Animation credit Wikipedia

The Moon & Earth Radiation Budget Experiment (MERBE)

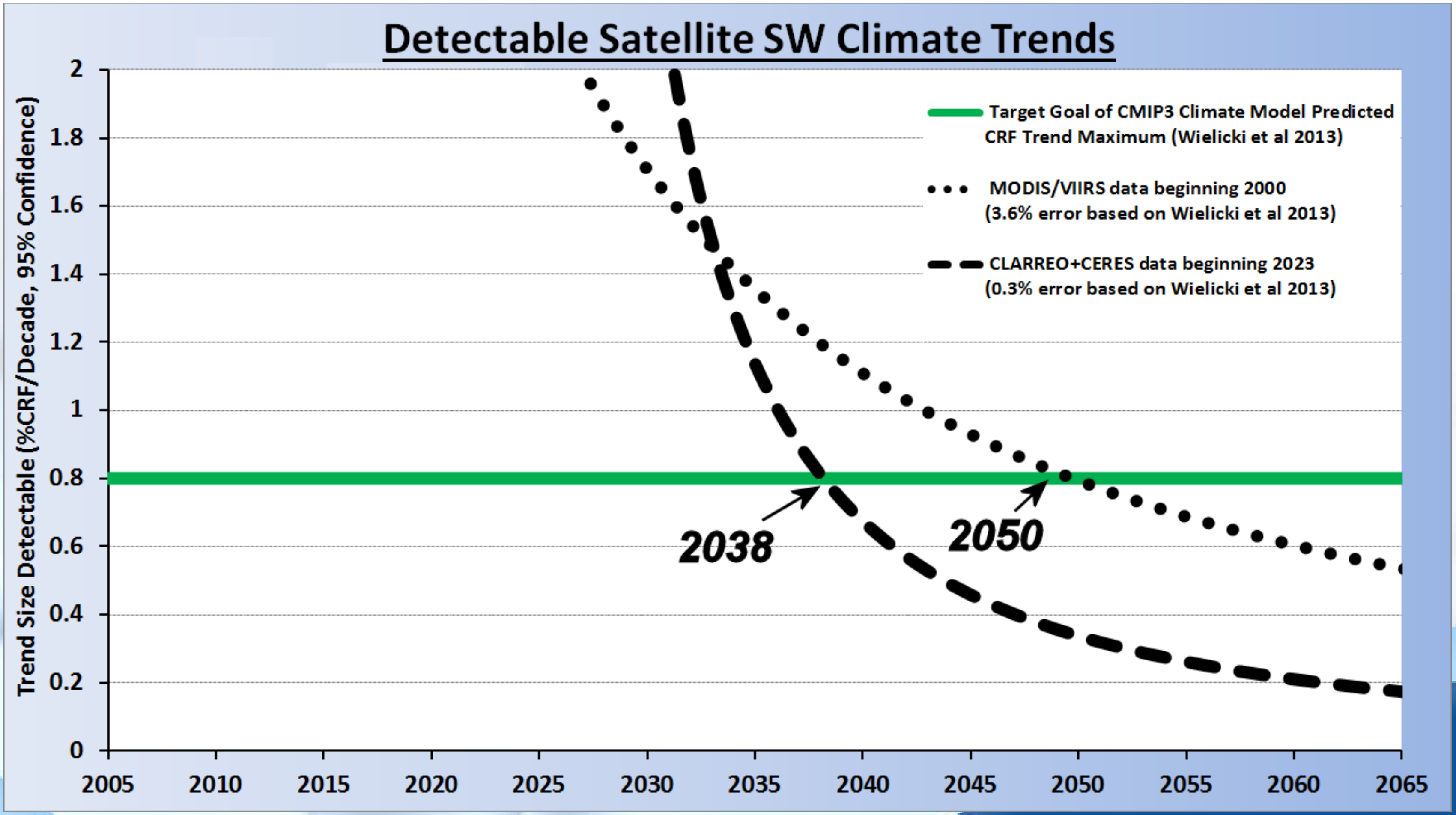
Grant Matthews

Accelerating certainty in climate change prediction

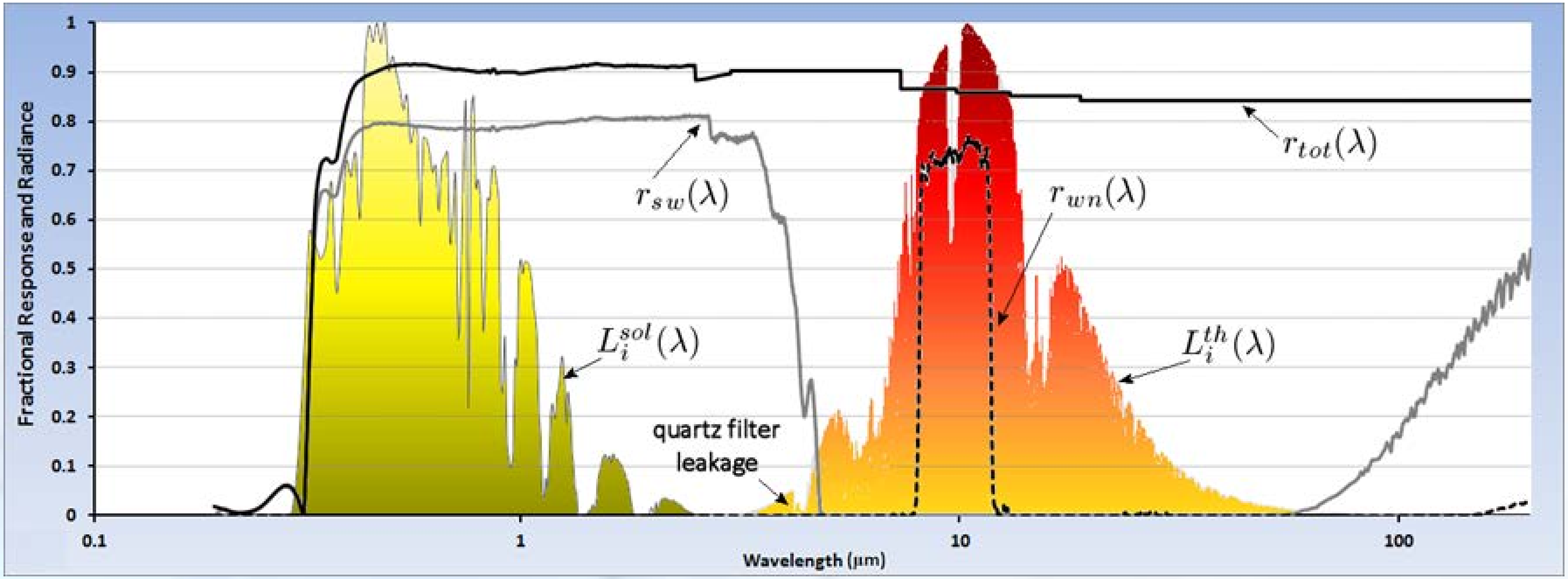
STAR JPSS
Science team meeting
11th Aug 2016

ZEDIKA

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



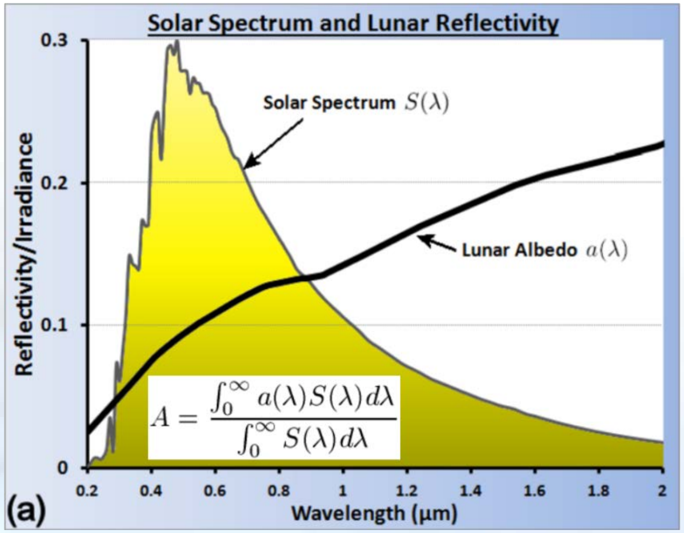
SW or Reflected Solar (0<λ<5μm)
LW or Thermal Infra Red (5<λ<200μm)

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]	?-?

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



$$\hat{A} = 0.1325$$

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

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

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

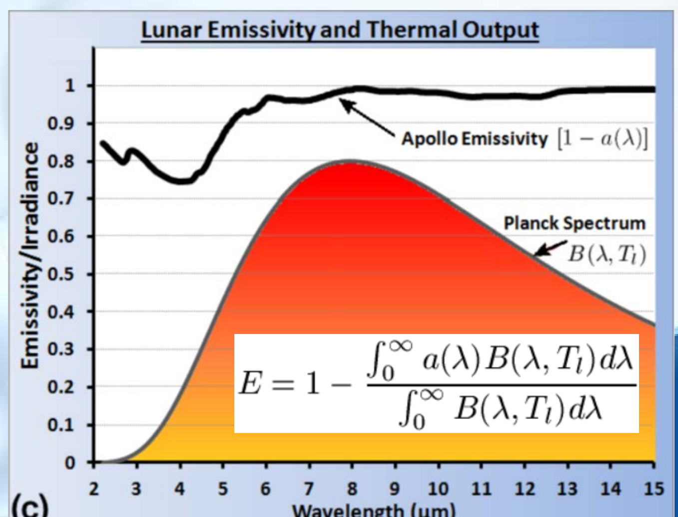
All instruments must measure same lunar reflectivity A & temperature T_l at +7° static phase angle **(see below)**

$$\hat{E} = 0.97154$$

$$\hat{T}_l = 365.291K$$

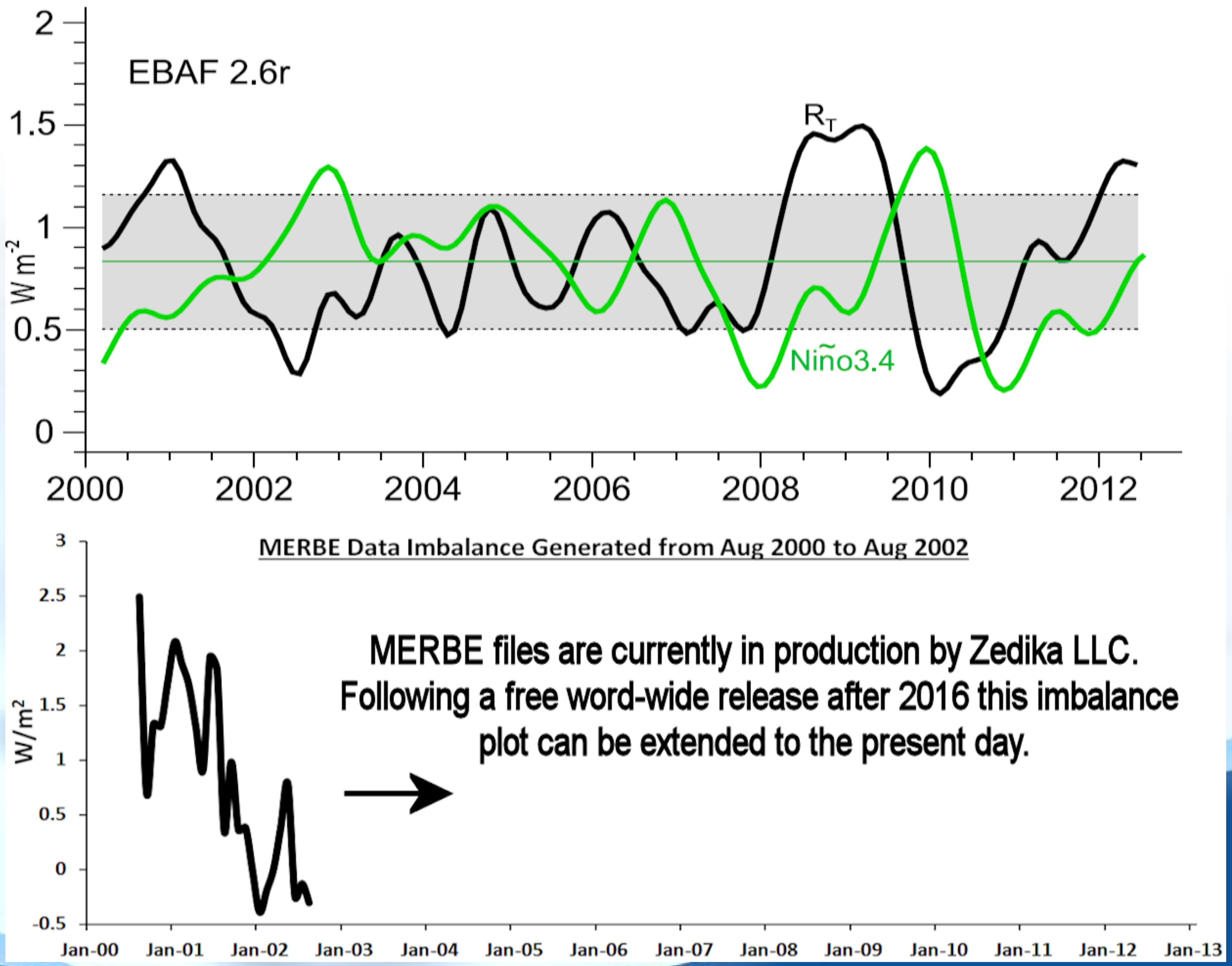
$$1W_t = \frac{E \times T_l^4}{\hat{E} \times \hat{T}_l^4} \quad (kg.m^2s^{-3}) \pm 0.6\%^*$$

Preliminary Results Shown

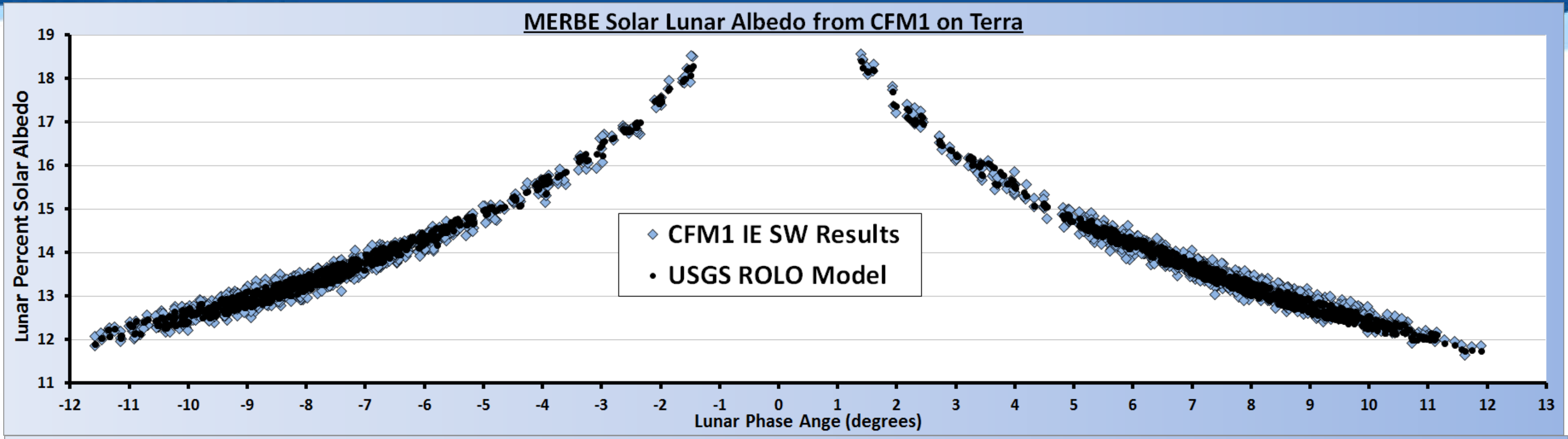


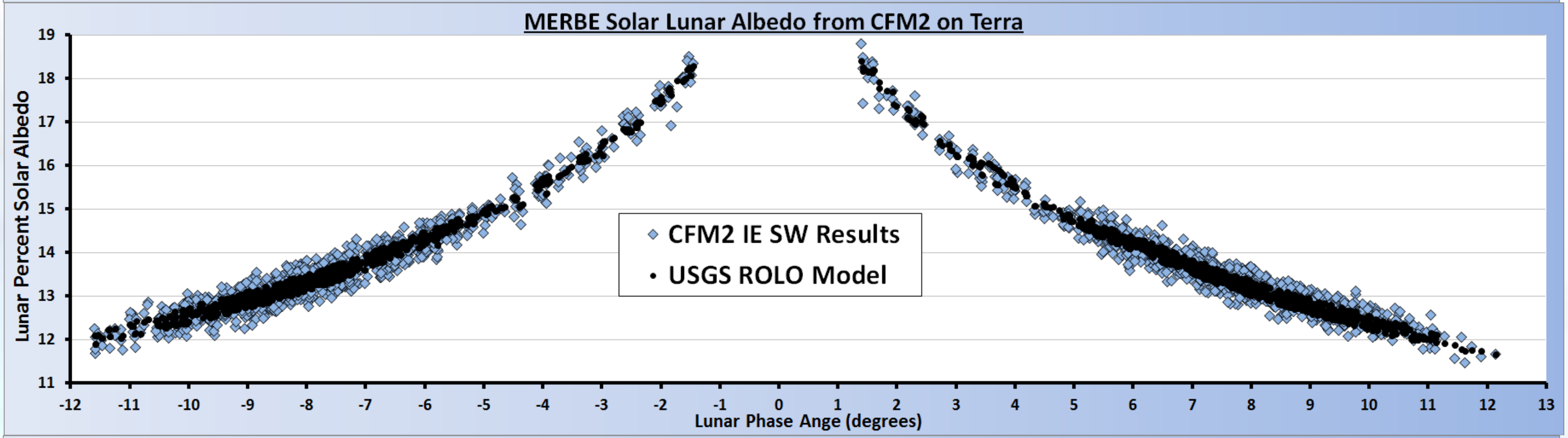
A=0.1325
T_l=365.291K

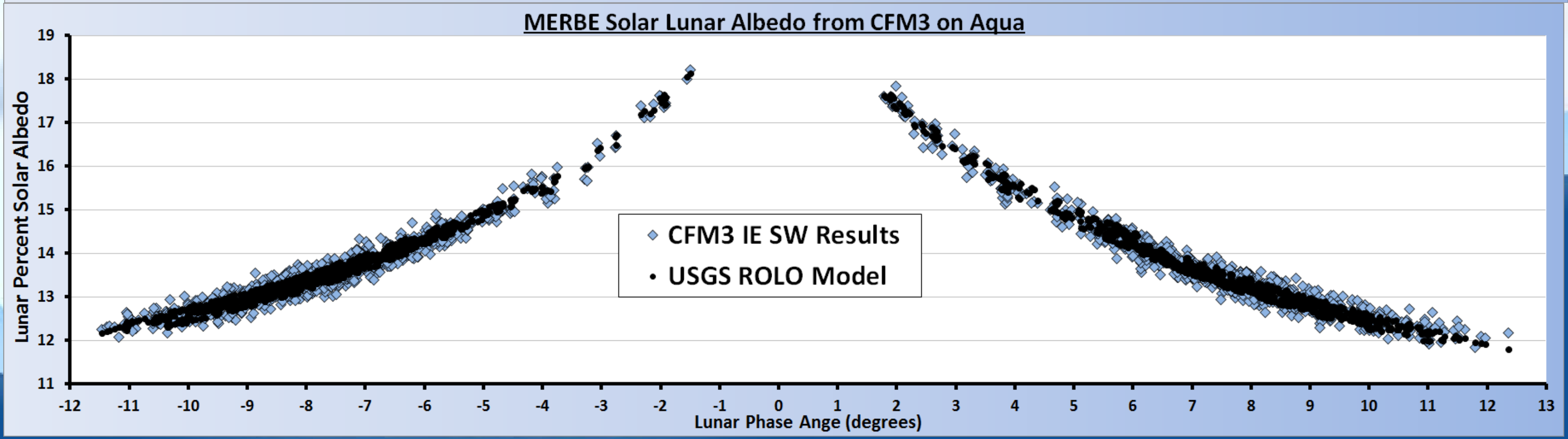
The MERBE Watt scale is chosen to give a +0.85W/m² ERB imbalance in the Aug 2000-Aug 2002 ENSO Neutral period



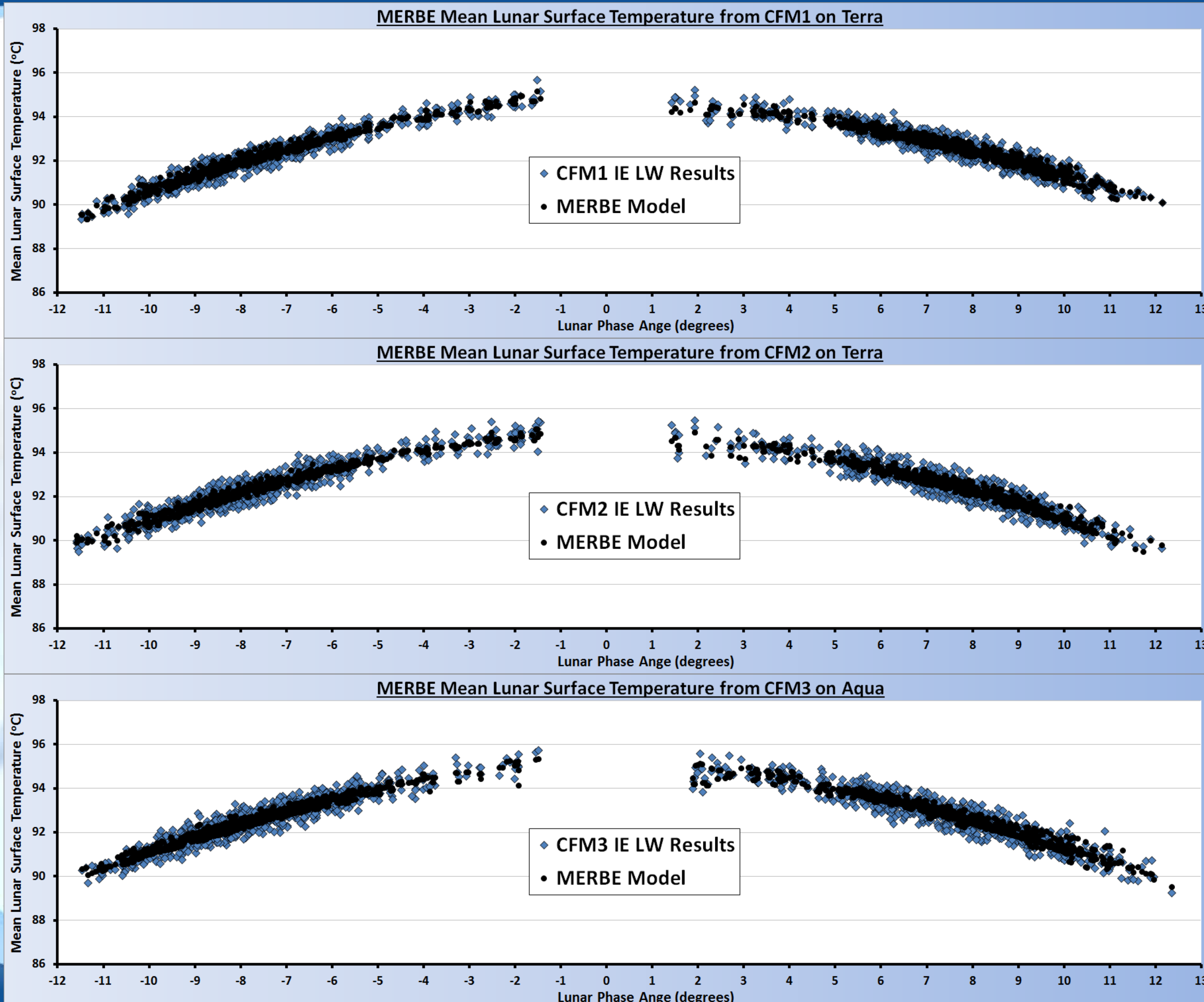
Preliminary Results Shown



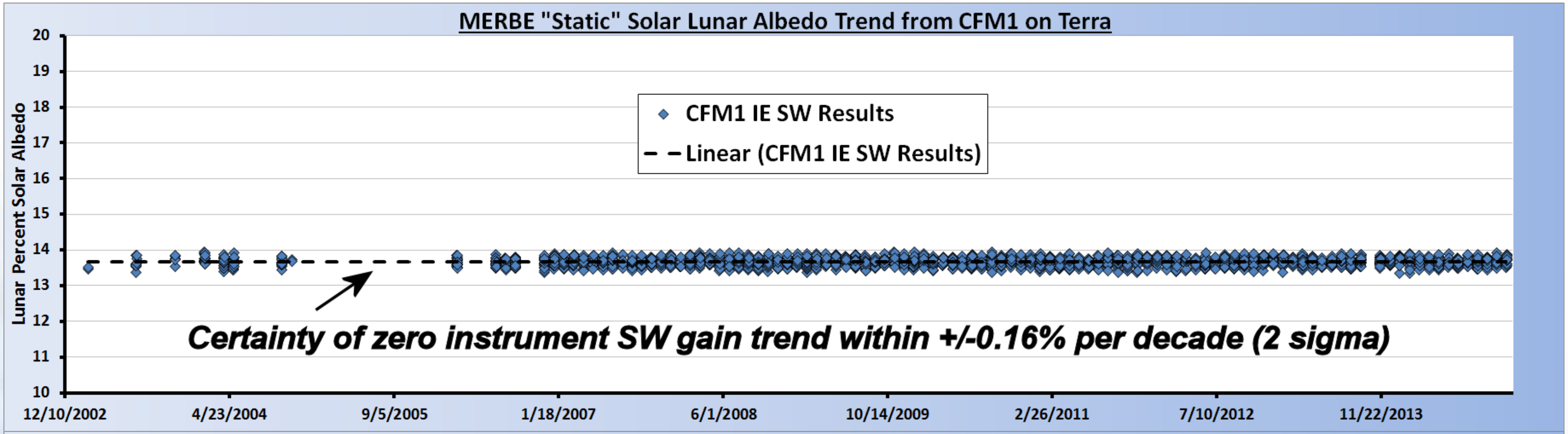


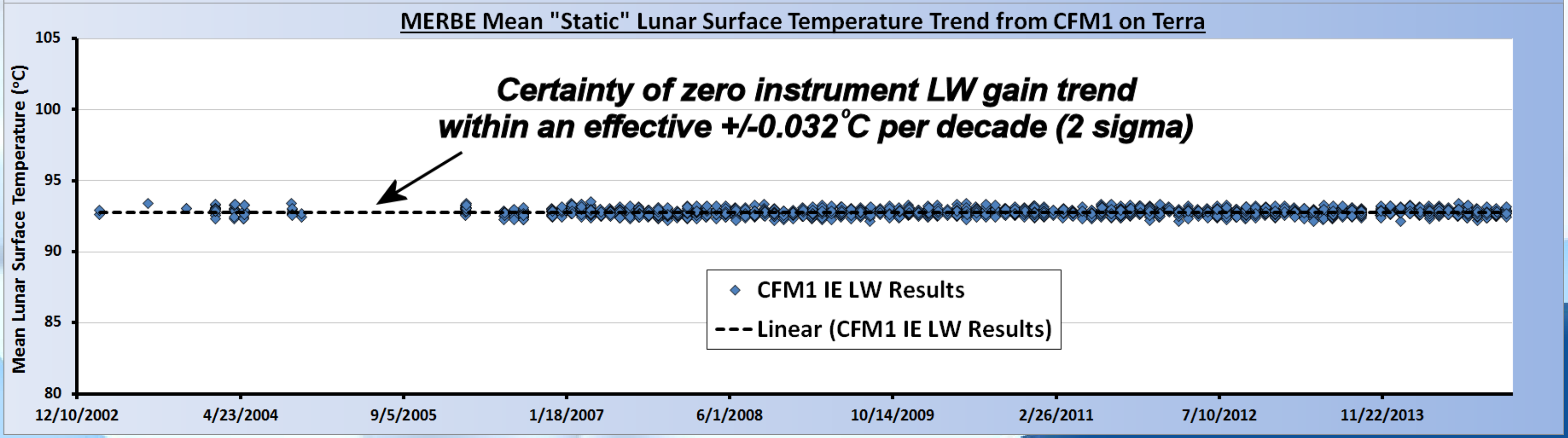


Preliminary Results Shown



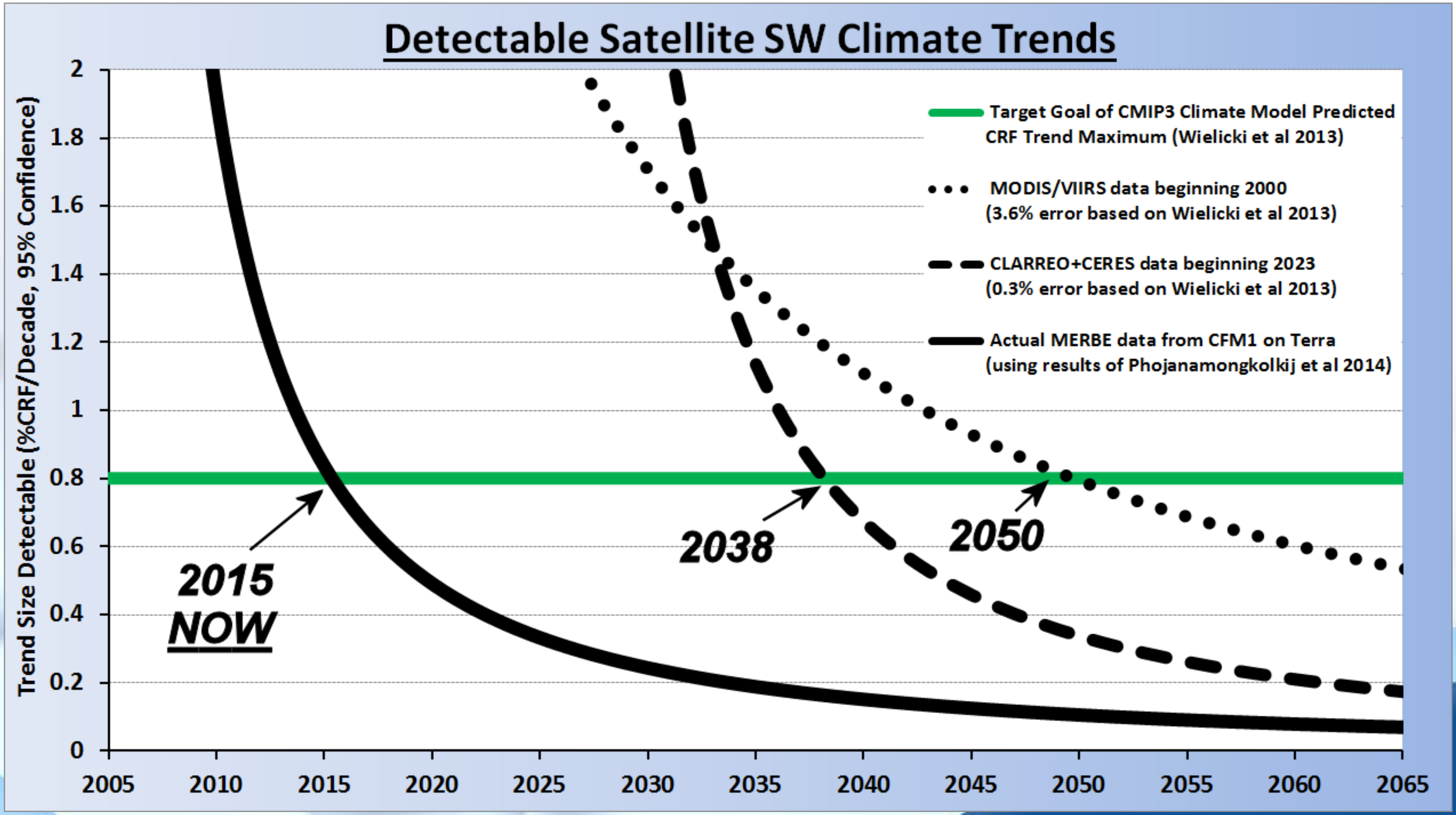
Trends in all MERBE Lunar Albedo and Temperature data are then eliminated and noise is <0.83%, more than twice improved on Matthews (2008)





Preliminary Results Shown

Due to IE, FOV mapping and device longevity, here also in solid black is when they actually do become detectable from MERBE data to be released in 2016 (using shown Moon data in the suggested Equations)



(using actual Terra Moon data)

But how many MERBE Watts to the Watt?

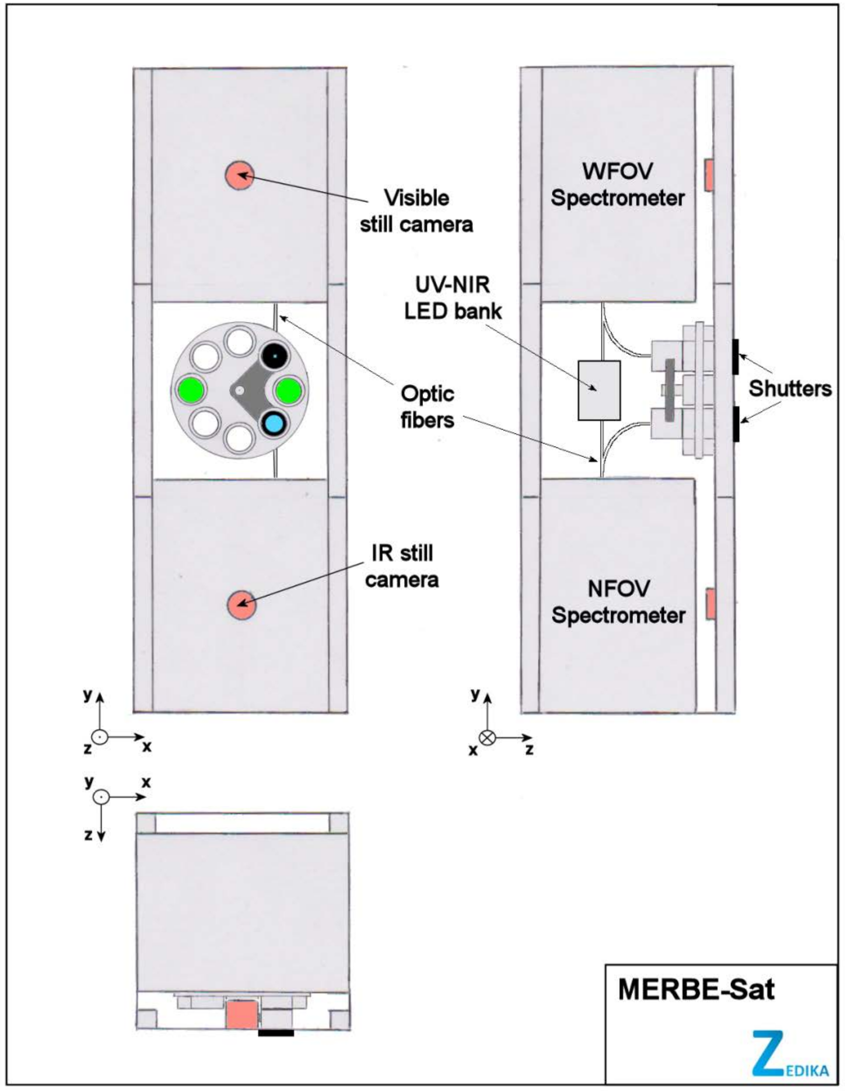
- This will require <0.15% accurate lunar albedo

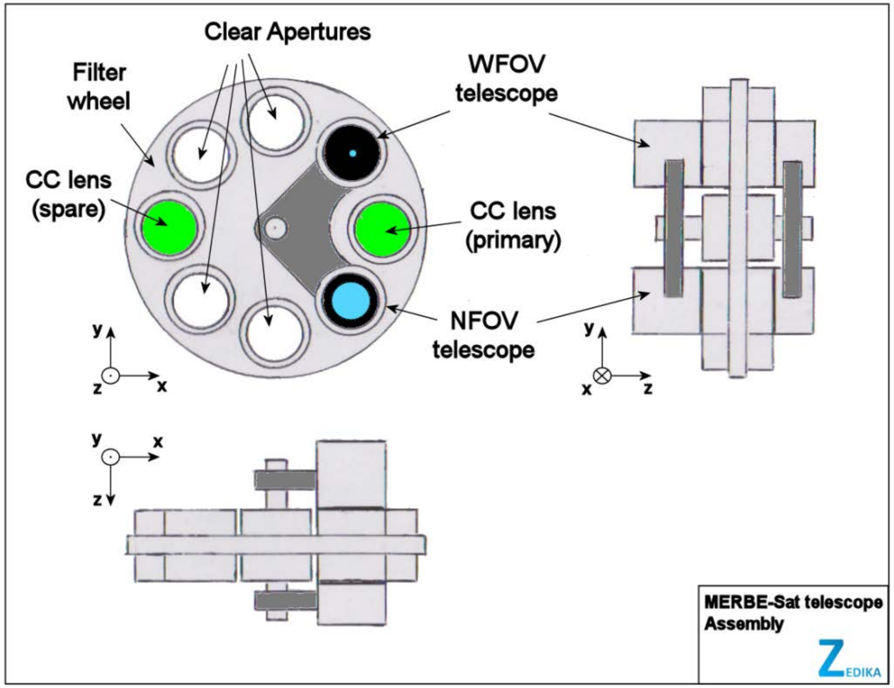
- How to use the Sun for calibration of a high spatial resolution solar spectrometer? Use angular rather than CLARREO proposed spatial attenuation:

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

- MERBE-Sat CubeSat Concept submitted to ESAS2017 Decadal survey RFI#2

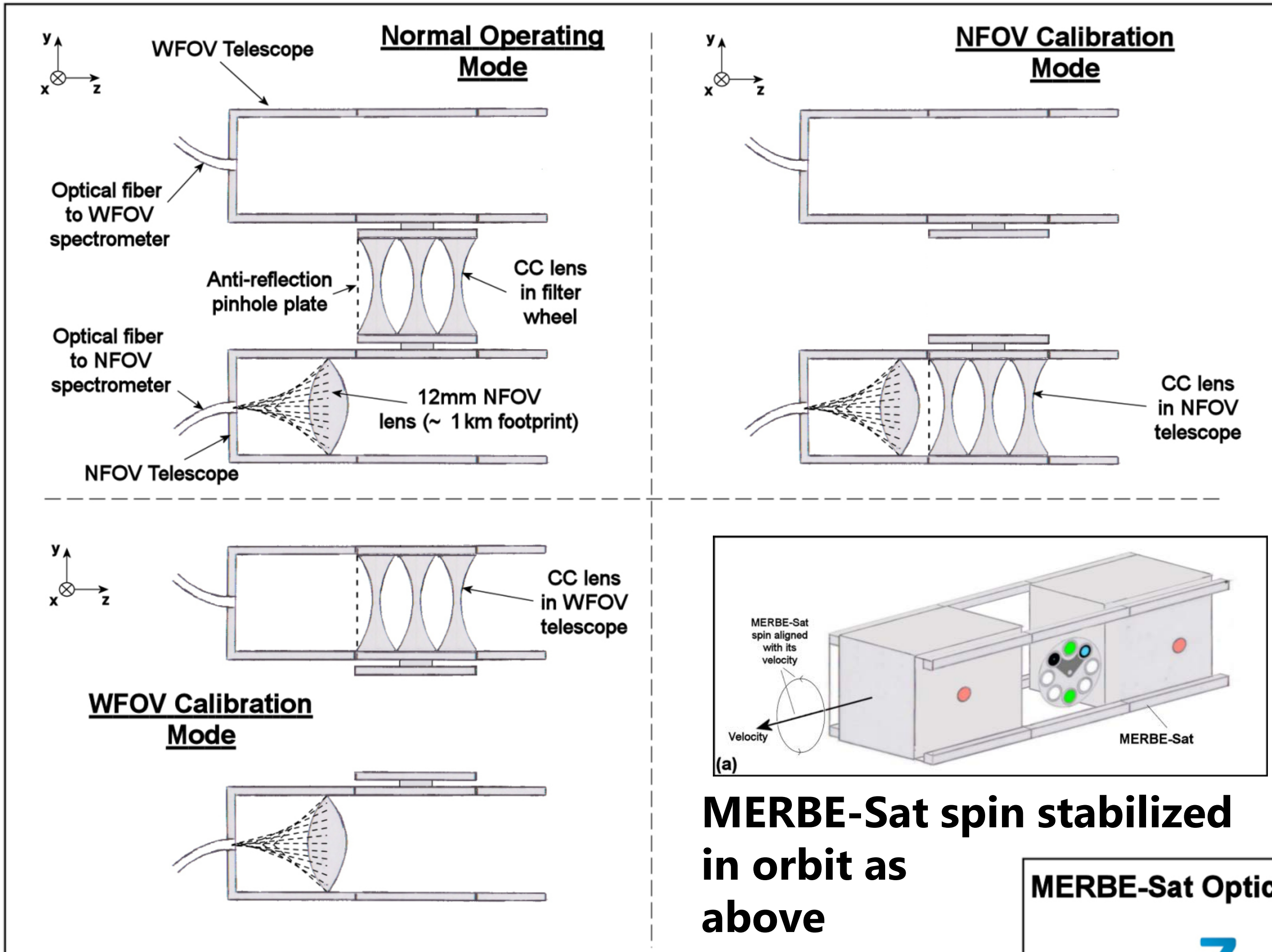
MERBE-Sat: SI traceable Extension to the Moon and Earth Radiation Budget Experiment (MERBE) Using a 3U CubeSat





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



MERBE-Sat spin stabilized in orbit as above

MERBE-Sat Optics

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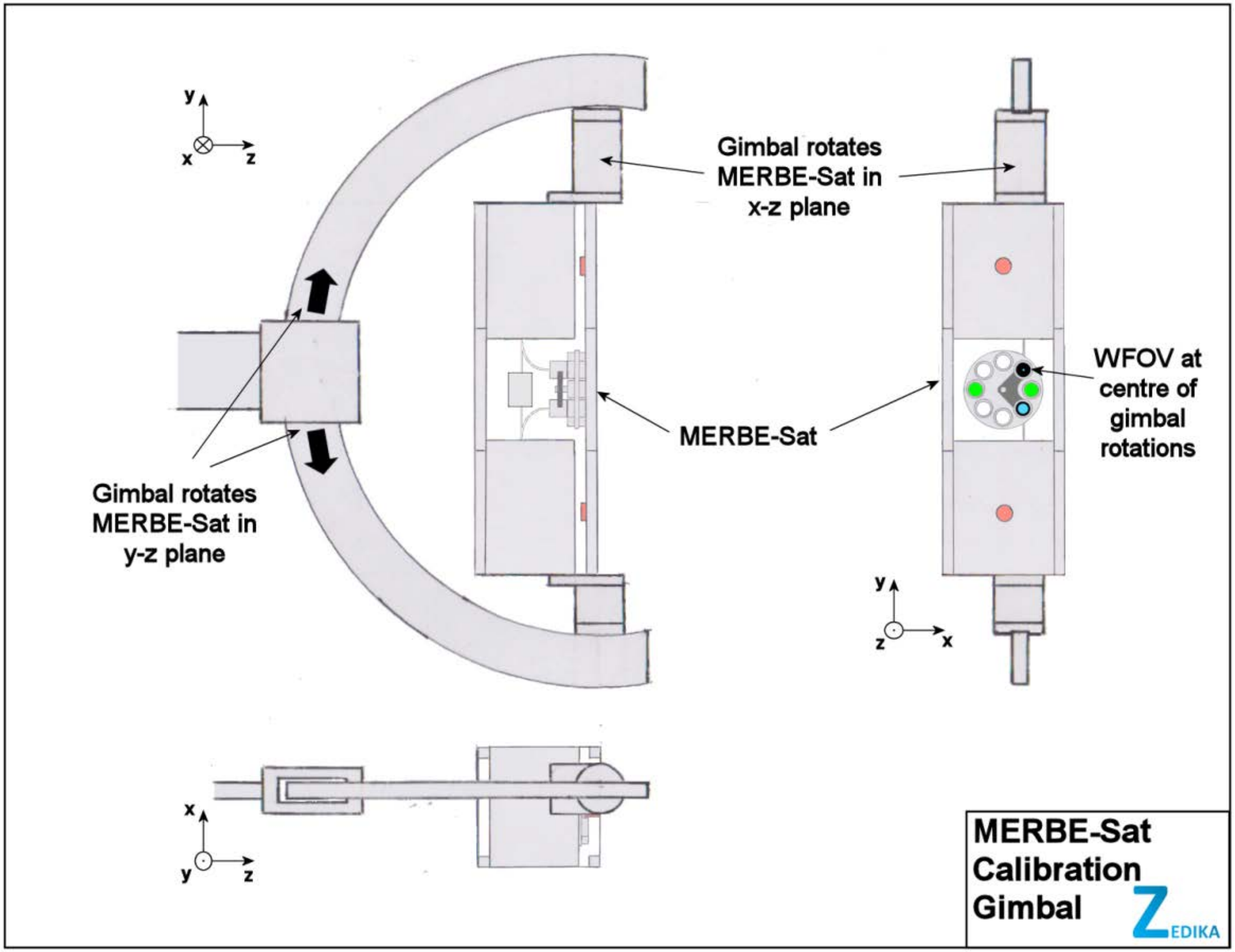
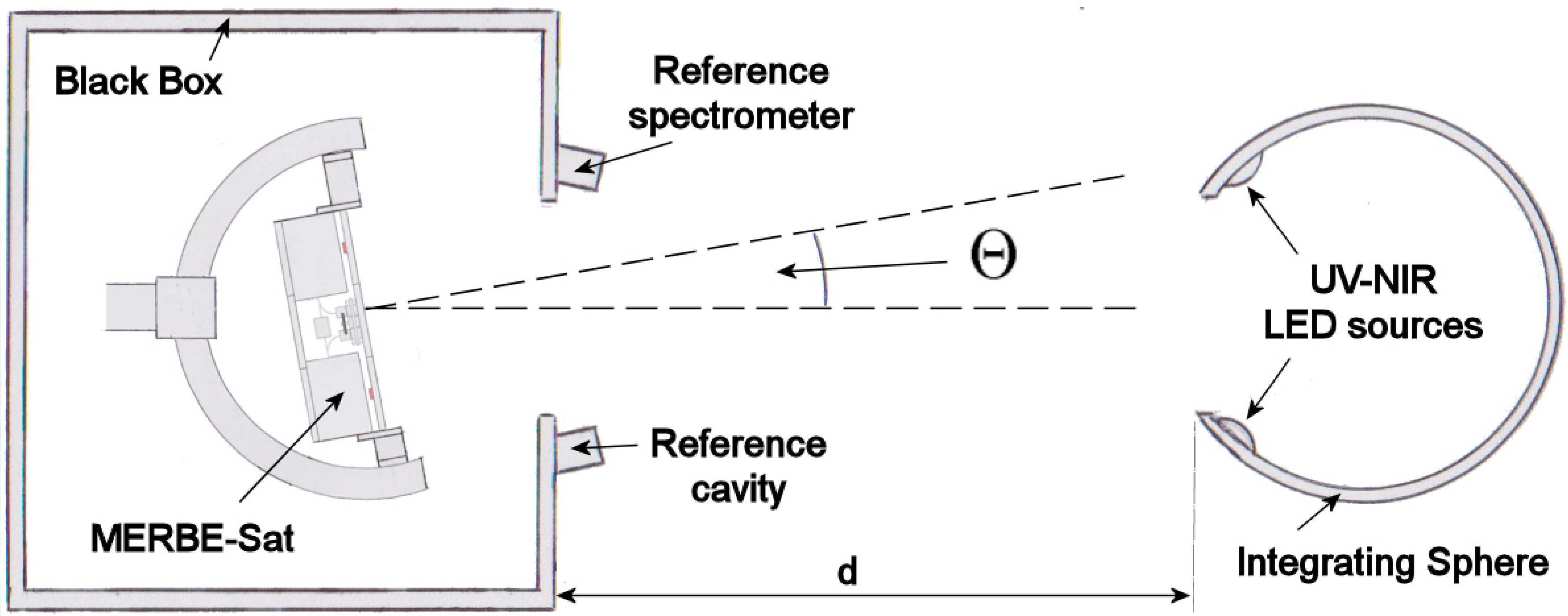
Ground Calibration of MERBE-Sat in a Gimbal to Measure Optical Alignment Ratio (OAR) - all other Calibration done on-orbit



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

Summary

- MERBE has improved existing satellite Earth radiance measurements at all stages from the detector voltages upwards to become SI traceable to <0.3%.
- Initial results suggest MERBE is an existing climate observing system decades old, with climate change detection accuracies beyond that planned for future CLARREO-like missions.
- MERBE-Sat is a low cost, low risk concept for determining solar lunar spectral albedo to <0.15% accuracy using Cube-Sats, in addition to the SW spectral fingerprints of Earth desired from CLARREO. Start with ground, then inflight tests to prove MERBE-Sat concept for costs in the $\$10^4$ to $\$10^5$ region.
- Any comments, ideas or suggestions?
- Grant.matthews@zedikasolv.com

Overview

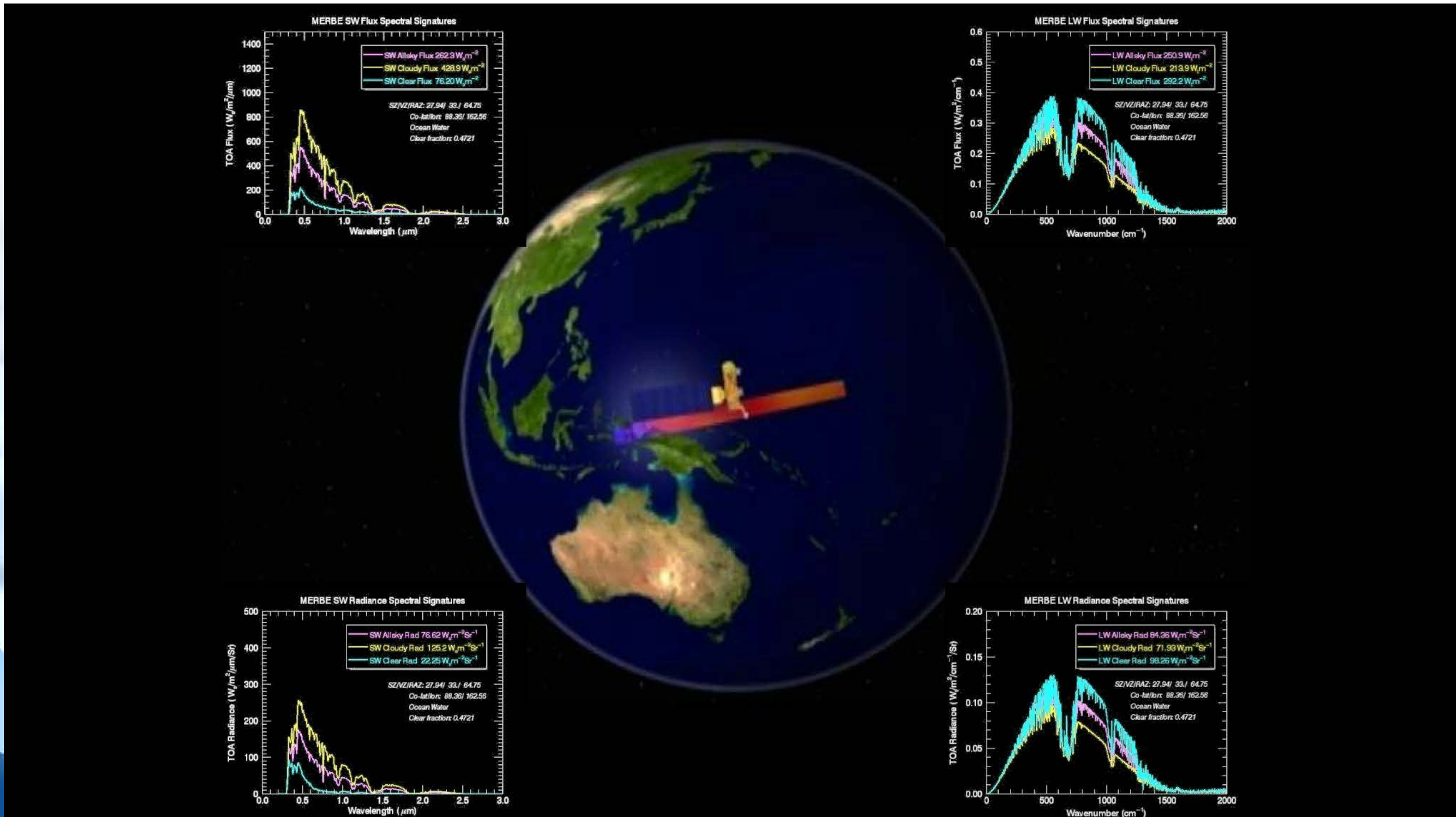
- New concept of MERBE, using existing data decades old and made SI traceable based on the Moon

- MERBE data soon due for a free release will allow the narrowing of climate feedback/forcing uncertainty to begin immediately, halving it within a decade.

- MERBE-Sat is a low cost CubeSat concept that will complete full SI traceability to a decades old climate observing system.

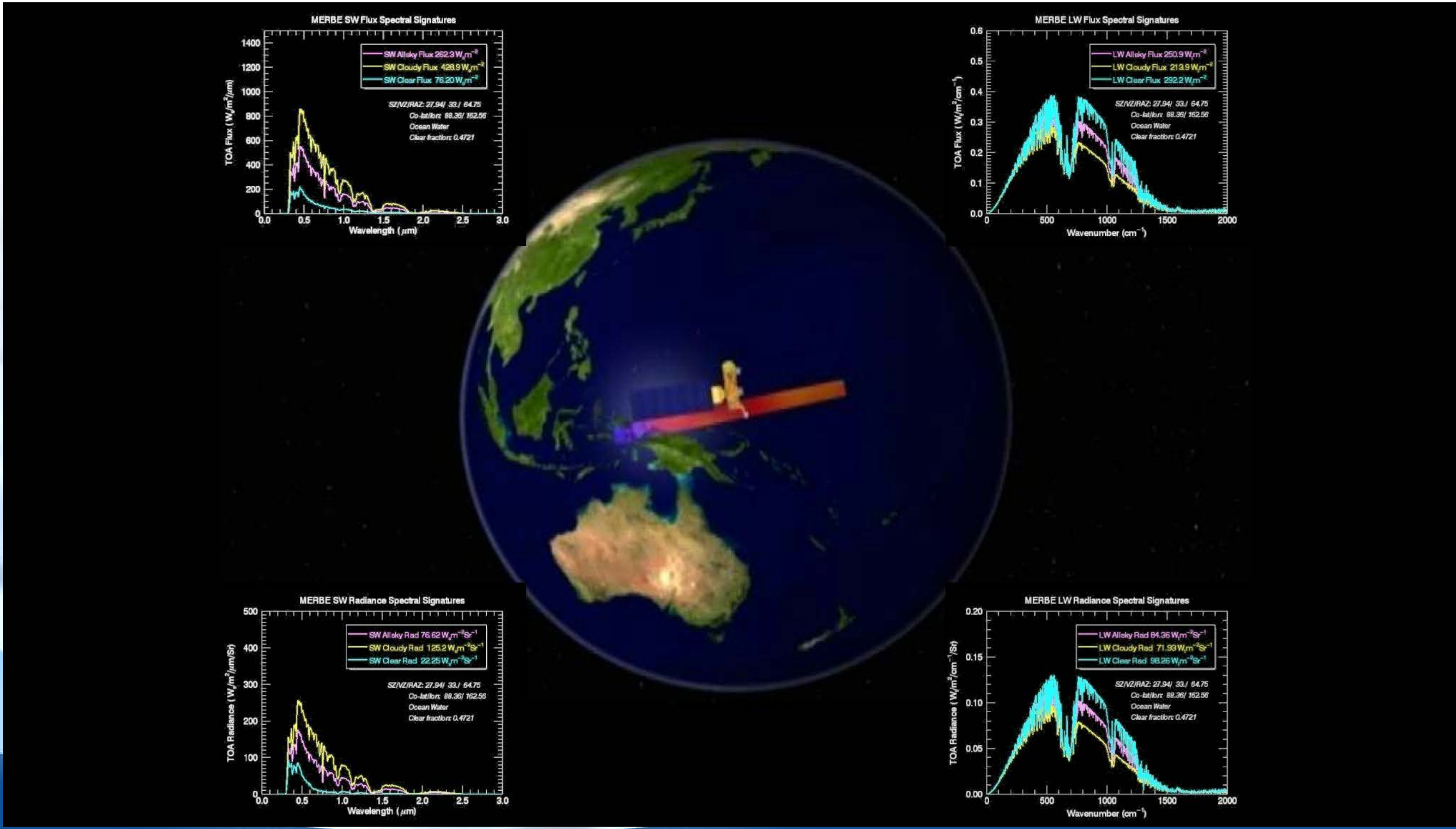
Animation credit NASA

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)

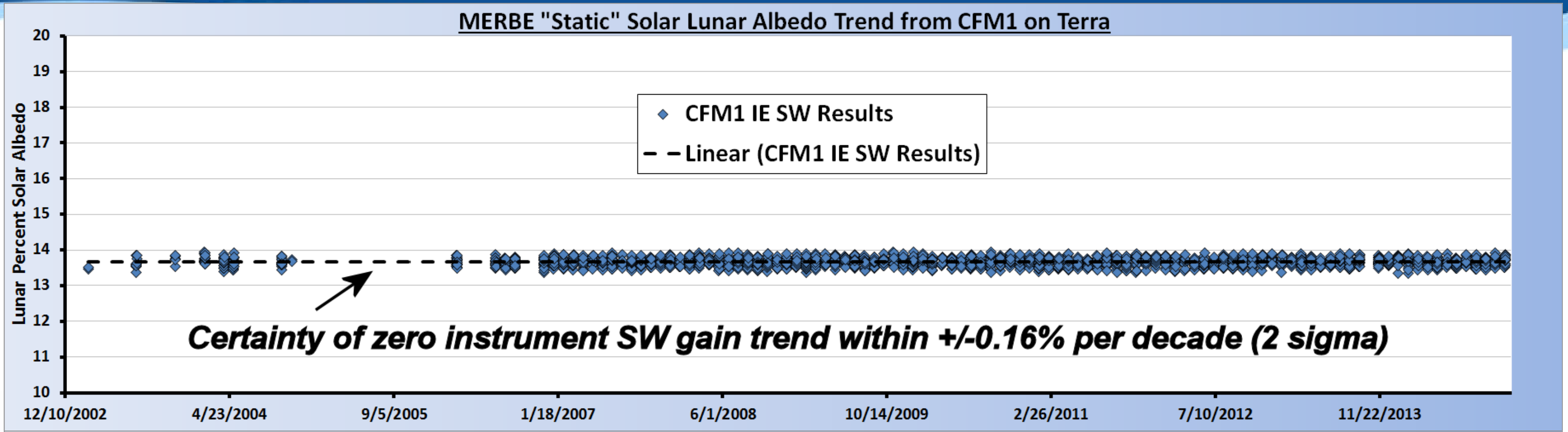


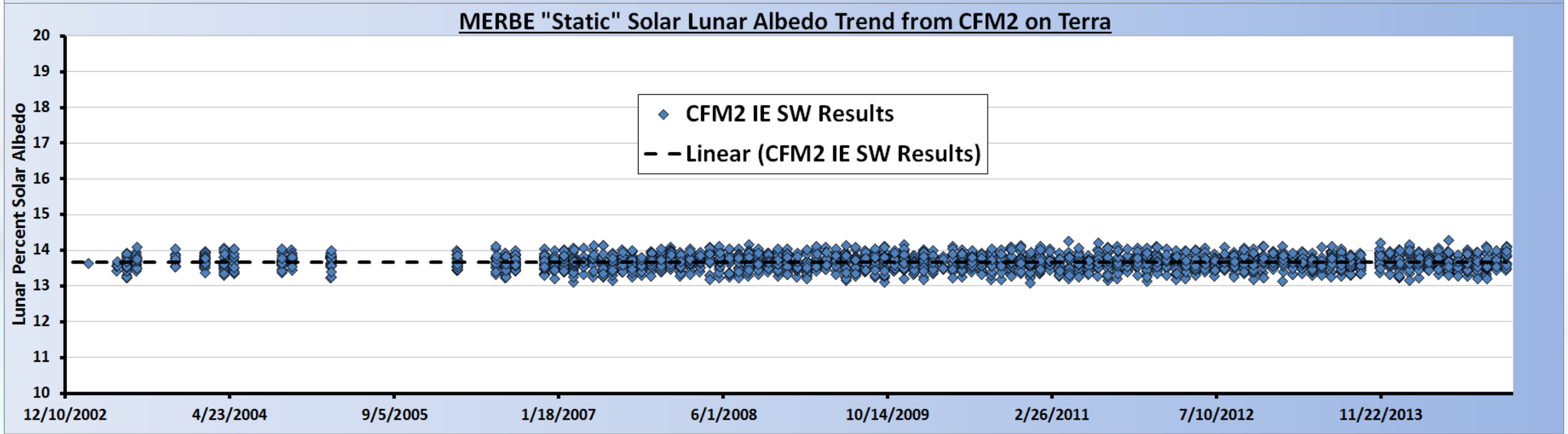
Animation credit NASA

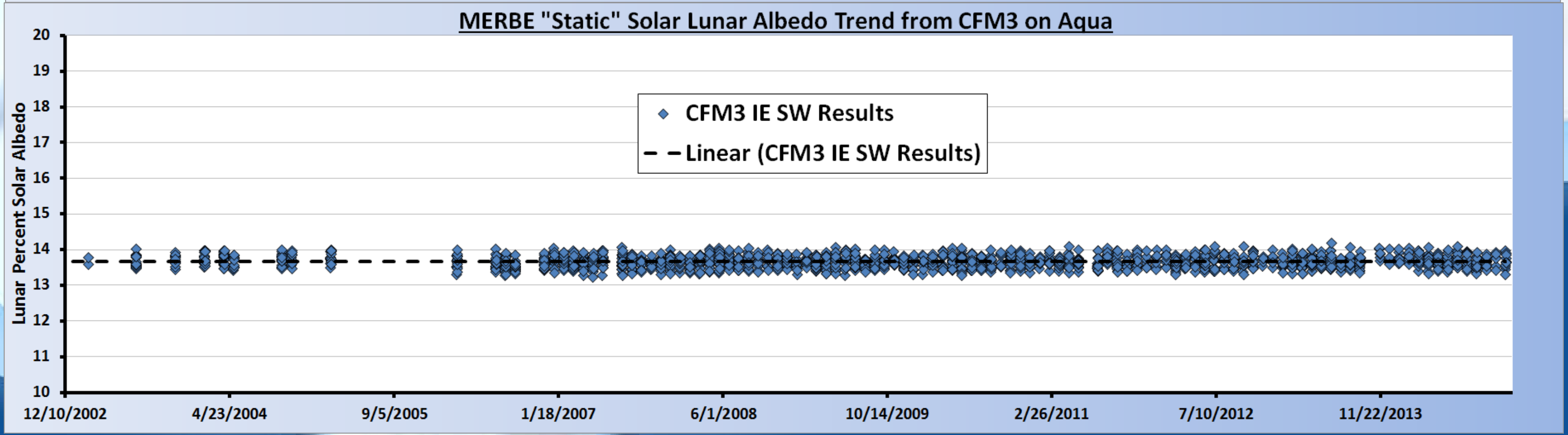
A Fourier series tensor instantaneously generates a clear, cloudy and all-sky MODTRAN 5.3 spectral signature for every footprint to be used in un-filtering (whose integral is constrained to SI traceable MERBE data)



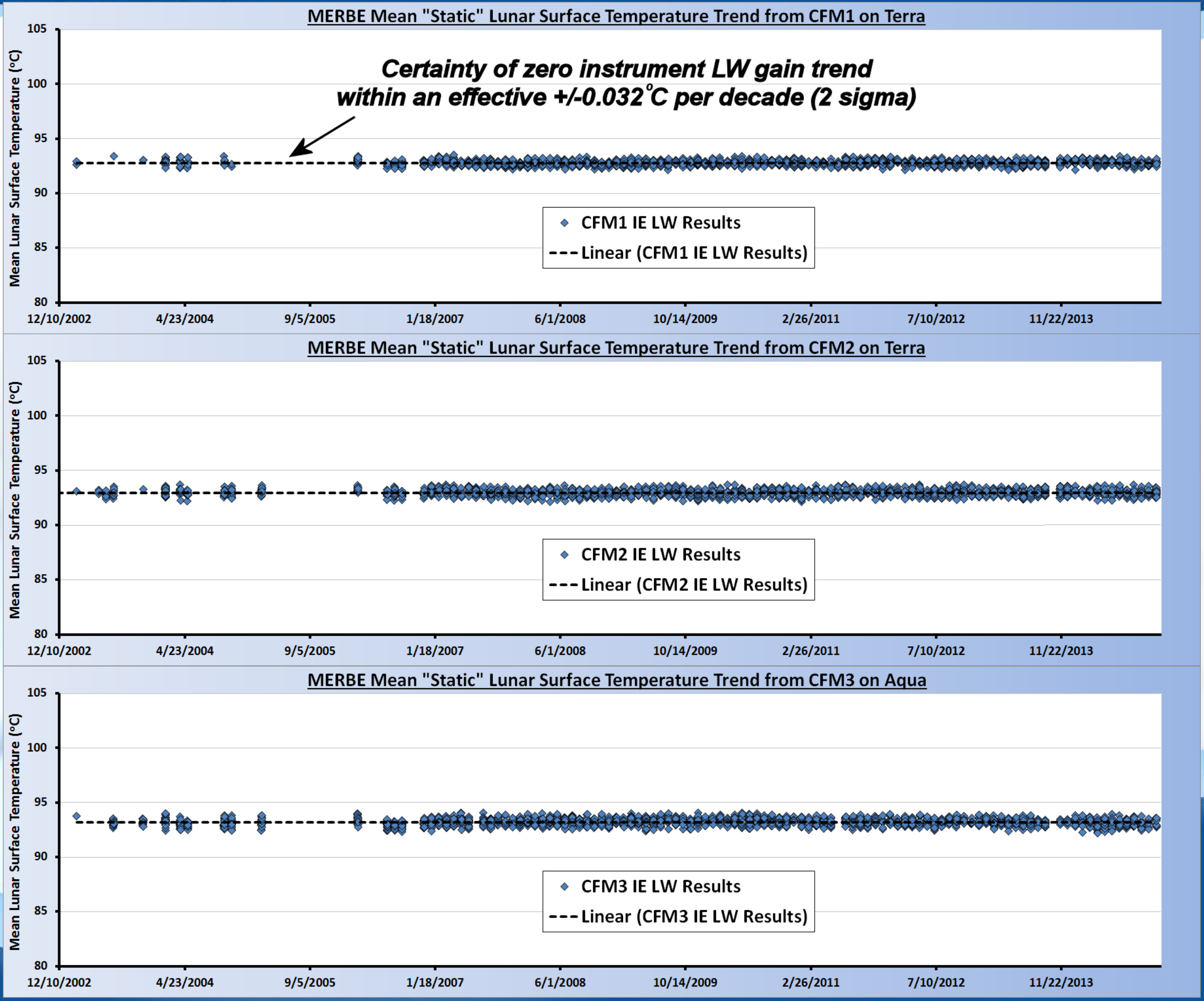
Preliminary Results Shown



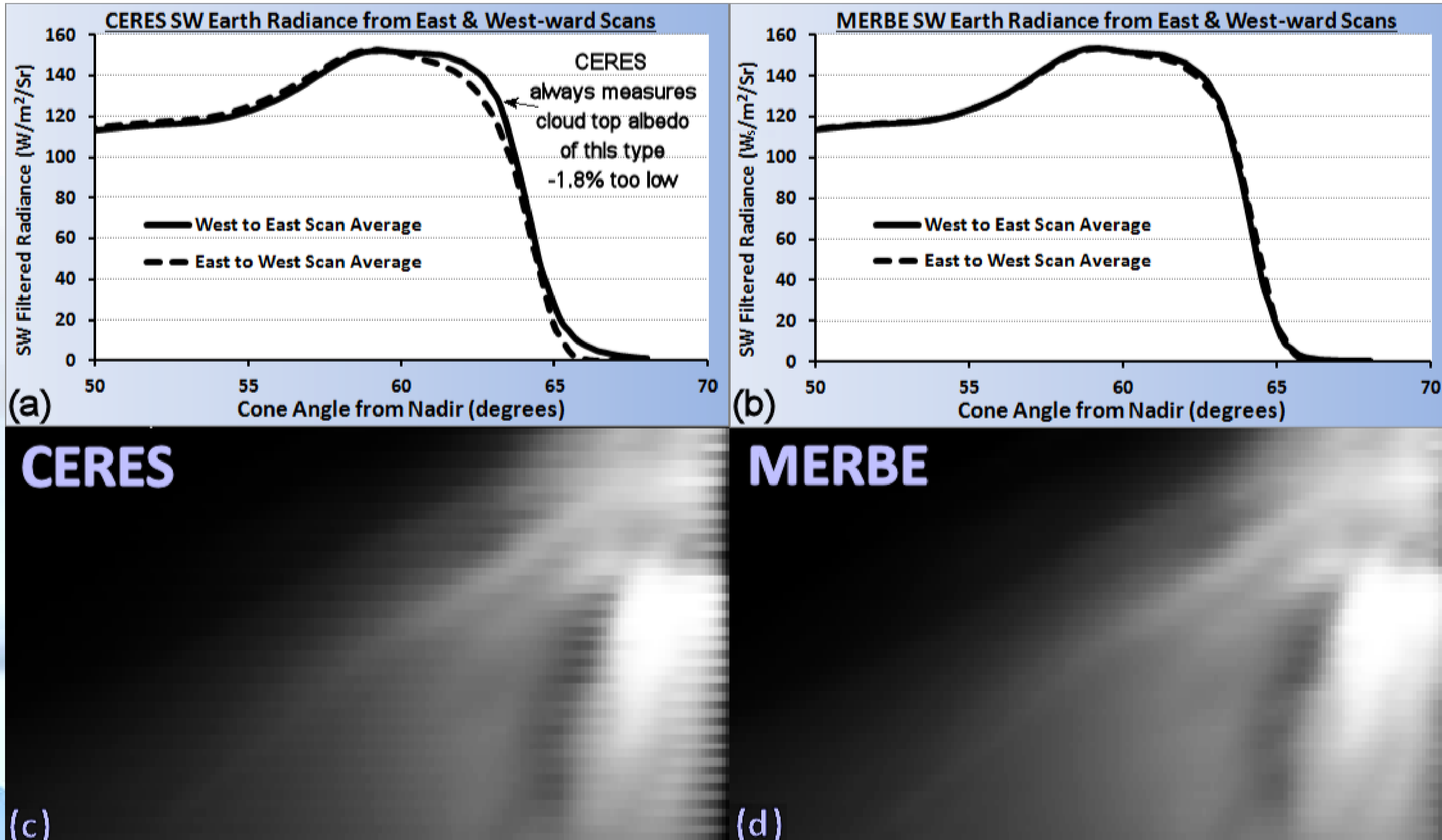




Preliminary
Results
Shown



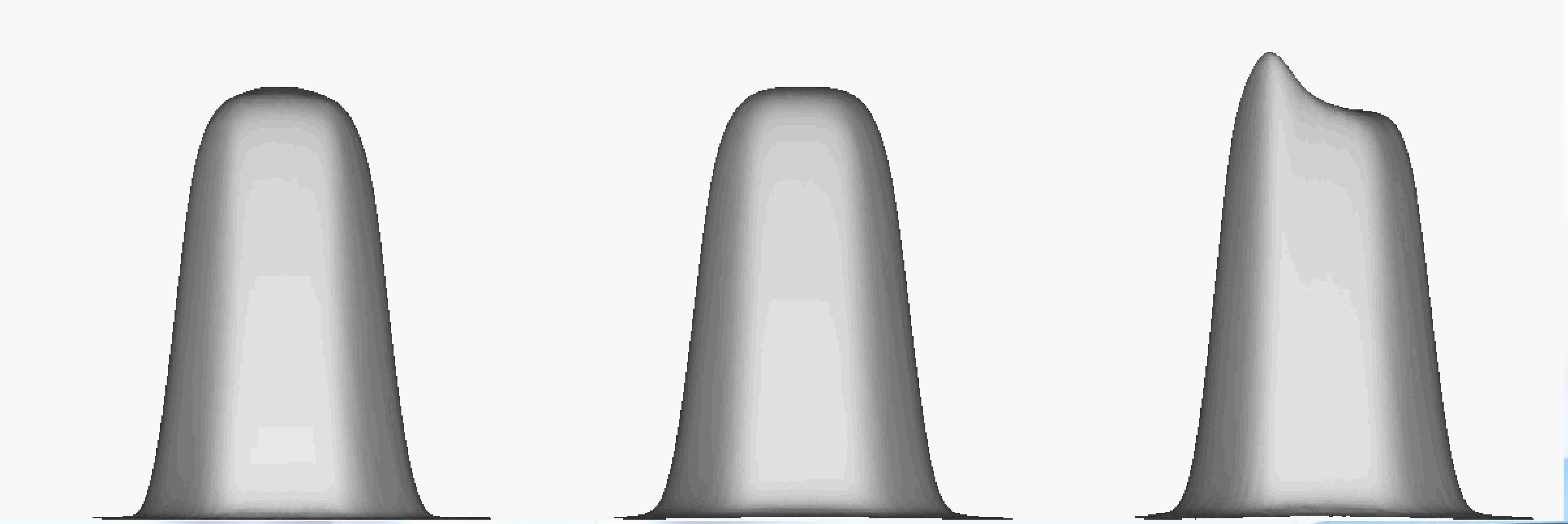
Impulse Enhancement also removes CERES scene dependent biases of >1%



MERBE Impulse Enhancement (IE) also allows a high resolution continuous analytical map M(θ,Φ) of each Moon-FOV to be made for direct lunar radiance inversion

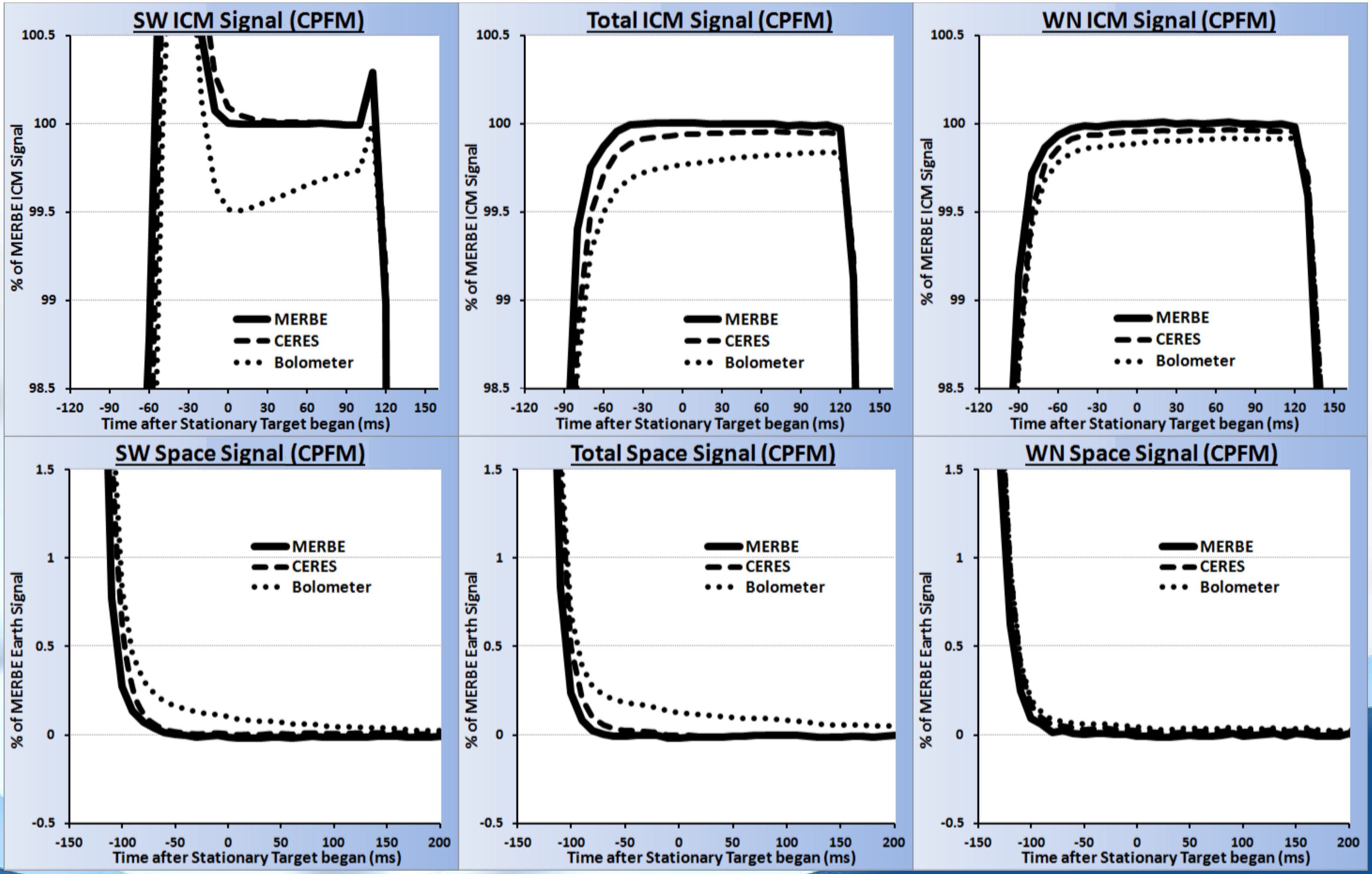
ERB channels for CFM1 on Terra

SW **Total** **WN**

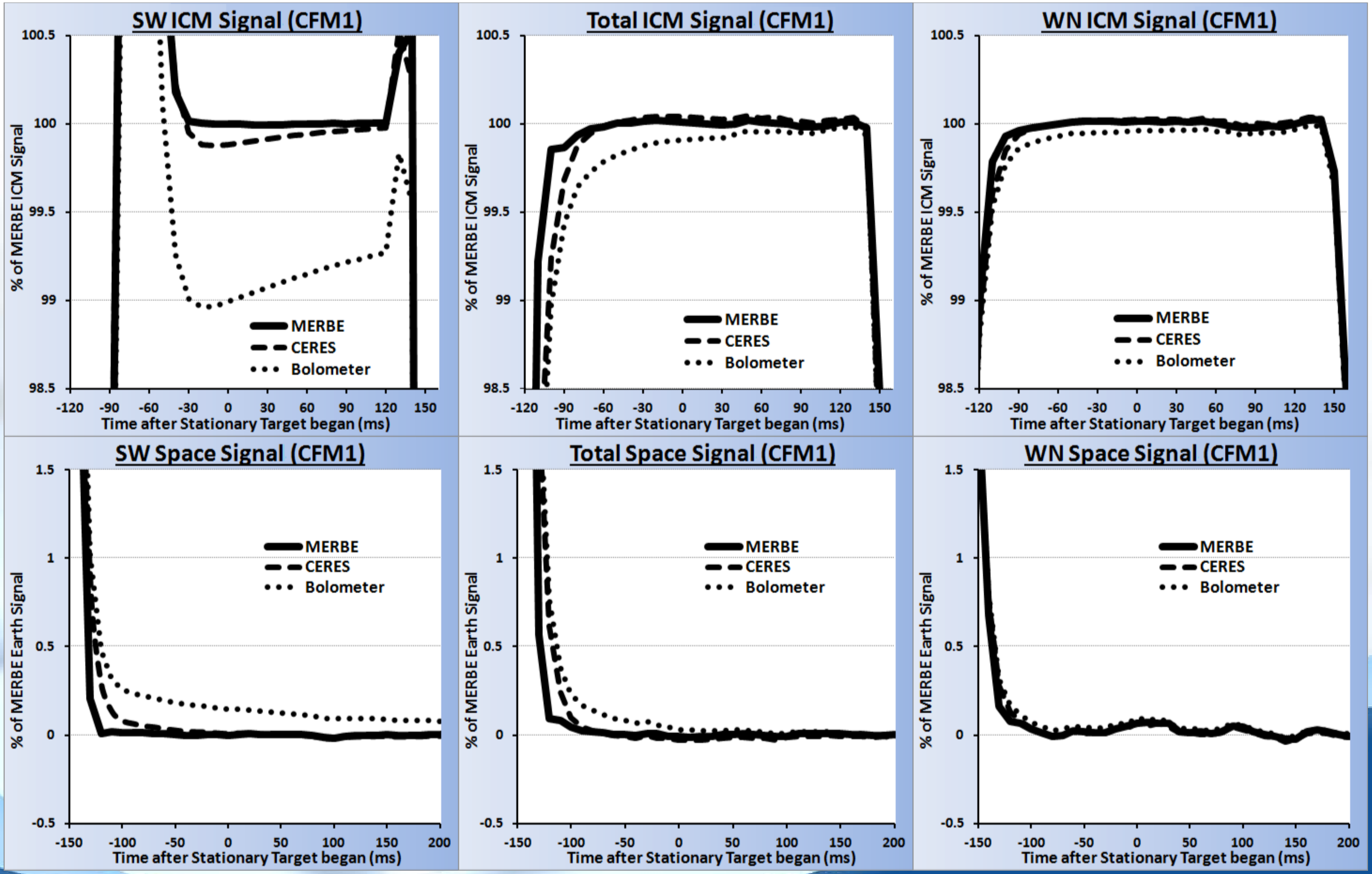


This enables lunar radiance measurements from each mere glimpse of the Moon giving 1000's of calibration points

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



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



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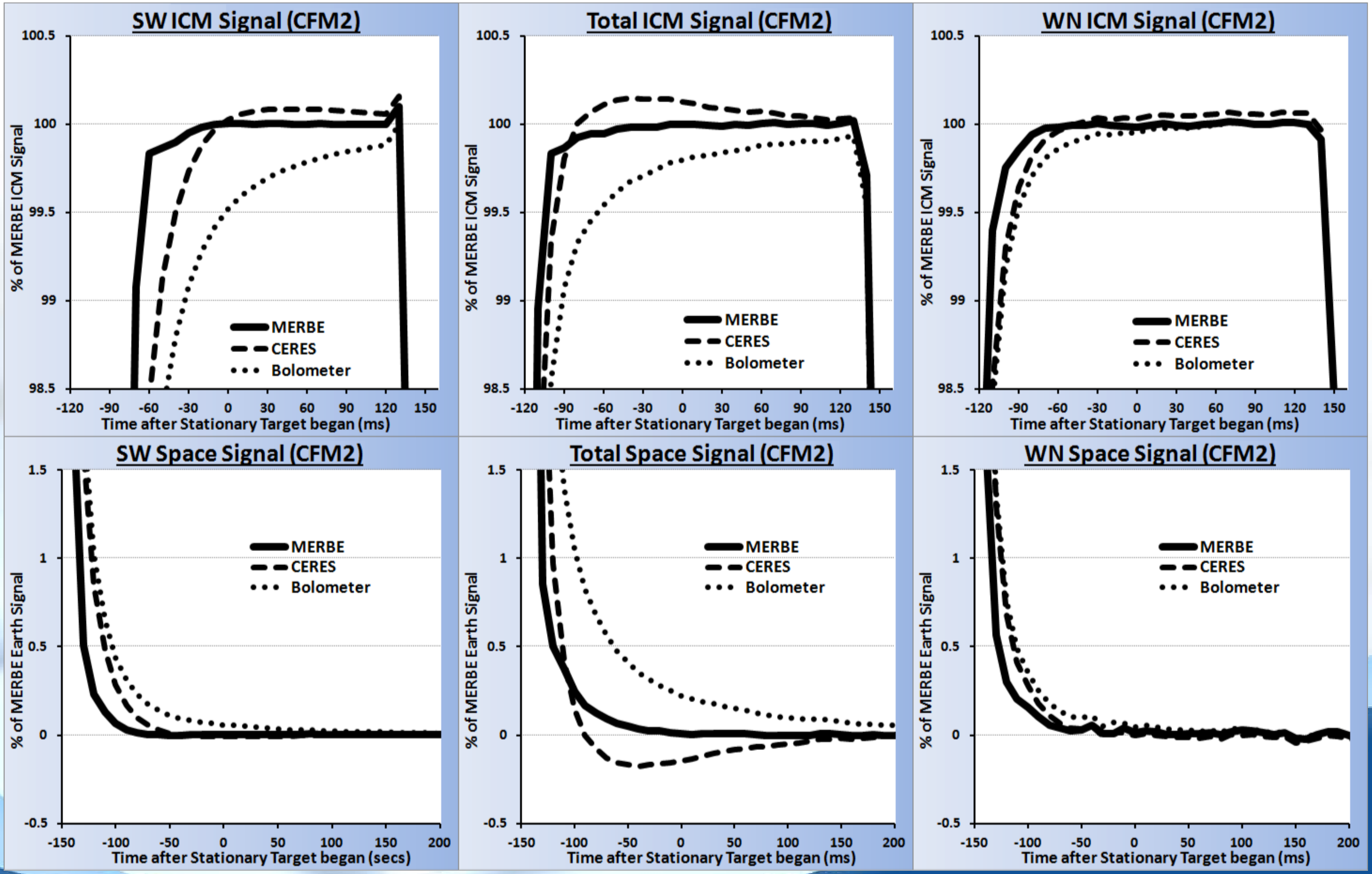
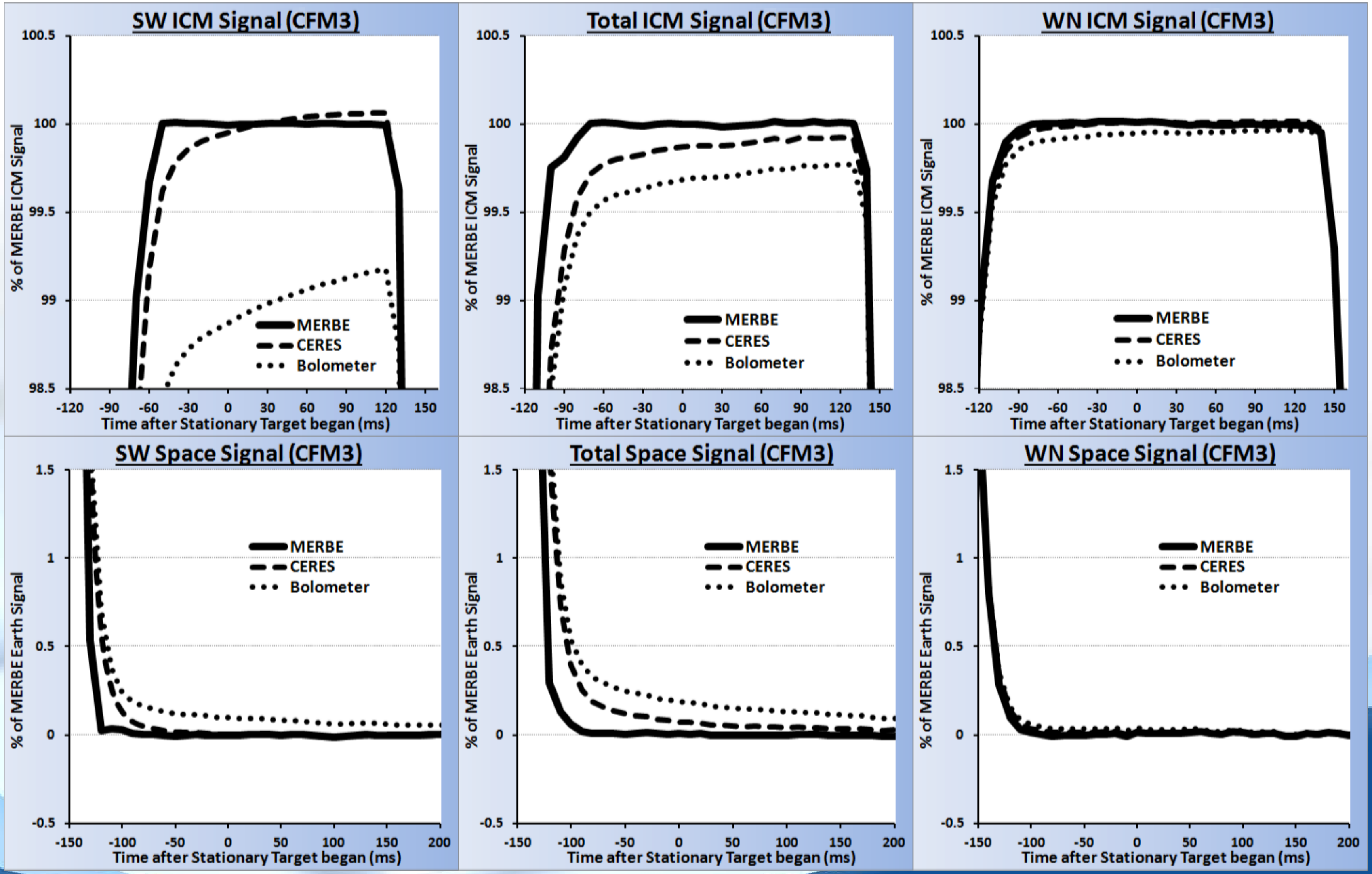
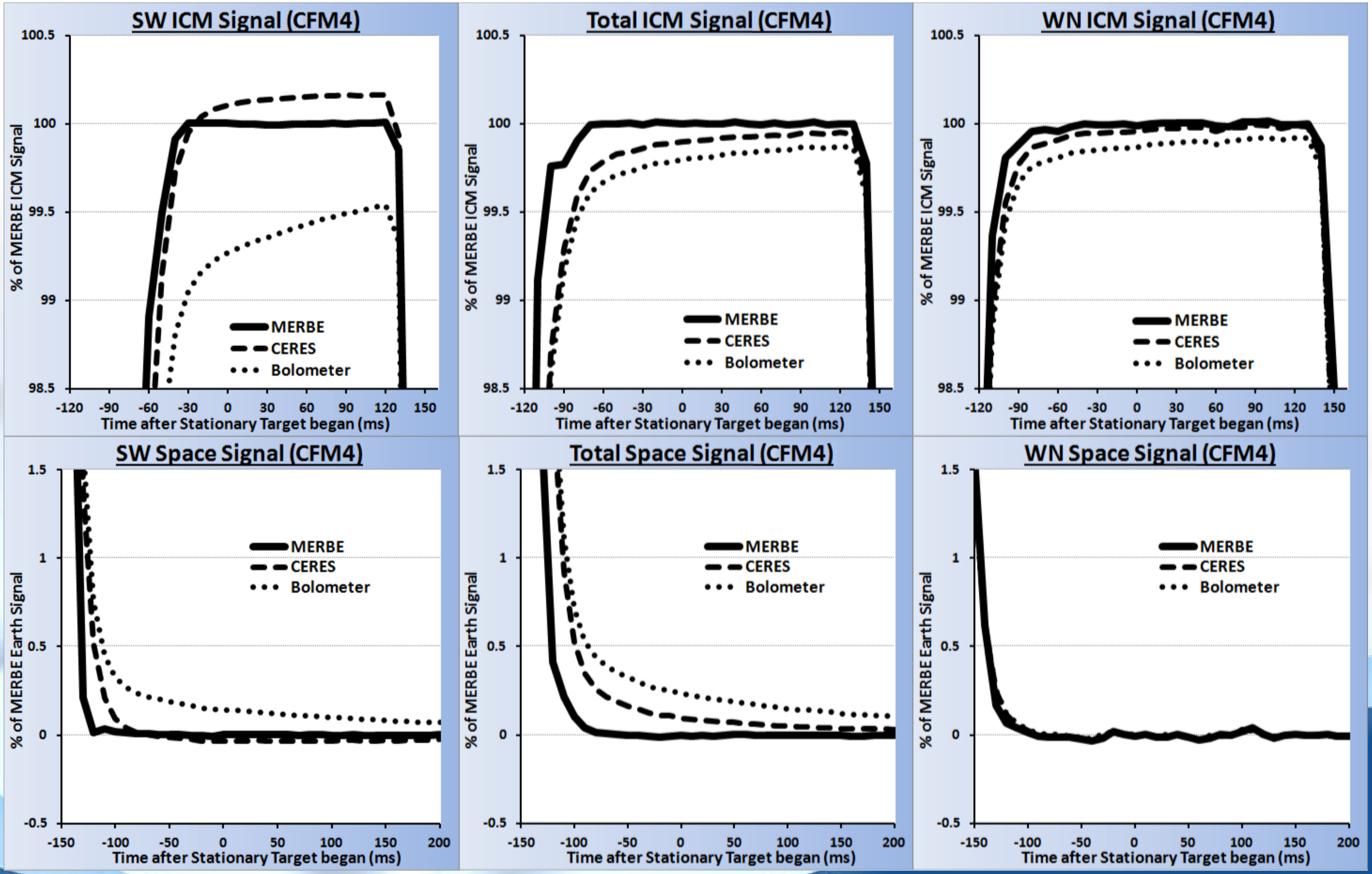


Impulse Response Found using In-flight Lamp/IBB/Space scans



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



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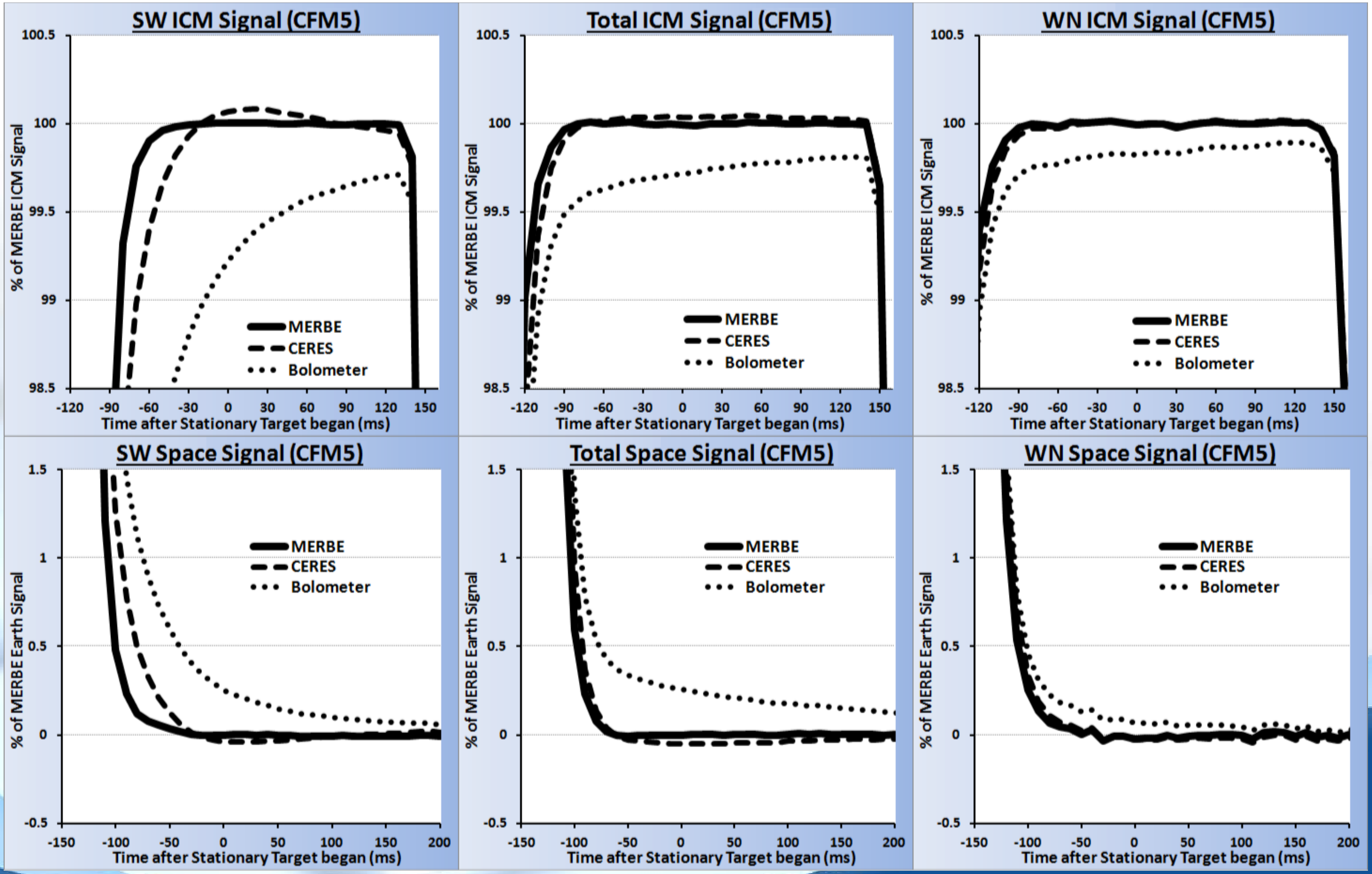
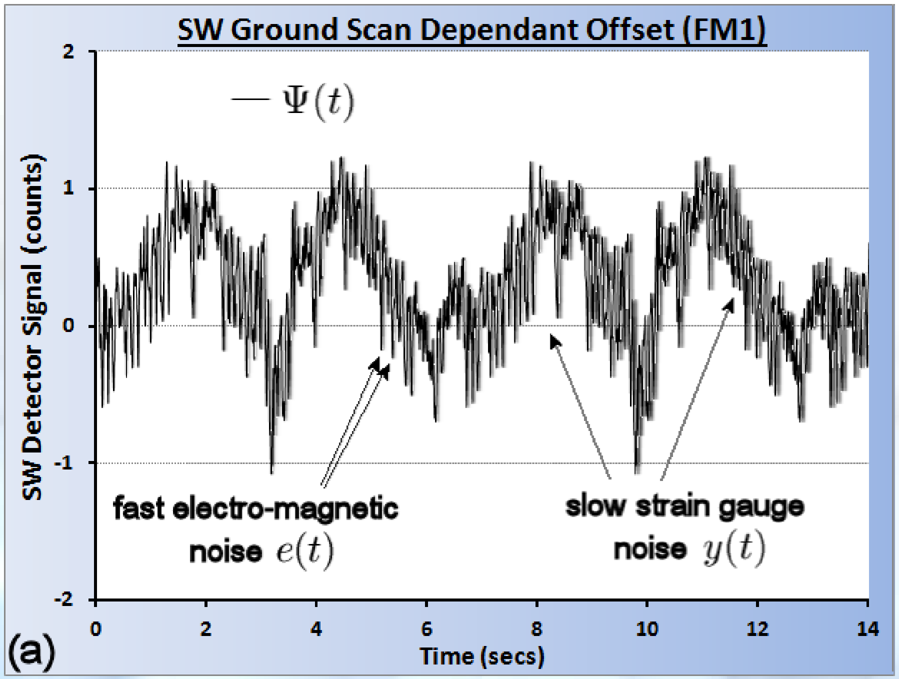
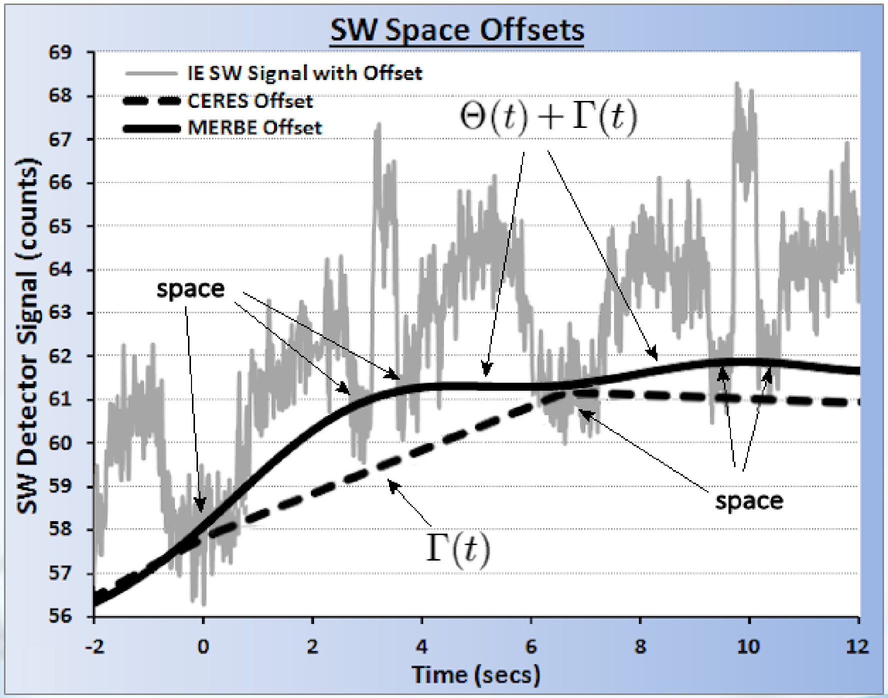
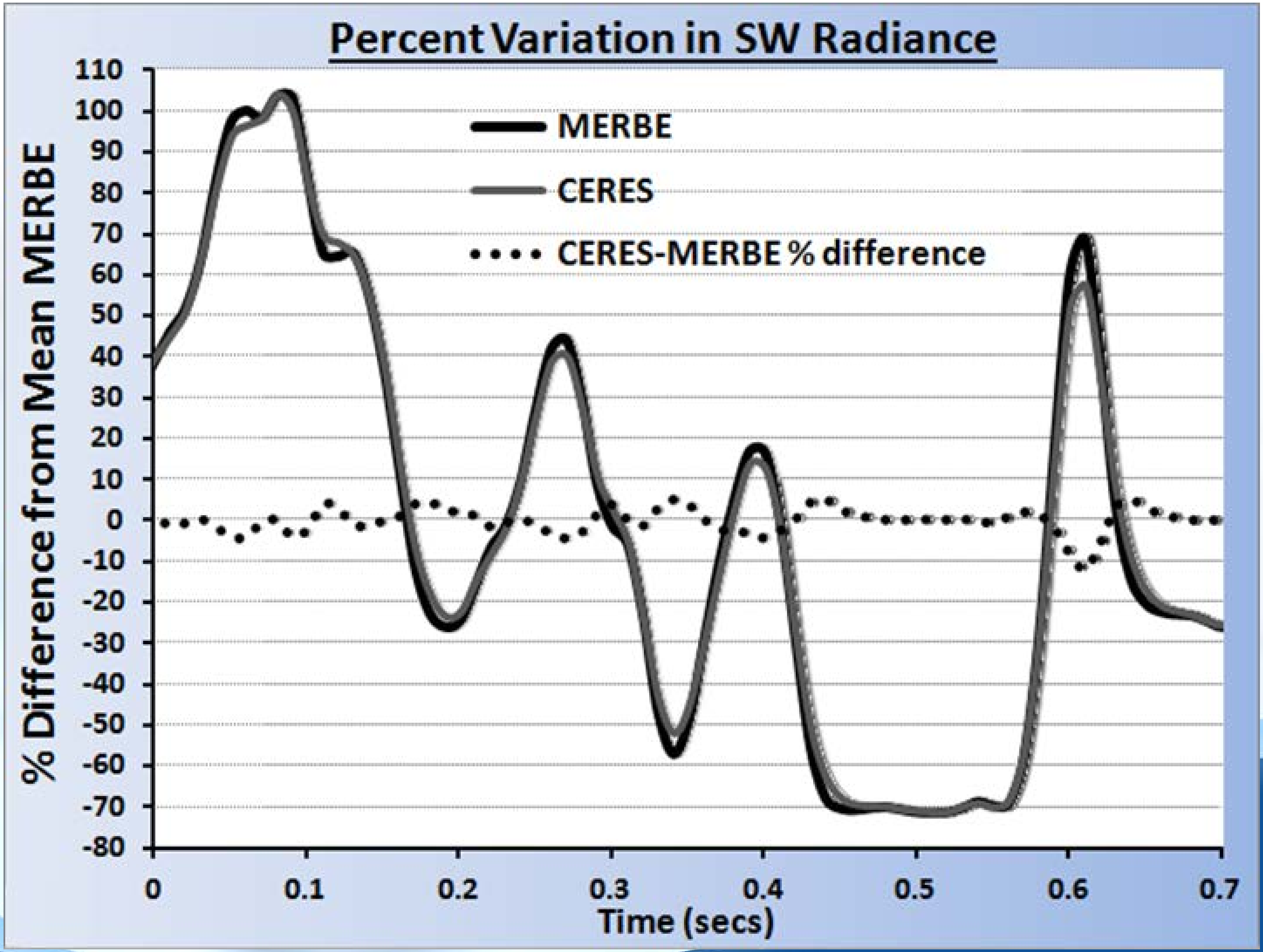


Non-Linear Fourier Series Offset Correction



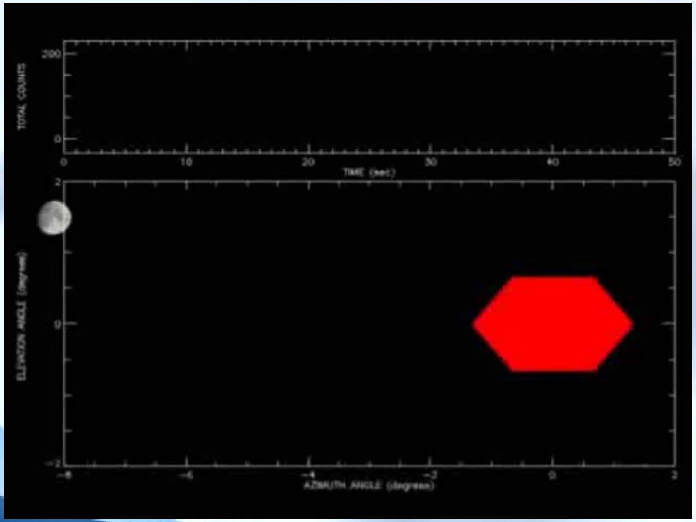


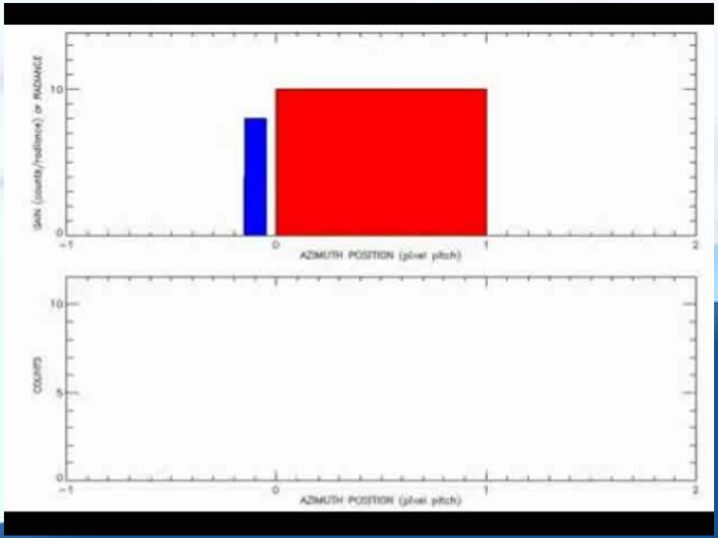
MERBE IE corrects Instantaneous CERES errors of > 10%

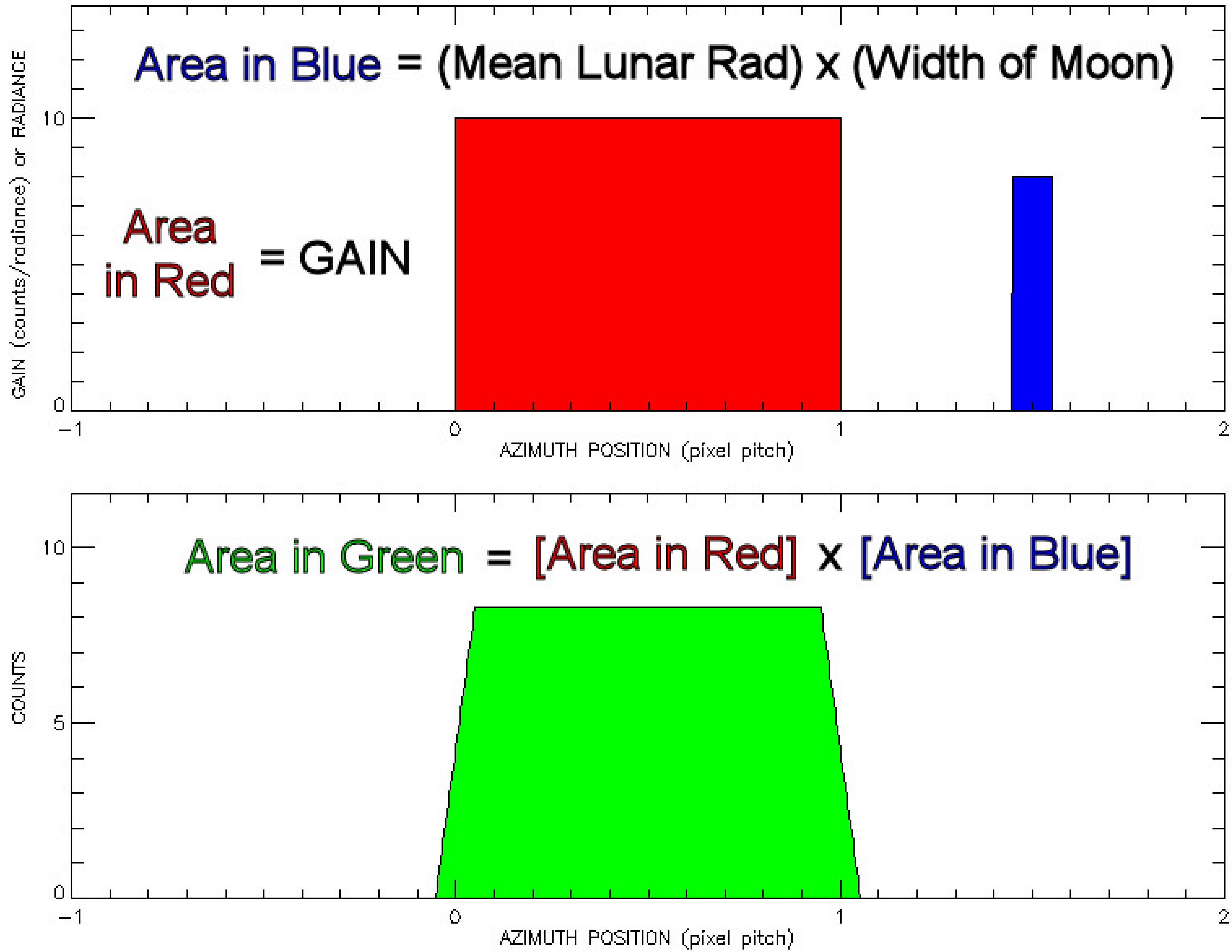


3. Placement on and Holding to the MERBE Watt SI Traceable Scale

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

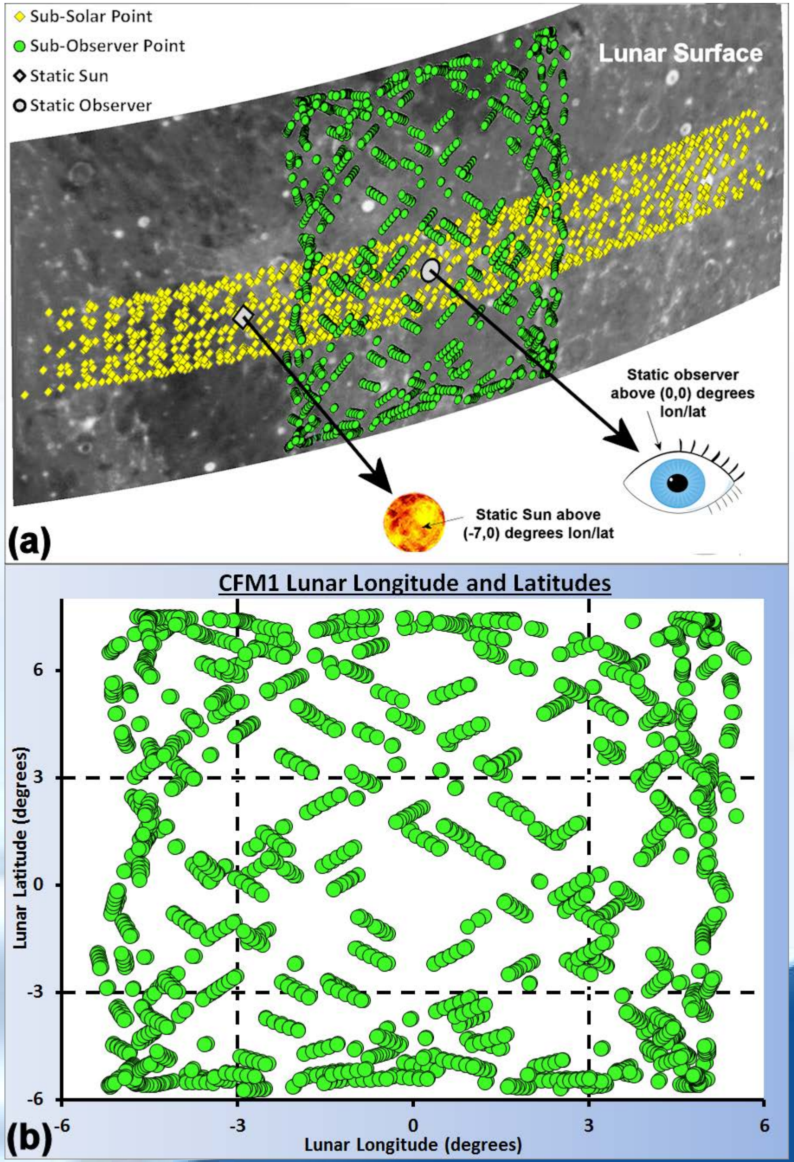




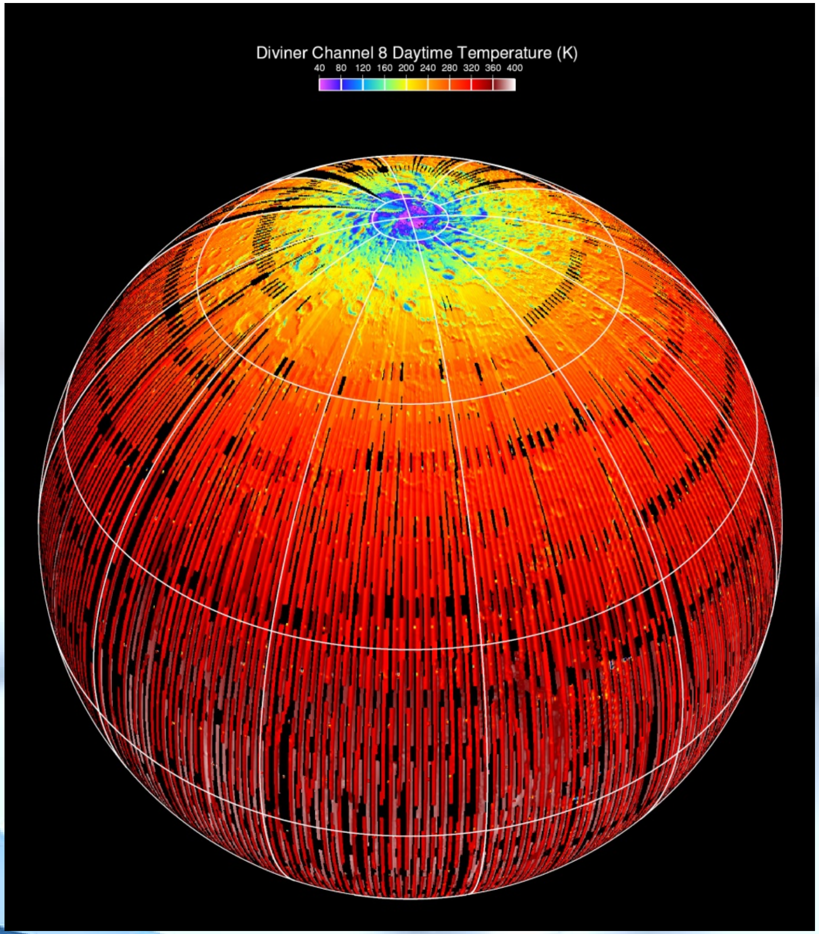


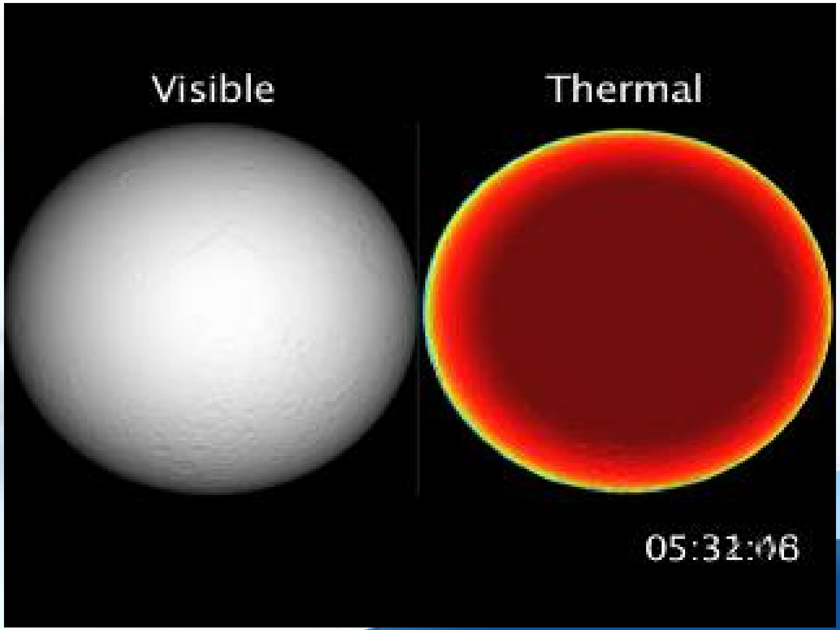
Area in Blue = (Mean Lunar Rad) x (Width of Moon)
Area in Red = GAIN
GAIN (counts/radiance) or RADIANCE
10
0
−1
0
1
2
AZIMUTH POSITION (pixel pitch)
Area in Green = [Area in Red] x [Area in Blue]
COUNTS
10
5
0
−1
0
1
2
AZIMUTH POSITION (pixel pitch)

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



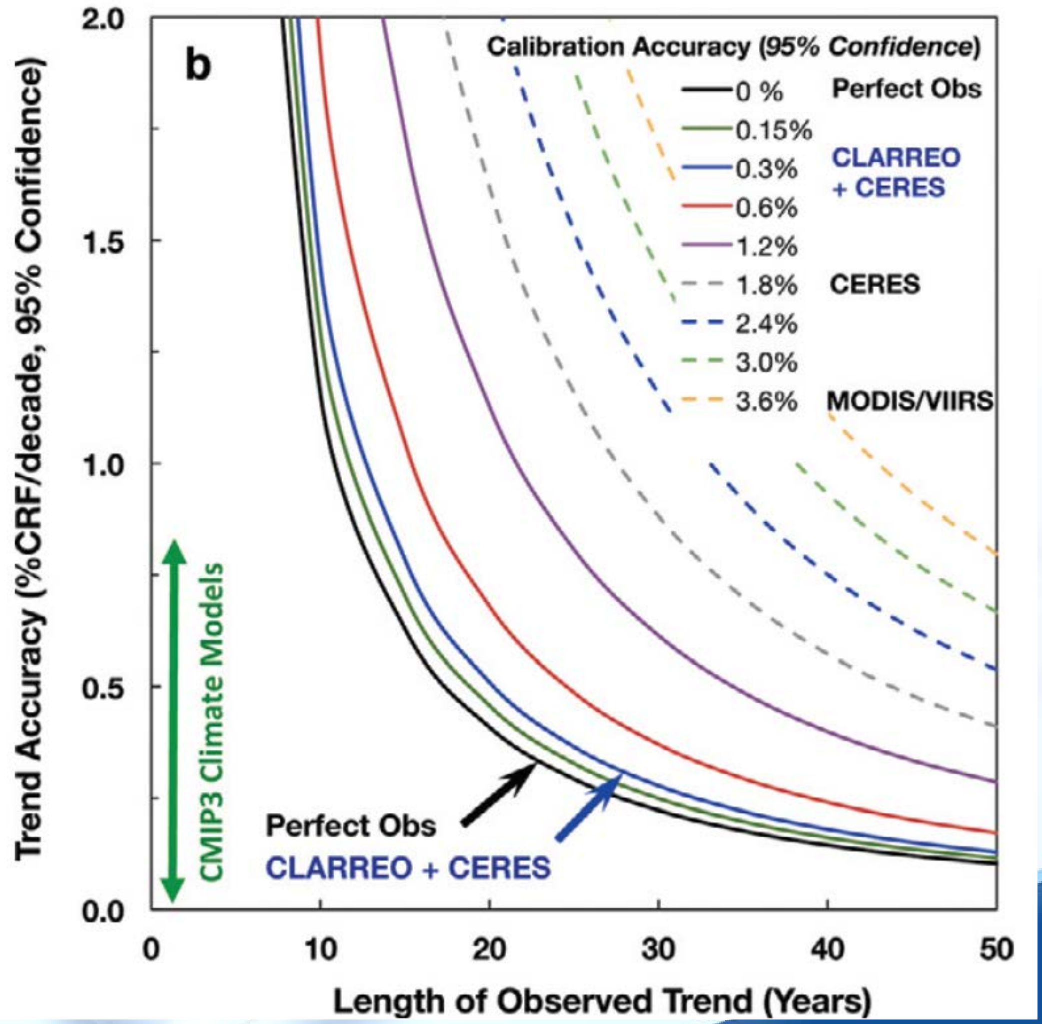


CERES detectors are linear to <0.1%

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

Fig. 3b from Wielicki et al (2013)



Quote from R. Cooke, B. A. Wielicki, D. F. Young and M. G. Mlynczak (2013)

"a uniform yardstick, however imperfect, can enable calculations supporting complex social decisions"

SeaWIFS PAR cannot be used to validate CERES to same 0.1%decade^{-1} level according to its cal team

Robert Frouin <rfrouin@ucsd.edu>

Re: Citing you on SeaWIFS PAR stability

To Grant Matthews

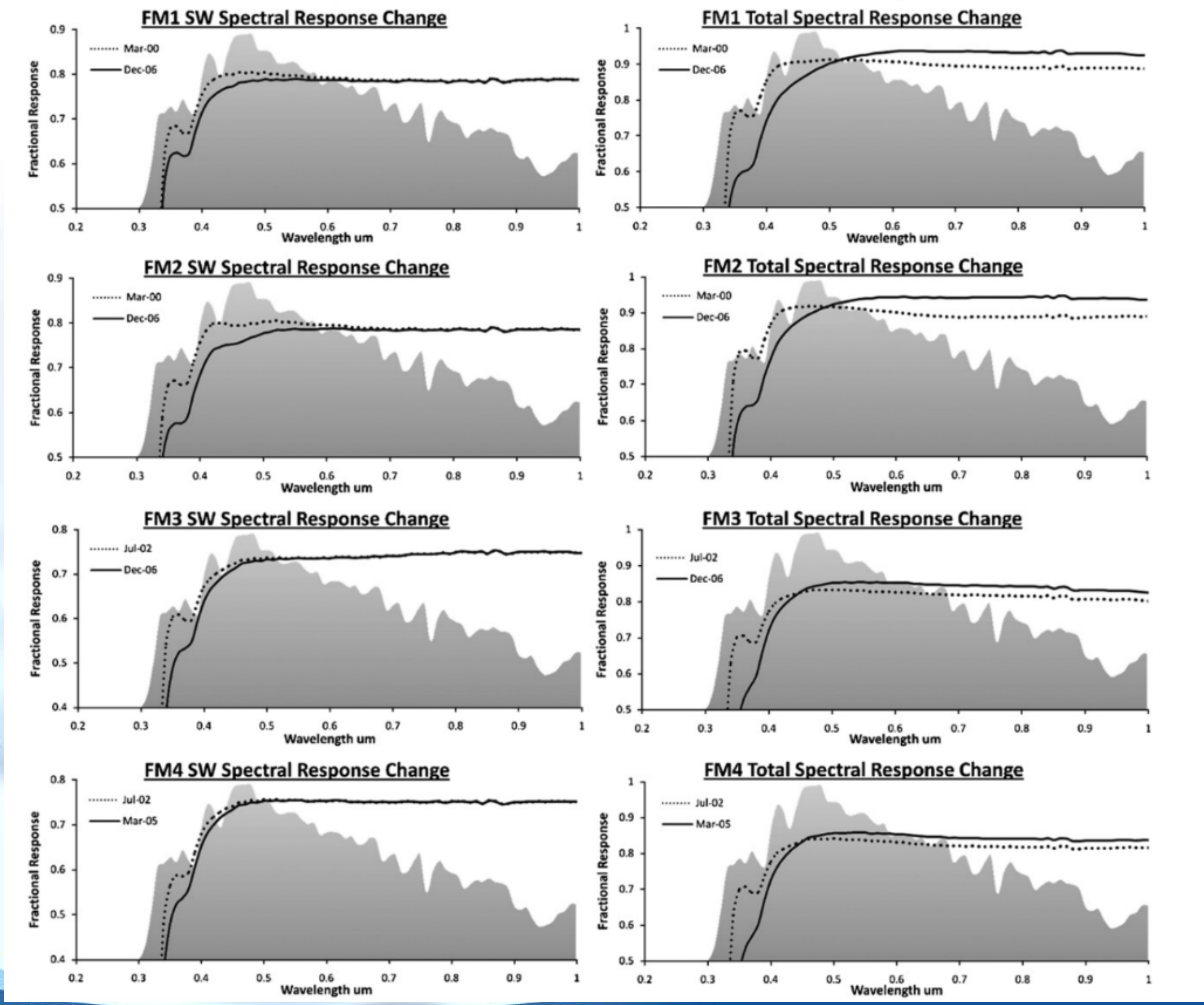
Ahoy Grant:

Comparing TOA SW flux anomalies from CERES with surface PAR anomalies from SeaWiFS, a well calibrated radiometer (they should be negatively correlated since the more radiant energy is reflected to space, the less radiant energy reaches the surface) is an indirect way to check radiometric stability of CERES. But assumptions in the modeling of PAR from SeaWiFS, in particular unchanged cloud properties during the day, and the fact that the SW and PAR fluxes cover a different spectral range (clouds do not absorb in the PAR spectral range, but do at longer wavelengths) may introduce uncertainties and biases. It is definitely preferable to cross-calibrate directly measured quantities, i.e., TOA radiance, whenever possible. (This may not be easy if the two instruments are on different polar-orbiters, since it is difficult to find observations with the same line-of-sight, or if the TOA radiance is not measured in similar spectral bands.)

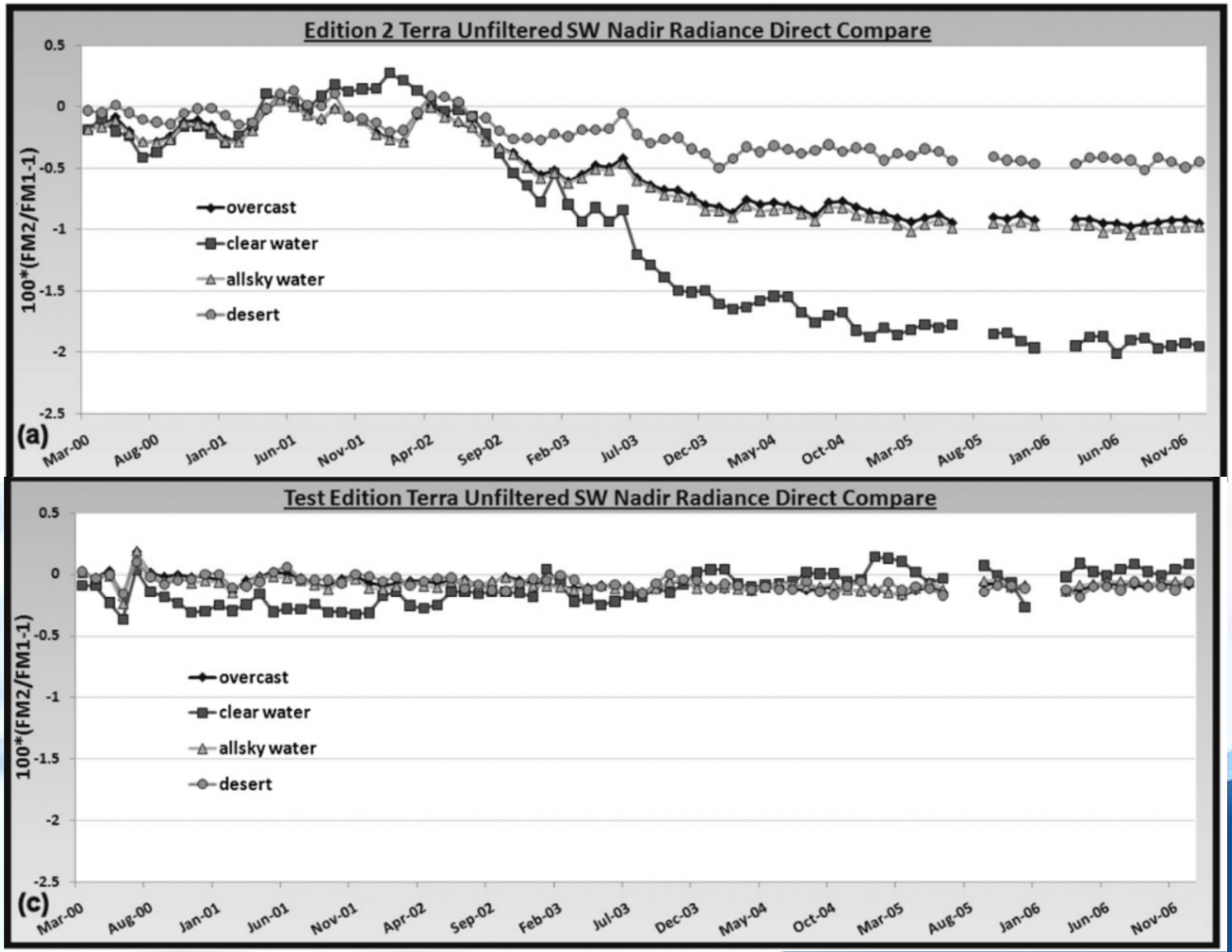
Regards, Robert.

Robert Frouin, Scripps Institution of Oceanography, (858) 534-6243

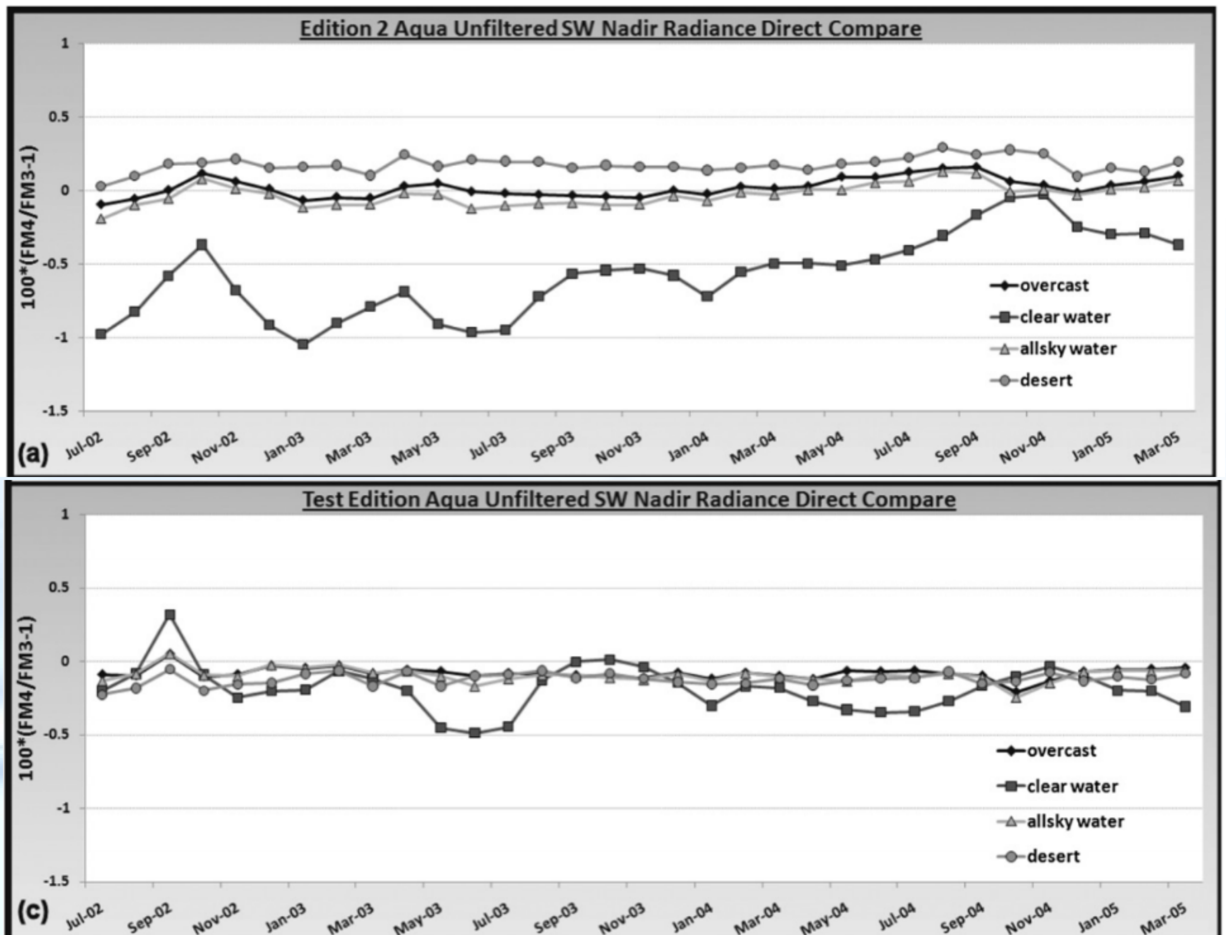
Matthews (2009) derived spectral responses for CERES units that unify nadir direct compare



Matthews (2009) derived spectral responses for CERES units that unify nadir direct compare



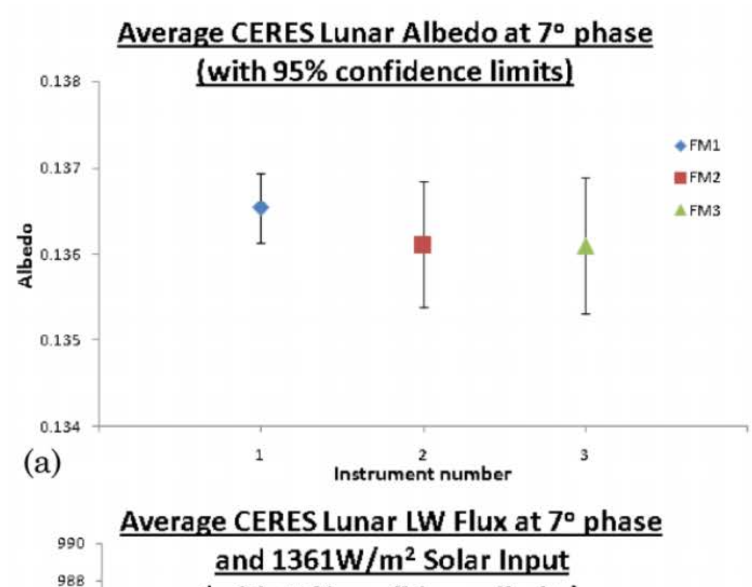
Matthews (2009) derived spectral responses for CERES units that unify nadir direct compare



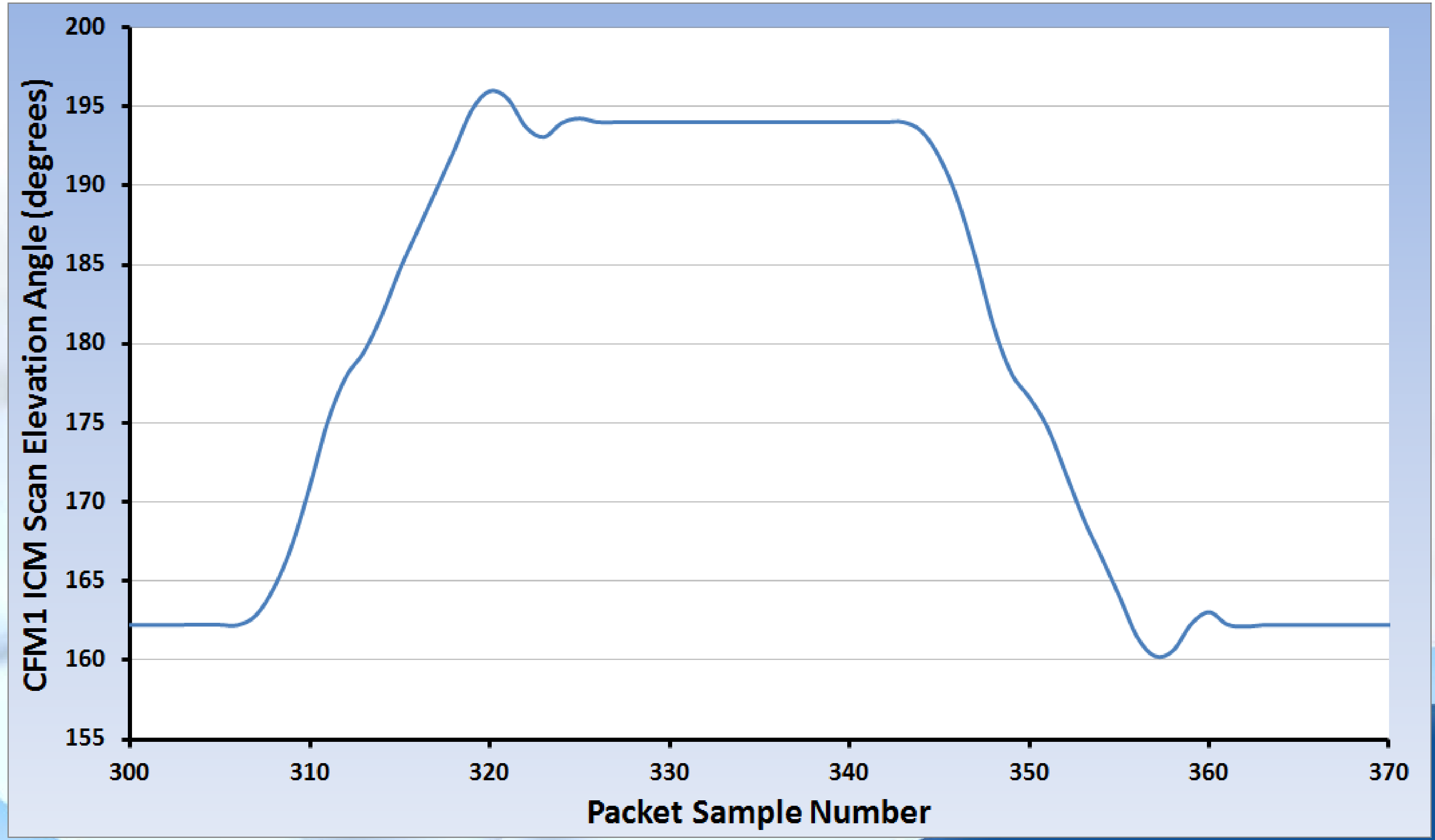
Matthews (2008) CFM1 & CFM2 Terra Moon albedo results agreed to <0.3% at <u>separate times</u> after unification from nadir Earth data, suggesting such an absolute standard is possible for MERBE

20 September 2008 / Vol. 47, No. 27 / APPLIED OPTICS 4989

The mission averaged thermal flux results $\chi^{\bar{LW}}$ and $\chi^{\bar{WN}}$ are shown for three instruments in Figs. 5(b) and 5(c), along with the corresponding 95% confidence intervals. The average thermal irradiance measured by all four instruments is $977\,\mathrm{Wm^{-2}}$. Figure 5(b) suggests there is statistical significance in the disagreement of lunar LW flux between FM1 and FM2. This is, however, to be expected because the technique of spectral balancing [7,8] was used to place FM1 and FM2 on a similar thermal radiometric scale for the average "allsky" Earth scene only. FM2 actually still consistently reads a 0.5–1% lower thermal flux than FM1 for warm scenes, such as tropical ocean and deserts (this is believed to be due to slight inaccuracies in knowledge of the Total-channel spectral response shape in the 5 <



ICM scan elevation



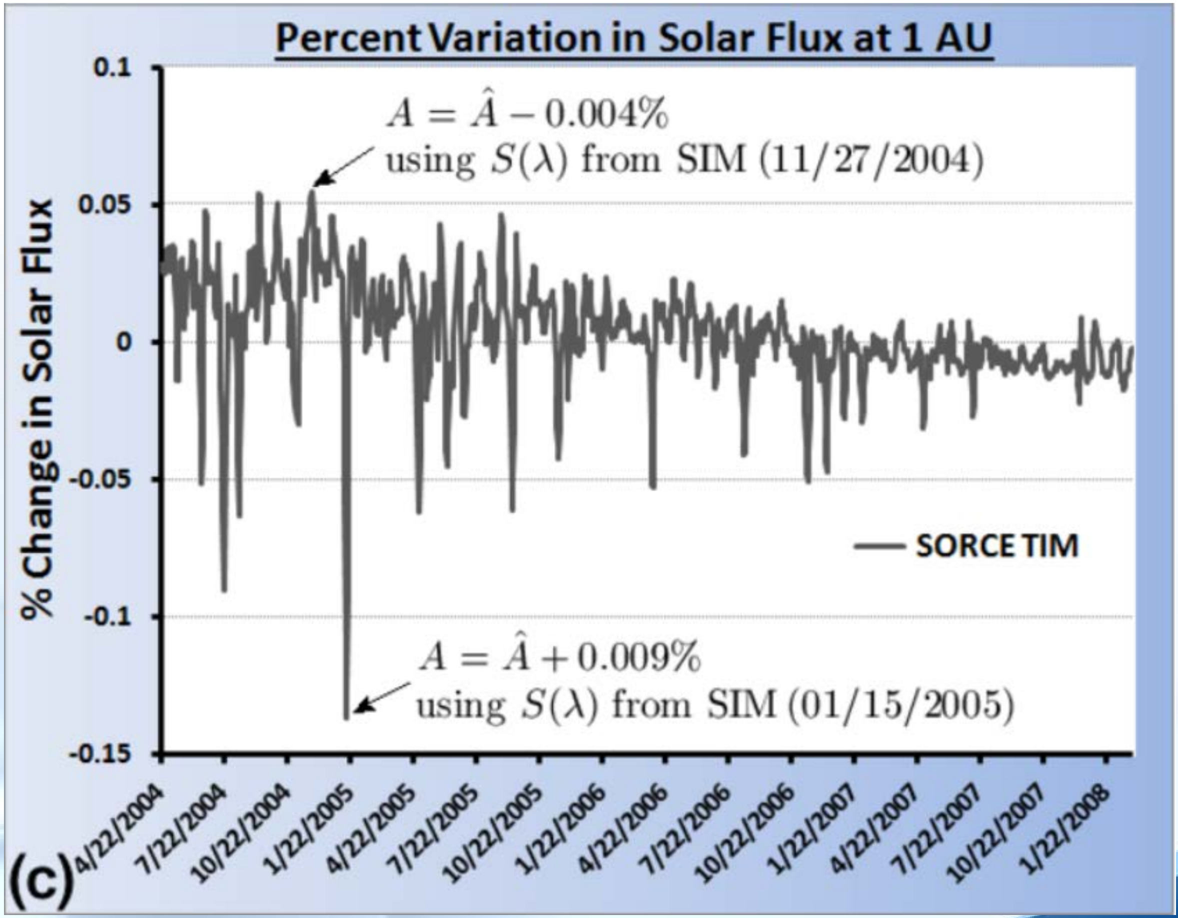
Impulse Response Found using In-flight Lamp/IBB/Space scans

https://sites.google.com/site/zedikasolv/terraMERBEcal.mp4?attredirects=0&d=1

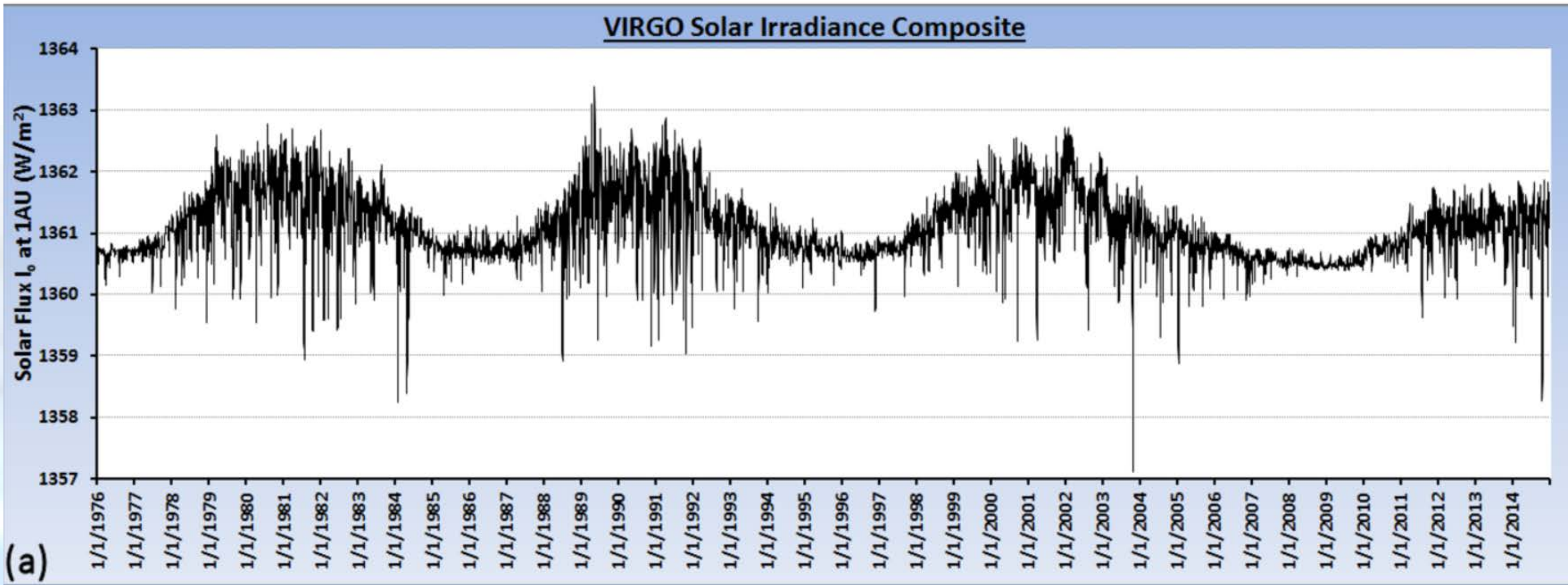
https://sites.google.com/site/zedikasolv/aquaMERBEcal.mp4?attredirects=0&d=1

https://sites.google.com/site/zedikasolv/trmmnppMERBEcal.mp4?attredirects=0&d=1

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.

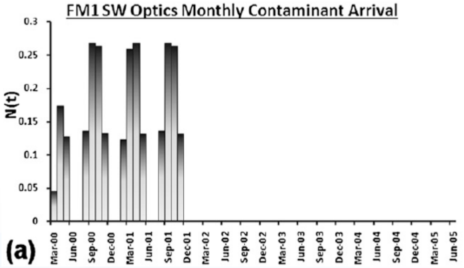
All filters were then fitted again with the same process, this time using fixed values for the nonlinear parameters to create the corresponding linear basis functions. Finally, the four coefficients for libration were fixed at their average over wavelength, and all data fitted again.

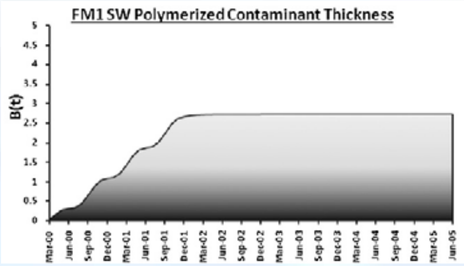
TABLE 4

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

Matthews 2009 details spectral response changes from contaminants





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

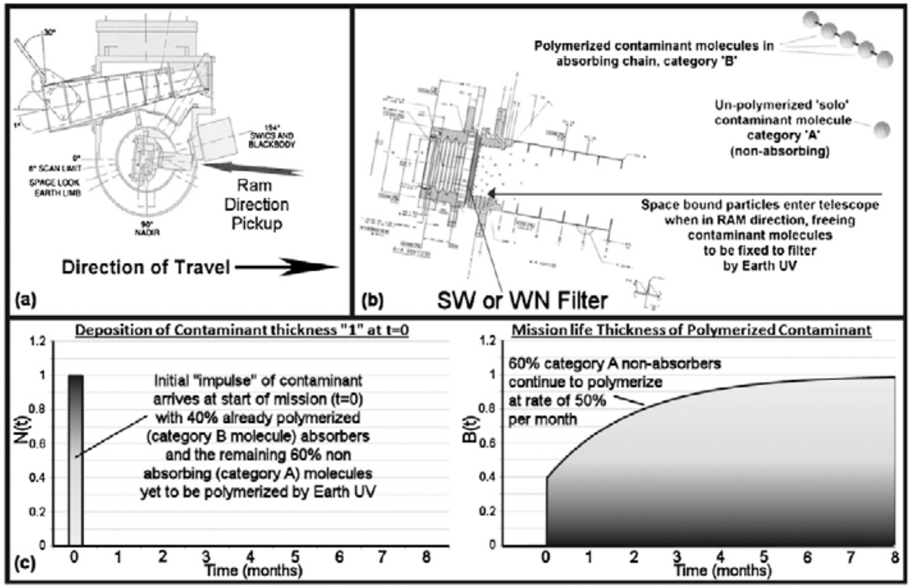
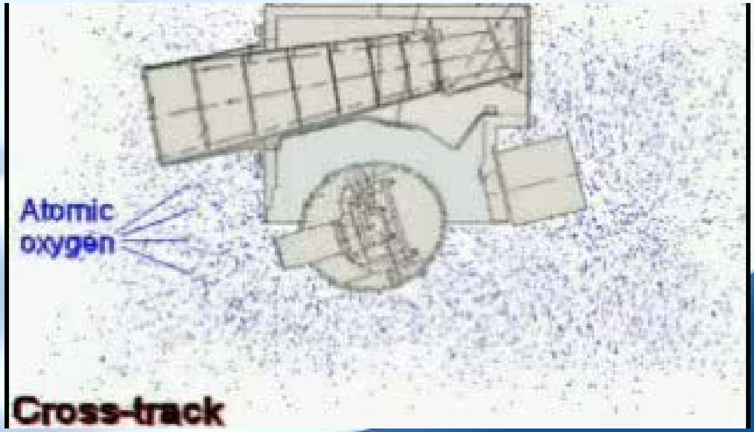


FIG. 5. (a) Diagram of CERES telescope ram exposure during RAPS mode. (b) Space-bound particle mobilization of category A and B contaminant molecules to filtering optics within telescope during ram exposure. (c) Example (left) impulse and (right) impulse response of polymerized contaminant thickness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



Matthews 2009 details spectral response changes from contaminants

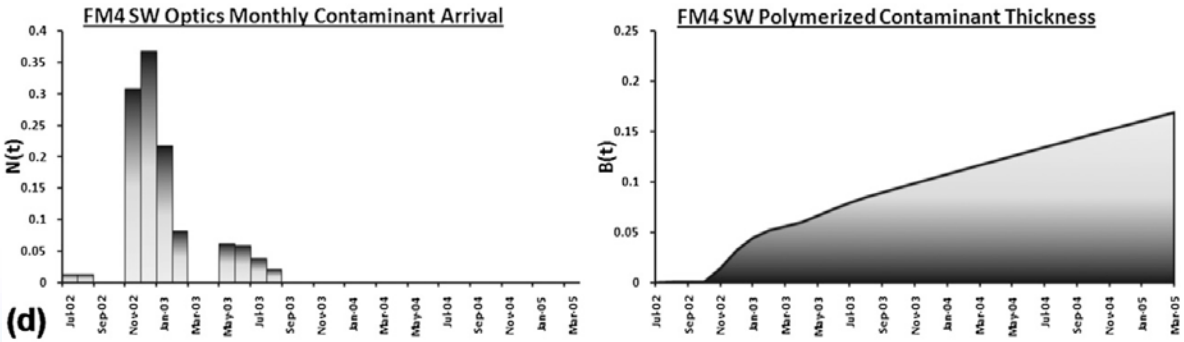
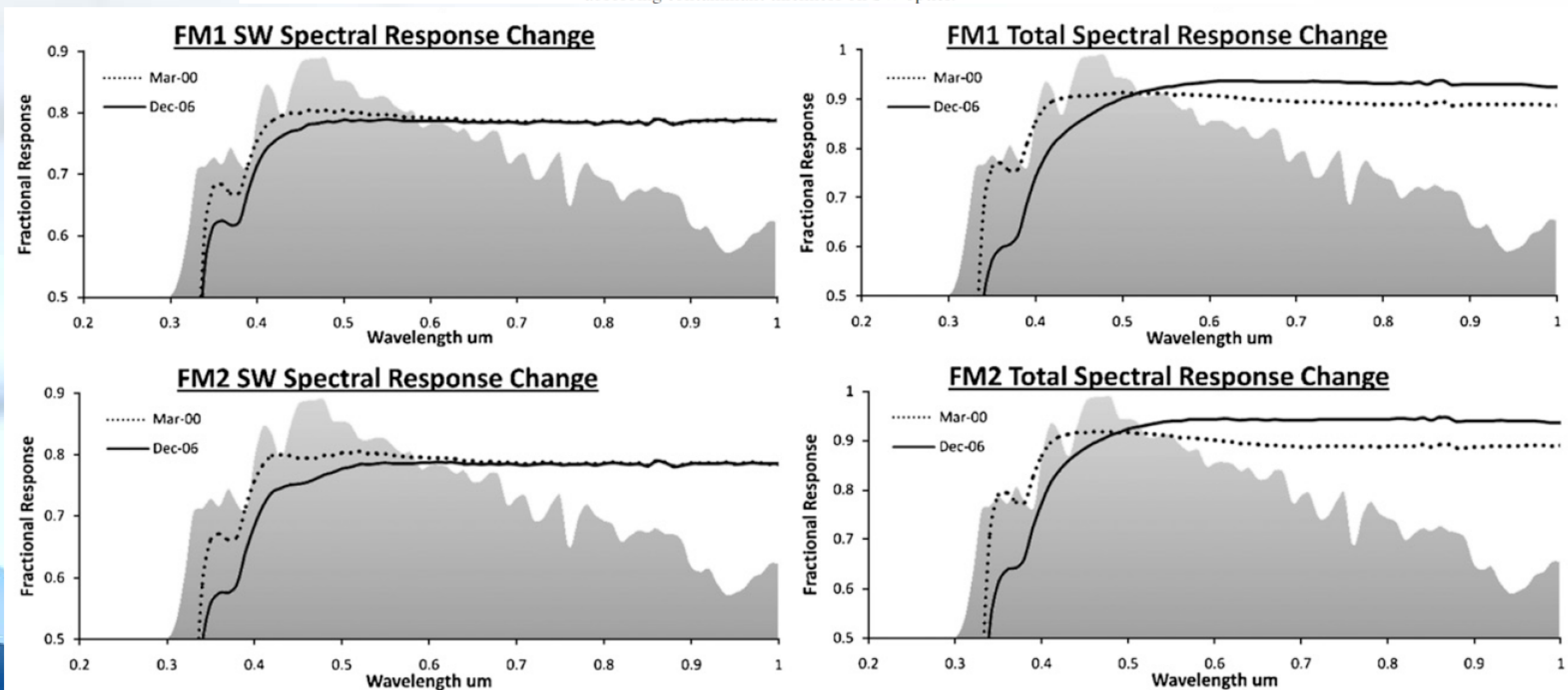
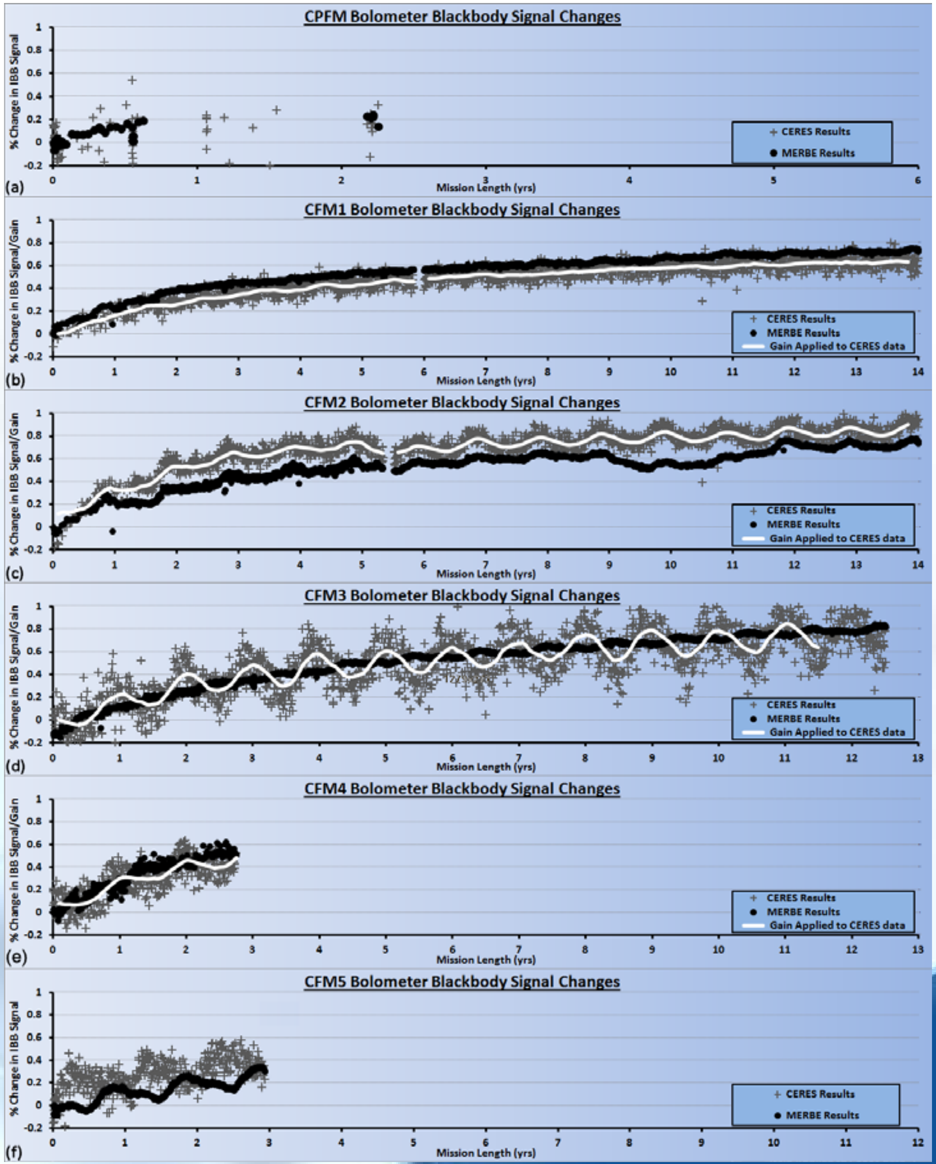


FIG. 7. Test edition model estimates of (left) monthly contaminant arrival thickness on SW optics and (right) monthly polymerized absorbing contaminant thickness on SW optics.



CERES bolometer gains all change in a very similar asymptotic way from out-gassing

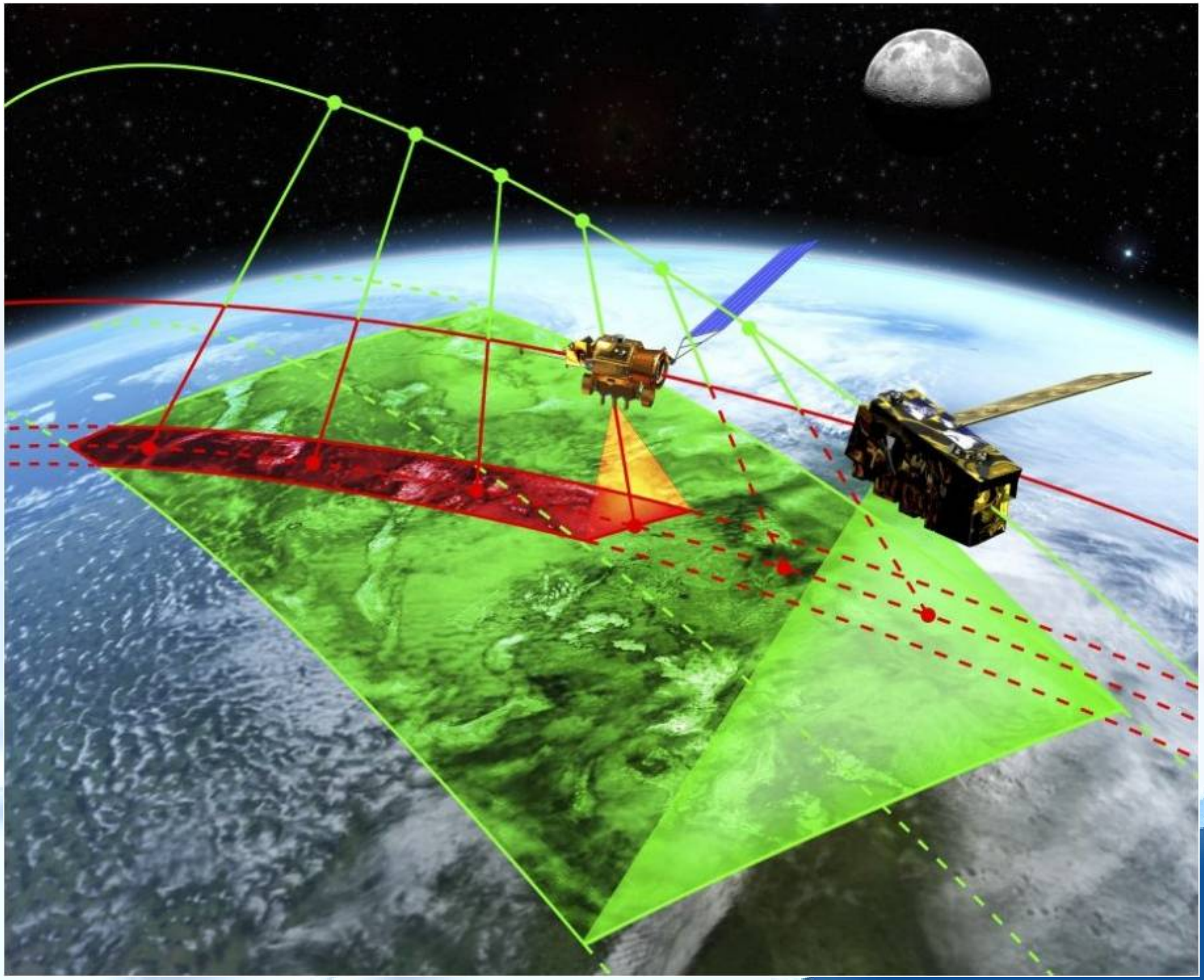


All ERB Missions

Table 1. Past, existing and future satellite missions measuring ERB parameters.

ERB Mission	Lifetime
NIMBUS 7 ERB[6]	1978-1993
ERBE [7]	1984-2005
CERES[8]	1998-Present
GERB[9]	2002-Present
SCARAB[10, 11]	2011-Present
DSCOVR(NISTAR) [12]	2015-Present
EarthCARE[13]	2016-?
RBI[14]	2021-?
CLARREO[4]	2023-?
TRUTHS[15]	?-?

Fig. 6 from Wielicki et al (2013)



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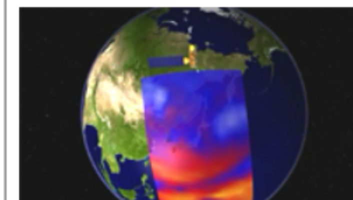
Clouds and the Earth's Radiant Energy System (CERES)

There are two CERES on Aqua, following two on the Terra satellite, launched in 1999, and one on the Tropical Rainfall Measuring Mission, launched in 1997. This artist's concept animation [16.6 MB QuickTime] shows the CERES instruments (one in cross-track scan mode, the other in biaxial scan mode) measuring heat emitted (outgoing longwave radiation) to space from the Earth's surface. (Animation by Jesse Allen)



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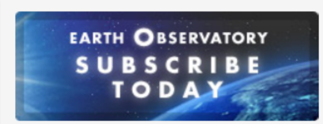
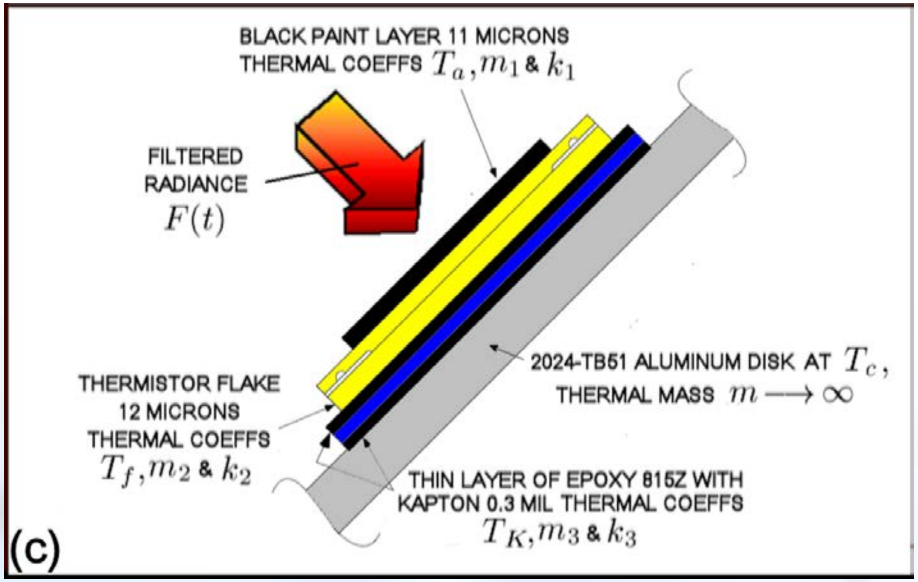


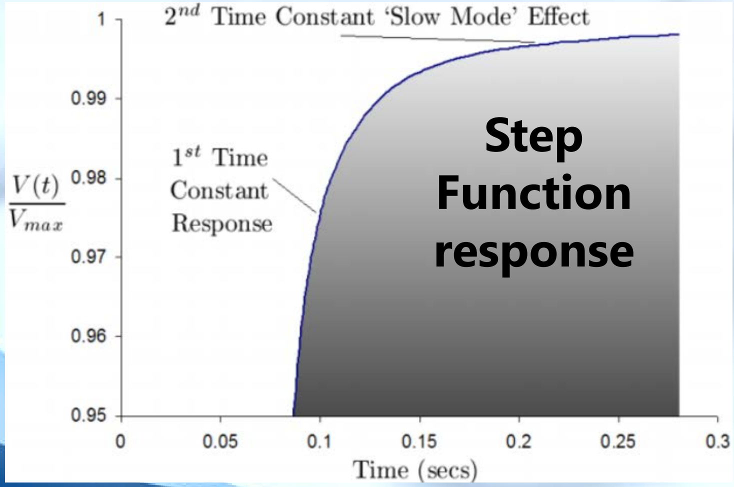
Bolometers have relatively slow time impulse responses

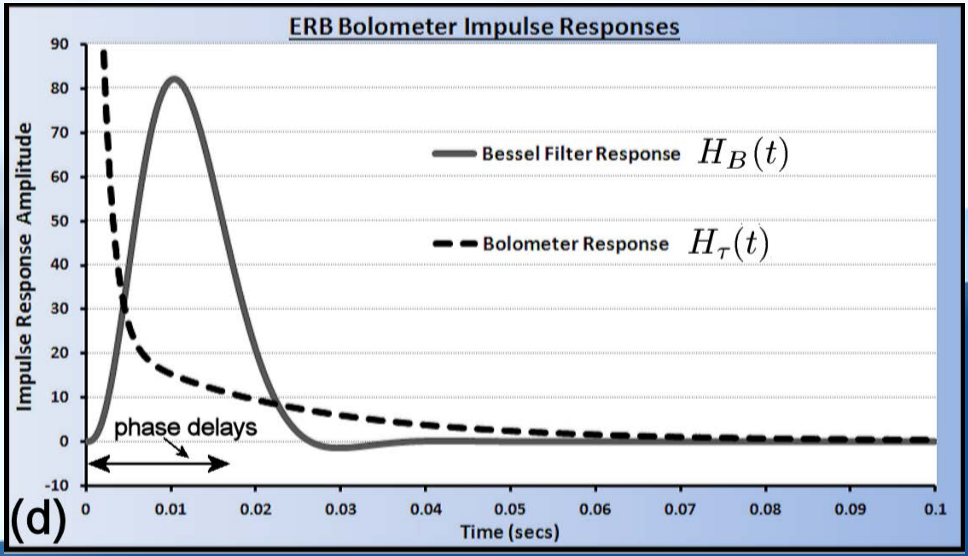


$$Q_1 = T_a - T_c$$
$$Q_2 = T_f - T_c$$
$$m_1 \frac{\partial Q_1(t)}{\partial t} = F(t) - k_1[Q_1(t) - Q_2(t)]$$

Thermal flow represented by four box Heat Equation model

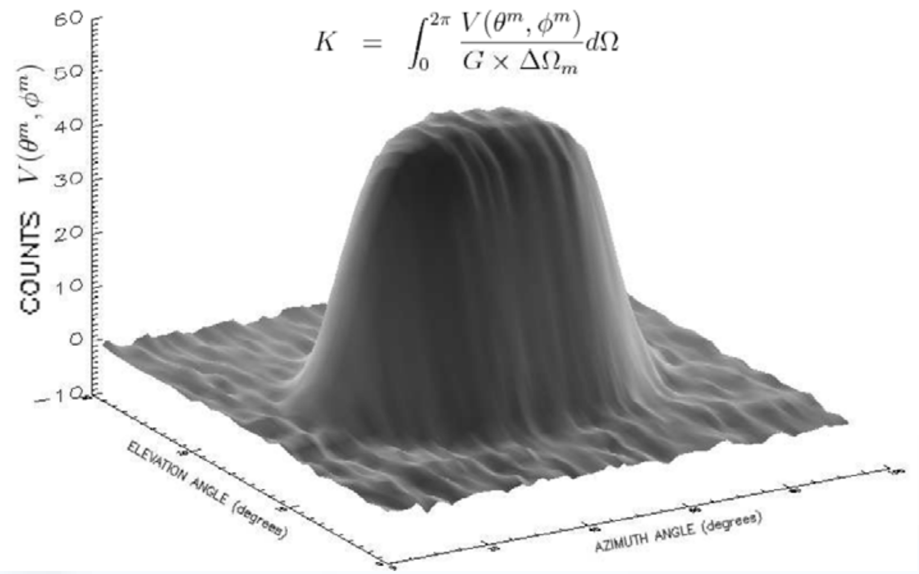
Also a 22Hz analogue four pole Bessel filter

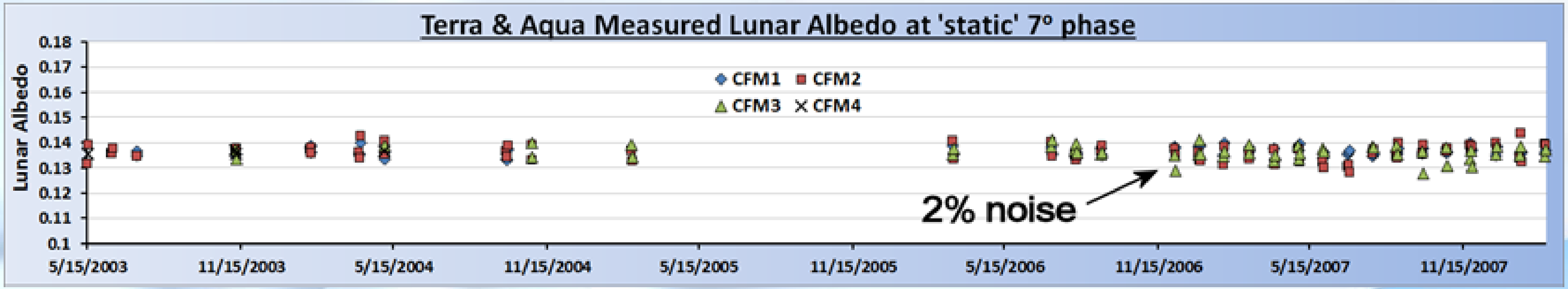




3. Placement on and Holding to the MERBE Watt SI Traceable Scale

The 2D numerical integral technique used by Matthews 2008 was prone to high noise and suffered in the case of sparse data





MERBE instead utilizes IE data to map ERB FOV from raster scans