Coupling of Horizontal, Vertical, and Temporal Resolving Power of a Satellite Temperature Sounder

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ABSTRACT

Satellite sensor optical systems now provide scan spots that are reasonably small and closely spaced compared with the horizontal scales of atmospheric variability that meteorologists might like to infer. Furthermore, geosynchronous deployment of meteorological satellites provides the opportunity for almost arbitrarily frequent observations, thus apparently increasing the temporal resolving power to almost an arbitrary degree. It is known, however, that the vertical resolving power of satellite sounding technology is poor compared with RAOBs. That is, finer scales of vertical atmospheric structure that can be resolved by radiosonde observations may not be detectable or resolvable by satellite radiance observations. In all retrieval methods, some external information or estimates of the ambient vertical structure must be included so that the apparent vertical resolution of the retrieval system is increased.

In this study we show that horizontal and temporal resolving power of satellite soundings is closely coupled to the vertical resolving power. This is demonstrated both empirically and theoretically. Moreover, we show that improving the horizontal or temporal resolving power is not a simple matter of improving scan spot optics or increasing the frequency of observation. Either the "vertical resolving power" of the satellite instrument itself must be improved, or the a priori external information must be extended to include correct horizontal and temporal structure. The vertical resolution limitation of satellite sounders has a direct effect on filtering out, or distorting, horizontal and temporal structural information.

1. Introduction

This paper is concerned with the ability of satellite radiometer measurements of spectral radiance to produce inferred temperature retrieval fields for which a user can say that the space–time structure of the ambient field has been resolved. Past research related to this problem may be organized into several categories. Studies of specific vertical resolving power of sounding instruments include those by Conrath (1972), Rodgers (1976), Thompson et al. (1976), Thompson (1982), and Shin and Scoggins (1988). Studies directed specifically toward the ability of satellite sounding systems to detect horizontal structure include those by Hillger and Vonder Haar (1979), Rosenkranz and Baumann (1980), Nathan et al. (1985), and Rosenkranz et al. (1985). Studies in which techniques are developed specifically to improve the vertical structural fidelity of retrieved soundings include those by Smith and Woolf (1976), Susskind et al. (1984), Uddstrom and Wark (1985), Thompson et al. (1985), Chedin et al. (1985), Goldberg et al. (1985), Lipton and Vonder Haar (1985, 1987), Lipton et al. (1986), and McMillin (1986, 1988). In addition, there are legions of studies in which the space–time resolving power of given retrieval systems is discussed in the context of more general goals. We call attention to work in which the validity of horizontal structures of retrieved fields is assessed in comparison with structures of conventional data fields, such as in Togstad and Horn (1974), Phillips et al. (1979), Schlatter (1981), Gruber and Watkins (1982), Koehler et al. (1983), Fuelberg and Meyer (1986), Koehler et al. (1987), Phillips et al. (1988), Reuter et al. (1988), Le Marshall (1988), and Chesters et al. (1988).

The present study is somewhere between the first and second category above: the specific focus is to study the interconnection between vertical resolving power and horizontal or temporal resolving power of satellite retrievals. While the results will relate to a specific atmospheric scenario of space–time structures, the general concept of the interconnection is relevant to a wide variety of applications of satellite soundings to meteorological problems. We will show that increased horizontal and temporal resolving power of a satellite sounder does not follow simply from decreasing the field of view, or increasing the sampling frequency. Rather, horizontal and temporal resolving power are subject to strong controls imposed by the vertical re-
solving power. We will further show that the resolution of retrievals derives only partly from the structure of the radiance measurements, and often significantly from the resolution of a priori information. Finally, we will show a provocative example in which too much vertical finestructure in a first-guess field evidently distorts and degrades horizontal resolving power.

2. Illustration of low horizontal resolving power of a high resolution satellite sounding system

In this section we present a hypothetical case of sounding an atmospheric thermal cross-section by satellite that will directly illustrate a problem in the coupling of horizontal and vertical resolution. This example will be done in a forward mode of calculation, rather than an inverse mode, leading to results not dependent on a particular retrieval algorithm. The results shown in this section reflect the ill-posed nature of the sounding problem and are two-dimensional extensions of previous work (Thompson et al. 1986).

Figure 1 shows a temperature cross-section that may be considered representative of a real atmospheric state. This cross section was produced by interpolating a set of RAOBs taken at Midland, Texas; Abilene, Texas; Fort Worth, Texas; Shreveport, Louisiana; Jackson, Mississippi; and Montgomery, Alabama to a uniform grid cross section with 100 vertical levels equally spaced in increments of $p^{2/7}$ between 1000 and 0.01 mb, and with 10 horizontal locations equally spaced at 200 km. Let us consider the resulting interpolated data at the $100 \times 10$ grid cross section to be a reasonably accurate representation of a real atmospheric cross section. Figure 2 shows a second spatial cross section of temperature data for the same grid, which was mathematically contrived by the authors. The two temperature cross sections in Figs. 1 and 2 have the following property: If $I(v_i, x)$ represents upwelling spectral radiance at frequency $v_i$, and at location $x$, which is related to temperature, $T(x, z)$, by the radiative transfer equation

$$I(v_i, x) = B[v_i, T(x, 0)]\tau(v_i, 0)$$

$$+ \int_0^{z_t} B[v_i, T(x, z)]\left[\frac{\partial \tau(v_i, z)}{\partial z}\right]dz, \quad (1)$$

where $B$ is the Planck function, $\tau$ is spectral transmittance, $z$ is some vertical coordinate of choice ranging from the surface to the "top" of the atmosphere, and if $\tau(v_i, z)$ are specified to correspond to an 11 channel sounding radiometer comprised of 4.3 $\mu$ and 15 $\mu$ HIRS-like channels as specified in Table 1, then

$$\max_{i,j} \left|\frac{I_1(v_i, x_j) - I_2(v_i, x_j)}{I_1(v_i, x_j)}\right| \leq 1%. \quad (2)$$

Here radiances are calculated using temperature profiles at each grid point and interpreted as though the instrument field of view were arbitrarily small, where $i, j$ run over 11 spectral frequencies and 10 horizontal locations, respectively, and subscripts 1 and 2 denote upwelling radiances defined by Eq. (1) for cross sections $T_1(x, z)$ and $T_2(x, z)$ defined by Figs. 1 and 2, respectively. The significance of inequality (2) is that the two cross-sections in Figs. 1 and 2 produce radiances in every instrument channel and at every horizontal
location that are within 1% of each other. We may therefore say that the two temperature cross sections in Figs. 1 and 2 are indistinguishable by the HIRS-like radiometer to within 1%. This is true of the upwelling radiance field and does not depend on any mathematical algorithm that one might apply to retrieve temperature information from the radiance information. Presumably, if some temperature retrieval algorithm were to "resolve" the differences between these two cross sections, the resolving power would be attributable to external information not involving the measured radiances, such as the first-guess field.

Figure 3 shows a cross section of the difference between the thermal structures in Figs. 1 and 2. The difference field is comprised of relatively short wavelength signals in both vertical and horizontal directions, but the reader should note that the horizontal scale of variation is distinguishably longer than the spacing between horizontal observing grid locations. Thus, in the evaluation of inequality (2), there is grid sampling in the horizontal direction every 200 km but no horizontal averaging of any quantity in deriving radiances. The inability of the instrument to resolve such vertical structure has been discussed by Thompson (1985) and Thompson et al. (1986) as a manifestation of the ill-posed nature of the problem, but one now sees that signals in the horizontal direction with scale spanning three observation sites could also disappear even in the forward problem. The amplitudes of these disappearing signals involve temperature variations as large as 16 K over three horizontal grid points.

The example shown here, even though it has been mathematically contrived, demonstrates that the horizontal resolving power of a satellite sounding radiometer may be significantly less than that defined by its optical field of view and sampling geometry. This loss of horizontal resolving power is related to the widely acknowledged limitations in vertical resolving power of such satellite-borne radiometers, as will be explained in the sections to follow.

3. Vertical and horizontal resolution of satellite retrievals of an atmospheric cross-section

In this section we will examine a case study of satellite retrievals of an atmospheric temperature cross-section to study the loss of horizontal structure information in the process. We will show that the inverse step by which satellite radiances are used to estimate atmospheric temperature may introduce further, and quite serious degradations in horizontal resolution. The strategy of this section is 1) to consider Fig. 1, which has been defined from RAOb's to be the "ground truth" version of an atmospheric thermal cross section; 2) to retrieve temperature profiles along the cross section at 200 km intervals using the 11 channel HIRS-like

Fig. 3. Cross section of the differences between thermal fields in Figs. 1 and 2.
sounder—Eq. (1) to synthesize upwelling radiances, and some particular retrieval algorithm to estimate temperature profiles; 3) to compare Fourier decompositions of true and retrieved cross-sections to determine losses of resolution in vertical and horizontal directions and their interrelationship.

Atmospheric transmittances for the spectral channel centers listed in Table 1 were made available to us by the NASA/GSFC Laboratory for Atmospheres. There are a variety of retrieval methods that could be used in this study. Retrieval algorithms vary along a spectrum from highly statistical [e.g., the regression method of Smith et al. (1970), the empirical structure function method of Smith and Woolf (1976), the analog method of Thompson et al. (1985)] to highly physical [e.g., the methods of Chahine (1970, 1974) and Smith (1970), the minimum information method of Foster (1961) or Smith et al. (1972), the minimum resolving length method of Conrath (1972)], with methods mixing statistics and physics lying in between [e.g., Strand and Westwater (1968); Rodgers (1970); Suskind et al. (1984)]. The present study focuses on the resolving power of satellite measurements with a minimum of a priori information added. Thus, we chose a retrieval algorithm close to the "physical" side of the spectrum, namely the iterative method of Smith (1970) but as modified by Smith and Woolf (1981) and using only a single, first-guess profile as a priori thermal information. In our implementation the cross-sectional mean vertical profile of temperature is used as a first guess and is the only a priori thermal information used. The Smith–Woolf algorithm also requires a priori information on radiometer noise tolerances. We used the values shown in Table 1 for each of the horizontal sounding sites, which correspond to 1% of the radiance of each channel at each sounding site, as calculated from the interpolated RAOB data. Iterations of the retrieval algorithm are continued until either the radiances computed from the retrieval iteration converge to the synthesized measurements, to within specified tolerance limits, or until the root mean square error (from 10–1000 mb) between retrieval iteration and actual profile ceases to decrease (a criterion that cannot be implemented in practice, but that produces a retrieval for every case in this study). We should point out that we do not consider this application of the Smith–Woolf algorithm to be a fair test of its use in practice because we are using less a priori information than one might have available, and are not "conditioning" the solutions with other near-time, near-space data as one might do in a data assimilation system. On the other hand, we believe this implementation gives a fair measure of the information that can be derived from satellite radiances with only limited a priori information added. To avoid degradation of results attributable to radiometer measurement errors, radiances are calculated from (1) with no random errors added. Although such perfect measurements are synthesized and used in this study, we retain measurement noise factors in the retrieval algorithm in order to better simulate the manner in which the algorithm might be used in practice. We make no attempt to "tune" the algorithm to such error-free measurements, but we do wish to eliminate measurement errors as a source of degradation of vertical resolution of resulting retrievals. By this approach, we hope to limit the causes of resolution degradation in this study to the influences of overlapping weighting functions, effects of first guess field, and the inherent nature of the retrieval algorithm. It is expected that radiometer measurement errors would degrade the results from those to be reported here, and that noise factors used in the retrieval algorithm would affect its convergence, accuracy, and resolution characteristics. When proper tuning of retrieval algorithm to measurement error levels is done, one would expect an improvement in vertical and horizontal resolving power to accompany improvement in system noise level, as indicated by the work of Togstad and Horn (1974).

Figure 4 shows the cross section of retrieved temperatures obtained from the procedure described above. The overall root mean square retrieval error, between 10–1000 mb and over 10 horizontal sounding sites is 2.76 K.

To analyze the horizontal and vertical resolutions of retrievals in Fig. 4 relative to the correct field in Fig. 1, the two cross sections were decomposed into two-dimensional Fourier series, with appropriate two-dimensional mean values subtracted beforehand. The

![Figure 4](image_url)

**Fig. 4.** A retrieval, $\tilde{T}(x, z)$, of temperature cross-section using satellite radiances synthesized from the thermal field, $T(x, z)$, in Fig. 1, and a modified physical retrieval algorithm after Smith and Woolf (1981).
decomposition and subsequent analysis is done only for the layer between 10–1000 mb (only 79 levels in the vertical coordinate). The choice of Fourier series was made so that interpretation in terms of length scales could easily be made. Thus, the temperature cross-section in Fig. 1 is decomposed into harmonics of the form:

\[
T(x, z) - \overline{T} = \sum_{m,n} [C_{\text{se}}(m, n) \sin(m\pi x/L) \sin(n\pi z/H) \nonumber \\
+ C_{\text{sc}}(m, n) \sin(m\pi x/L) \cos(n\pi z/H) \nonumber \\
+ C_{\text{cs}}(m, n) \cos(m\pi x/L) \sin(n\pi z/H) \nonumber \\
+ C_{\text{cc}}(m, n) \cos(m\pi x/L) \cos(n\pi z/H)]
\]

where \(\overline{T}\) is the cross-sectional mean of \(T(x, z)\) (between 10 and 1000 mb), \(L = 2000\) km, \(H = 79\) levels (10–1000 mb). The cross-section of retrievals, \(\overline{T}(x, z)\), represented in Fig. 4 has a decomposition similar to (3), but with coefficients \(\hat{C}_{\text{se}}, \hat{C}_{\text{sc}}, \hat{C}_{\text{cs}},\) and \(\hat{C}_{\text{cc}}\).

The first hint of difficulty with horizontal and vertical resolution of retrievals may be noticed by inspecting the ratios of corresponding expansion coefficients, \((\hat{C}_{\text{se}}(m, n)/C_{\text{sc}}(m, n), \text{ etc.})\). If the retrievals were perfect, the two Fourier decompositions would be identical and all such ratios would be unity. Instead, Fig. 5 shows such ratios for the longest scaled harmonics (harmonics 1–7 in the vertical coupled to harmonics 1–6 in the horizontal). In Fig. 5, contour lines are drawn to help organize the eye even though coefficients are discrete functions of parameters \(m\) and \(n\). For the largest horizontal harmonic, \(m = 1\), the various ratios are not too different from unity over the first 7 vertical harmonics; however, for the shorter horizontal harmonics, serious distortions occur in the retrievals. Some ratios may be seen to be near zero, indicating a damping of the true harmonic. Others are seen to be significantly greater than unity, indicating an apparent amplification of the

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**Fig. 5.** Ratios of corresponding Fourier expansion coefficients following Fourier decompositions of the cross-sectional thermal fields, \(T(x, z)\) and \(\overline{T}(x, z)\), in Figs. 1 and 4.
harmonic. Still others are significantly negative, indicating serious phase shifting of the harmonic during the retrieval process. An inspection of the coefficient ratios (as in Fig. 5) is provocative but tends to be too complex owing to the superposition of so many individual harmonics to produce a final retrieval field. We may alternatively look at the resolution problem in a manner involving that very superposition. Let $T(x, z, M, N)$ represent the partial Fourier reconstruction of a field $T(x, z)$ obtained by summing up all harmonics up to and including the $M$th horizontal and $N$th vertical harmonics. We may thus calculate partial Fourier reconstructions of the actual field, $T(x, z)$, and the retrieved field, $\hat{T}(x, z)$. Now, define $R(M, N)$ as the two-dimensional, root mean square difference between $T(x, z)$ and $\hat{T}(x, z, M, N)$. Further, define $\hat{R}(M, N)$ as the two-dimensional root mean square difference between the true field, $T(x, z)$, and the partial Fourier reconstruction of the retrieved field, $\hat{T}(x, z, M, N)$. The functions $R(M, N)$ and $\hat{R}(M, N)$ are shown in Fig. 6 as solid and dashed curves, respectively. There are several important features of the solid curves. The $R(M, N)$ shows an expected monotonic decrease whenever $M$ or $N$ is increased, and reaches the value 0 when all vertical and horizontal harmonics are included: $R(6, 39) = 0$. When all vertical scales are included ($N = 39$), the corresponding curve exhibits significant slope over the entire range of $M$ values, indicating that there is significant horizontal resolving power in the RAOB system over all represented scales. For fewer than all vertical harmonics ($N < 39$), $R$ approaches a value greater than zero, even for $M = 6$, as would be expected for a truncated representation of the vertical structure. Furthermore, the solid curves become increasingly flat as $N$ decreases from its maximum value. That is, the truncation of the vertical set of harmonics has the effect of reducing the slope of the curves with respect to $M$, which is a loss of horizontal resolution (of the RAOB analysis) since adding horizontal harmonics in these flattened regions adds very little real information. This means that even in a radiosonde observing system, a degradation of horizontal resolving power accompanies a reduction of vertical resolving power (following truncation of the vertical wave spectrum or, say, by layer averaging). For example, for $N = 8$, the horizontal resolving power of the vertically truncated RAOB information is limited to about $M = 3$ since very little additional information resides in shorter horizontal scales for this case.

An anonymous reviewer raised the interesting question of whether one could define an effective vertical resolving length of a RAOB network based on its fixed, horizontal spacing. One can imagine a global “network” consisting of a single RAOB site in which one cannot resolve any horizontal scales no matter how fine the vertical resolution of a sounding may be. It follows that a coarse RAOB network would be unable to objectively resolve certain horizontal scales, based on its grid spacing, no matter how fine the vertical resolution unless one had definitive, a priori information about the multidimensional scale spectrum of the atmosphere. Thus, we believe that the most useful answer to the question would be more empirical than theoretical. For the structure represented in this case study, the spacing between solid curves in Fig. 6 suggests that all vertical scales in the RAOB data contribute to improving the accurate resolution of each horizontal scale. But it is clear that the shorter vertical scales ($N > 32$) have a more profound influence on resolving the shortest horizontal scales (say, $M = 6$) than on resolving the longest ($M = 1$). The rather flat nature of all solid curves for $M > 3$ and $N < 32$ suggest further that the shorter horizontal scales can only be adequately resolved by data which include the shorter vertical scales.

Satellite temperature sounding systems incorporate vertical integrations and smoothing of vertical thermal structure information, which is manifested in loss of vertical resolution. An associated loss of horizontal resolution is apparent in the dashed curves of Fig. 6, which are somewhat analogous to the effects of truncating vertical harmonics in the RAOB data. Including all vertical and horizontal harmonics in the retrieval still leaves a residual retrieval error of 2.76 K. The loss of vertical resolution is apparent from the fact that the total information content of the retrievals, (i.e., $\hat{R}$ for $M = 6$ and $N = 39$), is only about as much as the information contained in the first 19 vertical harmonics.
of the RAOB data, (i.e., $R$ for $M = 6$, $N = 19$). The substantial loss of horizontal resolving power of the satellite soundings is apparent in the much flatter slope of all the dashed curves for $M \geq 3$. No matter how many vertical harmonics are included, little additional information is obtained about the spectrum of these shorter horizontal wavelengths (even though improvement in the representation of longer horizontal wavelengths decreases the overall retrieval error). The dips in the dashed curves in Fig. 6 reveal that, for a given value of $N$, the variation of error of the retrieval does not monotonically decrease with increasing $M$, as one might expect. Rather, retrieval error would be minimized in this experiment by using only two horizontal harmonics, since the inclusion of more than two degrades the results and apparently adds no useful or realistic information about the shorter horizontal scales.

The existence of the local minima at $M = 2$ in the spectra of retrieval errors raises an interesting issue. We interpret these minima as apparent distortions of the horizontal spectra of retrieval errors. The local minima at $M = 2$ are associated with crossover of the corresponding RAOB and retrieval curves. Thus, for $M = 1$, all retrieval spectra exhibit smaller, unresolved rms differences than corresponding RAOB spectra while for $M \geq 3$, the opposite (and more expected) result is true. We believe that this result is due to the existence of vertical scale structure in the first guess field which is finer than what may be justified for its use as first guess profile at all horizontal grids. That is, certain fine scale structure in the first guess profile cannot possibly relate to radiatively resolvable horizontal structures, and so act to distort the structure spectrum. To test this hypothesis, the retrieval experiments and Fourier analyses were repeated using a vertically smoothed first guess field. Figure 7 shows the vertical profile (solid curve) used for all retrievals analyzed in Fig. 6, while the dashed curve shows a vertically smoothed version of the solid curve. (This smoothing was accomplished by computing a vertically running mean over 8 vertical grid intervals.) Presenting the smoothed first guess field to the retrieval algorithm led to the analysis shown in Fig. 8. Comparing Figs. 8 and 6, one can see that while the asymptotic values ($M \rightarrow 6$) are not much different, the horizontal spectra of errors at low values of $M$ are substantially changed when the smoothed first guess field is used. While the partial sum differences for $M = 1, 2$ are worse, using the smooth first guess field, the shape of the horizontal spectra of retrieval errors in Fig. 8 is more representative of the shape of corresponding RAOB spectra than in Fig. 6 using the unsmoothed first guess field. This result is ironic for it suggests that too much fine scale structure in the first guess field can distort the retrieval representation of horizontal gradients in the thermal field. It is important to emphasize, however, that this result occurs in a retrieval system in which the same first guess field is used at each horizontal grid location. No a priori information on horizontal structure enters into these calculations.

Fig. 7. A priori first guess temperature profile for the retrieval field in Fig. 4, and a vertically smoothed version of the same profile.

Fig. 8. Two-dimensional Fourier structure spectra of the temperature cross section in Fig. 1 (solid curves), and of a retrieval of that cross section using the smoothed first guess field in Fig. 7 (dashed curves).
Notice in Figs. 6 and 8 that there is no apparent scale limitation to accuracy imposed by the number of vertical harmonics included. For each $M$, there is a monotonic decrease of $\bar{R}$ with increasing $N$. This is most likely due to the fact that the a priori information that is introduced to the retrieval algorithm is a vertical profile of temperature that, even though averaged over horizontal direction, still possesses a rather rich spectrum of information along the vertical derived from RAOBs. Since no a priori information on the horizontal structure is presented to the retrieval algorithm, the horizontal resolving power of the satellite sounding system becomes solely a function of horizontal resolving power of the radiance information. Section 2 has shown that this is limited by the ill-posed nature of the problem, and the integral smoothing of thermal information which produces radiance. The results of both sections 2 and 3 show that the horizontal resolving power of satellite measured radiances may be significantly less than the resolving power of the scanning optics of a radiometer, and intimately related to the vertical resolving power of the system. Thus, the vertical and horizontal resolution of atmospheric thermal structure by satellite radiometric sounders is largely a matter of knowing a lot of the structure beforehand.

4. Theoretical insight into the coupling of horizontal and vertical resolving power

Conrath (1972), using methods discussed by Backus and Gilbert (1968), presented a theoretical analysis of vertical resolving power of satellite sounders based on integral equations of radiative transfer, and linear equations of temperature retrieval. Using notation similar to Conrath, we may extend that analysis to two spatial dimensions to consider some simple aspects of the horizontal resolution problem.

If $t(x, z)$ is the difference between an ambient temperature field, $T(x, z)$, and a known basic state, $T^*(x, z)$, close to $T(x, z)$, and if $g(v_i, x)$ is the difference between spectral radiances upwelling at location $x$, from $T(x, z)$ and $T^*(x, z)$, then the radiative transfer Eq. (1) may be linearized around the basic state to obtain

$$g(v_i, x) = \int_0^z K(v_i, z') t(x, z') dz',$$

where $K(v_i, z)$ are known radiative transfer kernels appropriate to the spectral intervals of the radiometer and the prescribed basic state of the thermal field. If a vertical temperature profile retrieval algorithm can be expressed in the linear form,

$$\hat{t}(x, z) = \sum_i a_i(z) g(v_i, x),$$

where $a_i(x)$ are profile retrieval coefficients known from some retrieval theory, and where (5) is applied at each horizontal location, $x$, then Conrath’s analysis allows one to write the following relationship between retrieval estimate, $\hat{t}(x, z)$, and actual ambient $t(x, z)$:

$$\hat{t}(x, z) = \int_0^z A(z, z') t(x, z') dz'$$

where $A(z, z')$ is Conrath’s averaging kernel

$$A(z, z') = \sum_i a_i(z) K(v_i, z').$$

Now suppose that the ambient field of temperature can be expressed as an expansion of known horizontal and vertical structure functions,

$$t(x, z) = \sum_{m,n} C_{mn} \varphi_m(x) \psi_n(z).$$

Equations (8) and (6) imply that the satellite retrieved estimate of the temperature field would be expressible as

$$\hat{t}(x, z) = \sum_{m,n} C_{mn} \varphi_m(x) \hat{\psi}_n(z)$$

where

$$\hat{\psi}_n(z) = \int_0^z A(z, z') \psi_n(z') dz'.$$

The functions $\psi_n(z)$ and $\hat{\psi}_n(z)$ are clearly different functions of height that have been distorted by the integral transform (10). Furthermore, transform (10) depends on vertical wavenumber, $n$, and the distortion introduced by the transform may be quite different for different values of $n$. The functions $\psi_n(z)$ and $\hat{\psi}_n(z)$ represent expansion “coefficients” for the horizontal structure of temperature at every level, $z$, or over every layer $(z_1, z_2)$ over which equations might be averaged. Thus, the loss of vertical resolution embodied in the integral transform (6) also distorts the horizontal structure representation and degrades horizontal resolution as well. The horizontal resolving power of a satellite temperature sounding system is therefore coupled to its vertical resolving power through the radiative transfer equation and the temperature retrieval algorithm. This type of coupling is independent of the horizontal sampling geometry of the instrument and cannot apparently be improved by improvements on that geometry.

5. Temporal resolving power of a satellite temperature sounding system

Conclusions drawn in the previous sections regarding horizontal resolving power can also be applied to resolution in time, since the variable, $x$, in all the previous discussions could have represented time rather than horizontal distance. Thus, we can state that temporal resolving power of a satellite temperature sounding system is also limited by its inherent vertical resolving power. This hypothesis appears, at first glance, to be
utterly outrageous for one certainly has the right to hope that successive and frequent soundings in time will provide temporal resolution and coherence controlled strictly by sampling frequency. However, it is not difficult to understand that thermal signals that produce no radiance signals at satellite altitude could certainly not be tracked or resolved over time since they could not be detected at all. Following the reasoning given in this paper, thermal signals that are detectable by satellite, but that are highly distorted by the retrieval system may be tracked over time in a manner quite unrepresentative of the evolution of the true atmospheric processes under way.

6. Conclusions

In this paper, we have considered the interplay between vertical, horizontal, and temporal resolving power of a satellite temperature sounding system. The focus has been to examine the ability of a sounding system to retrieve horizontal temperature structure without any a priori information about what that structure may be. It is understood that better, more practical results can be obtained by adding representative a priori or contemporary information on horizontal structure to the analysis, when such is available. It is, however, important to understand that a good deal of the structural information of the result is information added by other observing systems or computing models that are not related to the satellite data.

It has been demonstrated that certain horizontal structure information, of significant amplitude and having scale greater than the scanning grid interval, may nevertheless be indistinguishable to a satellite radiometer even before one attempts to apply a temperature retrieval algorithm. It has been further demonstrated that a retrieval algorithm may produce a highly distorted depiction of horizontal (or temporal) variations due principally to poor vertical resolving power of the retrieval system. These results, which were drawn from synthesized calculations of radiance and retrieved temperatures, were rationalized by a straightforward theoretical analysis of the problem. This analysis shows that distortions in estimating vertical structure directly affect estimates of the amplitudes of horizontal structures contained in a complex thermal field.

The general implication of these results is to recognize that high fidelity temperature retrievals owe a good deal of their fidelity to a priori or additional information not contained in the radiance measurements. It is widely appreciated that this is true of the vertical structure information in temperature retrievals, and it is established here that it is just as true of horizontal structure information as well. Improvements in horizontal resolving power of the satellite radiance data must come from improvements of the "vertical resolution" of the radiance data; number and width of spectral weighting functions. Attempting to improve the vertical resolution of temperature retrievals by, say, the addition of finer scale a priori information about the ambient vertical profile will not cause a corresponding improvement in horizontal resolution of the retrievals. In fact, we have given evidence that using too much fine scale information in the first guess profile may actually degrade the representation of the horizontal structure spectrum. To improve horizontal resolution in this way requires good a priori information on the horizontal structure itself.

Conclusions drawn in this paper are based on a rather limited set of calculations, and must be interpreted in relation to the specific spectrum of variation in the thermal field used for calculations. Obviously, each sample of data would possess its own spectrum, not necessarily similar to that used here. If the concepts of these conclusions withstand further scrutiny, then one must move forward to a new set of questions. For example, there should be research leading to a more definitive, scale-specific understanding of the two-, three-, and four-dimensional resolution limits of a satellite sounder. There should be research leading to a better understanding of the relative contributions of satellite measurements, and external information, to the resolution of horizontal and temporal variations in the thermal field. Even though four-dimensional data assimilation techniques help circumvent some of these limitations in practice, research should continue concerning the optimal types, treatments, and placements of information in the retrieval and assimilation processes to produce the most faithful product possible. Research should proceed to construct multidimensionally optimized retrieval algorithms so that the horizontal, vertical, and temporal structure of the thermal field can be sought in a coherent manner that makes the most use of the multidimensional structures inherent in the radiation measurements. Finally, the coupled limitations of vertical, horizontal, and temporal resolution of satellite soundings should be recognized, and steps taken to improve system resolving power, beginning with higher spectral resolution instruments.

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