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An improved interpretation of VHF oblique radar echoes by a direct balloon C_n^2 estimation using a horizontal pair of sensors

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Abstract. Successful comparisons between VHF oblique (15°) radar echo profiles and reconstructed ones deduced from high-resolution temperature balloon measurements were presented by *Luce et al.* [1996]. The method was based on the evaluation of the three-dimensional isotropic refractive index spectrum at the Bragg wavelength from the available temperature profiles ("spectral method"). However, the isotropic hypothesis is questionable, especially in regions where temperature sheets [*Dalaudier et al.*, 1994] are observed. Indeed, the associated anisotropic temperature fluctuations should contribute to the one-dimensional vertical temperature spectrum at small scales. In the present paper, another method, less sensitive to anisotropic contaminations, is used. This method is based on an estimation of the temperature structure constant C_T^2 from variances of horizontal differences of temperature measured by two high-resolution sensors 1 m apart horizontally ("horizontal variance method"). It is shown that the main differences between the C_T^2 estimations obtained from the two methods are mainly observed at high resolution in stable regions where few turbulent fluctuations in the temperature field are observed. However, the two methods give approximately equivalent results at the radar range resolution (600 m) and the quality of the comparisons with the radar observations is slightly improved with the horizontal variance method. In order to demonstrate the full advantages of this technique, the use of radars with more powerful capabilities is suggested for future investigations.

1. Generalities

In a recent work by *Luce et al.* [1996], a new experimental investigation of the origin of VHF oblique radar echoes was presented. It was based on a reconstruction of the radar profile using balloon measurements and a spectral method in the frame of the isotropic hypothesis. This spectral method consists in evaluating the radar Bragg component of the three-dimensional (3-D) isotropic refractive index spectrum from an estimation of the vertical one-dimensional (1-D) temperature spectrum deduced from high-resolution balloon measurements. The radar and balloon measurements used for the comparisons were obtained during the RASCIBA90 (radars, scidar, balloons) campaign described by *Dalaudier et al.* [1994] and *Luce et al.* [1995, 1996]. It was shown that this model is sufficient in order to reproduce the shape, the dynamic range, and the level of the radar profiles for most of the oblique radar measurements. However, if the assumptions are sufficient for the model to be efficient, the results of the comparisons do not prove that the isotropic hypothesis is really consistent. Indeed, the method considers that all the components of the 3-D spectrum contributing to the 1-D spectrum are isotropic on scales smaller than 10 m [*Luce et al.*, 1996]. This hypothesis is only acceptable in stratospheric and tropospheric turbulent layers for which a transition scale between isotropic and anisotropic turbulence could be larger than 10 m. However, anisotropic structures exist at smaller scales like the atmospheric temperature sheets, identified by *Dalaudier et al.* [1994], with very strong temperature gradients of

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a few meters thickness. They are probably the most anisotropic structures at these scales. While these structures have a negligible contribution to the radar echoes in oblique incidence because most of the signal is reflected in the specular direction, they may contribute to the balloon vertical 1-D temperature spectrum level in the small-scale range. The importance of a possible contamination by these structures cannot be estimated from 1-D measurements because such an investigation needs the knowledge of the 3-D properties of the temperature fluctuation field. The direct comparison between refractive index spectra from balloon and radar measurements [*Luce et al.*, 1996] may then be biased by small-scale anisotropic effects in the 1-D vertical spectrum. However, because the experimental levels were fairly well reproduced at all altitudes, it was suggested that the contamination should have been usually weak. This affirmation can now be checked by using another technique which can reduce the possible contribution of the most anisotropic structures. The purpose of this paper is then to compare oblique radar profiles with reconstructed ones from in situ measurements by using an alternate method also based on the isotropic model but less sensitive to anisotropic contaminations. This method is based on the direct evaluation of the temperature structure constant C_T^2 from estimations of variances of horizontal differences of temperature measured by two high-resolution sensors 1 m apart horizontally [*Dalaudier et al.*, 1994]. Previous studies using in situ measurements [e.g., *Van Zandt et al.*, 1978] based the C_T^2 estimations on the local vertical gradient of the generalized potential refractive index M and the outer scale of turbulence L_0. The use of these parameters is not needed in the present approach since variance estimations can be performed directly in the scale domain where the VHF radar is sensitive. The technique of C_T^2 estimation from temperature difference measurements was used by *Barletti et al.* [1977], or *Gossard et al.* [1985], for example, and will be extensively analyzed in a future paper. It can be easily understood that the C_T^2 estimated by the method applied in this paper (referred to hereinafter as the "horizontal variance method") is necessarily less biased by the possible contribution of the anisotropic fluctuations than the C_T^2 estimated by the spectral method (which uses variances of vertical temperature profiles). Indeed, since the anisotropic fluctuations are mainly horizontally stratified, the horizontal temperature difference will exclude most of their associated variance, while the isotropic fluctuations will be relatively unaffected. The present paper also takes into account a variance correction compensating the effects of the various filterings necessary for the estimations. This correction was overlooked in previous studies.

2. Vertical C_n^2 Profiles Deduced From Radar and Balloon Measurements

2.1. C_n^2 Estimations From Radar Measurements

The VHF stratosphere-troposphere (ST) radars are sensitive to the 3-D spectrum of refractive index fluctuations [*Tatarski*, 1961] convolved with a spectral sampling function [*Doviak and Zrnic'*, 1984]. Experimental evidences [e.g., *Tsuda et al.* 1986] show that VHF radar performing oblique measurements are sensitive to a region of the 3-D spectral space which can be described as the 3-D spectrum associated with isotropic turbulence in the inertial subrange characterized by the structure constant C_n^2. Measurements of VHF radar oblique reflectivities are thus commonly presented as C_n^2 profiles. Radar C_n^2 profiles are estimated from signal-to-noise ratio profiles in oblique incidence (15°) by using the classical radar equation [i.e., *Röttger and Liu*, 1978; *Green et al.*, 1979] with the same conditions as given by *Luce et al.* [1996]. Radar C_n^2 profiles with a 6.5-min time resolution and synchronous with the four balloon ascents described by *Dalaudier et al.* [1994] are compared with the reconstructed profiles from in situ measurements in section 3.

2.2. C_n^2 Estimations From Balloon Measurements With the Horizontal Variance Method

Theoretical estimations. The temperature structure constant C_T^2 can be theoretically deduced from the estimation of the variance of temperature difference at a selected scale Δr (i.e. the temperature structure function $D_T(\Delta r)$), with the hypothesis of isotropic turbulence in the inertial subrange by using the classical relation [*Tatarski*, 1961, expression 4.40]

$$D_T(\Delta r) = C_T^2 \mid \Delta r \mid^{2/3} \quad (1)$$

In the general case, the temperature structure function D_T is related to the 3-D temperature spectrum Φ_T by the expression [*Tatarski*, 1961, relation 1.41]

$$D_T(\overrightarrow{\Delta r}) = 2\iiint_{\Re^3} (1 - \cos\vec{k}.\overrightarrow{\Delta r})\Phi_T(\vec{k})d\vec{k}$$
$$= 2\iiint_{\Re^3} H_{\overrightarrow{\Delta r}}(\vec{k})\Phi_T(\vec{k})d\vec{k} \quad (2)$$

Using an approach similar to section 4 of *Doviak and Zrnic'* [1984], the 3-D spectrum Φ_T can be written as the sum of an isotropic and an anisotropic part $\Phi_T = \Phi_T^i + \Phi_T^a$. Oblique VHF radar echoes are assumed to be produced by the isotropic part Φ_T^i (see section 2.1). The linearity of relation (2) allows us to write the 3-D structure function as the sum of an isotropic and an anisotropic part $D_T = D_T^i + D_T^a$. Consequently, estimations of C_T^2 profiles based on in situ measurements of structure functions need to reduce D_T^a as much as possible, i.e., the spurious contribution of the anisotropic part of the 3-D spectrum. Since the variance of the observed anisotropic structures is mainly contained in wave vectors close to the vertical direction, the weighting function $H_{\overrightarrow{\Delta r}}(\vec{k})$ present in relation 2 will reject these contributions with maximal efficiency for sensor separation Δr in the horizontal plane.

Application to the available temperature measurements. Two high-resolution sensors, 1 m apart horizontally, thus allow us to give an estimation of the temperature structure function for a horizontal separation of 1 m $D_T(\Delta r = 1\text{ m})$. As measured with a magnetometer, the maximal tilt of the sensor pair with respect to the horizontal is 2° and is neglected here. The orientation of the sensors in the horizontal plane is not important since it is assumed that the fluctuations are horizontally isotropic. However, other geophysical, technical, and data processing constraints prevent a direct evaluation from (1) of the searched C_T^2 profiles.

Geophysical constraints: The temperature fluctuation field is homogeneous only locally and not at the radar resolution, because there is an alternation of nonturbulent regions and turbulent patches or layers on a few tens of meters [*Barat*, 1982]. Furthermore, this fluctuation field is not isotropic and inertial at all scales: (a) It is well known that the fluctuations at the largest scales are wave-like and are highly anisotropic. (b) Anisotropic fluctuations may also exist at smaller scales especially associated with the sheet structures [*Dalaudier et al.*, 1994].

Technical constraints: (a) The low-frequency drift of the sensors and electronic instrumentation has to be suppressed. (b) The temperature data sets are affected by the instrumental noise, especially at the small scales for which the spectral power level of the temperature fluctuations is weak. (c) The temperature sensors and acquisition system have a finite bandwidth.

Data processing constraint: A band-pass filtering using the fast Fourier transform (FFT) technique is applied in the treatment of the data set in order to take into account the geophysical and technical constraints described just above.

Because of these various reasons, the direct estimation of the C_T^2 parameter will be biased. These problems, which are out of the scope of the present paper and are mainly related to the treatment of in situ measurements, will be extensively developed in a coming paper, and only the results necessary for the present investigation will be used.

Inhomogeneity of the temperature field. In order to obtain, as far as possible, meaningful C_T^2 values, local estimations of D_T are needed. The length of vertical data sections used for the estimations was chosen at about 50 m. This 50-m value corresponds to a compromise between geophysical variability (inhomogeneity) and the applied data processing discussed below.

Minimization of the anisotropic component contributions of the 3-D spectrum. Two treatments of the data set were made in order to minimize the contribution of the anisotropic components of the temperature field in the C_T^2 estimations

In order to suppress the contribution of the most anisotropic fluctuations at the large scales (problem 1a), a high-pass filter with a 10-m cut-off for the vertical scale was systematically used, as for the spectral method [*Luce et al.*, 1996].

The 10-m cutoff is without effect on the contribution of the anisotropic structures smaller than 10 m, when they exist (problem 1b). As discussed in the generalities and in section 2.2, the contribution of these components is minimized when the vector $\overrightarrow{\Delta r}$ is contained in the horizontal plane, i.e., when the sensors of the balloon are horizontally separated. In this case, the weighting function $H_{\overrightarrow{\Delta r}}(\vec{k})$ in relation (2) presents a zero along the kz axis, corresponding to the maximum strength of the 3-D anisotropic spectrum. However, even if the use of horizontal differences gives maximal damping of anisotropic contributions, the estimated horizontal structure function is still an overestimation (hopefully small) of the searched C_T^2.

Suppression of the sensor and electronic instrumentation drifts. A linear tendency removal on the temperature difference data sets, corresponding to 50 m of data, is introduced in order to avoid leakage in the FFT estimations. It also allows us to suppress the slow drift of the intrumentation (problem 2a). The residual contaminations of the drift (if it exists) are eliminated by the high-pass filtering.

Suppression of the instrumental noise (problem 2b). The instrumental noise affects the 1-D measurement profiles. In order to suppress, as far as possible, the main contribution of this instrumental noise at small scales, a time low-pass filter with a cutoff corresponding to the 1-m scale is used. The limits of the filtering are then the same as for the spectral method [*Luce et al.*, 1996]. However, the instrumental noise which is assumed to be white affects all the frequencies with a constant spectral density. The measured variance of temperature difference in the (1,...,10 m) band $V_{Tm(1...10\,m)}$ is then corrected for the instrumental noise N_T to give a corrected variance $V_{Tc(1...10\,m)}$ by using

$$V_{Tc(1...10\,m)} = V_{Tm(1...10\,m)} - 2Var_{(1...10\,m)}(N_T) \quad (3)$$

where $Var_{(1...10\,m)}(N_T)$ is deduced from the observed variance in the band (0.4,...,1 m) for which temperature fluctuations are assumed to be negligible with respect to the noise. The 0.4-m value corresponds to the minimal (Nyquist) observed scale.

Variance correction due to filtering operations. If the filtering suppresses most of the unwanted contributions, it also introduces variance losses of the signal contained outside the (1,...,10 m) band. The estimated structure function is then biased because of the filtering (problems 2c and 3). A theoretical correction factor is then needed to compensate the loss of variances. This theoretical correction factor was computed for a purely isotropic inertial 3-D spectrum $\Phi_T^i(k)$ with a -11/3 slope at all scales. The use of this factor assumes that the recovered variances in the (1,...,10 m) band result from a 3-D isotropic and inertial subrange. It is obvious that this factor is a function of the limits of the filtering, of the distance between sensors, and of the orientation of the sensors with respect to the balloon trajectory. The corrections needed to compare C_T^2 estimations from structure function evaluations at various scales and at various orientations will be emphasized in a future paper. In the present case, i.e., when a vertical ascent of the balloon is supposed (in the Lagrangian sense), and a (1,...,10 m) filtering is used, the variance

$$D^i_{T_{(1...10\,m)}}(\Delta r) = 2\int_{k_z=2\pi/(10\,m)}^{2\pi/(1\,m)} \left(\int_{k_x}\int_{k_y} 2\,(1-\cos\vec{k}.\vec{\Delta r})\Phi_T^i(k)dk_x dk_y \right) dk_z \quad (4)$$

is estimated. The difference with the isotropic part of relation (2) is only in the finite integration limits for k_z. The fraction of the total variance $F(\Delta r) = D^i_{T_{(1...10\,m)}}(\Delta r)/D^i_T(\Delta r)$ was numerically calculated using a NAG library routine and is equal to 0.687 (68.7%) for horizontal pairs of sensors 1 m apart. The corrected $C^2_{T_c}$ values are then obtained by assuming that the estimated variance in (3) corresponds to the biased structure function (relation (4)) for the 1-m scale in the horizontal plane:

$$C^2_{T_c} = V_{Tc_{(1...10\,m)}}/F(\Delta r = 1\text{ m}) \quad (5)$$

Operations for comparisons with radar measurements. The conversion of C_T^2 in C_n^2, the smoothing of the reconstructed profiles at the radar resolution, as well as the humidity contribution estimation in the troposphere, are processed in the same manner as for the spectral method already described by *Luce et al.* [1996].

3. Comparisons Between the Reconstructed Profiles Obtained From the Two Methods

A comparison between estimated C_T^2 profiles obtained with the horizontal variance and spectral methods at a 50-m resolution will be first presented for a selected altitude range (Figure 1). This comparison is made in order to investigate the kinds of structures in the temperature fluctuation field at the origin of the differences and similarities between these two kinds of profiles. A comparison will then be presented between the two C_n^2 estimations smoothed at the 600-m radar resolution (Figure 2) in order to study the differences between the two kinds of profiles at this lower resolution.

3.1. Comparison Between C_T^2 Profiles Estimated From the Two Methods at a 50-m Resolution

A comparison between C_T^2 profiles estimated from the two methods at a 50-m resolution for a selected region between 12.3 and 15.3 km on February 19, 1990, is shown in Figure 1. In order to compare the two kinds

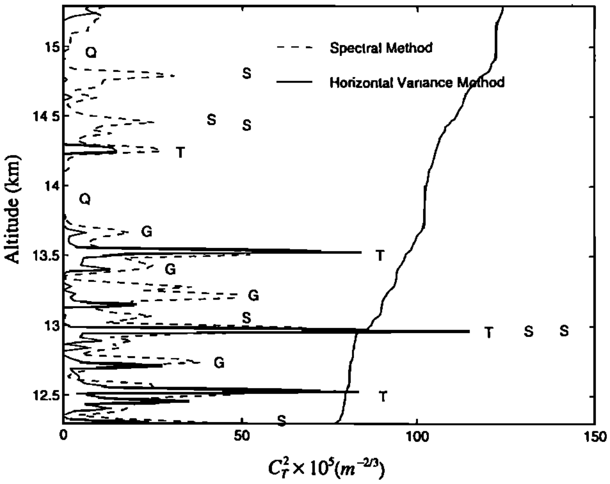

Figure 1. Comparison between the reconstructed C_T^2 profiles at a 50-m resolution for a selected region between 12.3 and 15.3 km on February 19, 1990. The reconstructed profiles deduced from the "spectral method" and the "horizontal variance method" are shown by dashed and solid lines respectively. At the right side of the figure, the potential temperature profile (300-400 K) is given. The sheet position is indicated by "S," the other strong gradients by "G," the strong turbulent layers by "T," and the quiet regions by "Q." Figure 1 is an enlargement of the dashed region in Figure 2.

of profiles, the estimated $\Phi_T(k)$ profile at the Bragg radar converted in terms of C_T^2 by using the classical relation (4.44) given by *Tatarski* [1961] valid for isotropic turbulence in the inertial subrange. This altitude range is presented because various structures are observed in the temperature profile: The position of the temperature sheets "S" (selected following the criterion of *Dalaudier et al.* [1994]), other stable gradients "G," turbulent layers (with strong overturning) "T," and quiet regions (with quasi-adiabatic gradient) "Q" are indicated on the figure, as deduced from high-resolution temperature measurements.

When the spectral method is used, the C_T^2 is overestimated in stable regions around 14.4 and 14.75 km where temperature sheets are observed. Other overestimations are also noted in stable regions at 12.75, 13.25, 13.45, and 13.6 km. On the other hand, both estimations are of the same order in turbulent regions at 12.55, 12.95, and 13.55 km, even when such layers can be associated with temperature gradients at 12.95 or 13.55 km. The very small estimations around 14 and 15 km are associated with a quasi-adiabatic zone.

This comparison showed that the main differences between the two estimations are produced in (statically) stable regions where few turbulent fluctuations on temperature profiles are observed. These differences reveal anisotropic contaminations in the 1-D vertical spectrum at a few meter scales. The C_n^2 parameter will then be biased (overestimated) in these regions when the spectral method (based on the 1-D vertical temperature spectrum estimation) is used. These results confirm that the horizontal variance method, which needs one pair of sensors in the horizontal plane, gives a weaker and probably more realistic estimation of the C_n^2 parameter than the spectral method which uses only one sensor in a vertical ascent.

It can also be observed that the strongest C_T^2 values are obtained in turbulent regions, where the contamination by the vertical gradients is not important. Then, the strongest C_T^2 values are produced by the turbulent layers. On the other hand, the contamination by the sheets (at 14.5 and 14.75 km, for example) is weak (but not negligible at this resolution) with respect to the contribution of the turbulent layers.

3.2. Comparison Between C_n^2 Profiles Estimated From the Two Methods at Radar Resolution

The C_n^2 profiles estimated from the two methods and smoothed to match the radar radial resolution (600 m) are plotted in Figure 2. At this range resolution, the comparisons between the two profiles show a still better agreement than at the previous resolution. The shape and the dynamic range are very similar. The main differences in level appear in stable regions where few turbulent fluctuations are observed (from careful examination of the temperature profiles), in particular, in the lower stratosphere (around 15 km on February 19 and above 13 km on February 22, for example). In other regions, the contribution of the anisotropic components between 1 and 10 m is not significant. Consequently, at the radar resolution, the horizontal variance method (which uses one pair of sensors in the horizontal plane) gives results approximately equivalent to the spectral method (which uses one sensor in vertical ascent).

4. Comparisons Between the Radar C_n^2 Profiles and Reconstructed Ones Obtained With the "Horizontal Variance Method"

The C_n^2 profiles estimated from the horizontal variance method and smoothed at the radar resolution are plotted in Figure 3 with the radar C_n^2 profiles. Several radar profiles obtained during each balloon ascent are shown in order to illustrate experimentally the temporal variability of the estimated C_n^2 parameter. The detecta-

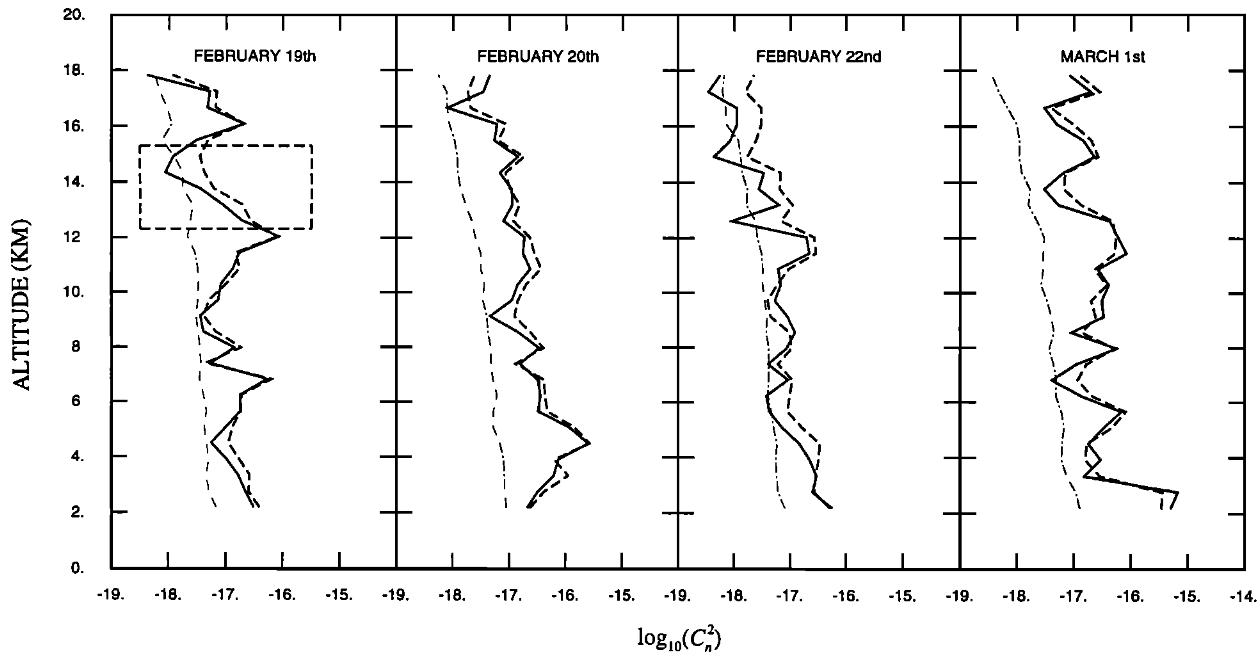

Figure 2. Vertical profiles, in logarithmic scales, of estimated C_n^2 deduced from the spectral and horizontal variance methods shown by dashed and solid lines respectively during the four balloon data sets at the radar range resolution (600 m). The noise level of the reconstructions is shown by a dash-dotted line. The humidity contribution is not introduced in the estimations. The dashed region is shown in Figure 1.

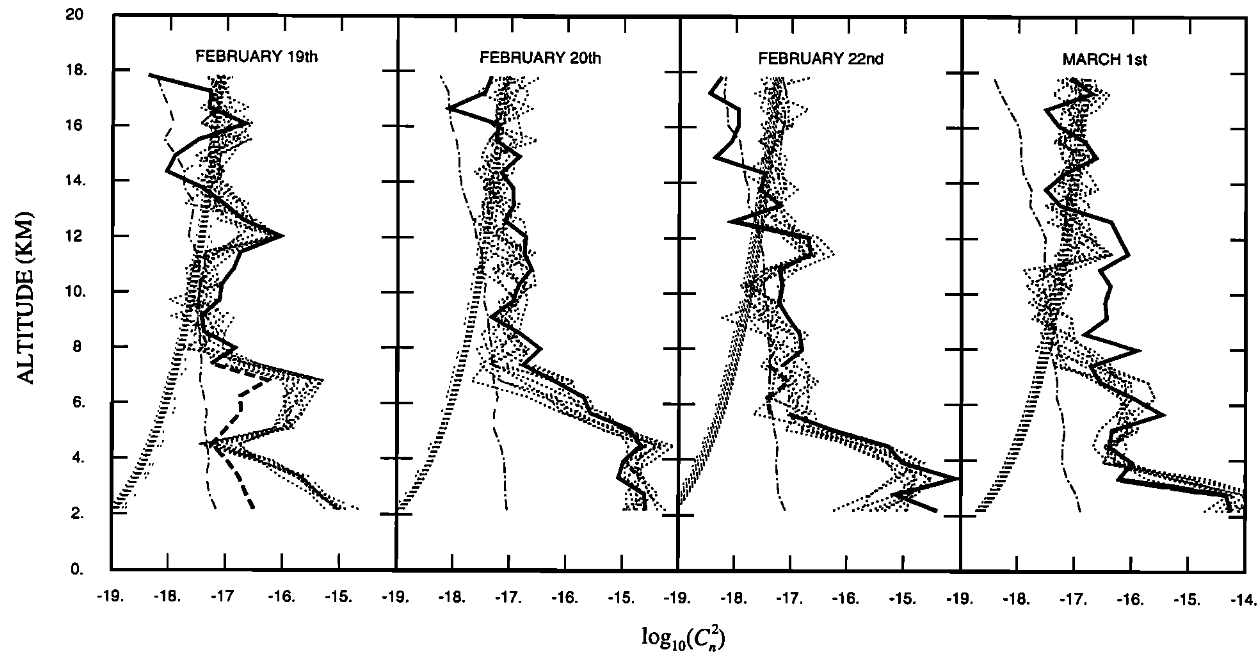

Figure 3. Comparisons, in logarithmic scales, between the C_n^2 radar profiles (dotted lines) synchronous with the four balloon ascents and the reconstructed profiles obtained with the horizontal variance method (solid lines). The standard radar detectability threshold is indicated for each profile by the dotted lines. The contribution of the humidity is introduced in the reconstructed profiles. The dashed lines are used in order to specify that humidity measurements were not available on February 19 and that data loss prevented humidity corrections on February 22 around 6.5 km.

bility profile discriminating the signal from the noise is plotted for each radar profile by using the estimation method given by *Ferrat and Crochet* [1994].

The main differences between the radar profiles and the reconstructed profiles using the horizontal variance method appear in regions where the radar signal is not detectable. Then, the large disagreements (around 15 km on February 19, above 16 km on February 20 and above 13 km on February 22, for example) are only apparent and are compatible with the radar observations. For the other altitude ranges, the comparisons give satisfying results in shape, and dynamic range and are slightly improved with respect to the reconstructed profiles obtained with the spectral method.

The worst result is obtained on March 1 as for the spectral method. These disagreements are probably not of geophysical origin and are discussed in detail by *Luce et al.* [1996].

5. Conclusion

In this paper, a method of C_n^2 estimation using variances of horizontal differences of temperature deduced from high-resolution balloon temperature measurements is applied. The results of this method are first compared with the results of the spectral method (presented by *Luce et al.* [1996]), which uses temperature measurements from one sensor during the "vertical" ascent of the balloon. The comparison between the two kinds of estimated profiles at a 50-m resolution confirms the theoretical considerations that the horizontal variance method allows us to reduce the main contribution of the anisotropic fluctuations contained in the (statically) stable gradients (Figure 1). Then, this method probably gives a more realistic estimation of the C_n^2 parameter than the spectral method. However, as it was suggested from the results of the comparison between radar and reconstructed profiles deduced from the spectral method, the contribution of the anisotropic components for scales smaller than 10 m is not quantitatively important at a 600-m resolution (Figure 2). In particular, the contamination by the vertical gradients in the spectral method is not significant when these gradients alternate with turbulent layers (Figure 1). This comparison between the two kinds of reconstructed profiles at a 50-m vertical resolution shows the advantage of making radar measurements with a better radial resolution owing to the frequency domain interferometry (FDI) technique [*Kudeki and Stitt*, 1987; *Kilburn et al.*, 1995], for example. Furthermore, the reconstructions obtained with the horizontal variance method agreed well with the radar observations (at 600-m resolution). This agreement is slightly improved with respect to the results of the spectral method [*Luce et al.*, 1996]. It can then be concluded that the scattering process from isotropic turbulence in the inertial subrange can constitute a good approximation of the mechanism responsible for the major part of the echoes at oblique incidence (15°). However, the main differences between radar profiles and the two kinds of reconstructed profiles appear in altitude ranges where the radar signal is not detectable. Future experiments with a higher-range resolution are now needed in order to compare with the two kinds of reconstructed profiles in regions where they differ strongly from each other, in order to demonstrate clearly the relative advantages of the new technique and to understand with more accuracy the mechanisms responsible for the radar oblique echoes. As it was shown earlier, most sheets occur in the lower stratosphere and only powerful radars have the capability to sound this region of the atmosphere with a high-range resolution. It is the case of the first VHF powerful MST radars like the Jicamarca radar [*Woodman and Guillèn*, 1974], the sounding system (SOUSY) radar [*Röttger and Liu*, 1978], the MU radar [*Fukao et al.*, 1986] or, more recently, the Indian ST radar [*Rao et al.*, 1995] and the French operational profiler [*Pilon et al.*, 1995]. High-resolution temperature measurements have been shown to be desirable on the site of these powerful radars.

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