Direct Solar Viewing Calibration Concept for Future CERES, GERB or Libera Type Earth Orbital Climate Missions

G. Matthews*

Zedika Solutions LLC, Fort Wayne, IN, USA

*Corresponding author address: G. Matthews, Zedika Solutions LLC, Fort Wayne, IN, USA.

E-mail: grant.matthews@zedikasolv.com, grant.matthews@gmail.com

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ABSTRACT

Better predictions of global warming can be enabled by tuning legacy and current computer simulations to Earth Radiation Budget (ERB) measurements. Since the 1970’s, such orbital results exist, and the next generation instruments such as one called “Libera” are in production. Climate communities have requested that new ERB observing system missions like these, have calibration accuracy obtaining significantly improved calibration SI traceability and stability. This is to prevent untracked instrument calibration drifts, that could lead to false conclusions on climate change. Based on experience from previous ERB missions, the alternative concept presented here utilizes directly viewing solar calibration, for cloud size Earth measurement resolution at <1% accuracy. However it neglects complex already used calibration technology like solar diffusers and on-board lights, allowing new lower cost/risk un-considered spectral characterizing concepts to be introduced for today’s technology. Also in contrast to near future ERB concepts already being produced, this enables in-flight wavelength dependent calibration of Earth observing telescopes using direct solar views, through narrow-band filters continuously characterized on-orbit.
1. Introduction

It is vital to both continue and significantly improve accuracy of orbital Earth Radiation Budget or ERB, short wave (SW, 0-5\(\mu\)m) and long wave (LW, 5-200\(\mu\)m) measurements of fluxes leaving the Earth at the Top of Atmosphere (TOA). In the field of climate model validation, this gives confidence in global warming computer predictions, if their legacy and current simulations match ERB measurements at the same time and locations, etc.

By far the most extensive ERB SW results come from a NASA mission called the Clouds and the Earth’s Radiant Energy System (CERES, Wielicki et al. (1996)), with six instruments covering the globe, providing a continuous climate measurement record since 2000. These measure from Sun-synchronous US polar orbiting satellites, called ‘Terra’ (Mar 2000\(\rightarrow\)) and ‘Aqua’ (Jul 2002\(\rightarrow\), see NASA (2021)). Such data are supplemented by those from the European Geo-stationary Earth Radiation Budget (GERB, Harries et al. (2005)) mission, which provides 15min time resolution from its higher orbit viewing Africa/Europe. CERES results however are known to have insufficient accuracy and calibration stability for climate forcing trend detection, as discussed by Wielicki et al. (2013); Fox et al. (2011). For example, CERES results long measured a TOA +7Wm\(^{-2}\) imbalance to the solar energy entering Earth, which is the solar flux arriving at Earth, minus reflected SW and emitted LW. This occurred prior to a one-time ‘ad-hoc’ adjustment to the CERES Edition 4.1 SW record’s full length by Loeb et al. (2018), to bring the imbalance to a value below +1Wm\(^{-2}\). That was simply because such a value is thought to be realistic by climatologists, but in no way is based on standards traceable calibration from ground or on-orbit (where the term ‘SI traceable’ used later, is from L-A-B (2019)).

Perhaps more serious though for climate change studies, was that untracked CERES telescope UV degradation caused the same one time adjusted SW results to still falsely drift, because of
spurious calibrations trends over time as discussed by Dewitte et al. (2019); Matthews (2018b, 2021). To this current date, the most recent CERES SW data is wrongly accepted stable to 0.3 W m\(^{-2}\)/decade by Dessler (2010); Trenberth et al. (2014) (as originally claimed by NASA at Loeb et al. (2007)). That makes it measure a false Earth albedo drop that would alone be sufficient to account for up to half of all global warming temperature increases since the year 2000 (Matthews (2021)). The cause of these absolute and stability errors is twofold.

First the SW absolute calibration of CERES was measured in the ground laboratory using lamps, referenced to a cavity detector called a Transfer Active Cavity Radiometer (TACR), also viewing the same lamps and counting photonic energy very accurately. However, the TACR needed to have the same narrow field of view of the laboratory lamps as the CERES device. Therefore, to provide this in pre-launch measurements, a CERES-like Cassegrain silver mirror telescope was installed at the cavity entrance. Unfortunately the actual TACR mirror telescope reflectivity was never measured at the time, causing analysis to rely on mirror witness samples instead (see Folkman et al. (1994); McCarthy et al. (2011)).

Secondly, CERES optics on orbit, underwent significant contamination and degradation from outgassed particles and atomic oxygen exposure, because of the telescope being pointed in the direction of spacecraft travel (see Levine (1992); Matthews et al. (2005, 2006); Matthews (2007, 2009)). Such degradation was highly spectrally dependent, with UV changes orders of magnitude greater than in the visible spectral region.

CERES was equipped with solar diffusers called Mirror Attenuated Mosaics or “MAM”s intended for SW calibration, which like the telescopes also spectrally degraded on-orbit, again most heavily in the UV. They were later deemed unusable by Priestley et al. (2011). CERES also had onboard Tungsten lamps called the SW Internal Calibration Source (SWICS), but as discussed by Priestley et al. (2000), they also drifted untraceably in output and do not emit UV light of the
needed proportions to calibrate an ERB telescope in any case (Loeb et al. (2007)). GERB from ESA also has a solar diffuser called a “CalMon”, but the constant rapid movement in solar illumination from Geo orbit made its use impractical for the moment (as well as there is no way to monitor inevitable diffuser degradation, as suffered by CERES). A follow on from the missions currently existing or in production, therefore should be designed to better prevent or counter these problems.

2. New Low/Cost Risk ERB Device Calibration Design for Future missions

a. Assumptions to Overcome Deficiencies in Existing Calibration Concepts

The concept shown here begins with the two discussed assumptions. First, the ground calibration will not transfer to orbit with better than around 1% accuracy because of issues in laboratory procedures, coupled with a possible expected ground contamination event. This contamination event is a worst-case scenario, but actually occurred to the EOS Aqua CERES devices between calibration and launch, as mentioned in Matthews et al. (2007a). It then resulted in the Priestley (2006) onetime 8% instrument SW ground to flight gain value change to be made, for use in device CFM3’s ground processing, with no SI traceable reason given (remembering that CERES is claimed to be 0.9% absolutely accurate by Wielicki et al. (2013); Fox et al. (2011)). Second and as with CERES, outgassing and/or atomic oxygen will put mostly UV absorbing contaminant on the optical mirrors and filters in orbit, continuously degrading their response, with no proven way to track using today’s on-board calibration technology.

b. Proposed Alternative Solutions

To save mass and cost, it is recommended to discontinue using solar diffusers and lamps, or other artificial on board light sources, that have yet to work anywhere near the required accuracy.
standards. Also, the ERB telescope must maintain the CERES 2005 onward implemented operational constraint, that no telescope can ever face atomic oxygen exposure by pointing the direction of travel (see Matthews et al. (2005); Matthews (2007)). Using the design of CERES as a template from the left of Fig. 1, this new concept’s approximate low mass and cost design is shown on the right compared to CERES, without solar diffusers or a lamp for SW calibration. It is however important to retain the azimuth rotation capability of CERES, so raster scans of the Sun and Moon can be performed (facing behind the satellite direction of motion to prevent atomic oxygen exposure). The SWICS lamp should be replaced with a blackbody, slightly warmer than normal, to allow better on-orbit spectral characterization of SW Quartz filter thermal leakage, as discussed by Loeb et al. (2001); Matthews (2018a).

The challenge of using the Sun for calibration is that its broadband radiance is around \(0.5 \times 10^5\) times what a cloud size resolution Earth viewing ERB radiometer can measure without saturating or being damaged, and that dynamic range is beyond current thermal detector technology. For this new concept, narrowband interference filters are installed above the space look on each of the two limb positions as in Fig. 1 right. Four different pairs of narrowband filters are recommended, of which an example is the 410 nm Alluxa filter shown in Fig. 2(a), with a bandwidth approximately 1.5nm. This will have a ground measured spectral throughput shape \(\tau_a(\lambda)\) with a true peak value of around 0.2, meaning a neutral density filter may need to be part of the spectral filter for added attenuation (although the \(\tau_a(\lambda)\) and \(\tau_b(\lambda)\) functions for use in Eqns. 1, 8 and 10 later will remain normalized to 1 as in Fig. 2(a)). Preferably this peak should be at spectral regions covering the UV to the visible, and where the solar spectrum is near to a stationary point, with a low second derivative, to minimize errors from interference filter thermal expansion. Fig. 3 makes some rough suggestions for filters to be at around 350, 410, 480 and 650nm, all with a narrow bandwidth around <2nm, as it provides greater attenuation and also reduced sensitivity to temper-
ature dependent filter wavelength shifts. All these values remain up for discussion however. The second near identical filter with spectral transmission shape $\tau_b(\lambda)$ is of course also needed. The Fig. 2(b)-(d) circular attenuating black metal mask with three holes and around 10% throughput ‘N’ (measured to $<0.1\%$ accuracy on the ground), is required for a further order of magnitude signal reduction. This 10% mask should be significantly more accurate and stable than for example higher attenuation pinholes or slits, allowing equal illumination of optical surfaces and also reducing diffraction concerns. The Solar disk fills an approximate fraction 0.1 of a high resolution ERB bolometer at the image plane. That allows a rough example calculation using transmission values of each part of the optical train to be given as in Eq. 1 (note this 0.1 fraction of detector area figure used in Eqn. 1 is only to demonstrate order of magnitude attenuation). Remembering that at the mission start peak transmission of filters $T_a$ and $T_b$ are both around 0.2, the needed $2 \times 10^{-5}$ factor reduction in solar radiance is achieved because solar signal transmission is:

$$\text{CalibrationOpticTransmission} = 0.1 \times N \times T_a \times \frac{\int S(\lambda) \tau_a(\lambda) d\lambda}{\int S(\lambda) d\lambda} \approx 2 \times 10^{-5}$$  \hspace{1cm} (1)$$

The two near identically made narrowband optical filters in the optical train can be rotated in and out of the field of view as in Figs. 2(c) and (d) with Eqn. 2 representing the Fig.(c) case. The normal to the plane of the filter surfaces naturally should not align with that of the telescope, to prevent backscatter affecting the results. The Eqn. 3 Steradian integral technique of Matthews (2008, 2018a) is to be used on the raw detector signal $v_1(\theta, \phi)$ in Eqn. 4, while raster scanning the Sun emitting known disk averaged solar spectral radiance $S(\lambda)$ (with $n$ from Eqn. 4 the number of the calibration orbit and $\Delta \Omega_{\text{sun}}$ being the Steradian angular size of the Sun).

SI traceable calibration is a then three step, or three orbit process illustrated in Figs. 2(b)-(d), with the scans performed at only one of the poles to prevent atomic oxygen exposure from the
RAM direction, depending on whether in a day ascending or descending orbit. During orbit number 1 the Sun is scanned with both filters in the optical train as in Fig. 2(b). With \( k \) the wavelength of filter being used, if in the instrument solar spectral response at the peak filter wavelength \( \lambda_k \) is \( R_{\lambda_k} \) (in Volts/Wm\(^2\)Sr), then the Eqn. 4 integrated result on orbit 1 is represented by Eqn. 5.

\[
\int d\Omega = \int_0^{2\pi} \int_0^{\pi/2} \sin \theta d\theta d\phi \tag{3}
\]

\[
V_{n,k} = \Delta\Omega_{\text{sun}}^{-1} \times \int v_n(\theta, \phi) d\Omega \quad [\text{Volts}] \tag{4}
\]

\[
V_{1,k} = R_{\lambda_k} \times N \times T_a \times T_b \times \int S(\lambda) \tau_a(\lambda) \tau_b(\lambda) d\lambda \tag{5}
\]

\[
V_{2,k} = R_{\lambda_k} \times N \times T_a \times \int S(\lambda) \tau_a(\lambda) d\lambda \tag{6}
\]

\[
V_{3,k} = R_{\lambda_k} \times N \times T_b \times \int S(\lambda) \tau_b(\lambda) d\lambda \tag{7}
\]

Whereas mentioned \( T_a \) and \( T_b \) are the now unknown peak transmissions of the two filters, at the same wavelength \( \lambda_k \) (e.g. 350, 410, 480 or 650nm). On the following two orbits the process is repeated with filter \( b \), then filter \( a \) removed from the optical train one at a time, represented by Eqns. 6 and 7 and shown in Figs. 2(c) and (d).

Since calibration here is done by scanning on and off celestial bodies, it is important the signal processing use the Impulse Enhancement (IE) that removes thermal transients in the bolometer signal, since such detectors take time to respond to radiance as described by Matthews (2018c). This will be important because bolometers have various finite time responses and as Fig. 4 shows for an Earth limb scan, other signal processing such as Smith et al. (2002) used by NASA for CERES, will cause a time constant dependent bias underestimate of Sun and Moon mean radiance, while overestimating that of deep space (i.e. the “space clamp” used to remove offsets). Because IE uses three time constants and is tailored to each bolometer as described by Matthews (2018c), it will put all instruments on the same radiance scale for all celestial bodies and remove any remaining space clamp biases that would affect absolute accuracy.
$S(\lambda)$ mentioned earlier is the known mean SI traceable solar radiance that is measured by the Total and Spectral Solar Irradiance Sensor mission (TSIS, LASP (2021)), monitoring total and spectral output from the Sun. The SI traceable $R_{\lambda_k}$ spectral response values at wavelengths $\lambda_k$ can then be found thus:

$$\alpha_k = \frac{\int S(\lambda) \tau_a(\lambda)d\lambda}{\int S(\lambda) \tau_a(\lambda)\tau_b(\lambda)d\lambda}$$  \hfill (8)

$$\beta_k = \int S(\lambda) \tau_b(\lambda)d\lambda \quad [Wm^{-2}Sr]$$  \hfill (9)

$$R_{\lambda_k} = \frac{1}{\alpha_k \beta_k} \times \frac{V_{2,k} \times V_{3,k}}{V_{1,k} \times N} \quad [Volts/Wm^{-2}Sr]$$  \hfill (10)

The Eqn. 8 and 9 constants $\alpha$ and $\beta$ are calculated from that day’s solar spectrum and the accuracy of this technique relies on the spectral shape of the filter throughputs $\tau_a(\lambda)$ and $\tau_b(\lambda)$ not significantly changing, but is independent of their absolute transmission peak magnitudes $T_a$ and $T_b$ (which will undergo inevitable degradation). Finally the $R_{\lambda_k}$ values derived from Eqn. 10 can be used to perform monthly spectral updates to the instrument spectral response, as in Fig. 3.

3. Summary and Conclusions

Official climate observing system accuracies, such as that on the Terra/Aqua satellites (NASA (2021)), have been assessed as being inadequate for steering and improving climate predictions, of fast arriving global warming (see Wielicki et al. (2013)). The Sun is the best calibration target currently in orbit, potentially for viewing and using to correct such on-orbit ERB instrument changes. However it was mentioned earlier that the difficulty of using it to better calibrate Earth viewing radiometers, is that solar radiance is near five orders of magnitude greater than that leaving the Earth. With the units of spectral radiance being $Js^{-1}/m^2/\mu m/Sr$, most next generation concepts have concentrated on attenuating the time and space units, by reducing detector integration time in seconds, and great spatial attenuation using pinholes or slits (i.e. reducing seconds $s$, and area
in $m^2$ as in Kopp et al. (2017)). This proposed concept does not attenuate in space as significantly, or time at all, but instead it does it in wavelength units of $\mu$m. That would be the first narrowband ERB concept which uses near direct views of solar radiance by an Earth viewing telescope, without relying on reflection off a diffusing, hence attenuating, secondary surface (which like all optical components will itself degrade in response). The GERB devices use a mechanism to move the LW rejecting SW quartz filter in and out of the optical train. This means 25 years later, the GERB-like mechanism could be modified to include the narrow band filters of this concept. It should also mean better spectral balancing of the GERB or CERES-like SW channel with its optical filter-less Total measuring counterpart, ensuring best accuracy of retrieved daytime LW results (i.e. from the difference in Total and SW channel signals, see Matthews et al. (2007b); Matthews (2018b)). It therefore has the potential to make fully SI traceable next generation ERB instruments with both the desired space/time resolution, accuracy and stability requested by Ohring et al. (2005); Fox et al. (2011); Wielicki et al. (2013); NRC (2018), making optimal use of all functioning worldly ERB devices.

Recently it has become the case that calibration stability confidence on the $10^{-1}\%$/decade level for data from CERES devices, has been actually already achieved using lunar calibration described by Matthews (2008, 2018a), as part of the Moon and Earth Radiation Budget Experiment (MERBE, Matthews (2018b,c, 2021)). This gives indication that even in the event of this concepts failure, the MERBE stability far superior to that of the higher cost CERES, will still be achieved by such a new device.

However, absolute SI traceable accuracy of MERBE data from the year 2000 does need to be better achieved and quantified, to determine the true value of the “MERBE Watt” introduced by Matthews (2018a). As an example then consider that right now it is assumed 1 MERBE Watt = 1 true Watt, in $Js^{-1}$. If later it is found lunar albedo is say 1% brighter than thought in creating the
Edition 1 MERBE Earth data, it will be the simple case that actually 1 MERBE Watt = 1.01 true Watts. With the success of this concept measuring the Moon as in Matthews (2008, 2018a,c,b), it would then be that Lunar calibrated MERBE Earth data back to the beginning of the century can undergo a onetime adjustment. Such lunar calibrated MERBE solar data up to 2015 already exists at Pangaea (2021b) for free download. So in the example just above, data users can simply apply a 1.01 multiplication of all MERBE SW Earth Edition 1 fluxes from 2000-2015 to achieve this. New avenues of improving climate model validation could then be opened, by creating excellent SI traceable closure of Earth’s true radiation budget, dating back to the year 2000.

Acknowledgments

MERBE EBAF-like Ed 1.0 incoming and reflected solar results are down-loadable at the FAIR compliant sites Pangaea (2021a,b). CERES instantaneous Edition 1-CV BDS results were obtained from the NASA LaRC Atmospheric Science Data Center.

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