First Lunar Results from the Moon & Earth Radiation Budget Experiment (MERBE)

Grant Matthews

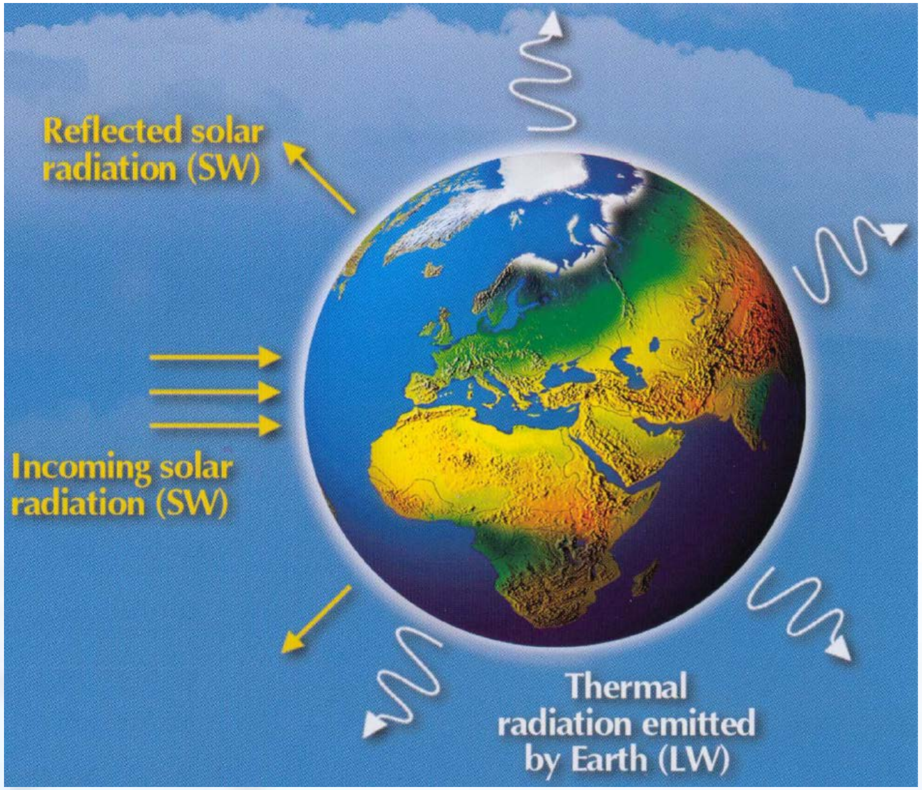
Accelerating certainty in climate change prediction

GSICS Lunar cal meeting
6th Dec 2016

Overview

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

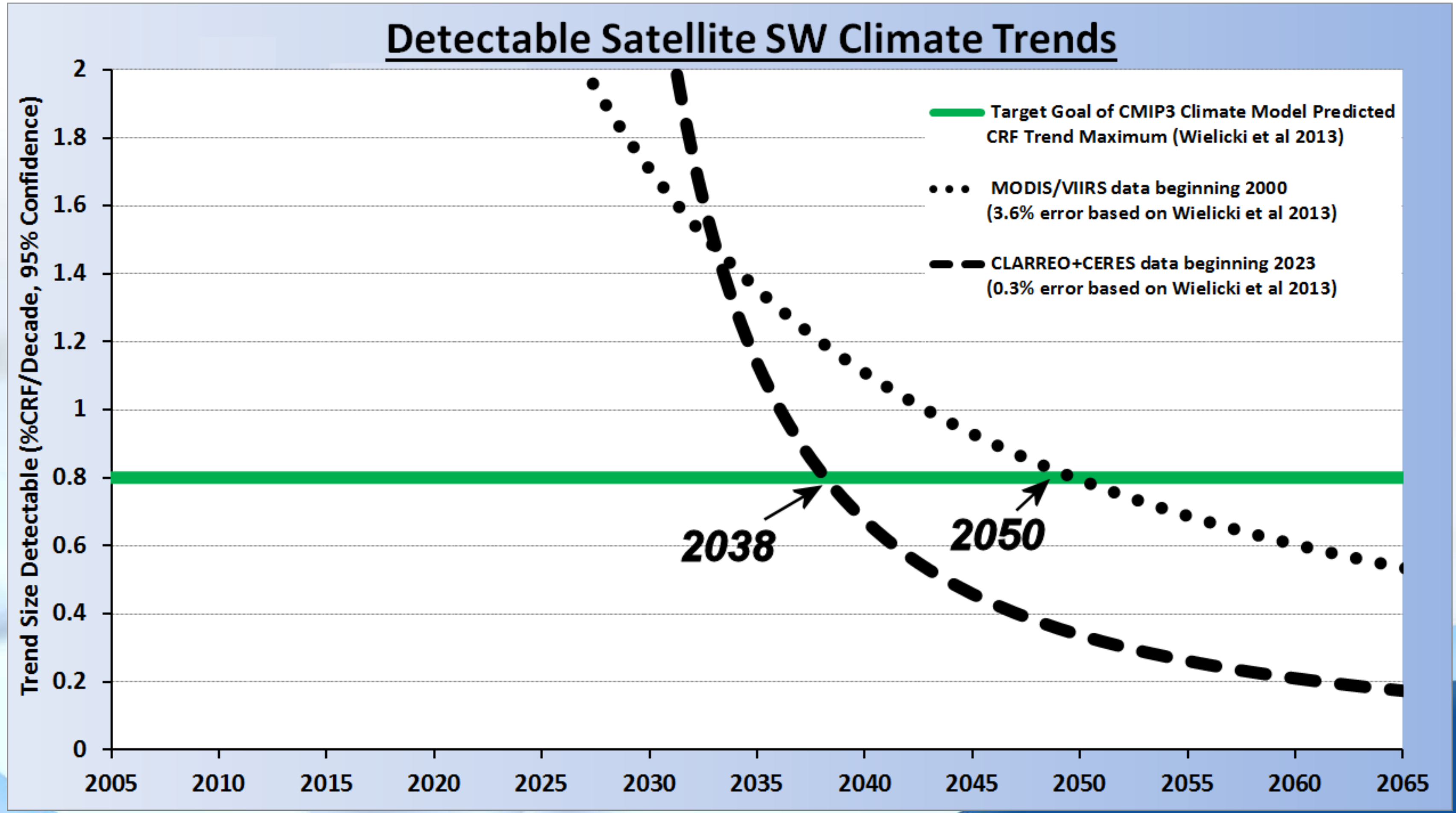
Earth's weather/climate system is the work done by a global heat engine driven by the Earth Radiation Budget (ERB – SW & LW), which must be measured from space to constrain and validate climate models



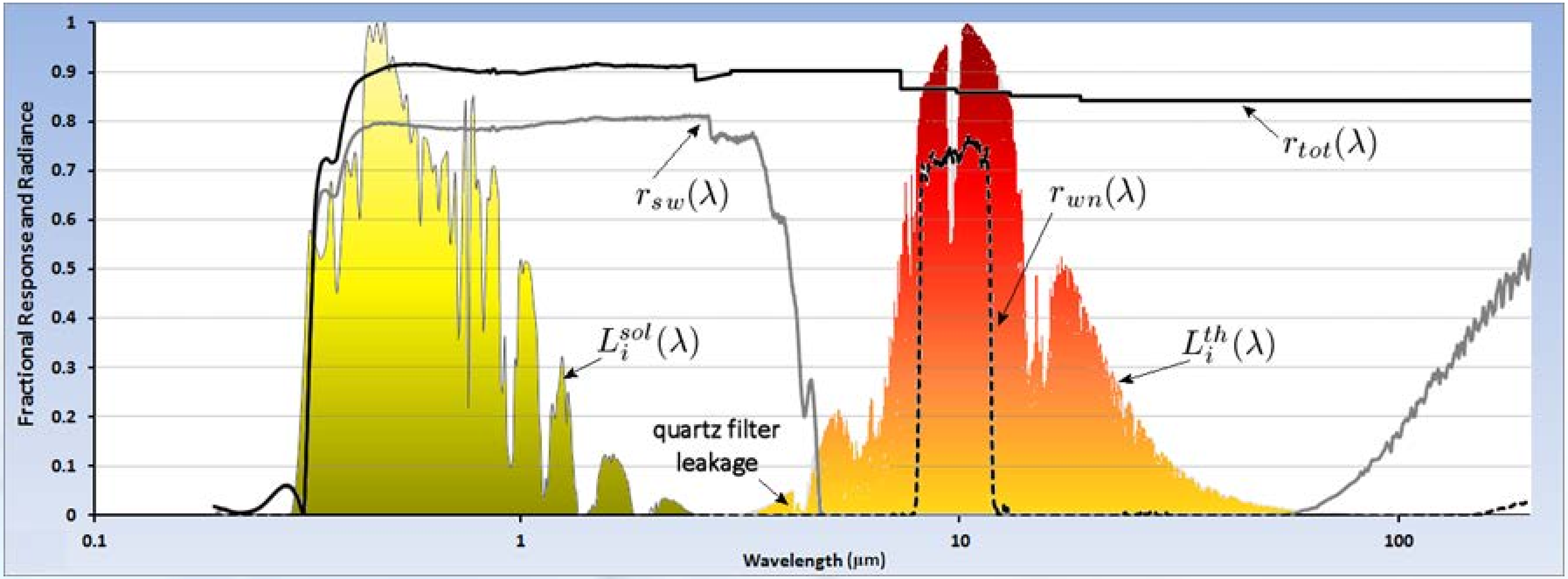
"*The single most critical issue for current climate change observations was their lack of accuracy and low confidence in observing the small climate change signals over long decade time scales*" **NRC 2007 decadal survey**

ERB Fig by H. E. Brindley

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



Earth Radiation Budget Short & Long Wave



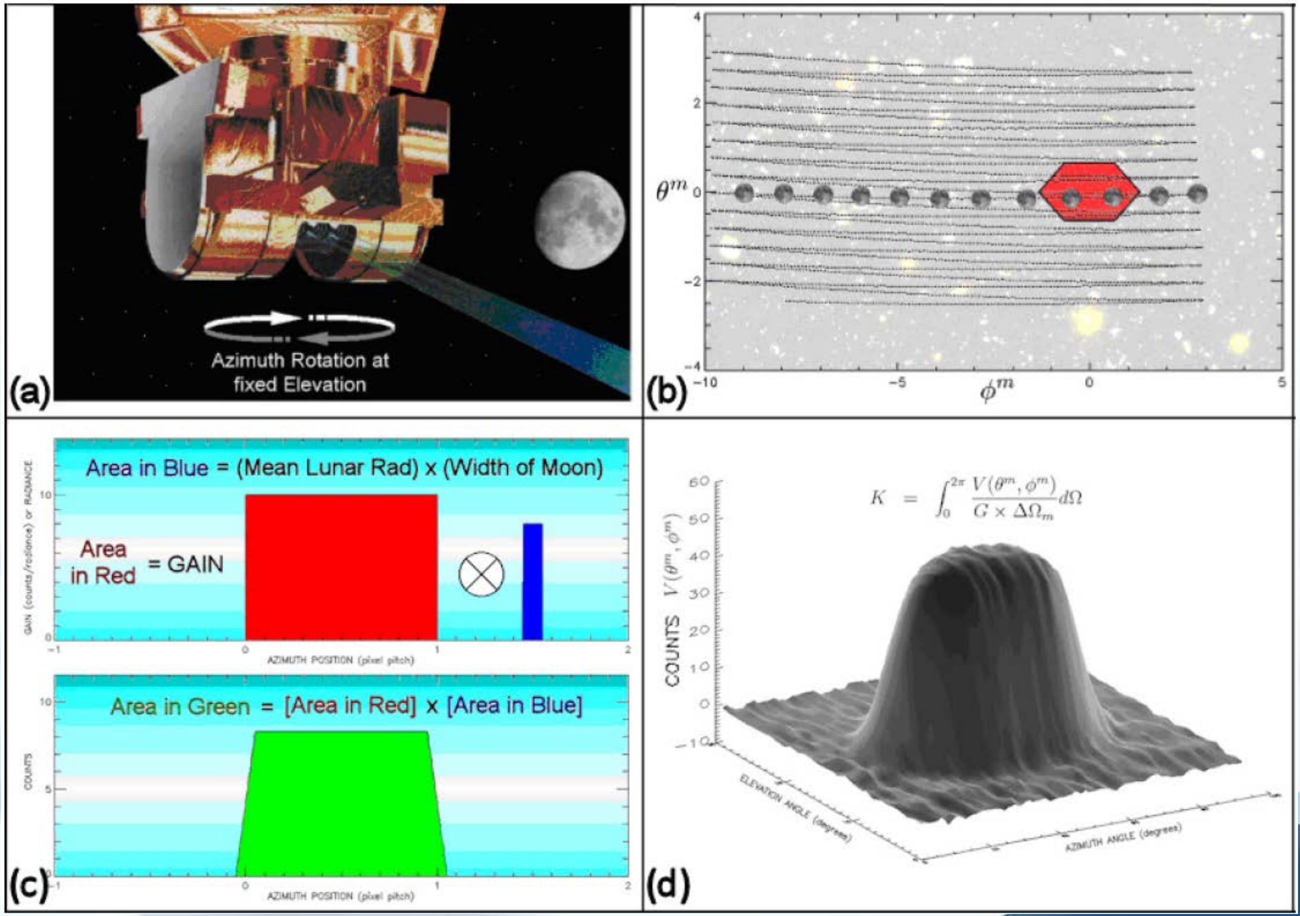
SW or Reflected Solar (0<λ<5μm)
LW or Thermal Infra Red (5<λ<200μm)

SeaWIFS is the one device to have 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.

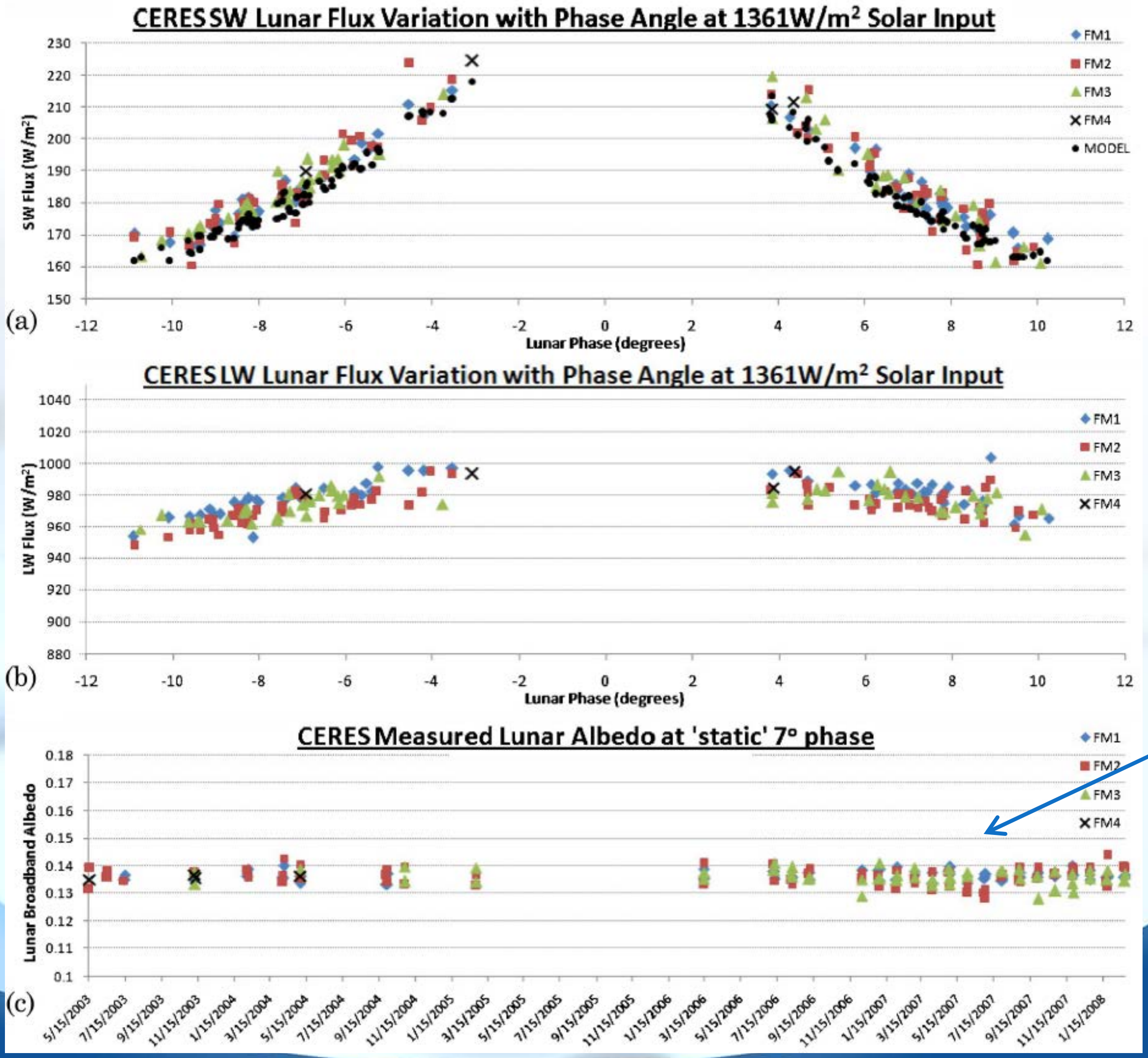
ERB Mission	Lifetime
NIMBUS 7 ERB[27]	1978-1993
ERBE [28]	1984-2005
CERES[6]	1998-Present
GERB[29]	2002-Present
DSCOVR(NISTAR) [32]	2015-Present
RBI[34]	2021-?
CLARREO[8]	2023-?
TRUTHS[5]	?-?

Led to the Concept of the Moon and Earth Radiation Budget Experiment (MERBE), building on Matthews 2008 and the 1000's of lunar scans already made but currently un-used by ERB devices such as CERES



Matthews 2008: Celestial body irradiance determination from an underfilled satellite radiometer: application to albedo and thermal emission measurements of the Moon using CERES, Appl. Opt. 47(27), 4981-4993

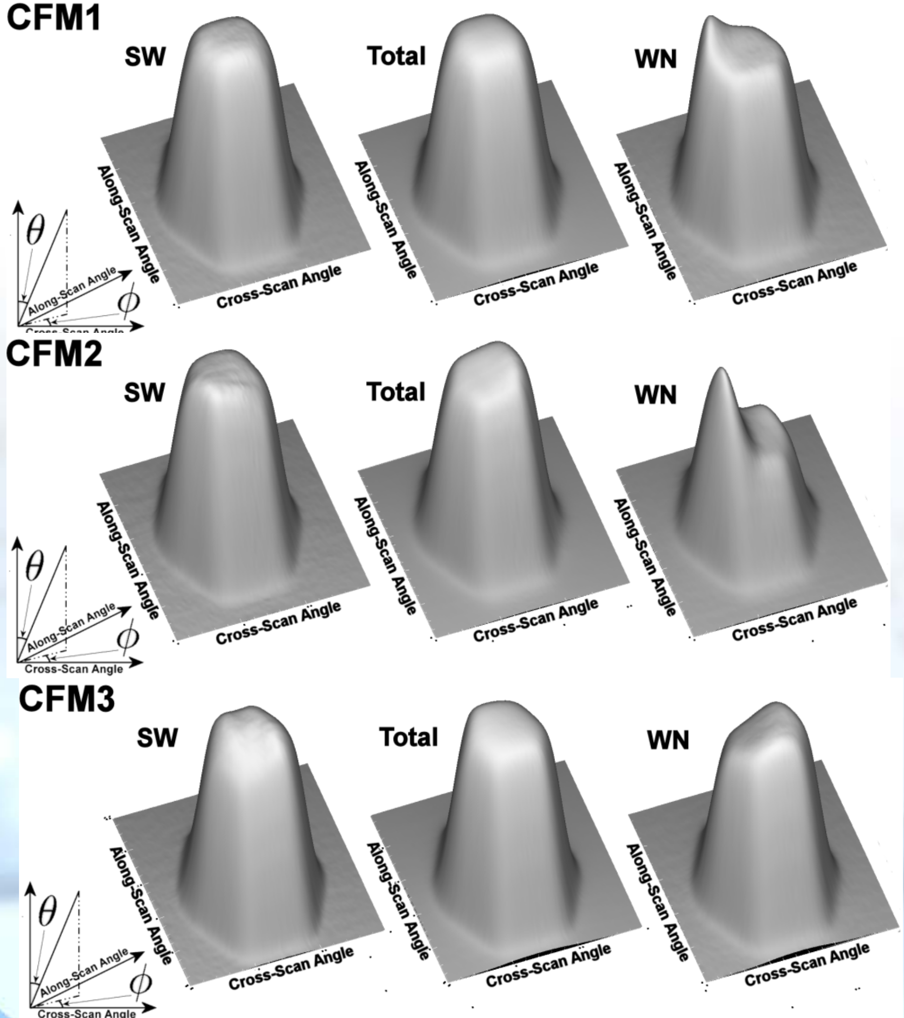
But the Matthews 2008 technique produced only one lunar result per day and the numerical integral accuracy suffered in the case of sparse coverage for CERES Flight Models (CFM) 1-3 on Terra & Aqua

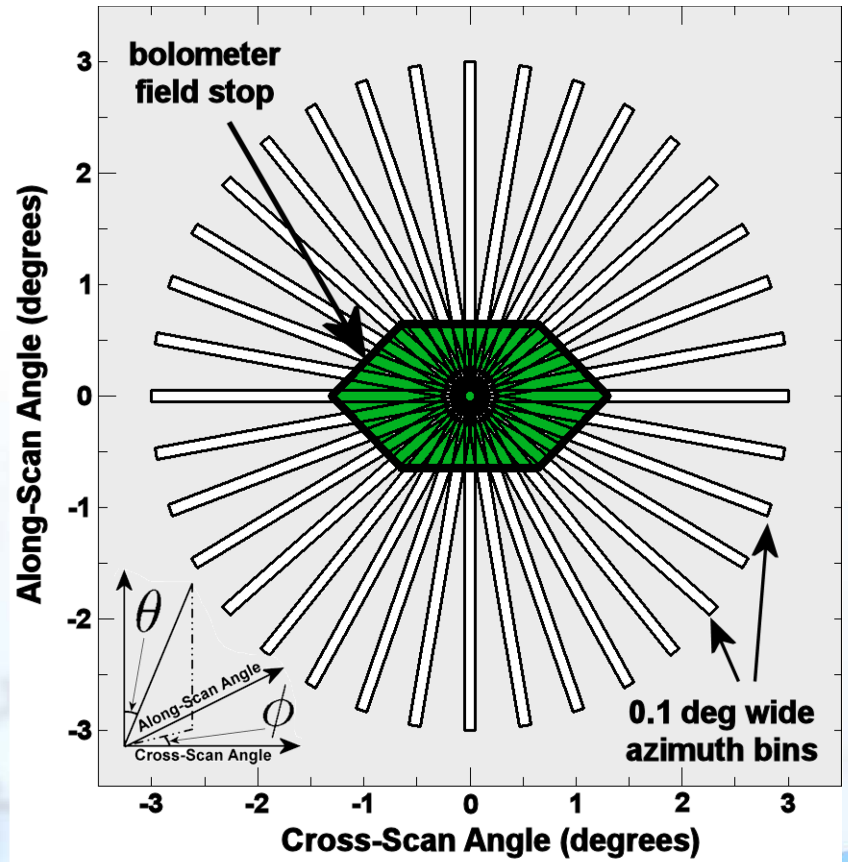


Matthews 2008: Celestial body irradiance determination from an underfilled satellite radiometer: application to albedo and thermal emission measurements of the Moon using CERES, Appl. Opt. 47(27), 4981-4993

Lunar Albedo results had a noise of around 2%

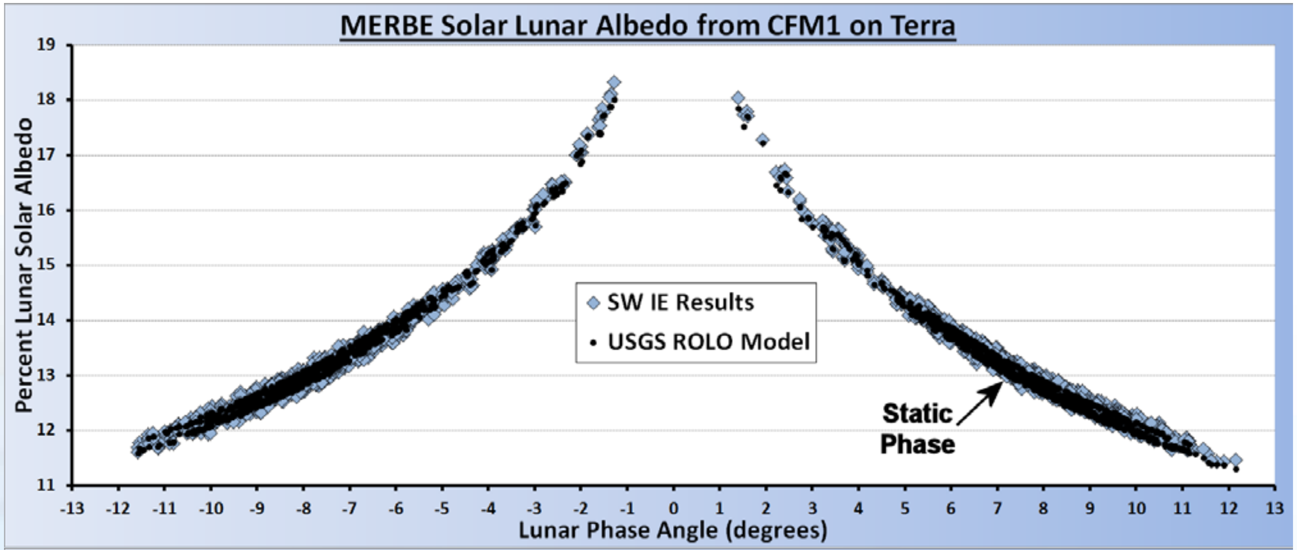
So instead each MERBE device Moon Field of View is now precisely mapped

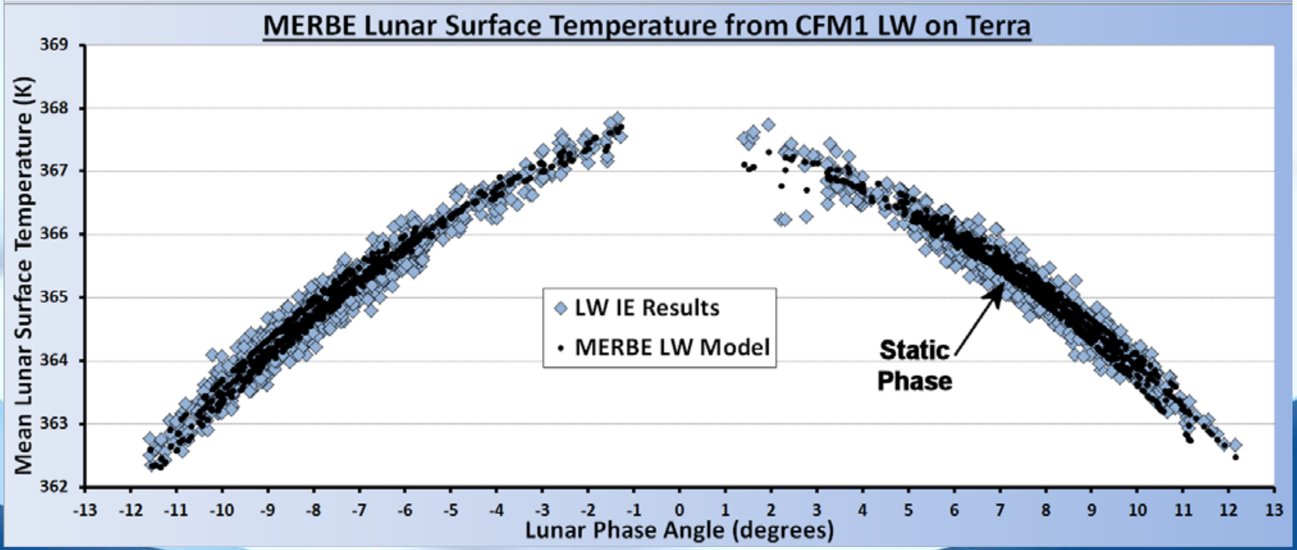




Mere `lunar glances' can be regressed against such maps, increasing the number of Moon measurements by an order of magnitude from Matthews 2008

This allows thousands of independent lunar radiance retrievals to be made since 2002 and a factor of three reduction in noise

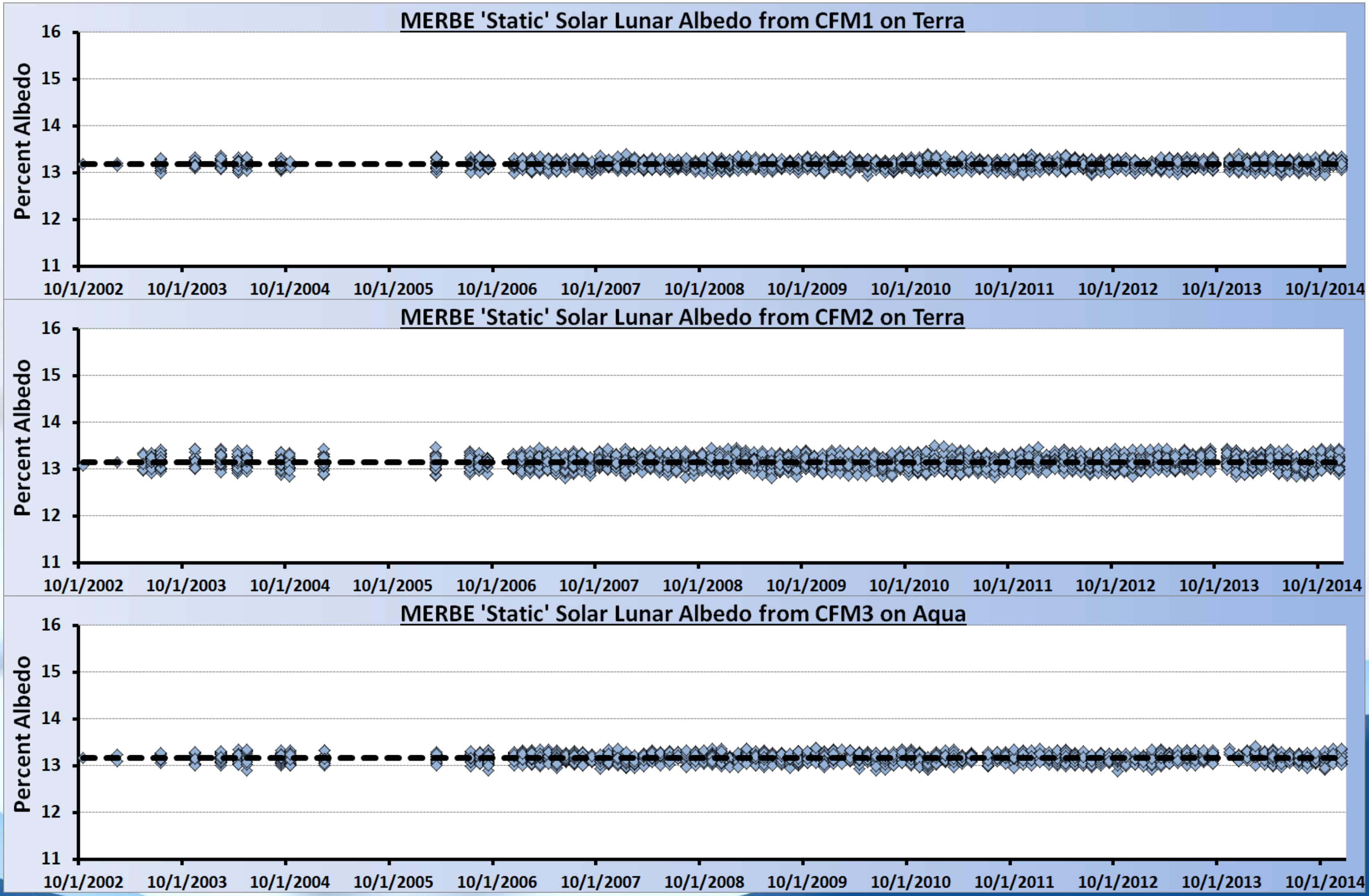




All instruments must measure same lunar reflectivity of **13.166%** & temperature/emissivity of **365.498K/0.97271** at +7^{o} static phase angle (see below)

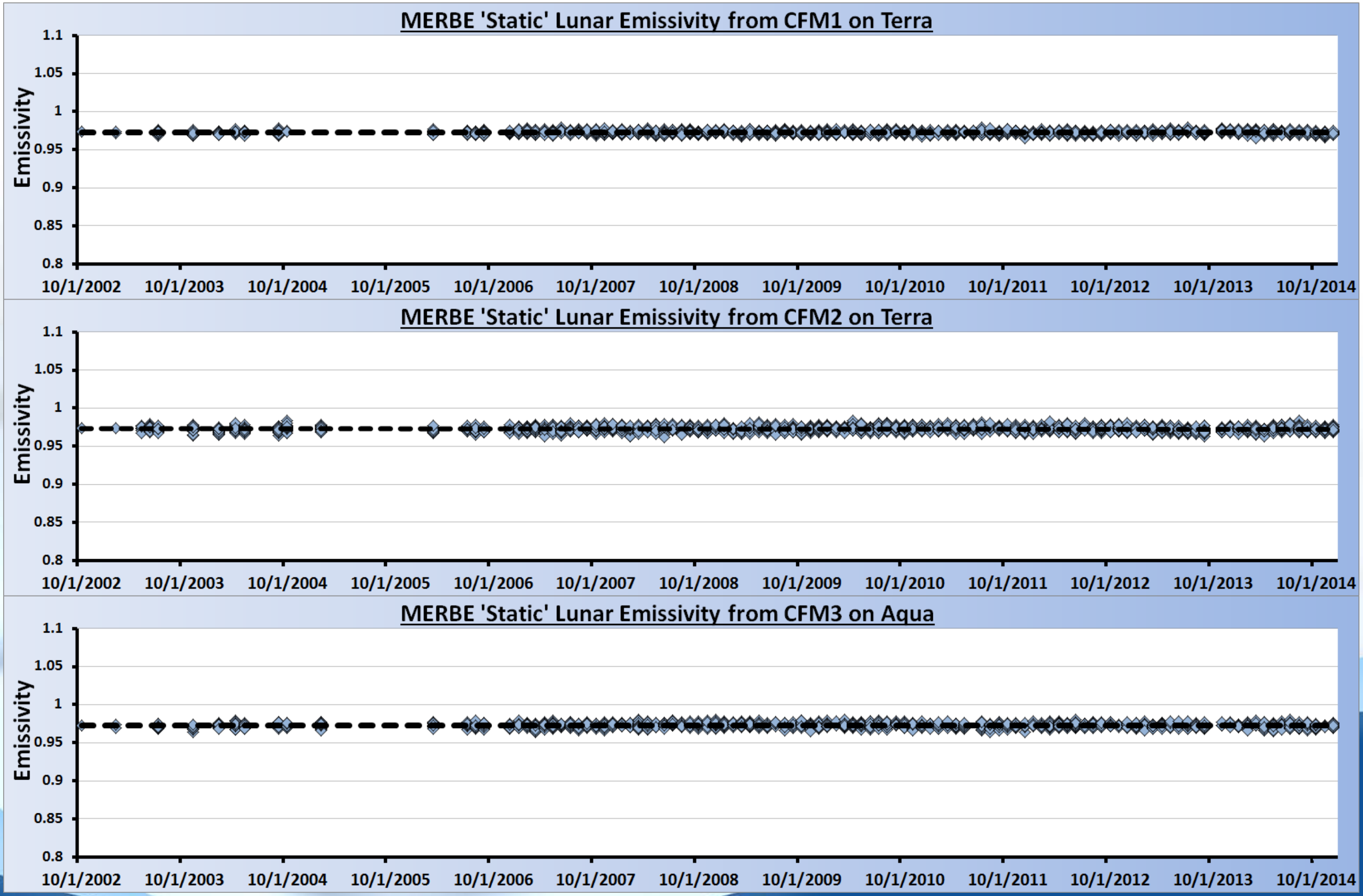
Preliminary Results Shown

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



Preliminary Results Shown

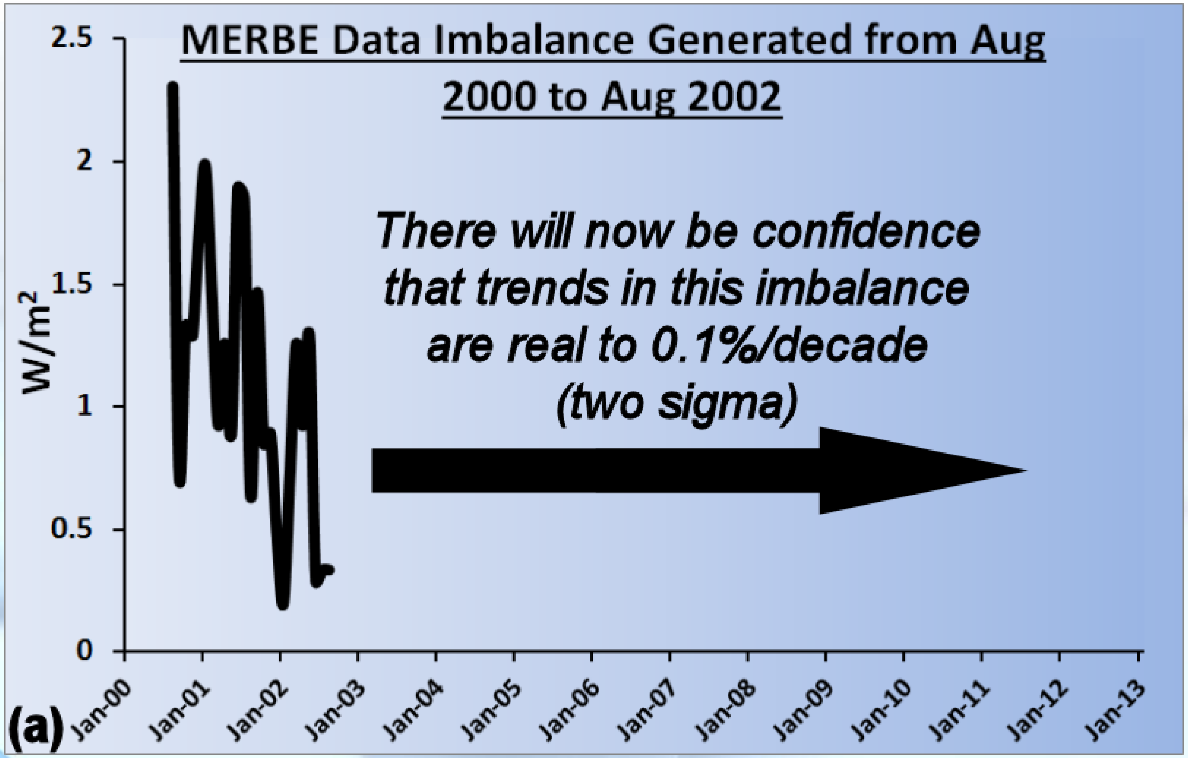
Lunar Emissivity Trends are Removed with < 0.01K $decade^{-1}$ confidence (one sigma)



Preliminary Results Shown

Why a Lunar Emissivity of 97.271% (364.498K) and Albedo of 13.166%?

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.

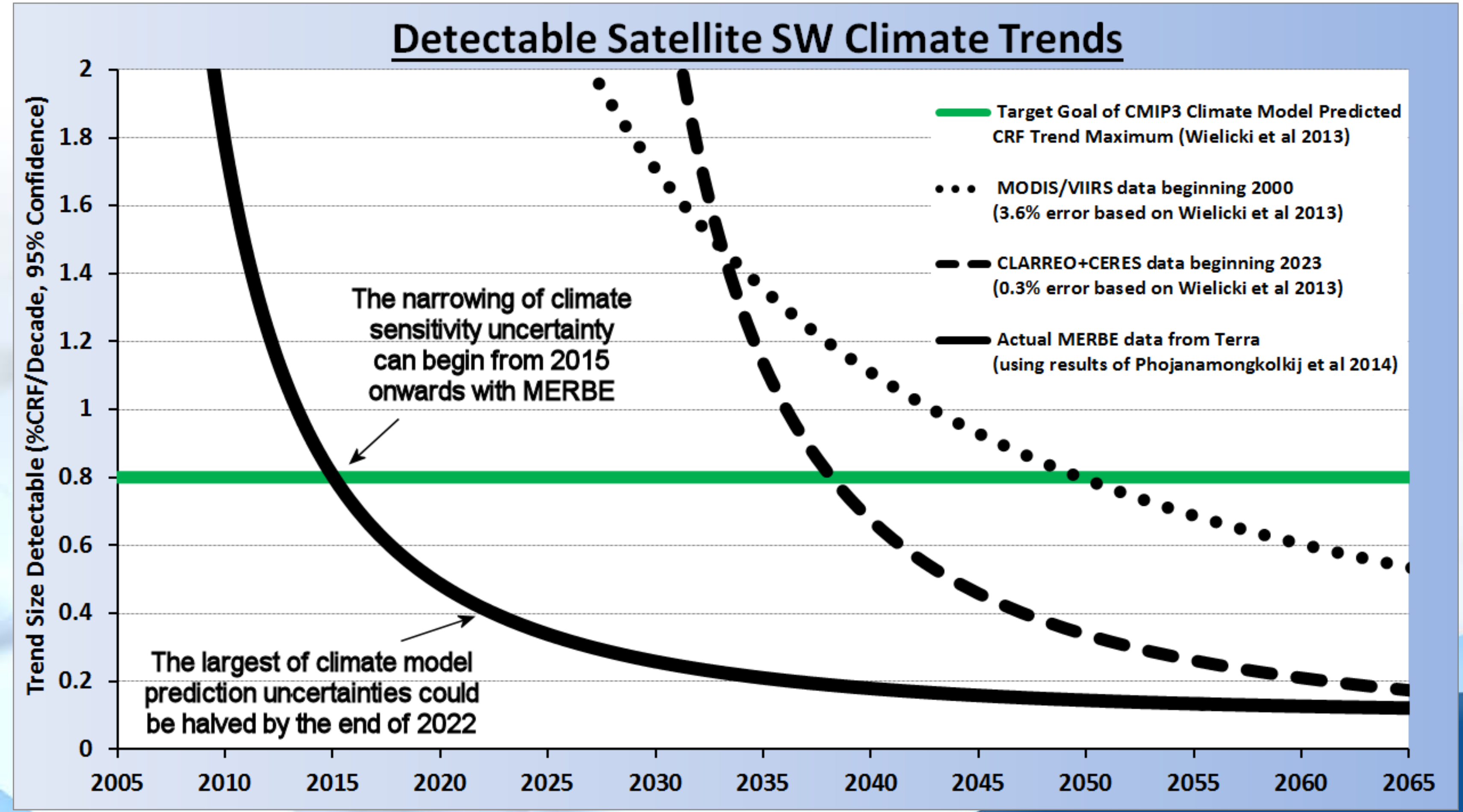


Thermal MERBE-Watt (lunar emissivity) chosen based on Terra LW Moon data.

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

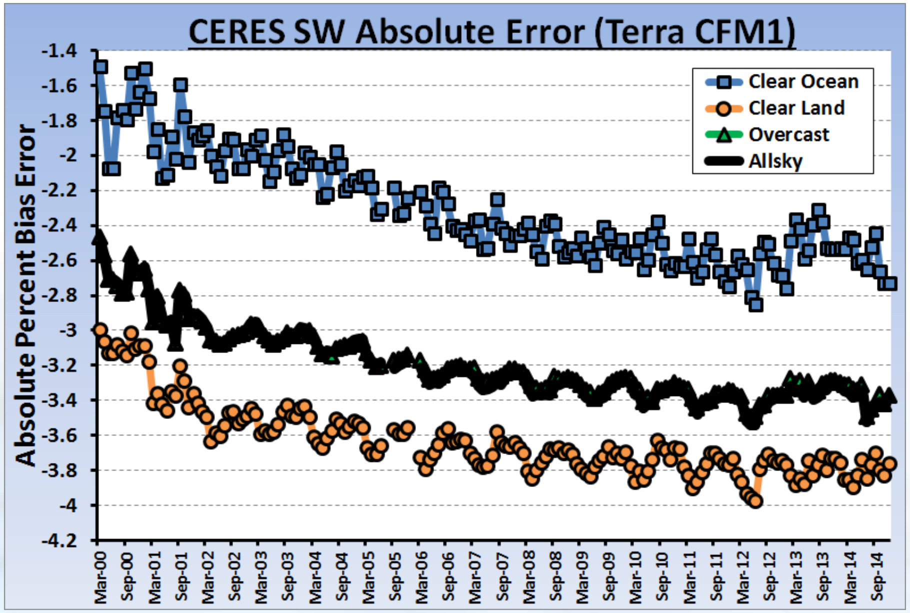
Preliminary Results Shown

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



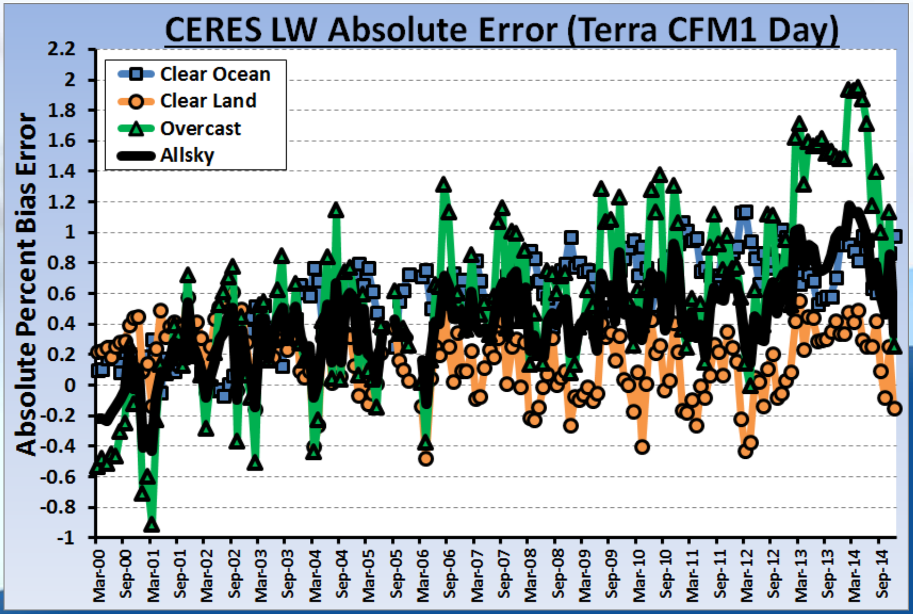
(using actual Terra Moon data shown 3 slides ago)

False Trends in CERES results for use today in GCM Validation



Primary CERES "climate device" on Terra has artificial negative Earth albedo bias sizes >2% and trends of -1% decade^{-1} (0.9% & max 0.2% decade^{-1} claimed respectively)

Primary CERES "climate device" on Terra has artificial positive Earth LW biases >1% and trends of +1% decade^{-1} (0.5% and max 0.15% decade^{-1} claimed respectively)



Preliminary Results Shown

Summary/Conclusions

- CERES ERB results available today for CRF trend detection and GCM validation are less accurate and far less stable or precise than the climate community is being told.

- MERBE has completely re-calibrated all US ERB measurements dating from the start of the century. 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 "climate observing system" already decades old, whose data will be provided free of charge to all. 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 2022.

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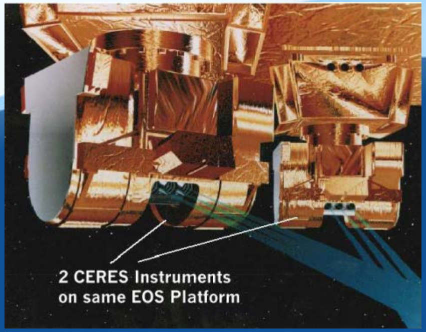
The Concept of the Moon and Earth Radiation Budget Experiment (MERBE) has simple Golden Rules

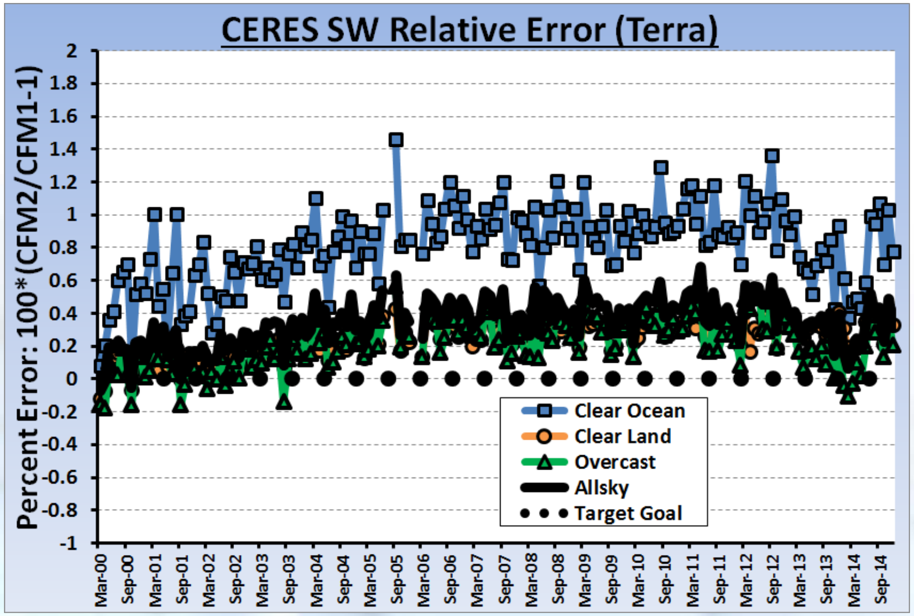
- 1. ***Different instruments viewing the same target must measure the same thing for all scenes***

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

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



Golden Rule 1 SW Earth Results: 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 quoted to the climate community (1 sigma)

Preliminary Results Shown

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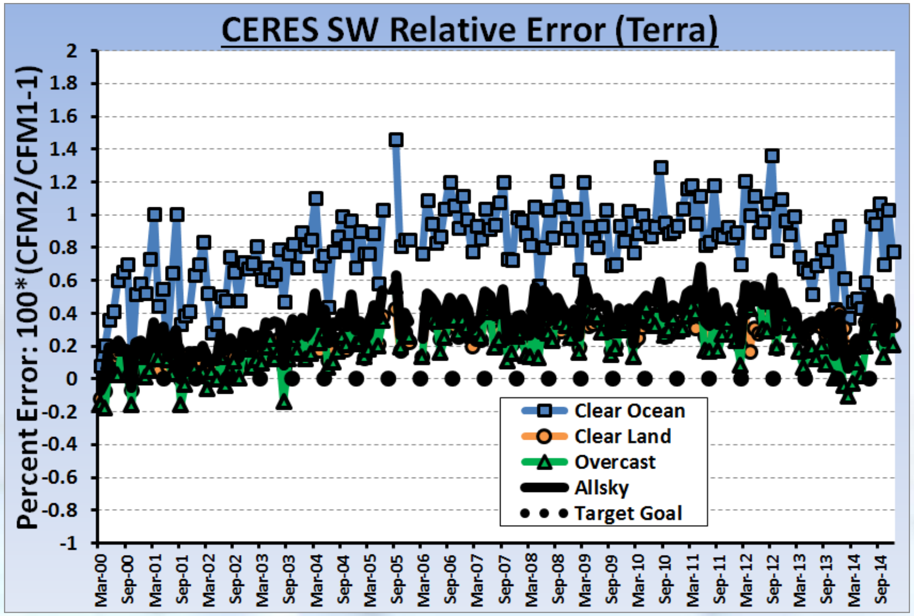

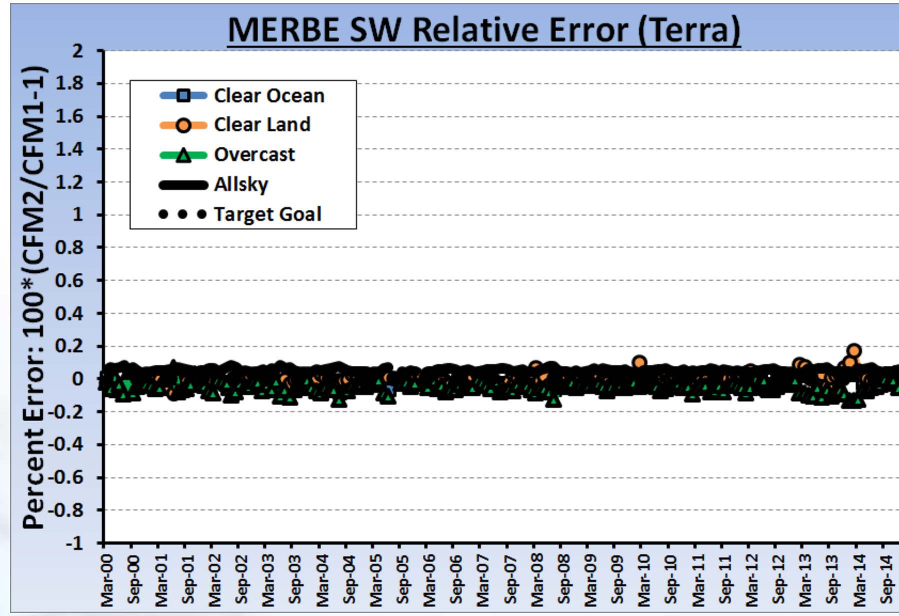

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Preliminary Results Shown

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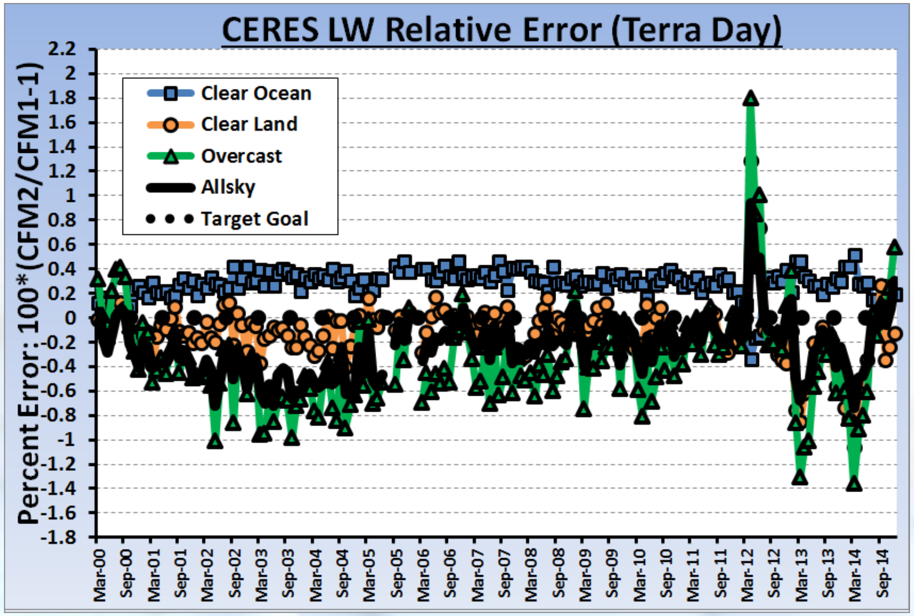

Using Loeb et al 2016: CERES Top-of-Atmosphere Earth Radiation Budget Climate Data Record: Accounting for in-Orbit Changes in Instrument Calibration, Remote Sens., 8(3), 182

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 quoted to the climate community (1 sigma)

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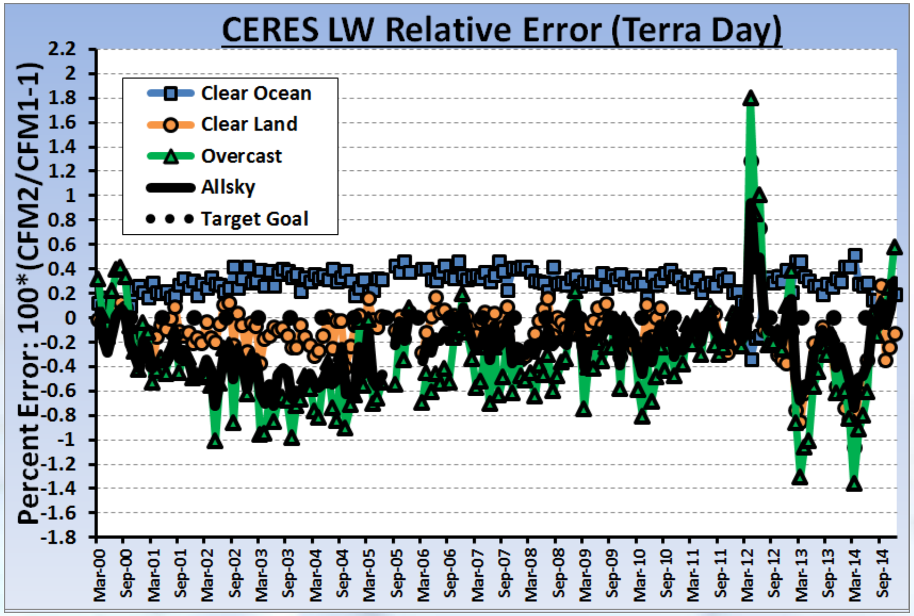

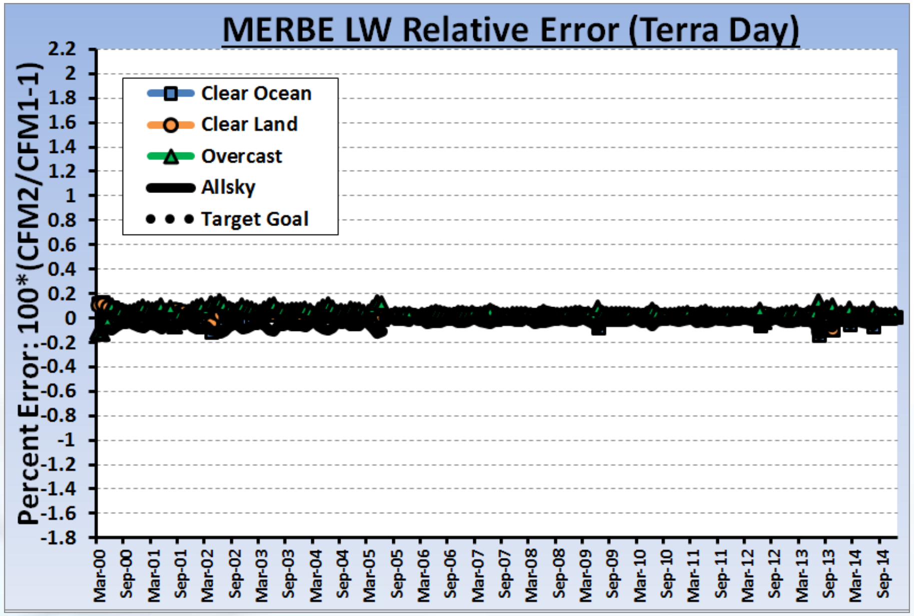

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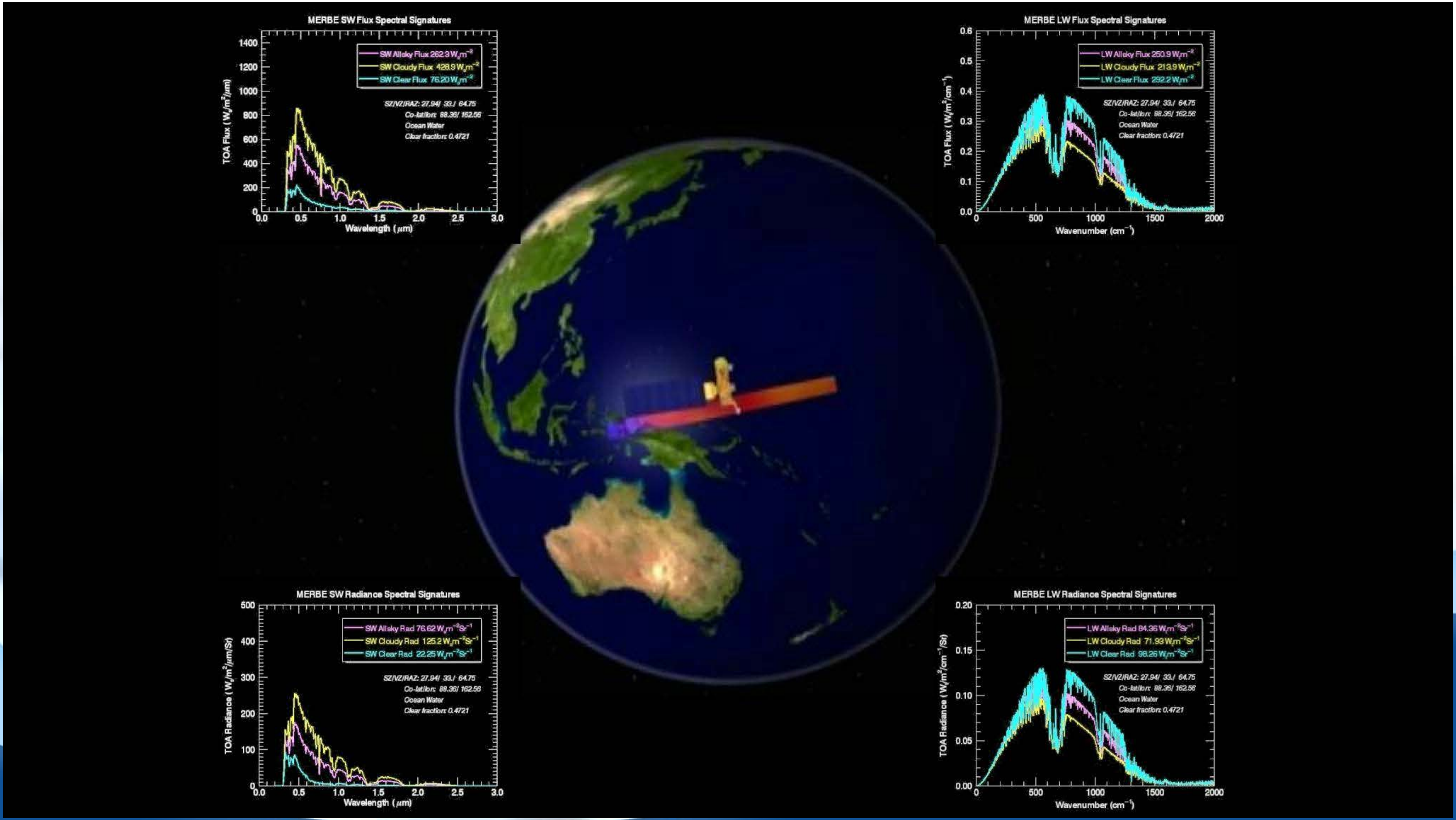
Preliminary Results Shown

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)



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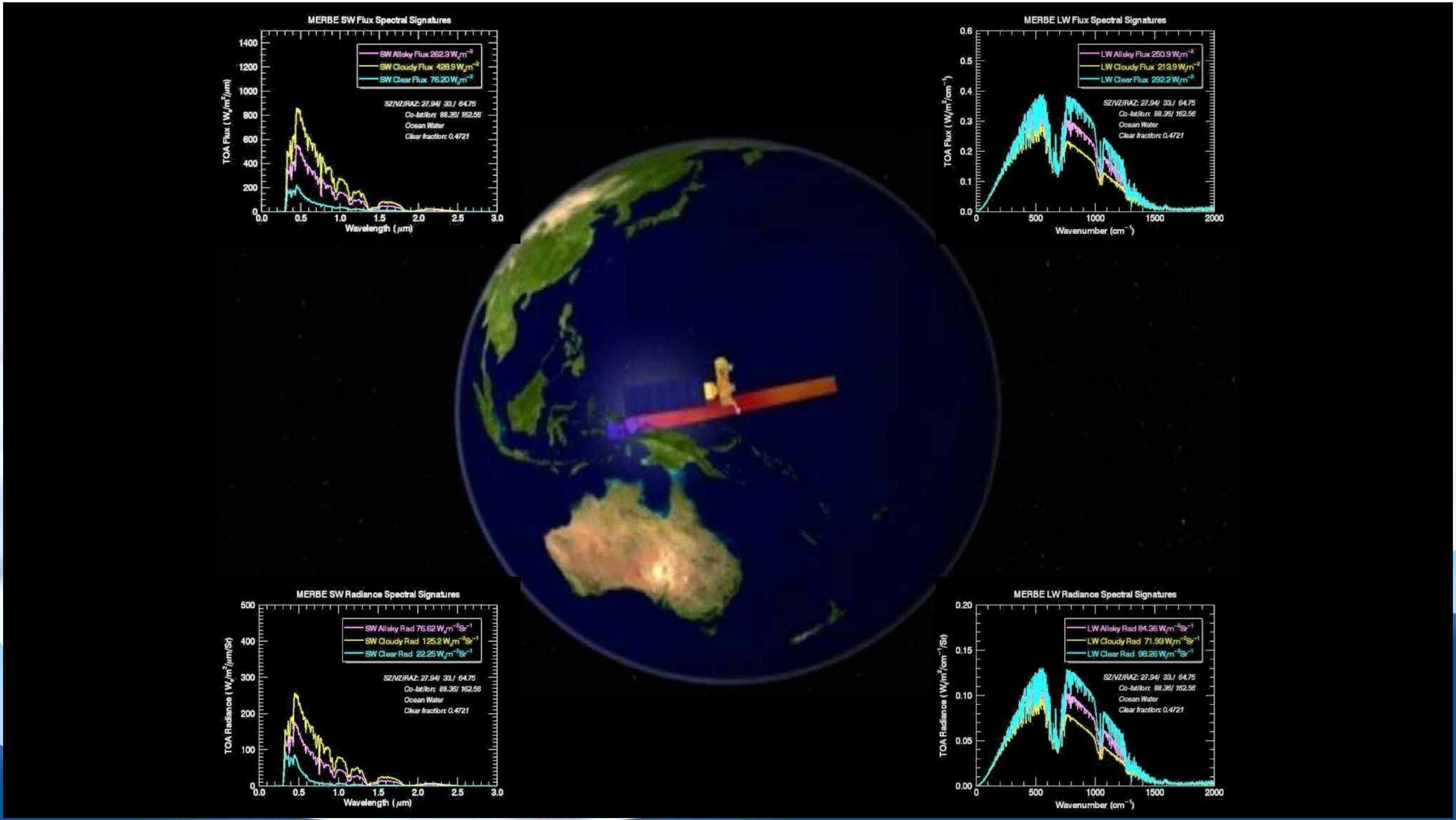
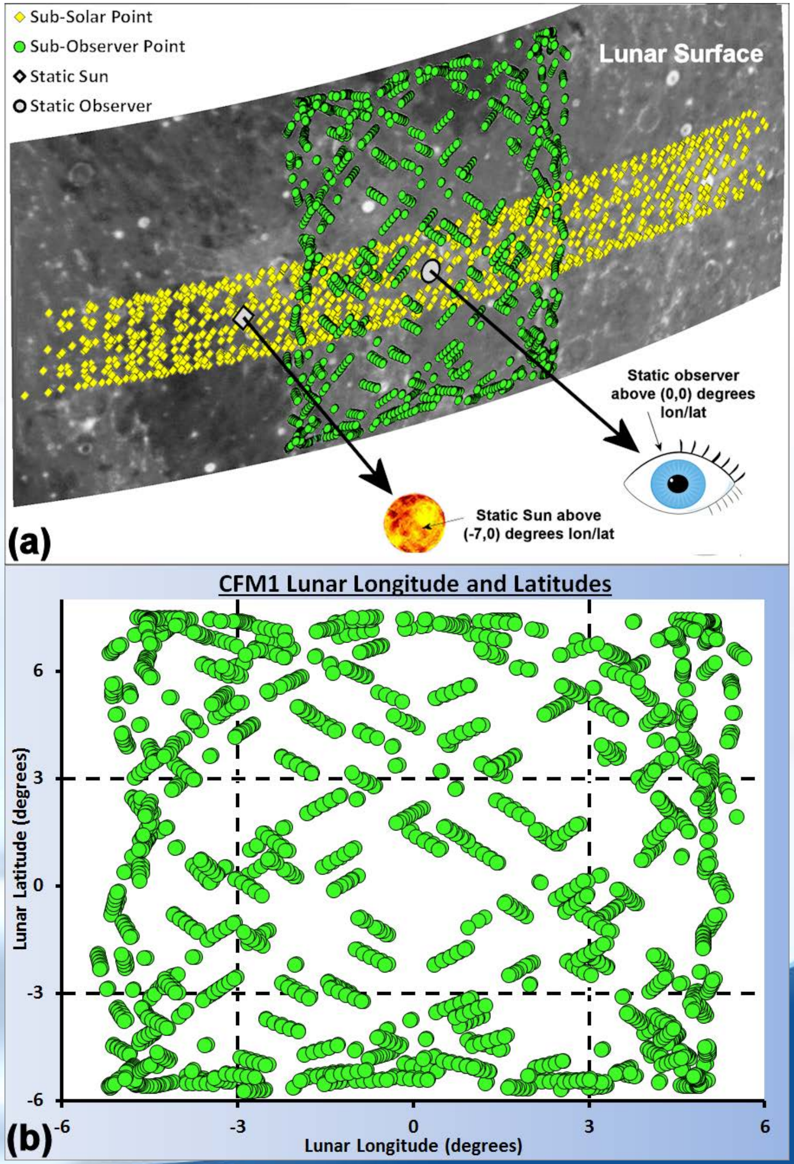
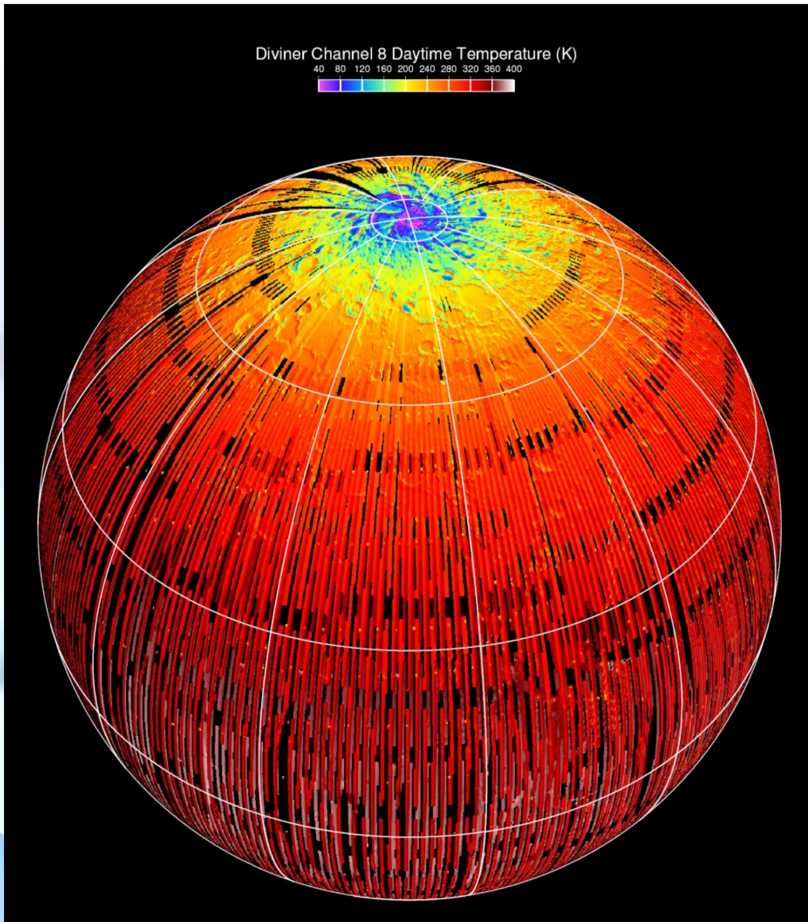
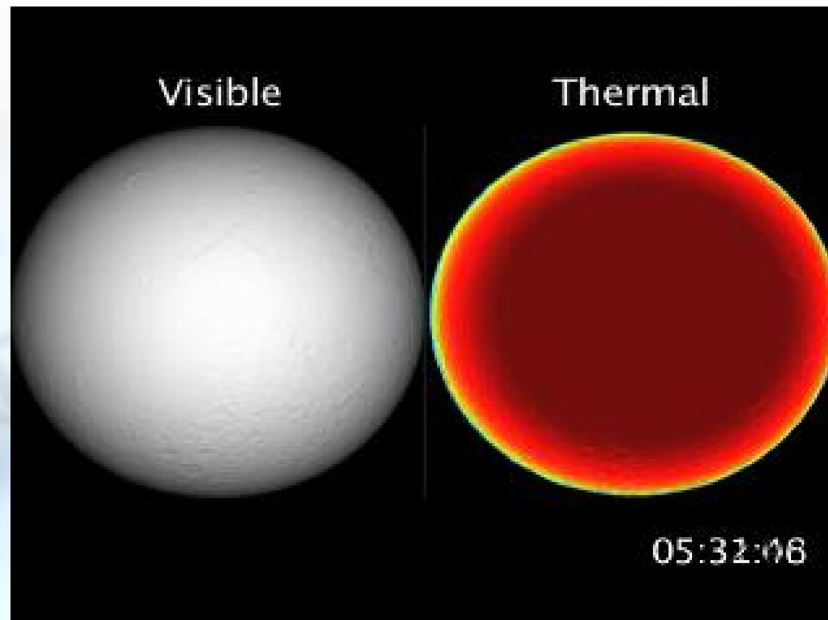


MERBE LW Lunar Model

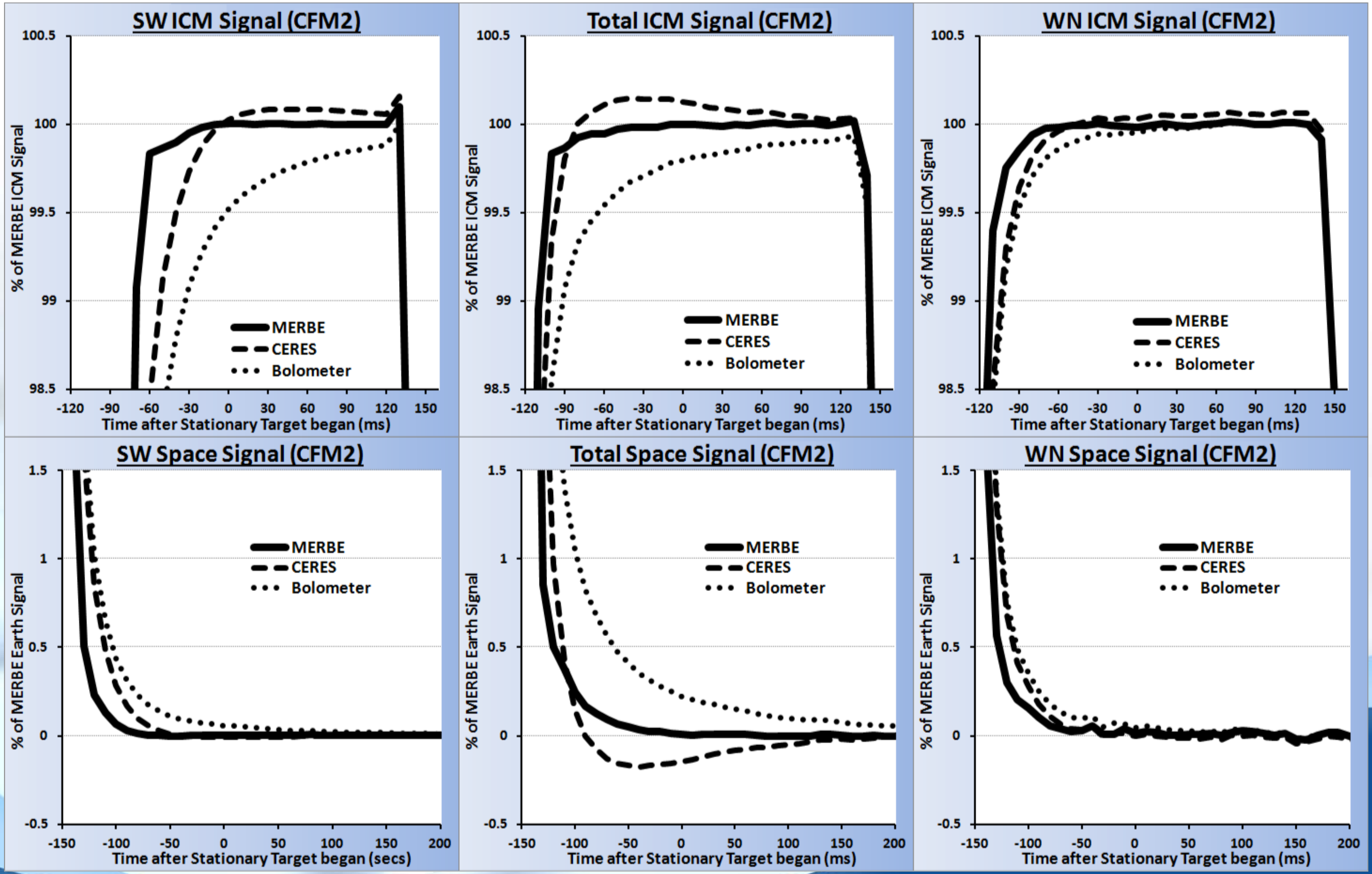


At 7 degrees phase the Lunar LW filtering factor is sensitive to the surface temperature gradients at the 0.1% level so thermal spectrum generation uses Diviner maps

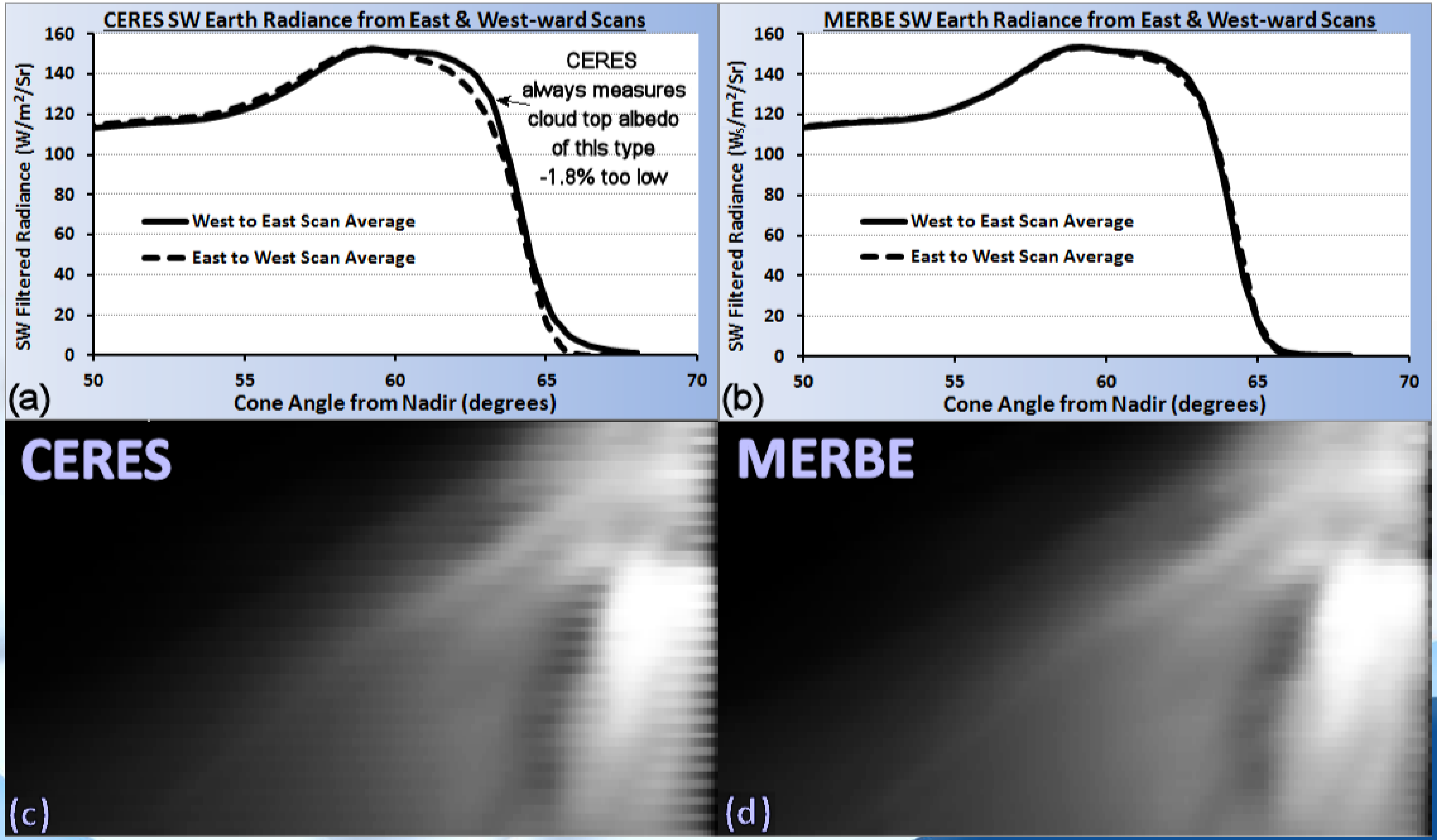




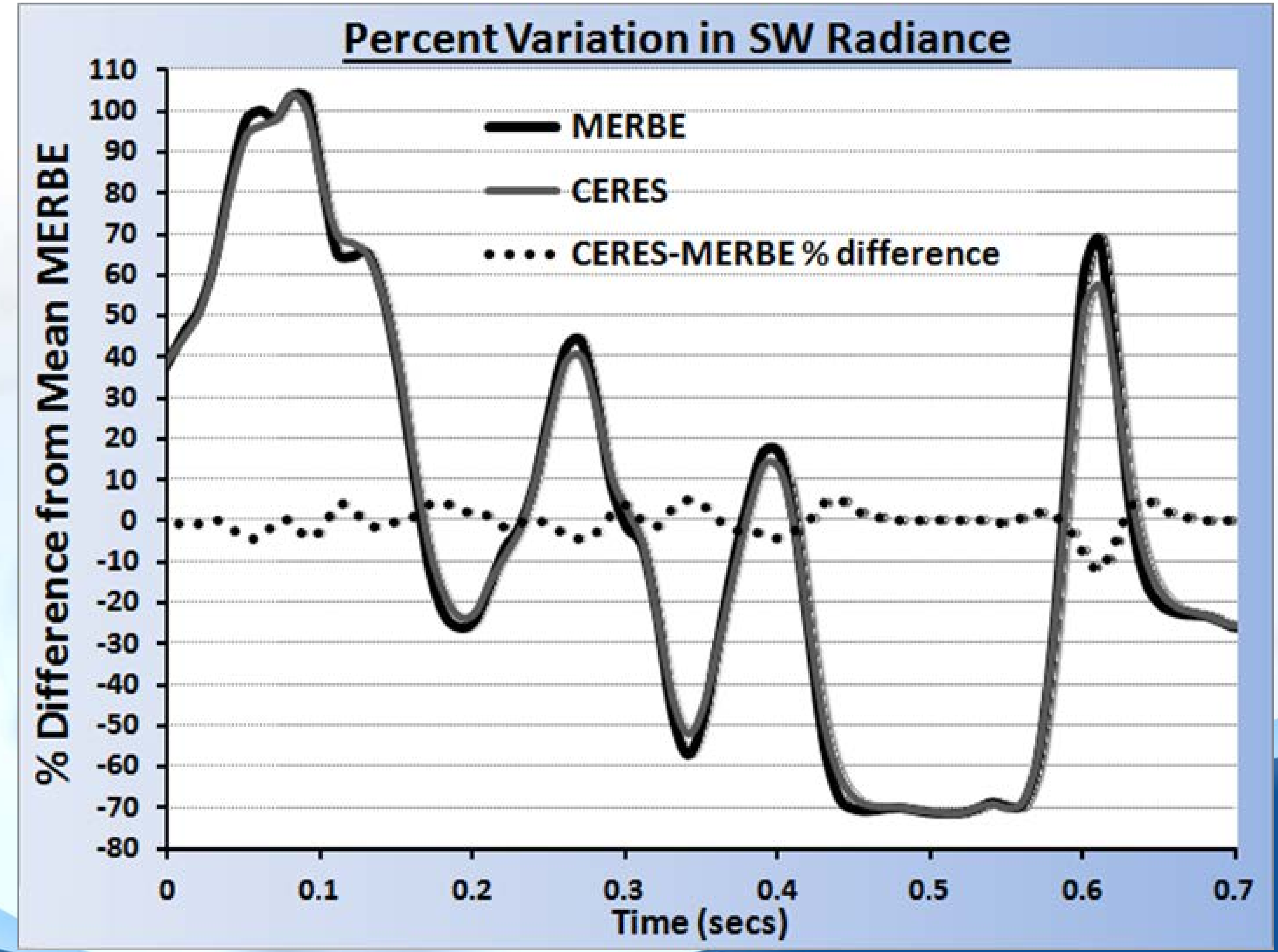
Impulse Response Found using In-flight Lamp/IBB/Space scans



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



MERBE IE corrects Instantaneous CERES errors of > 10%



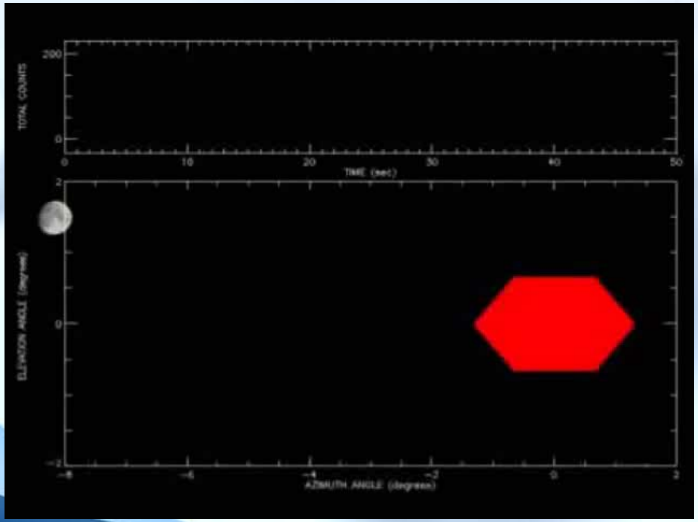
CERES detectors are linear to <0.1%

Opportunities to Intercalibrate Radiometric Sensors from International Space Station
C. M. Roithmayr et al 2014

The highest priorities for CERES intercalibration are gain, scan-angle-dependent electronic offset, and correction of spectral response function (Reference 10). CERES bolometer detectors are designed and verified to achieve less than 0.1% nonlinearity, and the spherical symmetry of the

3. Placement on and Holding to the MERBE Watt SI Traceable Scale

The mathematics of convolution integrals allowed absolute measurements of lunar radiance to be made by an under-filled ERB device (Matthews 2008, Applied Optics)



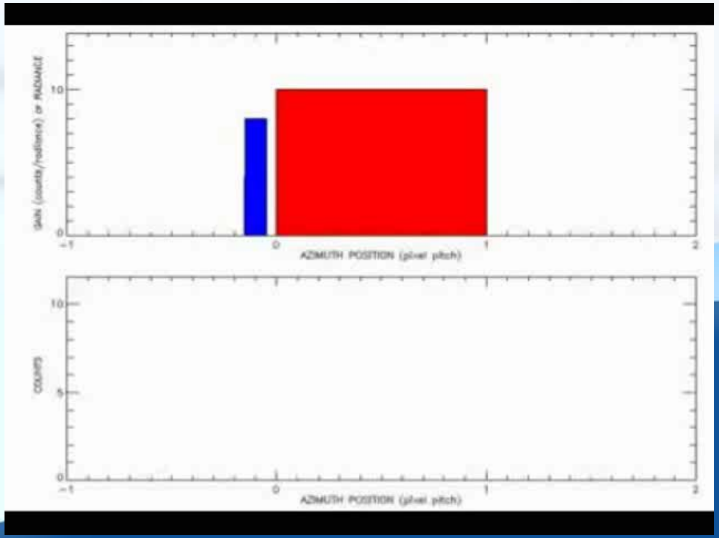
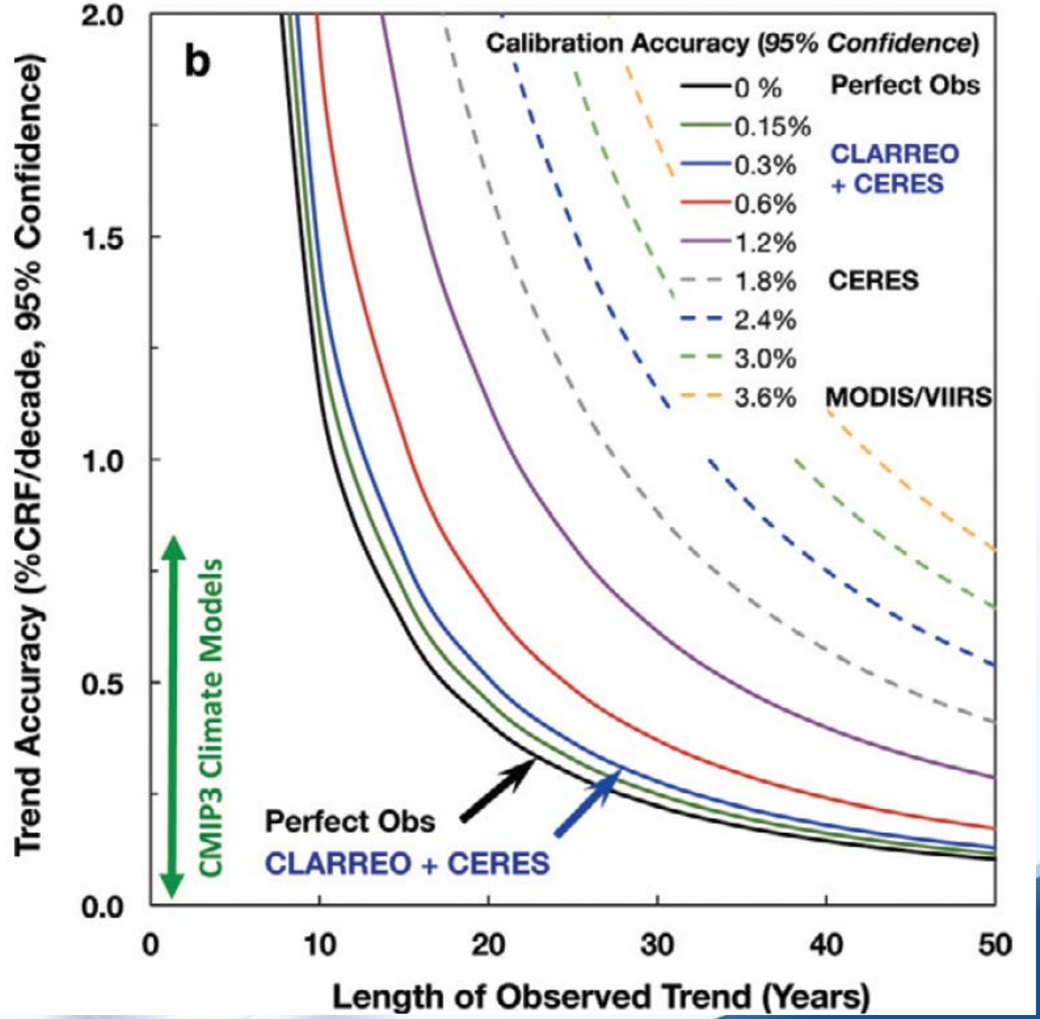
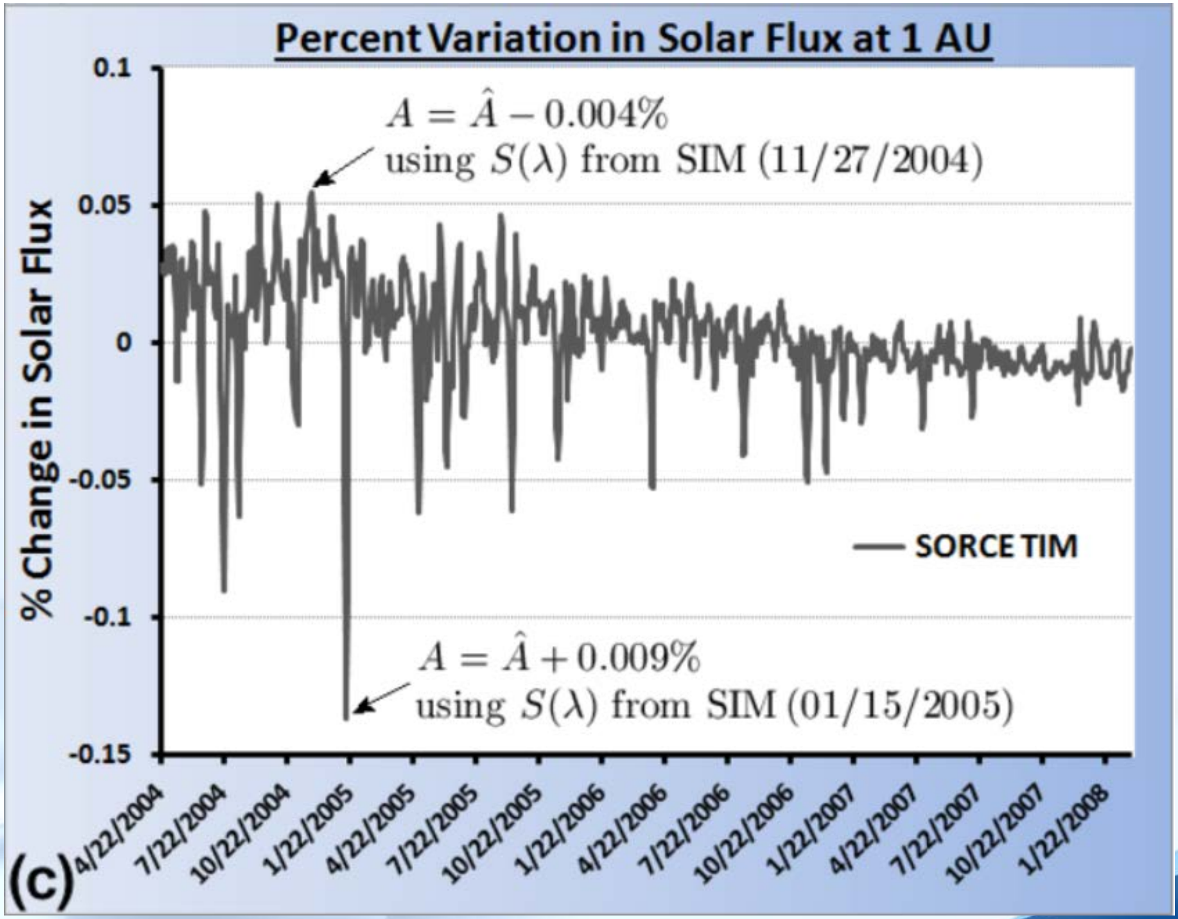


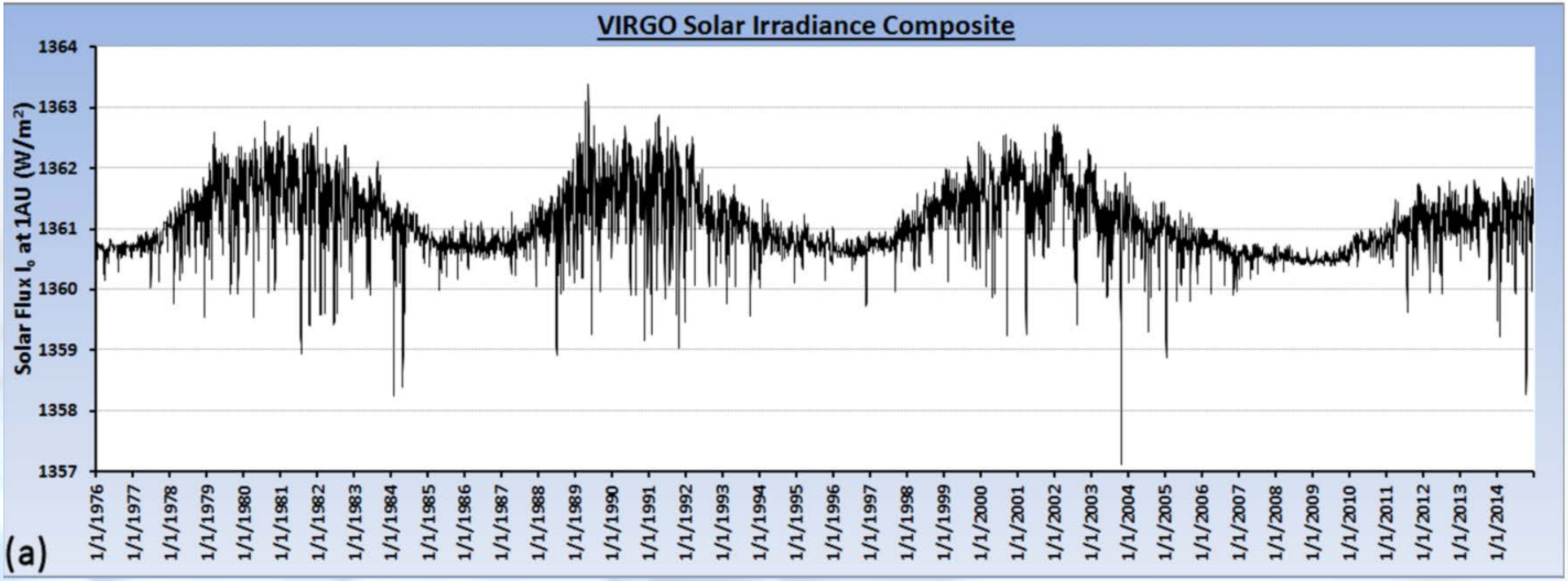
Fig. 3b from Wielicki et al (2013)



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

But how many MERBE Watts to the Watt?

- This will require <0.15% accurate lunar albedo

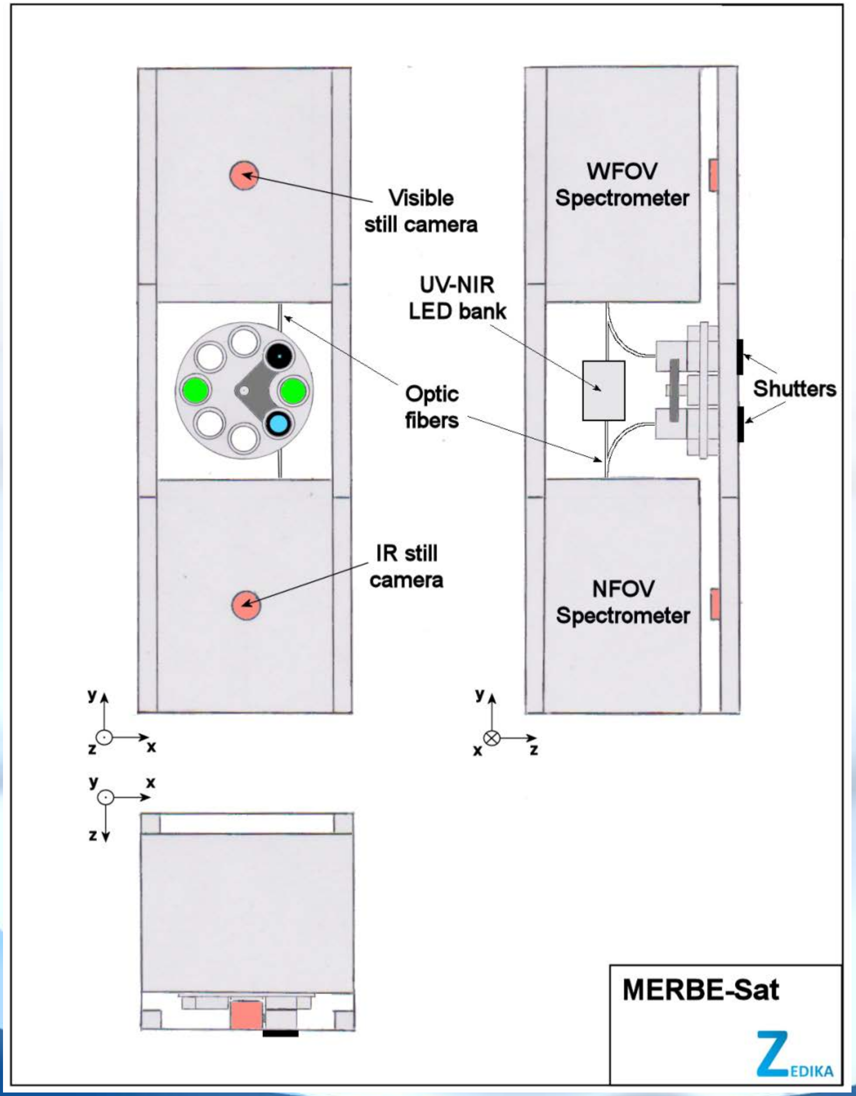
- How to use the Sun for calibration of a high spatial resolution solar spectrometer? Use angular rather than CLARREO proposed spatial attenuation:

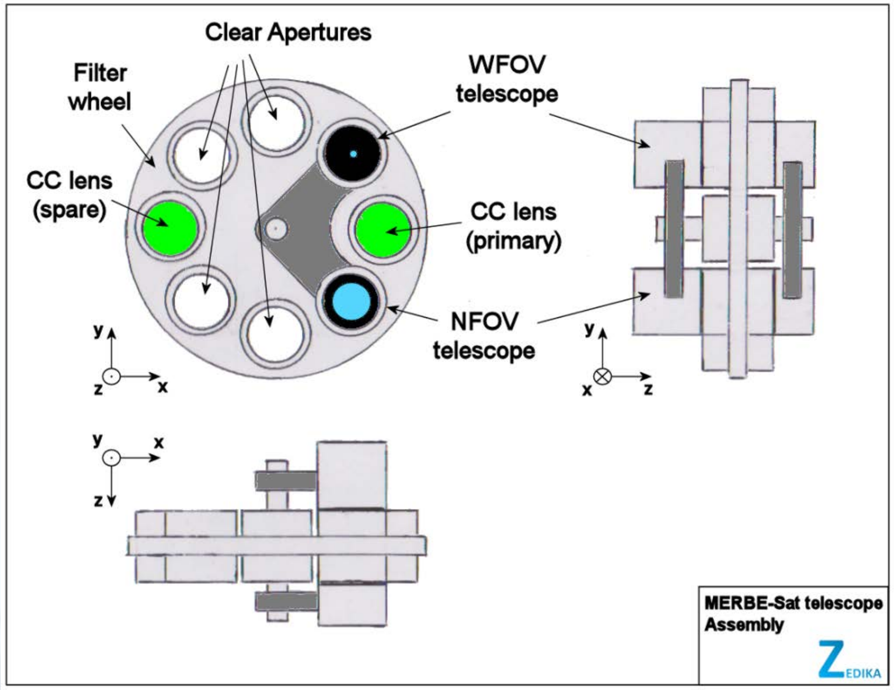
Radiance units are $W/m^2/Sr$

- MERBE-Sat CubeSat Concept submitted to ESAS2017 Decadal survey RFI#2 (click link below)

http://surveygizmoresponseuploads.s3.amazonaws.com/fileuploads/15647/2604456/26-1bf2db1b778f5a22e7f6dddf1b856ebb_MatthewsGrant2.pdf

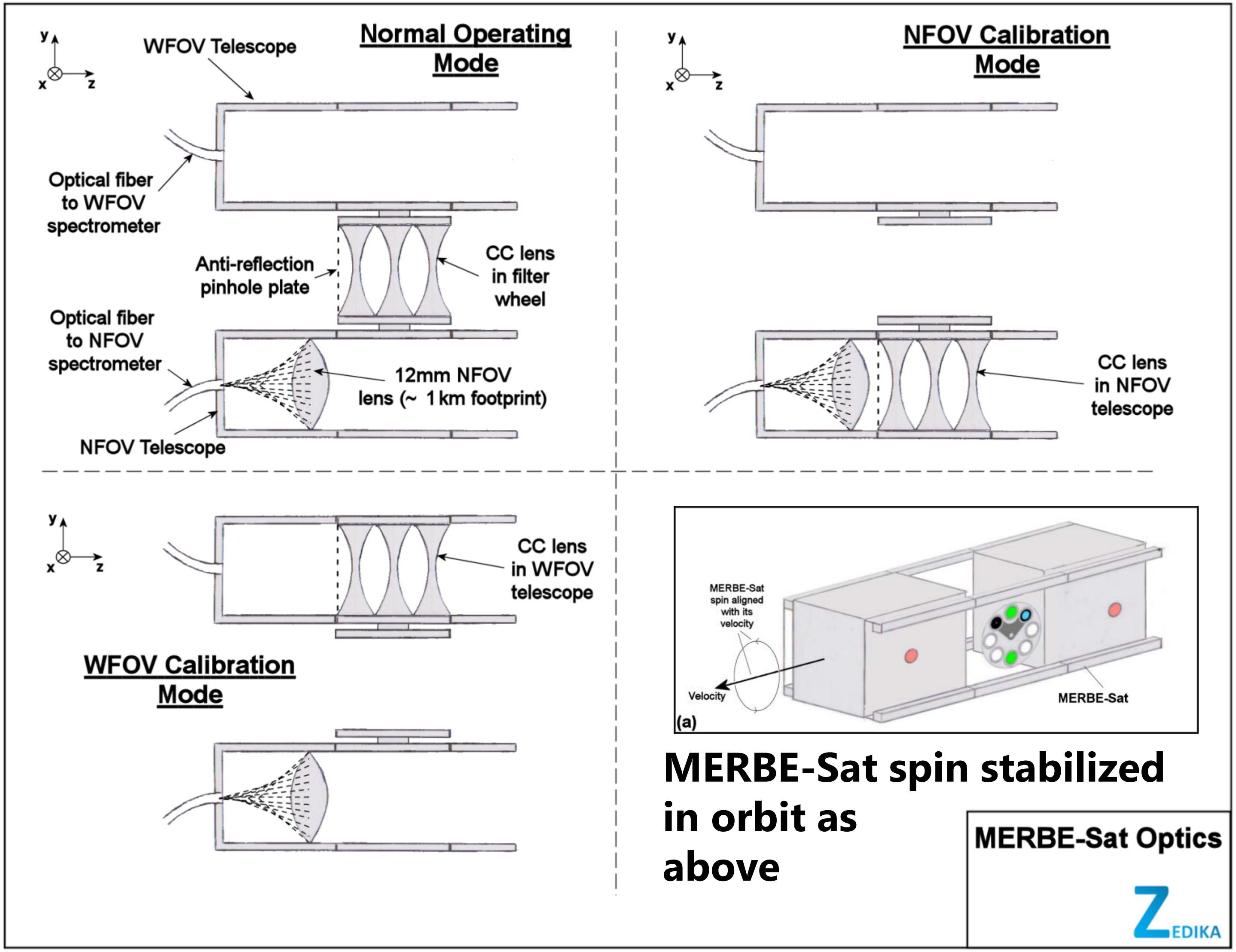
MERBE-Sat: SI traceable Extension to the Moon and Earth Radiation Budget Experiment (MERBE) Using a 3U CubeSat



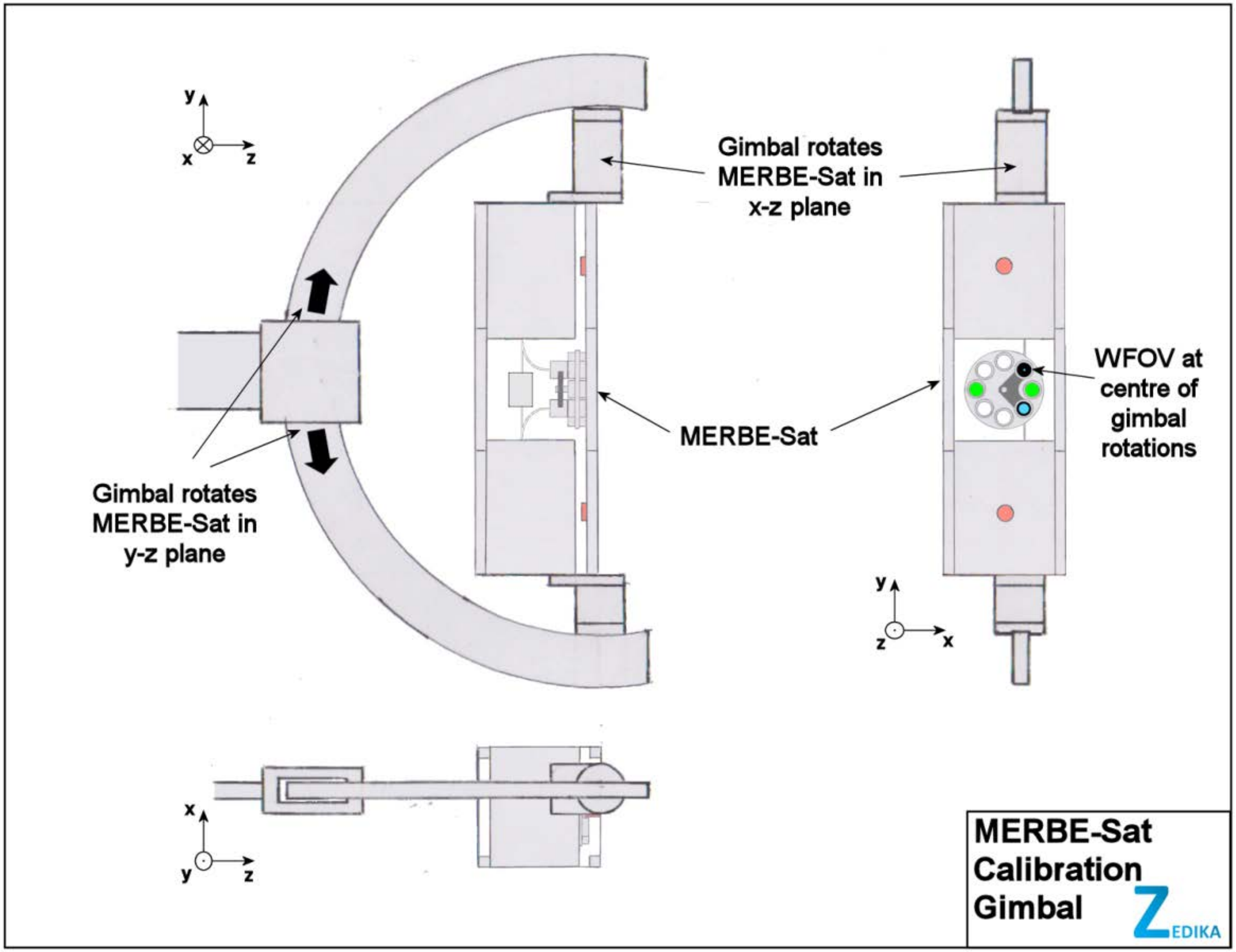


Use Ocean Optics STS VIS spectrometer already deployed in CubeSats

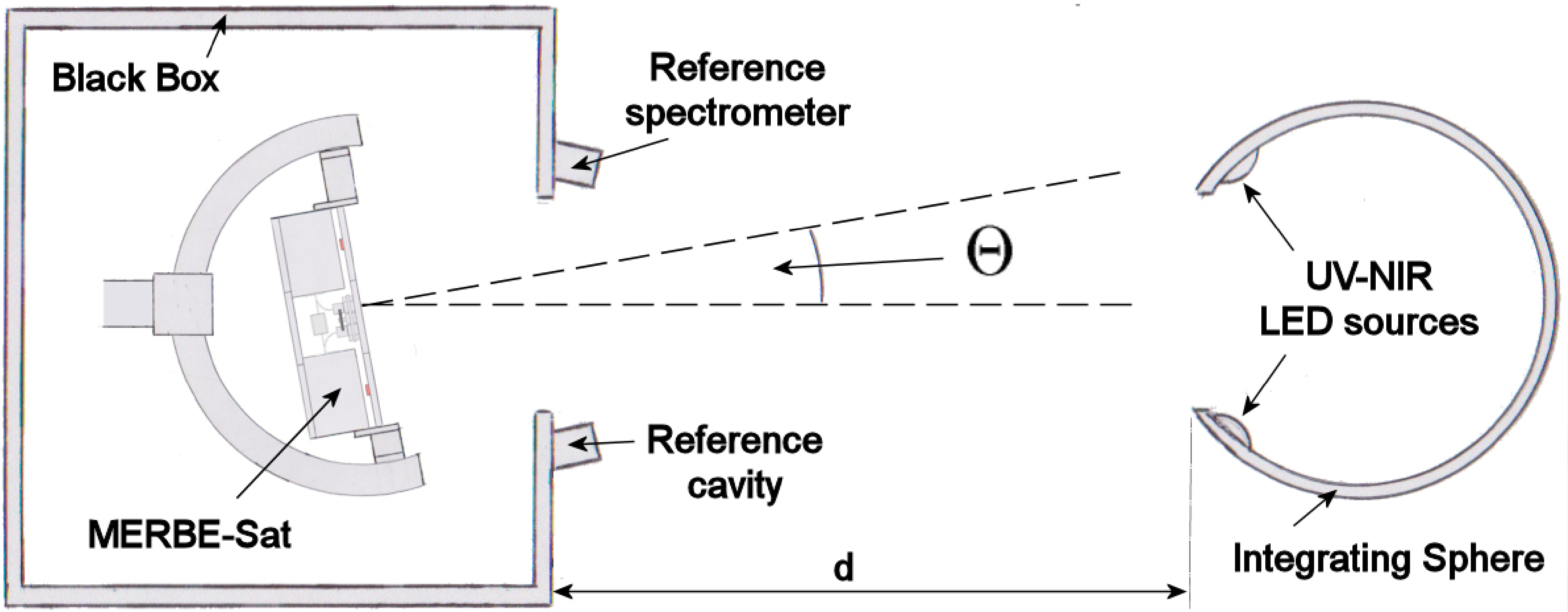
Two telescopes, one Wide field of View (WFOV), the other Narrow field of View (NFOV), both able to see through same compound ConCave (CC) lens



Ground Calibration of MERBE-Sat in a Gimbal to Measure Optical Alignment Ratio (OAR) - all other Calibration done on-orbit



Ground Calibration of MERBE-Sat Gimbal to Measure Optical Alignment Ratio (OAR) using LED illuminated Integrating Sphere



$$H_{ij}(\lambda_k) = \int_{2\pi} \left[\frac{V_{ij}(\lambda_k, \Theta, \Phi)}{R(\lambda_k, t)} \right] d\Omega'$$

$$O_k = \frac{H_{nc}(\lambda_k) \times H_{wn}(\lambda_k)}{H_{wc}(\lambda_k) \times H_{nn}(\lambda_k)}$$

Uniform degradation in-flight makes no change to OAR O_k value