The Moon & Earth Radiation Budget Experiment (MERBE)

Grant Matthews

Animation credit Wikipedia

Accelerating certainty in climate change prediction

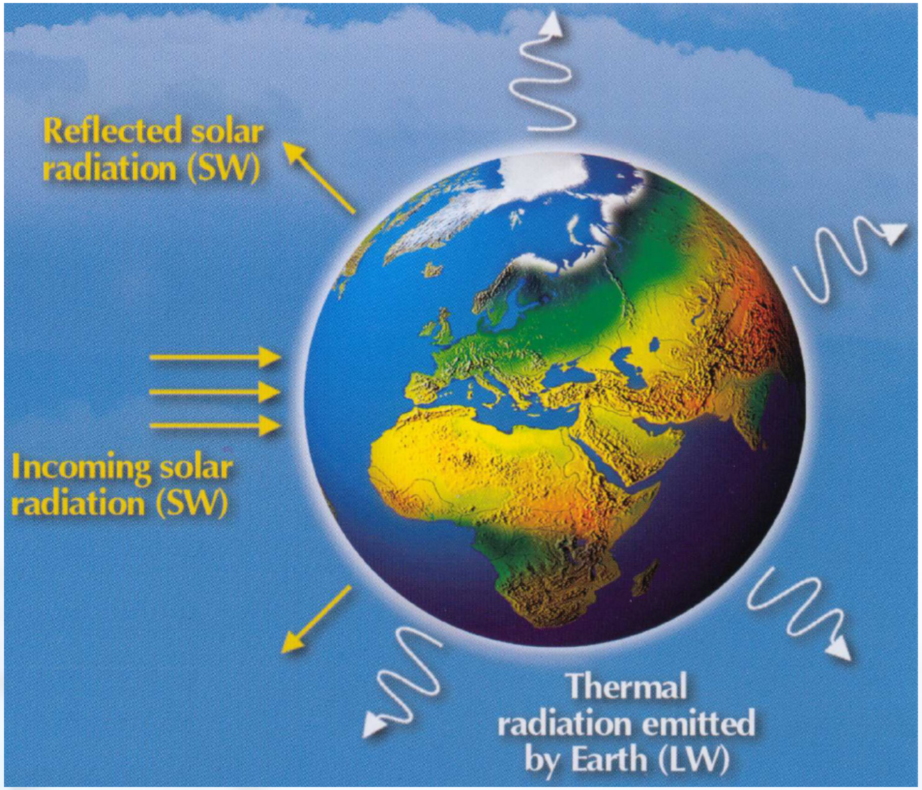
97th AMS Meeting
23rd Jan 2017
Seattle WA

EDIKA

Overview

"*The single largest uncertainty in determining the climate sensitivity to either natural or anthropogenic changes are clouds and their effects on radiation*" **IPCC**

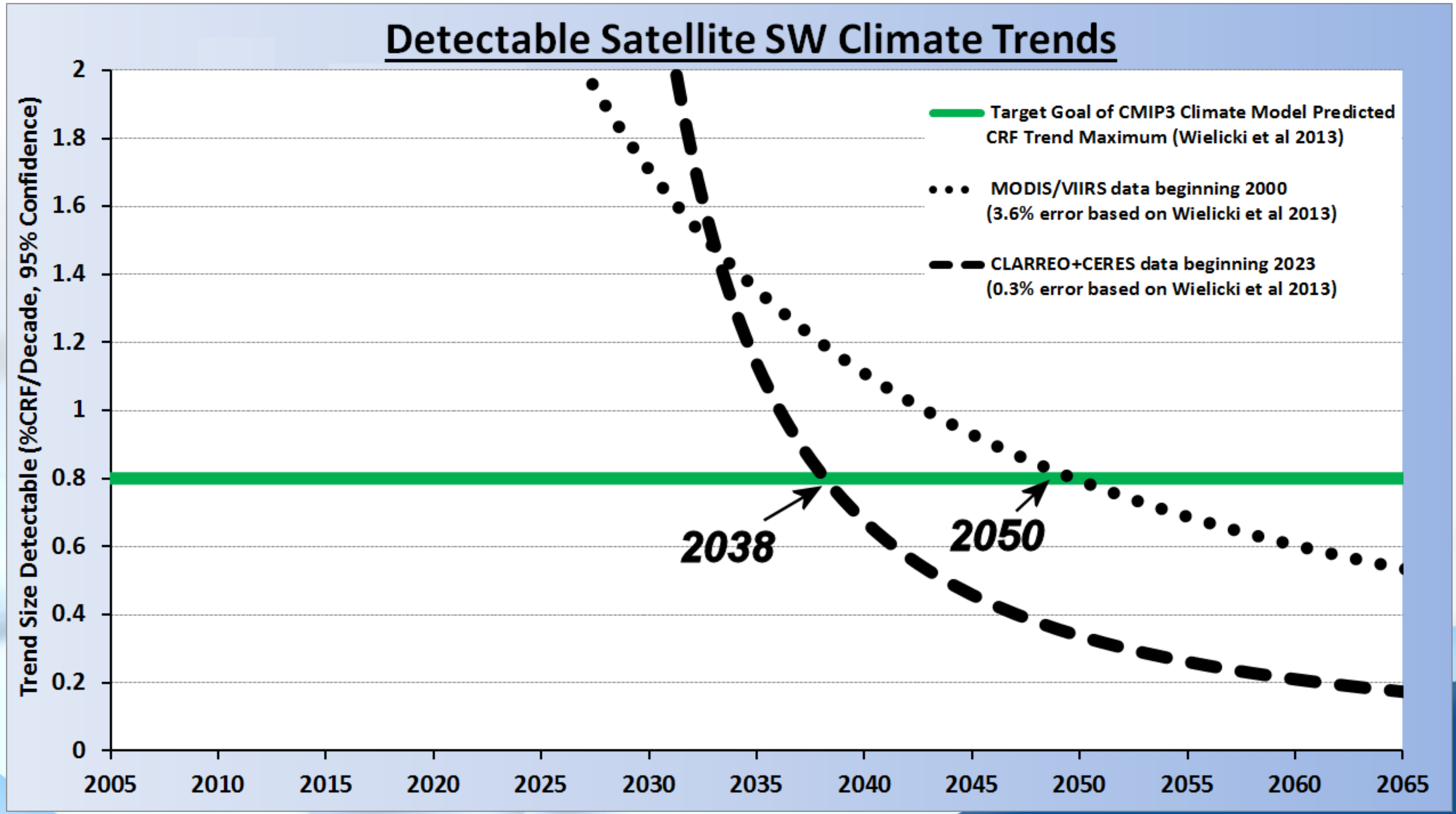
Earth's weather/climate system is the work done by a global heat engine driven by the Earth Radiation Budget (ERB – SW & LW), which must be measured from space to constrain and validate climate models



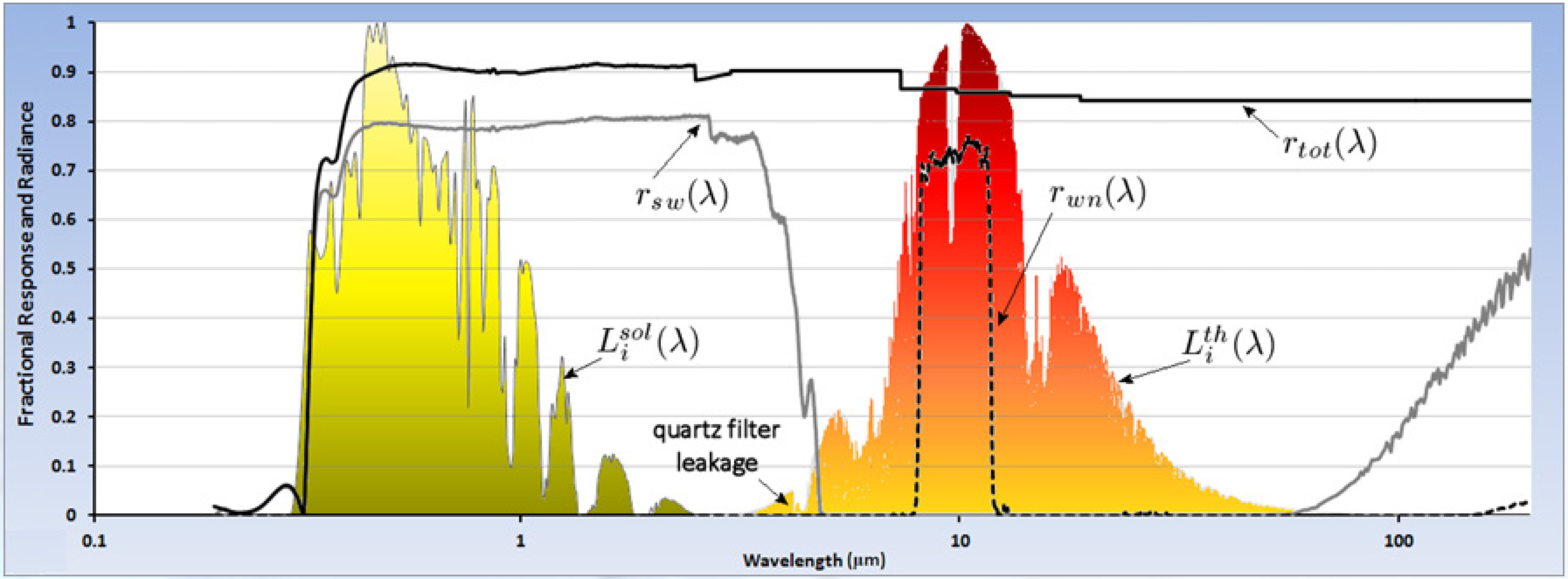
"*The single most critical issue for current climate change observations was their lack of accuracy and low confidence in observing the small climate change signals over long decade time scales*" **NRC 2007 decadal survey**

ERB Fig by H. E. Brindley

Wielicki et al (2013) Fig 3b finds we cannot detect and hence prove disputed Cloud Climate signals of size ≤ 0.8% decade^{-1} for around a quarter of a century



Earth Radiation Budget Short & Long Wave



SW or Reflected Solar (0<λ<5μm)
LW or Thermal Infra Red (5<λ<200μm)

SeaWIFS is the one device to have visible λ calibration stability sufficient for near term climate CRF trend detection by using the Moon as a 'perfect solar diffuser'. But all ERB missions on the right also have regular lunar/solar views (being largely un-used today)

Table 1. Past, existing and future satellite missions measuring ERB parameters with regular Lunar or Solar views to become traceable to SI MERBE Watt or Watt Units.

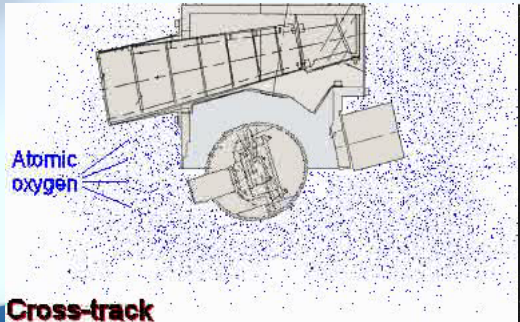
ERB Mission	Lifetime
NIMBUS 7 ERB[27]	1978-1993
ERBE [28]	1984-2005
CERES[6]	1998-Present
GERB[29]	2002-Present
DSCOVR(NISTAR) [32]	2015-Present
RBI[34]	2021-?
CLARREO[8]	2023-?
TRUTHS[5]	?-?

Led to the Concept of the Moon and Earth Radiation Budget Experiment (MERBE, 0.3% acc 1σ) with Simple Golden Rules

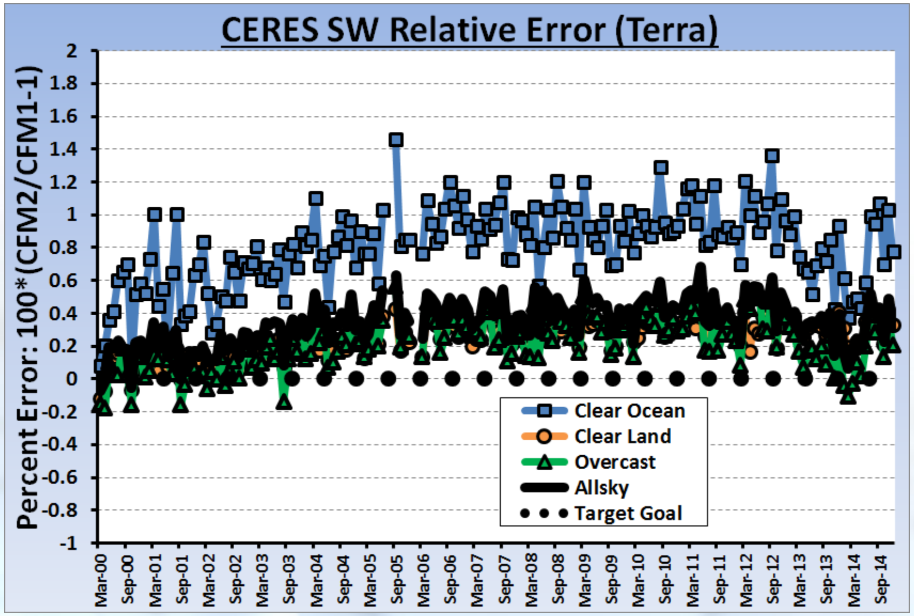
- 1. ***Different instruments viewing the Moon must measure the same SI traceable lunar albedo and emissivity for all time***

- 2. ***Different instruments viewing the same Earth target must agree for all scenes. Any differences set the minimum possible error/trend that can be quoted.***

MERBE does this while using pre-published and improved in-flight spectral calibration combined with more sophisticated signal processing and inversion techniques, making use of advances in computing and radiative transfer theory since the last century.



<u>Golden Rule 2 SW Earth Results</u>: Evaluation of CERES and MERBE relative accuracy of 2 identical ERB CERES Flight Models (CFM) on the same satellite

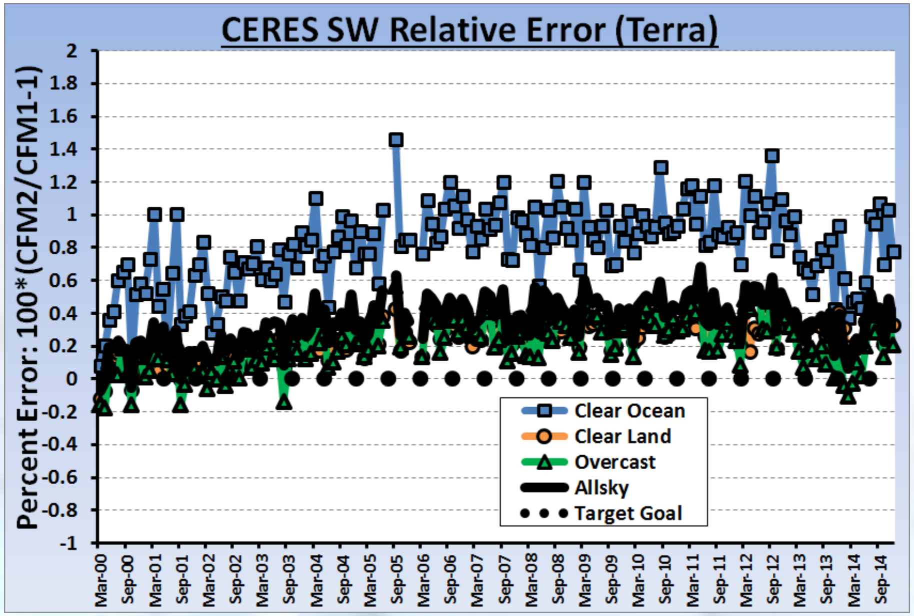


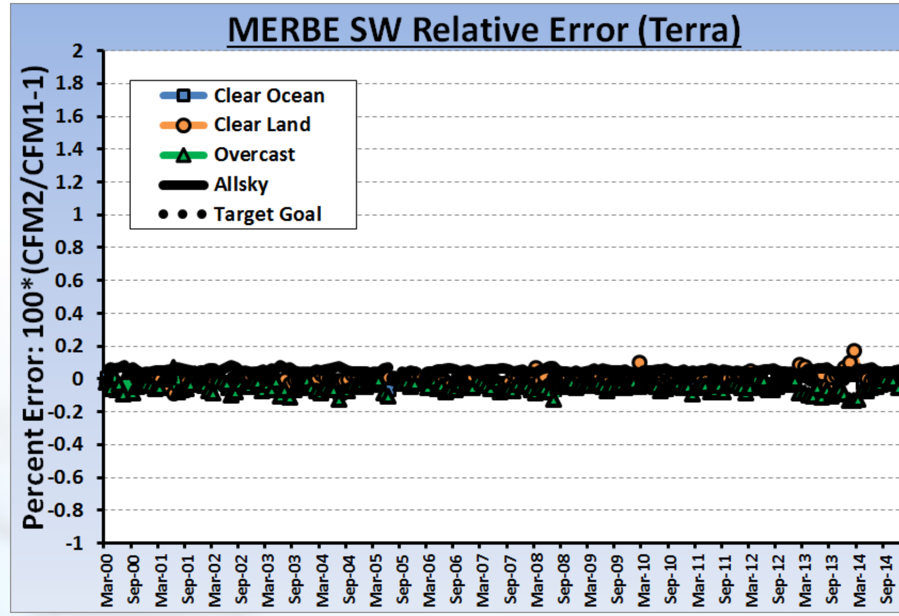
Using Loeb et al 2016: CERES Top-of-Atmosphere Earth Radiation Budget Climate Data Record: Accounting for in-Orbit Changes in Instrument Calibration, Remote Sens., 8(3), 182

Mere <u>relative</u> SW CERES errors and trends are larger than the <u>absolute</u> 0.9% and 0.2% decade^{-1} values assumed today (1 sigma)

Preliminary Results Shown

<u>Golden Rule 2 SW Earth Results</u>: Evaluation of CERES and MERBE relative accuracy of 2 identical ERB CERES Flight Models (CFM) on the same satellite





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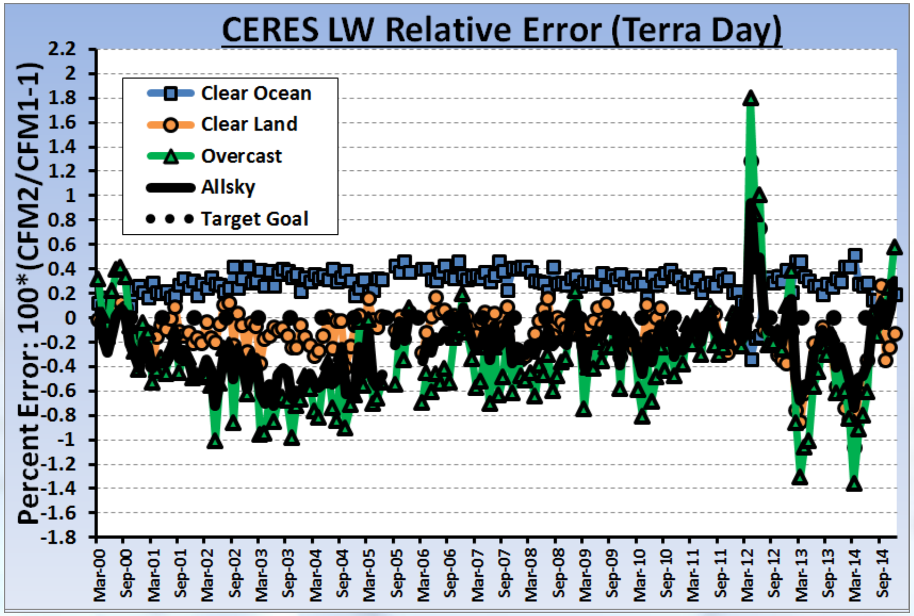
Using Matthews 2009: In-Flight Spectral Characterization and Calibration Stability Estimates for the Clouds and the Earth's Radiant Energy System (CERES), Journal of Atmospheric and Oceanic Technology 26(9), 1685-1716

Mere <u>relative</u> SW CERES errors and trends are larger than the <u>absolute</u> 0.9% and 0.2% decade^{-1} values assumed today (1 sigma)

Preliminary Results Shown

<u>Golden Rule 2 LW Earth Results</u>: Evaluation of CERES and MERBE relative accuracy of 2 identical ERB CERES Flight Models (CFM) on the same satellite

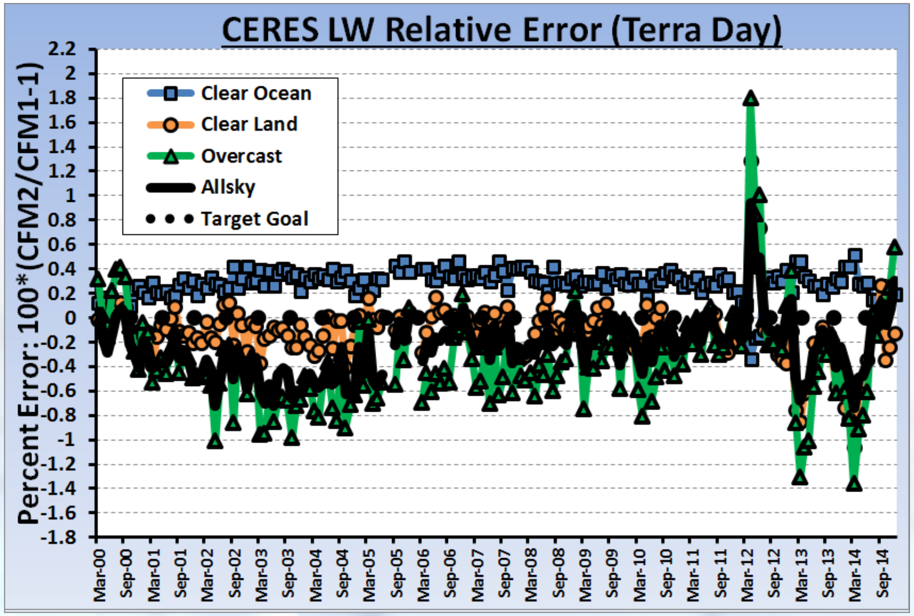


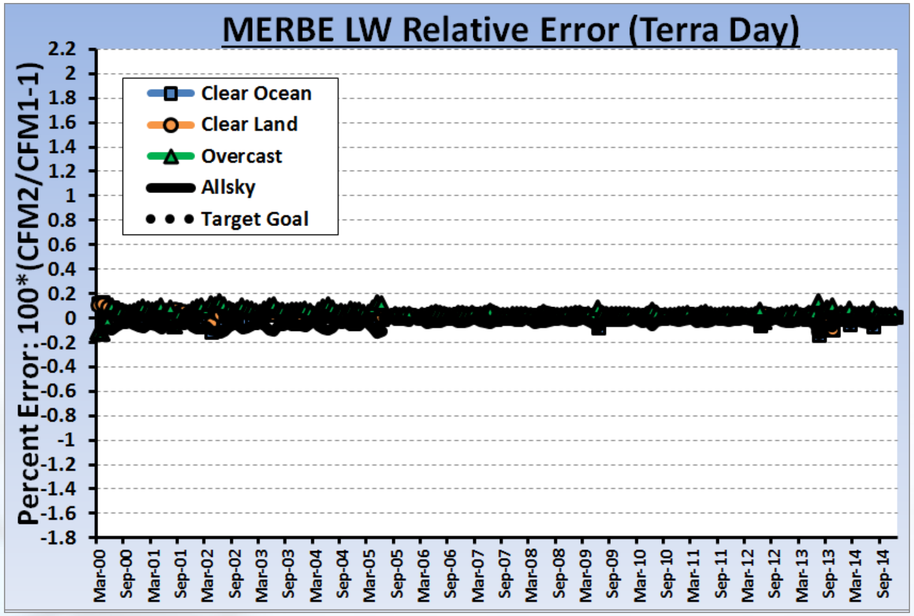
Using Loeb et al 2016: CERES Top-of-Atmosphere Earth Radiation Budget Climate Data Record: Accounting for in-Orbit Changes in Instrument Calibration, Remote Sens., 8(3), 182

Mere <u>relative</u> LW CERES errors and trends are well over twice the <u>absolute</u> 0.5% and 0.15% decade^{-1} values assumed today (1 sigma)

Preliminary Results Shown

<u>Golden Rule 2 LW Earth Results</u>: Evaluation of CERES and MERBE relative accuracy of 2 identical ERB CERES Flight Models (CFM) on the same satellite





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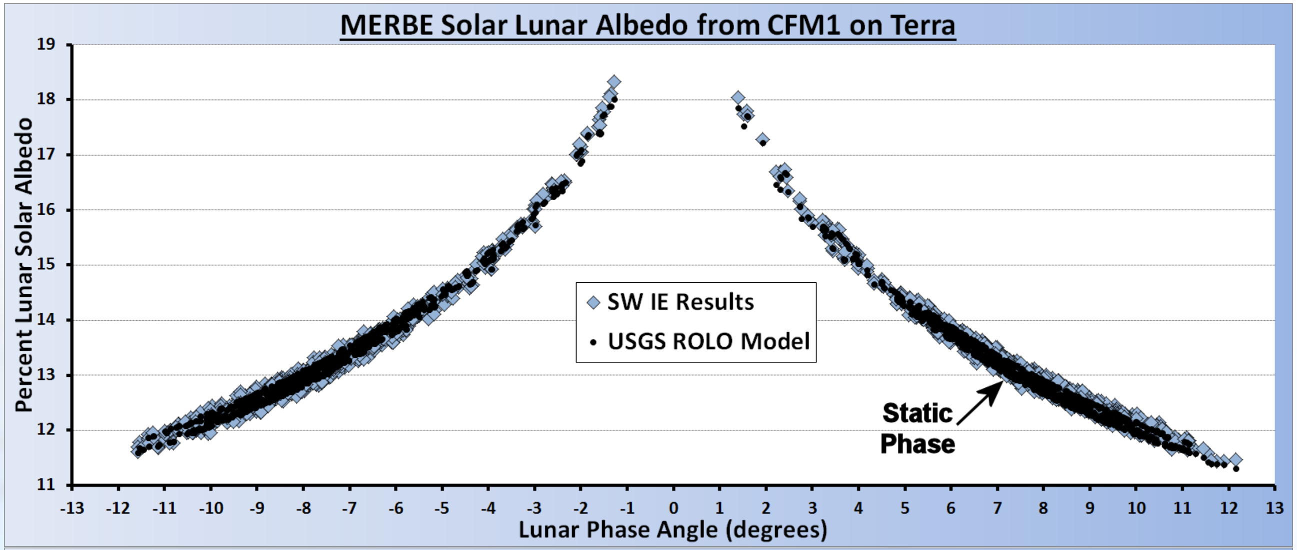
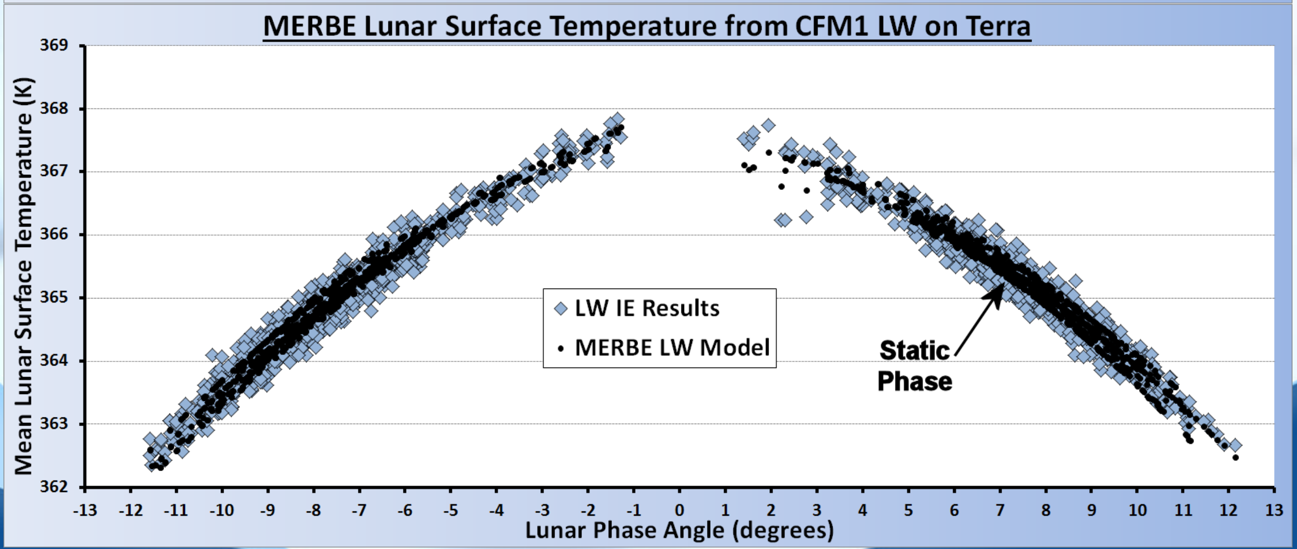
Mere <u>relative</u> LW CERES errors and trends are well over twice the <u>absolute</u> 0.5% and 0.15% decade^{-1} values assumed today (1 sigma)

Preliminary Results Shown

Golden Rule 1: Use of improved MERBE Impulse Enhanced (IE) signal processing allows thousands of independent lunar radiance retrievals to be made since 2002



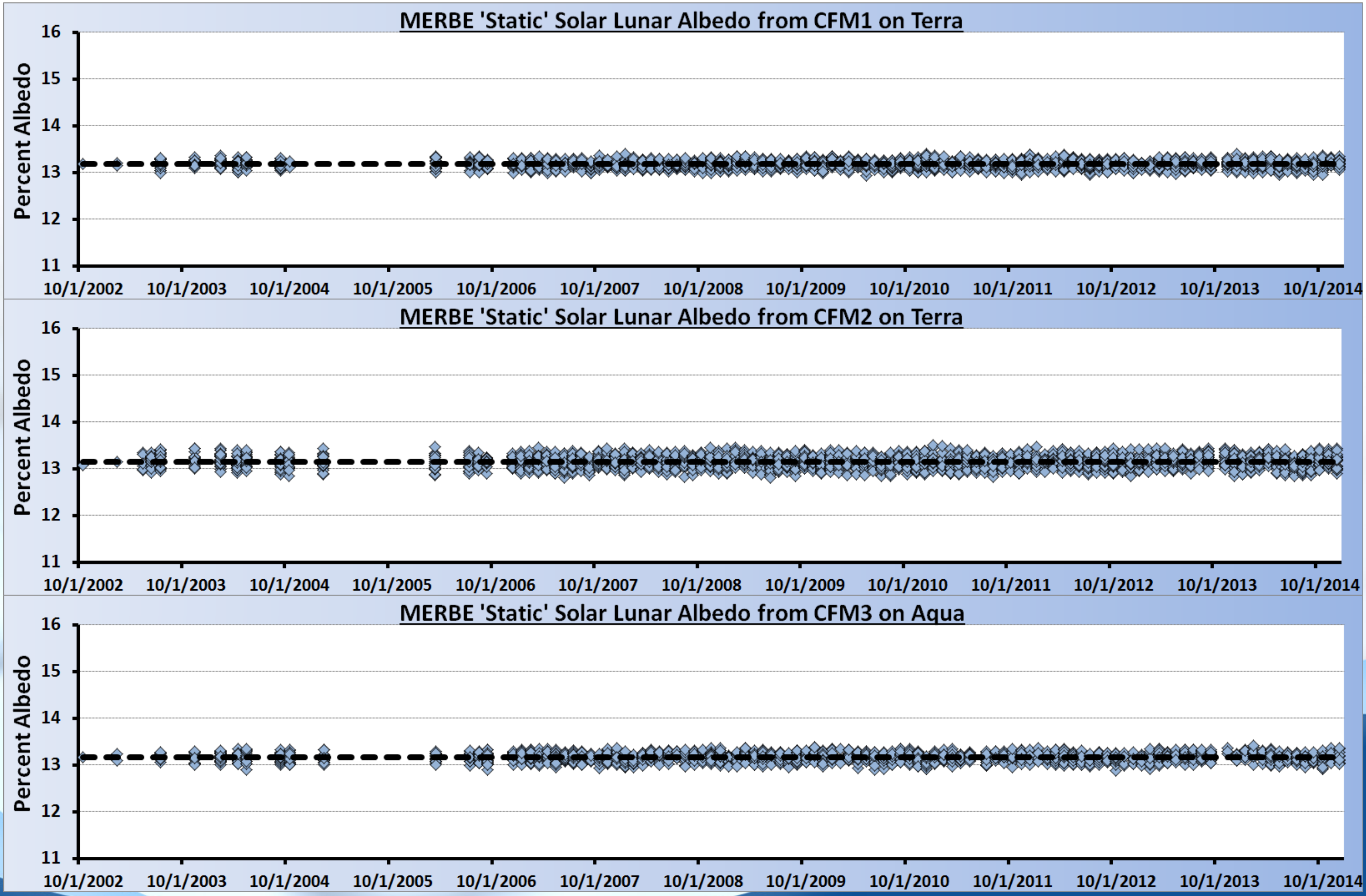


Results are fully SI traceable to units of the solar/thermal MERBE Watt

All instruments must measure same lunar reflectivity & temperature/emissivity at +7° static phase angle (see below)

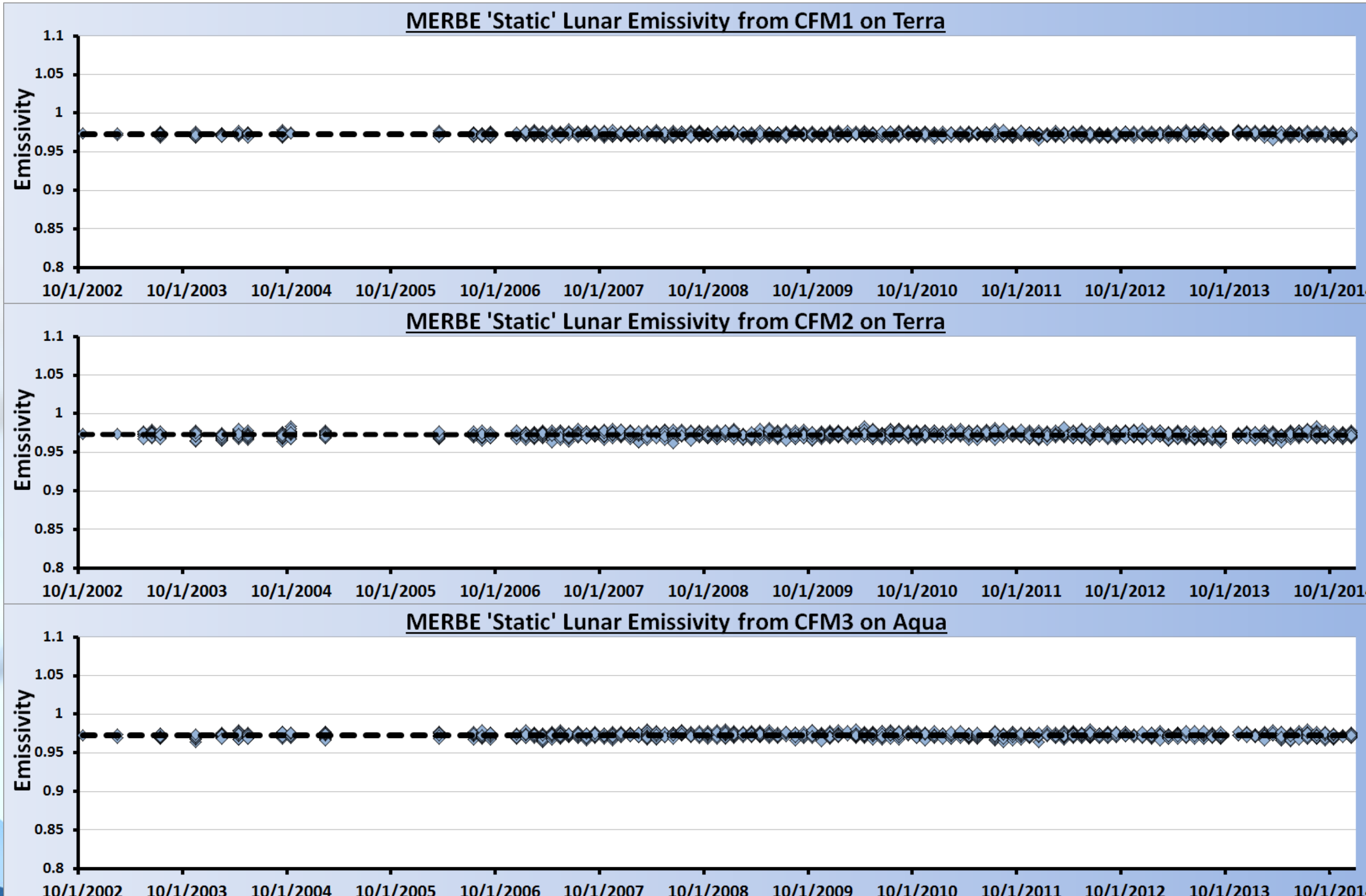
Preliminary Results Shown

Lunar Albedo Trends are Removed with < 0.05% decade^{-1} confidence (one sigma)



Preliminary Results Shown

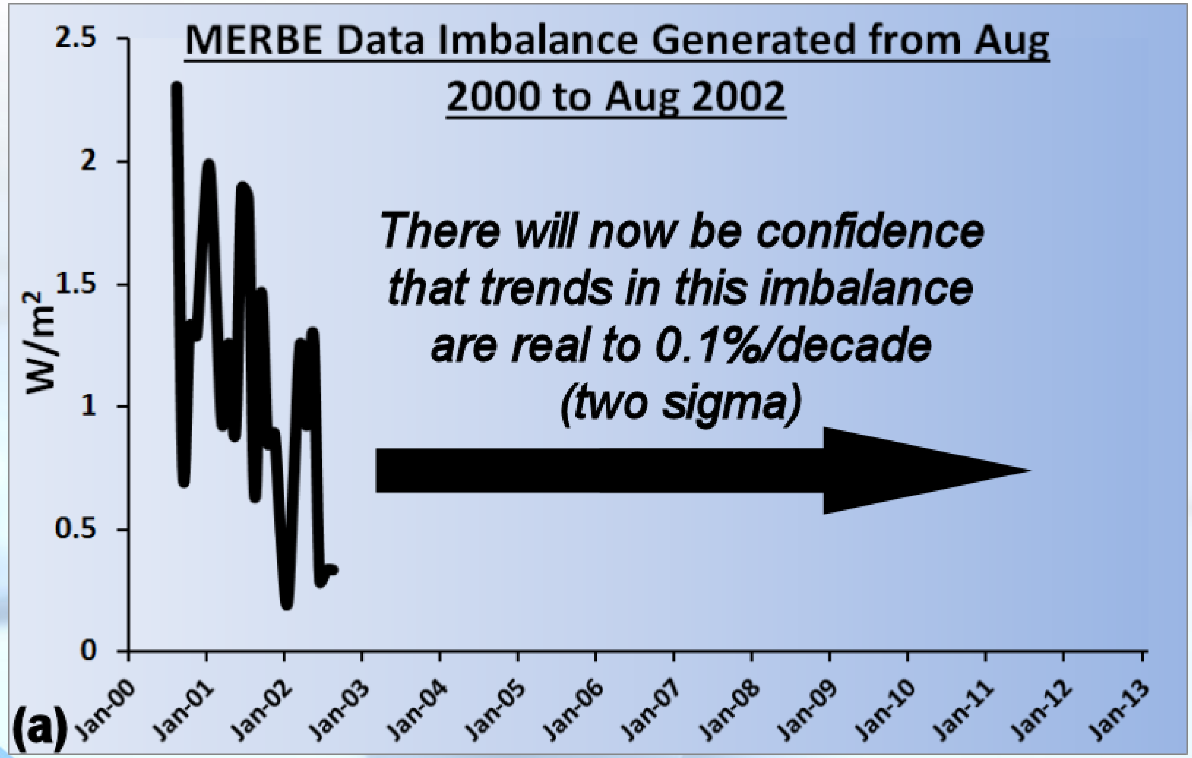
Lunar Emissivity Trends are Removed with < 0.01K decade^{-1} confidence (one sigma)



Preliminary Results Shown

Golden Rule 1: *Why define Lunar Emissivity and Albedo at such levels?*

CERES device ground & onboard LW calibration has fair SI traceability but the SW does not, largely due to **using un-characterized laboratory solar reference detectors**. This likely is a primary cause of the implausible CERES measured +7 Wm^{-2} ERB imbalance.

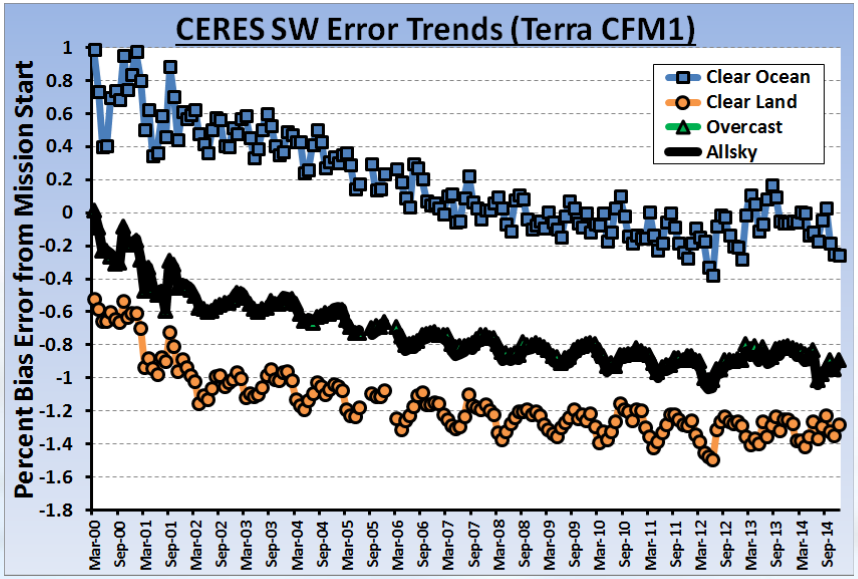


Thermal MERBE-Watt (lunar emissivity) based on Terra LW Moon data.

Solar MERBE-Watt (lunar albedo) derived to make a +0.85Wm^{-2} start of century ERB imbalance

Preliminary Results Shown

Use Golden Rules: Find False Trends in CERES results used today in GCM Validation



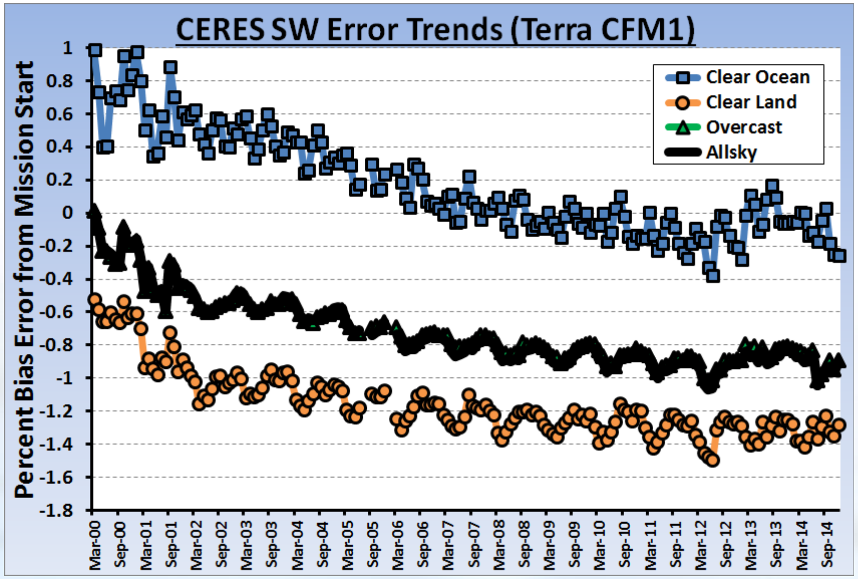
Primary CERES "climate device" on Terra has artificial negative Earth albedo trends of -1% decade^{-1} (max 0.2% decade^{-1} assumed).

SW CRF signals <0.8% decade^{-1}

Preliminary Results Shown

Preliminary Results Shown

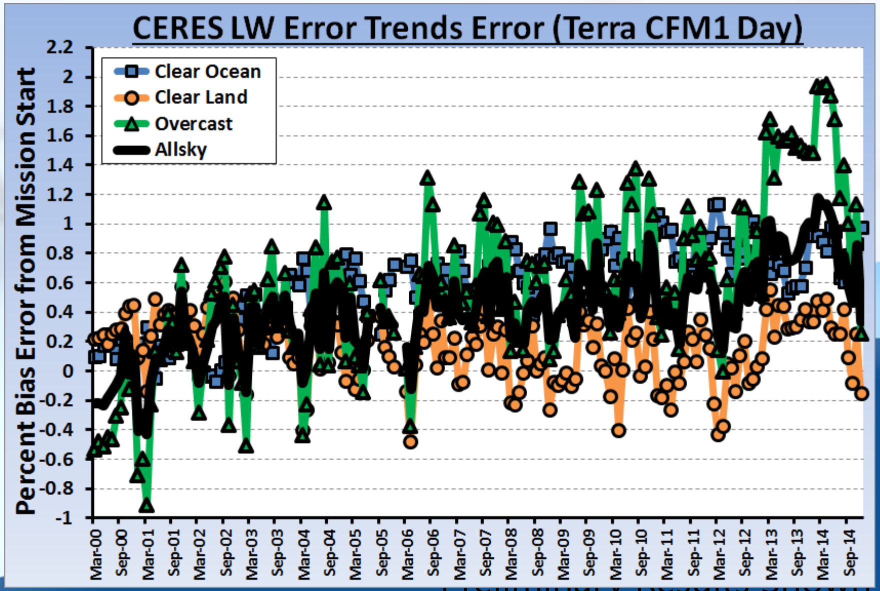
Use Golden Rules: Find False Trends in CERES results used today in GCM Validation



Primary CERES "climate device" on Terra has artificial negative Earth albedo trends of -1% $decade^{-1}$ (max 0.2% $decade^{-1}$ assumed).

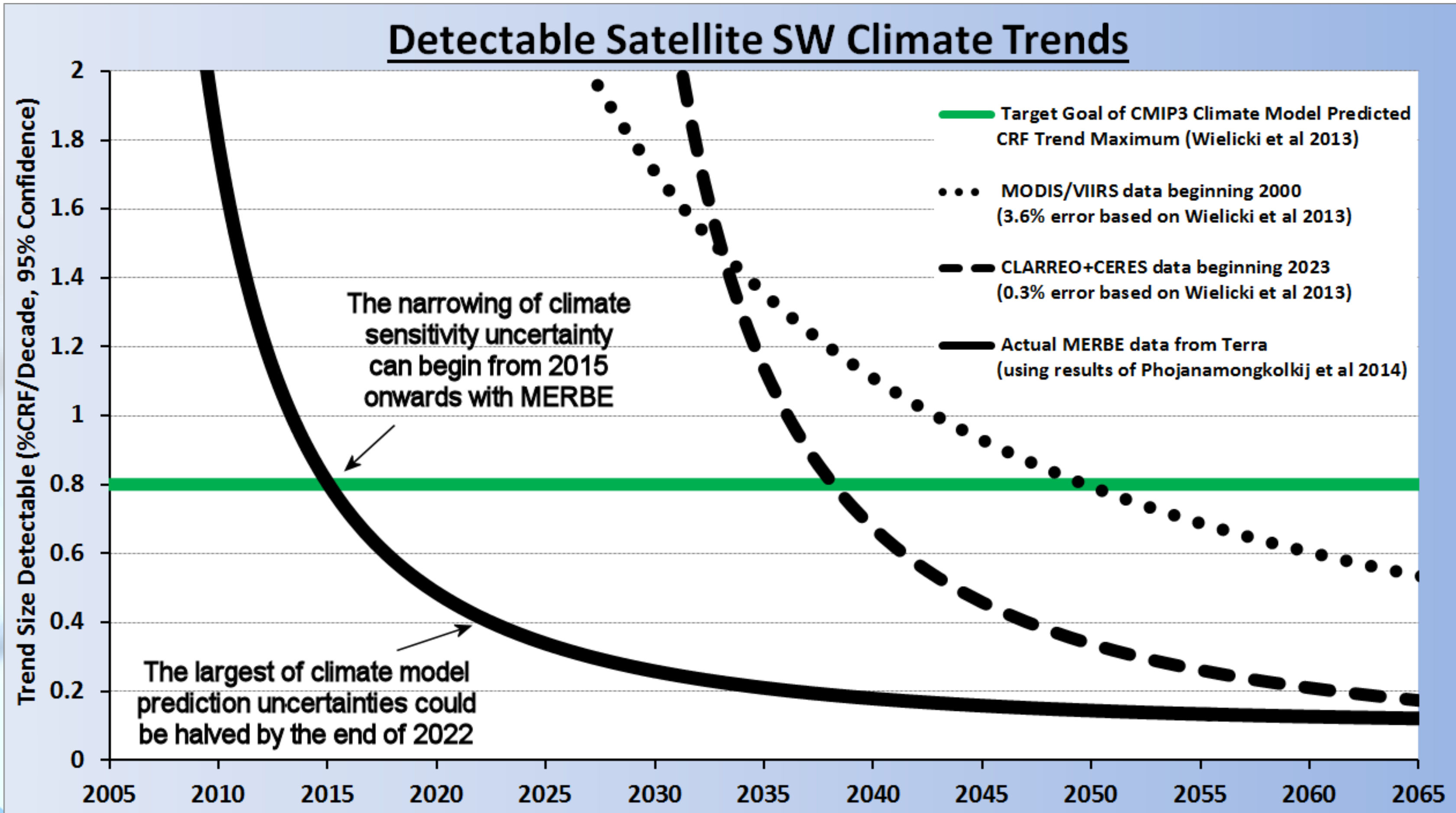
SW CRF signals <0.8% $decade^{-1}$

Primary CERES "climate device" on Terra has artificial positive Earth LW trends of +1% $decade^{-1}$ (max 0.15% $decade^{-1}$ assumed)



Preliminary Results Shown

Due to device longevity, below in solid black is when they actually do become detectable from MERBE data to be released in 2016



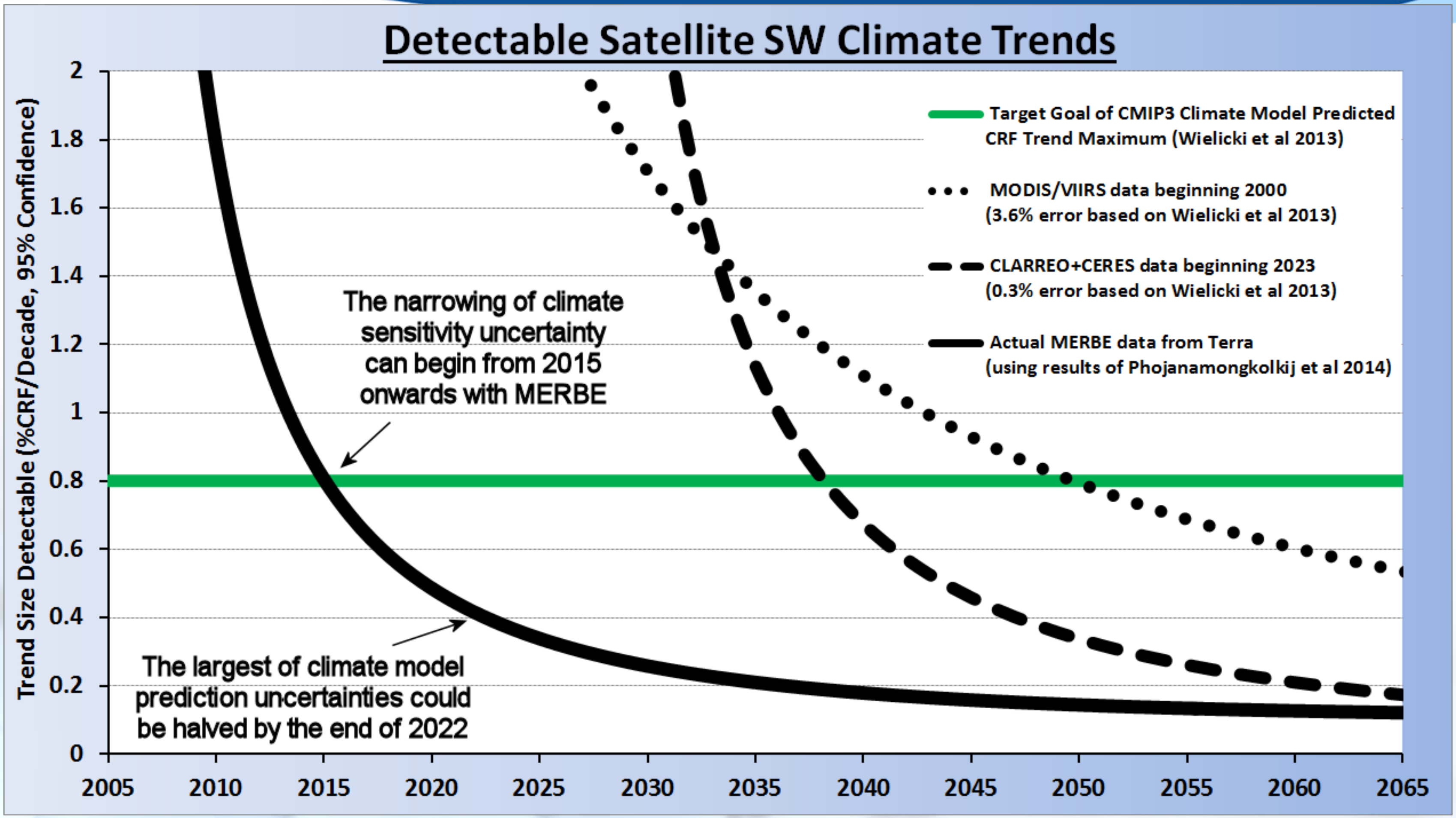
(using actual Terra Moon data shown 5 slides ago)

Summary/Conclusions

- CERES ERB results available today for CRF trend detection and GCM validation are less accurate and far less stable or precise than is currently assumed.

- MERBE has completely re-calibrated all US ERB measurements dating from the start of the century for a free release soon as HDF SSF files. It improves accuracy across the board often by an order of magnitude, based on lunar scans and pre-published calibration methodologies.

- Independent results suggest MERBE is an existing part of a “climate observing system” already decades old. It brings the desired climate change detection accuracies immediately and 23yrs before even future CLARREO-like missions could, with the added possibility of halving climate sensitivity uncertainties by 2023.



Three MERBE papers currently in AMS JAOT/JAMC/BAMS peer review:

- ❑ Calibration Enhancements to Improve Accuracy of a Scanning Bolometer: Application to the Moon and Earth Radiation Budget Experiment (MERBE), Part I
- ❑ Real-time Determination of Earth Radiation Budget Spectral Signatures for Non-Linear Un-filtering of Results from MERBE, Part II
- ❑ First Decadal Lunar Results from the Moon and Earth Radiation Budget Experiment (MERBE), Part III

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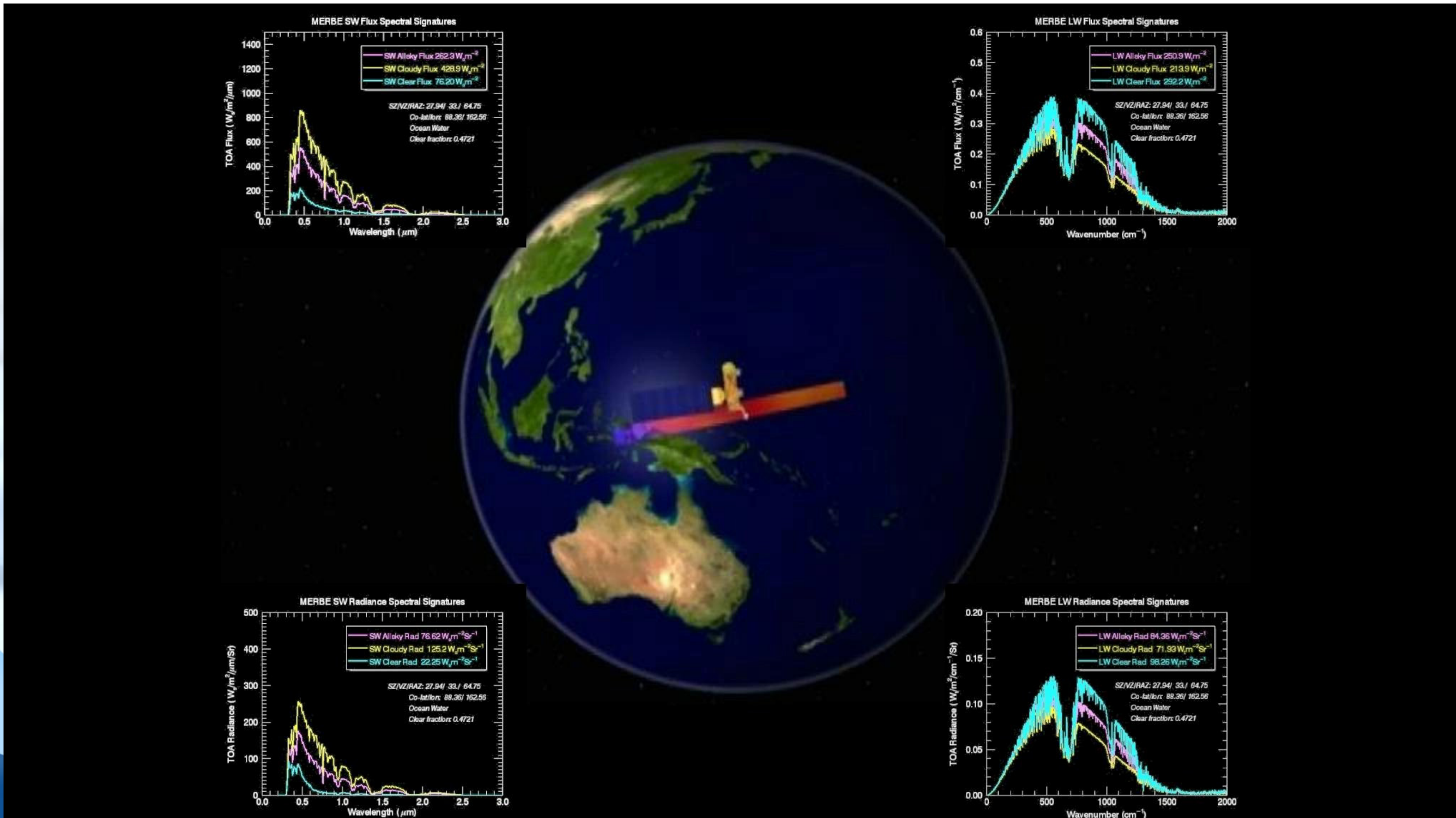
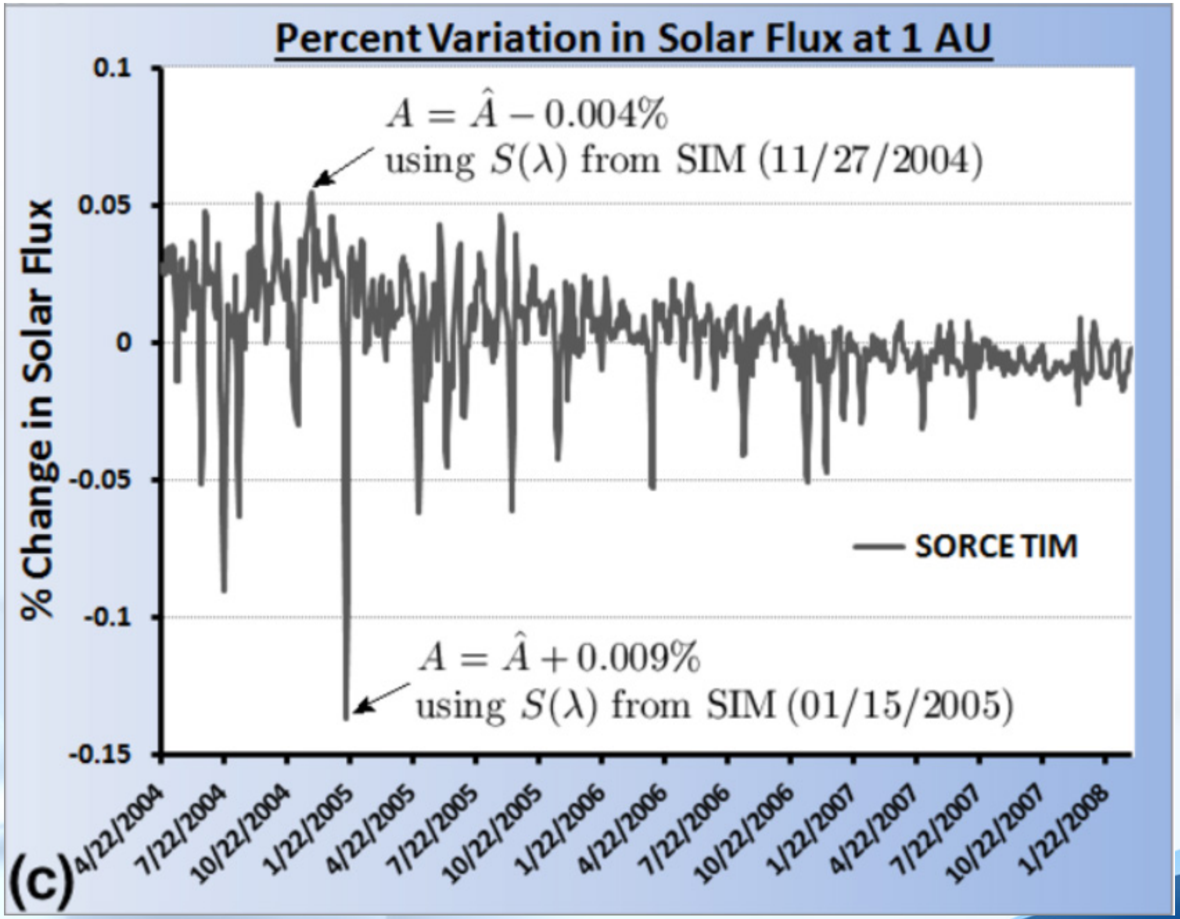
Animation credit NASA

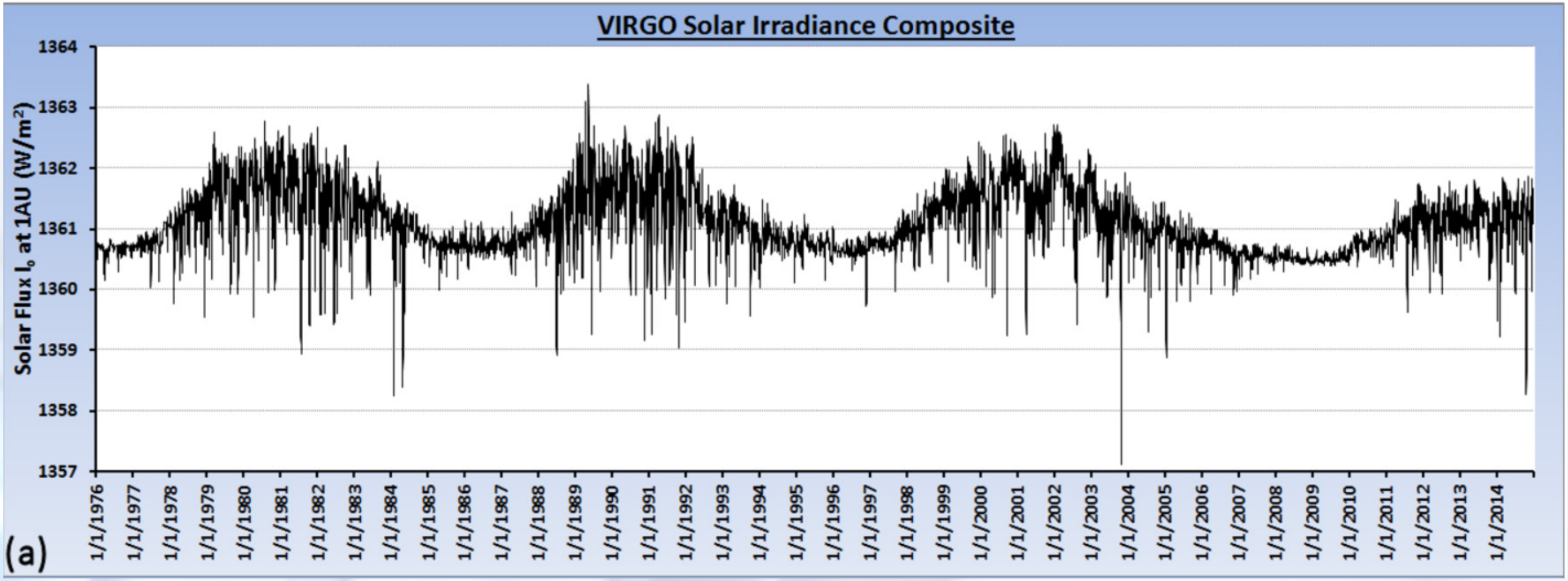
A Fourier series tensor instantaneously generates a clear, cloudy and all-sky MODTRAN 5.3 spectral signature for every footprint to be used in un-filtering (whose integral is constrained to SI traceable MERBE data)



Lunar A value is in-sensitive (~0.013%) to changes in solar spectrum S(λ)



All Un-filtering and lunar results normalized to VIRGO composite (by Claus Fröhlich)



ROLO model – Kieffer & Stone 2005

3.3.1. *Model Analytic Form and Derivation of Model Coefficients*

ROLO has developed a model of the equivalent reflectance of the entire lunar disk (regardless of illuminated fraction) as a function of geometry. To fit the ROLO observations, we have used an empirically derived analytic form based on the primary geometric variables:

$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\theta + c_2\phi + c_3\Phi\theta_+ c_4\Phi\phi + d_{1k}e^{-g/p_1} + d_{2k}e^{-g/p_2} + d_{3k}\cos[(g-p_3)/p_4], \quad (10)$$

where A_k is the disk-equivalent reflectance, g is the absolute phase angle, θ and ϕ are the selenographic latitude and longi-

filter.

Then, the ~38,000 residuals from all filters were averaged into 200 uniformly sized bins in phase angle, and these residuals were fitted with the nonlinear terms included, plus an additional linear term that was later dropped. A single exponential term was found inadequate to model the behavior at small phase angles. There is an extended solution curve in the four-dimensional nonlinear parameter space along which the χ^2 term varies negligibly; the solution with widest separation of the two exponential angles was chosen.

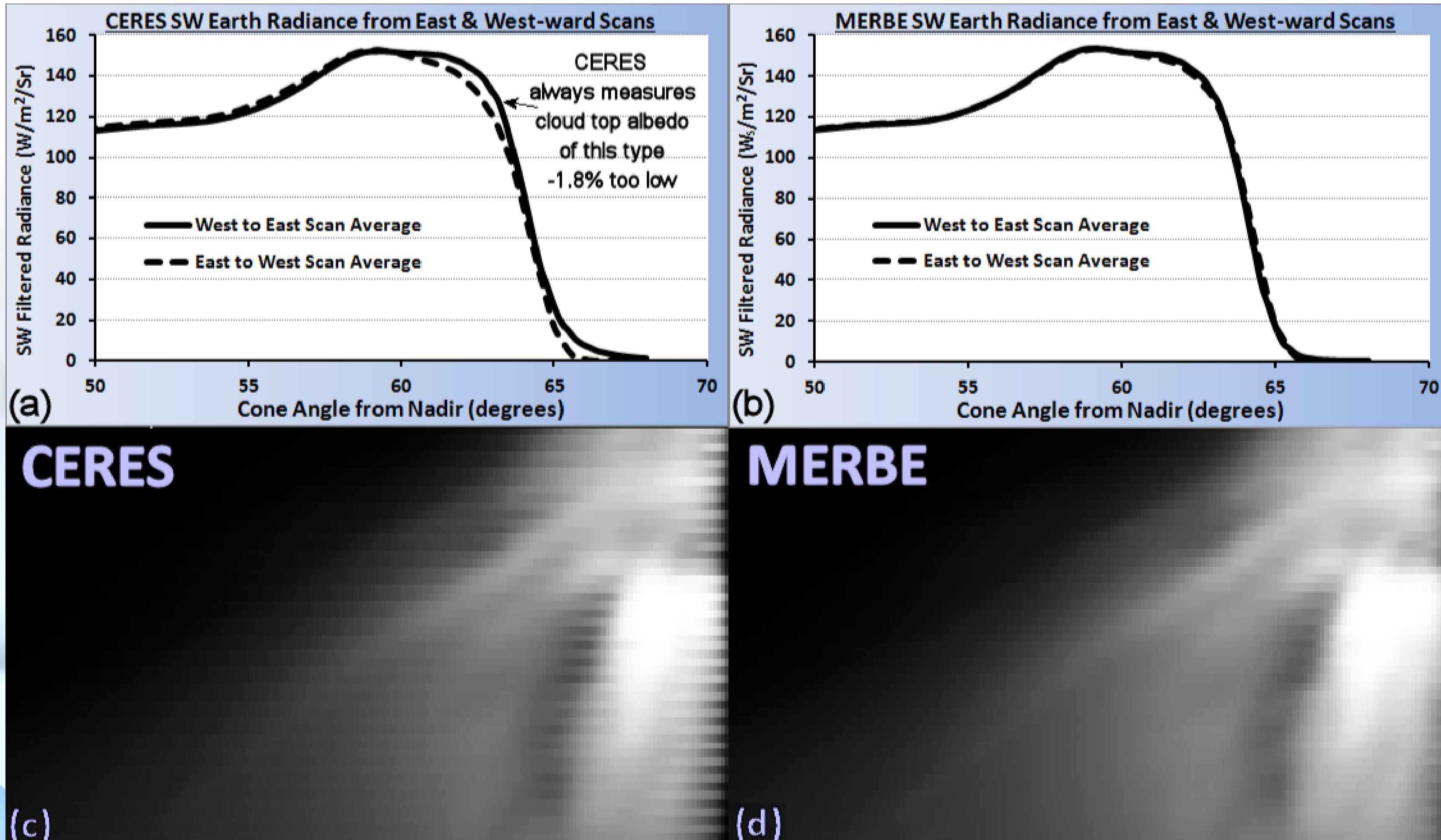
All filters were then fitted again with the same process, this time using fixed values for the nonlinear parameters to create the corresponding linear basis functions. Finally, the four coefficients for libration were fixed at their average over wavelength, and all data fitted again.

TABLE 4

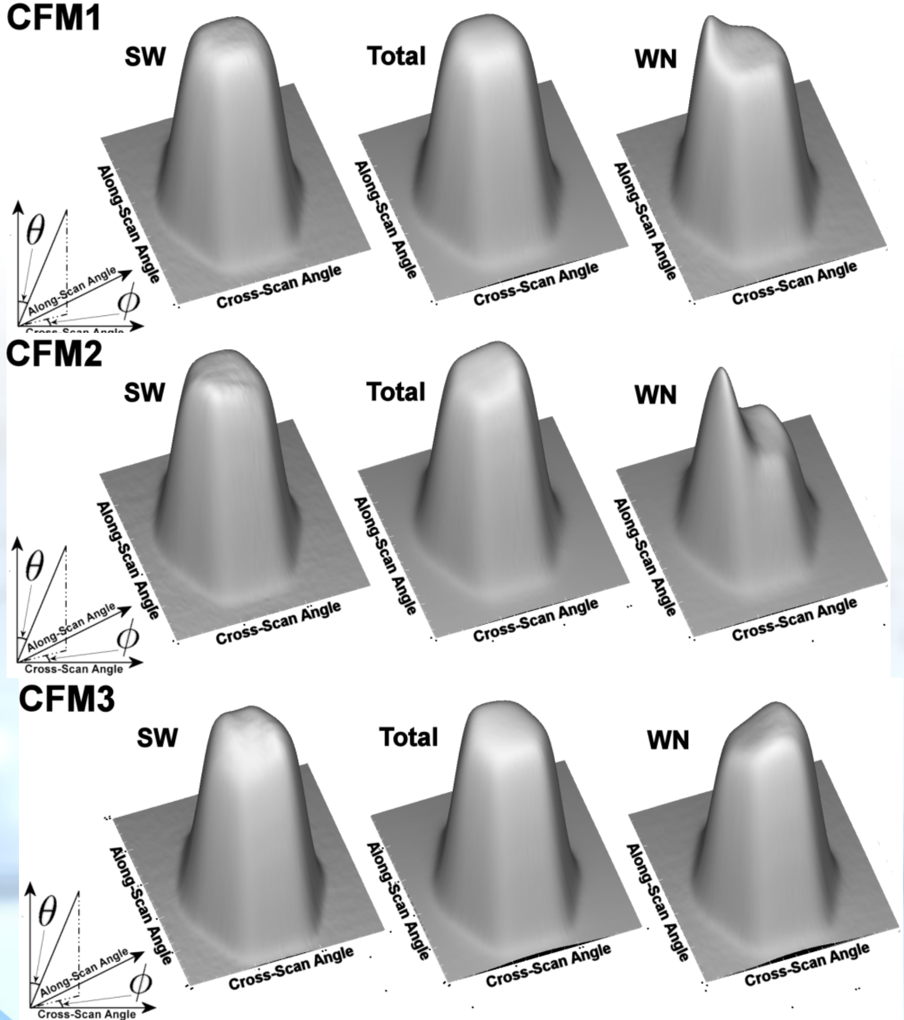
ROLO Lunar Irradiance Model Coefficients, Version 311g

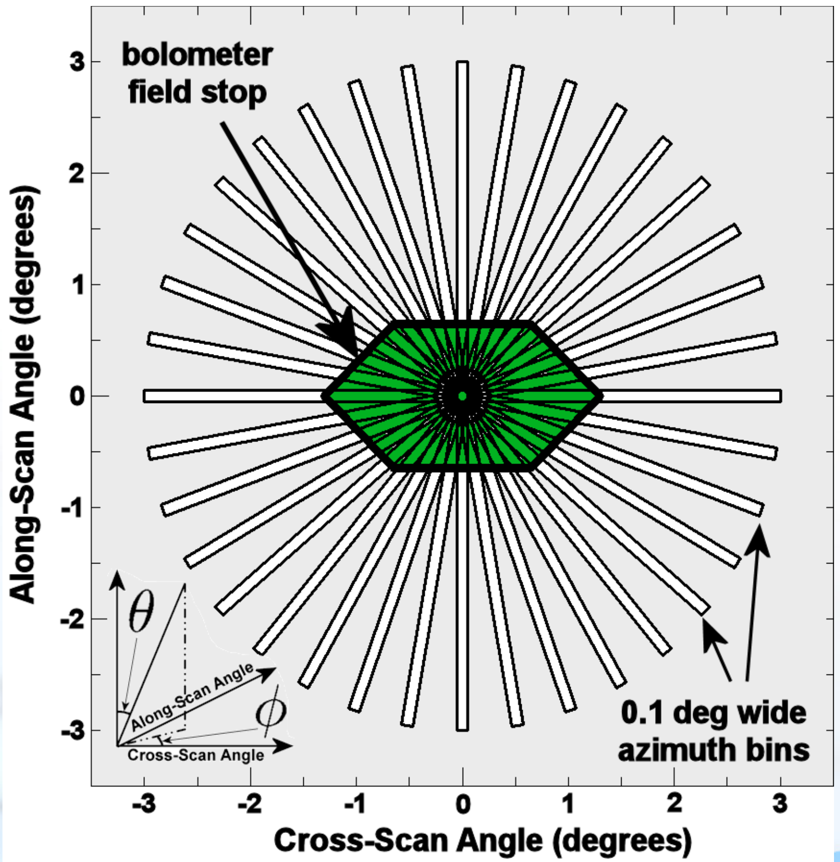
Wavelength (nm)	Coefficient, Term, Name									
	a_0, 1, Constant	a_1, g, Phase 1 (rad^{-1})	a_2, g^2, Phase 2 (rad^{-2})	a_3, g^3, Phase 3 (rad^{-3})	b_1, Φ, SunLon 1 (rad^{-1})	b_2, Φ^3, SunLon 3 (rad^{-3})	b_3, Φ^5, SunLon 5 (rad^{-5})	d_1, e^{-g/p_1}, Exponent 1	d_2, e^{-g/p_2}, Exponent 2	d_3, $\cos[(g-p_3)/p_4]$, Cosine
350.0	−2.67511	−1.78539	0.50612	−0.25578	0.03744	0.00981	−0.00322	0.34185	0.01441	−0.01602
355.1	−2.71924	−1.74298	0.44523	−0.23315	0.03492	0.01142	−0.00383	0.33875	0.01612	−0.00996
405.0	−2.35754	−1.72134	0.40337	−0.21105	0.03505	0.01043	−0.00341	0.35235	−0.03818	−0.00006
412.3	−2.34185	−1.74337	0.42156	−0.21512	0.03141	0.01364	−0.00472	0.36591	−0.05902	0.00080
414.4	−2.43367	−1.72184	0.43600	−0.22675	0.03474	0.01188	−0.00422	0.35558	−0.03247	−0.00503
441.6	−2.31964	−1.72114	0.37286	−0.19304	0.03736	0.01545	−0.00559	0.37935	−0.09562	0.00970
465.8	−2.35085	−1.66538	0.41802	−0.22541	0.04274	0.01127	−0.00439	0.33450	−0.02546	−0.00484
475.0	−2.28999	−1.63180	0.36193	−0.20381	0.04007	0.01216	−0.00437	0.33024	−0.03131	0.00222
486.9	−2.23351	−1.68573	0.37632	−0.19877	0.03881	0.01566	−0.00555	0.36590	−0.08945	0.00678

Impulse Enhancement also removes CERES scene dependent biases of >1%



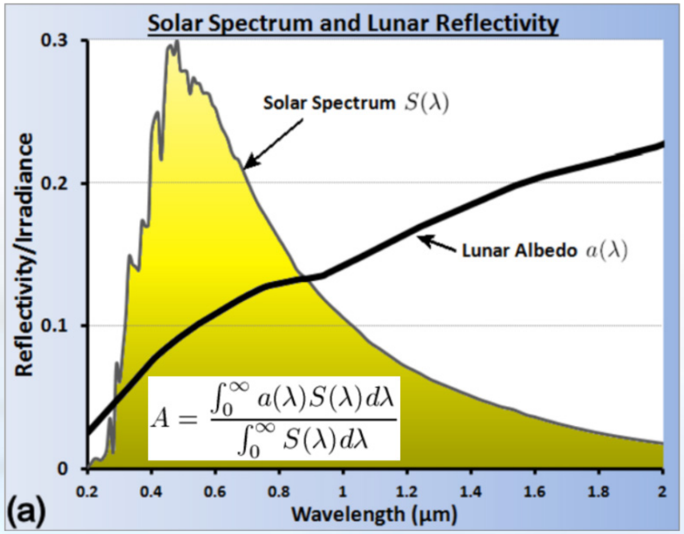
So instead each MERBE device Moon Field of View is now precisely mapped





Mere `lunar glances' can be regressed against such maps, increasing the number of Moon measurements by an order of magnitude from Matthews 2008

Concept of Solar & Thermal MERBE Watts (W_s & W_t) with the below Unbroken Chain of Equations to SI Traceability



$$\hat{A} = 0.13166$$

$$\hat{I}_0 = 1361 Wm^{-2}$$

$$1W_s = \boxed{\frac{\hat{A} \times \hat{I}_0}{A \times I_0}} \quad (kg.m^2 s^{-3}) \pm 0.6\%^*$$

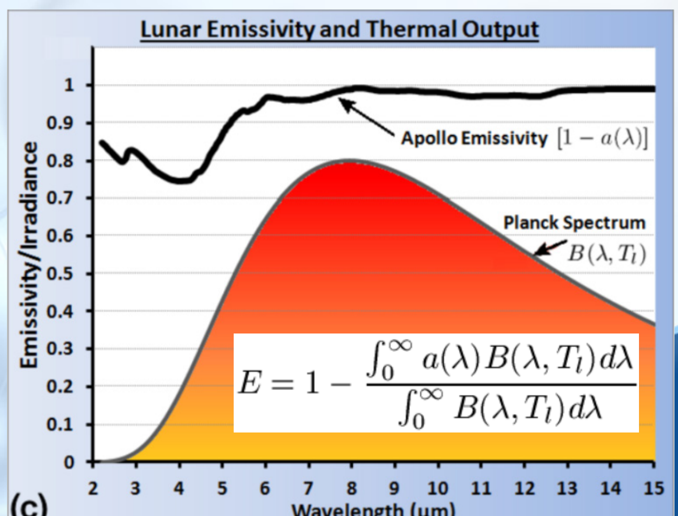
MERBE Watts W_s & W_t are defined on left in terms of kilograms, meters & seconds.

All instruments must measure same lunar reflectivity A & temperature T_l at +7º static phase angle (see below)

$$\hat{E} = 0.97271$$

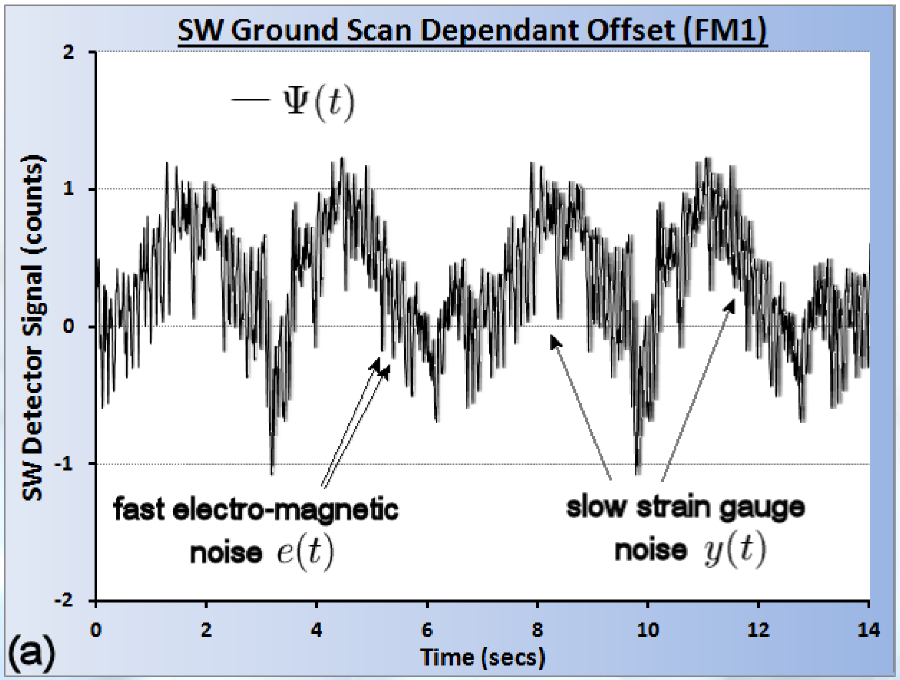
$$\hat{T}_l = 365.498K$$

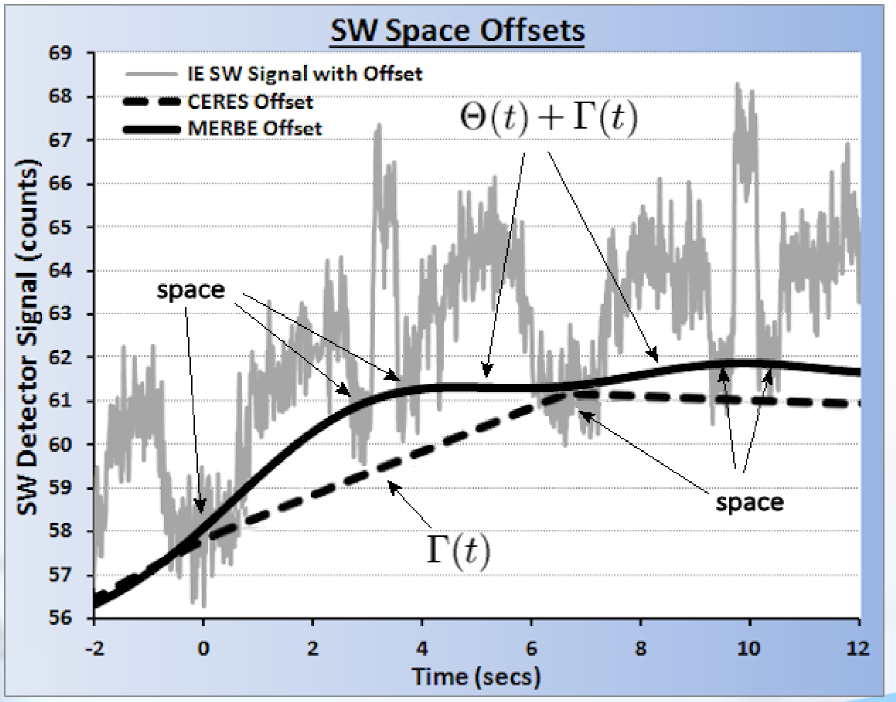
$$1W_t = \boxed{\frac{\hat{E} \times \hat{T}_l^4}{E \times T_l^4}} \quad (kg.m^2 s^{-3}) \pm 0.6\%^*$$



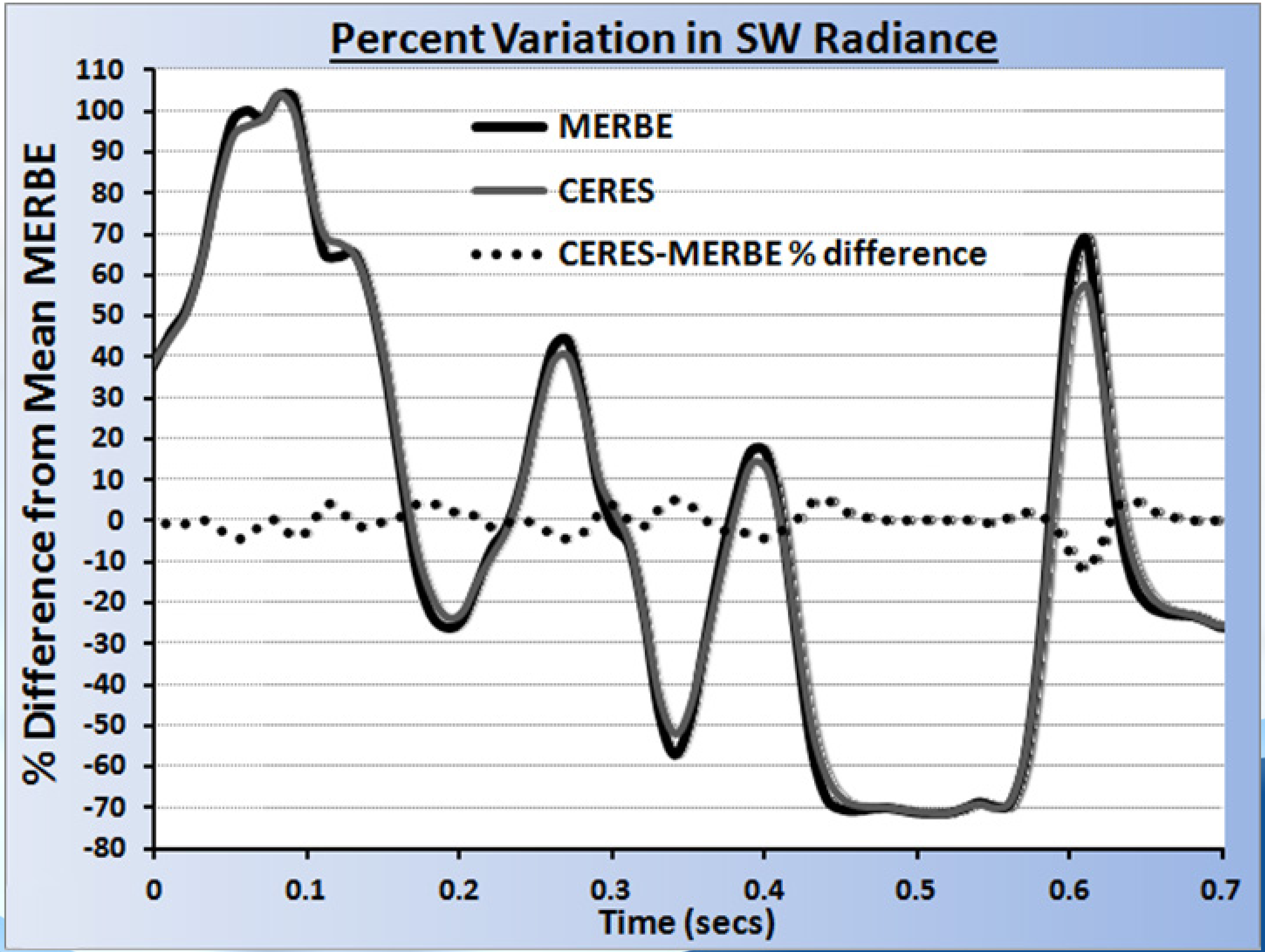
A=0.13166
E=0.97271
T_l=365.498K

Non-Linear Fourier Series Offset Correction

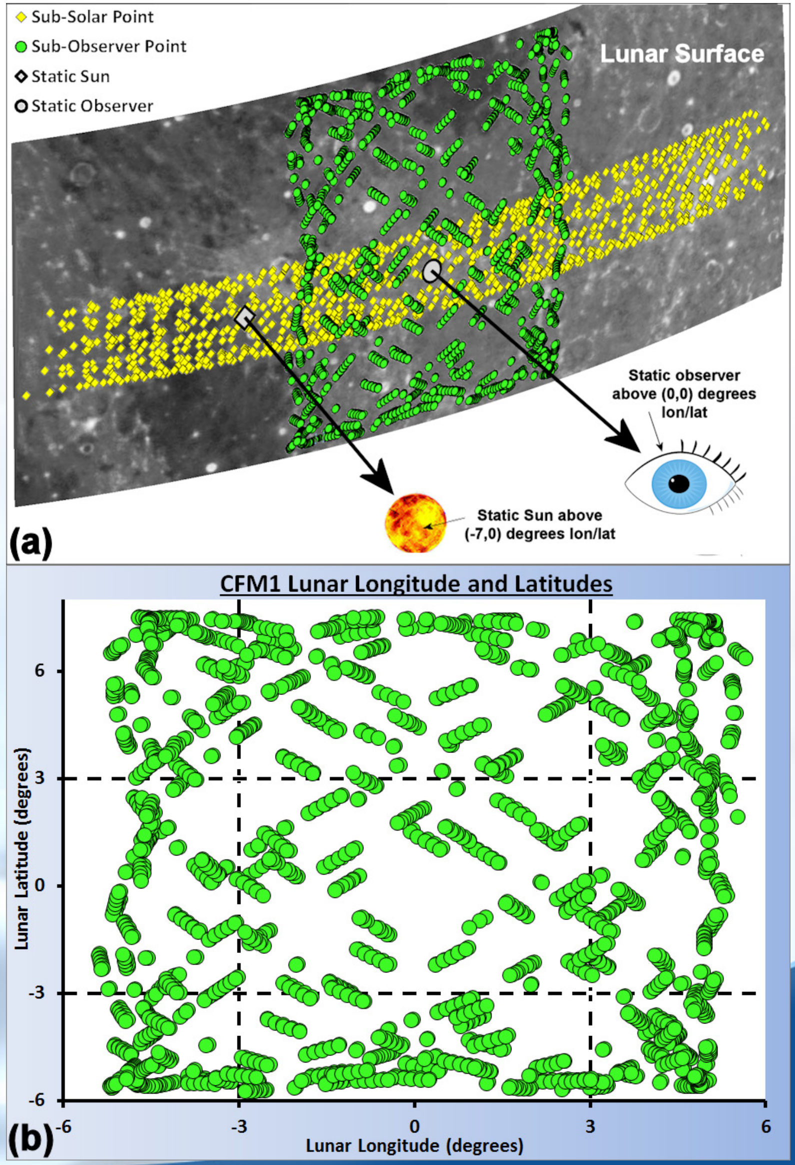




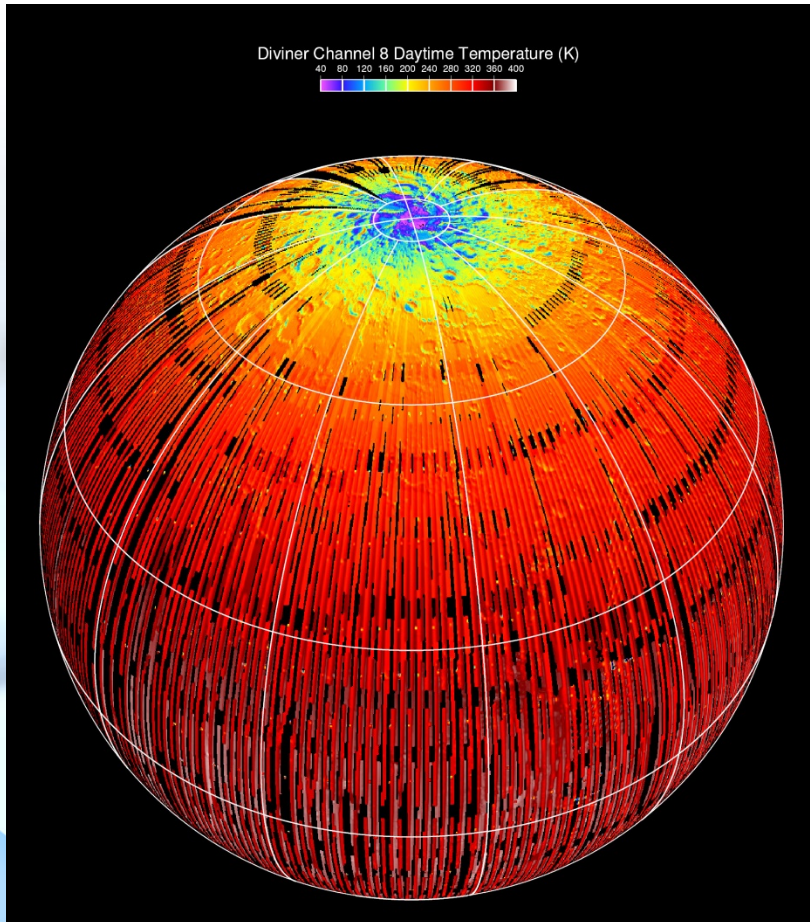
MERBE IE corrects Instantaneous CERES errors of > 10%



MERBE LW Lunar Model



At 7 degrees phase the Lunar LW filtering factor is sensitive to the surface temperature gradients at the 0.07% level so thermal spectrum generation uses Diviner maps



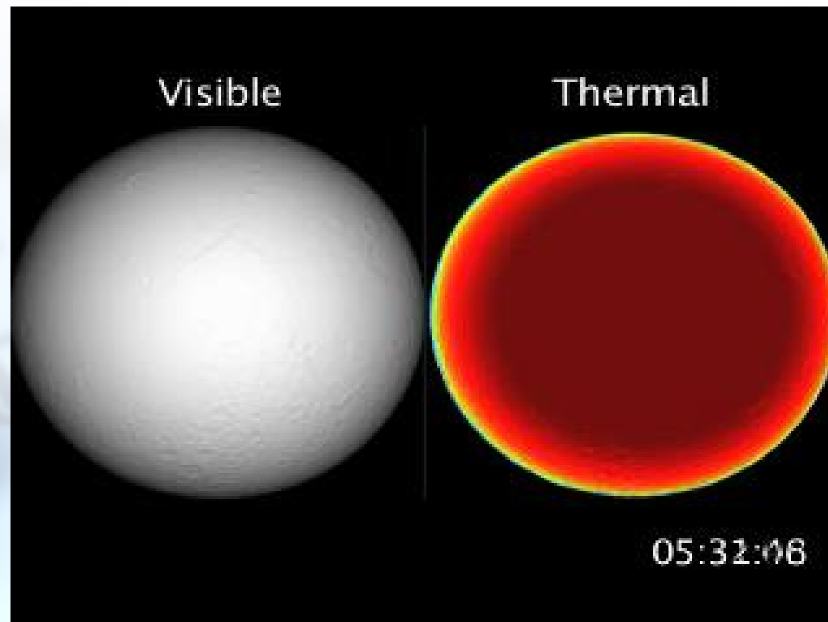
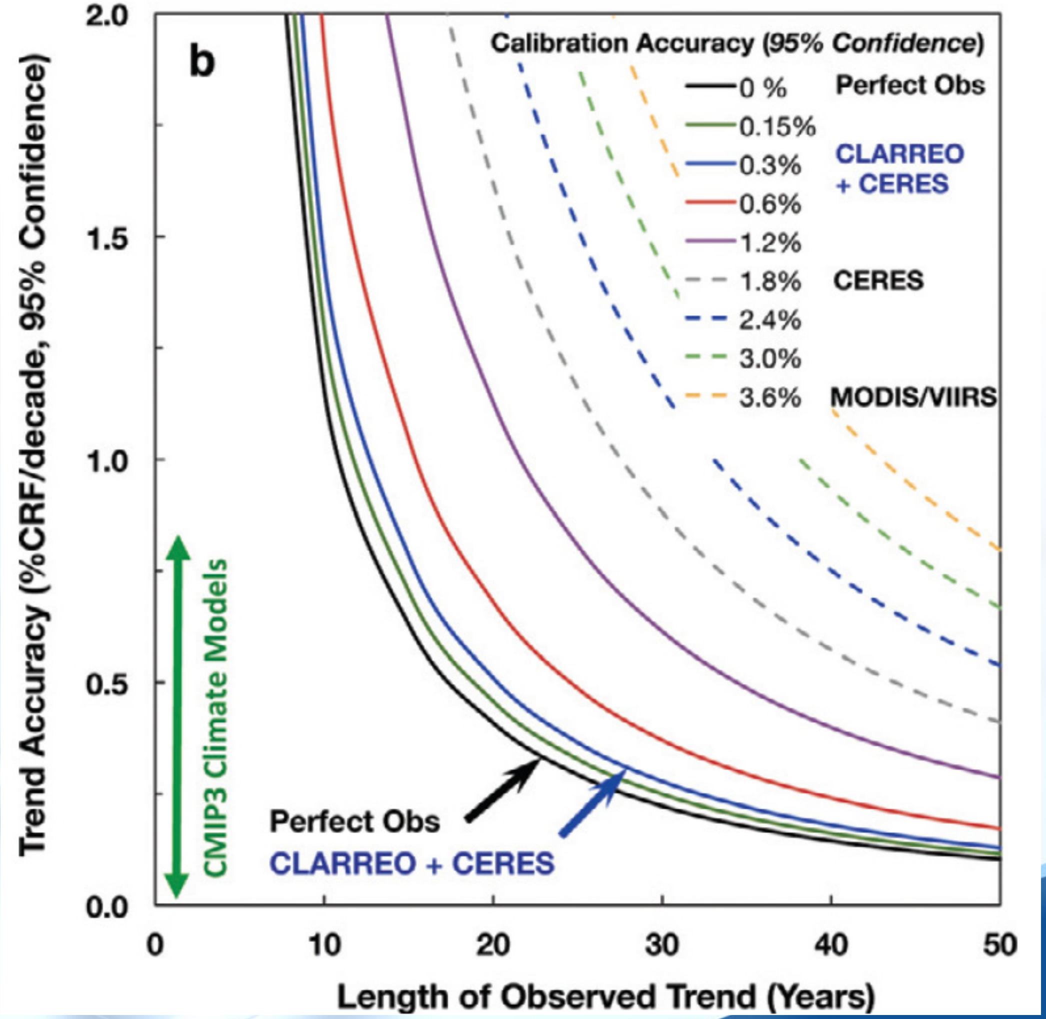


Fig. 3b from Wielicki et al (2013)



CERES Ed2 on Terra measures all Tropical LW greater at night than day due to un-balanced SW/Total Solar response

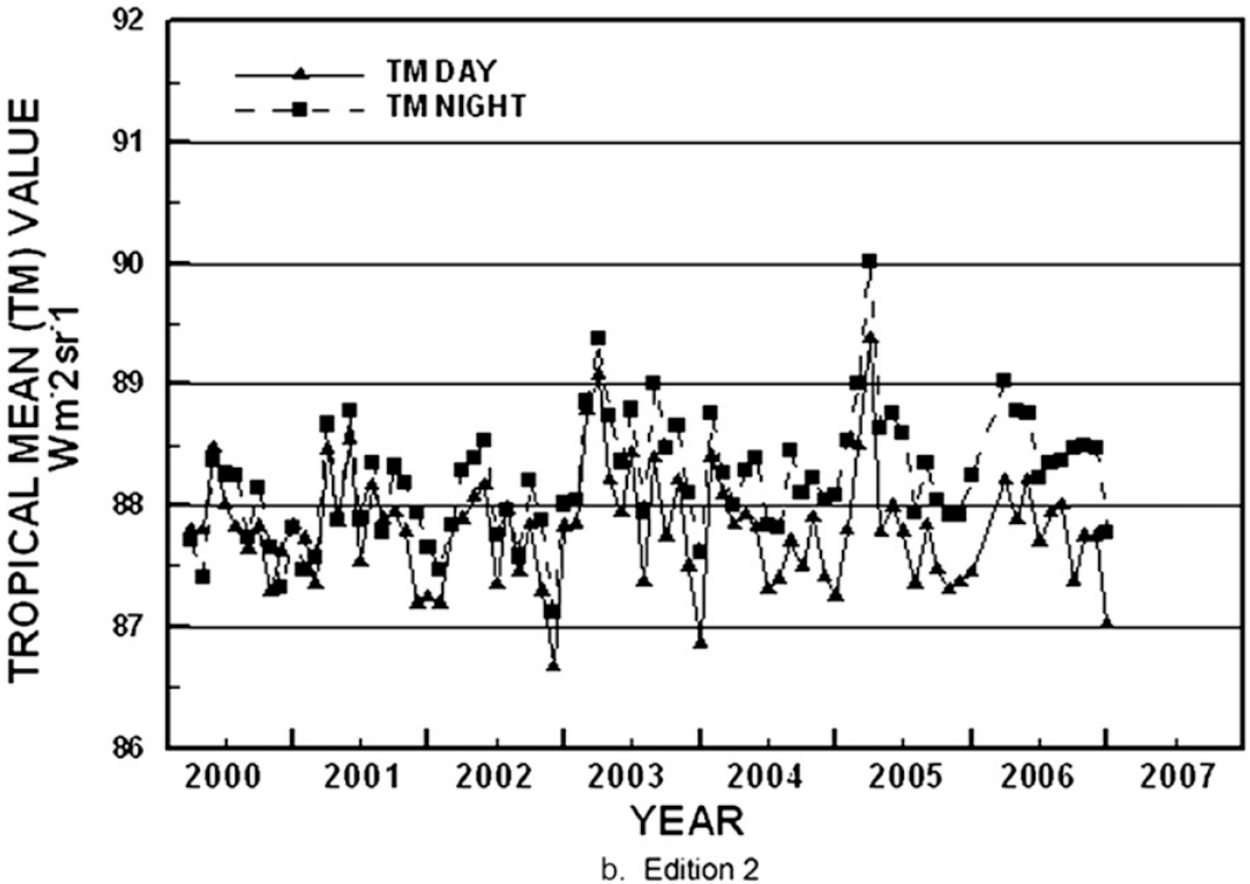
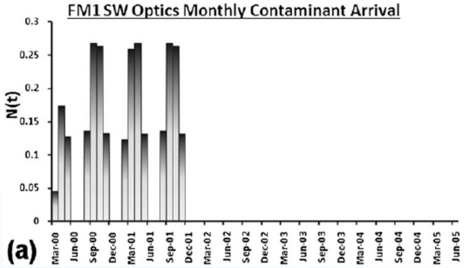
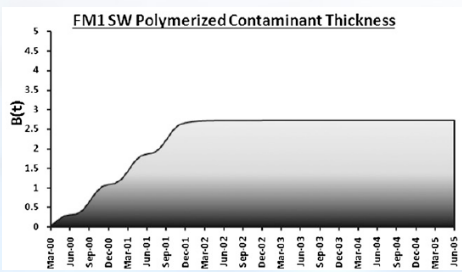


FIG. 11. Tropical mean longwave radiance at nadir for FM-1 during day and night from March 2000 through March 2007 for editions (a) 1 and (b) 2.

Matthews 2009 details spectral response changes from contaminants





$$\frac{\partial B(t)}{\partial t} = \rho\left[\int_0^t N(\xi)\,d\xi - B(t)\right] + \beta N(t).$$

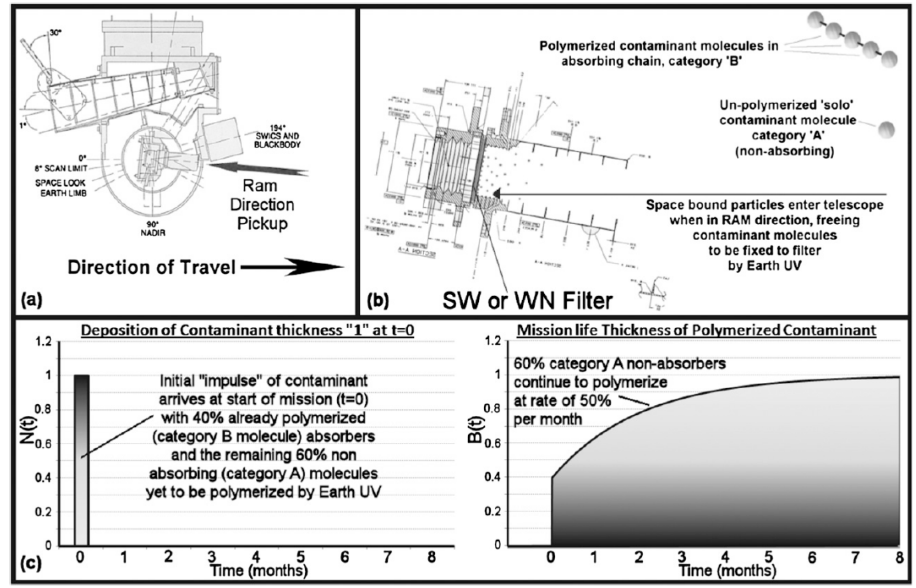
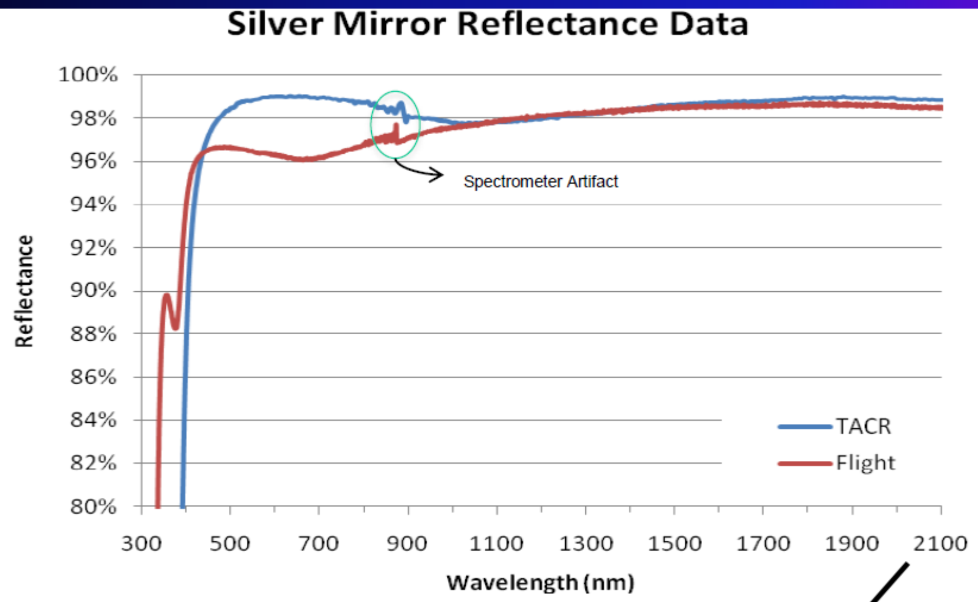


FIG. 5. (a) Diagram of CERES telescope ram exposure during RAPS mode. (b) Space-bound particle mobilization of category A and B contaminant molecules to filtering optics within telescope during ram exposure. (c) Example (left) impulse and (right) impulse response of polymerized contaminant thickness in event of one-time deposition of category A and B molecules at mission start.

CALCON 2014 slide: Enhancing the Ground Calibration in the Short-wavelength Region to Improve Traceability within the Reflected Solar Bands of the CERES Instrument

TACR Limitations

Clouds and the Earth's Radiant Energy System



- Legacy TACR mirror spectral reflectance differ from the flight mirrors which adds higher than desirable uncertainty in the shortwave
- The roll off in the short wavelength region introduces a source of error and reduces the signal-to-noise ratio in the TACR
- Measurements of Legacy inferred by **witness samples** rather than true spectral response of the telescope