The need for and lack of a highly accurate climate observing system led to the creation of the Moon and Earth Radiation Budget Experiment (MERBE), which unifies and stabilizes both ESA and NASA climate missions to a common SI traceable radiometric standard based on existing lunar scans. Preliminary MERBE results suggest it has the capability to validate climate model predictions of cloud feedback and forcing effects immediately upon its free worldwide release after 2015, a quarter of a century sooner than that possible with existing or even planned missions such as CLARREO or TRUTHS. New MERBE radiances are all calibrated based on the SI traceable standard of the MERBE Watt, formulated around certainty that both the Moon’s reflectivity and emissivity are universally available constants measurable with today’s technology. Although knowledge of the MERBE Watt scale is un-necessary for the desired cloud climate change detection thresholds, true closure of the radiation budget will one day also require highly accurate spectral characterization of lunar reflectivity and emissivity. Using new techniques described in this document, a low cost CubeSat mission is hence proposed that could provide measurements of lunar reflectivity within the desired < 0.15% climate observing system accuracy level, in addition to the Earth scattered solar measurements expected from the CLARREO mission. Spectrally resolved Earth albedo data will also aid in validating and improving the global spectral signatures generated for all instruments in the MERBE program (provided by Zedika freeware). Moon albedo results will additionally be highly beneficial to the dozens of international Earth observation missions by bringing absolute accuracy to all instruments with existing or future lunar views.

**Keywords:** MERBE, Climate Observing System, CLARREO, ROLO, Earth Radiation Budget observations
Table 1. Past, existing and future satellite missions measuring ERB parameters SI traceable to the Watt or MERBE Watt.

<table>
<thead>
<tr>
<th>ERB Mission</th>
<th>Lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIMBUS 7 ERB(^4)</td>
<td>1978-1993</td>
</tr>
<tr>
<td>ERBE(^4)</td>
<td>1984-2005</td>
</tr>
<tr>
<td>CERES(^5)</td>
<td>1998-Present</td>
</tr>
<tr>
<td>GERB(^6)</td>
<td>2002-Present</td>
</tr>
<tr>
<td>DSCOVR(^7)</td>
<td>2015-?</td>
</tr>
<tr>
<td>RBI(^8)</td>
<td>2021-?</td>
</tr>
<tr>
<td>CLARREO(^9)</td>
<td>2023-?</td>
</tr>
<tr>
<td>TRUTHS(^10)</td>
<td>??</td>
</tr>
</tbody>
</table>

1. SCIENTIFIC/TECHNICAL SECTION

1.1 Introduction: Objectives and Identification of Climate Observing System Calibration Challenges

The need to gain greater confidence in Global Circulation Model (GCM) computer predictions of coming changes to Earth’s climate is of growing importance, given the unprecedented anthropogenic loading rate of atmospheric greenhouse gases since the 19\(^{th}\) century. The largest of climate modeling uncertainties includes the total effect of Cloud Radiative Forcing (CRF), or more specifically whether clouds with their high reflectivity and thermal Infra-Red (IR) absorption will change in ways that enhance or slow the rate of global warming. All actions of Earth’s weather and climate system represent the work done from an effective planet scale heat engine. This happens in response to a net equatorial region solar input (or heat in) and an overall majority of emitted IR energy lost back to space from the poles as heat out. Complete constraintment of GCMs which simulate this system therefore requires highly accurate and long term spatial tracking of these energy sources and sinks. Such parameters are part of what is called the Earth Radiation Budget (ERB), which also requires knowledge of the incoming solar flux \(I_0^{1,2}\). The amount of sunlight that does not enter due to direct reflection in the spectral band \(0.2 < \lambda < 5\mu m\) is called Short Wave (SW).

Observing the expected SW signal trends of CRF is highly challenging because they are predicted to be only 0.8% decade\(^{-1}\) or less in absolute size\(^9,11\) (see threshold horizontal green line in Fig. 1). Also natural variability results in a minimum length of data that is required to determine statistically if a measured trend represents global decadal climate change or simply shorter term processes such as El Niño. In the optimal case, satellite instrument calibration would be held traceable to Système Internationale (SI) standards\(^12\) for all satellite missions extending over the needed time spans (e.g. see Table. 1). This brings the earliest confidence that climate signals reported are due to the Earth and not the satellite instrumentation changing over time. The current focus on cloud processes for GCM studies requires high spatial resolution radiance measurements that are 50km or less in size, enabling assignment of cloud property retrievals\(^13\) to footprints. Such a small footprint to isolate cloudy and cloud-free regions where possible is obtained using instrument focusing optics and relatively small photon sensitive detectors. The reflectivity, transmission and absorptivity of such optical components will vary throughout the ERB wavelength region of interest (0.2 – 200\(\mu m\)). Furthermore space shuttle recoveries of ERB-type optics from the low Earth orbit environment have shown UV transmission degradation to occur there in excess of 30% (i.e. due to sunlight exposure and contamination\(^{14,15}\)). The climate science community has highlighted the need\(^11\) to obtain solid evidence that any signal or trend in such satellite measurements of CRF are real, and not due to natural variability or the instruments changing. The dotted curve in Fig. 1 shows calculations by the CLARREO\(^9\) team of when the existing calibrated satellite SW observing system would be able to prove that such predicted trends are real with 95% confidence, and not due to instrument changes or natural variability. These estimates suggest that such a result could not be achieved using currently orbiting devices until the year 2050.
1.2 The Moon and Earth Radiation Budget Experiment (MERBE)

Due to such challenges, the 2007 NRC Decadal survey\textsuperscript{22} identified a critical need for a long-term global benchmark record of critical climate variables that are accurate over very long time periods, can be tested for systematic errors by future generations, are unaffected by interruption, and are pinned to international standards. Accordingly efforts have been made on developing future missions equipped with enhanced on-board calibration systems under development and due for launch in around ten years. However largely due to the time needed after deployment to see through signals of natural variability (e.g. El Niño), these new improved instruments will still not detect such predicted trends for decades from now. This is illustrated by the 2038 crossing of the dashed curve with the horizontal green threshold in Fig. 1, based on calculations\textsuperscript{9, 10} for either the CLARREO or TRUTHS mission concepts. Hence today using existing or even planned climate observing systems, no possible resolution of the greatest climate prediction uncertainties will be apparent still for a quarter of a century. This lead to the concept of the Moon and Earth Radiation Budget Experiment (MERBE\textsuperscript{17, 23–25}), which instead takes existing data both unified and stabilized to the SI traceable scale of the MERBE Watt (see Eqn. 4). Figs. 2(a) & (c) show initial solar phase dependent results from MERBE using data from the Terra satellite in comparison with the USGS ROLO\textsuperscript{16} and Zedika\textsuperscript{17} lunar models. Utilizing the same CLARREO team statistical analysis\textsuperscript{26} on such measurements normalized to a ‘static’ solar phase as in Fig. 2(b), MERBE SW data should have the capability to resolve the greatest of climate change uncertainties immediately upon release after 2015\textsuperscript{23} (see solid black curve of Fig. 1). Such MERBE data is already in production and due for a free worldwide release after 2015. However a secondary objective of MERBE is to provide an absolute reference calibration standard for all solar and thermal instruments sharing a satellite with an ERB device in its program. Such platforms in Table. 1 include NIMBUS 7, NOAA 9 & 10, TRMM, TERRA, AQUA, MSG 1-4, NPP and DSCOVR from both the USA and Europe. Hence this report summarizes a CubeSat mission concept called MERBE-Sat that is designed to not only help meet this secondary objective, but also provide the first fully SI traceable spectral characterization of both lunar and Earth albedos. Such Moon characterization then additionally brings the possibility of absolute traceability for any satellite with regular views of the Moon. This incorporates further dozens of instruments on platforms such as SeaWIFS, GOES 1-15 & GOES R-U (USA), Meteosat 1-11 & MTG 1-6 (EU), Himawari 1-9 (Japan), COMS-1 & GEO-KOMPSAT 2A-2B (S. Korea) and FenYung 2A-2F, FenYung 3A-3F & FenYung

![Detectable Satellite SW Climate Trends](image)

Figure 1. The size of SW/Solar climate trends detectable in Satellite Earth Observation data records with 95% confidence.
Figure 2. (a) Preliminary MERBE lunar reflectivity vs solar phase angle data taken from the Terra satellite between 2000 and 2015 and compared to the USGS ROLO\textsuperscript{16} model. (b) CLARREO statistical analysis applied to actual preliminary MERBE SW data showing 95% confidence with which climate trends can be detected. (c) Preliminary MERBE lunar surface temperature vs solar phase angle data taken from the Terra satellite between 2000 and 2015 and compared to the MERBE LW model.\textsuperscript{17} (d) CLARREO statistical analysis applied to actual preliminary MERBE LW data showing 95% confidence with which climate trends can be detected.
As a beginning to MERBE every ERB device on the satellites of Terra and Aqua has been completely recalibrated from the level of detector voltages upwards. Shown in Fig. 3, this uses improved signal inversion that significantly enhances Earth data by removing thermal and electronic time effects from bolometer data. In addition to correcting large CERES scene dependent biases (compare the left and right of Fig. 3), it also allows extraction of many thousands of independent lunar scans taken by Terra/Aqua instruments since the year 2003 (see Fig. 2). For the SW region which is the topic of this proposal, all such devices hence measure in Solar MERBE watt units $W_s$, as defined by Eqn. 4 in terms of the $kg$, $m$ and second:

$$\hat{a} = 0.1366$$

$$\hat{I}_0 = 1361 \, W \, m^{-2}$$

$$a = \frac{\int_\lambda M(\lambda) S(\lambda) d\lambda}{\int_\lambda S(\lambda) d\lambda}$$

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

Being required for SI traceability in the chain of equations above, $S(\lambda)$ is the mean spectrum of light from the Sun while $\hat{a}$ and $\hat{I}_0$ are the MERBE constants declared in Eqns. 1 & 2 and described further below. Disk averaged lunar surface reflectivity at $+7^\circ$ ‘static’ solar phase angle in Eqn. 3 is $M(\lambda)$. The term static indicates that it is the albedo to an observer above $0^\circ$ selonographic latitude and longitude on the Moon, with zero angular alignment libation. Using the USGS lunar ROLO model to normalize for non-static phases, the value of $a$ from Eqn. 3 is currently measured to be around 0.1366 on average, which therefore provides the basis for Eqn. 1’s proposed scaling factor $\hat{a}$. The SORCE mission has performed measurements of both solar input $I_0$ and
Figure 4. Real-time Clear, Overcast and Allsky Spectral Signatures provided to user by MERBE software (see animation here for more details)
and $S(\lambda)$ using its Total Irradiance Monitor (TIM) and Spectral Irradiance Monitor (SIM). SORCE is the SOlar Radiation and Climate Experiment and its results determine the Sun irradiance constant $I_0$ of 1361 W/m$^2$ in Eqn. 2. The purpose of MERBE-Sat is hence to accurately determine the exact time varying values of $M(\lambda, t)$, then $\bar{M}(\lambda)$ from Eqn. 3, so to close off the solar portion of the ERB by finding the $W_s$ to Watt ratio from Eqn. 4.

MERBE additionally uses a multi-dimensional Fourier series tensor to provide fast real-time MODTRAN estimations of the spectral signature or wavelength distribution of radiance being viewed by each instrument in its program. Such results are time, scene and latitude dependent; based on MODTRAN 5.3 calculations for all possible Earth viewing geometries with appropriate aerosol and cloud conditions. Examples of such spectral signatures are shown in Fig. 4. Such results are needed for MERBE to perform the improved non-linear un-filtering of broadband radiance measurements, but will also be made available to climate data users via freeware that operates the Fourier series tensor. It is however encouraged that users with specific climate spectral signal needs work with Zedika to produce tailor made Fourier tensors that could improve on the quality of results. To that end and as will become clear, this MERBE-Sat proposal shall be shown to also generate high spatial and spectral resolution Earth albedo data with absolute SI traceability. Given the potential to place a CubeSat in a polar orbit this will also provide half of the radiant climate benchmarks desired from the CLARREO$^9$ mission, as originally proposed in 2007.

1.3 MERBE-Sat: In-flight Calibration Traceability through direct Solar and Lunar Radiance

There is currently no proven way to generate stable SI traceable SW wavelength radiance from an on-board satellite calibration source, and hence update the calibration of an Earth climate observing radiometer through hardware. The alternative technique implemented on missions such as NIMBUS 7 and ERBE was to use the Sun itself, with its low 0.1% variability that has been tracked from orbit since the 1970s using optic-free cavity instruments. The narrow field of view (NFOV) required to measure a footprint small enough to examine CRF processes however places direct solar radiant power around 5 orders of magnitude too high for use in characterizing such an instrument in-flight. It is unclear whether spatial attenuation of direct solar radiance using pinholes or moving optical fibers will meet the climate observing system requirements either, since it illuminates only a fraction of the Earth viewing optics needing characterization. MERBE-Sat instead suggests use of a compound dispersive ConCave (CC) lens as in Fig. 5, allowing minimal optical size and an integration into a small CubeSat Module. In addition to the simplicity of the MERBE-Sat design, it shall also allow low cost ground characterization of a single calibration parameter known as the Optical Alignment Ratio (OAR), using simple LED sources and a two axis gimbal (see Figs. 9 and 10 later). MERBE-Sat could hence utilize two off the shelf compact spectrometers in close proximity (the chosen Ocean Optics devices have been used in orbit before and are of dimensions 40 x 42 x 24mm that are easily accommodated into a CubeSat). One of these is fed from an optic-less Wide Field of View (WFOV) telescope making it capable of direct solar radiance measurements, while the other telescope in Fig. 5 has focusing lens to sample reflected sun-light from either the Moon or Earth while in low earth orbit (designated the NFOV telescope). To give the needed spectral bandpass all lenses should be made of fused silica, while the CC lens can be placed in-front of either the NFOV or WFOV telescope using the filter wheel as shown in Fig. 6 (recommended lenses are 12mm diameter with a speed of f/1). MERBE-Sat direct solar measurements are collected and integrated over an entire hemisphere during each half orbit. Mathematically it then follows that the ratios of the separate angular integrals of WFOV data taken with and without the de-focuser in place will measure changes to spectral transmission $T_k$ of such a CC lens at wavelengths $\lambda_k$. The simplicity of this CubeSat concept shall rely on a ground measurement of OAR ($O_k$ from Eqn. 13), the procedure for which is detailed in Sec. 1.3.3. This $O_k$ coefficient is independent of net optical transmission changes, such that an equally distributed reduction in CC lens transmission $T_k$ will make no difference to the ground measured values performed in the laboratory before launch. As will be shown later, other than measuring $O_k$ on the ground all radiometric calibration of MERBE-Sat is performed on orbit.

1.3.1 CuboSat design

Due to their low cost, CubeSats are today being used for an increasing number of purposes. Also known as ‘nanosats’, each device is constructed using modular cube sections each 10 cm in side length and generally
Figure 5. MERBE-Sat WFOV and NFOV optical train design. Top Left: Normal operating mode ($ij = nn \& wn$) where on each orbit WFOV measures the Sun and NFOV measures the Moon and Earth. Top Right: NFOV calibration mode ($ij = nc \& wn$) with CC lens in Moon/Earth optical train so it can view the Sun directly. Bottom Left: WFOV calibration mode ($ij = nn \& wc$) with CC lens in Solar optical train.
connected together in a single dimension. The number of cubes utilized determines the type of nanosat and its definition in terms of number of 'u' modules. MERBE-Sat optical components are designed to entirely fit in a 3u CubeSat, or three modules fixed together. The two end sections shall house either the WFOV or NFOV grating devices separately. The spectrometers chosen are of miniature design and available off the shell28 as used in the concept example above. Such spectrometers have dimensions of 40.0 mm x 42.0 mm x 24.0 mm, easily fitting in a single 10 x 10 x 10 cm CubeSat module (note the concept Fig. 7 assumes more space may be needed, so multiple spectrometers can be used to cover a greater wavelength range). The collecting optics for both WFOV and NFOV spectrometers are almost identical, being baffled tubes painted black and blocked at the back end which houses the spectrometer fiber input (Fig. 5). Length and diameter of these baffle tubes is chosen so to give each telescope a 20° maximum possible angular field of view. The minor difference is that the NFOV telescope has a Suprasil focusing convex lens positioned to direct incoming collimated radiances onto its spectrometer fiber input (using a 12mm lens diameter and f/1 optical speed). A 0.036mm diameter fiber in this configuration will give an approximate 1km footprint on the Earth, matching that desired from CLARREO measurements. It is also important that both channels have a shutter in the optical train (Fig. 7), which for the NFOV is automatically activated by a solar proximity sensor to prevent direct sunlight from being focused on its fiber. The normal operating optical configuration for MERBE-Sat is shown in Fig. 5 (top left), and the entire unit is to be spin stabilized with a vector aligned with its velocity as in Fig. 8(a). On each illuminated side of the orbit this allows the WFOV to record direct solar spectral power while the NFOV measures scattered Earth radiance (or that from the Moon on the dark side of the orbit). A CubeSat rotation rate of 1Hz is recommended to optimize spatial lunar coverage and signal to noise (note an increased sampling rate is advised for Moon scans as the chosen spectrometer28 allows). Normal operating mode Earth data $V_{ij}(\lambda_k,t)$ shall therefore be the product of radiance $L(\lambda_k,t)$ and detector $k$ response $G_i(\lambda_k)$ of telescope 'i' (e.g. either NFOV $i = n$ or WFOV $i = w$). All offsets are removed by space looks on each MERBE-Sat rotation and here $j = n$, indicating ‘normal’ operating mode (or otherwise calibration mode $j = c$ with the CC lens is in place). On that same orbit the WFOV signal $V_{wn}(\lambda_k,\Theta,\Phi)$ will be a measure of solar output $S(\lambda_k,t)$, that will also depend on the relative angle orientation $\Theta, \Phi$ of the telescope to the Sun at time $t$ (see Fig. 8(b)). As described in previous work,27 it is possible to obtain an orientation independent measure of $S(\lambda_k,t)$ averaged over the entire orbit by performing a hemispherical integral on the result as in Eqn. 14 shown later. This result $U_w(\lambda_k,\text{Sun})$ is then the product of WFOV detector $k$ response $G_w(\lambda_k)$ with $S(\lambda_k)$, the mean solar spectral radiance. $G_n(\lambda_k)$ and $G_w(\lambda_k)$ will vary over time due to electronic drifts and optical degradation. Their absolute values however are not required as will be shown.

In the plane of $x$-$y$ the filter wheel from Fig. 6 will be positioned for rotation in the CubeSat. As illustrated in Fig. 5 the CC de-focusing optic is equipped with a partially transmitting grating to prevent scattering signal. Incorporated in the same wheel are multiple clear apertures of equal diameter to that of the CC lens. Minor rotation of this filter wheel shall therefore allow the CC lens to be placed in the path of either the WFOV or NFOV telescope as discussed earlier and shown in Fig. 6. The grating behind the CC lens is to be painted black in order to minimize net transmission of reflections between the NFOV focusing lens and the CC optic. The combination of sunlight lens dispersion over a 20° cone and around a 10% grating throughput will enable both WFOV and NFOV telescopes to directly view the Sun (i.e. the solar proximity sensor and shutter is de-activated when the filter wheel is in the NFOV optics).

1.3.2 Theory and In-flight Use of the Optical Alignment Ratio $O_k$

MERBE-Sat as described above therefore has a pair of telescopes, each capable of two different possible field of view responses both with and without the CC lens in the optical path. Optical theory suggests the CC lens concept will work given a pre-flight laboratory characterization of the instrument $O_k$ values defined by Eqn. 13. The primary intention of this proposal is to outline performance of a high resolution comprehensive computer validation of such theory using tailored techniques developed by Zedika Solutions LLC. It is therefore important in this section to outline precisely how the $O_k$ values are to be both used in-flight and measured on the ground.

The signal from the spectrometer telescope-lens configuration ‘$ij$’ when viewing the radiant source $L(\lambda_k,\theta,\phi)$ extended over angles $\theta, \phi$ at relative angular polar coordinates $\Theta, \Phi$ is given by Eqn. 6. Image plane and scene angular integrals are $dA = dX dY$ and $d\Omega = \sin\theta d\theta d\phi$ respectively as shown in Fig. 8(b), while $X, Y$ is the position at the image plane. $D_n(X,Y)$ and $D_w(X,Y)$ are the net spatial extents of the NFOV ($n$) and WFOV ($w$) spectrometer optical fiber input apertures at the image plane as in Fig. 8(b), each with an angular integral
Figure 6. Concept for MERBE-Sat telescope unit with filter wheel to position CC lens in either WFOV or NFOV optical trains for in-flight calibration.
Figure 7. Concept for 3u MERBE-Sat device with WFOV and NFOV spectrometers in the outer CubeSat modules and the optical components in the central module. Visible and Infra-Red still cameras are also incorporated to enable cloud mask production.
Figure 8. (a) MERBE-Sat in orbit with spin aligned with its velocity vector. (b) Geometry of MERBE-Sat optical alignment at scene, aperture and image plane.
of one when used in normal operating mode (Eqns. 7 and 8). \( P_{ij}(X, Y, \theta, \phi) \) is then the point spread function (PSF) of the optics between the fiber and the target radiance either with the CC lens in place or removed. In the case that either the NFOV or WFOV spectrometers are in normal operating mode \((ij = nn, or wn)\), the hemispherical integral of such a PSF is also defined as unity (Eqns. 9 and 10). Hence in this normal operating mode, the instrument response can be represented by a single gain constant \( G_{i}(\lambda_k) \) or \( G_{w}(\lambda_k) \) as in Eqn. 6, which tells the voltage output per unit of spectral radiant input at wavelength \( \lambda_k \) (in Volts per W/m²Srµm).

\[
\frac{g_i(\lambda_k, t)}{\nu_i(\lambda_k, t)} = \frac{V_{ij}(\lambda_k, \Theta, \Phi)}{D_i(X, Y)} = G_i(\lambda_k) \int_{2\pi} \int_{2\pi} P_{ij}(\lambda_k, X, Y, \theta, \phi) \nu_i(\lambda_k, t) \text{d}\Omega \text{d}A
\]

\[
\int_{2\pi} \int_{2\pi} P_{nn}(\lambda_k, X, Y, \theta, \phi) \text{d}A \text{d}\Omega = 1
\]

\[
\int_{2\pi} \int_{2\pi} P_{wn}(\lambda_k, X, Y, \theta, \phi) \text{d}A \text{d}\Omega = 1
\]

\[
\int_{2\pi} \int_{2\pi} P_{nn}(\lambda_k, X, Y, \theta, \phi) \text{d}A \text{d}\Omega = T_{nc}^{uc}
\]

\[
\int_{2\pi} \int_{2\pi} P_{wn}(\lambda_k, X, Y, \theta, \phi) \text{d}A \text{d}\Omega = T_{wc}^{uc}
\]

\[
O_k = \frac{T_{nc}^{uc}}{T_{wc}^{uc}}
\]

As discussed it is expected that the values of \( G_{i}(\lambda_k) \) will change significantly post launch and in-flight due to optical degradation and electronic amplifier drifts. The short term electronic drifts from thermal changes can be accommodated by including a bank of UV-NIR LEDs which are designed to blink on-off and feed into the spectrometer in question as shown in Fig. 7. The on-off timing de-activates the LEDs while the channel is facing its target or space, then that same channel is shuttered from external radiance while the LEDs are on to give signal \( \nu_i(\lambda_k, t) \) in Eqn. 5 (e.g. shutter on for the NFOV facing the Sun or Earth at night, while the WFOV shutter activates when viewing daytime Earth). The in-flight data can then be normalized by orbital varying result \( g_i(\lambda_k, t) \) as in Eqn. 6, which corrects the instrument to the average response that day \( \nu_i \) by Eqn. 5. Importantly the net transmission \( T_k \) of the CC lens will also change significantly over time, resulting in equal magnitude changes to the integrated PSF of the optics in when calibration mode \((ij = nc or wc)\). Eqns. 11 and 12 represent the net CC lens transmission when aligned with either the NFOV (nc) or WFOV (wc) instruments respectively, becoming scaler spectral variables \( T_k^{nc} \) or \( T_k^{wc} \). It should be acknowledged as likely that \( T_k^{nc} \neq T_k^{wc} \) largely due to differences in NFOV and WFOV alignment. Fundamentally the MERBE-Sat concept however assumes that \( T_k^{nc} \propto T_k^{wc} \) in an constant way, so a uniform degradation to operational optics will simply lower such values by an equal fraction, with no change to \( O_k \) as defined by Eqn. 13. The effects on accuracy of deviation from this assumption are part of what must be quantified by the work following this proposal. Knowledge of the ratio \( O_k \) could therefore enable SI traceable lunar and Earth albedo measurements to be made by MERBE-Sat as in Eqns. 14 to 17:

\[
U_{ij}(\lambda_k, b) = \frac{1}{\Delta \Omega_b} \int_{2\pi} \frac{V_{ij}(\lambda_k, \Theta, \Phi)}{g_i(\lambda_k, t)} \text{d}Y
\]

\[
B_k = \frac{U_{wn}(\lambda_k, Sun)}{U_{wc}(\lambda_k, Sun)} \times O_k
\]

\[
M(\lambda_k, t) = \frac{U_{wn}(\lambda_k, Moon)}{U_{wn}(\lambda_k, Sun)} \times B_k
\]
where $d\Omega' = \sin \Theta d\Theta d\Phi$, now being the hemispherical integral over relative polar coordinates \(\Theta\) and \(\Phi\) as in Fig. 8(b). The once per orbit measurement \(U_i(\lambda_k, b)\) is then obtained by Eqn. 14 from scanning celestial body \(b\) (i.e. \(b = \text{Sun} \) or \(\text{Moon}\)). As before this is done with telescope-lens configuration \(ij\), while $\Delta\Omega_b$ is then the current angular size of the body being scanned. Using such results it is possible to update the effective WFOV/NFOV device gain ratio $B_k$ in Eqn. 15 using two consecutive MERBE-Sat orbits and the ground measured $O_k$ values. SI traceable Lunar albedo $M(\lambda_k, t)$ results at time $t$ are then found from Eqn. 16, which can be made for all Moon phase angles between $-90^\circ$ and $+90^\circ$. Eqn. 17 additionally then provides Earth albedo $E(\lambda_k, t)$ at time $t$ from the NFOV instantaneous signal $V_{nn}(\lambda_k, t)$. In the event of a polar orbit for MERBE-Sat, the $E(\lambda_k, t)$ measurements will represent the climate benchmarks desired from the original CLARREO mission as first proposed in 2007. Even in a more common lower CubeSat orbit such as that of the ISS, $E(\lambda_k, t)$ SI traceable values will also provide validation or improvement for the Fourier tensors that give spectral signatures for the new MERBE climate data records. This will be aided using cloud masks based on images from the visible and IR digital still cameras also installed on MERBE-Sat as shown in Fig. 7.
1.3.3 Ground Measurement of the Optical Alignment Ratio $O_k$

Since it is fundamental to MERBE-Sat, this section now outlines a proposed experimental methodology for measuring the $O_k$ values on ground prior to launch. As with the CubeSat design itself, this is intended to make use of off the shelf components and low cost optical sources, allowing such measurements to be made rapidly and repeatedly for very low expense. To measure $O_k$ by simulating solar views in orbit would be challenging, since it requires collimation of lamp or laser light with a large dynamic range ($1 \rightarrow 10^5$). Instead it is proposed that $O_k$ values be determined as in the concept diagram of Fig. 10, where the LED target source covers a large solid angle. MERBE-Sat is therefore held in the two axis gimbal mount as shown in Fig. 9, either for WFOV calibration as illustrated or up-side down in the same gimbal for NFOV characterization. These two axis gimbals enable rotation around the center of the telescope aperture being characterized and each MERBE-Sat gimbal configuration is positioned in a dark ambient pressure black box as in Fig. 10, facing the integrating sphere illuminated by LEDs. Included at the calibration black box front is a broadband reference detector combined with a third, identical spectrometer to the type used within MERBE-Sat (the broadband radiometer can use either cavity or pyro-electric detectors). Such integrating sphere LEDs are chosen specifically to cover UV-VIS-NIR wavelengths of the SW ERB region. Then to allow the convolution integral mathematical theory to work most effectively, the LED brightness is suggested to be linearly ramped down as the viewing telescope reaches 50 to 70 degrees zenith angle $\Theta$ from the center of the integrating sphere (as in Fig. 10 this will also allow a zero radiance to be found by reference detectors with no need for a chopper).

Measurement of $O_k$ in the ground laboratory is then a four step repetitive process. First with the CC lens in the WFOV telescope and the gimbals centered on it as in Fig. 9, these gimbals proceed to rotate fast in the x-z and slow in the y-z planes simulating the gathering of data from an entire hemisphere over a simulated half orbit. WFOV detector signal is recorded along with that of the reference spectrometer $R(\lambda_k, t)$, before hemispherical integration gives the result $H_{wc}(\lambda_k)$ from Eqn. 18. Then the CC lens is removed by rotating the internal filter wheel from Fig. 6 and the process is duplicated to give $H_{wn}(\lambda_k)$ values. Next the MERBE-Sat is removed and placed upside down in the gimbal setup so now the rotation pivot is centered on the NFOV telescope entry aperture. Hemispherical scanning with the NFOV is performed a third time again with reference signals collected as before to give $H_{nn}(\lambda_k)$. Finally the internal filter wheel is rotated once more to place the CC lens now in the NFOV optical train, before the same hemispherical scan is performed a final fourth time to give $H_{nc}(\lambda_k)$. The values of $O_k$ are hence found using Eqn. 19:

$$H_{ij}(\lambda_k) = \int \frac{V_{ij}(\lambda_k, \Theta, \Phi)}{R(\lambda_k, t)} d\Omega'$$ (18)
\[ O_k = \frac{H_{nc}(\lambda_k) \times H_{wn}(\lambda_k)}{H_{wc}(\lambda_k) \times H_{nn}(\lambda_k)} \] (19)

The reference signal \( R(\lambda_k, t) \) measured at time \( t \) is derived on ground from the reference broadband and spectrometer detectors on the front of the black box in Fig. 10. It is advised that the broadband detector also be used to characterize any non-linearities in the MERBE-Sat spectrometer detectors.

REFERENCES