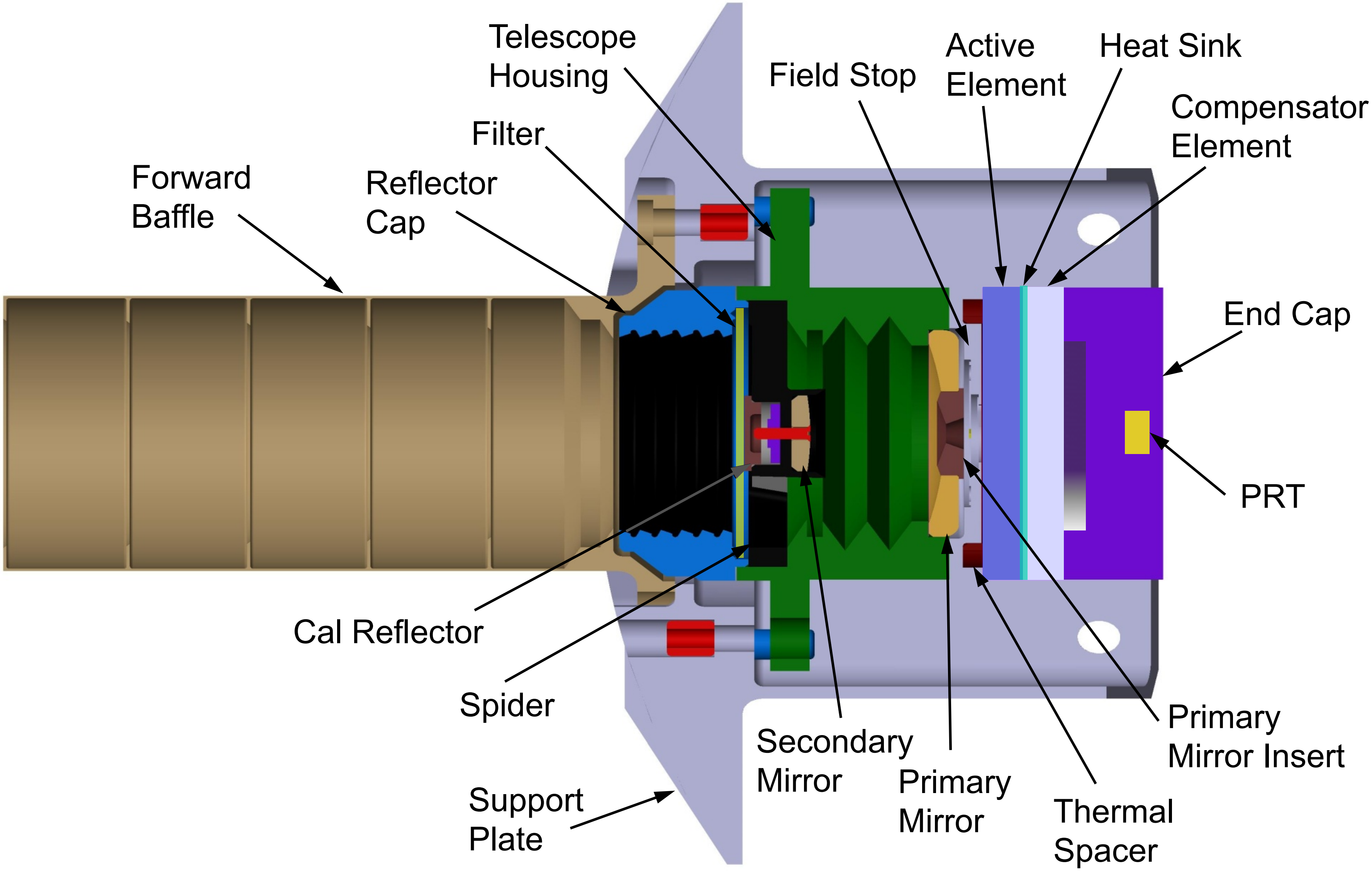


- **Three sensor assemblies**
  - Two-element reflective telescope
  - Stray light baffle
  - Pair of thermistor bolometer flakes
- **Sensors are ~1 in. Diameter**
- **Responsive from 0.3 μm to >100 μm**



CERES Sensor Assembly

Clouds and the Earth's Radiant Energy System



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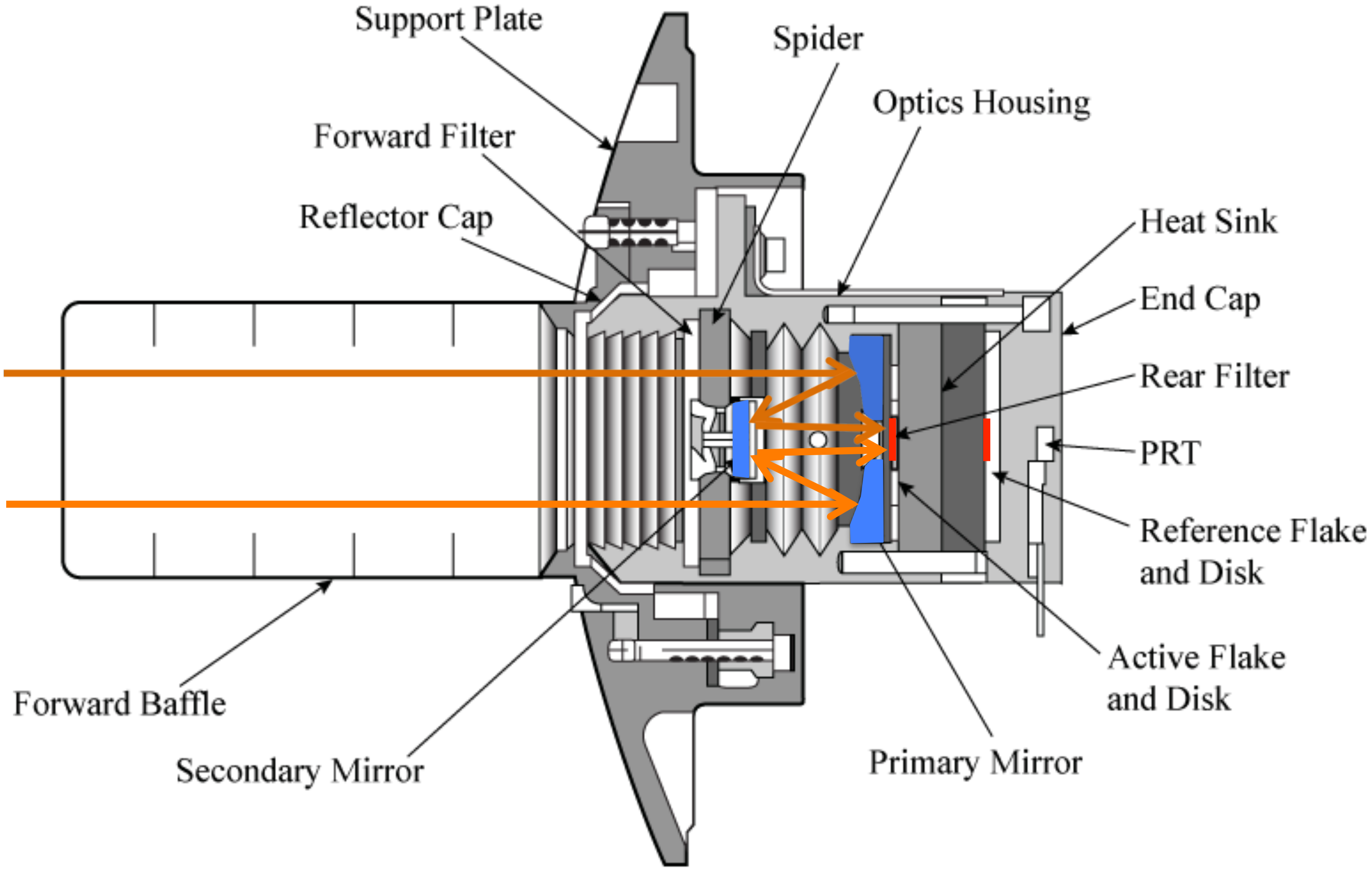
Support Plate
Spider
Optics Housing
Forward Filter
Reflector Cap
Heat Sink
End Cap
Rear Filter
PRT
Reference Flake
and Disk
Active Flake
and Disk
Forward Baffle
Secondary Mirror
Primary Mirror

Why is CERES Climate Quality Calibration so difficult?

A question of time scales, experience and balancing accuracy with providing data products to the community.

- *Calibrated Radiances have been released on ~6 month centers*
- *6 months is just a blink of an eye when analyzing decadal trends…*

Same time scale as phenomena which influence instrument response

- *Beta Angle*
- *Solar Zenith Angle*
- *Earth Sun Distance*
- *Solar Cycle*
- *Orbital shifts*
- *Instrument Operational modes (e.g. RAPS vs. Xtrack)*

Design weaknesses and anticipated failures in onboard calibration hardware

- *full spectral range of observations not covered by cal subsystems*

Complicates separation of instrument 'artifacts' from natural variability.

Traceability

Unique Challenges
- Large FOV
- Broadband
- Performance Requirements

Allocations
- Product Accuracy → Instrument Performance

Algorithmic Error Sources
- unfiltering
- inversion
- Spatial Averaging
- Temporal Interpolation

X

Calibration Equation

$$\tilde{L}(t-\tau) = A_V[m(t) - \bar{m}(t_k) - o(t)] + \frac{t - t_k}{\Delta t}\{A_S[\bar{m}(t_{k+1}) - m(t_k)]$$

$$+A_H[T_H(t_{k+1}) - T_H(t_k)] + A_D[V_D(t_{k+1}) - V_D(t_k)]$$

$$+A_B[V_{bias}(t_{k+1}) - V_{bias}(t_k)]\}$$

L = filtered radiance ($Wm^{-2}sr^{-1}$)
$m(t)$ = instrument output signal at time t (counts)
$m(t_k)$ = spacelook average (counts)
$o(t)$ = sensor scan angle dependent offsets (counts)
A_V = gain corresponding to the change in output signal ($Wm^{-2}sr^{-1}ct^{-1}$)
A_S = gain corresponding to a drift in the signal output during two adjacent space looks ($Wm^{-2}sr^{-1}counts^{-1}$)
A_H = gain corresponding to a change in heatsink temperature during two adjacent space looks ($Wm^{-2}sr^{-1}T_H{}^{-1}$)
A_D = gain corresponding to a change of V_D during adjacent space looks ($Wm^{-2}sr^{-1}V_D{}^{-1}$)
A_B = gain corresponding to a change of V_{bias} during adjacent space looks ($Wm^{-2}sr^{-1}V_{bias}{}^{-1}$)
T_H = heat sink temperature (K)
V_{bias} = sensor bridge bias voltage (counts)
V_D = drift balance digital to analog converter (DAC) voltage (counts)
Δt = total scan period of 6.6s
t = sampling instant (s)
t_k = time of last space look (s)
τ = lag between the instrument optical field-of-view and point spread function centroid (s)
Δt = total scan period of 6.6s

Calibration Equation

$$\tilde{L}(t-\tau)=A_V[m(t)-\bar{m}(t_k)-o(t)]+\frac{t-t_k}{\Delta t}\{A_S[\bar{m}(t_{k+1})-m(t_k)]$$

$$+A_H[T_H(t_{k+1})-T_H(t_k)]+A_D[V_D(t_{k+1})-V_D(t_k)]$$

$$+A_B[V_{bias}(t_{k+1})-V_{bias}(t_k)]\}$$

L = filtered radiance (Wm^{-2}sr^{-1})
$m(t)$ = instrument output signal at time t (counts)
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CERES Calibration

Clouds and the Earth's Radiant Energy System

- Spectral
  - FTS
  - ARMS
- Spatial
  - Raster Scan (detector)
  - Off-Axis (Sensor)
  - Alignment (sensors, Sensor Module, Baseplate)
  - Point Spread Function (sensor)
  - Lunar
  - Coastline
- Temporal
  - Sensor Characterization Station
  - Lunar
  - IBB
- Radiometric
  - NFBB → IBB
  - SWRS → SWICS
- Offsets
  - Test Caps
  - Pitch over maneuver

Cal-Val Approach

Pre-Launch

- Implement a rigorous & thorough ground calibration/characterization program
- Cal/Val role must be prominent in original proposal and SOW
- System level characterization is typically last test performed prior to delivery of the instrument
- Cost and schedule constraints typically drive programs at that point

Post-Launch

- Implement a protocol of independent studies to characterize on-orbit performance
- Studies should cover all spectral, spatial and temporal scales as well as data product levels
- Continuous development of new validation studies

Data Product Release Strategy

- Develop a logical and well understood approach to data release.
- Minimize the number of Editions/Versions of Data
- Utilize Data Quality Summaries for the community

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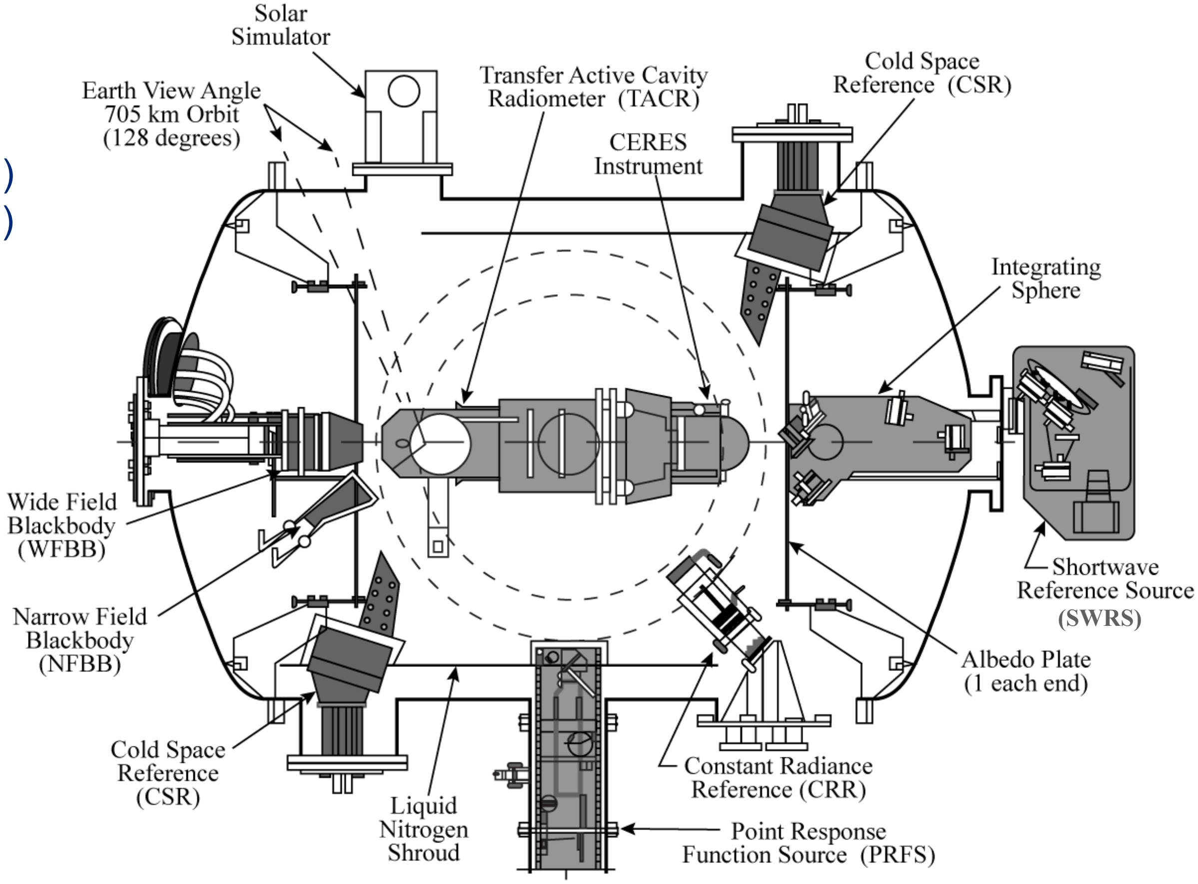
CERES Ground Calibration

Radiometric Calibration Facility

- ◆ Heritage ERBE calibration facility
- ◆ Revamped for CERES in 90's



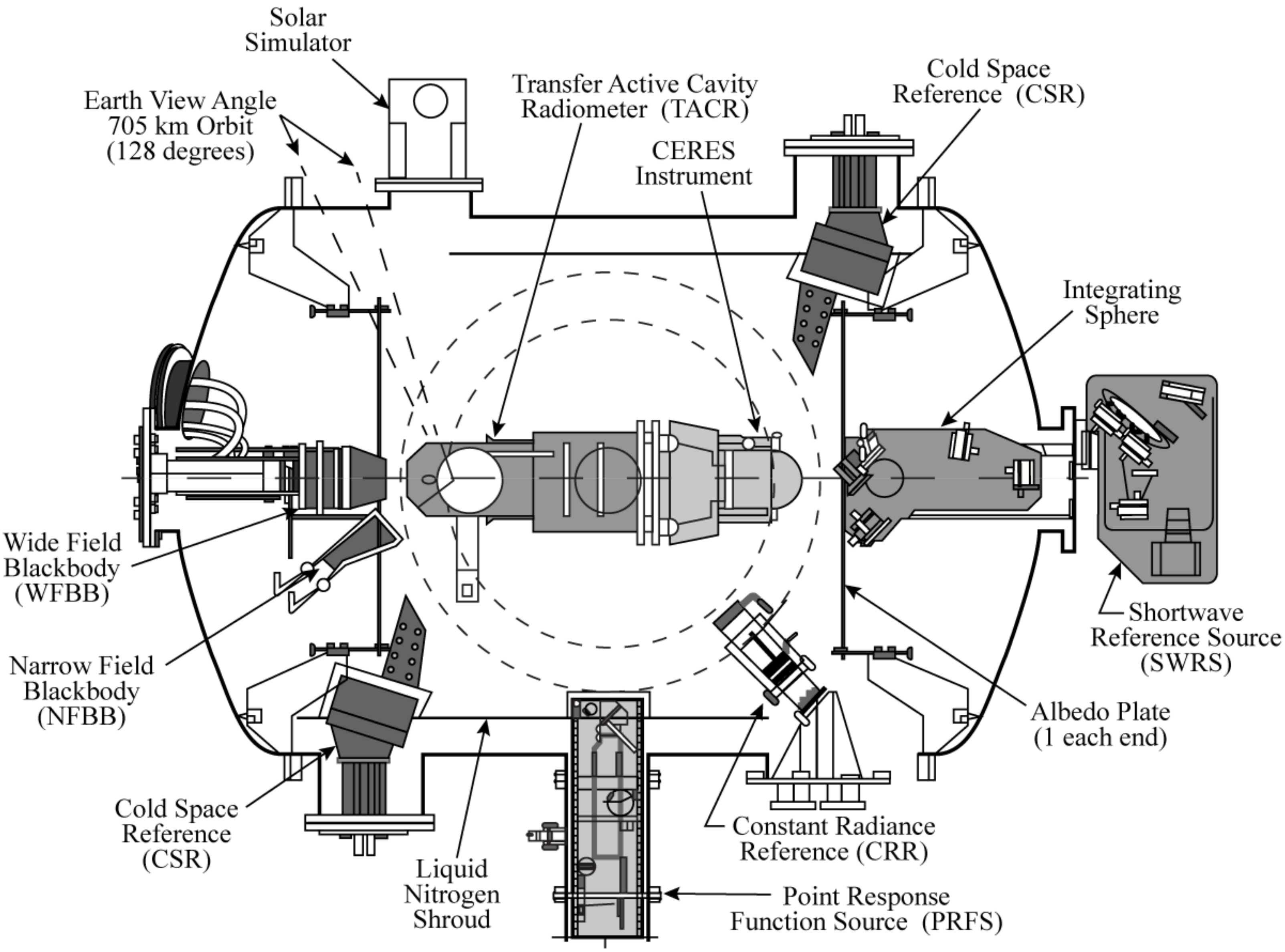
<u>Thermal IR Bands</u>

- Narrow Field of View Blackbody (NFBB) is primary standard (emissivity >0.9999)
- 12.5 cm Wide Field of View Blackbody (WFBB)
- Cold Space Reference (CSR) blackbodies

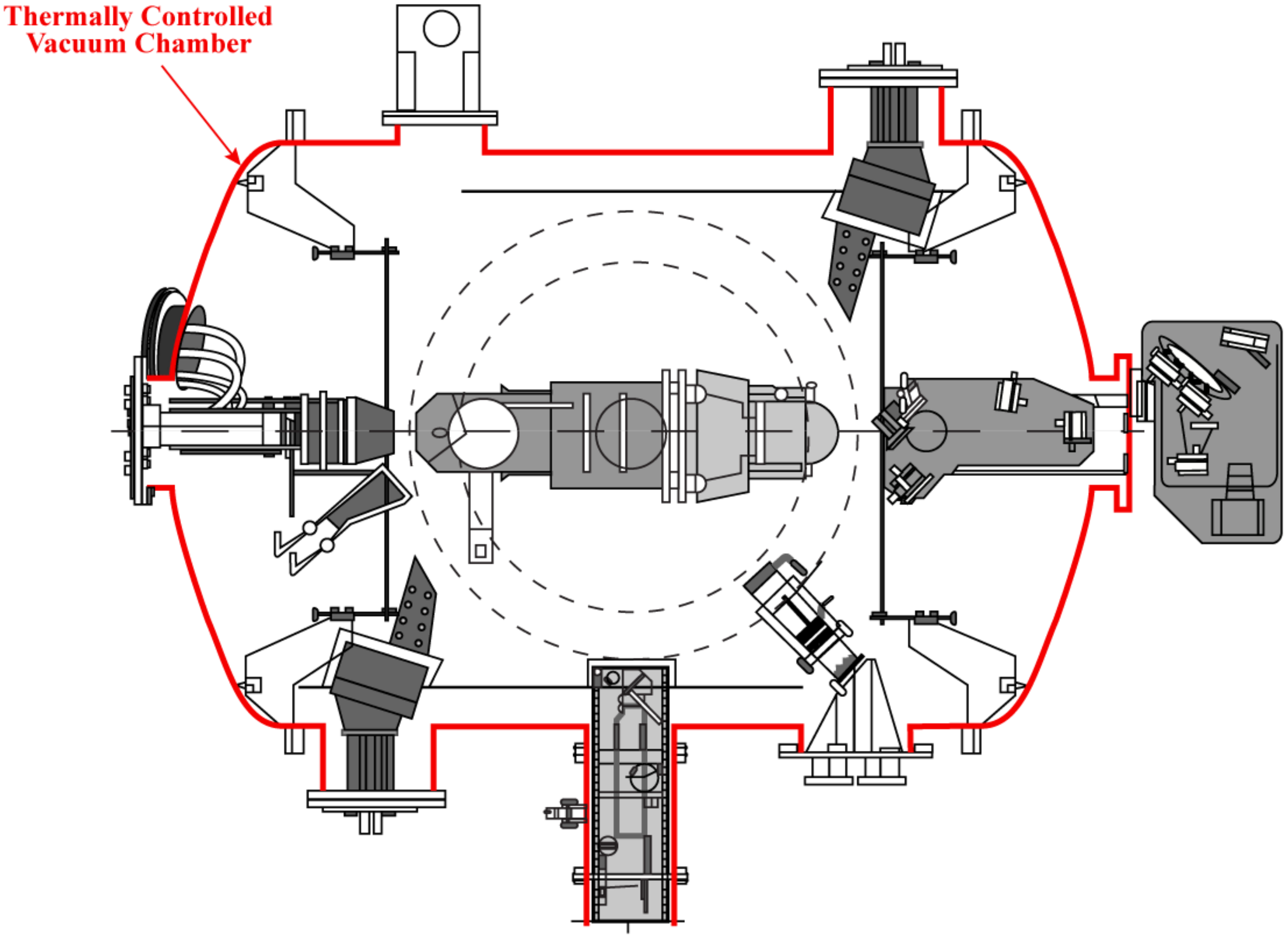
<u>Reflected Solar Bands</u>

- SW reference source (SWRS) with minimum LW variations and spectral characterization capability
    - 13 discrete bands between 420 and 1960 nm
    - 5 cm integrating sphere with associated optics
- Cryogenically cooled Transfer Active Cavity Radiometer (TACR)

Radiometric Calibration Facility

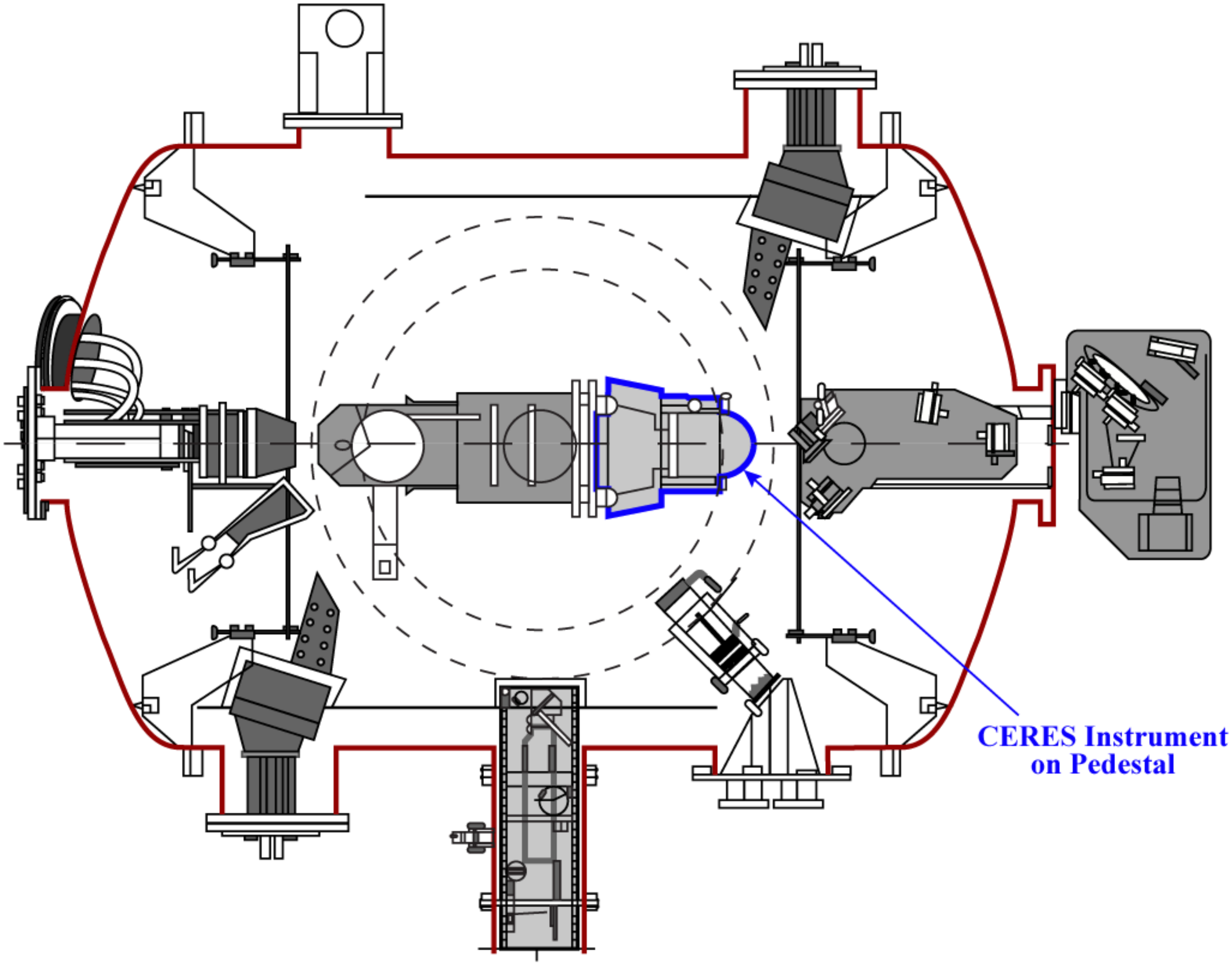


Radiometric Calibration Facility

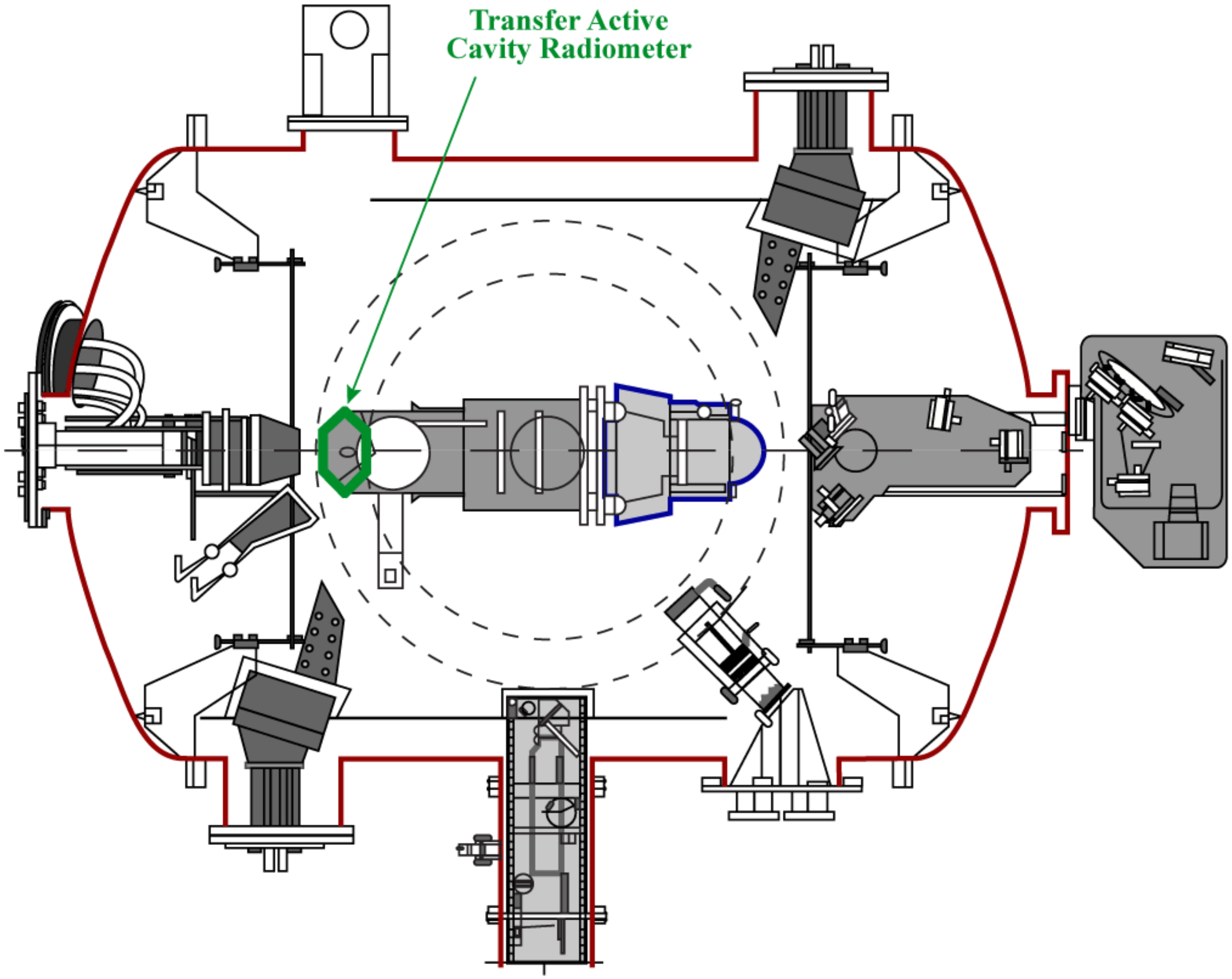


Radiometric Calibration Facility

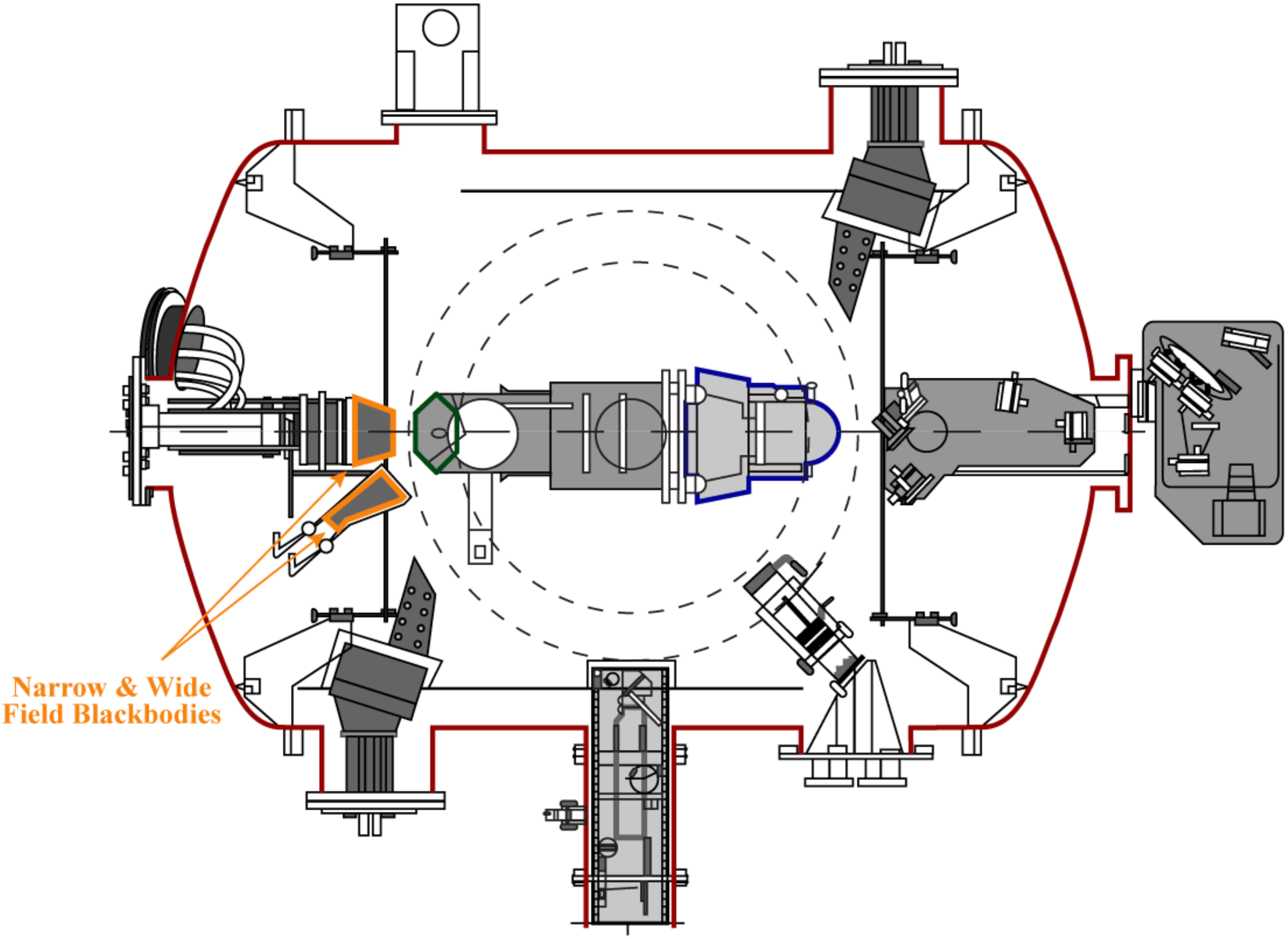
Clouds and the Earth's Radiant Energy System



Radiometric Calibration Facility

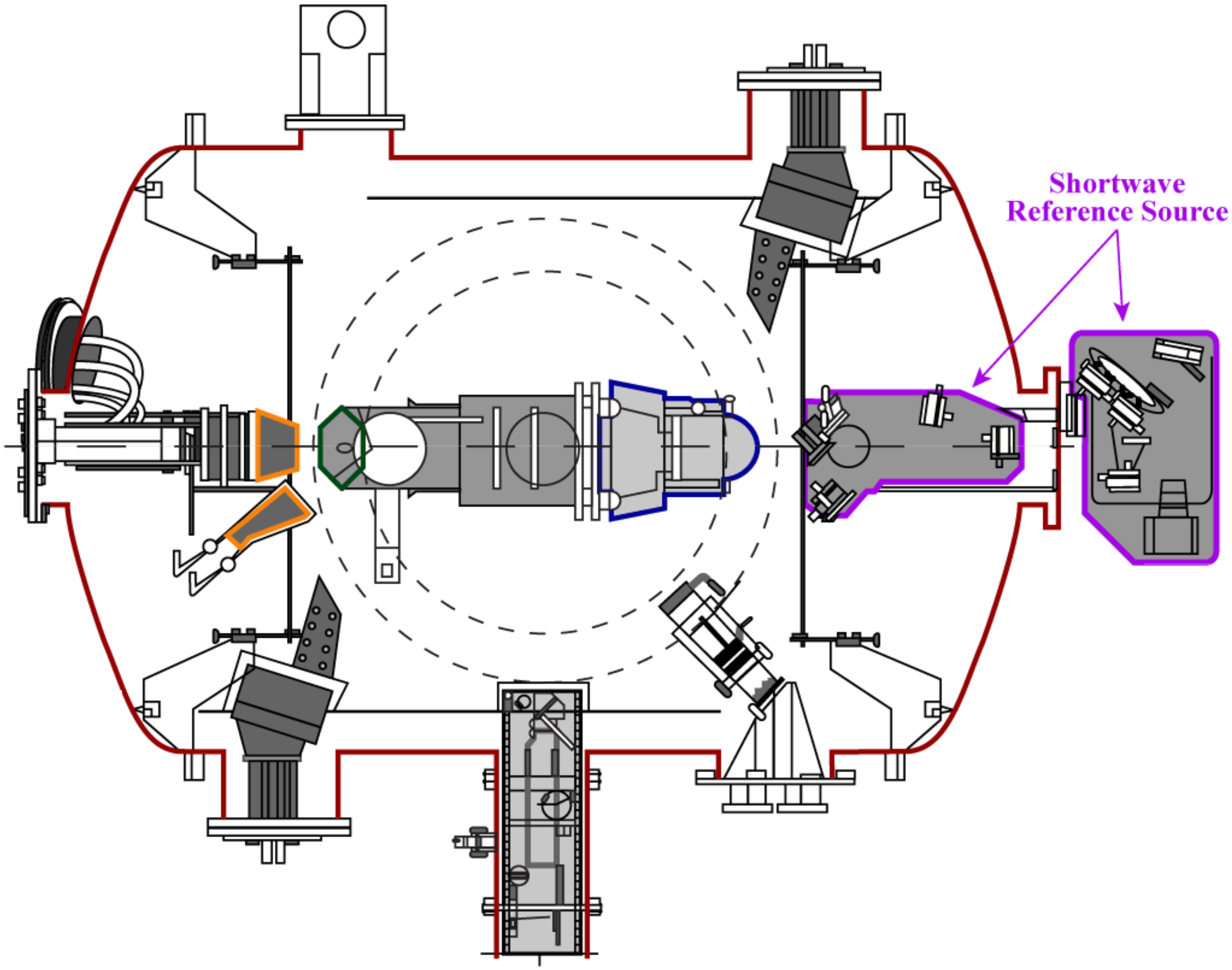


Radiometric Calibration Facility

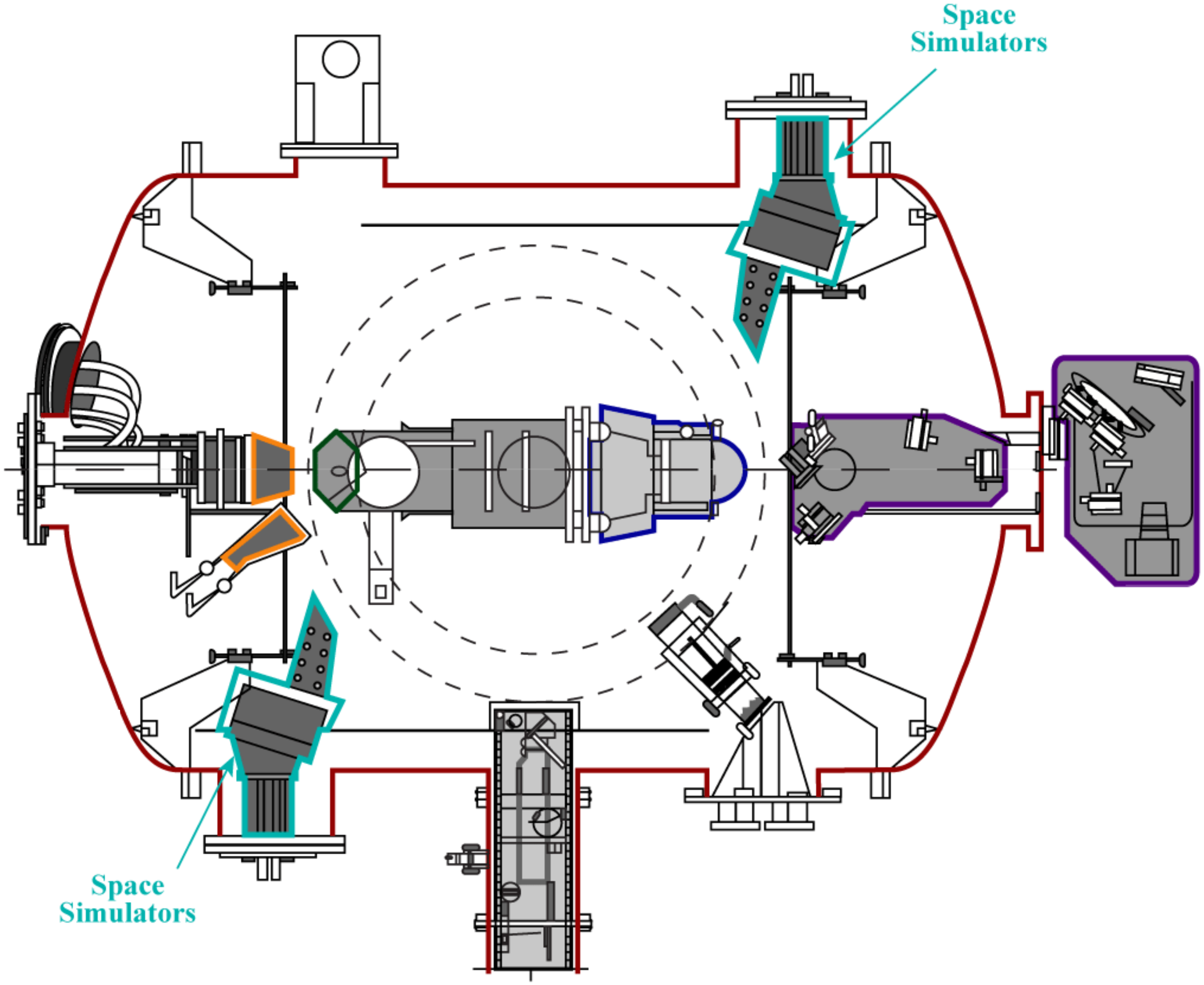


Narrow & Wide Field Blackbodies

Radiometric Calibration Facility

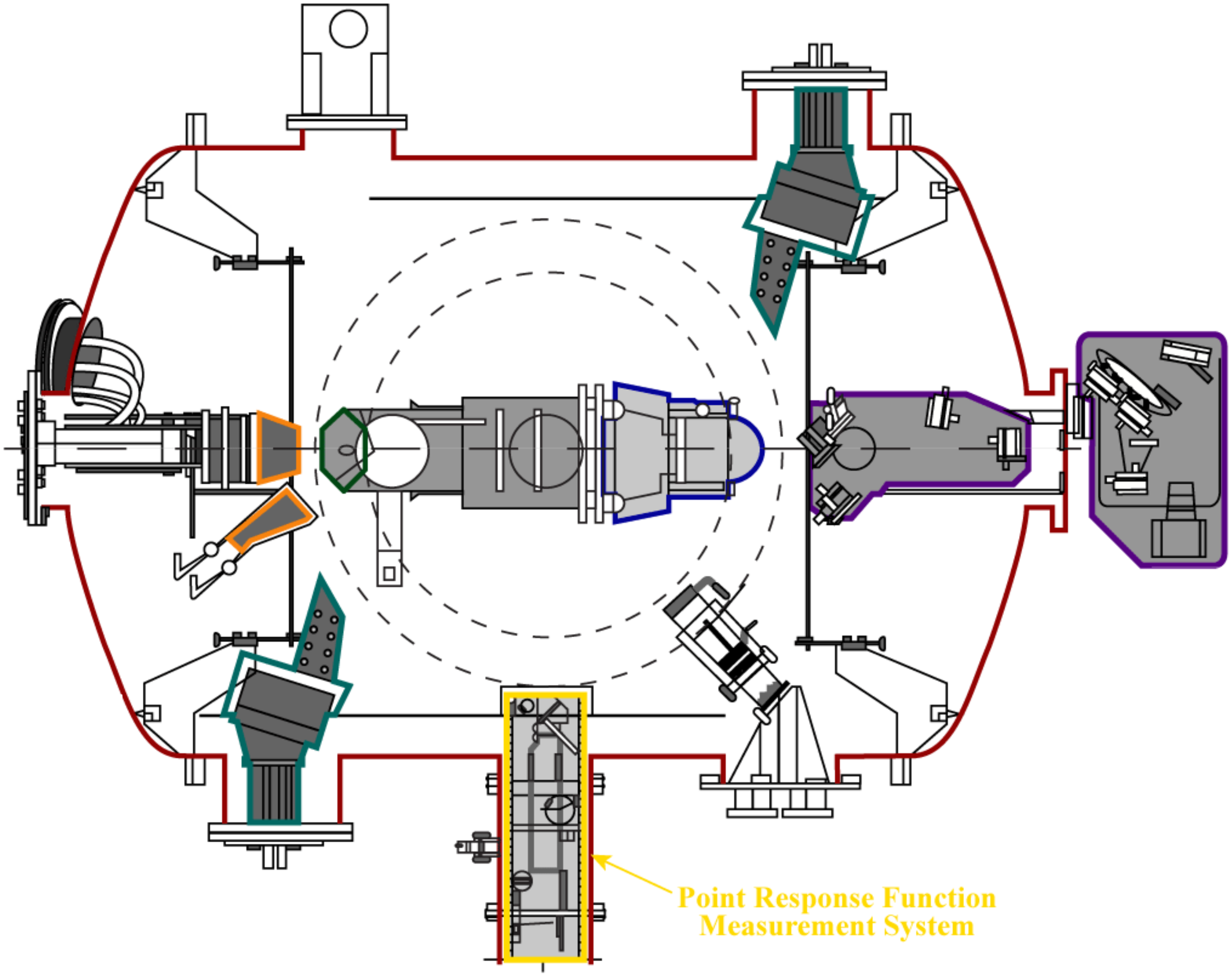


Radiometric Calibration Facility



Radiometric Calibration Facility

Clouds and the Earth's Radiant Energy System



Scan Dependent Offsets,
What are they and what is their origin?

Scan dependent offsets, o, are extraneous instrument artifacts which impart sample dependent biases on the radiometric measurements.

Typically arise from one of two sources:

1. Electromagnetic signals
   These signals are picked up as the sensor rotates through dynamic emf fields which surround the high voltage electronic circuitry
2. Micro-strains
   Thermistor bolometers act as strain gauges and rotating the sensor modules can impart micro-strains on the detectors.

Magnitude is typically a function of 6 parameters, the angular position, scan rate, and acceleration rate of the sensor about both the elevation (ε) and azimuthal (α) axes,

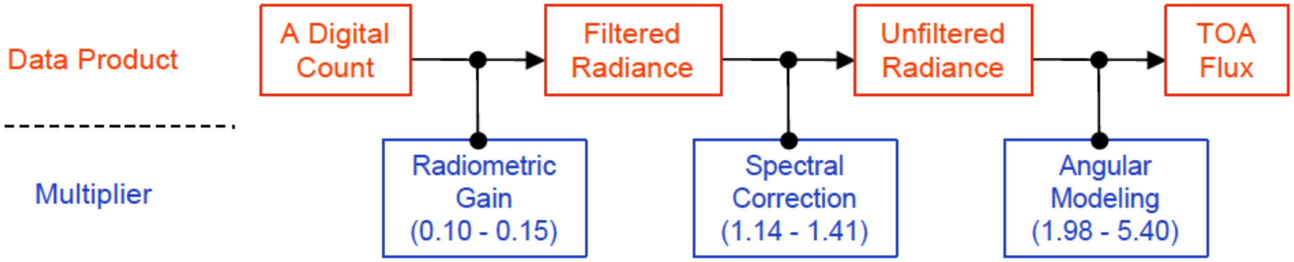
$$o = F(\varepsilon, \dot{\varepsilon}, \ddot{\varepsilon}, \alpha, \dot{\alpha}, \ddot{\alpha})$$

Scan Angle Dependent Offsets

How significant are they?

Mission accuracy requirements are 0.5% for Longwave 1.0% for Shortwave, or
1.2 W/m^2 TOA LW Flux
2.0 W/m^2 TOA SW Flux

Accurate knowledge of scan dependent offsets at the sub 1-count level is necessary to meet this objective. The relationship between a digital count and TOA Flux is…..



Data Product

A Digital Count → Filtered Radiance → Unfiltered Radiance → TOA Flux

Multiplier

Radiometric Gain (0.10 - 0.15)

Spectral Correction (1.14 - 1.41)

Angular Modeling (1.98 - 5.40)

SW : 1 count ~0.50 W/m^2 TOA Flux
LW_{NIGHT} : 1 count ~0.55 W/m^2 TOA Flux
→ **LW_{DAY} : 1 count ~1.05 W/m^2 TOA Flux** ←

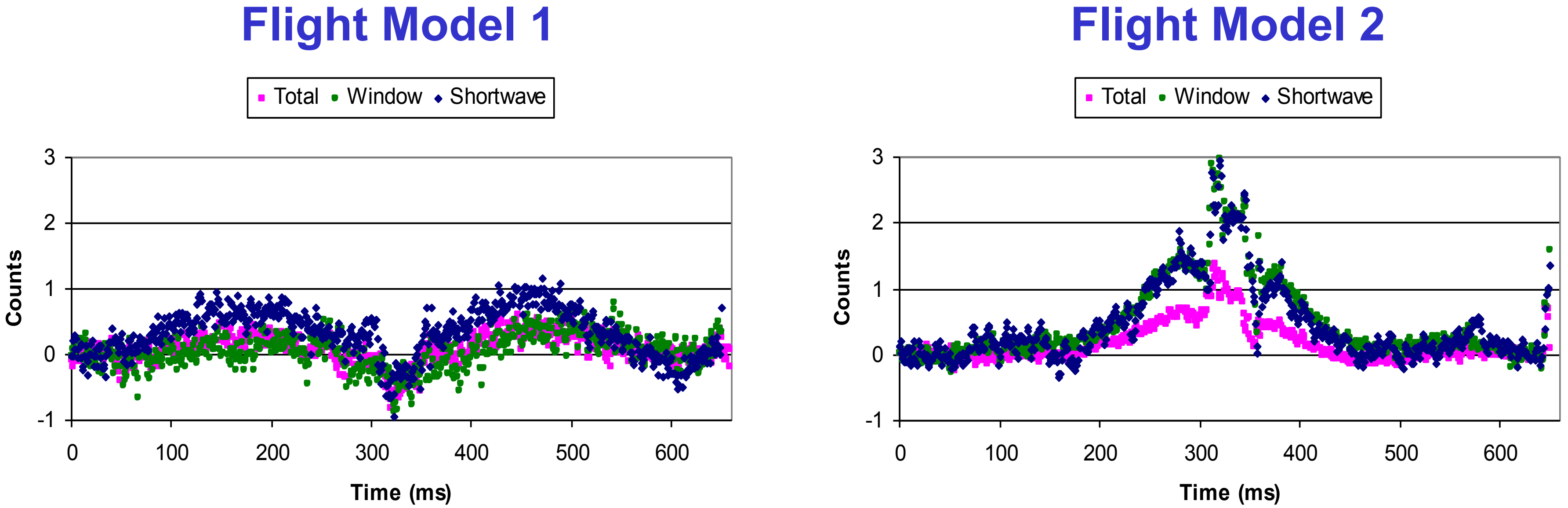
LW_{DAY} = Total - Shortwave

Therefore, the Total and Shortwave offsets are roughly additive in the worst case.

X

CERES Terra Scan Angle Dependent Offsets

Ground Derived Values
(Fixed Azimuth Plane Scan mode)



SW : 1 count ~0.50 W/m^2 TOA Flux

LW $_{NIGHT}$: 1 count ~0.55 W/m^2 TOA Flux

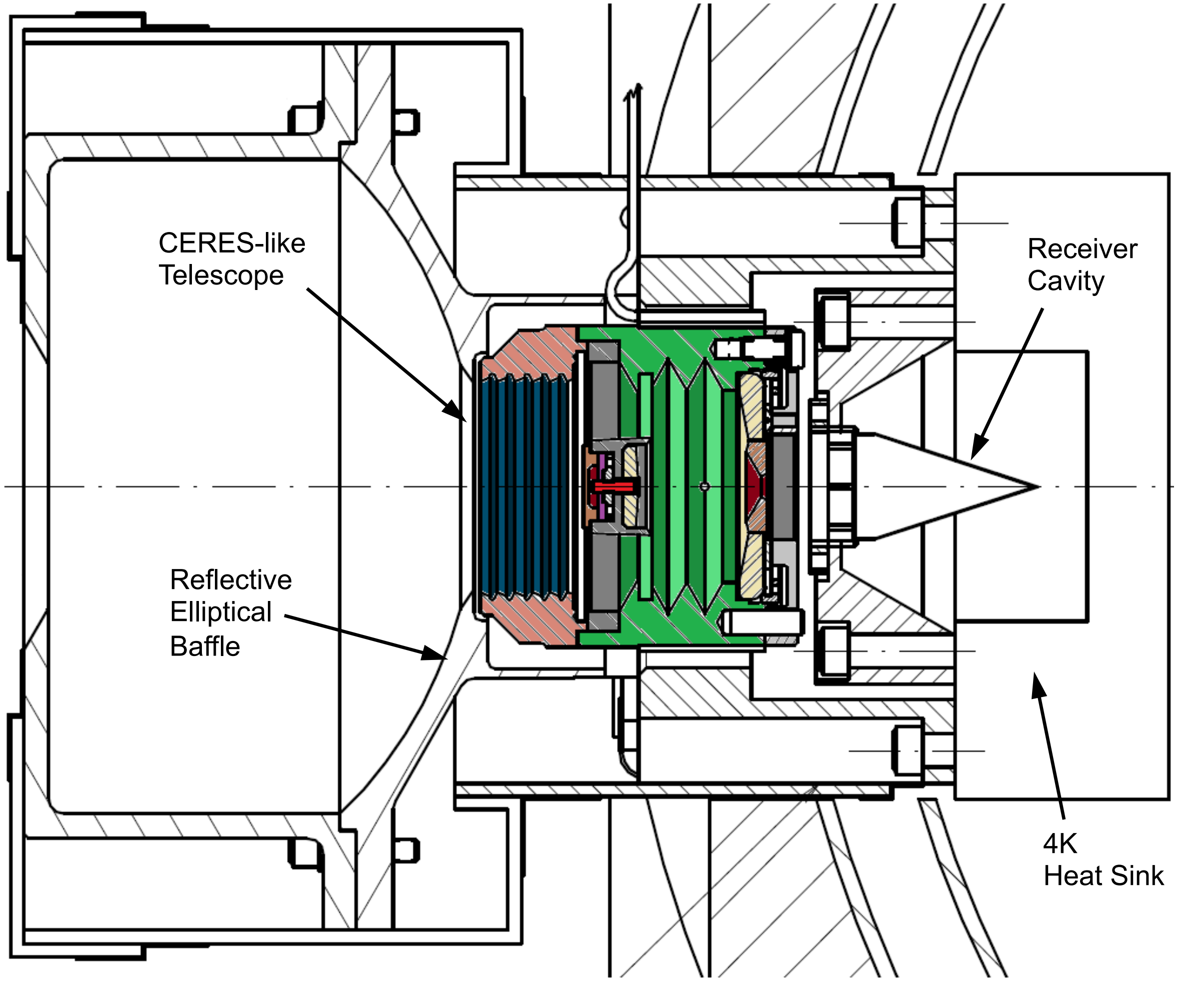
→ **LW $_{DAY}$: 1 count ~1.05 W/m^2 TOA Flux** ←

For all CERES 'Edition-1' data products the scan dependent offsets are assigned ground-determined values.

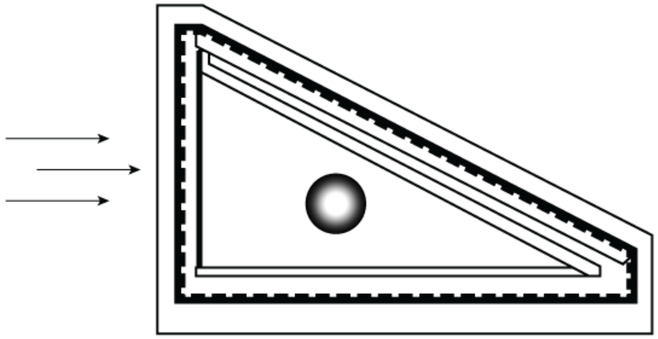
RCF Transfer Active Cavity Radiometer

TACR

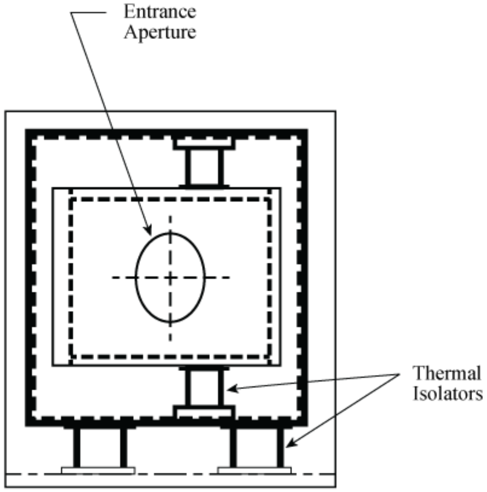
- **Cryogenic receiver cavity**
  - Black copper cone, thermally sunk to a liquid He dewar
  - Absorptance >0.999 from visible to IR
- **TACR telescope**
  - CERES-like fore optics
  - Telescope housing and baffle are optically identical to flight configuration
  - Nickel mirrors with flight optical prescription
- **Elliptical reflective baffle**
  - Replaces sensor forward baffle
  - Provides radiance heat rejection
  - Increases thermal stability



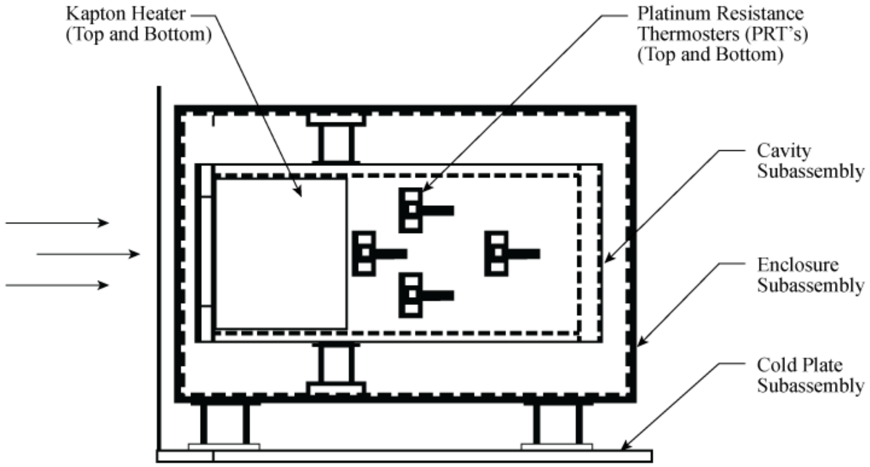
NFBB



TOP VIEW



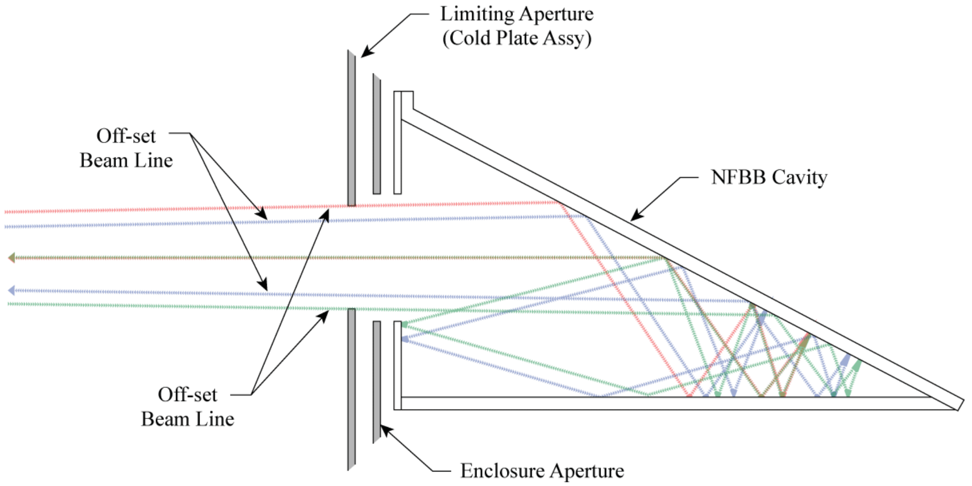
FRONT VIEW

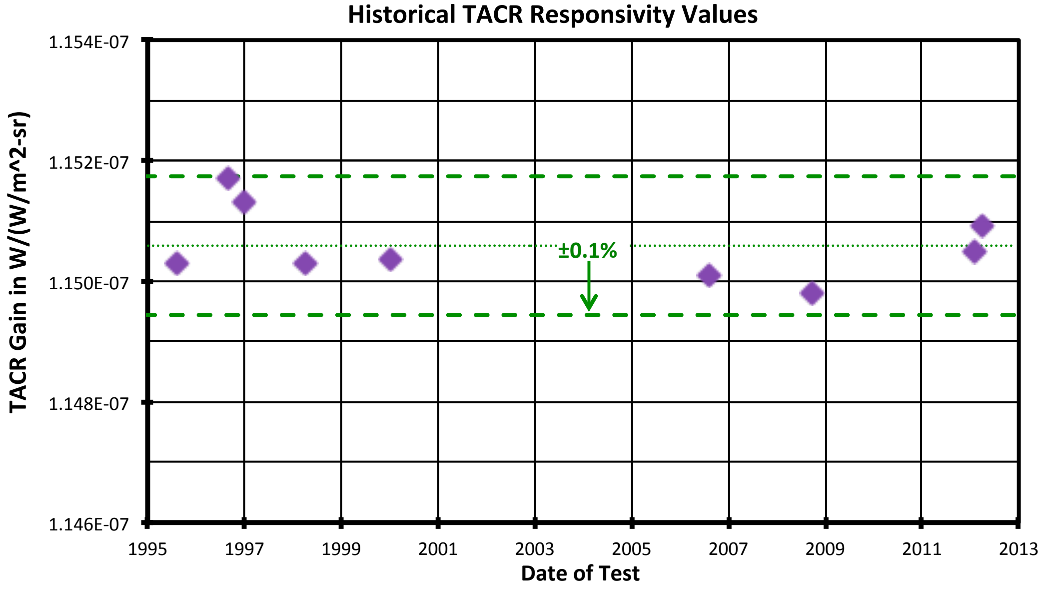


SIDE VIEW

X

NFBB Performance Specifications



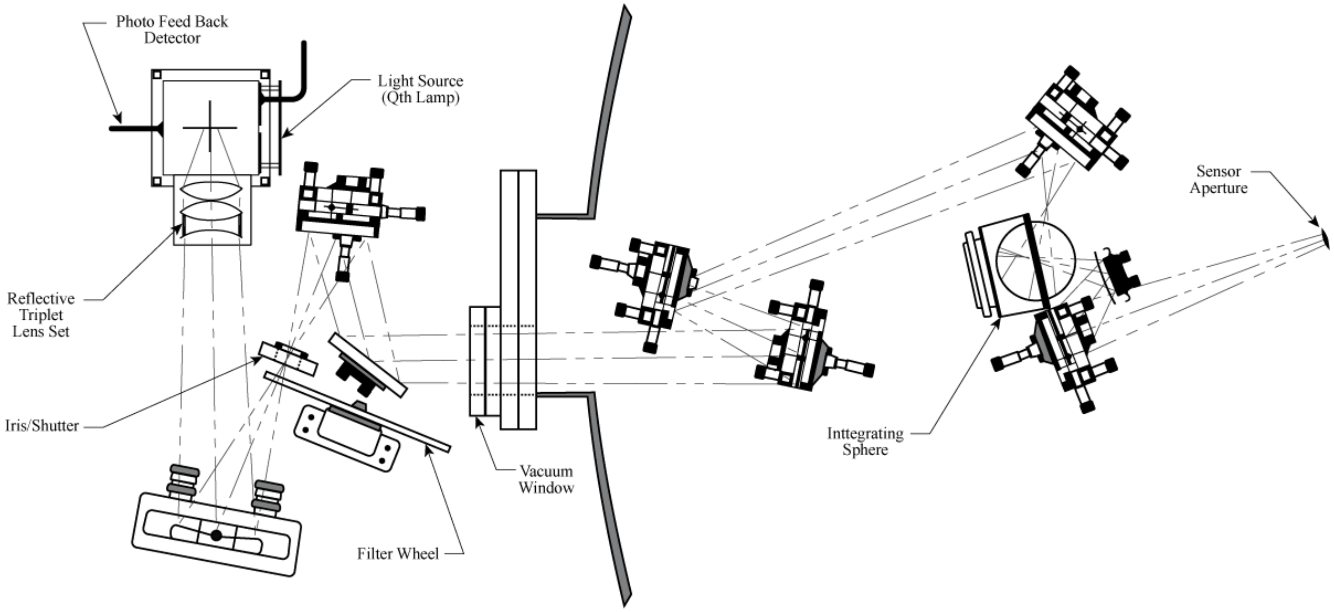


Parameter	Value
Wavelength Range (um)	3.0 to 100
Emissivity	>0.999994
Absolute Temperature Knowedge (Kelvin) (traceable to ITS-90)	+/- 0.023
Temperature Stability (Kelvin)	+/- 0.005
Temperature Uniformity (Kelvin)	+/- 0.007
Temperature Range (Kelvin)	200 to 320
Radiance Range (W/m2/sr)	29 to 190
Cooldown Time (Minutes)	100
Aperture (cm)	3.8 x 4.7 (elliptical)
Absolute Radiance Knowledge (%)	+_/- 0.04

RCF Shortwave Reference Source (SWRS)

The SWRS consists of a stabilized Halogen lamp fed into the RCF via optical train

- 8 mirrors, 1 triplet lens set,13 filters in a filter wheel, an iris aperture, a vacuum window and an integrating sphere



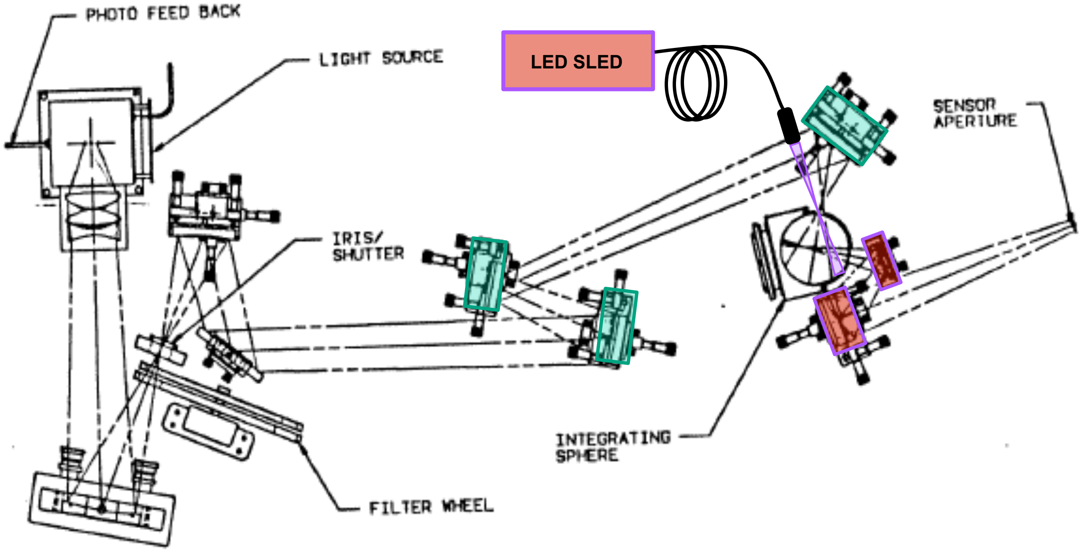
- 250-watt QTH lamp source @ ~3100K
- Precision power supply with <0.4% rms radiance ripple
- Photofeedback system using a thermally-stabilized silicon photodiode

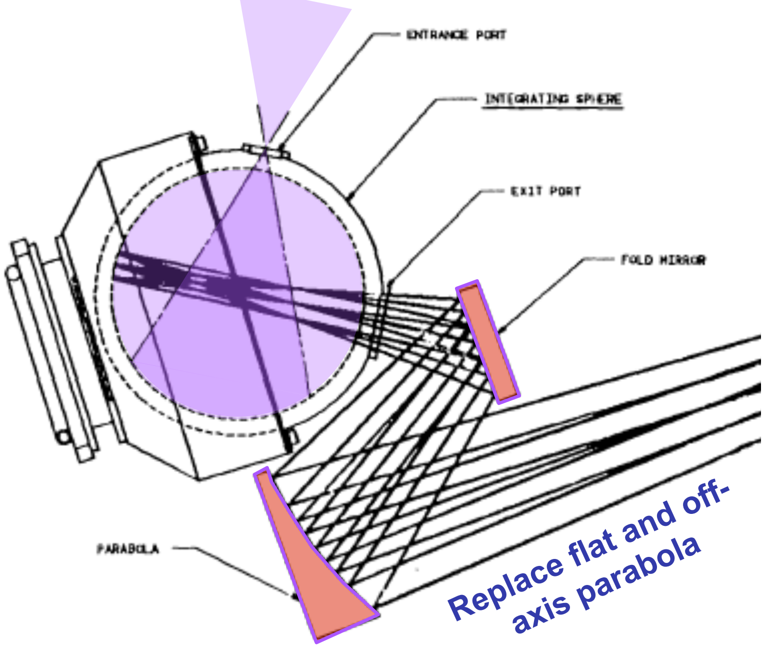
PARAMETER	VALUE
Filters used for CERES Calibration (center wavelengths in μm)	0.42, 0.46, 0.51, 0.62, 0.71, 0.81, 0.90, 1.00, 1.15, 1.25, 1.35, 1.63, 1.94
Broadband Radiance Range ($W/m^2/sr$)	13 to 2500
Exit Port Angular Subtense (degrees): cross-scan; in-scan	3.5; 7.8
Radiance Uniformity (peak to valley): aperture; field angle	± 0.5%; ± 1.5%
Radiance Fluctuation (0.01 sec. to hours)	< ± 0.1% (1-sigma)
Thermal Stability and Uniformity (Kelvin)	± 0.5
Sphere Operating Temperature (Kelvin)	< 85

FM 6 Ground Calibration Improvements

SWRS Improvements

- **Improve SWRS optics**
  - NASA has contracted mirror replacement – enhanced aluminum coatings on mirrors following sphere
  - Option to replace additional mirrors in SWRS optical train to improve throughput
- **Supplement SWRS for increased radiance at the shorter wavelengths**
  - NASA has contracted LED augmentation to existing SWRS
  - Discrete LED sources at 365nm, 385nm and 405nm
  - Option for additional LED coverage up to 970nm
  - Option for future coupling of coherent sources



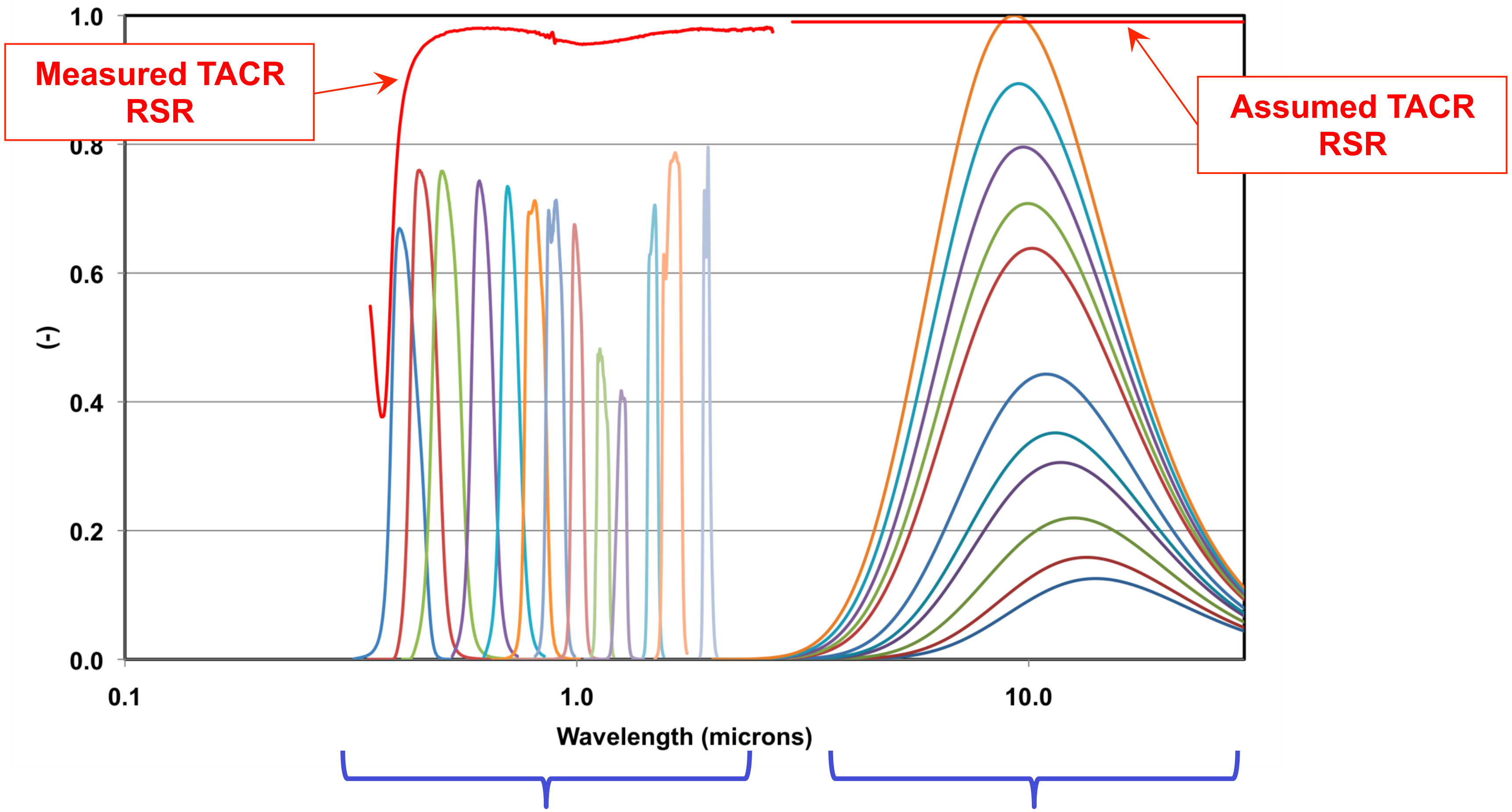


LED Injection through existing sphere port

Replace flat and off-axis parabola

CERES Traceability

- NFBB is used for long-wave calibration at temperatures between 205 K to 318K
- Short-wave calibration is achieved by transfer of NFBB standard to SWRS via TACR



Measured TACR RSR

Assumed TACR RSR

TACR Application Region
(SWRS Bands)

TACR Calibration Region
(NFBB Spectra)

Mathematical Model

The Spectral Response, S_λ, may be mathematically modeled as

$$S_\lambda^j \equiv \rho_\lambda^2 \tau_\lambda \alpha_\lambda \qquad j = \text{tot}, \text{sw}, \text{wn}$$

where

- ρ_λ is the spectral reflectance of the silvered mirrors
- τ_λ is the spectral transmittance of any optical filters
- α_λ is the spectral absorptance of the detector

Theoretically, the ratio of the spectral response functions of any two given channels results in cancellation of the spectral characteristics of common components, Thus

$$\frac{S_\lambda^{\text{tot}}}{S_\lambda^{\text{sw}}} = \frac{1}{\tau_\lambda}$$

Practically, this is only true to the extent of repeatability in the manufacturing process

Reflected Solar Band Spectral Characterization

(0.2 - 2.5 μm)

- **Shortwave Reference Source (SWRS) uses filters to provide 13 narrow band sources between 0.4 and 2.0 μm**
- **A cryogenically cooled Transfer Active Cavity Radiometer (TACR) places these sources on the same radiometric scale as the Narrow Field Blackbody (NFBB)**
- **By ratioing CERES measurements to TACR measurements, the relative SW spectral response, S^{sw}, is defined in each of these narrow spectral bands, Δλ, for both the SW channel and SW portion of the Total channel**

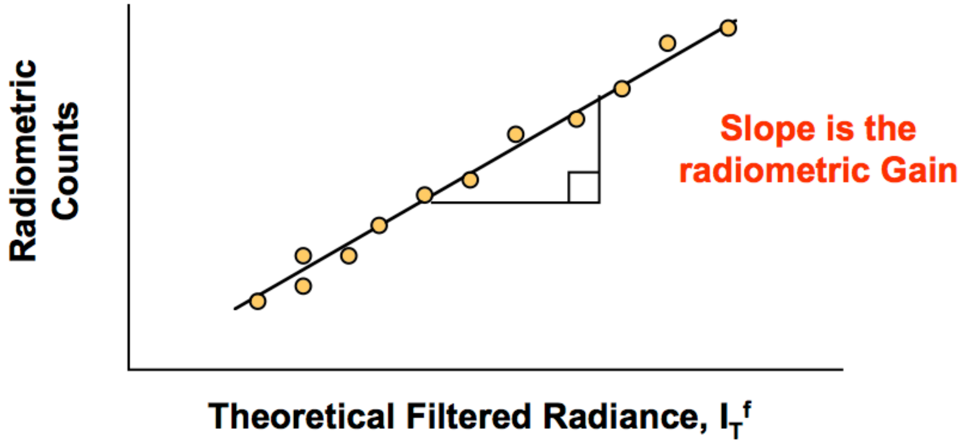
$$S^{sw}_{\Delta\lambda,\,\mathrm{CERES}} = \frac{m_{\Delta\lambda,\,\mathrm{CERES}}}{m_{\Delta\lambda,\,\mathrm{TACR}}}$$

- **Spectral measurements of the optical components are used to complete the spectral response curve between the narrowband SW sources and extend the curve down to the UV region (0.2 μm)**
- **Component measurements from 0.2 - 2.5 μm are made using a CARY5 grating spectrometer with the witness samples in a nitrogen purged chamber**

Thermal Band Spectral Characterization

(2.5 - > 100 µm)

Regressing sensor output (radiometric counts) as a function of theoretical filtered radiance, I_T^f, for each of the 12 calibration NFBB temperatures over the range of 205 to 315K yields



Slope is the radiometric Gain

$$I_T^f = \int_{\phi=0}^{\phi_1} \int_{\theta=0}^{\theta_1} \int_{\lambda=0}^{\infty} S_\lambda I_{\lambda,T_{NFBB}} \, d\lambda d\theta d\phi$$

- **The final LW spectral response, S_λ, is determined by optimizing this regression**
- **By optimizing we mean adjusting the estimate of S_λ within the understood FTS measurement uncertainty such that the residuals in the regression are minimized.**
- **This methodology ensures that CERES is optimally calibrated against longwave radiance sources that have Planck like spectral distributions.**

X

Determination of S_λ in the Longwave Region

(2.5 - >100 μm)

FTS Vacuum Chamber Facility

- **BIO-RAD Fourier Transform Spectrometer 60A Dual Source/Dual Detector system with an 896 interferometer and flip mirror.**
- **The first detector is a CERES sensor, including the entire optical train.**
- **Second detector is a spectrally flat Lithium Tantalate (α > 99%) Pyro-electric Reference Detector (PRD) with a trap configuration.**
- **S_λ is obtained by normalizing the transformed interferogram measurements of the CERES sensor to those of the spectrally flat reference detector...**

$$S_\lambda = \frac{m^f_{\lambda,\,\mathrm{CERES}}}{m^f_{\lambda,\,\mathrm{PRD}}}$$

- **Six combinations of beamsplitter and sources are used to completely cover the IR spectral regime**
- **Beyond approximately 30 microns the SNR of the FTS data decreases rapidly**

FTS

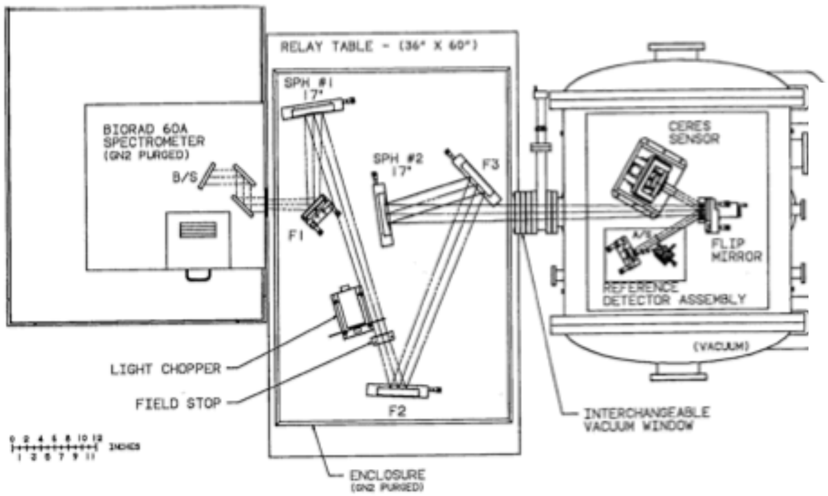


Figure 1. FTS Vacuum Spectral Characterization Facility Layout

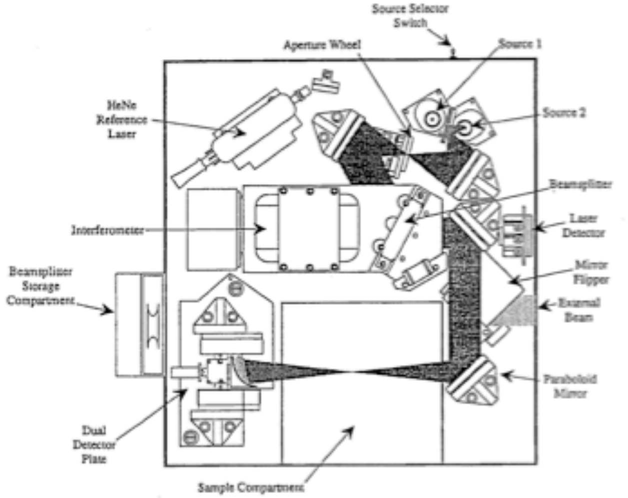


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Figure 2. Opto-Mechanical Layout of the BIO-RAD Model 60A Spectrometer

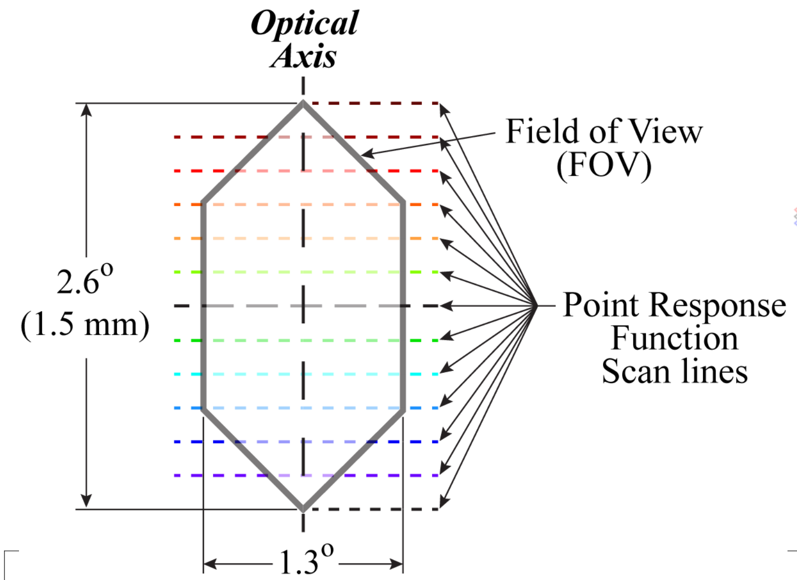
FTS Spectral Characterization

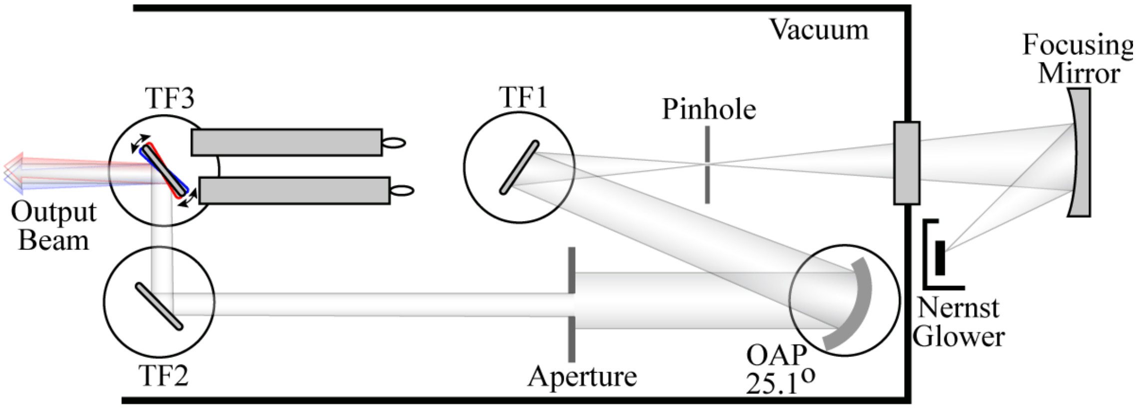
- BIORAD-60A Spectrometer is used as a broadband spectral source.
- Measurements taken by CERES instrument as well as a reference detector.
- Spectrally flat Lithium Tantalate Pyroelectric Reference Detector (PRD) is used as a reference.
- Spectral estimate is obtained by taking ratio of CERES sensor measurement with PRD measurement.

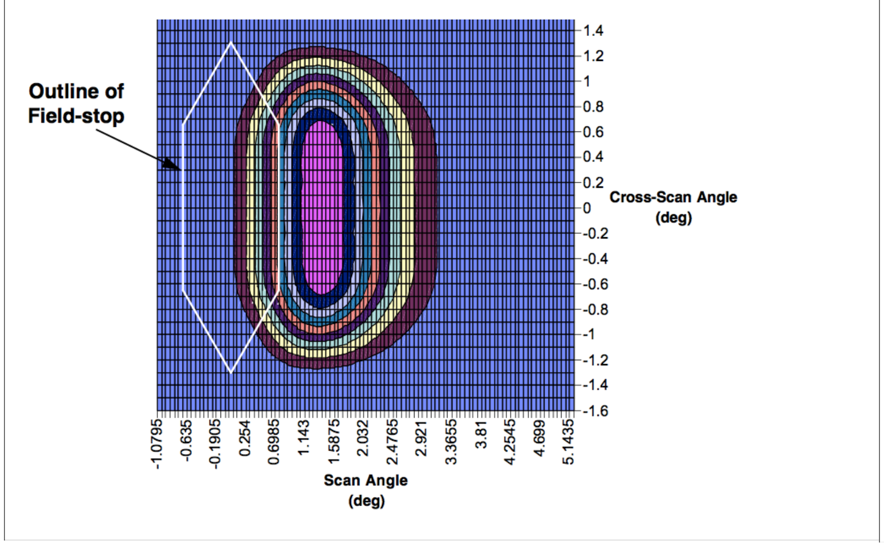
$$S_\lambda = \frac{m^f_{\lambda,CERES}}{m^f_{\lambda,PRD}}$$

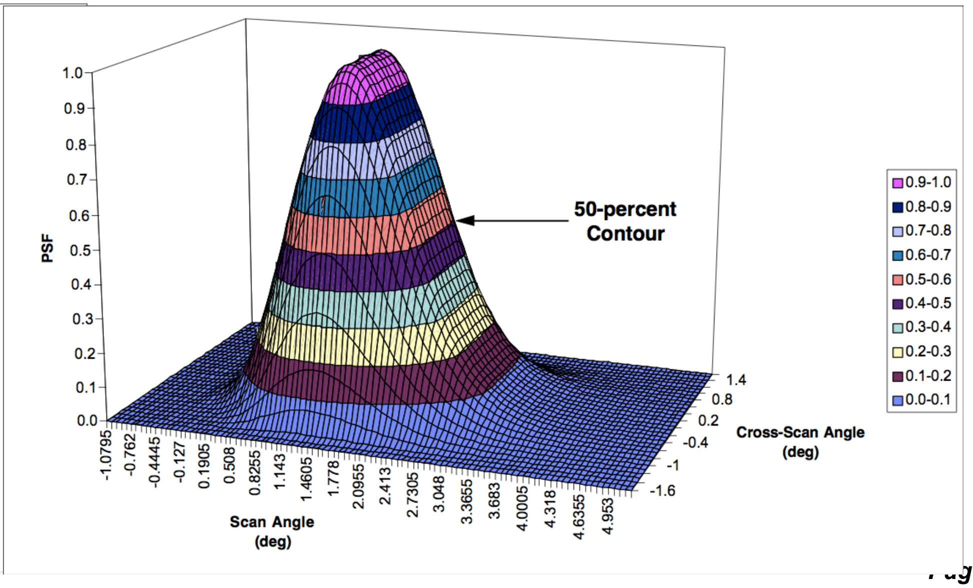
Point Response Function Source

Clouds and the Earth's Radiant Energy System









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Instrument Artifact Removal Strategy

Remote sensing instruments generally exhibit time varying artifacts in their data products. For CERES these artifacts stem from either of 2 physical entities…..

- **Radiometric Gain Change**
  - **Wavelength independent change in sensor responsivity**
  - **Corrections implemented in Count Conversion algorithm (SS1)**
- **Spectral Response Change**
  - **Wavelength dependent change in sensor optics**
  - **Corrections implemented in Spectral Unfiltering algorithms (SS2)**

Radiometric Channel	Spectral Region	
	SW	LW
Total	<3.0 um	>3.0 um
SW	<5.0 um	-
WN	-	8-12 um

Instrument and ERBE-Like Data Product Release Strategy

At_Launch - Static Algorithms and Pre-Launch coefficients - baseline product used during intensive Cal Val Period (Launch to SOC+8 Months)

Edition1_CV - Static Algorithms and coefficients - baseline product used in cal/val protocol (SOC+7.5 Months, continuous over mission)

Edition2 - Utilizes temporally varying coefficients to correct for traceable radiometric drift. All spectral changes are broadband and 'gray'. (L+1 yrs to ~5 yrs)

Edition3 - Will incorporate temporally varying spectral artifacts in the SW measurements. A complete re-analysis of Ground Calibration with additional component characterization measurements. (L+5 yrs)

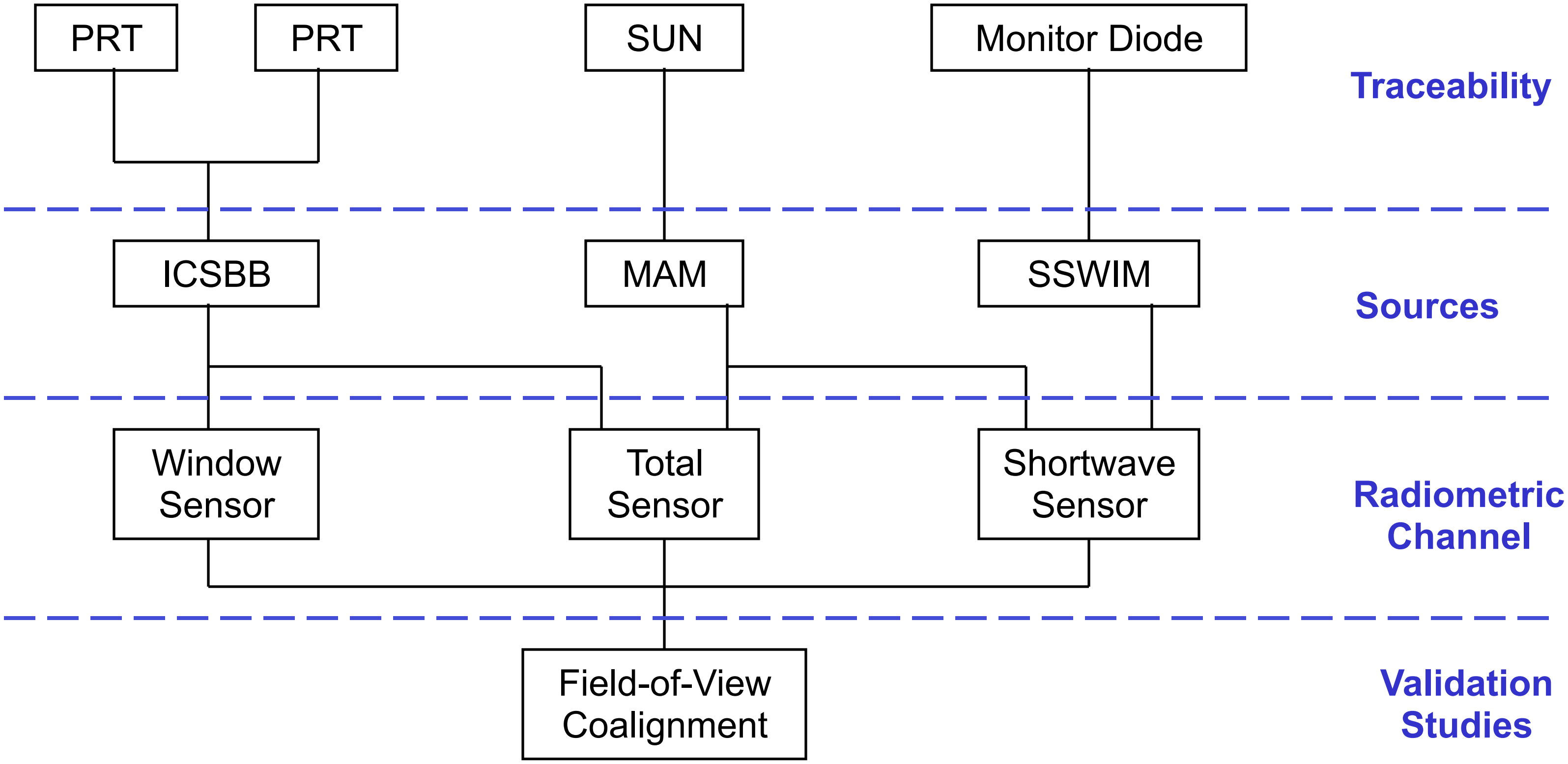
Edition2 products lag Edition1_CV by a minimum of 6 months

CERES Flight Radiometric Validation Activities

		Product	Spatial Scale	Temporal Scale	Metric	Spectral Band
On-Board	Internal BB	Filtered Radiance	N/A	N/A	Absolute Stability	TOT, WN
	Internal Lamp	Filtered Radiance	N/A	N/A	Absolute Stability	SW
	Solar	Filtered Radiance	N/A	N/A	Relative Stability	TOT, SW
Vicarious	Theoretical Line-by-Line	Filtered Radiance	> 20 Km	Instantaneous	Inter-Channel Theoretical Agreement	TOT, WN
	Unfiltering Algorithm Theoretical Validation	N/A	N/A	N/A	N/A	TOT, SW, WN
	Inter-satellite (Direct Comparison)	Unfiltered Radiance	1-deg Grid	1 per crossing	Inter-Instrument Agreement, Stability	TOT, SW, WN
	Globally Matched Pixels (Direct Comparison)	Unfiltered Radiance	Pixel to Pixel	Daily	Inter-Instrument Agreement	TOT, SW, WN
	Tropical Mean (Geographical Average)	Unfiltered Radiance	20N – 20S	Monthly	Inter-Channel Agreement, Stability	TOT, WN
	DCC Albedo	Unfiltered Radiance	>40 Km	Monthly	Inter-Instrument agreement, Stability	SW
	DCC 3-channel	Unfiltered Radiance	>100 Km	Monthly	Inter-Channel consistency, stability	TOT, SW
	TIme Space Averaging	Fluxes	Global	Monthly	Inter-Instrument Agreement	LW, SW
	Lunar Radiance Measurements	Filtered Radiance	Sub Pixel	Quarterly	Inter-Instrument Agreement	LW, SW, WN

CERES Onboard Calibration Philosophy

Clouds and the Earth's Radiant Energy System


PRT

PRT

SUN

Monitor Diode

Traceability

ICSBB

MAM

SSWIM

Sources

Window Sensor

Total Sensor

Shortwave Sensor

Radiometric Channel

Field-of-View Coalignment

Validation Studies

X

CERES Flight Radiometric Validation Activities

		Product	Spatial Scale	Temporal Scale	Metric	Spectral Band
On-Board	Internal BB	Filtered Radiance	N/A	N/A	Absolute Stability	TOT, WN
	Internal Lamp	Filtered Radiance	N/A	N/A	Absolute Stability	SW
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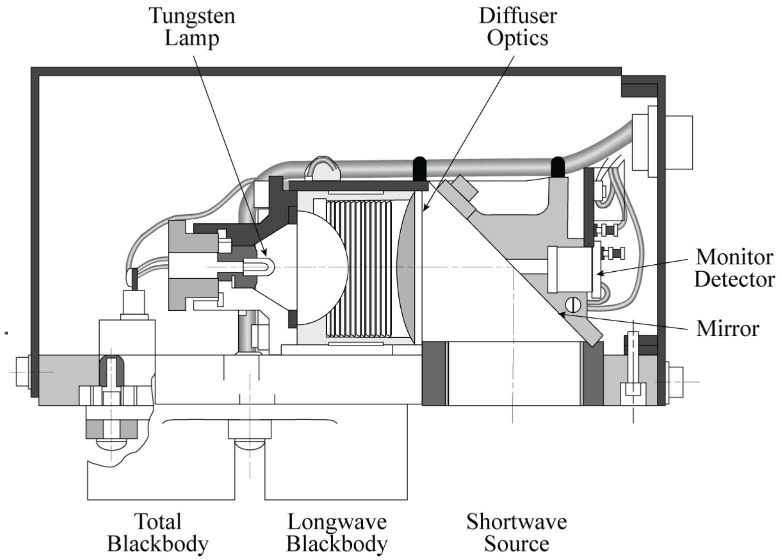
	Lunar Radiance Measurements	Filtered Radiance	Sub Pixel	Quarterly	Inter-Instrument Agreement	LW, SW, WN

CERES Calibration Subsystems

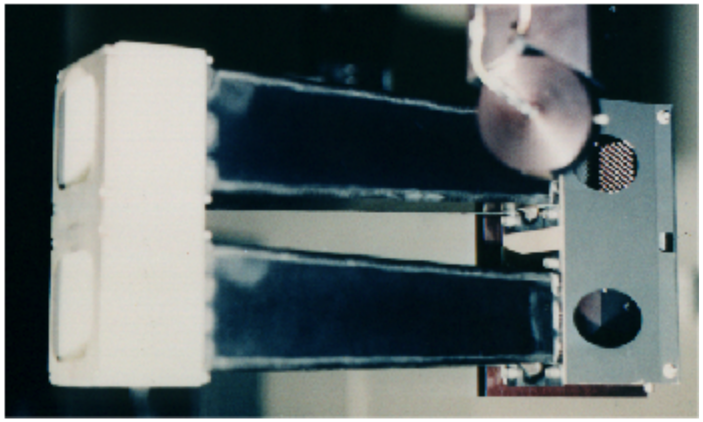
Internal Calibration Module

- Evacuated Quartz Tungsten lamp operated at 3 Levels (2100, 1900, 1700 K spectrums)
- Silicon Photodiode (SiPd) reference detector
- Design specification is +-0.5% stability over 5-year mission
- Designed primarily to transfer SW channel Ground Cal measurements to orbit

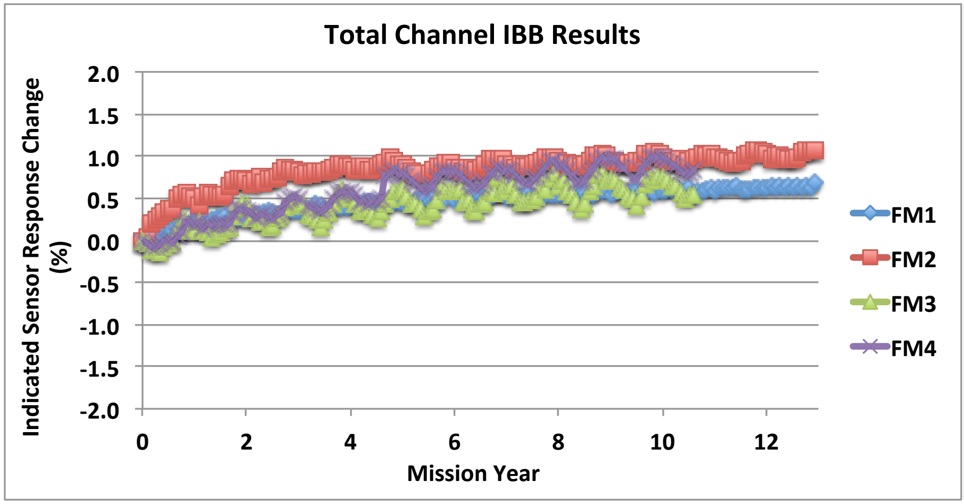


Mirror Attenuator Mosaic (MAM) Solar Diffuser

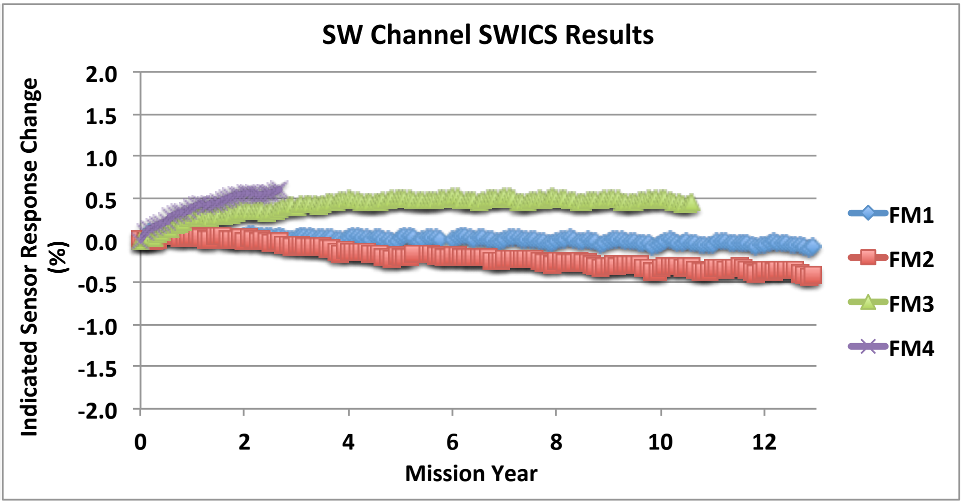
- Solar Diffuser plate attenuates direct solar view (~5800K Spectrum)
- MAM is a Nickel substrate with Aluminum coated spherical cavities or divots
- Provides a Relative calibration of the Shortwave channel and the SW portion of the Total channel
- Designed to provide a long-term on-orbit SW calibration source.



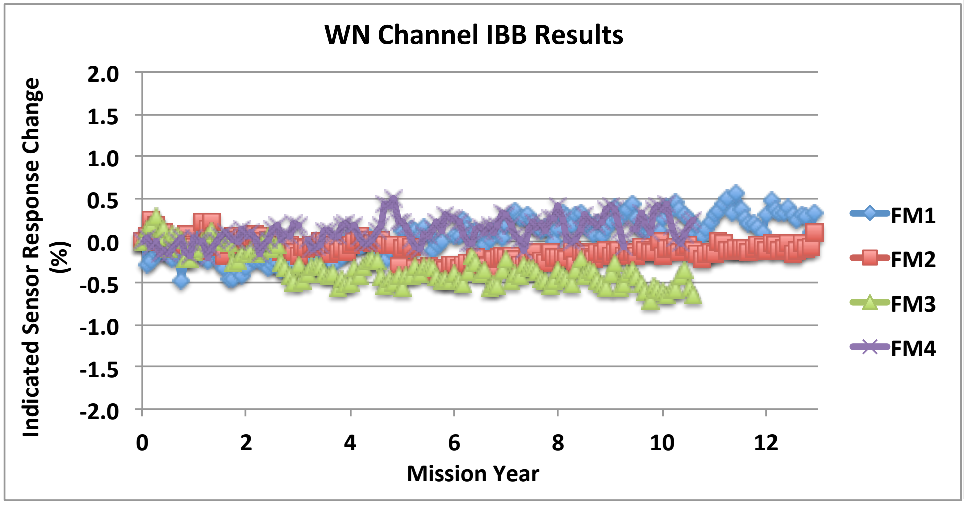
Internal Calibration Module Results



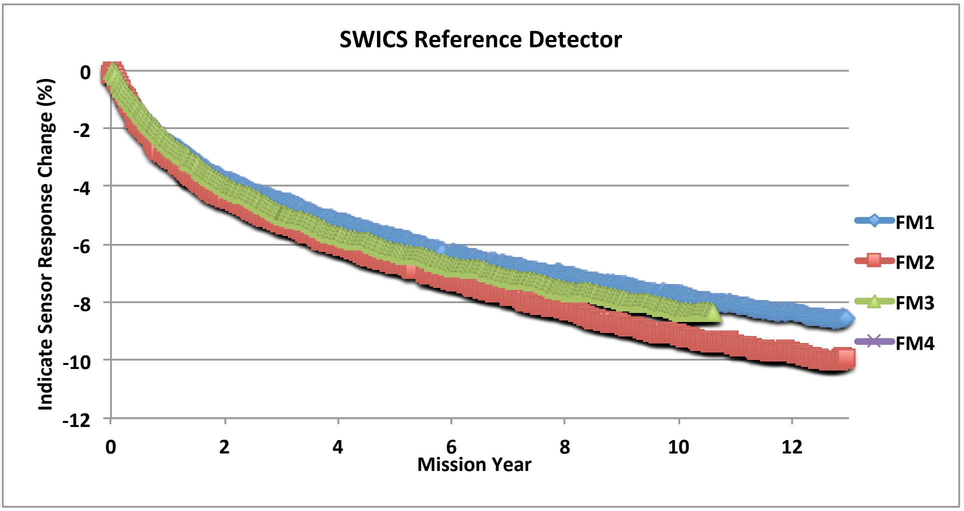
Total Channel IBB Results



SW Channel SWICS Results



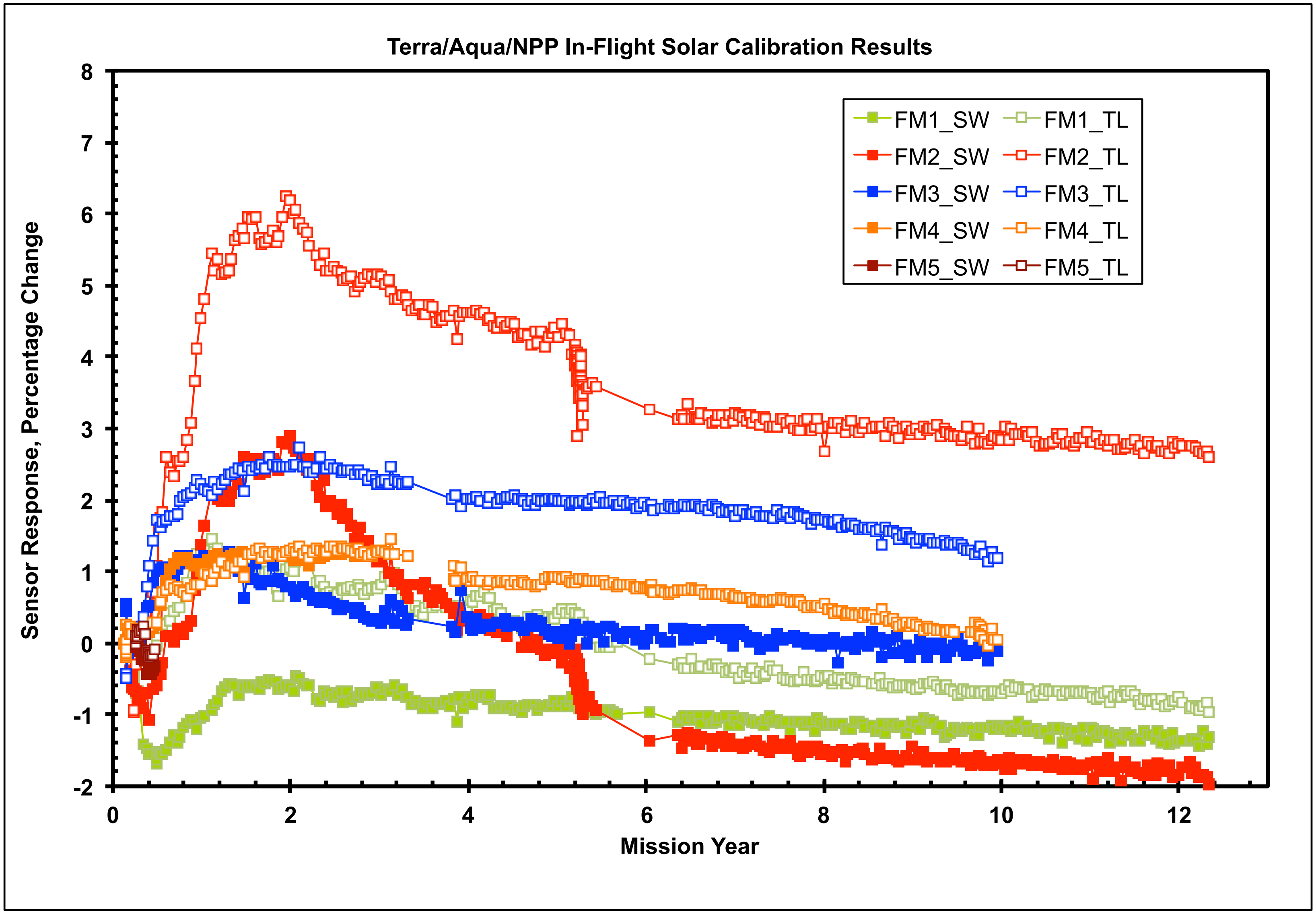
WN Channel IBB Results



SWICS Reference Detector

Solar Calibration Results

Clouds and the Earth's Radiant Energy System



CERES Flight Radiometric Validation Activities

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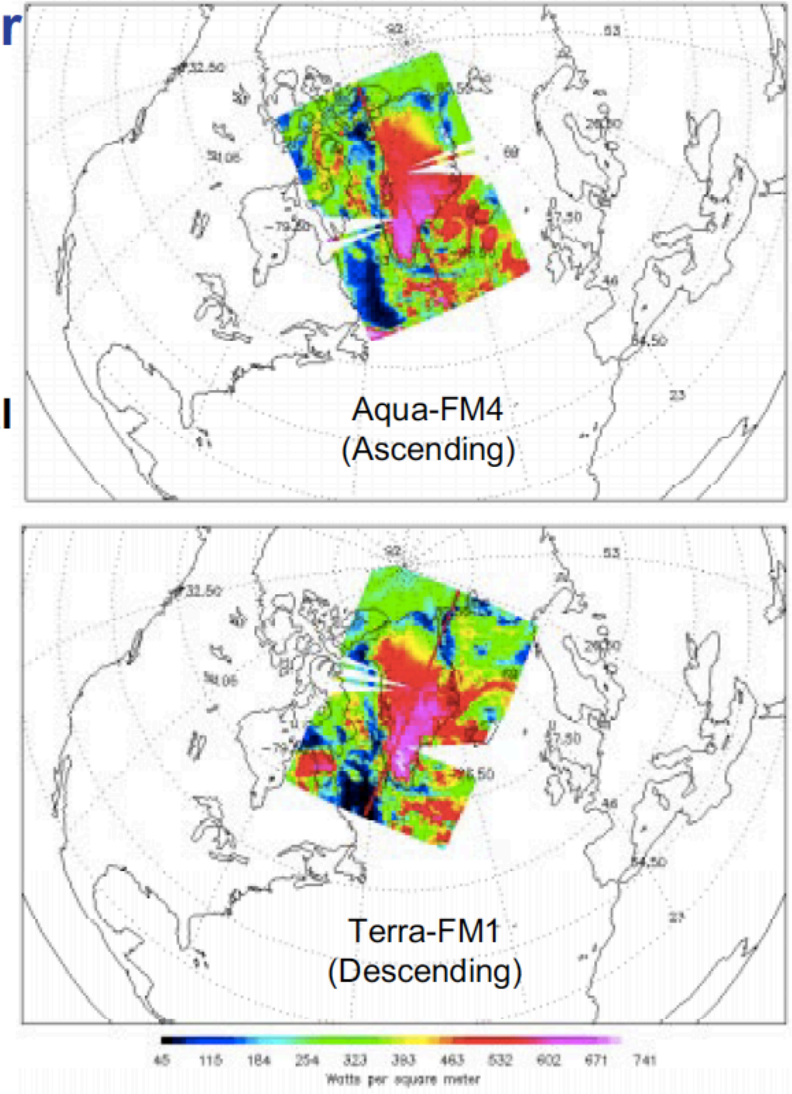
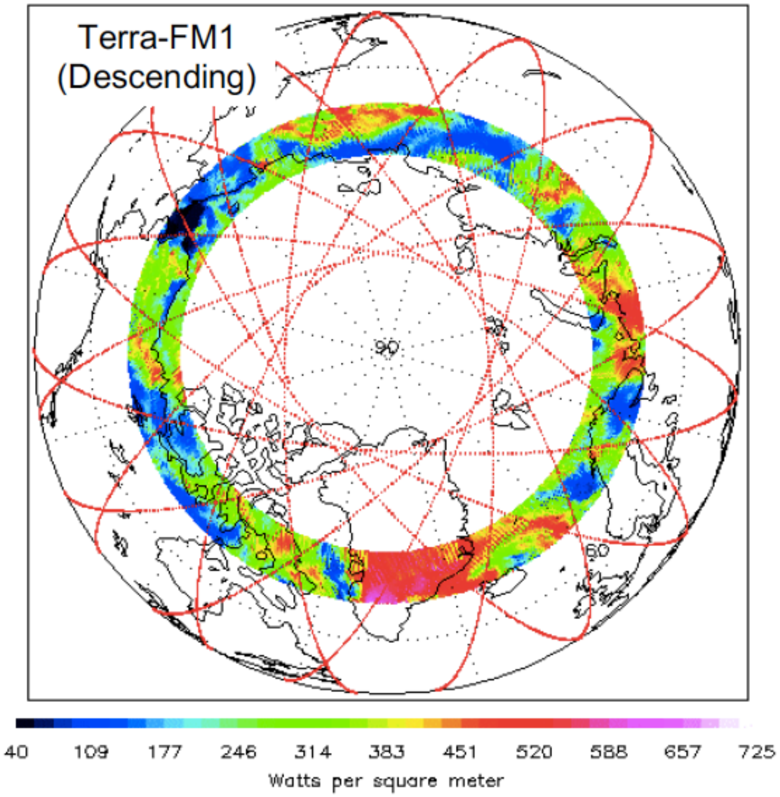
CERES Flight Radiometric Validation Activities

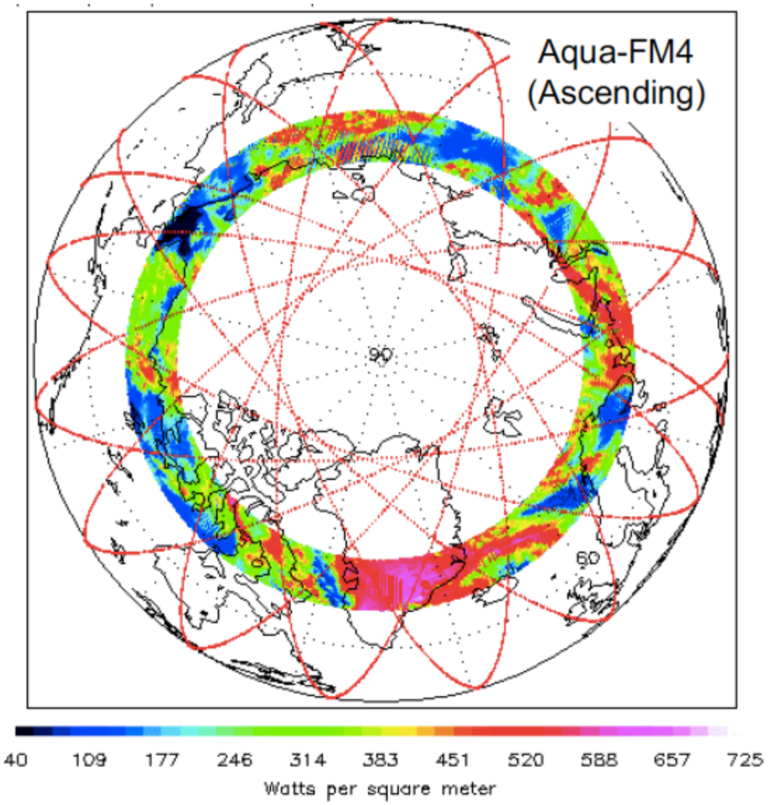
Aqua/Terra Inter-Calibration Over Greenland

- **Orbits intersect at 69.5 deg**
- **Temporal matching <15 mins**
- **Scan planes set orthogonal to principal plane**
- **Data collected for 5-deg lat. Swath**
- **Measurements during month of July**
- **FM1 and FM4 instruments were utilized**



Aqua and Terra Inter-Calibration Coincident Scan Planes - Daily





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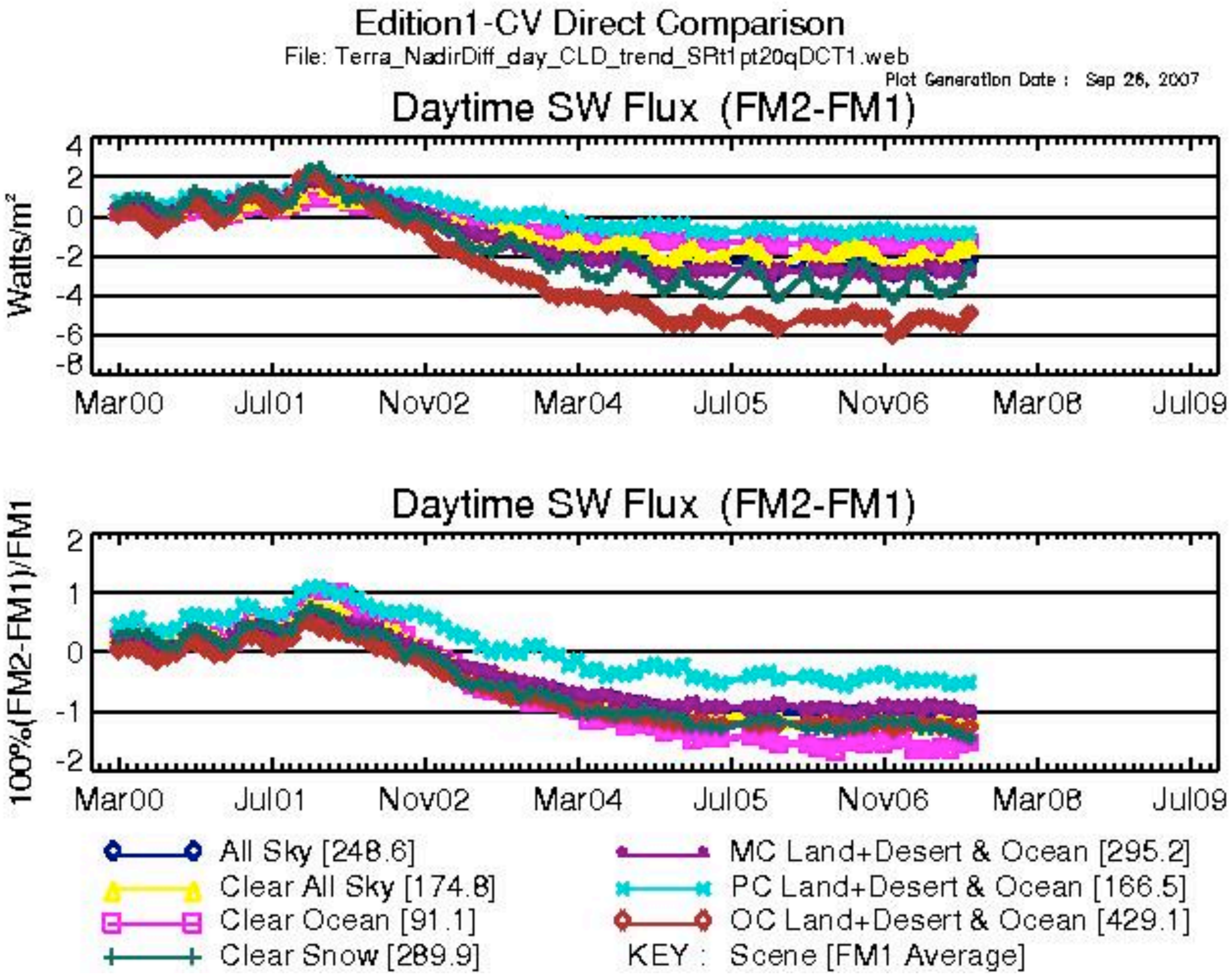
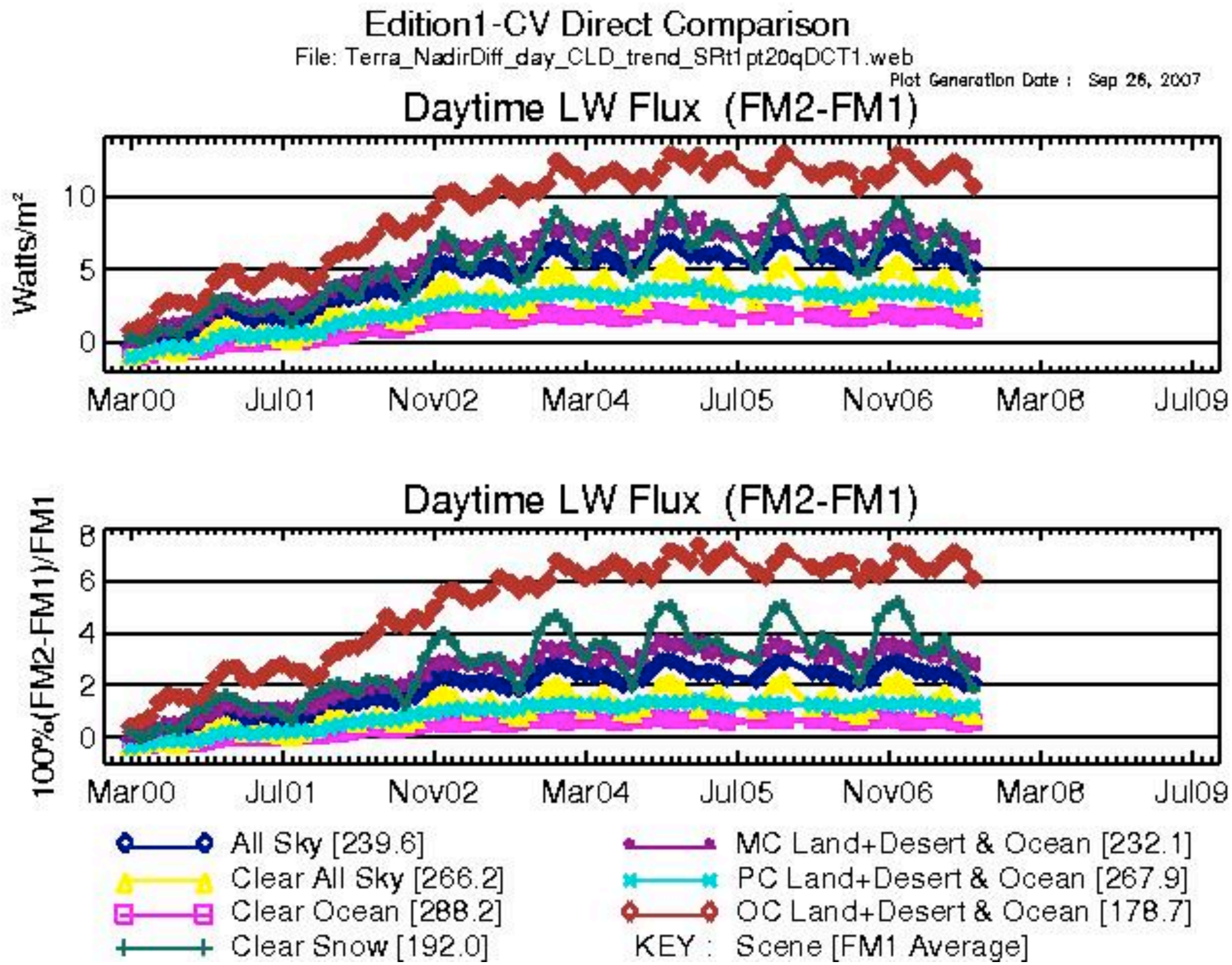
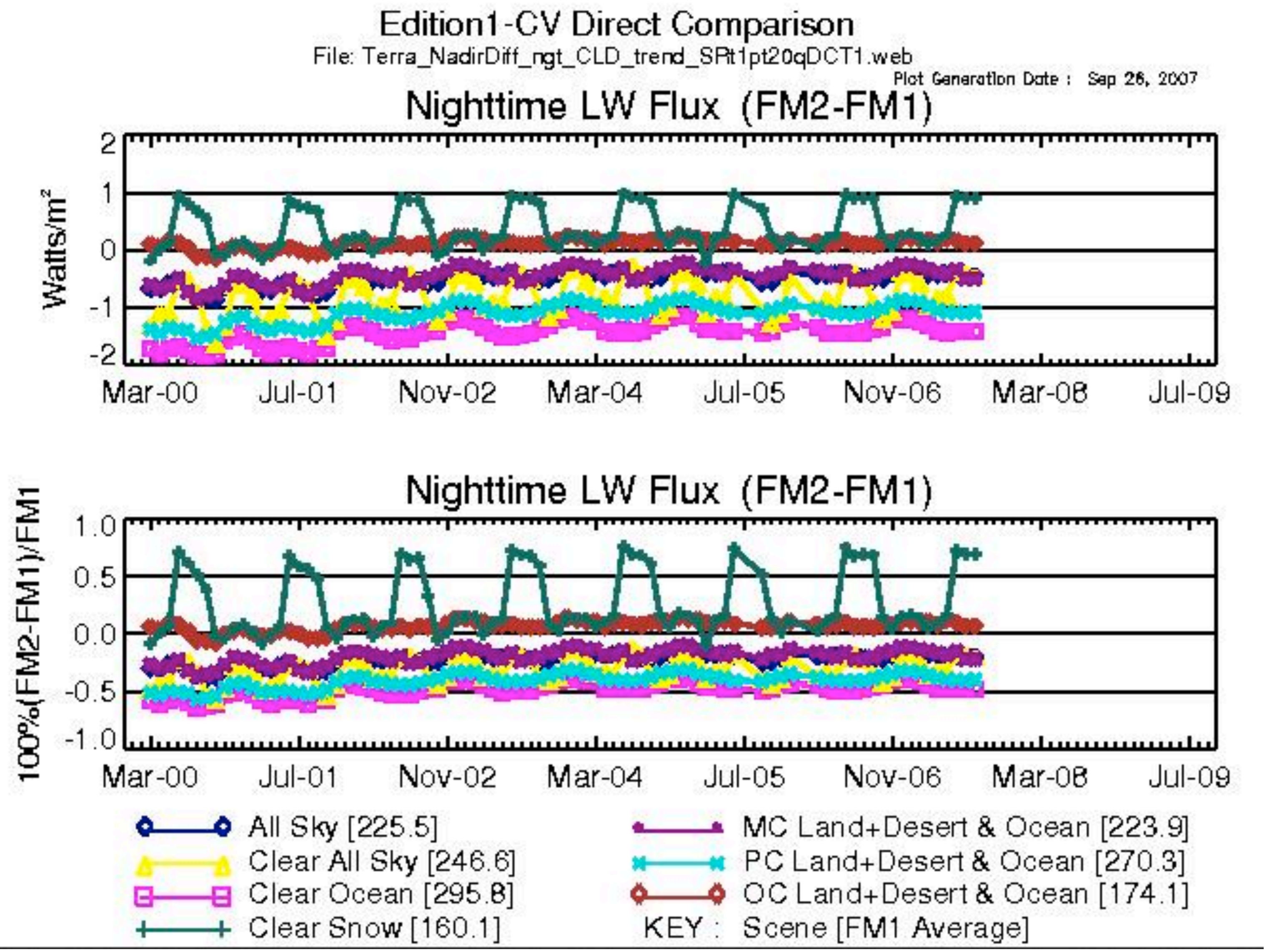
Daytime SW Flux : Direct Comparison



Daytime LW Flux : Direct Comparison



Nighttime LW Flux : Direct Comparison



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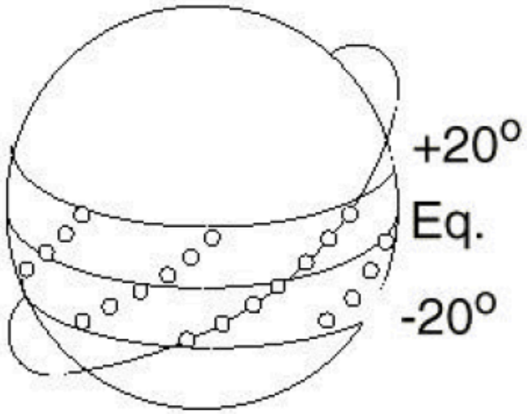
Tropical Mean Radiance as a Validation Tool

Tropical Mean

Tropical Ocean, All Sky, Noon Adjustment

Monthly Mean Nadir Radiance at Night for ERBS

	1985	1986	1987	1988	1989	Mean	Std
Mar	87.61	86.63	88.60	88.51	88.42	87.95	0.84
Apr	87.14	87.20	87.38	88.02	86.79	87.31	0.45
May	87.52	87.29	87.44	87.27	87.16	87.34	0.14
Jun	87.83	86.13	87.46	87.64	87.10	87.23	0.67
Jul	87.10	87.18	87.50	86.79	87.35	87.18	0.27
Aug	86.43	86.16	87.11	86.92	87.17	86.76	0.44
Sep	86.60	86.68	87.38	87.37	87.45	87.10	0.42
Oct	87.58	87.88	87.55	86.90	87.09	87.40	0.40
Now	87.20	86.20	87.00	86.54	86.49	86.69	0.41
Dec	87.06	85.74	87.38	86.36	87.08	86.72	0.67
Jan	86.77	86.73	86.84	86.81	86.00	86.65	0.36
Feb	87.56	87.21	87.86	86.29	87.17	87.22	0.59
Mean	87.20	86.76	87.45	87.12	87.11	**87.13**	
Std	0.44	0.62	0.45	0.67	0.57		**0.58**



Longwave Radiance

1 measurement: Std = 15 %

1 day (3200 meas): Std = 1.2 %

1 month (20 days): Std = 0.6 %

1 year (12 months): Std = 0.2 %

The TM is calculated for both day and night in two ways:

Primary (day) – Total minus SW

Primary (night) - Total

Synthetic (day and night) – Narrow to Broadband using the WN channel

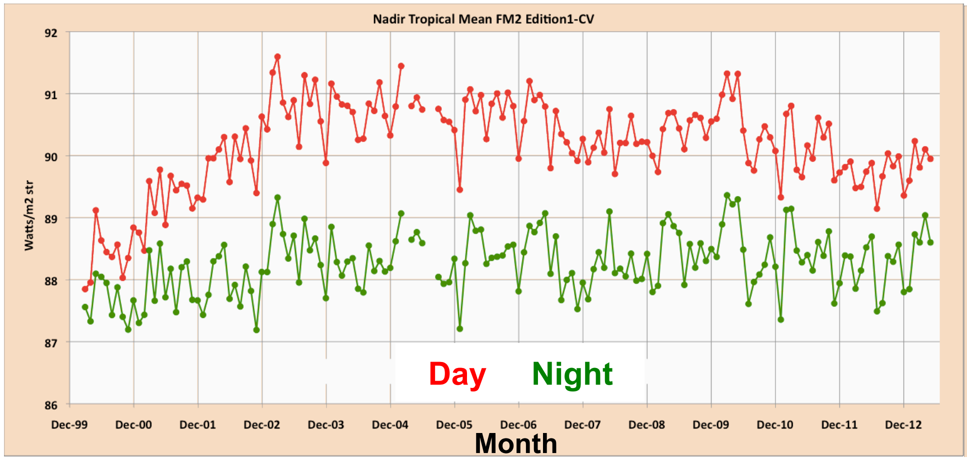
Tropical Mean Results : FM2

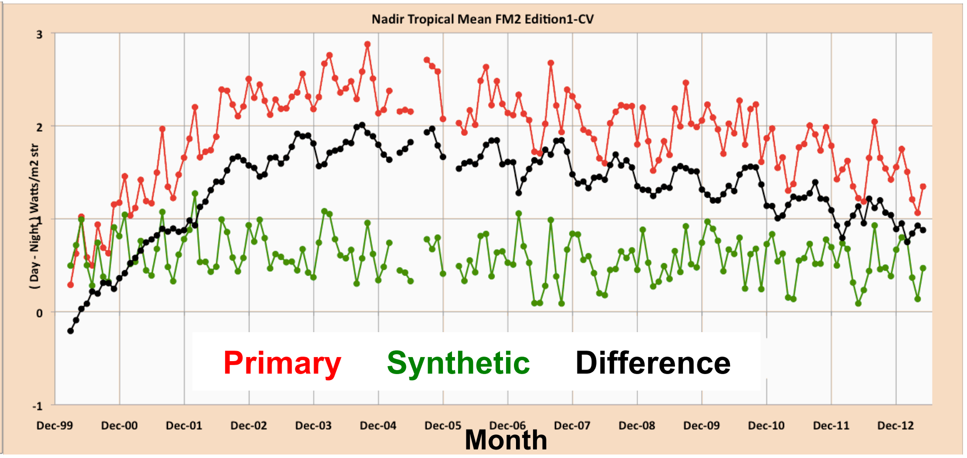
Tropical Mean

(Calculated for both Day and Night using Primary method)

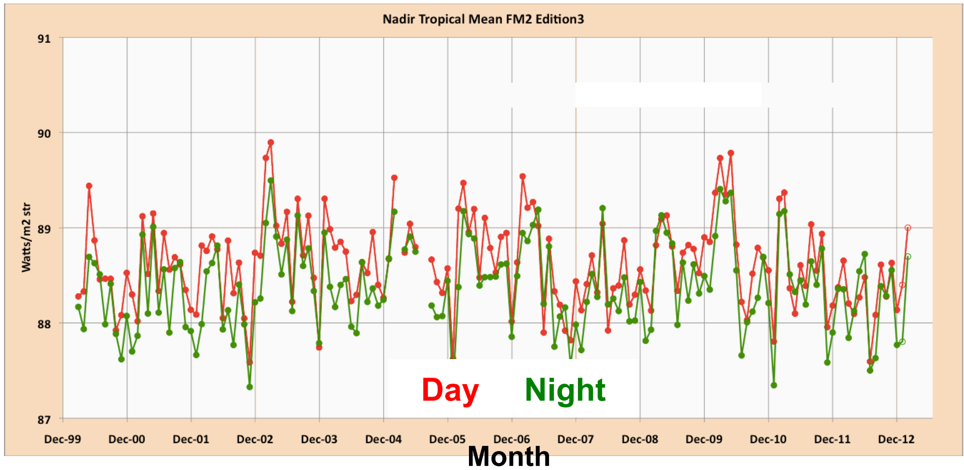
Day – Night Difference

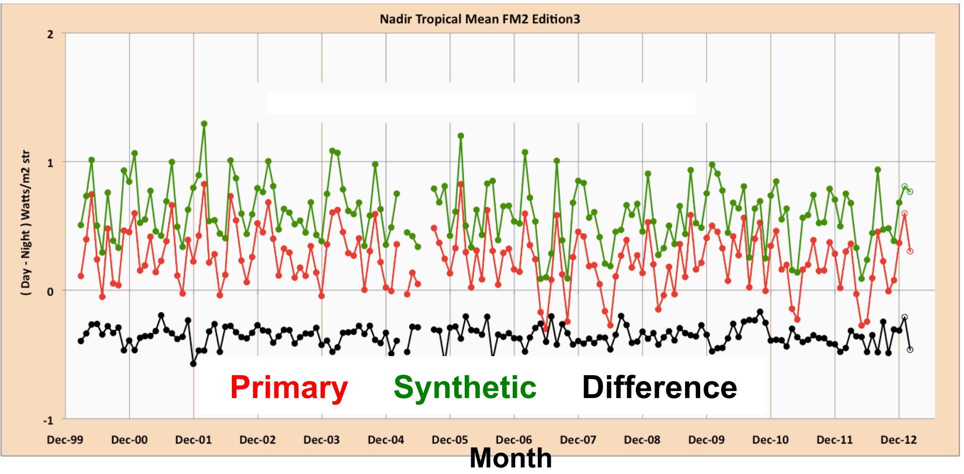
(Primary and Synthetic methods shown)





Edition1-CV





Edition3

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3-Channel Deep Convection Results

Assess the agreement between our best estimates of the unfiltering of the SW channel and the SW portion of the Total Channel.

With this method we cannot distinguish between errors in the spectral response function and relative errors in the spectral unfiltering method.

DATASET

Scene Type: Deep convective clouds

Cloud Size: Greater than 80 Km in ground track direction

Cloud Temperature: Less than 215K

Data Product: Terra FM-1 and FM-2 'Beta' BDS files

View Zenith: Nadir footprints only

Solar Zenith: Less than 80-degrees (PFM), 19 - 31 degrees (FM 1 & 2)

Latitude: 20 N to 20 S

Three Channel Intercomparison

Methodology

- Regress Filtered Window against Unfiltered Total (i.e. LW) radiances at night.
- Predict daytime LW with two methods

$$LW_{day} = Total_{day} - SW_{day} \qquad LW_{day} = C_1 * WN_{day} + C_2$$

- Difference these two estimates and plot as a function of Filtered SW, I_f^{sw}.

$$\Delta LW_{day} = (Total_{day} - SW_{day}) - (C_1 * WN_{day} + C_2)$$

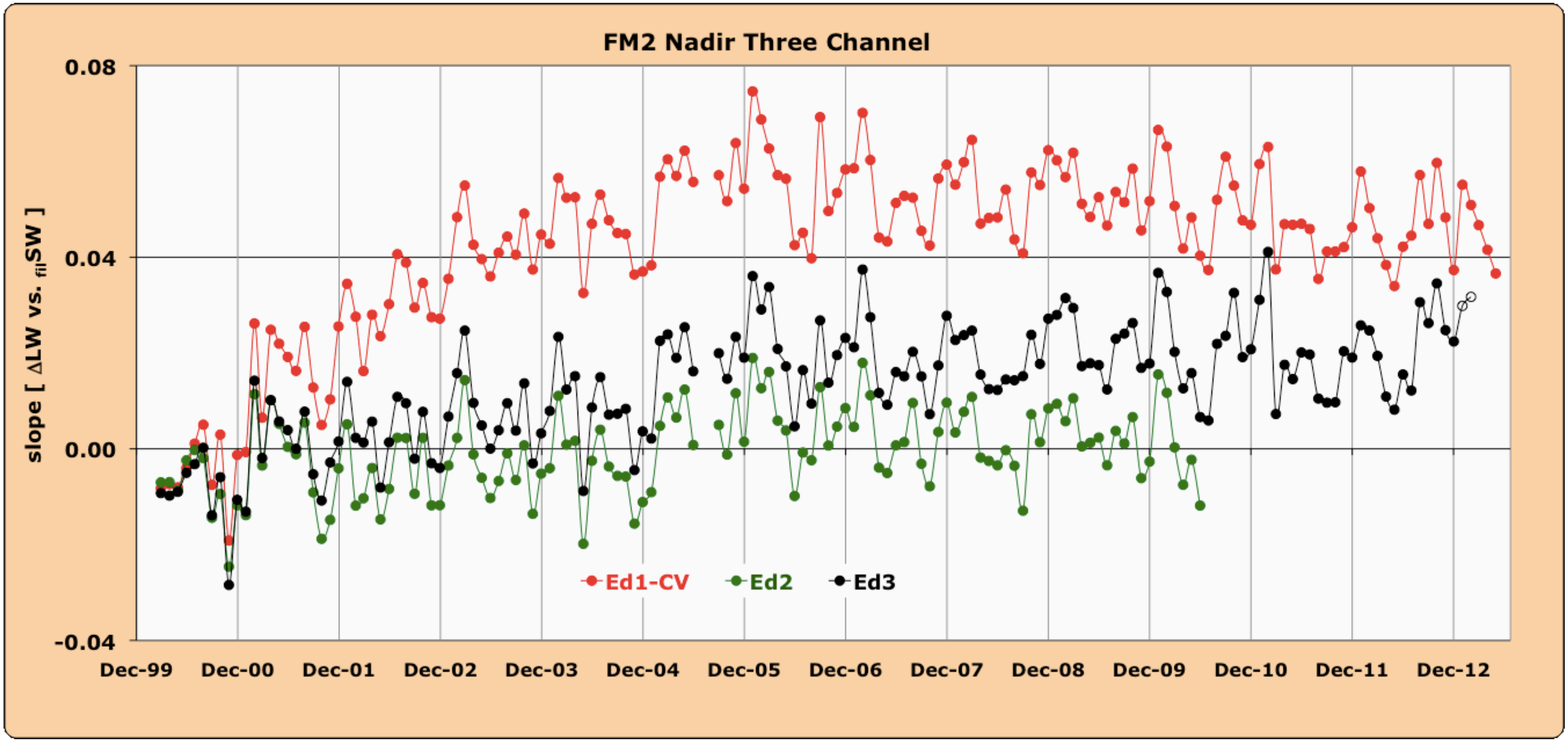
- Any error in the unfiltering process (either due to errors in S_λ, or in detemining the unfiltering coefficients) may be represented by

$$error = -\frac{\left(\frac{d\Delta}{dI_f^{sw}}\right)}{a^{lw/tot}\left(\frac{a^{sw}}{a^{sw/tot}}\right)} * 100$$

- where the a s are the spectral unfiltering coefficients for the longwave channel (lw), shortwave channel (sw) and the shortwave portion of the total channel (sw/tot) for DCC.

Three Channel Intercomparison

Clouds and the Earth's Radiant Energy System



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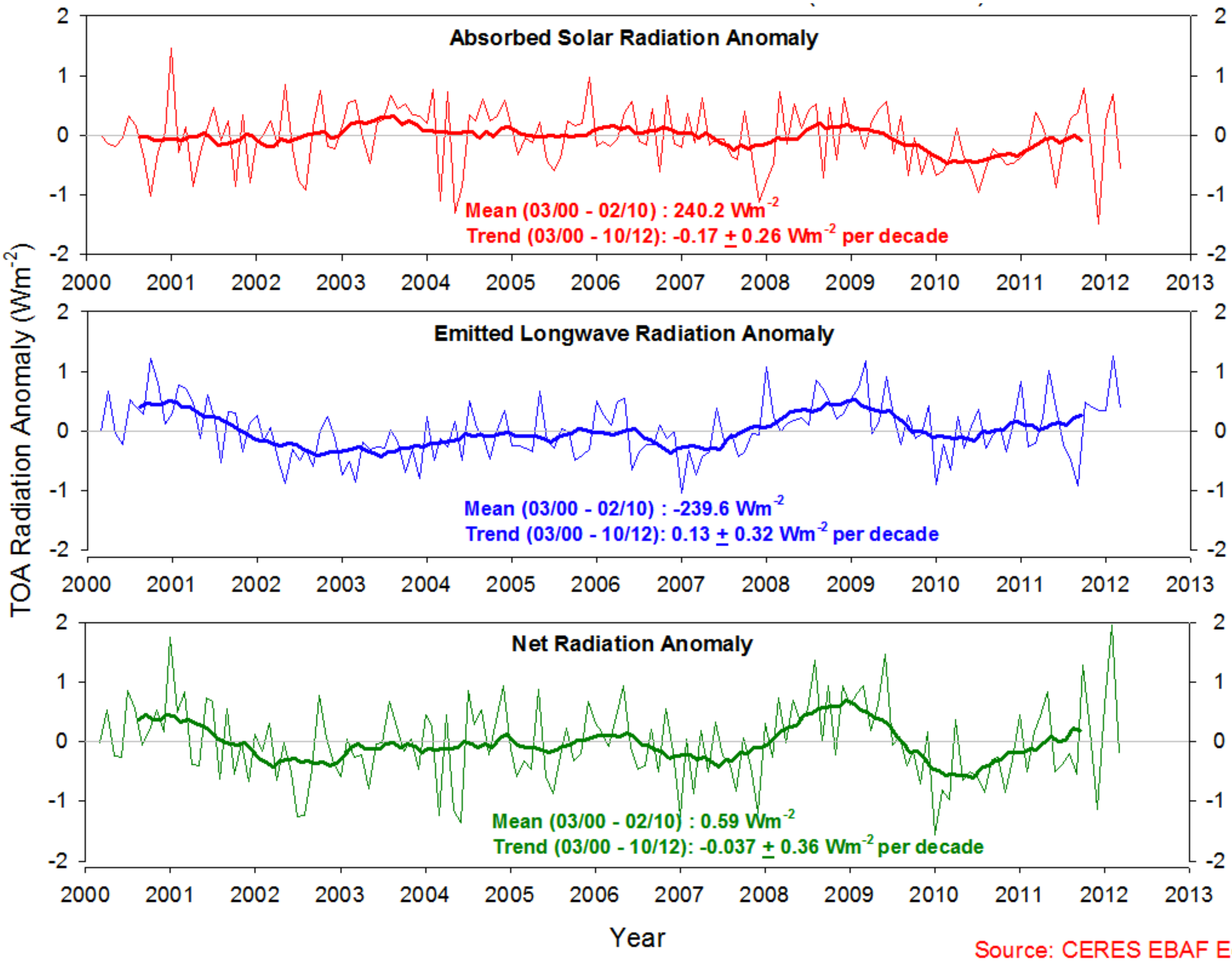
Global Top-of-Atmosphere Radiation Anomalies

Clouds and the Earth's Radiant Energy System



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Source: CERES EBAF Ed2.7

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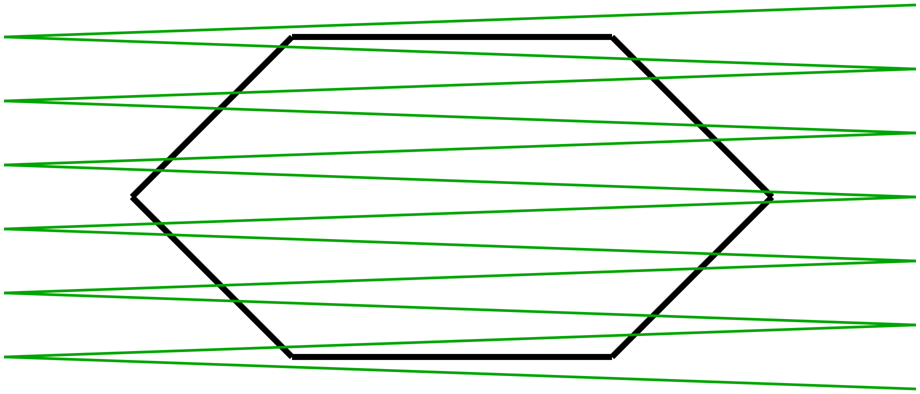
Validation of Pointing Knowledge Using Lunar Radiances

Objective: Utilize the full moon as a quasi-point source to complete a near steady-state raster scan across the CERES FOV.

Goals

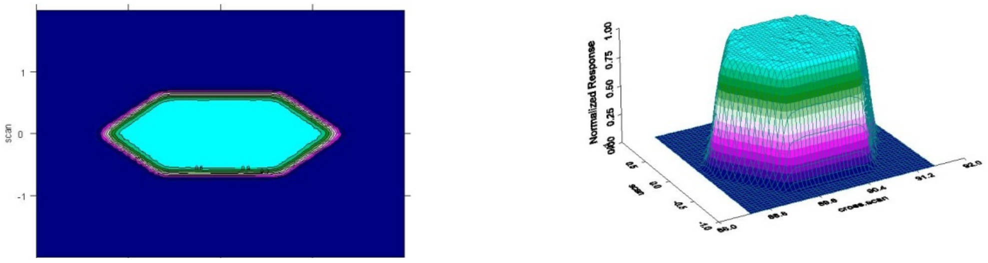
- **Validate pre-launch alignment measurements**
- **Measure inter-channel relative pointing accuracy**
- **Map out spatial non-uniformities in the CERES Optics/Detectors**
  - **This type of mapping is not performed *under vacuum* prior to launch.**
- **Measure Lunar Radiances for future instrument intercomparisons.**

~ By combining knowledge of the motion of the moon relative to the spacecraft and the programmability of the the CERES Instruments we obtain……..~

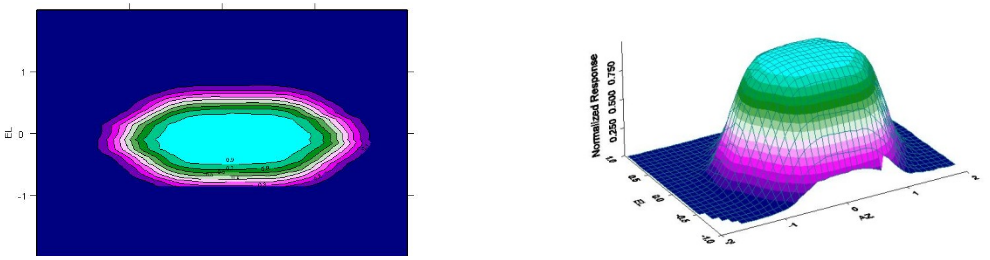


Lunar Scanning Results – CERES Optical Transfer Function

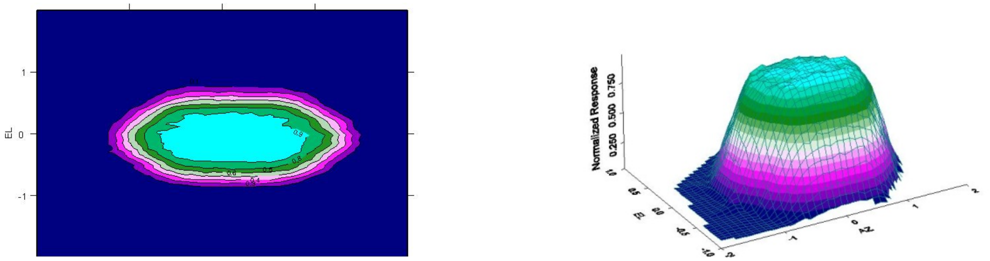
Monte-Carlo Ray Trace
(FELIX)



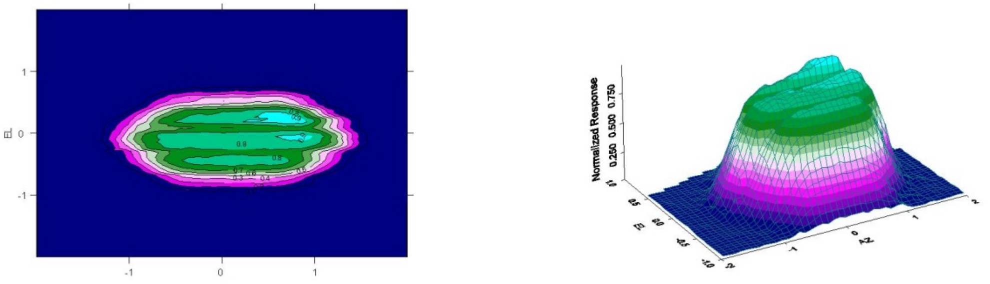
FM-1 Total



FM-1 Shortwave



FM-1 Window



CERES Unfiltered Radiance Summary

- **Cal/Val Protocol demonstrates radiometric stability of the data products through 12/2012 of….**

	Edition1_CV				Edition2				Edition2_Rev1				Edition 3			
	FM1	FM2	FM3	FM4	FM1	FM2	FM3	FM4	FM1	FM2	FM3	FM4	FM1	FM2	FM3	FM4
LW_{day}	.3	.6	.4	.4	.125	.125	.3	.3	.125	.125	.15	.15	<.1	<.1	<.1	<.1
LW_{night}	.1	.125	.125	.125	<.1	<.1	.1	.1	<.1	<.1	.1	.1	<.1	<.1	<.1	<.1
SW	.2	.4	.4	.5	.2	.3	.3	.4	<.1	<.1	.25	.25	<.1	<.1	<.1	<.1
WN	<.1	<.1	.1	.1	<.1	<.1	.1	.1	<.1	<.1	.1	.1	<.1	<.1	<.1	<.1

Note: **Values apply to all-sky global averages**
Units are in %/yr

Cal-Val Approach

Pre-Launch

- Implement a rigorous & thorough ground calibration/characterization program
- Cal/Val role must be prominent in original proposal and SOW
- System level characterization is typically last test performed prior to delivery of the instrument
- Cost and schedule constraints typically drive programs at that point

Post-Launch

- Implement a protocol of independent studies to characterize on-orbit performance
- Studies should cover all spectral, spatial and temporal scales as well as data product levels
- Continuous development of new validation studies

Data Product Release Strategy

- Develop a logical and well understood approach to data release.
- Minimize the number of Editions/Versions of Data
- Utilize Data Quality Summaries for the community

Instrument and ERBE-Like Data Product Release Strategy

At_Launch - Static Algorithms and Pre-Launch coefficients - baseline product used during intensive Cal Val Period (Launch to SOC+8 Months)

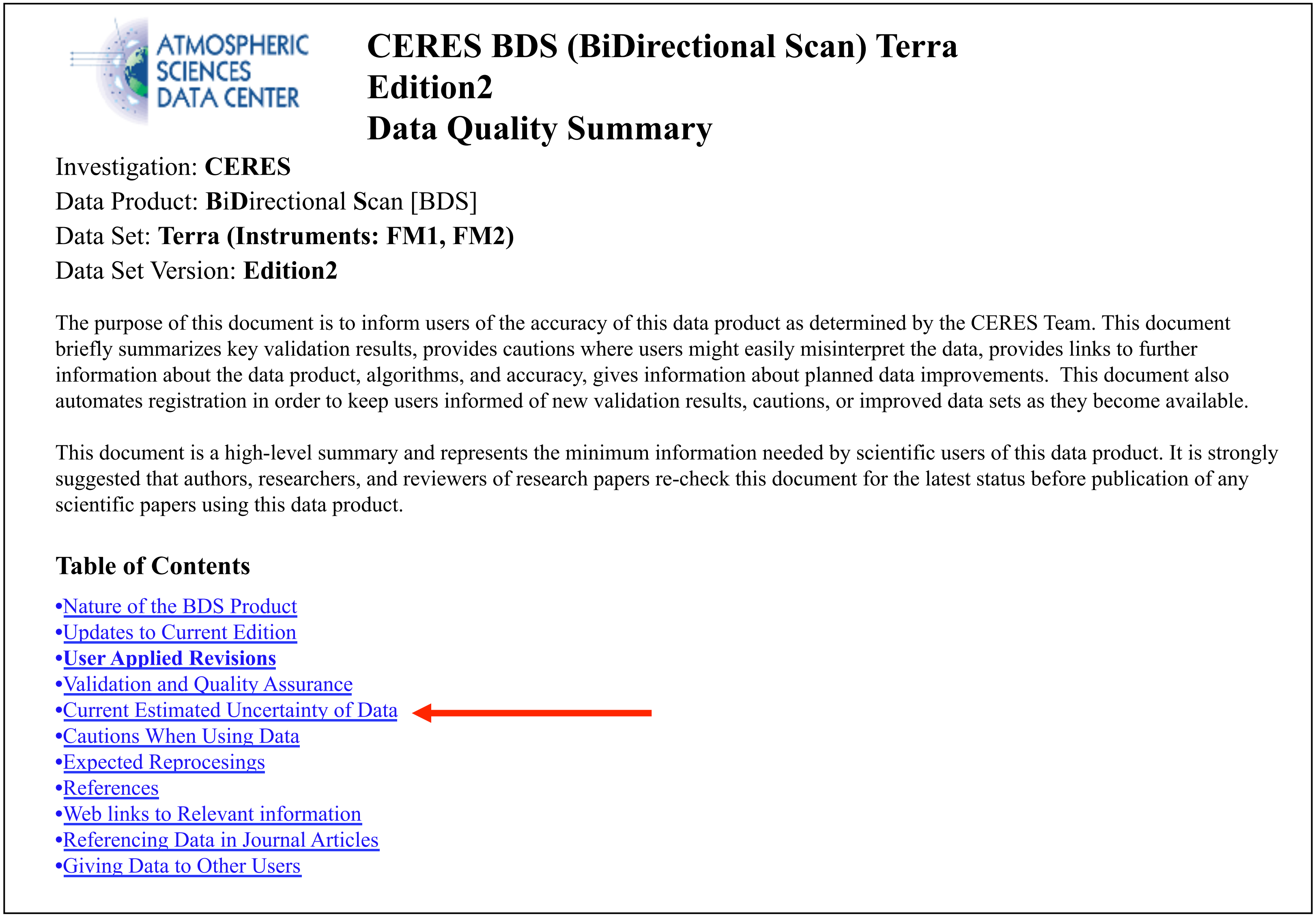
Edition1_CV - Static Algorithms and coefficients - baseline product used in cal/val protocol (SOC+7.5 Months, continuous over mission)

Edition2 - Utilizes temporally varying coefficients to correct for traceable radiometric drift. All spectral changes are broadband and 'gray'. (L+1 yrs to ~5 yrs)

Edition3 - Will incorporate temporally varying spectral artifacts in the SW measurements. A complete re-analysis of Ground Calibration with additional component characterization measurements. (L+5 yrs)

Edition2 products lag Edition1_CV by a minimum of 6 months

Data Quality Summary Provided to User’ s



CERES BDS (BiDirectional Scan) Terra Edition2 Data Quality Summary

Investigation: **CERES**
Data Product: **B**i**D**irectional **S**can [BDS]
Data Set: **Terra (Instruments: FM1, FM2)**
Data Set Version: **Edition2**

The purpose of this document is to inform users of the accuracy of this data product as determined by the CERES Team. This document briefly summarizes key validation results, provides cautions where users might easily misinterpret the data, provides links to further information about the data product, algorithms, and accuracy, gives information about planned data improvements. This document also automates registration in order to keep users informed of new validation results, cautions, or improved data sets as they become available.

This document is a high-level summary and represents the minimum information needed by scientific users of this data product. It is strongly suggested that authors, researchers, and reviewers of research papers re-check this document for the latest status before publication of any scientific papers using this data product.

Table of Contents

Lessons Learned

Establish a calibration team early and hold regular reviews/TIMS
Understand that the Science team has Lifecycle responsibility
Part science, part engineering, a lot of socialization
Understand requirement traceability
Be adept at responding to change
Be robust to withstand unknowns/change
Keep it simple
Don't be afraid to evolve with technology
Don't let Process replace sound judgment
Engineer knows long before the statistician
The only thing that is for certain is that if you don't try, you won't get it

Why is CERES Climate Quality Calibration so difficult?

A question of time scales, experience and balancing accuracy with providing data products to the community.

- *Calibrated Radiances have been released on ~6 month centers*
- *6 months is just a blink of an eye when analyzing decadal trends…*

Same time scale as phenomena which influence instrument response

- *Beta Angle*
- *Solar Zenith Angle*
- *Earth Sun Distance*
- *Solar Cycle*
- *Orbital shifts*
- *Instrument Operational modes (e.g. RAPS vs. Xtrack)*

Design weaknesses and anticipated failures in onboard calibration hardware

- *full spectral range of observations not covered by cal subsystems*

Complicates separation of instrument 'artifacts' from natural variability.

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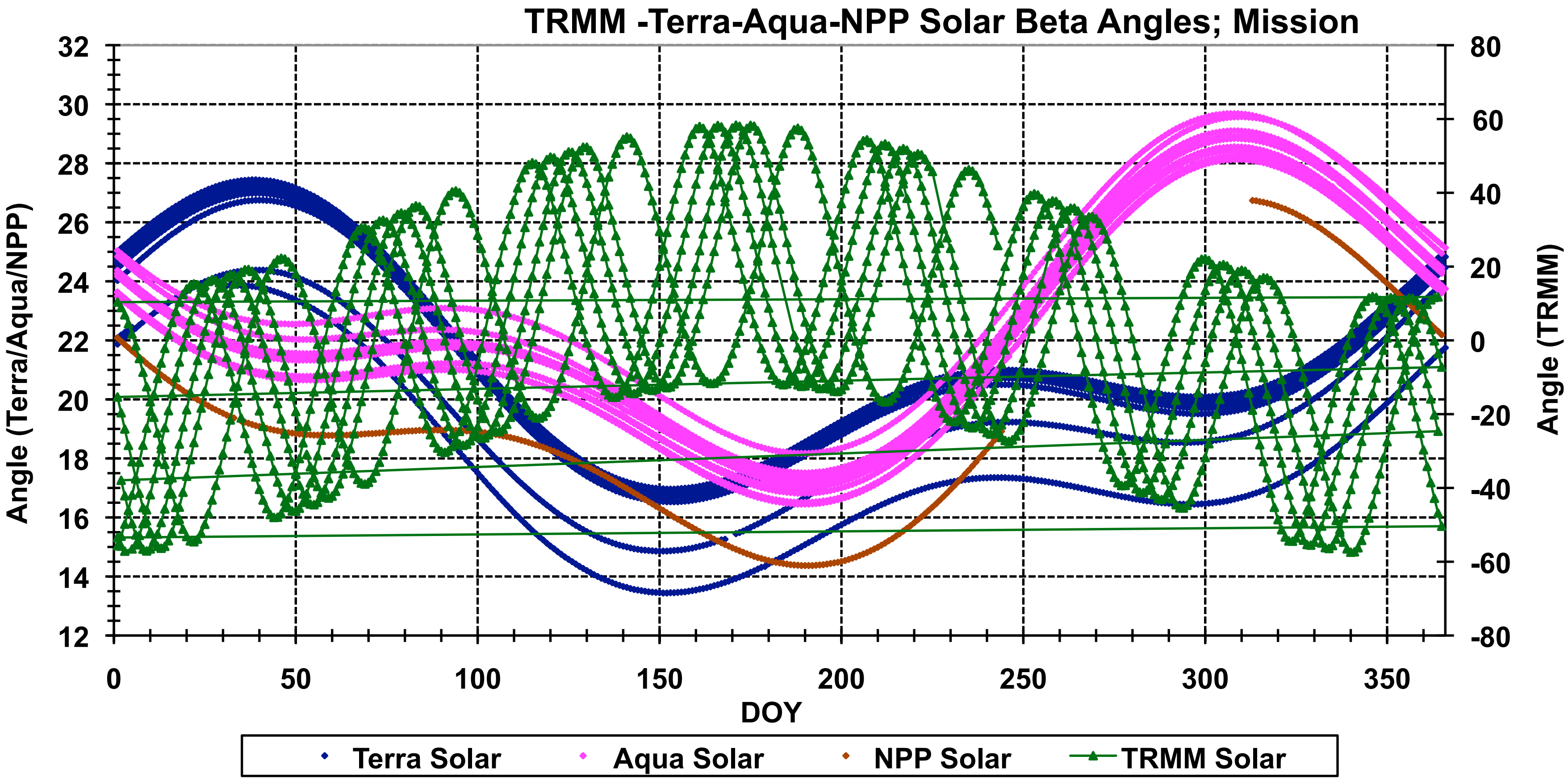
Beta Angle Annual Cycle

Clouds and the Earth's Radiant Energy System



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Lessons Learned / Future Direction

In the future CERES will fly in a single orbit with one instrument per spacecraft, eliminating key Direct Comparison validation capabilities…

Programmatic Implementation

- Increase weighting/influence of Radiometric Performance in cost/schedule trades
- Maintain positive/open relationship with hardware provider. Avoid 'Us' vs. 'Them' mentality.
  - *LaRC/NGST Team has proven track-record and experience*

Ground Characterization Procedures

- Re-verify traceability of calibration targets
- Establish collaborations with NIST, other international agencies
- Implement automated Data Acquisition System on Calibration Chamber

Operational Mode

- Do not point optics in 'forward' looking direction
  - *Strong Correlation to spectral darkening of SW channel optics*

Onboard Calibration Hardware

- Provide additional SW spectral characterization capability
  - *Stringent measurement requirements demand SW spectral capabilities*

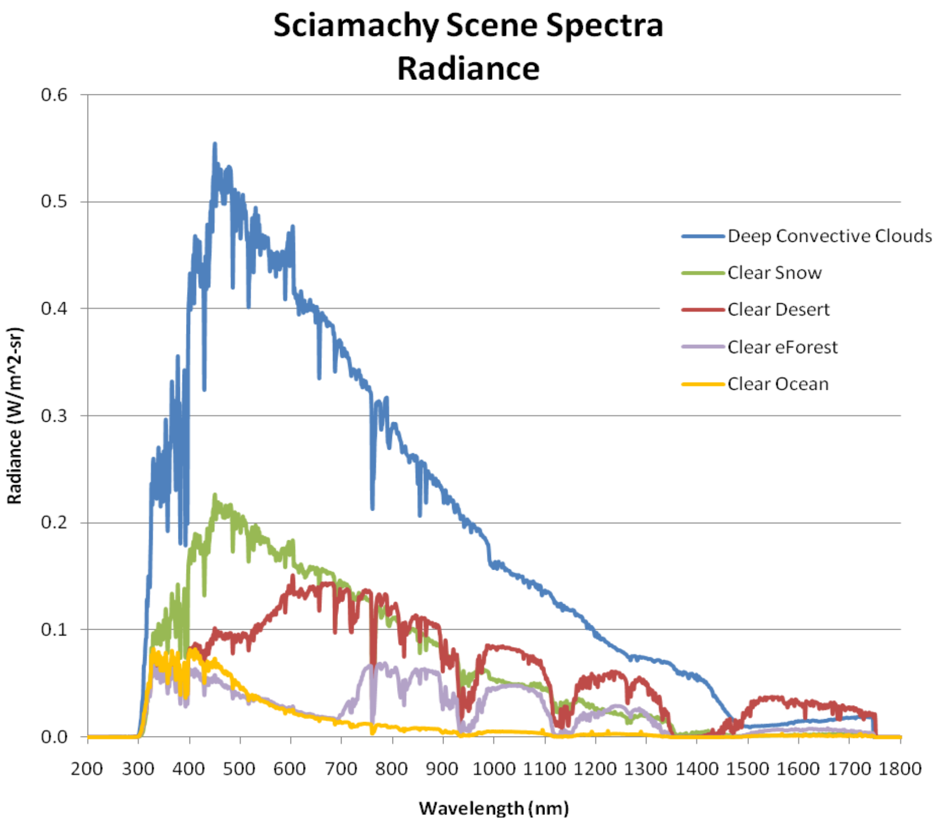
Handling Procedures

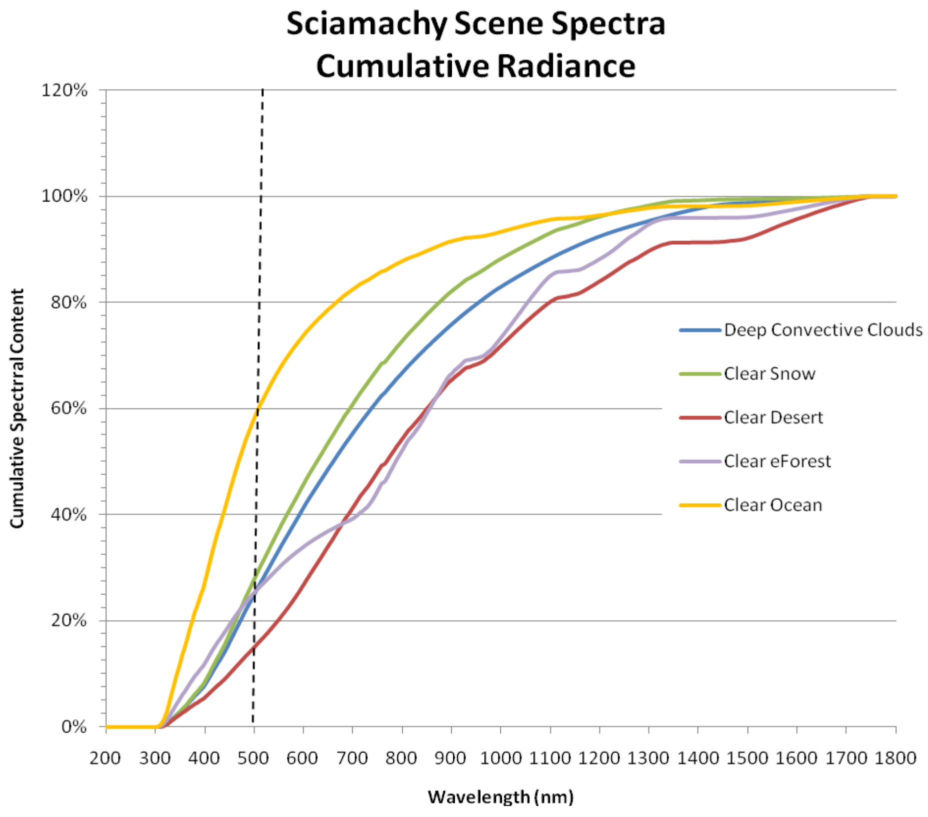
- Minimize possibility of contamination
- Develop Inspection and cleaning procedures

Reference Reflected Solar Scene Spectra

Clouds and the Earth's Radiant Energy System

Historically, the contribution of short wavelength radiance in reflected solar spectra has been underappreciated in the CERES calibration program



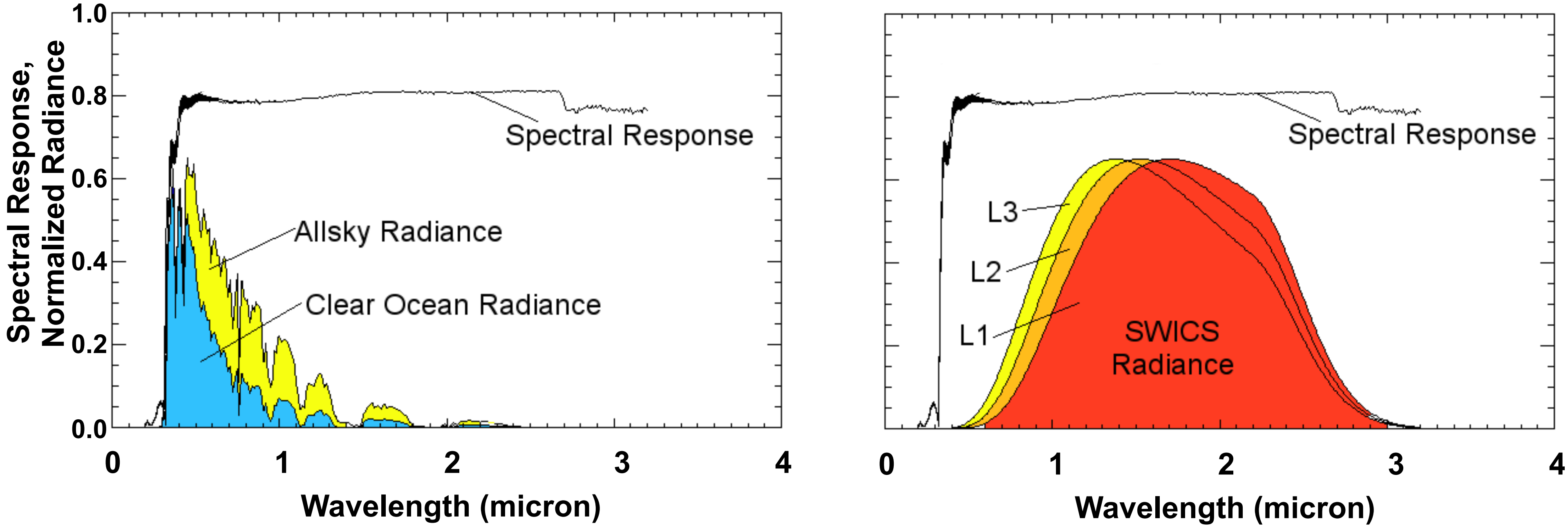


The globally averaged All Sky composite scene contains as much as 30% of its reflected solar radiance below 500nm

Spectral Coverage of Cal Sources

Clouds and the Earth's Radiant Energy System

Make certain the spectral content of your cal sources adequately represent the content of your science targets….

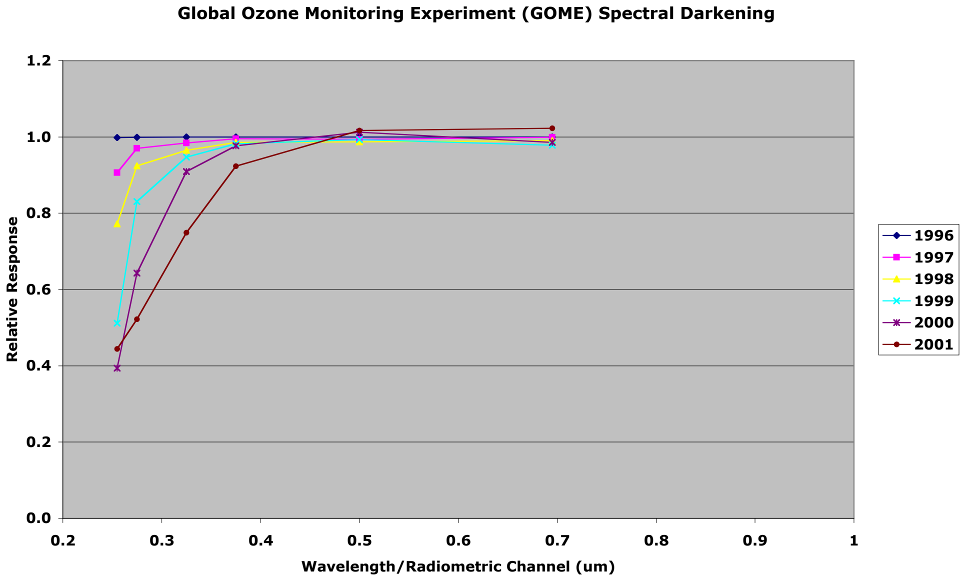


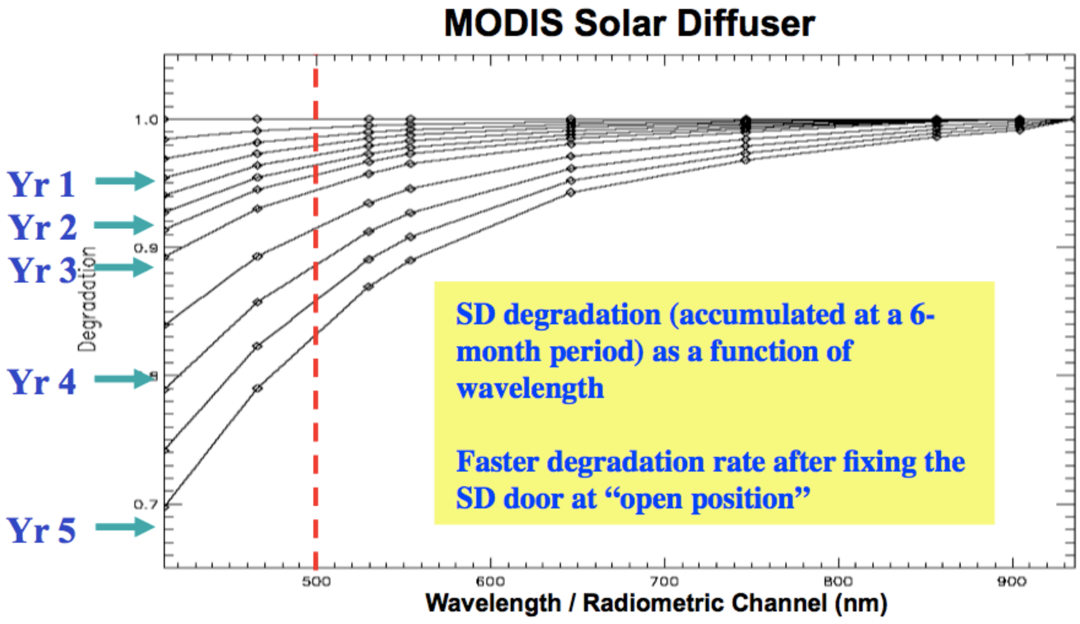
$$f^{sw}_{allsky} \text{ change} \approx -2\%$$

$$f^{sw}_{swics} \text{ change} \approx -0.1\%$$

Measurement to CDR

Degradation of optical surfaces/materials on multi-year timescales is a known issue

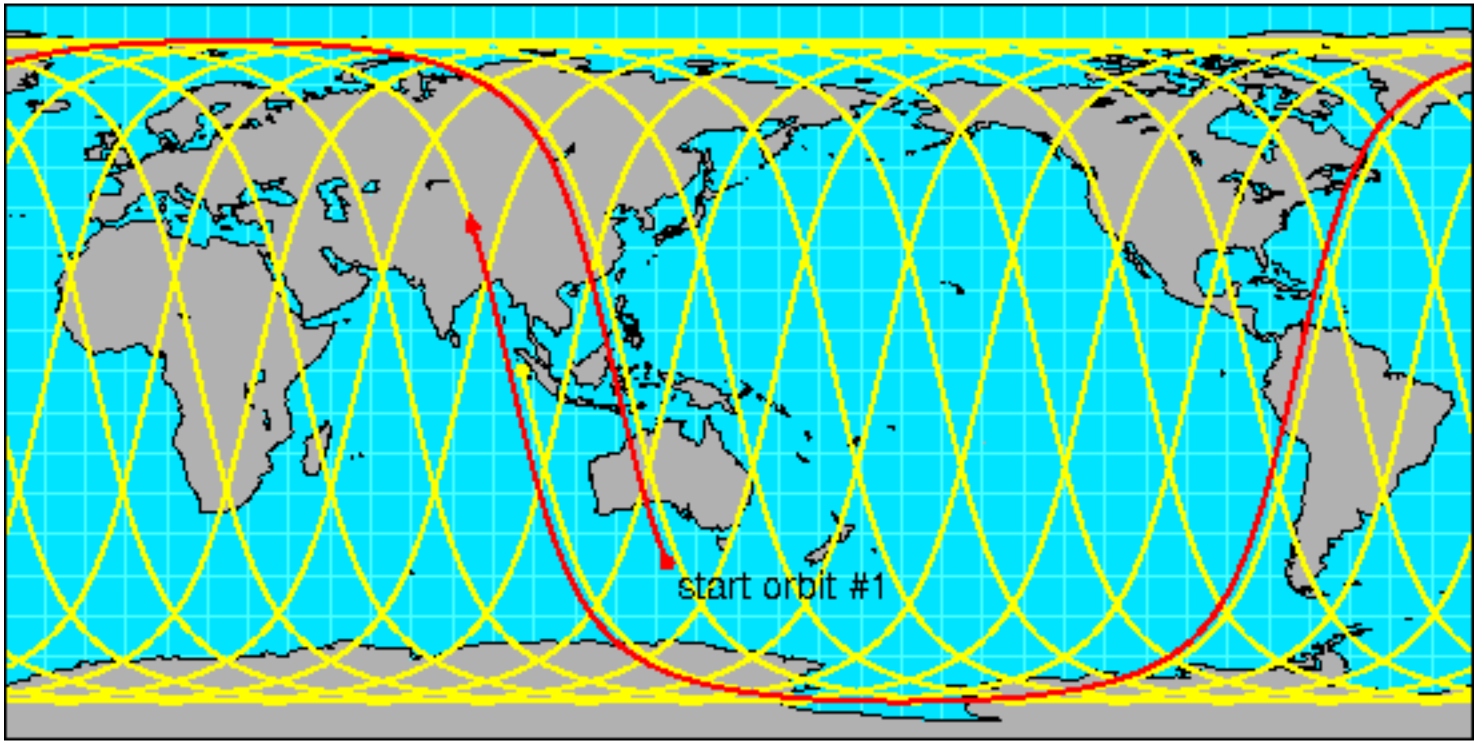

Global Ozone Monitoring Experiment (GOME) Spectral Darkening


MODIS Solar Diffuser

SD degradation (accumulated at a 6-month period) as a function of wavelength

Faster degradation rate after fixing the SD door at "open position"

Polar Orbital Tracks

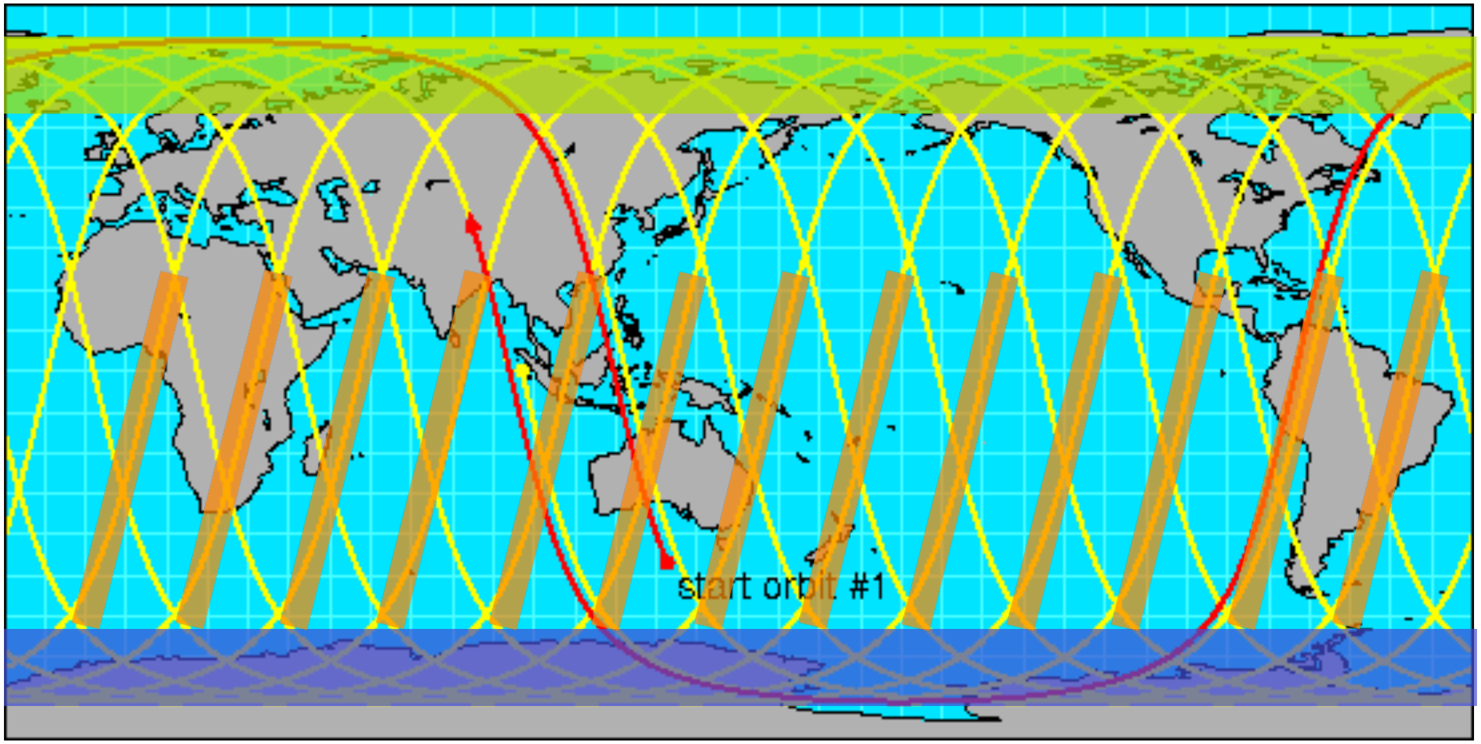


🟦 - Lunar Observations

🟩 - Solar Calibrations

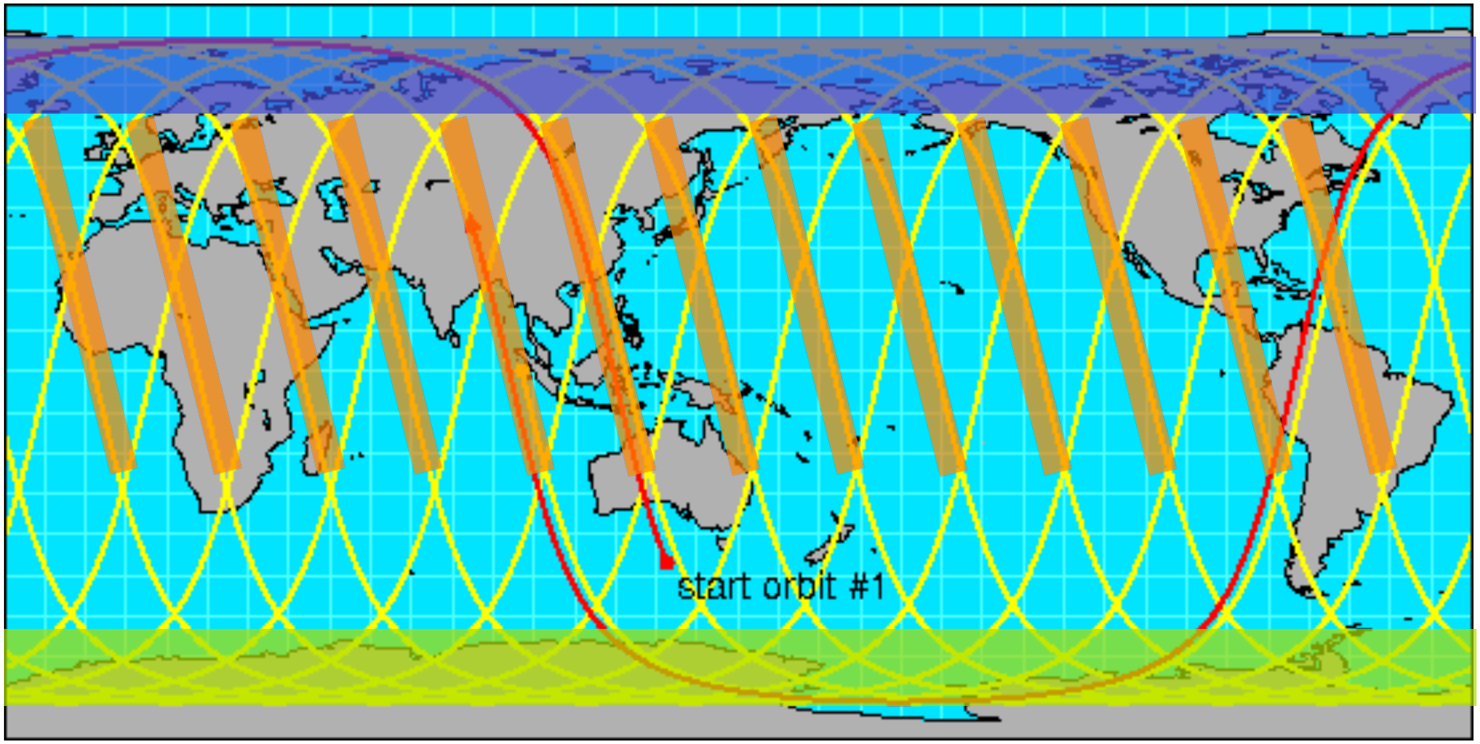
🟧 - Internal Calibration Sequence

Aqua/NPP Flight Cal Locations



- 🟪 - Lunar Observations
- 🟩 - Solar Calibrations
- 🟧 - Internal Calibration Sequence

Terra Flight Cal Locations



🟪 - Lunar Observations

🟩 - Solar Calibrations

🟧 - Internal Calibration Sequence