Compensation for spectral darkening of short wave optics occurring on the Cloud's and the Earth's Radiant Energy System

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ABSTRACT

Cloud's and the Earth's Radiant Energy System (CERES) is an investigation into the role of clouds and radiation in the Earth's climate system. Four CERES scanning thermistor bolometer instruments are currently in orbit. Flight model 1 (FM1) and 2 (FM2) are aboard the Earth Observing System (EOS) Terra satellite and FM3 and FM4 are aboard the EOS Aqua satellite. Each CERES instrument measures in three broadband radiometric regions: the shortwave (SW $0.3-5\mu m$), total ($0.3- > 100\mu m$), and window ($8-12\mu m$). It has been found that both CERES instruments on the Terra platform imply that the SW flux scattered from the Earth had dropped by up to 2% from 2000 to 2004. No climatological explanation for this drop could be found, suggesting the cause was a drift in both the Terra instruments. However, the onboard calibration lamps for the SW channels do not show a change in gain of this magnitude. Experience from other satellite missions has shown that optics in the orbital environment can become contaminated, severely reducing their transmission of ultra-violet (UV) radiation. Since the calibration lamps emit little radiance in the UV spectral region it was suggested that contaminates could be responsible for an undetectable 'spectral darkening' of the CERES SW channel optics and hence the apparent drop in SW flux. Further evidence for this was found by looking at the comparison between simultaneous measurements made by FM1 and FM2. The proposed mechanisms for contaminant build up would not apply to a CERES instrument operating in the normal cross track scan mode. Indeed it was found from the comparison between CERES instruments on Terra that the response of the instrument operating in rotating azimuth plane (RAPS) mode consistently dropped relative to the other cross track instrument. Since at all times one of the instruments operates in cross track mode, where it is not subject to spectral darkening, it allowed that unit to be used as a calibration standard from which the darkening of the other RAPS instrument can be measured. A table of adjustment coefficients to compensate for this spectral darkening are therefore derived in this paper. These figures are designed to be multiplied by SW fluxes or radiances produced in the climate community using Edition 2 CERES data. SW CERES measurements that have been revised using these coefficients are therefore to be referred to as ERBE-like Edition2_Rev1 or SSF Edition2B_Rev1 data in future literature. Current work to fully characterize the effect of spectral darkening on the instrument spectral response before the release of Edition 3 data is also described.

Keywords: CERES, LDEF, spectral darkening, optical contamination

1. INTRODUCTION

The Clouds and the Earth's Radiant Energy System (CERES[1]) is a broadband satellite radiometer program intended to resolve many of the remaining uncertainties surrounding the role of clouds in the Earth Radiation Budget (ERB) and future climate change. An evolution from the Earth Radiation Budget Experiment (ERBE[2]) in the 1980's, CERES uses scanning radiometer instruments to measure the scattered short wave (SW $0.3-5\mu m$) and emitted thermal long wave (LW $5- > 100\mu m$) radiative flux from the Earth. In order to perform these measurements, each instrument has 3 radiometric channels that are the SW ($0.3-5\mu m$), window (WN $8-12\mu m$) and total ($0.3- > 100\mu m$). The SW channel uses a spectral filter (quartz fused silica) to block longwave

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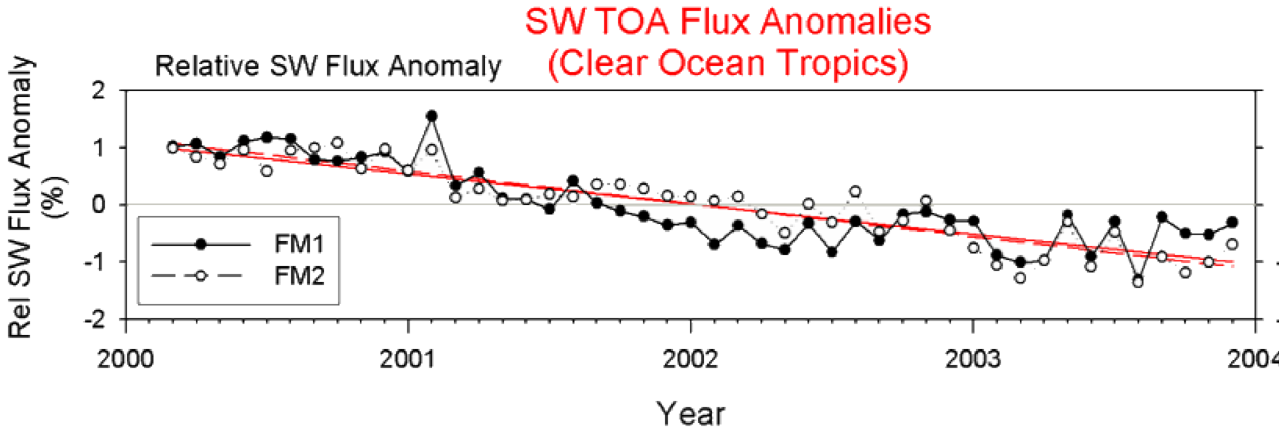

Figure 1. De-seasonalized Terra Edition 2B single scanner footprint (SSF) SW fluxes scattered from Clear Ocean in first 4 years of mission.

radiance, as does the window channel to select the infra-red part of the spectrum (using a zinc sulphide and cadmium telluride combination filter). The total channel has no filter, hence the LW measurement is obtained by subtracting the SW measurement from that made by the total channel. Each channel uses a painted black thermistor bolometer detector at the focus of a silver coated Cassegrain mirror telescope.

Four CERES instruments are currently operational, Flight Model 1 (FM1) and 2 (FM2) are onboard the Earth Observing System (EOS) platform 'Terra', launched in December 1999. FM3 and FM4 operate onboard the EOS 'Aqua' platform launched in May 2002. Both Terra and Aqua are in high inclination near polar, sun synchronous orbits. Terra crosses the equator at 10:30 am local time in the descending portion of the orbit while Aqua ascends across the equator at 1:30 pm local time.

It is estimated that in order to detect significant climate change, CERES measurement accuracy must be able to remain stable, to an accuracy of 0.3% per decade. To achieve this, each instrument has onboard calibration sources for every channel, with concentric groove blackbodies for the window and total channels and a stable tungsten lamp for the SW channel. These sources are used to monitor changes in gain over the mission lifetime. Any changes are then corrected in the Edition 2 data before release to the scientific community.

Based on the experience of ERBE, it was expected that these gain changes would compensate for any instrument drifts, producing the required stability in CERES data when used for climate records. However has been noted[3] that both instruments on the Terra platform suggest a significant drop in scattered SW radiation from the Earth over the first 4 years of the mission. Fig. 1 displays the de-seasonalized Terra measurements of SW flux scattered from tropical oceans, which show a 2% drop over 4 years. From a climatological standpoint this is unreasonably large since it cannot be accounted for by changes in ocean aerosol or variation throughout the 11 year solar cycle. However, as reported in Ref. 4 the SW channel signal from the internal calibration (SWICS) lamps has remained stable to the 0.2% level over the same period, implying the 2% drift is not due to a gain change in the instrument (see Figs. 3 (c) & (d)).

2. EVIDENCE FOR SPECTRALLY NON-UNIFORM DARKENING OF SW OPTICS

Assuming that the output from the on-board tungsten lamps is stable, there would need to be a previously un-detectable change in instrument response in order to account for the drop in SW fluxes. This would have to be a change that would lower the response to scattered Earth radiance but not for the emissions of a tungsten lamp. Because each CERES channel uses optical filters, mirrors and a non-cavity (bolometer) detector, its response to radiance at different wavelengths is not uniform. This non-uniformity is characterized on the ground in the spectral response measurement $S(\lambda)$.[5] The raw measurement made by CERES is therefore referred to as

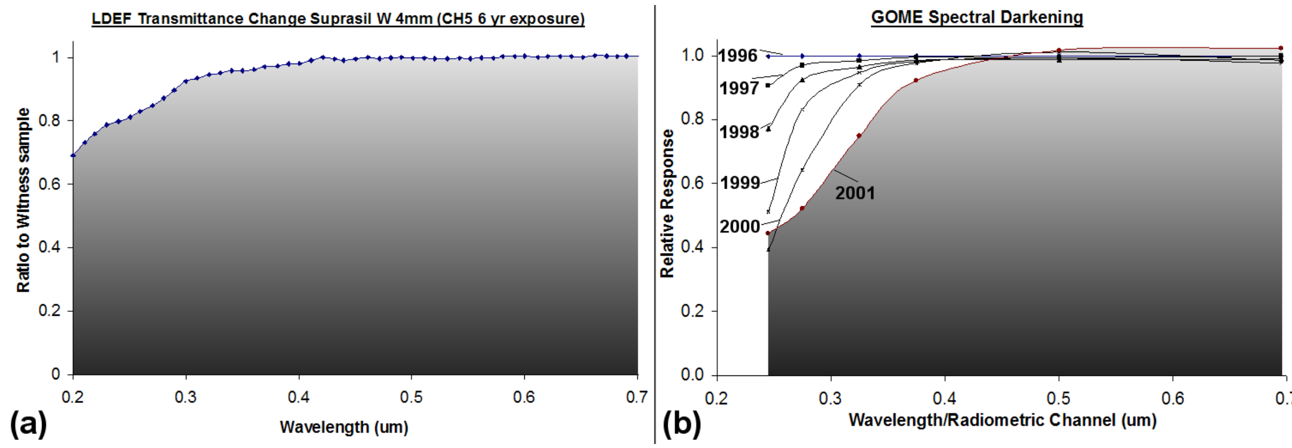

Figure 2. (a) Change in spectral transmission of fused silica (Suprasil) dome on LDEF mission. (b) Change in response of narrowband spectral channels on GOME mission throughout lifetime.

'filtered radiance' LF, given mathematically for the SW channel by Eqn. 1:

$$LF_i^{sw} = \int_0^\infty S^{sw}(\lambda) \times R_i^{sw}(\lambda) d\lambda \tag{1}$$

Where $R_i^{sw}(\lambda)$ is the scattered SW radiance from scene i. Of course what is required by the climate community is the 'unfiltered radiance' L_i^{sw} (Eqn. 2), which is related to the CERES measurements LF_i^{sw} by the scene dependant filtering factor f_i thus:

$$L_i^{sw} = \int_0^\infty R_i^{sw}(\lambda) d\lambda \tag{2}$$

$$LF_i^{sw} = L_i^{sw} \times f_i^{sw} \tag{3}$$

$$f_i^{sw} = \frac{\int_0^\infty S^{sw}(\lambda) \times R_i^{sw}(\lambda) d\lambda}{\int_0^\infty R_i^{sw}(\lambda) d\lambda} \tag{4}$$

For purposes of converting filtered to unfiltered radiance (unfiltering[6]), model estimates of spectral radiance are used to obtain $R_i^{sw}(\lambda)$ and hence the filtering factor f_i^{sw}. Given the relationship of Eqn. 3 and estimates of f_i^{sw} from Eqn. 4, the unfiltering becomes trivial (it is acceptable to use model input in deriving f_i^{sw} because modeling errors will be largely systematic in Eqn. 4).

In the 1980's there was a NASA mission called the Long Duration Exposure Facility (LDEF[7]) which placed spare NIMBUS 7 SW radiometers[8] in low Earth orbit for nearly 6 years before recovery by the space shuttle. The purpose of LDEF was to determine the long term effects of the orbital environment on various materials such as the quartz (fused silica) used to obtain SW measurements in ERB science. It found that optical filters became contaminated by space bourne molecules (largely from out gassing) when reacting to atomic oxygen. These contaminants then became fixed to optical surfaces and hardened by direct solar UV radiation. As shown in Fig. 2(a), it was found that the quartz dome transmission remained largely unchanged in the visible region, while a $10 - 20\%$ drop in transmission was seen in the UV region. Furthermore, it has also been found that on other missions such as the Global Ozone Monitoring Experiment (GOME[9]), the different narrowband channels show a drop in response which when plotted together resembles the apparent spectral darkening that occurred on LDEF (see Fig. 2(b)). It is therefore known that in the orbital environment of LDEF and GOME a spectral darkening occurs that increases with shorter wavelength. As shown in Fig. 3(a), if darkening such as that seen on LDEF had occurred on the CERES SW channel it could account for a $1-2\%$ drop in the instrument response to clear ocean scattered SW flux. The maximum output of the onboard lamp is approximately equivalent to a 2100K blackbody. Hence it can be seen that such darkening of the spectral response curve would have little impact on the signal received from the onboard lamp (Fig. 3(b)). Further evidence for this is seen by observing

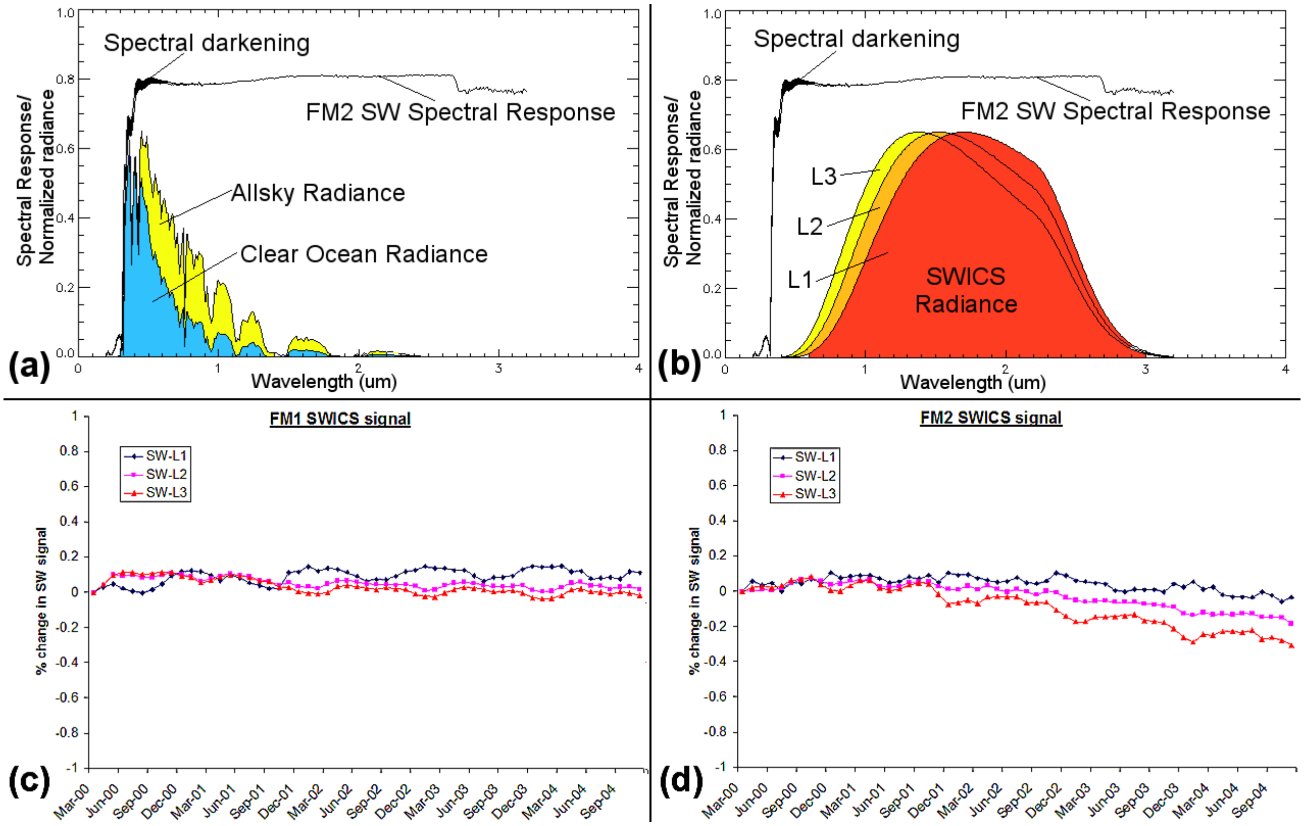

Figure 3. (a) Comparison of normalized clear ocean and allsky spectra with the CERES spectral response if darkened in a manner implied by LDEF. (b) Comparison of normalized tungsten lamp output with the CERES spectral response if darkened in a manner implied by LDEF. (c) Change in FM1 SW sensor response to onboard lamp at 3 different levels of intensity. (d) Change in FM2 SW sensor response to onboard lamp at 3 different levels of intensity.

how in Figs. 3(c) & (d) the change in response to lamp radiance at levels 1, 2 and 3 diverges (L1=1700K, L2=1900K, L3=2100K). As the lamp temperature increases and the Planck function progresses further towards the UV region, there is a marked drop in response compared to the coldest lamp temperature of 1700K.

One more piece of evidence that implies a spectral darkening of the SW optics is found from the results of the deep convective cloud (DCC) 3 channel inter-comparison.[4] Clouds which are very reflective to SW whose tops reside at high altitudes, DCC are the coldest targets found in tropical regions. They are hence easily identifiable by a particularly low signal from the window channel which only measures LW radiance. The filtered radiance measurement made by the total channel when viewing DCC is therefore:

$$LF^{tot}_{dcc} = f^{sw/tot}_{dcc} L^{sw}_{dcc} + f^{lw/tot}_{dcc} L^{lw}_{dcc} \tag{5}$$

Where $f^{sw/tot}_{dcc}$ and $f^{lw/tot}_{dcc}$ are the DCC filtering factors (Eqn. 4) for the SW and LW regions of the total channel spectral response $S^{tot}(\lambda)$ also measured on the ground. Because the DCC thermal emission spectrum is near Planck-like, there is a very good linear relationship between the nighttime filtered total and nighttime filtered window channel radiance $LF^{wn}_{dcc}(N)$ (at nighttime $L^{sw}_{dcc} = 0$ in Eqn. 5).

$$f^{lw/tot}_{dcc} L^{lw}_{dcc} = A \times LF^{wn}_{dcc}(N) + C \tag{6}$$

Since the regression coefficients A and C will be the same during the daytime as at night, it is therefore possible to find the filtered radiance absorbed by the SW portion of the total channel using the daytime filtered window

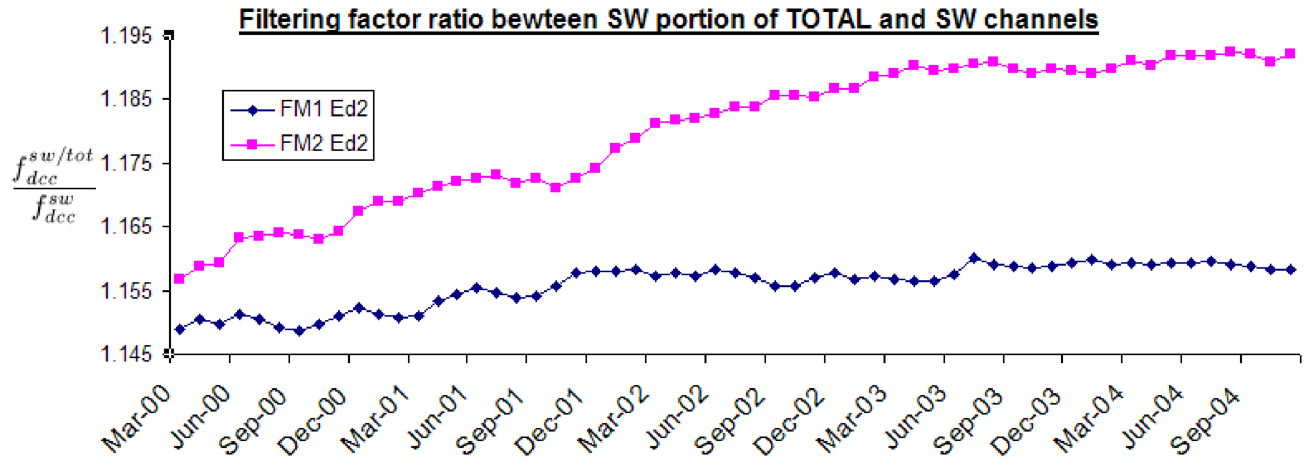

Figure 4. Plot of Edition 2 DCC filtering factor ratios between SW portion of TOTAL and SW channels.

channel radiance $LF_{dcc}^{wn}(D)$:

$$\begin{aligned} LF_{dcc}^{sw/tot} &= f_{dcc}^{sw/tot} L_{dcc}^{sw} \\ &= LF_{dcc}^{tot} - [A \times LF_{dcc}^{wn}(D) + C] \end{aligned} \tag{7}$$

Hence it is possible to take nadir DCC viewing footprints and find the ratio of Eqn. 7 with the simultaneously obtained filtered radiance measurements from the SW channel (Eqn. 3).

$$\begin{aligned} \frac{LF_{dcc}^{sw/tot}}{LF_{dcc}^{sw}} &= \frac{f_{dcc}^{sw/tot} L_{dcc}^{sw}}{f_{dcc}^{sw} L_{dcc}^{sw}} \\ &= \frac{f_{dcc}^{sw/tot}}{f_{dcc}^{sw}} \end{aligned} \tag{8}$$

The results of Eqn. 8 for Terra are plotted in Fig. 4 and show that for both FM1 and FM2 the filtering factor ratio has increased throughout the mission (FM1 +0.8%, FM2 +2.8%). This general increase can be caused by two possible scenarios. Firstly a greater decrease in the SW filtering factor than for the SW portion of the total channel is occurring (i.e. SW channel spectral darkening). Second is the possibility that there is a greater spectral darkening occurring in the LW portion of the total channel compared to the SW region. Since the total channel gain is updated using an on-board blackbody only, it would make the Edition 2 updated gain an underestimate of the true 'detector' gain. With the total channel updated detector gain an underestimate and a greater optical darkening in the LW than the SW, the DCC analysis would suggest that you need to raise the spectral response in the SW portion of the total channel (i.e. increase $f_{dcc}^{sw/tot}$). Since the SW calibration source (tungsten lamp) implies there were no significant changes to the SW channel, the latter option was accepted and the SW portion of the total channel spectral response on both FM1 and FM2 was raised accordingly for the Edition 2 release.[10] This had the necessary effect of balancing the SW channel with the SW portion of the total channel so the derived Edition 2 LW flux would be un-affected by spectral response changes in the SW region. However, in both FM1 and FM2 the total channel response to blackbody radiance has increased during the mission. The latter option would therefore require a far larger than anticipated increase in detector gain (given that the LW portion of the total channel spectral response would need to have darkened by several percent more than in the SW region on FM2 according to Fig. 4). This is then perhaps further evidence that the SW channel response is darkening in a spectral region where the on-board lamps have little to no spectral output (although the latter option of LW total channel darkening may also play a role).

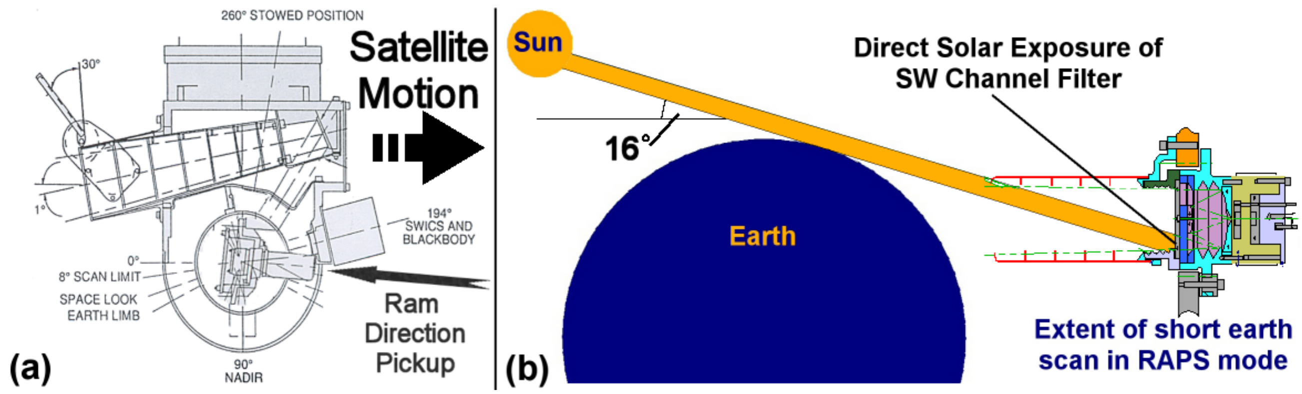

Figure 5. (a) Diagram showing how when azimuth axis is aligned with satellite direction telescope is subject to ram direction pickup of space bourne contaminants. (b) Illustration of how at the extent of the sun avoiding short Earth scan the SW filter can be exposed to direct solar radiance.

3. POSSIBLE CAUSES OF SW CHANNEL SPECTRAL DARKENING

Experience gained from the LDEF mission suggests that spectral darkening that could cause trends in CERES data are due to contaminants deposited on optical surfaces. Precisely how these contaminants could be deposited on the relatively warm SW optics is not yet known and currently a subject of intense investigation. However, it is known from LDEF that out-gassed molecules react with atomic oxygen and are then able to be 'fixed' to an optical surface when subjected to UV photons. For this to occur on the SW channel quartz filter, it must be possible for atomic oxygen and contaminants to somehow arrive at the filter surface. Due to the presence of the baffles on the telescope assembly this only becomes possible if the telescope were pointed in the ram direction (aligned with satellite motion vector as in Fig. 5(a)). Typically the collection of climatological ERB data by CERES utilizes the cross track mode, where the scan plane is perpendicular to the direction of satellite motion (i.e. scanning from side to side). In this mode it would be impossible for any atomic oxygen or contaminants in the satellites path to find their way down the telescope and onto the filter surface. However, the purpose of having two CERES instruments on each satellite platform was to have one operating in cross track mode for purposes of ERB science while the other operated in Rotating Azimuth Plane (RAPS) mode. The RAPS instrument has its scan plane continually rotated in azimuth so that multiple radiance measurements can be made of the same target from different viewing geometries. This allows the development of more sophisticated Angular Dependency Models (ADMs) for purposes of converting radiances to flux.[11] However, this means that as the scan plane of the RAPS instrument becomes aligned with the satellite motion vector, it is possible for space bourne contaminants to react with atomic oxygen, travel past the telescope baffles and land on the SW filter (see Fig. 5(a)). It is then possible that scattered UV from the Earth then fixes and hardens these contaminants on the filter surface. It was also found that the optics on LDEF that were subject to direct solar radiance showed significantly greater contaminant build up due to the greater presence on UV fixing/hardening photons. When in RAPS mode, each CERES instrument has strict solar avoidance criteria to prevent the detector or telescope mirrors from exposure to direct solar radiance. Hence as the scan plane becomes aligned with the solar plane, the instrument switches into a short Earth scan where the scan motion stops 16° below the Earths limb (preventing the instrument scanning up and through the Sun as in Fig. 5(b)). This 16° cut off prevents the detector and telescope from direct solar flux but does result in 2-3 seconds per day of SW filter exposure to direct solar photons for the instrument in RAPS mode.

The implication is from LDEF therefore that the spectral darkening should occur only on the instrument operating in RAPS mode since none of the possible causes apply to the cross track instrument. A powerful diagnostic tool that is used to maintain CERES in-flight calibration is that of direct compare between nadir filtered radiance measurements made by the two CERES units on the same satellite. Direct Compare (*DC*) footprint pairs are chosen only if they occur within a quarter of a scan of each other (1.65 secs) and have the same scene id. Also, to cut down on scene noise arising due to the time separation between the two measurements,

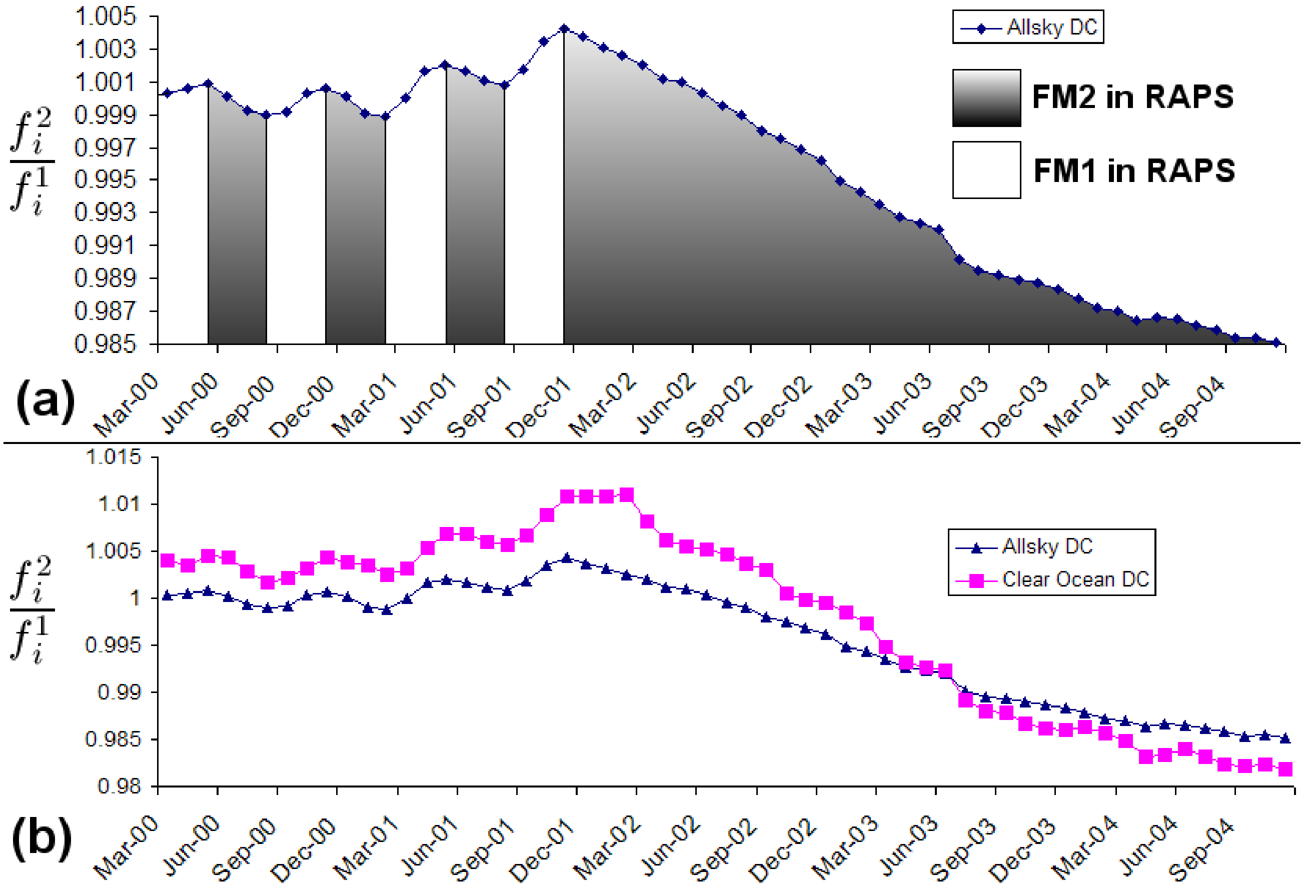

Figure 6. (a) Allsky SW direct compare showing excellent correlation of gradient to RAPS/Cross-track mode switch. (b) Over plot of Allsky and Clear ocean SW direct compare.

an average of a months nadir footprint measurements is made to form twelve data points per year.

$$DC_i = \frac{LF_i^2}{LF_i^1} = \frac{L_i \times f_i^2}{L_i \times f_i^1} = \frac{f_i^2}{f_i^1} \quad (9)$$

LF_i^j is the average filtered nadir SW radiance, measured by instrument j during month i, for a particular scene type. L_i is then the average unfiltered nadir SW radiance outgoing during month i for that scene type (Eqn. 2). So DC_i is the ratio of the two instrument filtering factors corresponding to the average monthly SW scene spectrum $R_i(\lambda)$. A seasonal variation in the spectral shape of radiance L_i will therefore have a slight effect on DC_i but using MODtran simulations with LDEF results the effect was shown to be far less than the 0.1% level (even for allsky direct compare). The direct compare can hence be used as a diagnostic on the relative changes between the two instruments with no influence from real changes to the climate of the Earth (e.g. changes in solar constant). This being the case, theory would suggest that the filtering factor f_i^j for the instrument in RAPS mode would decrease with time due to spectral darkening. It would therefore be expected that the direct compare from Eqn. 9 would have a positive gradient with FM1 in RAPS and a negative slope for periods of FM2 in RAPS mode. Fig. 6(a) shows that this is precisely the case. With the instruments switched from RAPS to cross-track every 3 months for the first 21 months, the direct compare gradient oscillates from positive to negative. Then, after Nov 2001 when FM2 was placed permanently in RAPS mode, the gradient of DC_i remains negative. This excellent correlation of the allsky direct compare to mode switches lends further credence to the theory that spectral darkening is occurring on the RAPS instrument (also the direct compare between the Aqua instruments FM3 & FM4, shows the same correlation to time spent in RAPS mode). Allsky direct compare uses all footprint pairs with matching scene id and does not discriminate by scene type. The proposed spectral darkening model would predict a greater direct compare gradient for a clear ocean scene, with a higher percentage of its spectral energy in the blue-UV region than for the average allsky spectrum (see Fig. 3(a)). This again is confirmed by Fig. 6(b) which suggests that the filtering factor for FM2 (f_i^2) drops considerably more for clear ocean compared to allsky scenes after being fixed in RAPS mode beyond Nov 2001 (note the clear ocean direct compare is significantly more noisy because of a generally lower signal, less footprint pairs and potential cloud contamination). Currently the FM2 instrument is performing special operations (modified RAPS modes). This will isolate to what extent ram pickup and direct solar exposure enhance the darkening of the SW optics. With these effects quantified and correlated to scene specific direct compare data, precise coloration changes to the SW spectral response can be made in preparation for the release of Edition 3 data. Until then and since the effect of darkening is significant for climatological studies, a table of monthly adjustment factors for Edition 2 fluxes must be derived using allsky and clear ocean direct compare data (clear ocean scenes will give a worst case measure of the darkening). Derivation of these revision ('Rev1') adjustment factors is detailed in the following section.

4. USE OF DIRECT COMPARE NADIR FILTERED RADIANCE TO DERIVE 'REV1' ADJUSTMENT FACTORS FOR EDITION 2 DATA

Evidence suggests that spectral darkening of SW optics occurs only when an instrument is in RAPS mode, hence the cross-track instrument should be unaffected. Since at all times one of the two instruments on the Terra and Aqua platforms is operating in cross-track mode, it allows that unit to be used as a calibration standard and compared to the RAPS instrument whose optics are being darkened. Using direct compare nadir measurements, this calibration standard can therefore be transferred back and forth between the two instruments as they take turns operating in RAPS or cross track modes. A relationship between the instrument filter factor in month $i+1$ and i can be written as:

$$\begin{aligned} \chi_i^j &= \frac{N_{i+1}^j + N_i^j}{2} \\ f_{i+1}^j &= \left[1 - \chi_i^j d_i^j\right] \times f_i^j \end{aligned} \tag{10}$$

N_i^j is the number of days in month i that instrument j spent in RAPS mode. χ_i^j is hence the mean number of days that instrument j spent in RAPS mode between months i and $i+1$. d_i^j is then the percent darkening per day of RAPS operation that occurred between the two months (in $days^{-1}$).

So the direct compare ratio (DCR) between the following and current months can be written as:

$$\begin{aligned} DCR_i &= \frac{DC_{i+1}}{DC_i} \\ &= \frac{1 - \chi_i^2 d_i^2}{1 - \chi_i^1 d_i^1} \end{aligned} \tag{11}$$

Initially on both Terra and Aqua the instrument chosen to operate in RAPS mode would be changed every 3 months. Hence for the other cross track instrument, in the transition from first to second and second to third month the value of χ_i^j would be zero. Thus for these periods, a value for the darkening ($d_i^{j\pm1}$) occurring on the other RAPS instrument can be obtained simply from Eqn. 11.

An estimate of the darkening factor for the first month after switching modes, when both χ_i^2 and χ_i^1 are non-zero, is then found using linear interpolation between those values of d_i^j found directly (as described above). Since this is only an estimate of the true darkening factor it is designated as $\overline{d_i^j}$ and must be perturbed by

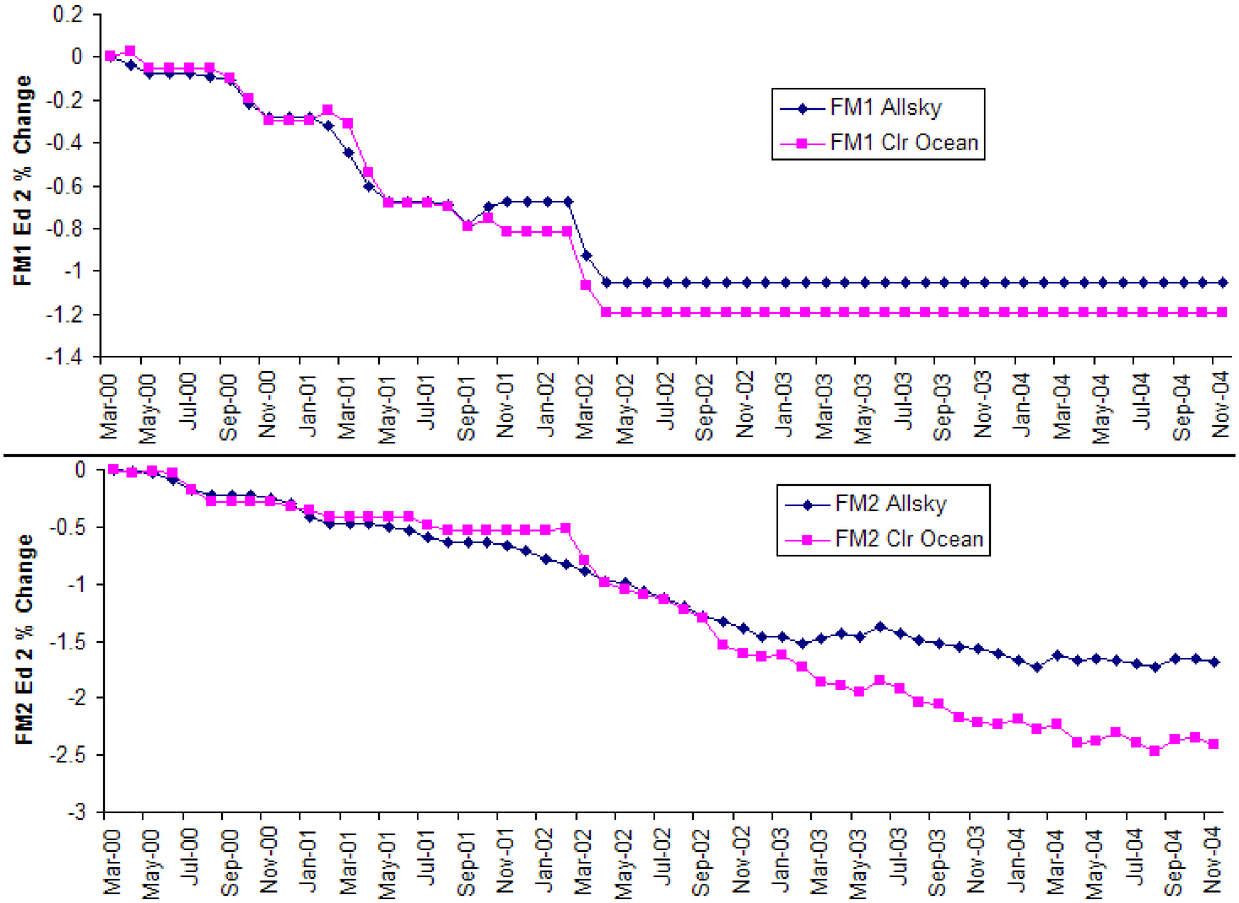

Figure 7. Percentage change to Terra ERBE-like Edition 2 instrument response for allsky and clear ocean scenes.

a further percent factor Δ_i in order to match the direct compare ratio for the transition month (where χ_i^2 & $\chi_i^1 \neq 0$):

$$DCR_i = \frac{1 - \chi_i^2 \overline{d_i^2}(1 + \Delta_i)}{1 - \chi_i^1 \overline{d_i^1}(1 - \Delta_i)} \tag{12}$$

This has the effect of increasing the $\overline{d_i^2}$ estimate by the same percentage as you decrease the $\overline{d_i^1}$ estimate in order to match the direct compare data (which is desirable assuming the error in your estimate is random between the 2 instruments). The perturbation factor Δ_i is simply found for a transition month by re-arranging Eqn. 12:

$$\Delta_i = \frac{1 - \chi_i^2 \overline{d_i^2} - DCR_i(1 - \chi_i^1 \overline{d_i^1})}{DCR_i \chi_i^1 \overline{d_i^1} + \chi_i^2 \overline{d_i^2}} \tag{13}$$

Therefore the derived darkening factor for the transition month is found from the perturbed estimate value:

$$d_i^j = \overline{d_i^j}(1 \pm \Delta_i) \tag{14}$$

This allows calculation of a darkening value d_i^j for each instrument and every month of the mission. The intention is then to formulate a table of adjustment coefficients which are to be applied to Edition 2 fluxes to

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CERES Terra Revision Table

2000 | 2001 | 2002 | 2003 | 2004 | Tab-delimited file

		All Sky		Clear Ocean	
Year	**Month**	**FM1**	**FM2**	**FM1**	**FM2**
2003	Jan	1.011	1.015	1.012	1.017
	Feb	1.011	1.015	1.012	1.018
	Mar	1.011	1.015	1.012	1.019
	Apr	1.011	1.014	1.012	1.019
	May	1.011	1.015	1.012	1.020

Figure 8. Table of Rev1 adjustment coefficients for application to Terra ERBE-like Edition 2 and SSF Edition 2B SW radiance or fluxes.

compensate for spectral darkening of the SW optics. It is therefore important to consider any Edition 2 changes made to the SW channel spectral response in order to balance daytime unfiltered radiances with the SW portion of the total channel.

$$\begin{aligned} g_{i+1}^j &= \left[1 - \chi_i^j d_i^j\right] \times g_i^j \\ a_i^j &= \frac{1 + \Delta SR_i^j}{g_i^j} \end{aligned} \tag{15}$$

g_i^j is the 'scene dependant gain' normalized to the start of mission (i.e. $g_0^j = 1$ for the first month implying no darkening had occurred by the first month of operation). ΔSR_i^j is the fractional change to the SW spectral response height for instrument j in month i that was made for the Edition 2 data release (to balance with SW portion of total channel and direct compare data). Hence a_i^j is the Rev1 adjustment coefficient to be applied to Edition 2 SW measurements in month i of the mission. Fig. 7 shows the estimated percent change in Terra SW channel response that the Rev1 coefficients compensate for during the first 4 years of the mission. As expected this shows how the darkening occurs in three months periods and ceases completely for FM1 beyond Nov 2001 (when that instrument was placed permanently in cross-track mode thus preventing any darkening). Comparison of the response change for allsky and clear ocean again illustrates how the darkening of response is occurring to a greater extent for clear ocean, with its higher proportion of spectral energy situated towards the blue/UV end of the spectrum.

5. APPLICATION AND EFFECT ON CLIMATE RECORDS

These adjustment coefficients for application to Allsky and Clear Ocean Climate records derived from Terra or Aqua instruments are available through the Edition 2 quality summary.[12] They are merely presented in tabular form (Fig. 8), containing the results of Eqn. 15. The numbers are to be simply multiplied by existing records for scattered SW flux or radiance that use ERBE-like Edition 2 or SSF Edition 2B CERES products. If these adjustments are applied the results should be described in literature as using ERBE-like Edition2_Rev1 or SSF Edition2B_Rev1 data.

Shown in Fig. 9 are the de-seasonalized ES4 Edition 2 SW fluxes before and after Rev1 adjustments. The top plot shows a downward trend in scattered SW in excess of -2%. The adjusted curve (bottom) shows that this trend has been significantly reduced to around -0.5%, which perhaps represents a realistic change in climate. The coefficients can be equally applied to any CERES Edition 2 SW measurement. Currently the alteration to any climate trends has an estimated uncertainty of 0.5% per 4 years (95^{th} percentile).

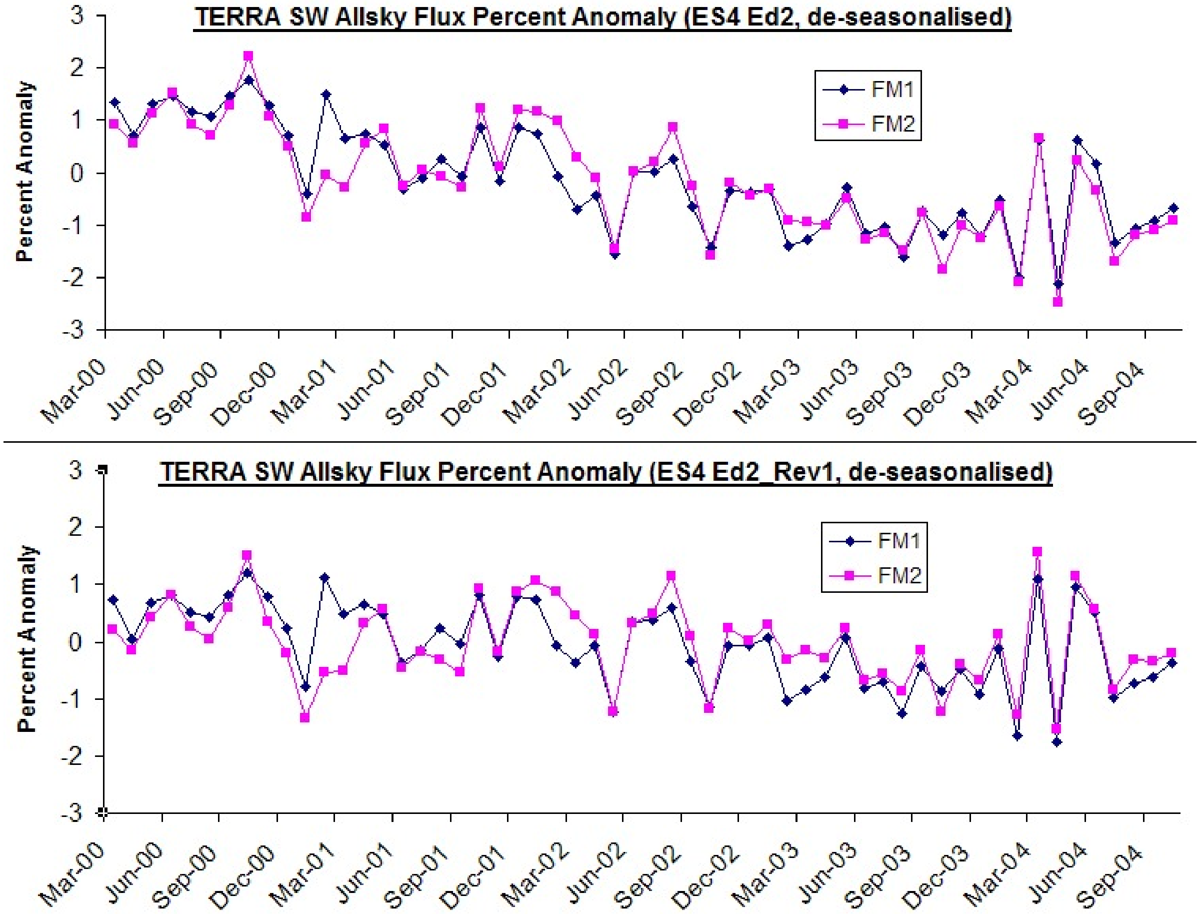

Figure 9. Terra ES4 Edition2 fluxes (top), TERRA ES4 Edition2_Rev1 'adjusted' fluxes (bottom).

6. SUMMARY

This paper detailed an investigation into a loss in CERES SW channel optical transmission, referred to as 'spectral darkening'. It showed how the effect was previously undetectable because it occurs in the blue-UV spectral region, where onboard calibration tungsten lamps are largely devoid of output energy. Experience from other missions (such as LDEF), led to the deduction that this spectral darkening was occurring due to UV hardening of contaminants on the optics. Since none of these apparent effects would occur on the cross track instrument, it allowed that unit to be used as a calibration standard from which the darkening on the other instrument could be derived. In order to confirm the theory that the cross track instrument is subject to no darkening, the FM2 unit is currently being held in stow to remove all exposure to UV photons and space bourne contaminants. When re-activated into normal operation, a direct compare with the FM1 instrument will indicate whether its optics darkened while operating in cross track. This darkening effect and the methodology developed to compensate for it may be of interest on other missions that employ elaborate scan modes or reflective/transmissive optics to maintain a broadband calibration when in-flight.

The derived allsky adjustment coefficients can be applied to the majority of climate data to remove most of the optical darkening effect. It is recommended that the Clear Ocean coefficients only be used on cloudless water body targets (perhaps for studies involving aerosol forcing etc). Ultimately what is needed is full spectral characterization of the change to the SW channel transmission. This requires isolating the precise causes of the darkening, such as direct solar exposure and ram contaminant pickup. After its period in stow, the FM2 instrument will undergo special operations to separately eliminate solar exposure and/or ram contaminant exposure while in RAPS mode. These effects, once confirmed or eliminated as the cause, can then be quantified and used in a contamination model currently under development at LaRC. This will allow production of a new spectral response that best matches direct compare data for a multitude scene types with radically different spectra.

This spectral response will then be used for un-filtering of Edition 3 CERES data, hence making a scene specific adjustment to all measurements that removes effects of spectral darkening. A stability target of 0.3% per decade should then become achievable.

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