Diurnal Bias in Calibration of Broad-Band Radiance Measurements from Space

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***Abstract*—We examine the problem of determining the separate shortwave (SW) and longwave (LW) components of the Earth radiation budget from space. Because true broad-band longwave filters do not exist, daytime LW radiance determinations can depend entirely or in part on subtraction of the measured SW radiance from the "Total" (TW) radiance involving integration over the entire electromagnetic pectrum. Examining radiances measured in the three channels (SW, imperfectly filtered broad-band LW, TW) of the Earth Radiation Budget Experiment (ERBE) scanners on board the NOAA-9, ERBS and NOAA-10 satellites, we find small discrepancies in the daytime estimates of broad-band ("unfiltered") LW radiances using the ERBE "spectral correction" procedure. We show that these result from errors (of order 2.5%) in the calibration of the SW channel and possibly in the spectral characterization of the SW and/or TW channel of the ERBE scanners on NOAA-9 and NOAA-10. Nighttime estimates show no such bias, and there appears to be no such error in the data from ERBS. Considering the LW radiant exitances determined from ERBE scanner data from the three satellites, we find systematic differences in individual satellite estimates of simultaneous instantaneous regional means and of regional monthly means, consistent with the radiance discrepancies. instantaneous daytime LW estimates can be in error by 20% in the extreme case of very bright cold cloud, and LW cloud radiative forcing may be significantly biased. We consider the implications of these small SW-dependent errors on the determination of diurnal variation and of cloud radiative forcing in the longwave domain. We show how the ERBE estimates can be corrected, and consider how our procedures can be used to validate results of future experiments (ScaRaB and CERES).**

I. Introduction

THE radiation budget of the Earth is fundamental in determining its physical state. The only significant energy input to the system is the absorbed solar shortwave (SW) flux at wavelengths between 0 and approximately 4 μm. This forcing varies with the astronomical diurnal and annual cycles. The longwave (LW) flux emitted to space by the Earth-atmosphere system over a given area is an integrator of the physical state of surface, atmosphere and clouds in that area, which vary as a result of the SW forcing and the storage and redistribution of energy within the system. Measurement of the Earth radiation budget (ERB) components can only be made from space. Global coverage requires observing from satellites in polar orbits, although geostationary satellites can provide continuous diurnal coverage for large but limited geographical regions. Accuracy of estimates of monthly mean values of the reflected shortwave (SW) and emitted longwave (LW) radiant exitances (fluxes) is limited by a variety of instrumental and sampling considerations [1]. In the Earth Radiation Budget Experiment (ERBE) [2], considerable attention was given to these difficulties, and in particular the experiment was planned as a multi-satellite mission in order to improve the time sampling and obtain unbiased monthly mean values of the TOA ERB components [3], and also to determine, on a regional scale, the monthly average diurnal cycle of the Earth-atmosphere system [4].

Manuscript received September 20, 1993; revised December 13, 1994.

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IEEE Log Number 9411232.

The reliability of these determinations depends in the first place on the accuracy of the in-flight calibration of the observed radiances. The problem of calibration has been a major problem of Earth radiation budget studies, because it has been difficult to find sufficiently sensitive detector-filter combinations which provide flat spectral response while separating the solar shortwave and thermal longwave domains [5]. Thermal detectors (pyroelectrics, thermistor bolometers) can however provide a reasonably flat spectral response, and fused quartz filters can cut off radiation at wavelengths longer than 4–5μm quite cleanly with constant transmittance close to unity at shorter wavelengths, thus forming a good shortwave channel. Stated accuracy goals for the broad-band radiance measurements needed for determining the Earth radiation budget are generally more stringent for the LW than for the SW measurements, partly because it is believed that higher accuracy can be reached in the LW than in the SW. It is however difficult to produce a good longwave channel, because there are no usable materials providing flat spectral transmittance across the broad (say 5–50μm) longwave domain while cutting off shortwave radiation. Of course longwave radiation from the night side of the Earth can be measured using an unfiltered "total" (TW) channel, because shortwave radiation is then negligible. Such measurements can be calibrated with high absolute accuracy, because it is relatively straightforward to check or determine the gain in the LW portion of the TW channel using measurements of an on-board blackbody simulator. Such devices can have an emittance very close to unity, and the temperature can be determined with high accuracy using platinum temperature sondes.

The procedure is not so simple for daytime LW measurements, because the TW channel measurements then include a SW contribution which must be taken into account. Absolute calibration in the shortwave domain is difficult, because the instruments used to observe the Earth with fairly high spatial resolution cannot be used to observe the Sun directly, and because lamps are not very good simulators of the 5800 K blackbody which would be ideal for a good calibration.

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Despite the great care taken in the ERBE calibrations, we have found that some of the ERBE LW results include a small but non negligible spurious diurnal variation in the LW. These originate in small errors in the calibration of the ERBE SW channel and possibly in the spectral characterization of the TW channel, which influence the daytime estimates of LW radiances and fluxes. They also may influence the SW radiance determinations. However, other sources of error are more important for the SW flux estimates, in particular because of deficiencies in the angular correction procedures and in the time sampling. Observed SW radiances and the reflected SW fluxes to be deduced from them depend on the bidirectional reflectance [6], which is a function of both solar and satellite zenith angles as well as of relative azimuth, depending also on surface, atmosphere and cloud properties. For a given surface and atmospheric condition, the LW angular corrections [6], [7] depend only on satellite viewing zenith angle; although flux estimates for individual pixels may be in error, these errors are not large and there is no reason to expect them to depend on local solar time. Of course, the determination of monthly mean quantities requires that one take diurnal variations into account. Note that the "observed" LW diurnal cycle will be distorted by any SW calibration errors because these influence the daytime LW estimates. Thus there may be a confusion between calibration effects and effects of imperfect time sampling. The latter have been evaluated using narrow-band data from geostationary satellites to estimate monthly mean diurnal variations of LW flux [8] as well as SW [9]. These effects are significant in some cases, but precise assessment and correction is difficult because the spectral coverage of the geostationary satellite imager channels is limited.

Our study shows that it is possible to detect the SW calibration errors and correct the daytime LW radiances and radiant exitances on the basis of physical considerations. With additional assumptions we show that it is possible to correct SW radiances as well. We discuss the implications for the ERBE results on LW diurnal variation and cloud forcing, and for the validation of future ScaRaB [10] and CERES [11] LW flux determinations.

II. Broad-Band Calibration and Spectral Correction

A. Broad-Band LW Calibration

For daytime LW measurements, two approaches are possible. One can rely on a model-based correction of measurements made with an imperfect broad-band LW channel or a set of narrow-band LW channels [12]–[16]. Alternatively, one can carry out a spectral *subtraction* of a broad-band SW channel from a "total" (TW) channel sensitive to the entire electromagnetic spectrum. In the latter case, the estimates of broad-band longwave radiances depend on the characterization/calibration of the SW response of both SW and TW channels. Absolute SW calibration (on ground or in flight) is notoriously more difficult than a LW blackbody calibration. In the case of ERBE, examination of the SW and filtered and unfiltered LW radiances shows that the "spectral correction" scheme, which transforms the radiances filtered and measured by the instruments into estimates of the true broad-band LW radiance that would be obtained if the spectral response of the instrument were perfect (the "unfiltered" LW radiance), introduces a LW error which depends on the scanner/satellite and on the reflected SW radiance observed.

B. Longwave Measurement by Spectral Subtraction

For *daytime* LW measurements, one may estimate broad-band LW radiance by subtracting the SW from the TW measurement. This is the case for both the ScaRaB [10] and the CERES [11] instruments, and we shall show that it is very nearly the case for the ERBE scanners. For ScaRaB, we write the filtered LW radiances $L_f(\mathrm{LW})$ as

$$L_f(\mathrm{LW}) = (1/G_{\mathrm{TL}})[N_T - AN_S]. \quad (1)$$

Here N_T and N_S are the digital counts (after removal of any offset) in the TW and SW channels respectively, and G_{TL} is the gain (counts per unit filtered radiance) in the LW portion of the TW channel. Parameter A is an appropriately weighted mean ratio of the response in the SW portion of the TW channel to that in the SW channel. Gain G_{TL} can be monitored by frequent blackbody calibrations in flight, and the stability of A can be checked using in-flight lamp calibrations and analysis of Earth-viewing data [17].

Each channel still has filtering properties, depending on the spectral reflectance of the mirror optics, the transmission of the SW filter, and the departure of the detector absorptance from unity. The true (or "unfiltered") LW radiance must be determined using an appropriate spectral correction which in principle depends on the spectrum of the scene being observed. However, to the extent that spectral response in the useful SW domain is the same in the SW and TW channels apart from a multiplicative constant (filter transmission), and provided that departures from a flat response in the LW domain of the TW channel are very small, this spectral correction is obtained directly (for ScaRaB) as a simple multiplicative factor with high accuracy [18]

$$L_u(\mathrm{LW}) = (1/R_{\mathrm{TL}})L_f(\mathrm{LW}) \quad (2)$$

where R_{TL} is the average spectral filtering of the TW channel in the LW domain.

An alternative approach for estimating unfiltered LW radiance is to use an *imperfect* LW channel, of which an extreme example is the 11μm infrared window channel. This approach is used in particular by NOAA to produce LW flux estimates from the AVHRR 11μm channel data [12], [13], and systematic errors are known to result in certain areas, as shown also when Meteosat data are used with or without the 6.3μm "water-vapor" channel in addition to the 11μm channel [8], [14]. In this case, additional information is needed for an accurate spectral correction, for example the tropospheric humidity profile.

C. ERBE Spectral Correction

The ERBE scanners consist of three broad-band channels: a shortwave (SW) channel sensitive at wavelengths from 0.2 to approximately 5μm; a total (TW) channel; and a broad-band longwave (LW) channel obtained using a diamond filter [19]. The spectral filtering of these channels depends on the spectral reflectance of the two mirrors of the Cassegrain optics, on the absorptance of the black paint coating the detectors, and on the filter transmittance. A *Suprasil* filter provides a rather clean cutoff between 4 and 5μm in the SW channel. However, the spectral transmittance of the diamond filter is certainly not flat and departs strongly from unity. Consequently, although the LW channel is a broad-band channel and so better than a narrow IR window channel, it has filtering properties which depend on the scene spectrum (and thus on cloud cover, height and emissivity, as well as on atmospheric water vapor profile). The measurements made in the three ERBE channels provide what are called "filtered" radiances, i.e., a convolution of the scene spectral radiance with the channel spectral response. The ERBE filtered LW radiance is therefore very strongly filtered indeed, and quite different from the ScaRaB *synthetic* filtered LW radiance obtained by spectral subtraction following (1). A first step in obtaining broad-band SW and LW radiant exitances is to determine the "unfiltered" SW and LW radiances, i.e.,, spectral radiances integrated over the entire SW and LW spectral domains respectively, with a perfectly flat and well calibrated spectral response. This operation, called "spectral correction," differs between night and day for the LW radiances in the ERBE data processing [20].

In discussing the ERBE procedure, we write filtered radiances and digital counts (after removal of offsets) in channel $k(k = S, L, T,$ for SW, LW and TW channels respectively) as m_k^f and n_k respectively. Using conversion coefficients c_k (in fact inverse gains, in $\mathrm{Wm^{-2}sr^{-1}counts^{-1}}$), the filtered radiances are given by

$$m_k^f = c_k n_k. \tag{3}$$

In the ERBE spectral correction, the *un*filtered shortwave and longwave radiances m^{SW} and m^{LW} are computed from the filtered radiance measurements m_k^f, using spectral correction coefficients which depend on the viewing geometry (including Sun angle for the SW) and on the nature of the scene. During daytime the spectral correction takes the form

$$m^{\mathrm{SW}} = A^{\mathrm{SW}} c_S n_S + B^{\mathrm{SW}} c_L n_L + C^{\mathrm{SW}} c_T n_T \tag{4a}$$
$$m^{\mathrm{LW}} = A^{\mathrm{LW}} c_S n_S + B^{\mathrm{LW}} c_L n_L + C^{\mathrm{LW}} c_T n_T. \tag{4b}$$

Typical values of the spectral correction coefficients are given in Table I [21], [22]. We may rewrite (4b) in the form

$$m^{\mathrm{LW}} = C^{\mathrm{LW}} c_T [n_T - \alpha n_S + \beta n_L], \tag{5a}$$
$$\alpha = (-A^{\mathrm{LW}}/C^{\mathrm{LW}})(c_S/c_T), \tag{5b}$$
$$\beta = (B^{\mathrm{LW}}/C^{\mathrm{LW}})(c_L/c_T). \tag{5c}$$

Noting that β is very small, this has practically the same form as the equation deduced by combining (1) and (2)

$$L_u(\mathrm{LW}) = (R_{\mathrm{TL}} G_{\mathrm{TL}})^{-1} [N_T - A N_S]. \tag{6}$$

This means that although α is a function of the scene-dependent spectral correction coefficients, it in fact stands for the ratio of SW response between the TW and SW channels, and most of the scene dependence must cancel out. Indeed

TABLE I
"TYPICAL" ERBE SPECTRAL CORRECTION FACTORS

Case	A^{SW}	B^{SW}	C^{SW}	A^{LW}	B^{LW}	C^{LW}	Scene type
1 [21]	+1.63	-0.03	+0.02	-1.40	-0.17	+1.22	not given
2 [22]	+1.77	0	-0.001	-1.34	0	+1.11	Clear tropical
3 [22]	+1.59	-0.26	+0.16	-1.27	+0.09	+1.06	Tropical cloud
4 [22]	+1.72	-0.07	+0.04	-1.32	+0.02	+1.10	Partly cloudy tropical
5 [22]	+1.61	-0.12	+0.07	-1.26	+0.11	+1.05	Clear desert
6 [22]	+1.46	-0.28	+0.18	-1.09	+0.32	+0.91	Mid lat ocean

examination of the few sets of values available to us ([21], [22], Table I) shows that the ratio $(-A^{\mathrm{LW}}/C^{\mathrm{LW}})$ remains very close to 1.20 for significantly different scene types and essentially is the inverse of the average SW transmittance of the Suprasil filter (see Appendix). Also, the variation of C^{LW} over a somewhat wider range (0.91 to 1.22), as a function of scene type and viewing geometry, is in fact almost exactly compensated by the variation of the term involving B^{LW}.

At night, neglecting thermal radiation at the 4–5μm edge of the SW channel, reflected SW radiances are zero. The TW channel alone performs an excellent measurement of the LW radiances, with relatively little filtering in contrast to the nominal LW channel with the diamond filter. The LW unfiltered radiance can then be computed using only the total channel count, provided that SW radiance is indeed zero. This last point may introduce errors in the case of ERBE pixels overlapping the terminator (frequently for NOAA-10, on occasion for ERBS), especially when these pixels are near the end of the scan, because part of the pixel may be in sunlight and produce a nonzero SW radiance. In such cases, when the ERBE nighttime spectral correction [i.e., omitting the SW term in (5)] is used because the solar zenith angle is greater than 90° at the pixel center, the nonzero SW contribution to the TW channel radiance is included without spectral subtraction and the unfiltered LW radiance is overestimated. Note however that these radiance values are not converted into fluxes in the ERBE processing.

During daytime, the TW channel responds to reflected SW radiation as well as to LW radiation. In practice (5), the ERBE procedure takes the form of a weighted subtraction of the filtered SW radiance from the filtered TW radiance, with the filtered LW measurement carrying hardly any weight. The daytime unfiltered LW determination thus depends on the SW calibration as well as on the blackbody calibrations of the LW channel and the LW portion of the TW channel. It also depends on the scene-dependent ERBE spectral correction coefficients, which were computed on the basis of the presumed SW and LW response of the various channels. These spectral correction coefficients are part of what is called the "Inversion" system [20], which includes taking into account the anisotropy of the reflected SW and emitted LW radiation in order to identify the scene (in practice the cloud cover, since the geographical location of the scene tells us what the underlying surface is), and so to choose the anisotropic factor to use in the radiance-to-flux conversion. Scene identification is based on a Maximum Likelihood Estimate (MLE) [23], applied to estimates of *un*filtered SW and LW radiances and using tabulated angular models [6]. However, the calculation of the spectral correction yielding the unfiltered radiances depends itself on knowing the scene type, and yet estimates of the unfiltered radiances are needed to carry out the scene identification. In a first step, a "neutral" set of spectral correction coefficients, *not* dependent on scene type, is used to obtain initial values for unfiltered radiances. Spectral correction is then iterated using the resulting scene types. There is no further iteration in the ERBE processing. Although the iterated spectral correction can yield unfiltered radiances incompatible with the scene identification, such cases appear to be rare and unimportant.

In the ERBE spectral correction procedure, it is assumed that the calibrations of the different channels are perfectly accurate and that their filtering properties are known. The ERBE count conversion coefficients c_k for each channel k were determined during ground calibration [24] on sources of known spectrum, assuming that the radiometer spectral filtering function $S_k(\lambda)$ was known on an absolute scale (from 0 to 1), as determined by "the product of the telescope mirrors' reflectance squared, the absorptance of the flake's black paint, and the transmissions of the filters." We examine the consequences of possible errors in this procedure in the Appendix. The spectral correction coefficients themselves were obtained by means of a minimum variance linear estimator (MVLE) algorithm applied to a large set of radiation transfer calculations simulating filtered and unfiltered radiances expected to be observed by ERBE scanners for different scene types and viewing geometries [25], [26].

D. Spectral Subtraction for ERBE on NOAA-9, ERBS and NOAA-10

Equation (5) shows that by day the estimates of unfiltered LW radiances depend mainly on the SW and TW filtered radiances measured by the ERBE scanners on board NOAA-9, ERBS and NOAA-10. The ERBE spectral correction is essentially a spectral subtraction process. Consequently, spurious day/night differences depending on the satellite concerned may arise if there are errors in the calibration or spectral characterization of one or more of the ERBE scanner SW and/or TW channels [27]. There may also be problems arising from the large set of (mostly unpublished) ERBE spectral correction coefficients derived from the MVLE algorithm, although most of these probably again relate to the assumed spectral response rather than to any geophysical factors. However, any attempt to detect in the data the influence of a SW characterization error on one or another of the scanners must take into account the geophysical dependencies that exist between emitted LW and reflected SW radiation, principally in relation to cloudiness. Clouds are generally brighter reflectors than the underlying surface and clear atmosphere, and at the same time they are generally colder than the surface and often optically thick in the LW domain. Thus regions of cloud, especially high cold cloud, are regions where LW radiances are lower than average, while SW radiances are higher than average. It is therefore to be expected that unfiltered (and filtered) LW radiances (and radiant exitances) depend on the SW radiance. If we consider the LW spectral correction, i.e., the difference between unfiltered and filtered LW radiances, this depends on the LW spectrum, which is a function of the temperature and spectral emittance of the emitting surface (often a cloud top), and of the water vapor (and also ozone, etc.) to be found above that surface. Thus to the extent that cloud properties are involved, there are good geophysical reasons to expect the LW spectral correction also to be related to the SW radiance.

However, if we consider a *small* range of variation of the filtered LW radiance, we can expect that the LW spectral correction should depend very little if at all on the SW radiance, in the case of a good spectral correction/subtraction. We have studied this dependence for different classes of the filtered LW radiance for the ERBE scanners on NOAA-9, ERBS, and NOAA-10. We consider the difference

$$F^{\mathrm{LW}} = m^{\mathrm{LW}} - m_L^f = m^{\mathrm{LW}} - c_L n_L \tag{7}$$

between the unfiltered LW radiance estimate and the filtered LW radiance measurement, and we examine its dependence on filtered SW radiance when filtered LW radiance remains in a small range.

The results for all radiance measurements made on Dec. 24, 1986 (from the ERBE S-8 data) are shown on Fig. 1. For each of the three ERBE scanners, we have represented separately for each filtered LW radiance class l the regression line which has slope

$$S_l = dF^{\mathrm{LW}}(\mathrm{LW} = \mathrm{LW}_l)/dm_{\mathrm{SW}}^f \tag{8}$$

obtained by taking into account nighttime as well as daytime measurements to ensure continuity. For the seven classes l (corresponding to the range 10–60 $\mathrm{Wm}^{-2}\ \mathrm{sr}^{-1}$), the points are distributed fairly well along straight lines. Apart from very poorly represented classes (such as hot bright deserts in Northern Hemisphere winter at the early morning/evening NOAA-10 passages), the slopes S_l are approximately the same for all classes l.

Slope S_l can be interpreted as follows (see also the Appendix). Considering (5), (7), and (8), and writing the filtered radiances in channel k in terms of digital counts n_k (offset removed) and conversion coefficients (inverse gains) c_k, we have

$$\begin{aligned} S_l &= d/d(c_s n_s)[C^{\mathrm{LW}} c_T n_T + A^{\mathrm{LW}} c_s n_s + (B^{\mathrm{LW}} - 1) c_L n_L] \\ &= d/d(c_s n_s)[C^{\mathrm{LW}} c_T n_T] + A^{\mathrm{LW}} \end{aligned} \tag{9}$$

considering the restriction of n_L to a relatively small range of values. The TW channel counts can be written in terms of spectral radiance $L(\lambda)$ in the SW and LW domains as

$$n_t = \frac{1}{c_T} \cdot \left[\int_{\mathrm{SW}} S_T(\lambda)\, d\lambda + \int_{\mathrm{LW}} S_T(\lambda) L(\lambda)\, d\lambda \right]. \tag{10}$$

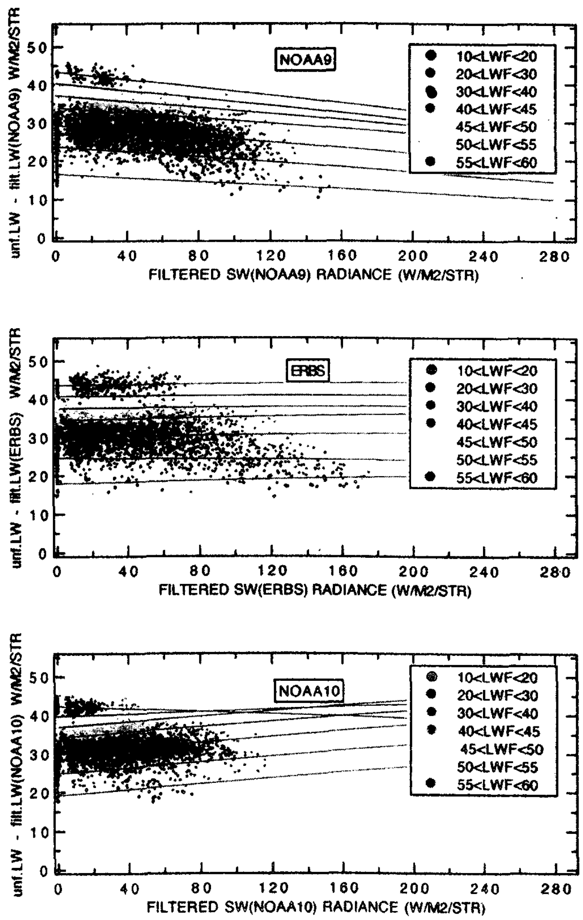


Fig. 1. Difference F^{LW} between unfiltered LW and filtered LW radiance versus filtered SW radiance, for the day of December 24, 1986 and for the three satellites of the ERBE mission. Seven classes have been extracted from the data, corresponding to seven intervals of LW filtered radiance.

Similarly, the SW counts can be written as

$$n_T = \frac{1}{c_s} \cdot \int_{\text{SW}} S_S(\lambda) L(\lambda)\, d\lambda$$
$$\approx \frac{1}{c_s} \cdot \int_{\text{SW}} T_s(\lambda) S_T(\lambda) L(\lambda)\, d\lambda. \tag{11a}$$

where $T_S(\lambda)$ is the spectral transmission of the SW filter, assuming mirror and detector spectral properties to be the same in the two channels [24], [25]. Then, neglecting problems at the SW/LW transition near 4μm, and considering an average value of T_S over the useful SW domain (say up to 3.5μm), we can write

$$n_S \approx (T_S/c_S) \int_{\text{SW}} S_T(\lambda) L(\lambda)\, d\lambda. \tag{11b}$$

Using (10), we can then write

$$c_T n_T = c_S n_S / T_S + \int_{\text{LW}} S_T(\lambda) L(\lambda)\, d\lambda. \tag{12}$$

The second term on the right-hand-side is independent of $c_S n_S$, and so combining (9) and (12), the slope is given by

$$S_l = C^{\text{LW}}/T_S + A^{\text{LW}}. \tag{13}$$

We see that if $C^{\text{LW}} = -A^{\text{LW}} T_S$, the slope is zero. This concords with our interpretation of (6).

In the case of the measurements made on ERBS, the observed slopes S_l are all very close to zero, as expected on physical grounds. However, for the measurements made from NOAA-9 and -10, the slopes are significantly different from zero. This implies that the daytime unfiltered LW radiances from NOAA-9 and -10 are biased in proportion to the reflected filtered SW radiances. As these radiances go to zero, the value of the LW spectral correction approaches that found at night. For NOAA-9, the ERBE unfiltered LW radiances are underestimated, for NOAA-10 they are overestimated. This is in agreement with some results for NOAA-9, obtained in analysis of consistency of the three ERBE scanner channels which (for Apr. 13, 1985) gave a bias which was strongest for scenes (snow, mostly cloudy ocean, overcast) brightest in the SW [28], [29].

We have computed daily mean slopes $\langle S \rangle$ by a least squares regression against filtered SW radiances in which we replace the LW differences F_l by the reduced differences $[F_l - \langle F_l(\text{night}) \rangle]$, i.e., subtracting the mean nighttime spectral correction for filtered LW radiance class l, and then combining points of all classes l. The numerical values obtained for the mean slopes $\langle S \rangle$ for Dec. 24, 1986 are equal to -0.036, $+0.003$ and $+0.040$ for NOAA-9, ERBS and NOAA-10 respectively. For ERBS, the data are not quite global, because polar latitudes are not observed; equatorial crossing times on Dec. 24, 1986 were 0130 and 1330 LT. The LW spectral correction appears to be independent of SW radiance. This is not the case for the ERBE scanners on NOAA-9 and NOAA-10 (global data).

For NOAA-9, the negative slopes indicate that unfiltered LW radiances are underestimated, assuming that the nighttime unfiltered radiances are correct. This is a reasonable assumption because the TW channel's blackbody calibration should be highly accurate for LW radiation, and its filtering properties are slight ($R_{\text{TL}} = 0.90$). Indeed only small differences are observed in nighttime regional mean radiant exitances between the three satellites (see Section III-A). The underestimate of daytime unfiltered LW radiance does appear in daytime LW flux estimates. We consider that the ERBS unfiltered LW radiances are correct by day as well as by night, because they do not depend on the SW radiance. Conversely, the slopes S that are positive for NOAA-10 indicate an overestimate of the daytime unfiltered LW radiance that appears when comparing the NOAA-10 and ERBS daytime radiant exitance estimates.

We have computed the statistical significance of the regression analyses performed in Fig. 1. The results are presented in Table II where we have reported for each of the seven classes l and for all the classes taken together, the slope S, the associated probable error σ_S and the linear correlation coefficient r (also called *Pearson's* r) [30]. The absolute values of S for NOAA9 and NOAA10 are an order of magnitude greater than corresponding values for ERBS. The

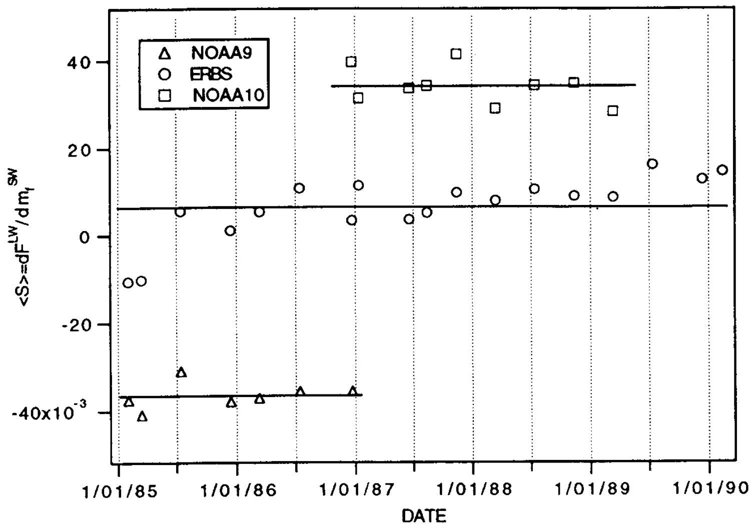


Fig. 2. Temporal dependence of the daily mean slopes $\langle S\rangle$ for the ERBE scanners on the different satellites. The overall mean slope $\langle S_{\rm all}\rangle$ is also shown as a horizontal line for each satellite.

TABLE II
STATISTICAL SIGNIFICANCE OF THE REGRESSION ANALYSIS DECEMBER 1986 LW SPECTRAL CORRECTION VERSUS FILTERED SW RADIANCE

SATELLITE	m_L^f	$S = dF^{LW}/dm_{SW}^f$	σ_S	r (Pearson)
NOAA9	10-20	-0.024	± 0.0042	-0.58
	20-30	-0.033	± 0.0015	-0.49
	30-40	-0.037	± 0.0012	-0.50
	40-45	-0.035	± 0.0016	-0.53
	45-50	-0.040	± 0.0019	-0.52
	50-55	-0.049	± 0.0028	-0.49
	55-60	-0.052	± 0.0073	-0.50
	All	-0.036	± 0.0006	-0.51
ERBS	10-20	0.009	± 0.0029	0.32
	20-30	-0.002	± 0.0014	-0.05
	30-40	0.005	± 0.0014	0.06
	40-45	0.008	± 0.0014	0.13
	45-50	0.003	± 0.0015	0.04
	50-55	0.001	± 0.0019	0.02
	55-60	0.004	± 0.0042	0.05
	All	0.003	± 0.0006	0.05
NOAA10	10-20	0.037	± 0.0104	0.39
	20-30	0.037	± 0.0023	0.34
	30-40	0.038	± 0.0015	0.40
	40-45	0.035	± 0.0024	0.39
	45-50	0.035	± 0.0023	0.38
	50-55	0.015	± 0.0025	0.15
	55-60	-0.016	± 0.0058	-0.12
	All	0.040	± 0.0009	0.41

values of σ_S are similar for all classes l and between the three satellites, but are smaller by a factor 2–10 when all the classes are mixed together. These values ensure the significance of the slopes S. The absolute values of the correlation coefficient r which are approximately 1/2 for NOAA9 and NOAA10, indicate that the LW spectral correction is well correlated with filtered SW radiance for these satellites, whereas the low values of r for ERBS indicate that these variables are uncorrelated for the scanner on this satellite.

E. Time Dependence of the ERBE Biases

The time dependence of the anomalies has been studied using the observed variation of the slopes $\langle S\rangle$. For this study, 19 days between Feb. 2, 1985 and Feb. 15, 1990 were selected and the S-8 data analyzed. The results are shown on Fig. 2. The first observation to make is that the slopes are not strongly dependent on time. We show the overall means of these slopes ($\langle S_{\rm all}\rangle$) for each satellite, obtained by considering together all points obtained on all of the dates analyzed. In this case the procedure has been the same as for determining the mean slopes $\langle S\rangle$ for all classes for a single day.

As may be seen from (13) in Section II-D above, slope S should be zero if the effective SW filter transmission $T_S20 = -C^{\rm LW}/A^{\rm LW}$. The fact that this ratio is fairly close to a fixed value (≈ 0.83) for all of the sets of spectral correction coefficients available to us (Table I), tends to confirm the hypothesis that the SW spectral filtering is relatively insensitive to realistic scene spectral differences. However, the fact that observations give nonzero slopes $\langle S\rangle$ must be understood. The overall consistency and constancy of the slopes for a given instrument (Fig. 2), observing a very large variety of Earth scenes at different seasons, suggests that we consider only broad-band aspects. Considering (5b) above, and assuming the blackbody calibration of the LW response of the TW channel to be reliable, the source of the error must be sought in the SW calibration (coefficient c_S), and/or in a difference between the real SW filtering T_S and the value T_S^* assumed in computing $(-C^{\rm LW}/A^{\rm LW})$.

We examine possible error sources in more detail in the Appendix, where we consider how errors in broad-band spectral properties of the ERBE channels are propagated and in certain cases cancelled in the ERBE procedures. It must be remembered that the ERBE count conversion coefficients c_k are obtained by regressing counts observed during ground calibration against filtered radiances computed assuming channel k spectral properties to be perfectly known. In principle we must envisage possible errors in the assumed transmission of the Suprasil filters used in the SW channels of the 3 ERBE scanners, and in the assumed spectral reflectances of the mirrors. Leaving aside the practically irrelevant LW channel, one must consider the primary and secondary mirror surfaces of the TW and SW channels of the 3 scanners, i.e., 12 mirrors in all, which are assumed to have identical spectral properties in the ERBE ground calibration [24] and spectral correction procedures. However, we show in the Appendix that it is almost certainly the instability of the integrating sphere used for the SW calibration of the ERBE scanners of the three satellites that is responsible for the discrepancies observed in the LW spectral correction. These discrepancies can be completely corrected using the observed value of the slope S (Section IV-A below and the Appendix); however, correction of SW radiances (Section IV-B) requires additional information. As shown in the Appendix (A-23), the SW gain error is given by S/A^{LW} (of order 2.5%) if the TW channel spectral response is perfectly known, but this may not be the case. Can intercomparisons of simultaneous SW observations be used to fix the SW error? From the point of view of Sun-Earth-satellite geometry, there are practically no completely comparable simultaneous SW radiance measurements by more than one ERBE scanner. There are more or less simultaneous regional mean flux values obtained from ERBE scanners on ERBS and NOAA-9, or ERBS and NOAA-10. These reveal a large range of differences, mostly attributable to the inaccuracies in the bidirectional reflectance models; the observations do not exclude a small contribution due to SW calibration error, of order 2%, but they cannot confirm it.

Errors of a few percent may appear to be very small, considering that the mean reflected SW flux (averaged over 24 hours) is of order 100 Wm^{-2}. However, in tropical areas of bright high cloud, instantaneous reflected SW flux may approach 1000 Wm^{-2}, while emitted LW radiant exitance may be as low as 120 Wm^{-2}. Considering the values of the bidirectional reflectance, the corresponding measured SW radiance may range from 200–450 $\mathrm{Wm}^{-2}\ \mathrm{sr}^{-1}$, and with a SW gain error of 2.5%, the SW radiance error could be in the range 5–11 $\mathrm{Wm}^{-2}\ \mathrm{sr}^{-1}$. With the assumption $A^{\mathrm{LW}}/C^{\mathrm{LW}} = -1.2$, a slightly larger absolute error appears with opposite sign in the LW radiance. Consequently, for LW radiance of order 40 $\mathrm{Wm}^{-2}\ \mathrm{sr}^{-1}$, the relative error in instantaneous LW radiances or fluxes will be of order 20%, and could conceivably be higher than 30%. The error will be much weaker over cloud-free areas for which SW reflectance is much lower (ocean or tropical forest), so that estimates of LW cloud radiative forcing may be significantly biased.

III. Comparison of LW Radiant Exitances

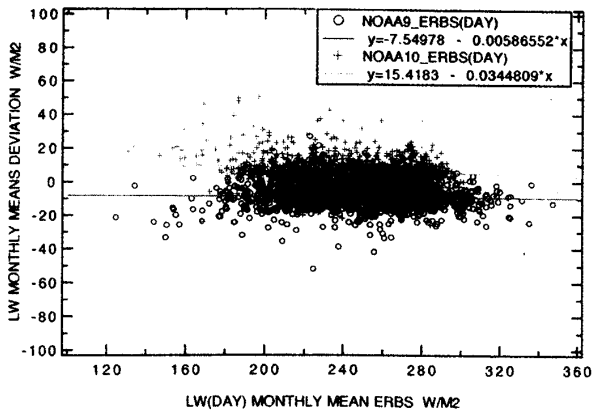
A. Monthly Means

As noted above, we expect the bias in daytime LW (and SW) radiance estimates to appear in the LW and SW radiant exitances. The scanners of all three satellites of the ERBE experiment were simultaneously operational during three months between Oct. 24, 1986 and Jan. 20, 1987. For this period, it is possible to compare the LW and SW radiant exitances obtained from the three satellites. We have made this comparison for the LW, for Dec. 1986. The regions considered have been all those located between latitudes 50° N, 50° S and longitudes 50° W, 50° E, corresponding roughly to the Meteosat disk. On Fig. 3(a) and (b), we show the regional monthly mean LW flux differences for day and night respectively: these are ΔM(NOAA-9-ERBS) and ΔM(NOAA-10-ERBS). Note that in the ERBE diurnal interpolation/ extrapolation procedure, one cannot produce strictly separate daytime and nighttime monthly mean values. We have obtained these monthly means by calculating the arithmetic mean of all the determinations obtained during the month for each region, separating daytime and nighttime values. In the two figures, we also show the linear regression lines representing the mean difference ΔM as a function of M, by day and by night, for the two pairs of satellites. The nighttime determinations agree better than do the daytime ones (Table III). [For example, for the daytime determination, ΔM(NOAA-9-ERBS) $= -8.9$ Wm^{-2}, for a monthly mean LW flux (according to the ERBE scanner on ERBS) of 230 Wm^{-2}, whereas the corresponding value for the nighttime is -2.65 Wm^{-2}. The corresponding difference for NOAA-10 is ΔM(NOAA-10-ERBS) $= +7.48$ Wm^{-2} for the daytime, $+0.53$ Wm^{-2} at night]. Although not negligible, the scatter around these mean differences does not mask the biases found, and is comparable during daytime and nighttime. Note that the slopes of these regression lines in Fig. 3 are small, and result from the effects of the SW calibration errors on the LW radiances and fluxes combined with the geophysical correlations between SW and LW, angular correction and time sampling effects. These results are consistent with results found in other studies which did not distinguish between daytime and nighttime LW flux averages [27].

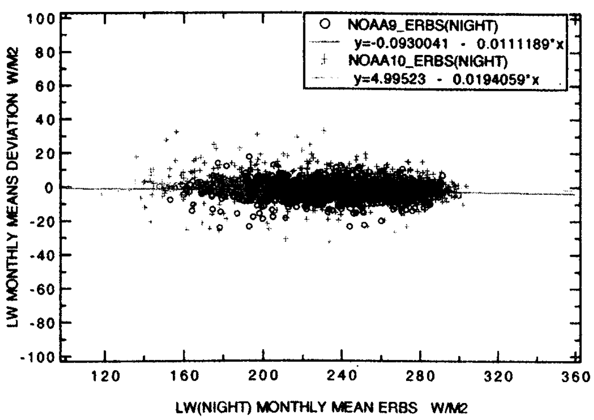
TABLE III
LW Flux Bias and RMS Scatter
December 1986 Regional Means (Wm^{-2})

SATELLITE PAIR	NOAA-9 - ERBS	NOAA-10 - ERBS
Daytime Bias	-8.90	+7.48
rms	±6.28	±6.94
Nighttime Bias	-2.65	+0.53
rms	±4.12	±6.02

The results found in the previous sections indicate that these systematic differences are artefacts related to the calibration and spectral correction (in fact subtraction) procedures, rather than a true diurnal variation, on the scale of the Meteosat disk, of the LW radiation emitted to space. Note that the ERBE scanner on ERBS samples nearly all local times in the course of the month, so that the result may represent a good monthly mean, although some residual bias cannot be excluded because of the convolution of diurnal and interdiurnal variation. There still could be a bias in the ERBS results arising from the calibration or subsequent data reduction procedures. The times sampled by NOAA-9 and NOAA-10 are significantly different, and the systematic day-night differences could be the sign of large-scale diurnal variation. However, although quite strong LW diurnal variations are well known over the Meteosat area [31], [32], the bias found here is relatively large by day and weak by night. Moreover these differences are opposite in sign to those which might be expected from physical diurnal LW



(a)



(b)

Fig. 3. Comparison between regional monthly mean LW radiant exitances obtained during December 1986 by the ERBE scanners on NOAA-9, ERBS and NOAA-10. The regions included are between 50° N, 50° S and 50° W, 50° E. All scene types are included. (a) Day measurements. (b) Night measurements.

variations dominated by maximum land surface temperature during the day and maximum high cloud coverage at night. Therefore the simplest explanation is that of an artefact related to a SW characterization error biasing LW determination by spectral subtraction.

B. Simultaneous Regional Means

Another way to check this point is to compare the simultaneous and colocated *instantaneous* regional means obtained by the two pairs of satellites at the same period, i.e., Dec. 1986. By "simultaneous" we mean that we consider only regional mean radiant exitance values obtained when observations are made of the same region during the same hour on the same day from two satellites (ERBS and NOAA-9, or ERBS and NOAA-10; NOAA-9/NOAA-10 crossings can only take place at latitudes poleward of our 50° limit). We consider all days of Dec. 1986 and the 24 hour boxes per day, separating day and night. In practice the Sun-synchronous NOAA-9 and NOAA-10 satellites provide data mostly in a few hour boxes close to their nominal equatorial crossing times, except at the higher latitudes (still less than 50° in this study). If the differences found in the daytime monthly means are intrinsic and arise from differing sampling of diurnal variations, these comparisons of nearly simultaneous LW flux determinations should yield much smaller differences. Results are shown in Table IV and in Fig. 4(a) and (b) in which we have separated the day and night measurements as in Table III and Fig. 3(a) and (b). As for the monthly means, agreement is better at night than by day. As may be expected considering the smaller sample size and the fact that the angular models have at best only statistical validity, the rms scatter values are greater than the corresponding values for the monthly mean comparisons, by an amount between 2 and 4 Wm^{-2}. These results agree well with those obtained for the regional monthly mean fluxes, and tend to show that the systematic differences observed in the regional day/night monthly means do not represent true diurnal variation revealed by the different sampling times. On the contrary, they correspond to the systematic differences in the instantaneous regional mean radiant exitances determined using ERBE scanner data from the three satellites presumably observing the same radiation fields, and so they must be artefacts of the calibration and data processing algorithms.

TABLE IV
LW FLUX BIAS AND RMS SCATTER (Wm^{-2}) DECEMBER 1986
INSTANTANEOUS REGIONAL MEANS SIMULTANEOUS OBSERVATION PAIRS

SATELLITE PAIR	NOAA-9 - ERBS	NOAA-10 - ERBS
Daytime Bias	-8.21	+6.04
rms	±10.66	±8.61
Nighttime Bias	-2.6	+0.36
rms	±8.62	±8.03

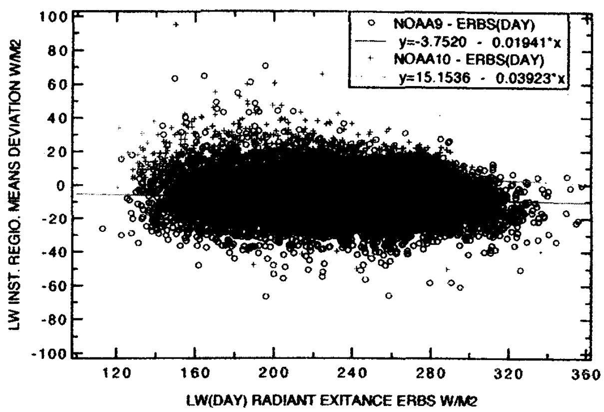
IV. CORRECTION PROCEDURES

A. Correction of the LW Radiance and the LW Radiant Exitance

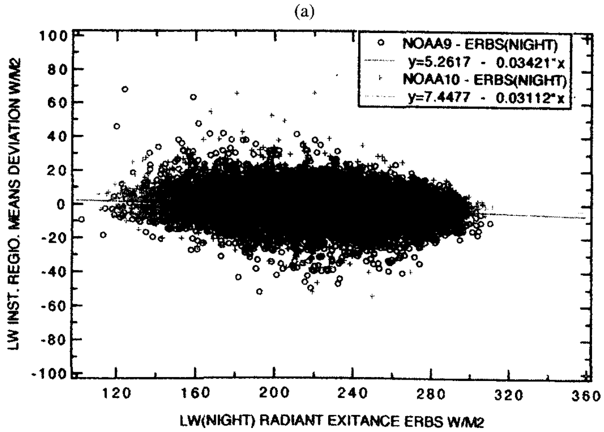
Our results can be used to correct the unfiltered LW radiances given in the ERBE S-8 products, and consequently the LW radiant exitances given in S-9, by the following approach. We consider that the nighttime unfiltered LW radiances are correct. We can then estimate the correct daytime unfiltered LW radiance by "levelling" the relation between unfiltered LW and filtered SW radiances for a given filtered LW radiance class, i.e. using the formula

$$\begin{aligned} m_{\mathrm{cor}}^{\mathrm{LW}} &= m_{\mathrm{LW}}^{f} + F^{\mathrm{LW}} - S \cdot m_{\mathrm{SW}}^{f} \\ &= m_{u}^{\mathrm{LW}} - S \cdot m_{\mathrm{SW}}^{f} \end{aligned} \tag{14}$$

where $m_{\mathrm{cor}}^{\mathrm{LW}}$ and m_{u}^{LW} are respectively the corrected and uncorrected unfiltered LW radiances, F^{LW} is the LW spectral correction before revision, i.e. the difference between unfiltered and filtered LW radiance, as defined in (8), and $\langle S \rangle$ is the mean slope determined in the previous analysis (Fig. 2) and tabulated in Table V, considering average values determined for observations made up to the end of the individual ERBE scanner's operation.



(a)



(b)

Fig. 4. Comparison between instantaneous regional mean radiant exitances obtained during Dec. 1986 by ERBE scanners on NOAA-9, ERBS and NOAA-10. Regions and scene types as in Fig. 3. (a) Day measurements. (b) Night measurements.

TABLE V
LW CORRECTION FACTOR FOR THE 3 ERBE SCANNERS

SATELLITE	Observation Period Considered	Mean Slope $<S_{all}>$
ERBS	February 1985 - February 1990	+0.001
NOAA-9	February 1985 - December 1986	-0.036
NOAA-10	December 1986 - May 1989	+0.034

This correction can be used to correct the radiant exitance because of the linear dependence between the radiance and the radiant exitance, assuming that the radiance correction does not change the scene identification which would change the choice of angular model. However, this correction must be made at the level of the pixel and cannot be made at the level of the instantaneous 2.5° regional mean, because the slopes S have been obtained before the inversion procedure which is not a linear process. This implies that we cannot deduce the LW radiant exitance correction directly from (14) on the S-9 database, because while the correction of the regional mean LW radiance is linear in the regional mean SW *radiance*, the SW radiance-to-flux conversion is very nonlinear. We have to re-calculate the spatial average of the LW radiant exitance from the corrected pixel LW radiant exitances at the S-8 level. We have corrected the ERBE datasets for Dec. 1986, July 1986 and Aug. 1987 using this procedure.

B. SW Corrections

If it is assumed that the daytime LW bias is only due to a SW channel calibration error because of the instability of the integrating sphere (see Appendix), we can propose a formulation for correcting the unfiltered SW radiances. Rewriting (A-22) with notation adopted in (14), the unfiltered SW radiances can be corrected using the formula

$$m_{\rm cor}^{\rm SW} = m_u^{\rm SW} - (S/A^{\rm LW})m_u^{\rm SW} \tag{15}$$

where $m_{\rm cor}^{\rm SW}$ and $m_u^{\rm SW}$ are respectively the corrected and uncorrected unfiltered SW radiances. In order to apply (15) we used coefficient $A^{\rm LW}$ which is not published and is not accessible in the S8 database. However if we consider the set of values of $A^{\rm LW}$ available to us (Table I) it varies between -1.4 to -1.09. If we consider that the variation of this set of spectral factors is representative of the variations of all the spectral factors, we can take a mean value for $A^{\rm LW}$ of approximately -1.3 without making a great error in the correction of the unfiltered SW radiances.The corrections of SW radiant exitances will have to be performed pixel by pixel at the S-8 level before proceeding to the correction of regional means, because the anisotropic factors (normalized bidirectional reflectances) can vary strongly from pixel to pixel depending on the scene identification. To some extent, because overestimates of the reflected SW (as in the NOAA-9 ERBE scanner) result in underestimates both of the absorbed SW flux and of the emitted LW flux, there would be a degree of error compensation when computing the net radiation. This could in part explain why the ERBE global annual radiation balance comes out to be fairly close to zero, not only for the 3-satellite period in the autumn of 1986, but also for the period when only ERBS and NOAA-9 were operating, even though there may be small but non negligible systematic errors in the SW gain of the ERBE scanner on NOAA-9. The same holds for the ERBS/NOAA-10 period (1987–1989).

V. IMPLICATIONS FOR ERBE RESULTS

A. Diurnal Variations

For the period (Jan. 1985–Dec. 1986) during which the ERBE scanner on NOAA-9 was operating, the various ERBE products (monthly mean Earth radiation budget components and in particular the monthly mean diurnal variation) depend significantly on the data coming from this scanner, not only in the polar zones not observed by ERBS, but also in tropical and mid-latitude zones observed every day by NOAA-9 near local times 0230 and 1430. The unfiltered SW radiances corrections given by (15) are of order 2.5%. These corrections of a few percent are small compared to the uncertainties in the angular correction and the diurnal amplitude of the reflected solar SW flux.

For the LW, as we have noted, the relative corrections can be fairly large, and they apply only to the daytime (1430 LT) NOAA-9 determinations and not to the nighttime (0230 LT). For clear land and desert scenes, the ERBE LW diurnal cycle is established using the half-sine model which for each day will interpolate LW values at daytime hours not observed from either NOAA-9 or ERBS. For desert areas, the reflected SW radiances are fairly high, and since most of the observations of maximum LW during the month will be observations from NOAA-9, the maximum LW flux may be underestimated by as much as 8–10 $\mathrm{Wm^{-2}}$. Minimum LW flux, deduced essentially from nighttime data or near-dawn observations from ERBS, should be unaffected, and thus the desert LW diurnal amplitude may be somewhat underestimated even though (and because) the time of LW maximum is well sampled from NOAA-9. This may explain part of the discrepancy between the estimate of the LW diurnal cycle amplitude using Meteosat data and that yielded by ERBE [8]. The midday LW corrections will also be large over bright SW reflectors such as clouds. In the case of low stratiform cloud over ocean, for which Meteosat estimates and ERBE give maximum LW corresponding to minimum cloud cover in the late afternoon [33], correcting the NOAA-9 daytime estimates by a few $\mathrm{Wm^{-2}}$ may be a significant change in the form of the rather weak LW diurnal cycle. Work in progress on LW diurnal variations (manuscript in preparation) shows that indeed much better agreement between ERBE and Meteosat can be obtained once the ERBE LW values are corrected for the SW-dependent bias.

For land areas, ERBE may underestimate significantly the LW emission of the component of convective cloud having an afternoon maximum, and so overestimate the LW diurnal amplitude for overcast scenes. For land and ocean areas where convective cloud cover reaches its maximum during the night, so that maximum LW emission occurs during the day, the effect will be the same (an underestimate of the daytime LW emission), provided the scene remains overcast during the day, but this will give an underestimate of the LW diurnal amplitude. However for clear tropical vegetated land areas, the daytime LW correction will be small because of the low albedo, and therefore impact on the estimate of the LW diurnal amplitude will be negligible. Impact on the mean LW diurnal variation in regions with a mixture of clear and cloudy areas will depend on the relative importance of surface temperature and cloud cover and height variations, and this impact will be hard to extract from the effects of incomplete time sampling.

The above discussion applies to the period when the ERBE scanner on NOAA-9 was operating together with that on ERBS. During the later period (Oct. 1986–May 1989) when the NOAA-10 ERBE scanner was providing data, the LW errors are of opposite sign and smaller. Because the NOAA-10 passages are far from midday, the impact on the clear land/desert diurnal variation determination is probably slight, since the midday half-sine extrapolation will nearly always be dominated by measurements from ERBS. There may again be an impact on the small LW diurnal variation determined for low stratiform cloud over ocean, in the sense that the diurnal amplitude may be underestimated.

B. Cloud Radiative Forcing

An error of a few percent in the SW gain will of course appear as an error of the same order in the SW cloud radiative forcing ($\mathrm{CF_{SW}}$). Using the superscript cor to denote corrected values, we can write the error as

$$\begin{aligned} E(\mathrm{CF_{SW}}) &= \mathrm{CF_{SW}} - \mathrm{CF_{SW}^{cor}} \\ &= M_{\mathrm{SW}}(\mathrm{clr}) - M_{\mathrm{SW}}^{\mathrm{cor}}(\mathrm{clr}) - M_{\mathrm{SW}}(\mathrm{cld}) \\ &\quad + M_{\mathrm{SW}}^{\mathrm{cor}}(\mathrm{cld}). \end{aligned} \tag{16}$$

where the M_{SW} denote the SW fluxes. In the special and unlikely Lambertian case where there are no angular corrections so that the relative SW flux error is the same as the radiance error, a relative SW error S' (adjusted for SW filtering, $S' = -\langle S \rangle / A_{\mathrm{LW}}$) yields a SW cloud forcing error $E(\mathrm{CF_{SW}}) = -S'\mathrm{CF_{SW}}$. For results depending mainly on the ERBE scanner on NOAA-9, this is a slight overestimate in the absolute value of the SW CRF. However, such an error (at worst a few $\mathrm{Wm^{-2}}$) is small compared to the large uncertainties arising from the angular correction and diurnal modelling procedures. In the same special case, considering that a relative error S' in unfiltered SW radiance translates directly into a relative error of opposite sign $S'A^{\mathrm{LW}}/A^{\mathrm{SW}}$ in the LW flux, we can write the error in the daytime LW CRF as $E(\mathrm{CF_{LW}}) = -S'(A^{\mathrm{LW}}/A^{\mathrm{SW}})\mathrm{CF_{SW}}$, where typically $A^{\mathrm{LW}}/A^{\mathrm{SW}} = -0.8$. On the regional scale, if cloud cover is important during the daytime, the error in the absolute value of the daytime LW cloud radiative forcing, an underestimate in the case of NOAA-9, can be as high as 5–10 $\mathrm{Wm^{-2}}$. Although it may still be a minor factor, it is of the same sign as the differences between ERBE and other estimates of LW CRF (cf. [34]). Contrary to the situation for the period with NOAA-9 observations, daytime LW CRF may be slightly overestimated for the 1987–1989 period with NOAA-10 observations.

VI. Conclusions

Analysis of the ERBE LW products (monthly and instantaneous regional mean unfiltered LW radiant exitances, filtered and unfiltered LW and SW radiances) obtained during December 1986 with the ERBE scanners operating on board the three satellites ERBS, NOAA-9, and NOAA-10, and during other months when two of the three satellite scanners were operating, shows that the LW spectral correction introduces systematic day/night differences. These differences, analyzed at the level of pixel radiances, arise from an error in LW spectral correction which is linear in the SW radiance. One can then correct the daytime ERBE LW (and with certain assumptions the SW) radiances and radiant exitances at the level of the S-8 database; correcting the radiant exitances at the regional scale (on the S-9 database) requires reprocessing the space averaging of the corrected pixel radiant exitances. The results of this reprocessing will be analysed in a further paper. These errors can most simply be interpreted physically as small (of order 2.5%) errors in the gains used for the SW channels of the ERBE scanners on NOAA-9 and NOAA-10, with no error for the scanner on ERBS. However, they can depend on errors in the assumed ratio of SW/LW filtering in the TW channel. We may note that although the ERBE accuracy requirements in the SW are satisfied even with 2.5% SW gain errors, the resulting daytime LW errors may not be acceptable for some products such as LW diurnal variations or cloud radiative forcing on a regional scale.

These results are relevant to the ongoing ScaRaB and upcoming CERES missions in which broad-band sensors are used to measure the Earth Radiation Budget components. Because of the relatively unsatisfactory filtering properties of the LW diamond filter used in ERBE, and of the nonexistence of materials providing a flat spectral transmittance over the entire LW range (say 5–50 μm), both ScaRaB and the CERES scanners are designed with only two broad-band channels, one of these being the unfiltered TW channel, the other being a SW channel using a fused silica filter to cut off wavelengths greater than 4–5μm. Although the additional channels (an 8–13μm window channel on CERES, a narrower IR window channel on ScaRaB) do contain considerable information, they can only be used to compute the broad-band radiances with strong reliance on modelling. Thus the ScaRaB and CERES daytime unfiltered LW radiances will be determined by a "spectral subtraction" (TW - SW) procedure: compared with (4), we have *no* filtered LW radiance measurements. The exact values of the coefficients A^{LW} and C^{LW} (5), or of coefficients $S_{\mathrm{TL}}, G_{\mathrm{TL}}$, and A in (6), depend on ground calibration. The fact that a highly accurate LW calibration of the TW channel can be obtained using the on-board blackbody does not in itself ensure the same accuracy in the daytime LW measurements, which will depend on the SW calibration procedures. Thus with a calibration accuracy requirement of 1% in the SW as opposed to 0.5% in the TW channel, the accuracy of daytime CERES LW products cannot be guaranteed to be of order 0.5%; indeed the instantaneous near midday LW determinations for cold bright clouds can be in error by as much as several percent, as noted earlier for ERBE. The key point for the LW measurement is the ratio of response of the SW channel to the SW portion of the TW channel. In any event, given that the new instruments (both ScaRaB and CERES) include IR window channels, one can check the accuracy of the determinations of daytime unfiltered LW radiances and fluxes using a procedure similar to that applied in this study of ERBE results, plotting estimated LW radiance against measured filtered SW radiance, stratified by the radiance measured in the IR window channel. The method may be applied to LW radiance determinations from a single instrument; two-scanner intercomparisons are not essential. One may also derive parameter A from statistical analysis of the daytime and nighttime data in the TW, SW and IR window channels, forcing diurnal consistency, i.e., zero slopes S_l. Another possibility may be to compare the daytime broad-band LW radiances (and thus fluxes) obtained by spectral subtraction with estimates made along the lines used in the Nimbus-3 determinations [15] and further developed [16], [35] for the full set of HIRS (High-Resolution Infra-Red Sounder) channels, i.e. using narrow infrared bands whose calibration is identical by day or night.

VII. Appendix

Although ERBE spectral correction appears complex and involves a very large number of (unpublished) spectral correction coefficients, it can be interpreted in relatively simple terms. Plotting LW spectral correction versus SW filtered radiance, we find that for 2 of the 3 ERBE scanners, the slopes S_l for LW filtered radiance classes l and all scene types, are different from zero, and moreover that these nonzero slopes are essentially constant over the scanner lifetimes. This suggests that there are errors or inconsistencies in the ground calibration parameters.

Consider the 3 ERBE scanner channels (SW, LW, TW), denoted using indices S, L, T in what follows. We consider a sum of SW and LW spectral radiance distributions

$$L(\lambda) = L_S(\lambda) + L_L(\lambda). \tag{A-1}$$

The spectral filtering functions in ERBE scanner channel k are

$$S_k(\lambda) = R_k(\lambda)T_k(\lambda) \tag{A-2}$$

where $R_k(\lambda)$ is the product of the mirror optics spectral reflectance and the spectral absorptance of the detector flake's black paint, while $T_k(\lambda)$ is the spectral transmittance of the filter, if any, in channel k. In the ERBE calibration and processing, it is *assumed* that

$$R_k(\lambda) = \rho\lambda^2 a\lambda \tag{A-3}$$

for all three channels; of course the TW channel has no filter, i.e., $T_T(\lambda) = 1$. Now for some set of reference spectra $L_S(\lambda), L_L(\lambda)$, we can write:

$$c_S n_S = R_S T_S L_S \tag{A-4 S}$$
$$c_L n_L = R_L T_L L_L \tag{A-4 L}$$
$$c_T n_T = R_{TS} L_S + R_{TL} L_L \tag{A-4 T}$$

where the $L_k = \int L_k(\lambda)\, d\lambda$ are the unfiltered radiances, and:

$$R_S T_S L_S = \int_{\mathrm{SW}} R_S(\lambda) T_S(\lambda) L_S(\lambda)\, d\lambda \tag{A-5 S}$$
$$R_L T_L L_L = \int_{\mathrm{LW}} R_L(\lambda) T_L(\lambda) L_L(\lambda)\, d\lambda \tag{A-5 L}$$
$$R_{TS} L_S = \int_{\mathrm{SW}} R_T(\lambda) L_S(\lambda)\, d\lambda \tag{A-6 S}$$
$$R_{TL} L_L = \int_{\mathrm{LW}} R_T(\lambda) L_L(\lambda)\, d\lambda. \tag{A-6 L}$$

Considering the ERBE spectral correction formalism in these terms, we may write $m^{\mathrm{SW}} = L_S, m^{\mathrm{LW}} = L_L$, and combining (4) and (A-4), we have:

$$\begin{aligned} L_S =& [A^{\mathrm{SW}} R_S T_S + C^{\mathrm{SW}} R_{TS}] L_S \\ &+ [B^{\mathrm{SW}} R_L T_L + C^{\mathrm{SW}} R_{\mathrm{TL}}] L_L \end{aligned} \tag{A-7 S}$$
$$\begin{aligned} L_L =& [A^{\mathrm{LW}} R_S T_S + C^{\mathrm{LW}} R_{TS}] L_S \\ &+ [B^{\mathrm{LW}} R_L T_L + C^{\mathrm{LW}} R_{\mathrm{TL}}] L_L. \end{aligned} \tag{A-7 L}$$

Considering the nighttime case ($L_S = 0$), we have

$$B^{\mathrm{SW}} R_L T_L + C^{\mathrm{SW}} R_{\mathrm{TL}} = 0 \tag{A-8 S}$$
$$B^{\mathrm{LW}} R_L T_L + C^{\mathrm{LW}} R_{\mathrm{TL}} = 1 \tag{A-8 L}$$

and we must also have

$$A^{\mathrm{SW}} R_S T_S + C^{\mathrm{SW}} R_{\mathrm{TS}} = 1 \qquad \text{(A-9 S)}$$
$$A^{\mathrm{LW}} R_S T_S + C^{\mathrm{LW}} R_{\mathrm{TS}} = 0 \qquad \text{(A-9 L)}$$

Hypothesis (A-3) entails $R_{\mathrm{TS}} = R_S = R_S^*, R_{\mathrm{TL}} = R_L = R_L^*$, so that

$$B^{\mathrm{SW}} T_L^* + C^{\mathrm{SW}} = 0 \qquad \text{(A-10a)}$$
$$B^{\mathrm{LW}} T_L^* + C^{\mathrm{LW}} = 1/R_L^* \qquad \text{(A-10b)}$$
$$A^{\mathrm{SW}} T_S^* + C^{\mathrm{SW}} = 1/R_S^* \qquad \text{(A-10c)}$$
$$A^{\mathrm{LW}} T_S^* + C^{\mathrm{LW}} = 0 \qquad \text{(A-10d)}$$

where $T_L^*, T_S^*, R_L^*, R_S^*$, are the values assumed in the ERBE computation of the spectral correction coefficients.

The values from Table I obey $B^{\mathrm{SW}} = -1.57\ C^{\mathrm{SW}}$ quite precisely, giving $T_L^* = 0.64$; we also find that we can write $C^{\mathrm{LW}} = 1.11 + \varepsilon(|\varepsilon| \leq 0.2)$, with $B^{\mathrm{LW}} = -1.59\varepsilon$ quite exactly, yielding

$$1/R_L^* = 1.11 + \varepsilon - \varepsilon = 1.11, \quad R_L^* = 0.90.$$

Values of A are more scattered as a result of real scene dependence of ERBE spectral filtering. Nevertheless $A^{\mathrm{LW}}/C^{\mathrm{LW}} \approx -1.20$, yielding $T_S^* = 0.83$. We also have, very approximately, $A^{\mathrm{SW}} = 1.73 - 1.24\ C^{\mathrm{SW}}$, yielding $A^{\mathrm{SW}} \approx 1.61$ and $R_S^* \approx 0.70$.

The assumed starred values may be wrong, but they are used in computing the count conversion coefficients c_k^* in the ground calibration. We must consider the impact of possible errors. In what follows, we continue to use an asterisk (*) to denote values assumed by ERBE or resulting from such assumptions.

The ERBE ground calibrations using a blackbody source with zero SW radiance provide conversion coefficients

$$c_L^* = R_L^* T_L^* B / n_L(B) \qquad \text{(A-11 L)}$$
$$c_T^* = R_{\mathrm{TL}}^* B / n_T(B) \qquad \text{(A-11 T)}$$

where B is the spectrally integrated (unfiltered) blackbody radiance, and $n_L(B)$ and $n_T(B)$ are counts (with offset removed) in the LW and TW channels respectively. We have:

$$c_L/c_L^* = (R_L T_L)/(R_L^* T_L^*) \qquad \text{(A-12 L)}$$
$$c_T/c_T^* = R_{\mathrm{TL}}/R_{\mathrm{TL}}^*. \qquad \text{(A-12 T)}$$

The SW calibration relies on an integrating sphere I which has spectral radiance:

$$I(\lambda) = I_S(\lambda) + I_L(\lambda) \qquad \text{(A-13)}$$

and I_L is estimated using the LW channel: $I_L^* = c_L^* n_L(I)/(R_L^* T_L^*)$, so that:

$$I_L/I_L^* = (c_L/c_L^*)(R_L^* T_L^*)/(R_L T_L) = 1. \qquad \text{(A-14)}$$

Thus we see that I_L is correctly estimated even if the value assumed for $R_L^* T_L^*$ is incorrect, because this error is cancelled by the corresponding error in c_L^*.

The SW radiance of the integrating sphere is estimated using the TW channel and the above estimate of I_L. Considering (A-4 T) $c_T n_T(I) = R_{\mathrm{TS}} I_S + R_{\mathrm{TL}} I_L$, we obtain, using possibly incorrect parameters

$$I_S^*[T] = [c_T^* n_T(I) - R_{\mathrm{TL}}^* I_L^*]/R_{\mathrm{TS}}^* \qquad \text{(A-15)}$$

and we can show, using (A-12) and (A-14), that

$$I_S(T)/I_S^*(T) = (R_{\mathrm{TL}}/R_{\mathrm{TL}}^*)(R_{\mathrm{TS}}^*/R_{\mathrm{TS}}) = r/r^* \qquad \text{(A-16)}$$

where $r = R_{\mathrm{TL}}/R_{\mathrm{TS}}$, assuming that the intrinsic LW radiance of the integrating sphere is the same for the LW view as for the TW view (i.e., that the integrating sphere is thermally uniform and stable). With this proviso, the accuracy of the estimate $I_S^*(T)$ of the SW radiance of the integrating sphere during the TW view, depends on the accuracy with which the ratio r is known. This estimate is used to calibrate the SW channel, which obtains a signal $n_S(I)$ when viewing the integrating sphere. We rewrite (A-4 S) and (A-16) as

$$c_S n_S(I) = R_S T_S I_S(S)$$
$$I_S(T)/I_S^*(T) = r/r^*$$

where we allow for possible differences (instability or spatial inhomogeneity) of the intrinsic SW radiance of the integrating sphere between views by the SW and TW channels. We note that since $I_S^*(S) = I_S^*(T)$ is assumed, we have

$$c_S^* n_S(I) = R_S^* T_S^* I_S^*(T)$$

so that

$$\frac{c_S}{c_S^*} = \frac{R_S T_S}{R_S^* T_S^*} \frac{I_S(S)}{I_S(T)} \frac{r}{r^*}. \qquad \text{(A-17)}$$

As a result, the SW radiance E_S^* estimated for an Earth scene E will be

$$\begin{aligned} E_S^* &= c_S^* n_S(E)/(R_S^* T_S^*) \\ E_S/E_S^* &= (c_S/c_S^*)(R_S^* T_S^*)/(R_S T_S) \\ &= (r/r^*)[I_S(S)/I_S(T)]. \end{aligned} \qquad \text{(A-18)}$$

Considering (A-4 T) rewritten as:

$$\begin{aligned} E_L &= c_T n_T(E)/R_{\mathrm{TL}} - E_S/r \\ &= \frac{c_T^* n_T(E)}{R_{\mathrm{TL}}^*} - \frac{I_S(S)}{I_S(T)} \frac{1}{r^*} E_S^* \\ &= E_L^* + [1 - I_S(S)/I_S(T)](1/r^*) E_S^* \\ E_L &= E_L^* + [1 - I_S(S)/I_S(T)](1/r^*) c_S^* n_S(E)/(R_S^* T_S^*). \end{aligned} \qquad \text{(A-19)}$$

We note that if $I_S(S) = I_S(T), E_L = E_L^*$. Thus the fact that we find nonzero slopes S_l ((8) and (9)) is a strong indication of a SW ground calibration error, with $I_S(S) \neq I_S(T)$. Considering that estimated filtered SW radiance is given by $c_S^* n_S(E)$, we have:

$$\begin{aligned} E_L - E_L^* &= -S c_S^* n_S(E) \\ S &= -[1 - I_S(S)/I_S(T)](1/r^*)[1/(R_S^* T_S^*)] \\ &= -[1 - I_S(S)/I_S(T)](R_{\mathrm{TS}}^*/R_{\mathrm{TL}}^*)[1/(R_S^* T_S^*)]. \end{aligned} \qquad \text{(A-20)}$$

With $R^*_{\mathrm{TS}} = R^*_S$ as assumed by ERBE,

$$S = -[1 - I_S(S)/I_S(T)][1/(R^*_{\mathrm{TL}}T^*_S)] \quad \text{(A-21)}$$

from (A-10d) we have $T^*_S = -C^{\mathrm{LW}}/A^{\mathrm{LW}}$, and to first order we have $C^{\mathrm{LW}} = 1/R^*_{\mathrm{TL}}$. Thus we have

$$S = [1 - I_S(S)/I_S(T)]A^{\mathrm{LW}},$$

and so

$$I_S(S)/I_S(T) = 1 - S/A^{\mathrm{LW}},$$

and from (A-18) we obtain

$$E_S/E^*_S = (r/r^*)[1 - S/A^{\mathrm{LW}}] \quad \text{(A-22)}$$

writing $E^*_S = E_S + \delta E_S$ and $r^* = r + \delta r$, we obtain, to first order, the relative unfiltered SW error as

$$\delta E_S/E_S = \delta r/r - S' \quad \text{(A-23)}$$

where $S' = -S/A^{\mathrm{LW}}$.

ACKNOWLEDGMENT

This work was supported in part by the European Space Agency, and by CNES (the French national space agency). The authors thank M. Viollier for his advice concerning spectral correction, and P. Raberanto for assistance with data processing at LMD. Among ERBE/CERES colleagues, R. N. Green, R. B. Lee III and G. L. Smith of NASA LaRC made particularly helpful comments. The authors are indebted to an unidentified referee (possibly one of the last three) for carefully reading the first version of this paper and pointing out that mischaracterization of the SW portion of the TW channel could also account for part of the LW diurnal bias.

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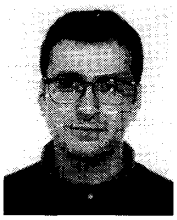

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