RADIOMETRY FROM SPACE

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Abstract

We compare the performance of broadband radiometers with spectrally-dispersed measurements. Spectrally-dispersed radiometers may be more accurately calibrated than is possible with broadband filter instruments. They also have a larger information content than have filter measurements. Accuracy and information content are two important requirements for climate observations.

1. Introduction

We recently submitted an article to *Journal of Climate* based on data from IRIS, a fourier transform spectrometer with black body calibration that was flown on Nimbus 4 in 1970/71. In response to our submission, an Editor, Dr. James A. Coakley, stated (in part) as follows:

> First, I challenge you to demonstrate that accurate absolute measurements over limited spectral intervals are possible. Broadband observations [Dr. Coakley is referring to the Earth Radiation Budget Experiment, or ERBE] can be absolutely calibrated because there are well-defined standards to which they can be referenced. There are no such standards by which observations over limited spectral intervals can be compared. In the case of IRIS, for example, one would have to demonstrate that the instrument [response] was flat, or at least that its response was corrected for over its bandpass.

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This statement differs strikingly from the views of quantitative spectroscopists who believe that spectrometers, if well-designed and calibrated, are capable of much more precise radiometry than is possible with broadband filters. Subsequent discussions have suggested to us that other ERBE investigators share Dr. Coakley's views, and we believe that it may be appropriate to present the issues in the climate literature.

We shall show that, precisely to the contrary of the above statement, the instrument sensitivity *does not need to be flat* to permit accurate radiometry with spectrally-resolving instruments, while broadband filter measurements can have serious errors on this account. In addition we shall show that spectrally-resolved data contain important information that is denied to ERBE.

Whether radiometers employ spectral resolution or broadband filters, they must be calibrated. For satellite instruments this calibration involves successive views of Earth, space, and a black body. For accurate radiometry this calibration must be performed with great care but, because the procedure is common to all radiometers, we shall not discuss it in this note.

There are, of course, many aspects to the design of reliable, accurate radiometers, and we shall mention some of them in § 5. It is possible to design good and bad instruments whether broadband or spectrally-resolving. But the key features of spectrally-resolving instruments, namely insensitivity to instrumental spectral characteristics,and high information content, are independent of all other matters.

To illustrate a fundamental feature of this comparison between radiometers, consider the following simple calculation in which all gradients are constant (see figure 1 for definition of terms). When viewing the Earth the instrument response will be (assuming that the zero has been determined from a space view),

$$\tilde{I} = g\int_{\nu_1}^{\nu_2} S_\nu I_\nu d\nu, \qquad (1)$$

and, when it views the black body its response will be,

$$\tilde{B} = g\int_{\nu_1}^{\nu_2} S_\nu B_\nu d\nu, \qquad (2)$$

where g is the instrument gain (all frequency-dependent factors are included in the sensitivity, S_ν).

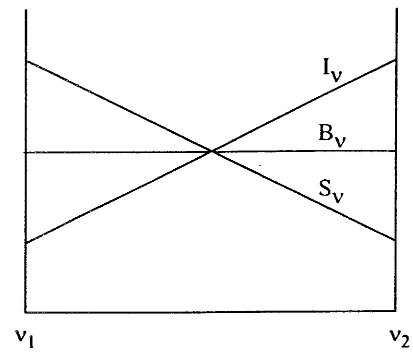

Figure 1: In the spectral interval between frequencies ν_1 and ν_2 the radiance from Earth is I_ν, the black body radiance is B_ν, and the instrument sensitivity is S_ν. Gradients are constant over the interval.

We wish to determine,

$$I = \int_{\nu_1}^{\nu_2} I_\nu d\nu, \tag{3}$$

given,

$$B = \int_{\nu_1}^{\nu_2} B_\nu d\nu. \tag{4}$$

For this particular example, $I = B$.

We may calibrate $\tilde{I}$ by multiplying by the ratio $B / \tilde{B}$ to obtain an estimate for I,

$$I(\text{est}) = \tilde{I}\frac{B}{\tilde{B}} = B\left\{1 + \frac{1}{12}(\nu_1 - \nu_2)^2 \frac{\partial I_\nu}{\partial \nu}\frac{\partial S_\nu}{\partial \nu}\right\}. \tag{5}$$

The second term in brackets is an error term. For this example its maximum value is 1/3, but for other spectral distributions it can be larger. The error term varies as $(\nu_1 - \nu_2)^2$. If we were to divide the spectral interval into n equal parts, perform the integrals and sum them, the error would be smaller by a factor of n^2 For a broadband filter of width 10^3 cm^{-1} and a spectrometer of resolution 1 cm^{-1}, the spectrometer could have, other things being equal, an accuracy advantage of 10^6.

2. The Earth Radiation Budget Experiment

The ERBE radiometer (and its successor CERES) is a workhorse for NASA's climate program. It measures integrated solar radiances (ν>2000 cm^{-1}) and integrated longwave or thermal radiances (50 cm^{-1}<ν <2000 cm^{-1}). Three filters are used, one for thermal radiances, one for solar radiances, and one that includes both (Lee et al., 1989). We shall limit discussion to the longwave channel (see figure 2) because it brings out all of the essential differences between the two types of radiometer.

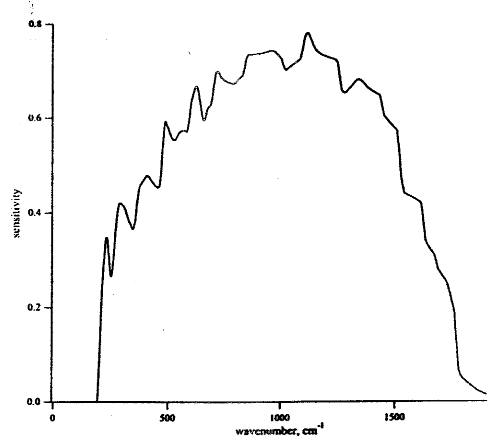

Figure 2: The instrument sensitivity for the longwave channel of the ERBE radiometer.

The procedure used by ERBE investigators to obtain radiation fluxes is described in detail by Green and Avis (1996). In terms of the foregoing equations, we measure $\tilde{I}$ and $\tilde{B}$ (equations 1 and 2), we know B (equation 4), given the temperature of the black body, and we wish to derive I (equation 3). First, determine the gain. We can do this because we know B_ν and S_ν so that we can compute the integral in (2) and determine g from the measured $\tilde{B}$ (there is the possibility here that the instrument sensitivity may change during a long space mission, when there will be errors in this determination; this is one of the many second-order problems that beset accurate radiometry from space).

Given the gain, we may now use (1), together with the measured $\tilde{I}$, to evaluate the integral in absolute terms. To determine I we now need the ratio of the integrals in (1) and (3). This ratio depends on the spectral distribution of the observed radiance, I_ν. Unlike B_ν, this is not known in advance, but is a function of the observed terrestrial scene. An absolute determination of I, independent of the observed scene, is impossible for a broadband radiometer. If ERBE were flown to an unknown planet the longwave flux measurement could be in error by almost any amount.

The ERBE investigators argue that they are not on an unknown planet and that the range of I_ν in terrestrial scenes is limited. Green and Avis (1996) report calculations of $gI / \tilde{I}$ (called either c_{12} or c_{15} in their paper) for many scenes, eleven in the tropics alone. c_{12} varies from 1.7362 for tropical deserts to 1.9193 for polar snow, a difference of 10.5%. We repeated a number of these scene calculations with essentially the same results.

The ERBE investigators further reduce this uncertainty by assuming that they have *a priori* knowledge of the specific field that is being observed (for example, the fractional cloudiness). It is not clear what uncertainty remains, but it is believed to be small enough to be useful for climate monitoring. But these are semi-empirical results, with unknown statistical qualities, and are not absolute measurements.

3. Radiometers with spectral resolution

There are two principal classes of spectral radiometer, the grating spectrometer and the fourier transform spectrometer or interferometer. EOS-AIRS is an example of the former (Aumann and Miller, 1995; Aumann, et al., 1996). HIS is a fourier transform spectrometer with performance similar to that of AIRS (Smith, et al., 1983). These instruments have similar spectral range and similar spectral resolution; we do not need to distinguish between them at the level of this discussion.

The output signal from either instrument is compounded from radiances in a range of frequencies in a narrow band surrounding the frequency ν ,

$$\bar{I}_\nu = \int_0^\infty I_{\nu'} f(\nu - \nu')d\nu' , \qquad (6)$$

$$\bar{B}_\nu = \int_0^\infty B_{\nu'} f(\nu - \nu')d\nu' . \qquad (7)$$

The weighting function $f(\nu - \nu')$ is the *spectral transfer function* . It is normalized,

$$\int_0^\infty f(\nu - \nu')d\nu' = 1. \qquad (8)$$

Three examples are shown in figure 3. For both IRIS and AIRS, the full width to half-maximum of the spectral transfer function (δ, the half width) is about 1 cm^{-1}; for IRIS it was 2.8 cm^{-1}.

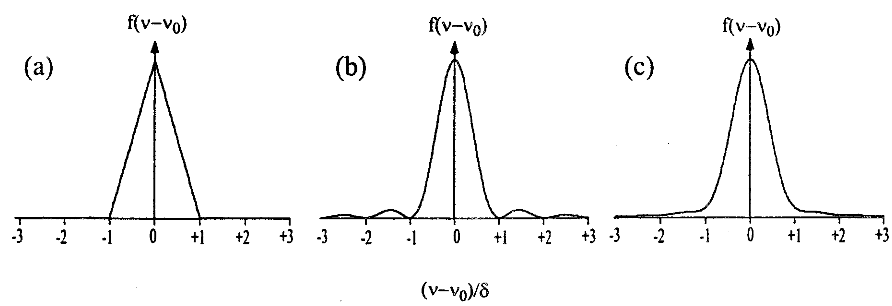

Figure 3: Spectral transfer functions. (a) Triangular, for an energy-limited grating spectrometer. (b) $\left\{\dfrac{\sin[2\pi(\nu-\nu_0)/\delta]}{2\pi(\nu-\nu_0)/\delta}\right\}^2$, appropriate for a diffraction-limited grating spectrometer, or a fourier transform spectrometer with triangular apodization. (c) The AIRS spectral transfer function.

In terms of the spectral transfer function and the spectral sensitivity, the measured quantities may be written,

$$\tilde{I}_\nu = g\int_0^\infty I_{\nu'} S_{\nu'} f(\nu - \nu')d\nu', \tag{9}$$

$$\tilde{B}_\nu = g\int_0^\infty B_{\nu'} S_{\nu'} f(\nu - \nu')d\nu'. \tag{10}$$

With a finite spectral response function it is not possible to recover the fully-resolved radiance, I_ν. At best we can recover the smoothed radiances, equations (6) and (7). We shall discuss the way in which smoothed radiances can be used in §4; for the remainder of this section we consider their calibration in terms of a black body. Smoothed radiances conserve energy in the sense

$$\int_0^\infty \bar{I}_\nu d\nu = \int_0^\infty I_\nu d\nu. \tag{11}$$

They are also *approximately* energy-conserving for finite spectral intervals. The error depends upon the exact form of I_ν and can only be assessed numerically, but it is normally much smaller than $\delta/(\nu_1 - \nu_2)$, where ν_1 and ν_2 define the spectral interval. The column labeled "smoothing" in table 1 shows fractional differences between smoothed and unsmoothed data for the integrals in equation 11 taken over four finite spectral intervals, and for three scenes. The differences are erratic, but in no case are they large.

We estimate $\bar{I}_\nu$ in absolute terms from the normalization,

$$\bar{I}_\nu(\text{est}) = \tilde{I}_\nu \frac{\bar{B}_\nu}{\tilde{B}_\nu}. \tag{12}$$

For any spectrometer, $S_{\nu'}$ will vary little over $f(\nu - \nu')$. To first order it may be taken outside the integrals in equations (9) and (10) and by virtue of the normalization (8) we find $\bar{I}_\nu(\text{est}) = \bar{I}_\nu$; and we have achieved an absolute calibration of the smoothed radiance. This calibration is independent of both the instrument sensitivity and the spectral transfer function, and there is no scene dependence. If the optical characteristics of the spectrometer change during the course of a long mission, as is likely to be the case, the calibration is not affected to first order, unlike broadband filter measurements.

Table 1: Fractional differences for integrals over finite spectral intervals. The "smoothing" column is $\left| \int_{\nu_1}^{\nu_2} (I_\nu - \bar{I}_\nu) d\nu \bigg/ \int_{\nu_1}^{\nu_2} I_\nu d\nu \right|$. The "recovery" column is $\left| \int_{\nu_1}^{\nu_2} [\bar{I}_\nu - \bar{I}_\nu(\text{est})] d\nu \bigg/ \int_{\nu_1}^{\nu_2} \bar{I}_\nu d\nu \right|$. Radiances were calculated at 1 cm^{-1} intervals from MODTRAN and smoothed with a triangular spectral response function of width $\delta = 2.5$ cm^{-1} for the smoothing calculation and 5 cm^{-1} for recovery.

ν_1, cm^{-1}	ν_2, cm^{-1}	scene	smoothing	recovery
200	1400	tropical	8.1×10^{-5}	1.1×10^{-4}
		mid-latitude	5.6×10^{-5}	9.9×10^{-5}
		polar	6.1×10^{-4}	8.0×10^{-5}
200	800	tropical	2.9×10^{-4}	1.8×10^{-4}
		mid-latitude	2.4×10^{-4}	1.6×10^{-4}
		polar	6.5×10^{-5}	1.1×10^{-4}
400	600	tropical	1.3×10^{-3}	1.3×10^{-4}
		mid-latitude	1.3×10^{-3}	8.7×10^{-5}
		polar	1.3×10^{-3}	6.4×10^{-5}
450	550	tropical	1.6×10^{-3}	2.4×10^{-4}
		mid-latitude	1.7×10^{-3}	1.6×10^{-4}
		polar	2.9×10^{-4}	6.5×10^{-5}

In order to assess the second-order errors in the the calibration, we have calculated all of the terms in equation (12) using the ERBE instrument sensitivity (figure 2). This is not a very desirable filter for a spectrometer. The small-scale structure in figure 2 is partly responsible for the errors that are shown in figure 4, but we use this filter in order to preserve comparability with the calculations for ERBE. The fractional error in figure 4 has a maximum value of 5×10^{-3}, and an rms error less than 5×10^{-4}. The errors are similar for the three scenes.

Table 1 shows recovery errors for finite spectral intervals. These are the errors that should be compared to the ERBE "scene" errors. Fort all practical purposes, this error, which is troublesome for broadband filters, is absent when spectrally-resolved measurements are made.

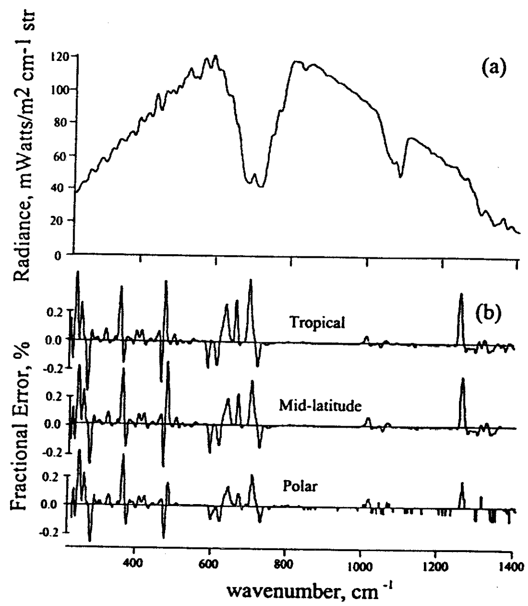

Figure 4: Evaluation of errors in the absolute calibration of smoothed radiances, equation (12) (recovery errors). MODTRAN data at 1 cm^{-1} intervals have been used. The spectral transfer function is triangular with a width of 5 cm^{-1} in order to provide some contrast to the MODTRAN resolution. (a): $\bar{I}_\nu$ for a tropical atmosphere. (b): Percentage error, $\frac{\bar{I}_\nu(\text{est}) - \bar{I}_\nu}{\bar{I}_\nu} \times 100$ for tropical, mid-latitude and polar atmospheres.

4. Using the spectral structure

If an anomaly is detected in integrated radiation fluxes simultaneous information on atmospheric parameters must be available before it can be understood. Such information is not available from ERBE, but much of the relevant data can be extracted from calibrated, resolved spectra. The best known example of how this may be done is the inversion of radiances to yield profiles of temperature and humidity. EOS-AIRS objectives are to measure temperatures to 1K and humidity to 20% with a vertical resolution of 1 km. Spectral information may also be used in other ways. Goody, et al. (1995) discuss the use of spectral fingerprints to distinguish between different climate forcings. Haskins, Goody and Chen (1997) discuss methods of statistical analysis, using resolved spectra, for the purpose of testing climate models.

Any analysis of quantitative spectra comes down to a comparison between an observation and a theoretical prediction, followed by adjustment of model parameters to minimize differences between theory and observation in a least-square sense. This will be most successful if the spectral transfer function is known with precision, and the AIRS project is investing a large effort in a pre-flight calibration. However, even if the spectral transfer function is not well-established, as was the case for IRIS, the high-resolution information is not lost. From the physical characteristics of the spectrometer, assuming high-quality optics, we can make an estimate of the spectral transfer function. In figure 5 we compare radiance errors associated with a 10% uncertainty in the line width with those for a 1K temperature uncertainty and a 20% humidity uncertainty.

The line-width uncertainty in figure 5 is not very important. The numerical magnitude is small and it has zero average over a few line widths, unlike all other errors; an average over 5 line widths is shown in figure 5(c). To first order it will not affect a least-squares fit between observed and theoretical spectra.

5. Discussion

We do not wish to give the impression that because spectral radiometers can avoid field errors, and can be accurately calibrated independently of the optical properties of the radiometer, they are free of all pitfalls (see Aumann, et al., 1996, for a thorough discussion of AIRS). Errors from space and black-body views can be significant, as can be errors associated with the pointing mirror. Detector non-linearities can be corrected numerically for a grating spectrometer. For an interferometer non-linearities can give rise to false radiance harmonics; but these may be detected during ground calibration and used to adjust the electronics. All spectral instruments can suffer from internally scattered radiation and outliers in the spectral transfer function. But there are discriminating laboratory tests for both, and both may be minimized with careful optical design.

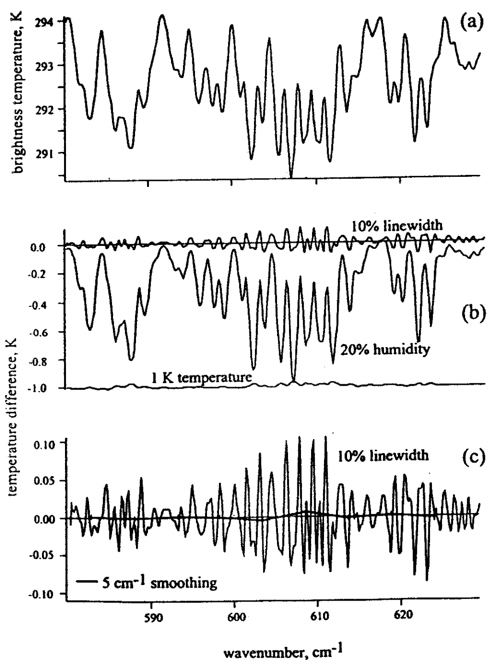

Figure 5: Panel (a): Brightness temperatures were calculated with a line-by-line program and smoothed with a triangular spectral transfer function with a width of 1 cm^{-1}. Panel (b): Brightness temperature differences for: a temperature change of 1 K; a humidity change of 20%; a half width change of 10%. Panel (c): Half-width data from (b) on a larger scale, and an average over 5 cm^{-1}.

The most important requirements for space climate measurements are relevance, accuracy, and high information content. All radiometers are relevant. Apart from the obvious value of high accuracy, there is the additional advantage that comparable data can be gathered with different instruments at different times, avoiding the need for expensive cross calibrations with simultaneous satellites. High information content is particularly important in a difficult and poorly defined subject, such as global climate change. In all of these respects the spectrally-resolving radiometer is a very powerful instrument.

Acknowledgments

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