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Communication

Assessment of Terra/Aqua MODIS and Deep Convective Cloud Albedo Solar Calibration Accuracies and Stabilities Using Lunar Calibrated MERBE Results

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Abstract: Moon calibrated radiometrically stable and relatively accurate Earth reflected solar measurements from the Moon and Earth Radiation Budget Experiment (MERBE) are compared here to primary channels of coaligned Terra/Aqua MODIS instruments. A space-based climate observing system immune to untracked drifts due to varying instrument calibration is a key priority for climate science. Measuring these changes in radiometers such as MODIS and compensating for them is critical to such a system. The independent MERBE project using monthly lunar scans has made a proven factor of ten improvement in calibration stability and relative accuracy of measurements by all devices originally built for another project called 'CERES', also on the Terra and Aqua satellites. The MERBE comparison shown here uses spectrally invariant Deep Convective Cloud or DCC targets as a transfer, with the objective of detecting possible unknown MODIS calibration trends or errors. Most MODIS channel 1–3 collection 5 calibrations are shown to be correct and stable within stated accuracies of 3% relative to the Moon, much in line with changes made for MODIS collection 6. Stable lunar radiance standards are then separately compared to the sometimes used calibration metric of the coldest DCCs as standalone calibration targets, when also located by MODIS. The analysis overall for the first time finds such clouds can serve as an absolute solar target on the order of 1% accuracy and are stable to $\pm 0.3\%$ decade^{-1} with two sigma confidences, based on the Moon from 2000–2015. Finally, time series analysis is applied to potential DCC albedo corrected Terra data. This shows it is capable of beginning the narrowing of cloud climate forcing uncertainty before 2015; some twenty five years sooner than previously calculated elsewhere, for missions yet to launch.

Keywords: solar forcing; climate observing system; MODIS; deep convective cloud (DCC) albedo; earth radiation budget; earth observation; lunar calibration; MERBE

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1. Introduction

Earth's weather and climate system can be considered the work done by a global scale heat engine. This is with absorbed solar sunlight or Short Wave (SW: λ = 0.2–5 µm) and emitted Long Wave (LW: λ = 5–200 µm) irradiances being the driving heat energy entering at the equator and leaving the planet at the poles. Such systems are best simulated by computer numerical Global Climate Models (GCMs), which are used in predicting how the climate will respond to the recent unprecedented anthropogenic loading rate of greenhouse gases (GHG). Validation of such models requires comparison and agreement with observations, ideally made globally from satellites (assuming they are accurate themselves).

Amongst the most uncertain climate changes to come, however, are those involving Cloud Radiative Forcing (CRF), or how clouds will change in response to the warming. For example, as increasing CO_2 warms the planet, how will this affect clouds, will there be more or less solar reflection and infra-red trapping? Will this accelerate or slow down global warming as positive or negative feedback? Therefore, it is vitally important to maintain accurate and global measurements of cloud radiative properties from instruments such as MODIS (Moderate Resolution Imaging Spectroradiometer, [1]). This must be done in addition to recording these driving SW and LW total broadband fluxes, which are known as components in the Earth Radiation Budget or ERB [2]. The building of greater confidence in GCM predictions of the future will then come through comparisons of simulations, to such measurements in the past and present, as constraining and validating model boundary conditions. The first step, however, is to make sure such measurements are both accurate and stable, hence representing climate reality.

The SW CRF signals (trends) being looked for have been estimated to be only ±0.8%/decade or less in size of global albedo [3,4]. This makes it extremely difficult to detect them with confidence in only the few decades available of satellite Earth observing measurements (e.g., due to natural variability alone). Broadband ERB SW data have been obtained from separate instruments, co-located with MODIS on the Terra/Aqua Earth Observing System satellites (EOS [5]). These devices are those built for the Clouds and the Earth Radiant Energy System, or CERES project of [6] (see Figure 1a for comparative solar spectra/spectral responses of MODIS and CERES). SW transmission measurements were made of Solar Earth observing instrument optics on the ground, including those of CERES. Unfortunately, these responses have been found to degrade on-mission in ways un-trackable with on-board calibration targets, particularly for the ultraviolet region [7,8]. A resulting CERES approximate −0.5%/decade false trend of reflected solar radiation has been noted by multiple studies relative to the Moon [9,10] and will lead to incorrect climate model tuning that will suggest the Sun is largely responsible for global warming [11]. It is noted that there is also currently a statistically significant very slight decrease in the arriving solar flux to the Earth over time [12], but since this is a cross-instrument/albedo comparison that is independent of incoming solar, it plays no relative factor.

The MODIS climate observing instrument has in-flight calibration sources making use of a Solar Diffuser (SD) to attenuate direct sunlight, so the Earth viewing telescopes can view reflected solar photons to track their own degradation [13]. Like all solar diffusers, they will themselves degrade on orbit. MODIS, however, is equipped with a solar diffuser stability monitor (SDSM, [14]), to track this using alternate views of the Diffuser and Sun through a separate integrating sphere [14–16]. MODIS Percent albedo change calibration stability per decade has not yet been firmly established, hence it is the purpose of this study to preliminarily do so using the Moon. The NRC requested [17] stability of ±0.15%/decade is unlikely to have been achieved by MODIS on-board calibration alone, however, as its solar diffusers have been estimated to degrade at over 20%/decade [18].

Alternatively for broadband SW ERB results, the CERES instruments flying with MODIS have no functioning on-board way at all to detect optical degradation for visible to shorter wavelengths. This is noted about the on-board CERES lamps drifting by up to 1.44% in ground tests [19], which have no UV output anyway [20]. CERES diffusers also degraded and were deemed un-usable [21]. Infra-Red calibration is maintained using onboard blackbodies that are far more stable than lamps, but still not sufficient for the newly desired goals [4]. These challenges were noted by the 2007 NRC decadal survey [17], which stated ***"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"*** (the following 2017 survey [22] reached a similar conclusion).

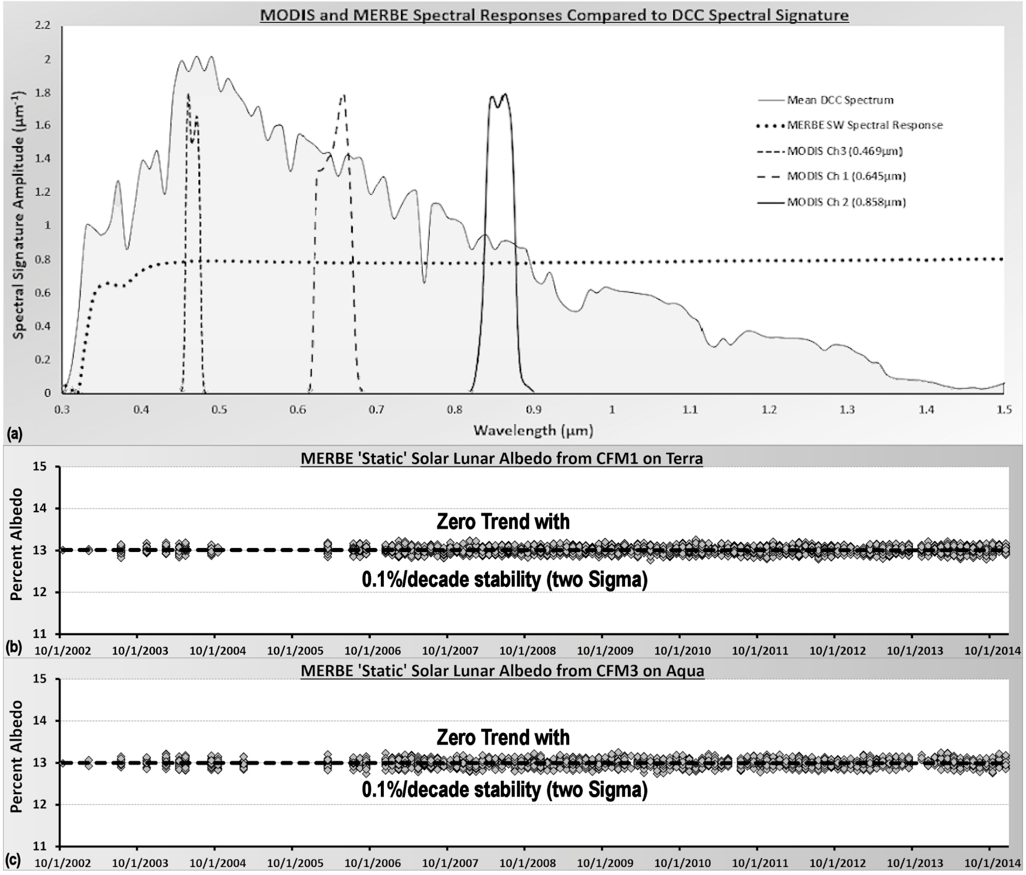

Figure 1. (**a**) MODTRAN 5.3 Deep Convective Cloud (DCC) spectral signature from MERBE, along with MERBE and MODIS Ch 1–3 Spectral responses. (**b**,**c**) MERBE Terra & Aqua measured lunar albedo by CERES Flight Model 1 & 3 (CFM1&3) giving 0.1%/decade stability (2σ [23])).

Until 2018 [10], only one satellite Earth observation data set coming from the SeaWIFS device [24,25] had demonstrated calibration stability sufficient to detect a 0.8%/decade reflected solar signal, over a mere 15-year period. This was achieved using monthly scans of Earth's Moon as a calibration standard because its solar reflectivity is a constant. Unfortunately, SeaWIFS is in a completely different orbit to the EOS satellites, so it cannot be accurately used to compare to ERB SW or MODIS results at the <1%/decade accuracy level (and the mission is no longer functioning). MODIS satellites themselves do a monthly pitch maneuver to scan the Moon, but the results have not yielded a calibration confidence better than ±1%/Decade [26]. This is because they do not utilize the convolution integral technique first described in 2008 [27]. The combination of this with the 2D mapping of detector field of view lunar responses using angular Fourier series bins has limited noise to 0.05%/decade in recent studies (one sigma, [23]).

Since 2002, each EOS ERB CERES (rather than MODIS) device has also performed regular raster scans of the Moon [28] that, importantly, are monthly, and therefore more regular than for MODIS. It has been shown straightforward [27] to use such scans to measure the broadband average lunar disk SW and LW output. Signal processing improvements [29] now enable the recovery of around an order of magnitude more lunar measurements than those from the CERES team for each fully functional Terra/Aqua ERB device, compared to previous studies [27,30] (see Figure 1b [23]).

MERBE

Given this unused radiometrically traceable calibration data set of CERES lunar scans, a new project is underway called the Moon and Earth Radiation Budget Experiment, or MERBE. It is an attempt to answer needs highlighted in both the past two decadal surveys, first by improving results from the ERB devices on Terra/Aqua and making up to an order of magnitude increase in their climate data stability/accuracy [10,23,29]. This is achieved using strict calibration guidelines, one of which forces all devices in the MERBE project to measure a constant traceable lunar albedo (at a ±1.0% two sigma absolute accuracy goal [10]). Now with thousands of lunar results per ERB device, the MERBE lunar results demonstrated [23] better than ±0.1%/decade calibration stability for Terra SW (two sigma, see Figure 1b after normalization to zero-libration or 'static' +7° using the ROLO model [23,31]). In the MERBE Edition 1 data release, this then allowed correction [10] for the known CERES instrument drifts [9,11], still present and largely unknown by the science community, in the latest NASA CERES Ed4.1 released ERB climate results. This work therefore provides the first ever comparison of many hundreds of thousands of MODIS Earth footprints with those from a proven traceable solar calibration source from 2000–2015 [10,23,29].

It then goes on to use the Moon to assess exactly how stable DCC albedo would be as a standalone target if identified by an imager like MODIS.

2. MERBE SW Comparisons to MODIS Solar Channels 1–3

2.1. Methods

MODIS imagers and ERB instruments on the Terra/Aqua satellites are quite different in design to facilitate the desired varied spatial resolutions and spectral responses. The spectral responses of ERB SW channels and MODIS solar channels 1–3 are displayed in Figure 1a. Such miss-matched responses require that any comparisons be done using an Earth scene with a consistent spectral signature or shape, for which this study chooses to use Deep Convective Clouds (DCCs), since their tops are typically high-altitude ice particles with relatively minimal atmosphere above them. MODIS cloud retrievals [32] also stored in the MERBE files are used to identify DCC for comparison. They must have the following criteria of 100% Daytime Ocean, 0% Clear, 100% Imager Coverage, $<\pm 45°$ Latitude, Viewing Zenith $< 1°$, Cloud Effective Temperature < 250 K and Cloud Effective Optical Depth > 10. The MERBE solar DCC spectral signature when viewed at these nadir footprints is also shown in Figure 1a and importantly remains consistent in shape over time.

2.2. Data and Results

Shown in Figure 2, Terra and Aqua MODIS Ch 1–3 results from 2000 up to 2015 were quadratically regressed against Moon stabilized MERBE Earth SW results from both satellites using Equation (1):

$$V'_{MODIS} = A + B \cdot V_{MERBE} + C \cdot V^2_{MERBE} \quad (1)$$
$$\Delta V_{MODIS} = V_{MODIS} - V'_{MODIS} \quad (2)$$

These regressions were then used to produce the mission life anomaly plots of Figure 3. In effect, they are therefore MODIS results V_{MODIS} minus that estimated from a MERBE cross-calibrated MODIS device V'_{MODIS} (Equation (2)). As calibration is improved upon over time, MODIS data are released by NASA in different what are called 'collections'. MODIS solar collection 5 channels accuracy is estimated [3,4] to be around 3% (two sigma) and these comparisons to Moon calibrated MERBE SW results show for the majority of Ch 1–3 data, this is indeed the case in terms of stability. For Terra in Figure 3a, both Ch 1 and 2 do not show drifts greater than 3%. The 0.858 µm Ch 2 showed a marked degradation of nearly 2% in 2009. The shorter wavelength 0.469 µm Terra Ch 3, which is more likely to suffer in-flight degradation as it is nearer the UV, does show a near 4% reduction in responsivity up to 2015. For Aqua in Figure 3b, Ch 1 and 3 show better calibration stability compared to Terra, but it seems that the longer wavelength Ch 2 (0.858 µm) shows a degradation paramount to Ch 3 on Terra of nearly 4%. To a lesser extent than for Ch 2 on Terra, Ch 1 on Aqua displays a marked 0.5% drop in response in late 2010.

These Figure 3 results agree in magnitude to the lifetime MODIS collection 5 calibration drifts found elsewhere [33], using DCC to find negative trends for Terra and Positive slopes for Aqua. Again, it is not expected to be an exact match as DCC albedo is not a worldwide radiometrically traceable standard today. This agreement with the errors found by the MODIS calibration team for collection 5 bodes well for the now released MODIS collection 6 data, with which this study could soon be repeated.

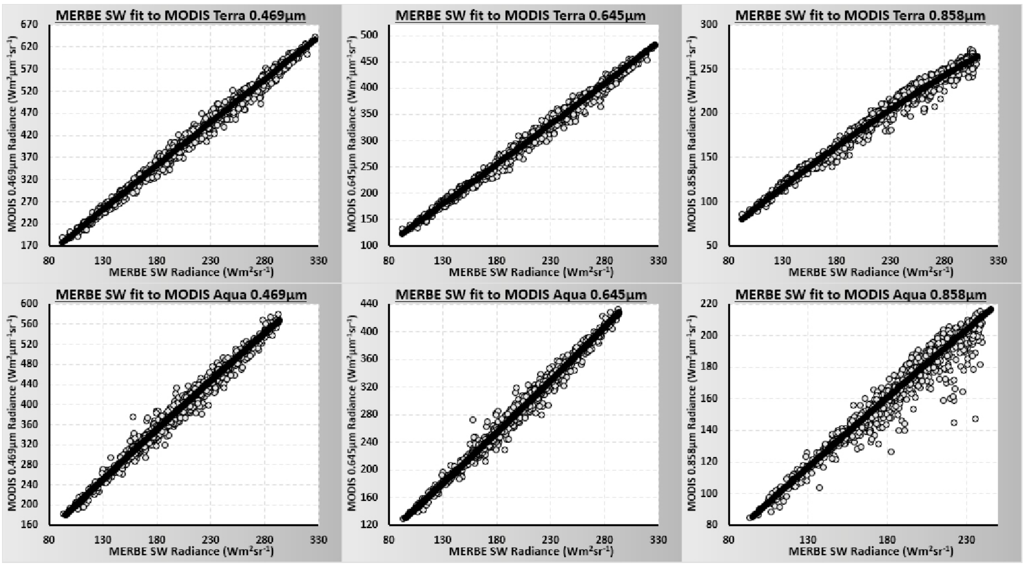

Figure 2. Quadratic regressions of MERBE SW data with MODIS Terra and Aqua Channels 1–3.

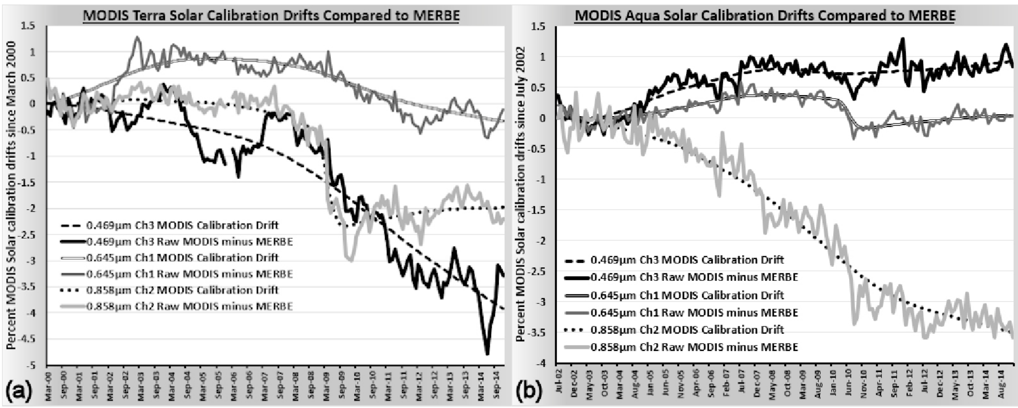

Figure 3. (**a**) MERBE Estimates of Terra MODIS Ch 1–3 calibration drifts; (**b**) MERBE Estimates of Aqua MODIS Ch 1–3 calibration drifts (both from the start of mission).

A final absolute accuracy comparison to MODIS again takes advantage of the spectral signatures generated by the MERBE Fourier series Earth spectral tensors [10,34]. This absolute analysis shall concentrate only on the first 12 months of each MODIS climate device's mission life, to give a baseline for the traceability of the calibration soon after launch. By definition, MERBE spectral signatures $L(\lambda)$ have an integral of one across all wavelengths [10]. Therefore, given radiometrically traceable MERBE broadband solar DCC nadir radiance R and spectral signature $L(\lambda)$, it should be possible to estimate the absolute value of MODIS channel result M between the wavelengths of λ_1 and λ_2 as:

$$M = \frac{R}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} L(\lambda) d\lambda \quad \mathrm{Wm^{-2}sr^{-1}\mu m^{-1}} \tag{3}$$

where the bandwidth ranges of the three channels in ascending wavelength order are Ch 3 0.459–0.479 µm, Ch 1 0.620–0.670 µm and Ch 2 0.841–0.876 µm.

The 'MERBE Watt' is a traceable unit [23], tied to a lunar albedo at a static +7° zero libration solar phase angle of exactly 0.129975. This means that a future determination that the Moon's albedo is actually say 0.13125 simply means that one MERBE Watt is exactly 1.01 Watts, etc., making it one day fully traceable to national standards. Such absolute comparisons of Terra and Aqua MODIS Ch 1-3 solar radiances to the solar MERBE Watt results of Equation (3) are shown in Figure 4, and agree with the approx. 2% absolute accuracy dispersion found elsewhere [33]. The one sigma absolute accuracy goal of MERBE is shown to perhaps be as high as 0.3% by Terra and Aqua lunar albedo comparisons (see Figure 10d in [23]). Perhaps then of equal or even greater value is the comparison between Terra and Aqua MODIS measurements. The Ch 1 results are both less than 1% above MERBE and very close between Terra and Aqua. The next two best channels are Ch's 2 and 3 on MODIS Terra, each slightly better than −2% below the MERBE Watt. The same channels 2 and 3 on Aqua are around −3% below the MERBE Watt. With a MODIS absolute accuracy goal of 3%, this analysis therefore shows that the target has largely been met for these primary channels.

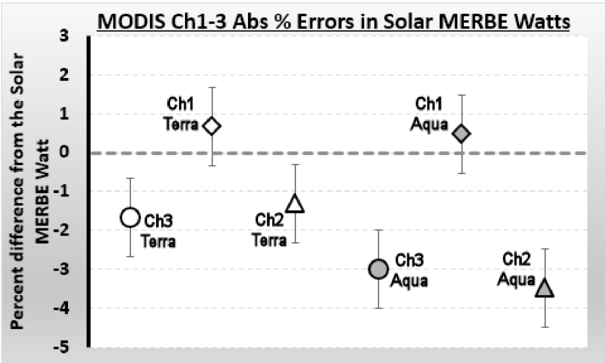

Figure 4. Estimates of absolute MODIS start of mission calibration errors in solar MERBE Watts.

3. MERBE Assessment of DCC Target Albedo Stability and Accuracy for Solar Calibration, Based on the Moon

3.1. Methods

Vicarious Earth calibration targets are still widely used to calibrate space based meteorological/climate devices. Surface targets such as deserts and glaciers suffer from variation in atmospheric conditions such as aerosol content. This means they cannot be used to obtain desired calibration accuracies [4]. There has been discussion about the use of the coldest and highest of DCC since they are often described as effective "ice particles on the edge of space" and therefore less subject to variation from lower atmosphere variations. They can also be identified largely using cloud top temperature measurements from imager thermal channels, whose calibration uses the mentioned more stable on-board blackbodies, therefore being superior to solar channels in almost all cases. Despite this, there is valid skepticism about how good DCCs truly are as a stable and accurate solar calibration target for climate instruments. This section uses Moon calibrated SW MERBE data for the first time to estimate just how accurate and stable the most extreme of DCC scenes are, if used as a calibration target when located by an imager like MODIS. A more stringent criteria [8] is applied here to find such MERBE irradiances from these Earth targets. This is more extreme than Section 2, as it limits the ocean scenes to a cloud top temperature of <205 K, an optical depth of >120 and latitude of ±30°. Importantly, the imager reflected solar radiance standard deviation is also restricted to 3% across each instantaneous ERB footprint, while no limit is made on Viewing Zenith (to maximize the size of what is a very small data set). Again [8], the directional models derived from the precessing TRMM satellite are also used to adjust the cloud top albedo to that of the overhead sun. MERBE DCC albedo results from the ERB instruments called CERES Flight Model 1 (CFM1) on Terra and CFM3 on Aqua are shown in Figure 5.

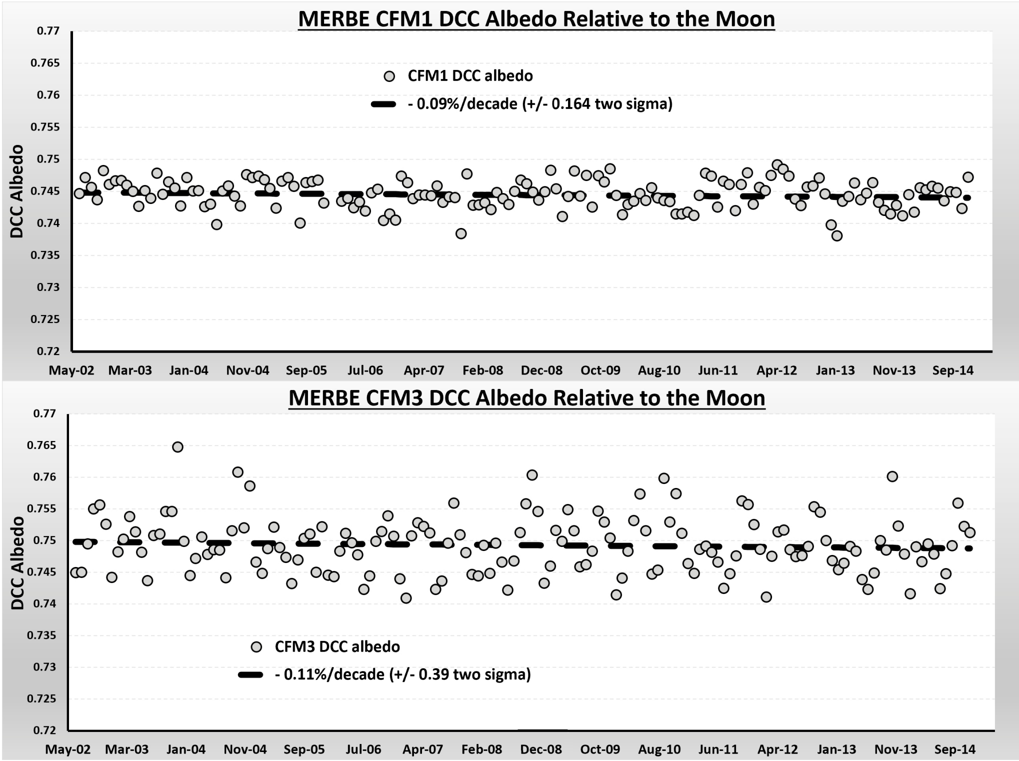

Figure 5. (**Top**): MERBE Terra CFM1 measured DCC Albedo up to 2015. (**Bottom**): MERBE Aqua CFM3 measured DCC Albedo up to 2015.

3.2. Data and Results

Both Terra and Aqua DCC targets in Figure 5 exhibit slight negative trends of around −0.11%/decade or less, but in neither case are these changes statistically significant at the two-sigma confidence level. The CFM3 Aqua DCC results are considerably more noisy than those for CFM1 on Terra, which warrants further investigation. This acts as evidence, however, that DCC albedo could be used as a solar calibration target metric when identified by an instrument such as MODIS with around 0.3%/decade stability (two Sigma), which makes it a valid tool to then identify CRF signals at the levels required by [3,4].

CFM1 and CFM3 are instruments on separate satellites, but their MERBE calibration is in both cases tied to the same Moon albedo of 0.129975 [23]. That makes it useful to compare the absolute value of DCC albedo from the two different ERB devices, when different MODIS imagers separately on Terra and Aqua are used to find such targets. Terra (CFM1) and Aqua (CFM3) DCC albedos are 0.745 and 0.749, respectively, and the slightly over 0.5% absolute bias is statistically significant at the two-sigma level. This also therefore provides additional evidence based on the Moon, suggesting that DCC albedo may be useful as an absolute calibration metric at the 1% or slightly better accuracy level, when identified by an imager like MODIS (i.e., twice the two sigma 0.5% difference).

4. Summary, Conclusions and Future Work

This work has made a simultaneous comparison between Terra and Aqua MODIS results, with the only continuously traceable solar radiometric standard currently in orbit from MERBE because it is normalized to the soon to be traceable MERBE Watt [23]. Its results generally agree with the MODIS team's own analysis of collection 5. The forthcoming MERBE Ed2 data set shall allow a more detailed and mission long analysis of MODIS accuracies, but for now this shows as an initial calibration to demonstrate potential MERBE capabilities and gives confidence in the MODIS collection 6 data release.

In larger consideration of work such as this, NASA time series calculations have analyzed benefits of a rapid development of a new advanced global climate monitoring satellite such as the proposed NASA CLARREO Pathfinder (CPF), or UK TRUTHS mission [4,35], with 0.3% (1σ) absolute accuracy. They showed the anticipated 0.8%/decade CRF signals [3] could still not be proved real with CPF improved observations until the year 2041. As illustrated by the compounded CLARREO/TRUTHS line in Figure 6 (right), this is mainly due to natural variability and the time after launch needed to see through it. This is from NASA calculations [4], assuming a quick 2023 CLARREO/TRUTHS launch and operation well beyond say the CPF instrument design life of one year. Hence, a lack of progress in creation of this new improved CPF/TRUTHS "climate observing system" has encouraged lower cost solutions such as MERBE, using existing instrumentation to help resolve climate uncertainty at a sooner date.

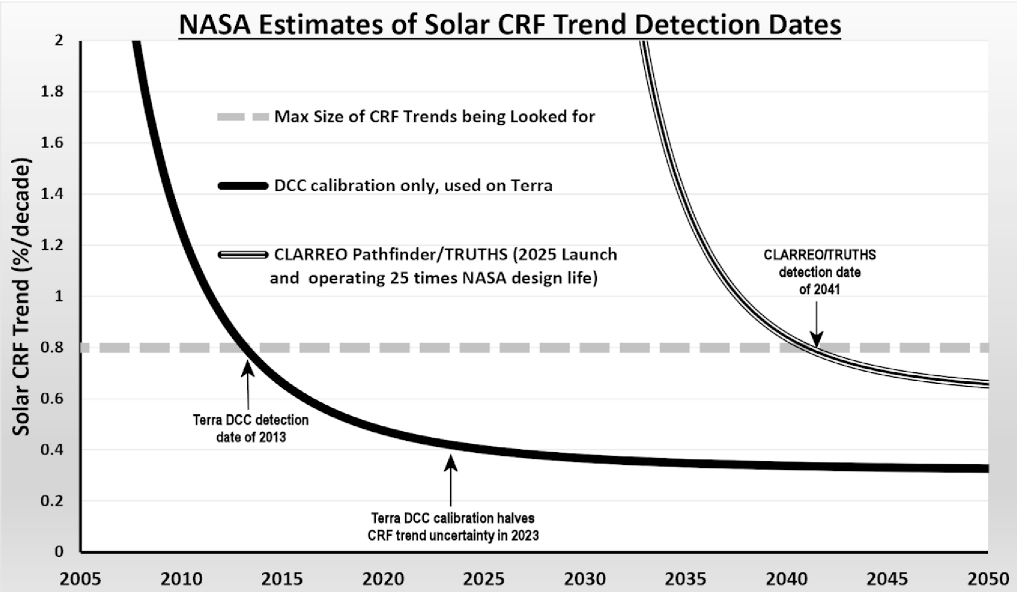

Figure 6. NASA calculated Solar cloud climate signal sizes and dates of their possible detection instruments combined with CLARREO Pathfinder/TRUTHS (grey) [3,35,36]. The same using DCC albedo is shown in black, in which case the narrowing of CRF uncertainty in GCM simulations could begin before 2015, using existing Terra results at no cost.

This paper has now taken such lunar calibrated MERBE results and made comparisons to co-aligned MODIS imagers on the same platforms because constant lunar albedo could ultimately be a traceable standard for all instruments. This confirmed that the majority of primary solar MODIS Channels 1–3 are accurate to within their specified 3% goal upon launch, although the Terra channels tend to have a slight advantage in initial absolute accuracy (i.e., for MODIS collection 5). Similarly, most of the same channels maintain calibration stability better than ±3%/decade, except for Ch 3 on Terra and Ch 2 on Aqua which both degrade by more than 3% over ten years. The MODIS Ch 1 absolute accuracy and stability of both Terra and Aqua being better than 1% and 1%/decade, respectively, is well within specification [37] and therefore noteworthy (see Terra and Aqua Ch 1 results in Figures 4 and 5).

However as stated in Section 2, despite MERBE SW stability, the spectral differences between MODIS and ERB devices mean that the stability of such a corrected data set is not at present claimed to be better than 0.3%/decade (two sigma, see confidence limits of Figure 5 trends). This means that DCC albedo may be a more immediately available calibration target for MODIS collection 5 data users (i.e., before MERBE can make a comparison with a more recent MODIS data collection release [38]).

Further work in cross calibration should therefore try and compare MERBE results with a later collection release of MODIS results, in addition to those from the VIIRS instruments on NPP and JPSS-1. It may also be of interest to expand the MERBE comparisons to imager channels with different wavelengths, although this will begin to rely more heavily on the MERBE spectral signatures [10,34].

Finally, NASA analysis [3,4] is applied to potential DCC adjusted MODIS results as in Figure 6 (solid black). The self-imposed conservative 0.3%/decade (two sigma) calibration signal detection threshold of course limits the ultimate size of CRF trend that can ever be detected. As with MERBE SW, however, the fact that MODIS calibration can be improved in the past, spanning back to the start of mission in the early 2000s, results in the possibility of CRF signal detection using imager data before 2020. Therefore, shown by that same lunar data curve and at no cost, this is more than two decades earlier than CLARREO/TRUTHS, using the same NASA calculations [4]. Additionally, Figure 6 further suggests that, by the year 2023, a 0.4%/decade CRF signal could be resolved. This would mean that cloud modeling uncertainties could be halved in just the next couple of years.

Thus, DCC Albedo or MERBE cross calibrated MODIS data are hence perhaps among the best that can be achieved with the existing observing system today, with significant opportunities for resolving the largest unknowns in climate science. However, such a finding must not hinder the important development of CLARREO-like devices to finally bring full 0.3% traceability to Earth observation records, through the Moon.

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Conflicts of Interest: The author declares no conflict of interest.

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