Evaluating Performance of Clouds and the Earth's Radiant Energy SYSTEM (CERES) Instruments That Enable a Multi-Decadal Climate Data Record

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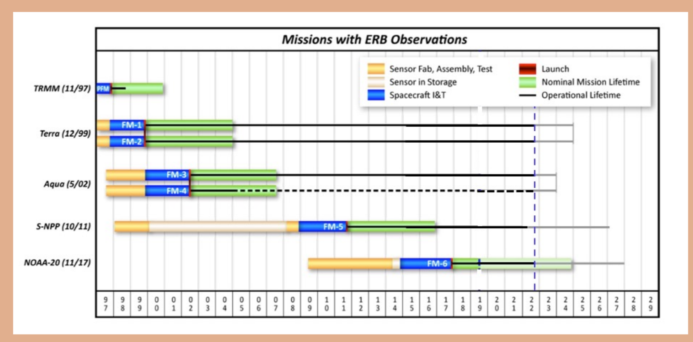
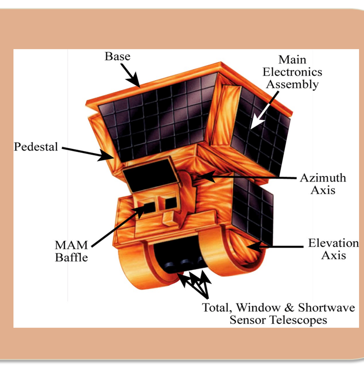
OVERVIEW



- **The CERES project objective is to provide highly accurate radiance measurements to facilitate the production of a long-term global data record of the Earth's radiation budget at the top-of-atmosphere (TOA), within the atmosphere, and at the surface, with consistent cloud and aerosol properties at climate accuracy.**
- **Currently, there are six operational CERES instruments on four spacecraft (Terra, Aqua, Suomi-NPP and NOAA-20) that provide a continuous ERB dataset used to produce the data products. In order to produce a continuous record that involves the use of multiple instruments, a methodology is developed to place all the instruments onto a common radiometric scale.**
- **The Radiation Budget Science Project (RBSP) consists of an integrated science team that produces, validates, and distributes higher-level data products (Levels 1-3) and investigations. The generation of these data products involves a high level of data fusion; merging inputs from 25 unique input data sources to produce 18 CERES data products.**
- **A rigorous pre-launch calibration campaign helped to achieve the pre-launch accuracy goals of 1% reflected solar and 0.5% emitted thermal (1–σ confidence intervals) radiance measurements.**
- **CERES is a broadband instrument and requires the use of a suite of calibration and validation experiments to evaluate its performance over a vast range of spectral and temporal scales. Rigorous calibration and validation protocol is performed to characterize on-orbit performance, detect changes in instrument sensitivity and implement necessary corrections. Algorithm improvements addressing in-orbit instrument sensitivity changes are evaluated with various validation tools (Inter-satellite TOA flux/radiance/reflectance comparison, DCC albedo analysis, tropical mean evaluation). Data products used in this study (Terra/Aqua Edition4, Suomi-NPP Edition2 and NOAA-20 Edition1B). have incorporated all the necessary and latest calibration corrections.**

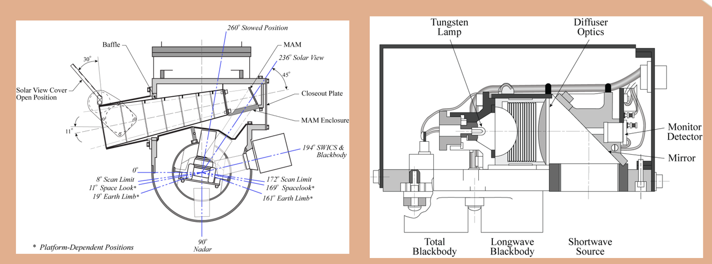
CERES Instrument

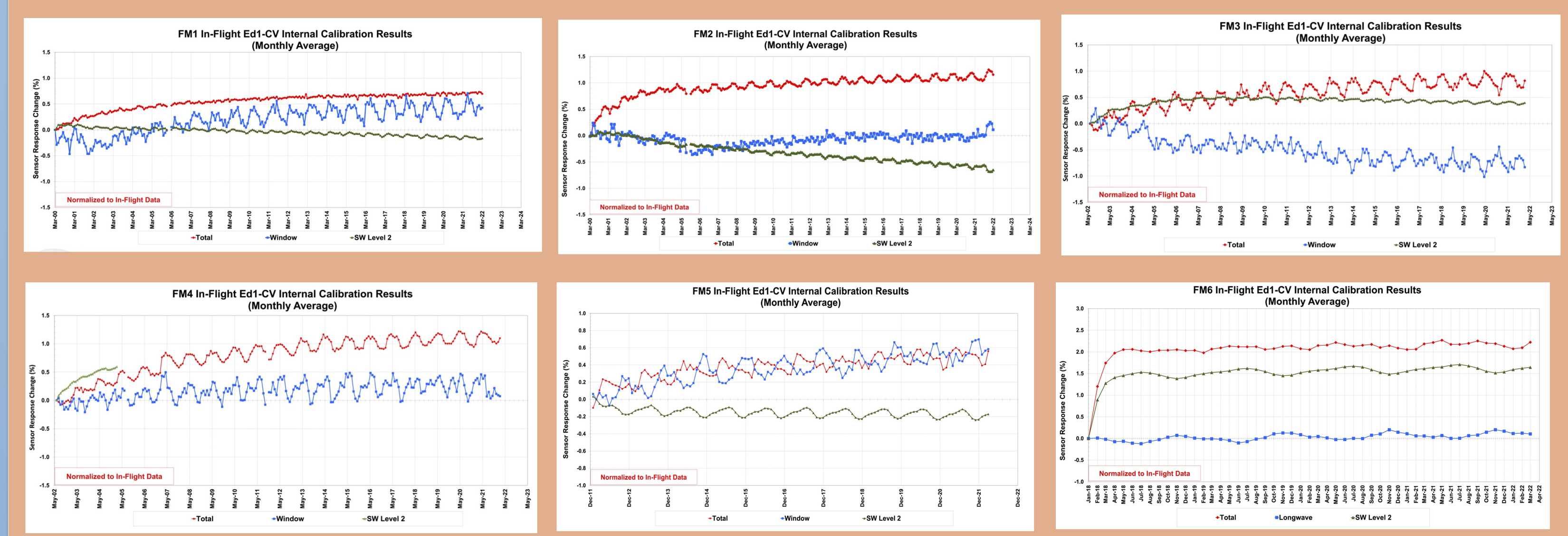
- **Consists of a scanning sensor assembly with baffled Cassegrain telescopes thermistor bolometer detectors.**
- **Spectral Channels: Shortwave: 0.3 – 5.0 µm**
  Total: 0.3 - 200 µm
  Window: 8 – 12 µm (Terra, Aqua, S-NPP)
  LWC (NOAA-20): 5 – 35 µm



In-Flight Calibration

- **Primary Calibration Systems: Internal Calibration Module (ICM)**
  Mirror Attenuator Mosaic (MAM)
- **ICM – consists of two blackbody calibration sources (operating at temperatures of 295K, 305K and 315K) to monitor the total and window channels and the Shortwave Internal Calibration Source (SWICS) is an evacuated quartz tungsten lamp operating at three discrete levels generating spectra equivalent to T_b of 2100K, 1900K and 1700K, to monitor the shortwave channel.**
  – monitors/ evaluates sensor gain stability and gain variations.

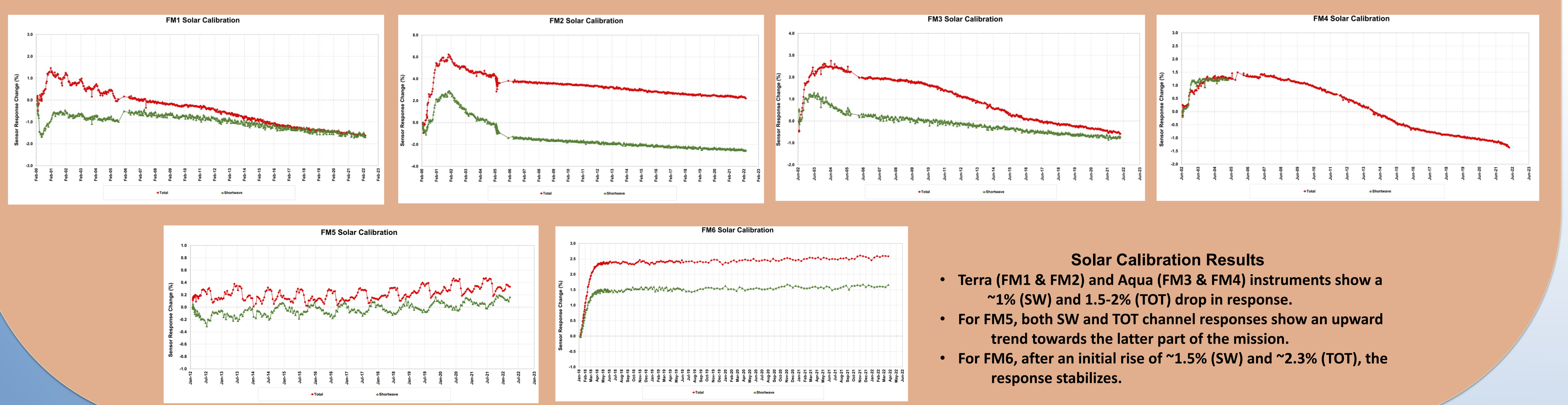




FM# / Sensor	SW	TOTAL	WN (FM1-FM5) LWC (FM6)
FM1	~0.1 % ↓	~0.7 % ↑	~0.4 % ↑
FM2	~0.6 % ↓	~1.2 % ↑	0 %
FM3	~0.4 % ↑	~0.8 % ↑	~ 0.8 % ↓
FM4		~1.0 % ↑	~0.25 % ↑
FM5	~0.6% ↑	Stable at ~0.2 %	~0.6 % ↑
FM6	Initial ~1.5% ↑ but stable	Initial ~2% ↑ but stable	0 %

Trends in Internal Calibration from Beginning of Mission

- **MAM – consists of a baffled solar diffuser plate assembly to monitor the shortwave and total sensors.**
  – evaluates stability of the shortwave sensor and the shortwave portion of the total sensor



Solar Calibration Results

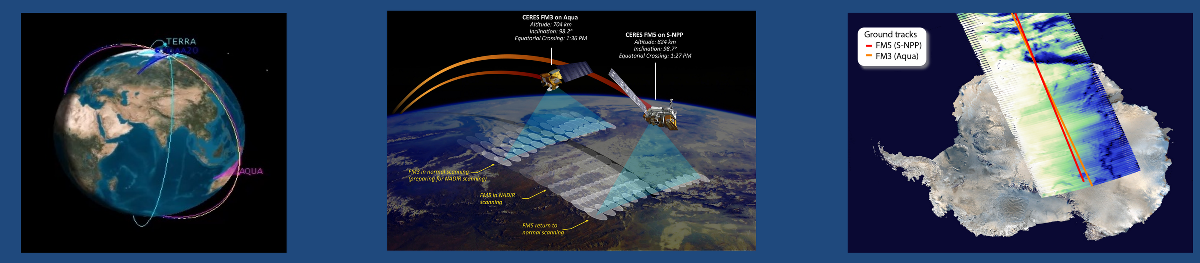
- Terra (FM1 & FM2) and Aqua (FM3 & FM4) instruments show a ~1% (SW) and 1.5-2% (TOT) drop in response.
- For FM5, both SW and TOT channel responses show an upward trend towards the latter part of the mission.
- For FM6, after an initial rise of ~1.5% (SW) and ~2.3% (TOT), the response stabilizes.

Algorithm Improvements

- **A calibration protocol is set in place to ensure radiometric accuracy. Instrument gain coefficients and spectral response functions (SRFs) are required to convert the CERES sensor output signal to radiances.**
- **Time-varying gain coefficients are calculated from on-board calibration system and applied to account for broadband sensitivity for each sensor.**
- **To account for any spectral changes in the Shortwave (SW) and SW portion of the Total channels, time-varying spectral response function (SRF) corrections are applied. Loeb et al describes the approach to characterize instrument gain and SRF changes.**

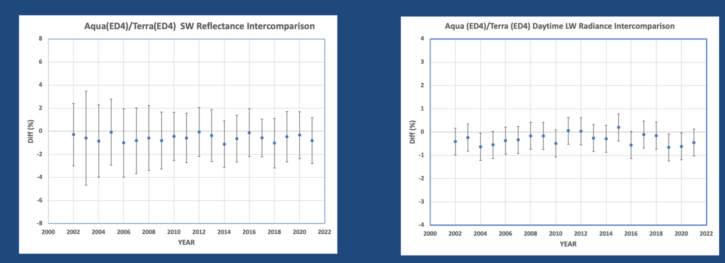
* Loeb, N.G, Manalo-Smith, N., Su, W., Shankar, M. and Thomas, S: CERES Top-of-Atmosphere Earth Radiation Budget Climate Data Record: Accounting for in-Orbit Changes in Instrument Calibration, *Remote Sens*, 2016, 8(3), 182.
https://doi.org/10.3390/rs8030182

Inter-satellite Comparison



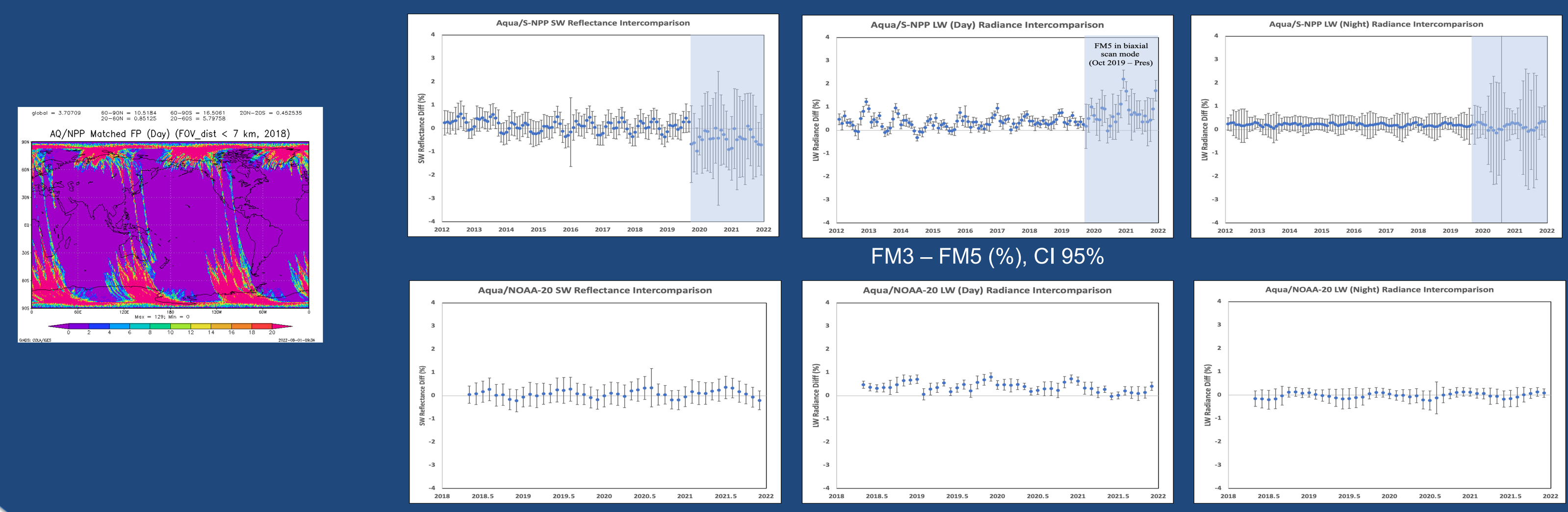
Aqua/Terra Intercomparison
(SSF: Single Satellite Footprint - Terra/Aqua Ed4)

- *Terra and Aqua orbits intersect at 69.5° N, providing radiance and flux intercomparison opportunities mostly between 68° N and 72° N. (June/July/August)*
- *Matching Criteria: ΔSZA, ΔVZA < 2°, ΔRAZ < 5°, Nadir footprints (VZA < 10°), Identical surface type, FOV centroid distance < 5 km, Δt < 60 min*



Aqua/S-NPP/NOAA-20 Intercomparison
(SSF: Single Satellite Footprint - Aqua Ed4, S-NPP Ed2, NOAA-20 Ed1B)

- *With the orbital geometries for Aqua/S-NPP and Aqua/NOAA-20, the orbital overlaps occur every ~ 64 hours. This provides ample intercomparison opportunities to obtain spatially and temporally matched observations during each crossover.*
- *Matching criteria: ΔSZA, ΔVZA < 2°, ΔRAZ < 5°, FOV centroid distance < 7 km*
- *Obtain monthly all-sky SW reflectance* $Reflectance = \frac{SW_{rad}*\pi}{F*\cos(SZA)}$ where F=1361 W/m²) *and daytime (nighttime) LW radiance differences using the matched footprints.*
- *All instruments continue to operate at their normal operational modes. Aqua (FM3), NOAA-20 continue to operate in the cross-track scan mode while FM5 on S-NPP switches from cross-track scan mode to biaxial scan mode in October 2019. Since FM5 is operating in biaxial mode (10/2019), the number of matched footprints is drastically reduced to which the large differences (and uncertainties) in reflectances and radiances are attributed to.*

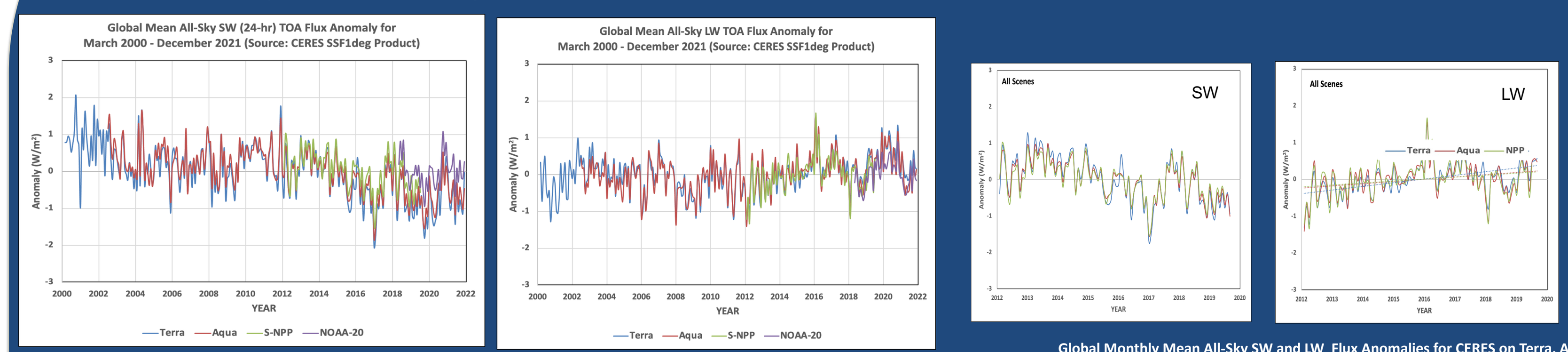


FM3 – FM5 (%), CI 95%

FM3 – FM6 (%), CI 95%

TOA Flux Intercomparison
(SSF1deg Product - Terra/Aqua Ed4, S-NPP Ed2, NOAA-20 Ed1)

- *Although each instrument on the different platforms are calibrated independently, acquiring a high level of consistency in TOA fluxes enhances confidence in the calibration.*
- *Anomaly trends are consistent for all instruments.*



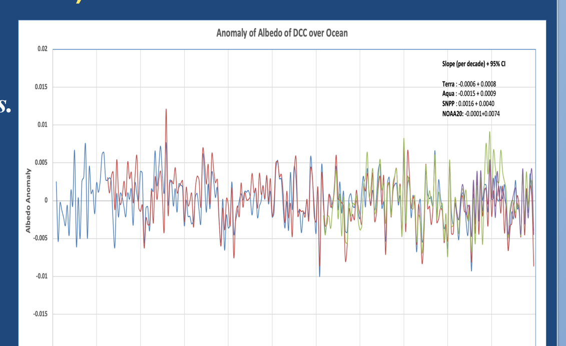
SW Platform / Surface Type	Terra Slope (per decade)/ 95% conf	Aqua Slope (per decade)/ 95% conf	S-NPP Slope (per decade)/ 95% conf
Ocean	-2.065 / 1.214	-1.645 / 0.962	-0.599 / 1.262
Land	-0.499 / 1.262	-0.344 / 1.279	0.093 / 1.197
All Scenes	-1.597 / 0.992	-1.444 /0.763	-1.125 / 0.803

LW Platform / Surface Type	Terra Slope (per decade)/ 95% conf	Aqua Slope (per decade)/ 95% conf	S-NPP Slope (per decade)/ 95% conf
Ocean	1.324 / 1.172	0.946 / 1.250	0.890 / 1.334
Land	0.250 / 1.231	-0.164 / 1.283	-0.292 / 1.246
All Scenes	1.003 / 0.838	0.614 / 0.951	0.536 / 1.066

Global Monthly Mean All-Sky SW and LW Flux Anomalies for CERES on Terra, Aqua and S-NPP from February 2012-September 2019

DCC Albedo Long-term Trends
(SSF: Single Satellite Footprint - Terra/Aqua Ed4, S-NPP Ed2, NOAA-20 Ed1)

- *Tropical deep convective clouds (DCC) are ideal for monitoring radiometric stability because they are highly invariant bright targets that have expansive coverage. DCC albedo can be used to assess the performance consistency of various instruments on different platforms.*
- *Criteria used to identify DCC footprints*
  VZA, SZA < 40°, Latitude bands: 30° N - 30° S, Over Ocean, Cloud Fraction= 100%
  T_B < 210 K (11µm channel from MODIS/VIIRS imager), WN channel filtered radiance < 1 $Wm^{-2}sr^{-1}\mu m^{-1}$
- *DCC trends show consistency among the instruments with no significant long-term trends.*



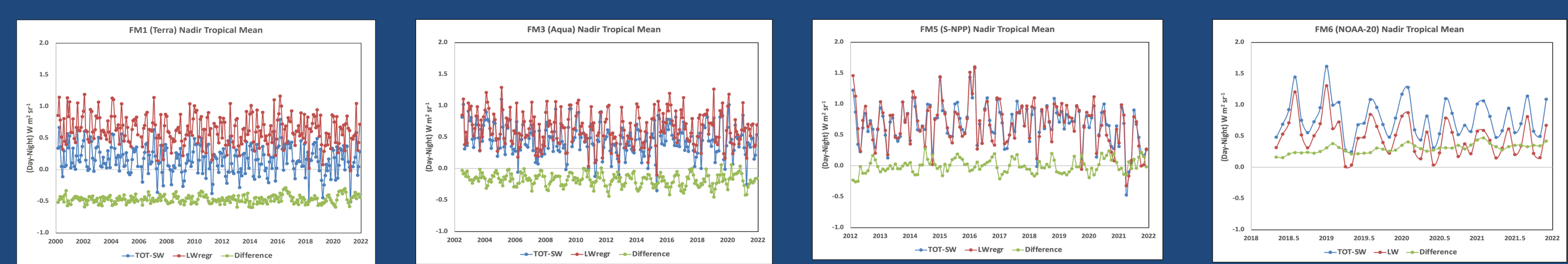
Tropical Mean Evaluation
(ES-8 Product - Terra/Aqua Ed4, S-NPP Ed2, NOAA-20 Ed1B)

- *The Tropical Mean (TM) value is Nadir LW radiance average for All-sky Ocean in ± 20 °latitude band. It is used to monitor inconsistencies in the shortwave region of the TOT sensors.*
- *TM Day-Night (DN) differences are calculated with 2 sets of LW measurements (on each instrument).*

$$DN_1 = TMD(TOT\text{-}SW) - TMN(TOT) \qquad DN_2 = TMD(LW) - TMN(LW)$$

Where: LW (FM1-FM5) : Obtained by Simulated LW radiance from Window channel
LW(FM6) : Radiance from the LW channel (LWC)

- *The difference between two DN values highlight any inconsistencies in the shortwave region of the TOT sensor.*



SUMMARY

- CERES instruments are continually being monitored and rigorous calibration and validation protocols are implemented to ensure calibration accuracy. CERES instruments continue to perform nominally and are stable.
- After incorporating algorithm improvements, validation results show long-term trends in radiances and global fluxes are consistent among the instruments and do not exhibit anomalous behavior or drifts in performance.