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Effects of Melting Layer in Airborne Meteorological X-Band Radar Observations

Olivier Pujol, Frédéric Mesnard, and Henri Sauvageot

Abstract—Most civil aviation aircraft are equipped with meteorological radar working at the X-band ($f \approx 10$ GHz; $\lambda \approx 3.2$ cm). These radars use a small antenna and, thus, a large beamwidth, around 3° – 4° , for observations over long distances (up to 350 km). In the presence of microphysical inhomogeneities inside a radar sampling volume, as filling by different hydrometeor categories, radar reflectivity measurements are biased. An important bias occurs when a radar cell is cut by a nonresolved layer of melting snowflakes whose attenuation is high compared to those of rain and dry snow. This paper illustrates the effects in precipitation-attenuation correction schemes (PACS) of the inhomogeneity associated with the 0°C isotherm. It proposes a method to take into account these effects in PACS. Adaptation of the method to other frequency bands and ground-based radar observations is easy.

Index Terms—Airborne radar, melting layer, microphysical heterogeneities, wet snow, X-band attenuation.

I. INTRODUCTION

THE RADAR equation used for quantitative interpretation of precipitating system radar observations, and notably for correction of attenuation by precipitation, implicitly assumes that the radar resolution volume (the radar cell) $\mathcal{V}_r$ is homogeneously filled by the meteorological target. Obviously, this is not always true, because the scattering medium inside a radar cell may be composed of various hydrometeors with different electromagnetic properties [1], [2]. Microphysical heterogeneities are expected to occur along the distance between the meteorological target and the radar; they are all the more probable as this distance increases. At range r , the vertical extent of a radar cell can be approximated by $r \tan \theta_{3\text{dB}}$, with $\theta_{3\text{dB}}$ being the 3-dB beamwidth. For example, in civil aviation, aircraft are equipped with X-band meteorological radars with a small-sized antenna (for bulkiness reasons) and, thus, a large beamwidth ($\approx 3^\circ$ – 4°). For observations over long distances ($r > 200$ km), the radar cell extends over 14 km (i.e., all the troposphere depth at midlatitudes). The measured radar reflectivity factor Z_m (in dBZ) is thus a quantity averaged over

the considered radar cell. The same holds for attenuation k (in $\text{dB} \cdot \text{km}^{-1}$) which is linked to Z_m by (e.g., [3])

$$Z_m(r) = Z(r) - 2 \int_0^r k(s) ds \quad (1)$$

where Z (in dBZ) denotes the nonattenuated (or “true”) reflectivity factor. Herein, only attenuation by precipitation ($k = k_p$) is considered (atmospheric gas attenuation at the X-band is negligible compared to precipitation, and cloud droplets are not detectable in reflectivity with a single-wavelength radar; that is why this paper focuses only on attenuation by precipitation). Algorithms devoted to k_p correction are based on relationships of the form $k_p = aZ_m^b$, where a and b are coefficients depending on the precipitation type (e.g., [4]–[7]). A largely used attenuation estimation scheme is the iterative one [8]: $Z_m(r)$ is converted into attenuation $k_p(r)$, and a new estimate $Z_m(r)'$ is calculated using (1). This new estimate gives then a revised attenuation estimate $k_p(r)'$ and, subsequently, a second estimate $Z_m(r)''$ and so on at the successive range bins. This iterative scheme terminates when the reflectivity factor estimation in the range bin along a radial no longer changes significantly. The final reflectivity factor distribution along the radial is considered to be $Z(r)$ with a good approximation. In order to estimate Z as best as possible, it is important to take into account microphysical heterogeneities. If not, k_p and Z are biased since Z_m is a mean value over $\mathcal{V}_r$. In the context of civil aviation, such biases have to be avoided, because a pilot must estimate the dangerousness of a precipitating system with the least uncertainty. Radar-cell microphysical heterogeneity presents two general features: 1) variability of the same phase hydrometeors within sampling volume, a subject known usually in the strict sense as nonuniform beam filling (NUBF), which has been studied in, for instance, [9]–[11] (this last reference is about the influence of NUBF on the radar propagation phase shift at the X-band), and 2) filling by different hydrometeor species, i.e., nonuniform hydrometeor category (NUHC).¹ An important case of heterogeneity of type 2), which is considered in this paper, occurs when $\mathcal{V}_r$ contains melting snow, so $\mathcal{V}_r$ is divided into three parts: a snowy one at negative temperature (T), a wet snow layer of few hundred meters thick for $T \geq 0^\circ\text{C}$, and, below, a rainy part. In the context of civil aviation, omitting melting-

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¹Nonuniform beam filling can appear as an ambiguous terminology since, by explicitly indicating beam filling, it could be understood by referring to either 1) or 2). This terminology might be clarified: we would like to suggest “variability of the same phase.”

Fig. 1. Squall line observed with the S-band Nexrad radar KFFC ($33^{\circ} 21' \text{ N}$, $84^{\circ} 33' \text{ W}$) in Georgia, USA (May 2, 2003), and example of the field of view of an X-band airborne radar located at the convergence point of the white lines representing radial observations for different azimuths. The two extreme white lines delimit the field of view of the airborne radar ($\pm 60^{\circ}$ from the aircraft heading direction). For the sake of clarity, only a few white lines are displayed. The black solid line AB represents the azimuth of the vertical cross section which is considered further in the text.

layer attenuation is problematic since convective mesoscale systems are made of convective cells embedded in a stratiform background. If attenuation by precipitation is underestimated, meteorological hazard due to convective cells will also be underestimated, which could be dramatic. Melting-layer reflectivity and attenuation, at various microwave frequencies, have been extensively studied using theoretical models of snow melting processes, simulations of radar observations, and observational data (e.g., [12]–[21]). For observing efficiently the melting layer, high-resolution vertically pointing radars are necessary, whereas airborne radar with large-beamwidth aperture prevents from observing the melting layer. However, its contribution to attenuation should be considered since melting-layer attenuation is higher than equivalent rain attenuation [18], [21].

This paper proposes a way to compute attenuation by a layer of melting snow and to take into account the corresponding contribution in precipitation-attenuation correction schemes (PACS), particularly when the radar cell is too large to observe the melting layer in detail. The method presented herein for an airborne meteorological X-band radar is suitable for measurements performed with a single-frequency and single-polarization radar. It is also valuable for ground-based radar observations and other frequency bands.

II. EFFECT OF A LARGE BEAMWIDTH

The degradation of reflectivity fields at long distances carried by a large value of $\theta_{3\text{dB}}$ is illustrated with the example of a squall line occurring in Georgia (USA), on May 2, 2003. Fig. 1 shows a Constant Altitude Plan Position Indicator (CAPPI), at an altitude of 8.1 km, of the S-band ($f \approx 3 \text{ GHz}$; $\lambda \approx 10 \text{ cm}$) reflectivity of a precipitating system retrieved by the Nexrad U.S. radar Falcon Field City (KFFC) (Georgia, USA, $33^{\circ} 21' \text{ N}$, $84^{\circ} 33' \text{ W}$). Maximum reflectivity reaches 50 dBZ. In some place, hail should thus be expected.

The observation of this precipitating system by an airborne X-band radar, located at the convergence point of the white

Fig. 2. Simulation of X-band airborne radar 8-km CAPPI observations with 3-dB beamwidths of (a) 4° and (b) 0.5° .

lines drawn in Fig. 1, has been simulated using the methodology described in [22]. The white lines represent the azimuthal domain scanned by the airborne radar antenna. Radar altitude is $z_r = 8 \text{ km}$, a common value for flight level of commercial aircraft, and $\theta_{3\text{dB}} = 4^{\circ}$. Microwave polarization is vertical. The black solid line AB represents the azimuth of the vertical cross section which is considered further in the text.

Fig. 2 shows the X-band simulation of the CAPPI shown in Fig. 1 for $\theta_{3\text{dB}} = 4^{\circ}$ (a) and, for comparison, $\theta_{3\text{dB}} = 0.5^{\circ}$ (b). The Z_X -field degradation caused by a large $\theta_{3\text{dB}}$ beamwidth appears clearly for medium and long distances: convective cell boundaries are strongly blurred in Fig. 2(a) because each pixel receives an average value of Z_X over large $\mathcal{V}_r$, so that details in the Z_X -field structure are lost.

The same conclusion holds for range height indicator (RHI) scans. The vertical structure of the precipitating systems is strongly degraded for large 3-dB beamwidth (Fig. 3). With $\theta_{3\text{dB}} = 4^{\circ}$ [Fig. 3(a)], the vertical extent of the beamwidth is, at $r \approx 150 \text{ km}$, greater than 10 km, i.e., the troposphere thickness at midlatitudes. Therefore, the radar is not able to resolve the vertical reflectivity profiles, contrary to observations with $\theta_{3\text{dB}} = 0.5^{\circ}$ [Fig. 3(b)].

Because large 3-dB beamwidth leads to reflectivity measurements averaged over large $\mathcal{V}_r$, PACS are biased in the presence of (nondetectable) radar-cell microphysical heterogeneity. For instance, using an analytic approach and a simple model of X-band ground-based radar rainfall observations, Gosset and Zawadzki [10] have shown that NUBF effects can be of two types: 1) The averaging of the reflectivity factor over $\mathcal{V}_r$ tends to increase the specific attenuation k attributed to $\mathcal{V}_r$, and 2) the

Fig. 3. Simulation of X-band airborne radar RHI observations along the line AB (Fig. 1) with 3-dB beamwidths of (a) 4° and (b) 0.5° .

nonuniform attenuation properties of the propagation medium between the radar and the radar cell tend to decrease k and the two-way path-integrated attenuation (PIA). However, in the case of ground-based radar observations considered in [10], the two effects would compensate each other with distance. Moreover, Gosset and Zawadzki [10] have encouraged the study of other configurations of observations. In the present work, focus is put on NUHC and on observations from an airborne radar.

III. MELTING-LAYER INFLUENCE

Correcting $\mathcal{V}_r$ from heterogeneity of the illuminated hydrometeor species requires knowing the microphysical properties of the target inside $\mathcal{V}_r$. Looking at the structure of a precipitating system (e.g., Fig. 1), it appears that Z_m exhibits high spatial variations which prevent an automatic correction of NUHC in a horizontal plane. However, along the vertical, one can observe, in most precipitation areas, a melting layer made up of wet snow, defining a transition between dry snow ($T < 0^\circ\text{C}$) and rain ($T > 0^\circ\text{C}$). This melting layer, also called the radar bright band, is observed inside stratiform and shallow convective precipitation because dry precipitating hydrometeors of small size and low density melt over a layer of small thickness (e.g., [23] and [24]). Inside deep convective cells, in the presence of heavy precipitation made up of dense ice particles occupying a wide size spectrum (graupel and hail), the bright band is not observed because the radar reflectivity is dominated by the hail contribution and melting occurs over a layer of very large and irregular thickness.

Fig. 4. Radar beam modeling in the vertical plane Oyz including the melting layer. The radar (altitude z_r , elevation $\theta < 0$, range r , and 3-dB beamwidth aperture $\theta_{3\text{dB}} > 0$) is located at point O . It defines at distance r a resolution volume centered in G . g is the local vertical direction.

The radiosounding referenced as 72215 Falcon Field City (FFC) Peachtree City Observations at 0000 Universal Time Coordinate (UTC) (May 3, 2003) (available at <http://weather.uwyo.edu/upperair/sounding.html>) provides the 0°C level altitude $z_0 \approx 3.65$ km. Melting layers have a typical thickness of a few hundred meters, and a common value of 500 m can reasonably be used: Altitude of the base of the melting layer is thus $z_b = z_0 - 0.5$. This value can be changed if z_b is provided from other sources of data (e.g., *in situ* measurements).

A. Geometry of the Observation

Fig. 4 shows, in the vertical plane Oyz , the geometry of a radar cell which contains a melting layer. Point O is occupied by the radar (altitude z_r , beamwidth $\theta_{3\text{dB}}$), and point G (range r , elevation θ) is the center of the radar cell. To make further formulas shorter, let us introduce the radii $r_1 = r - \Delta r/2$ and $r_2 = r + \Delta r/2$ of the arc of circles AD and BC , respectively, with Δr being the range bin (1440 m), and angles $\varphi_1 = \pi/2 + \theta - \theta_{3\text{dB}}/2$ and $\varphi_2 = \pi/2 + \theta + \theta_{3\text{dB}}/2$.

The question is to calculate the fractions of $\mathcal{V}_r$ above z_0 , between z_0 and z_b , and below z_b . Because the radar cell is assumed to be microphysically uniform over azimuth, only surfaces need to be determined. The total surface of the radar cell $ABCD$ is $S_t = 0.5(r_2^2 - r_1^2)\theta_{3\text{dB}}$. Let S_s , S_{ws} , and S_r be the surfaces of the radar cell occupied by snow, wet snow, and rain, respectively, i.e., those defined by the polygons $ABMN$, $NMKLD$, and LKC .

Surface S_s is easy to calculate from geometrical considerations

$$S_s = \frac{1}{2}(z_r - z_0)^2(\tan \varphi_M - \tan \varphi_N) - \frac{1}{2}r_1^2(\varphi_M - \varphi_N) + \frac{1}{2}(r_2^2 - r_1^2)(\varphi_2 - \varphi_M)$$

where the term $0.5(r_2^2 - r_1^2)(\varphi_2 - \varphi_M)$ has to be considered only if $M \in [BC]$. Using the same considerations, surface S_r is

$$S_r = -\frac{1}{2}(z_r - z_b)^2(\tan \varphi_K - \tan \varphi_L) + \frac{1}{2}r_2^2(\varphi_K - \varphi_L) + \frac{1}{2}(r_2^2 - r_1^2)(\varphi_L - \varphi_1)$$

Fig. 5. Same as Fig. 4 when the ground intersects the radar cell.

where the term $0.5(r_2^2 - r_1^2)(\varphi_L - \varphi_1)$ has to be considered only if $L \in [AD]$. Surface S_{ws} is thus

$$S_{ws} = S_t - (S_r + S_s).$$

Angles φ_M , φ_N , φ_L , and φ_K depend on the positions of points M , N , K , and L

$$\begin{aligned} \varphi_M &= \begin{cases} \varphi_2, & \text{if } M \in [AB] \\ \arccos[(z_r - z_0)/r_2], & \text{if } M \in [BC] \end{cases} \\ \varphi_N &= \begin{cases} \varphi_1, & \text{if } N \in [CD] \\ \arccos[(z_r - z_0)/r_1], & \text{if } N \in [AD] \end{cases} \\ \varphi_K &= \begin{cases} \varphi_2, & \text{if } K \in [AB] \\ \arccos[(z_r - z_b)/r_2], & \text{if } K \in [BC] \end{cases} \\ \varphi_L &= \begin{cases} \varphi_1, & \text{if } L \in [CD] \\ \arccos[(z_r - z_b)/r_1], & \text{if } L \in [AD] \end{cases} \end{aligned}$$

The following particular cases must be considered.

- 1) $z_A \leq z_b$, $S_s = S_{ws} = 0$, and $S_r = 1$.
- 2) $z_b \leq z_A \leq z_0$, $S_s = 0$.
- 3) $z_0 \leq z_C$, $S_r = S_{ws} = 0$, and $S_s = 1$.
- 4) $z_b \leq z_C \leq z_0$, $S_r = 0$.

z_A and z_C are the altitudes of A and C , respectively.

Moreover, ground has to be considered since it affects the radar-cell geometry. Denoting P and Q as the points of intersection of the polygon $ABCD$ with the ground ($P \in [CDA]$ and $Q \in [ABC]$), the surface of the underground part of $ABCD$ is (Fig. 5)

$$\begin{aligned} S_{ug} &= \frac{1}{2}r_2^2(\varphi_Q - \varphi_P) - \frac{1}{2}z_r^2(\tan \varphi_Q - \tan \varphi_P) \\ &\quad + \frac{1}{2}(r_2^2 - r_1^2)(\varphi_P - \varphi_1) \end{aligned}$$

the last term occurring only if $P \in [DA]$. Angles φ_P and φ_Q are such that

$$\begin{aligned} \varphi_P &= \begin{cases} \varphi_1, & \text{if } P \in [CD] \\ \arccos(z_r/r_1), & \text{if } P \in [AD] \end{cases} \\ \varphi_Q &= \begin{cases} \varphi_2, & \text{if } Q \in [AB] \\ \arccos(z_r/r_2), & \text{if } Q \in [BC]. \end{cases} \end{aligned}$$

Obviously, $S_{ug} = 0$ if the radar cell does not intersect the ground.

Thus, the fractions α_s and α_r of the radar cell occupied by snow and rain, respectively, are as follows: $\alpha_s = S_s/(S_t - S_{ug})$ and $\alpha_r = (S_r - S_{ug})/(S_t - S_{ug})$ (if $z_b > 0$) and $\alpha_r = 0$ (if $z_b \leq 0$). If A (C) is inside the melting layer, α_r (α_s) keeps the same expressions as those previously mentioned. Fraction occupied by wet snow ensues straightly: $\alpha_{ws} = 1 - (\alpha_r + \alpha_s)$.

B. Specific Attenuation of a Radar Cell Containing Wet Snow

Specific attenuation k of a radar cell containing wet snow is computed using the following methodology developed around six items.

- 1) For given z_r and z_0 (and, hence, z_b), fractions α_r , α_s , and α_{ws} are computed as explained in the previous section.
- 2) Since only radar cells which contain wet snow (and so *a fortiori* dry snow and rain) are of interest, only the cells characterized by $0 < \alpha_{ws} \leq 1$ are considered.
- 3) For each of these identified radar cells, a mean reflectivity and a mean specific attenuation are computed by considering realistic reflectivity profiles which involve a melting layer. The simulated X-band reflectivity profiles obtained in [17] (see Fig. 1 of this reference) through a melting-layer model can be used as an example: dry snow reflectivity Z_s is 25 dBZ at z_0 , wet snow presents a maximum reflectivity of about 48 dBZ, and rain has a uniform reflectivity $Z_r = 35$ dBZ. In this paper, many X-band Z profiles have been considered: Z_s varies from 5 to 35 dBZ, maximum melting-layer reflectivity ranges from 25 to 50 dBZ, and Z_r extends from 15 to 45 dBZ. Obviously, profile shape is conserved between these different cases. Above z_0 , it has been assumed that Z_s decreases with a rate of about $2 \text{ dBZ} \cdot \text{km}^{-1}$. However, this value has been modified and has not appeared as important. This is because dry snow reflectivity is lower than wet snow and rain reflectivities. Therefore, a uniform value of Z_s ($z \geq z_0$) can be taken without resulting in any significant modifications.
- 4) A mean reflectivity $\langle Z \rangle$ over each identified radar cell is then deduced from these realistic profiles. For such a given profile, it has been assumed that dry snow and rain contributions are $\alpha_s Z_s$ and $\alpha_r Z_r$, respectively. Wet snow contribution is defined similarly with $\alpha_{ws} Z_{ws}$, where Z_{ws} is the average reflectivity over the melting layer. By this way, underline that the entire reflectivity profile inside the melting layer is contained in Z_{ws} , so that this last one takes into account the fact that wet snow reflectivity is higher than dry snow and rain reflectivities. Hence, for a given profile, reflectivity is $\alpha_s Z_s + \alpha_r Z_r + \alpha_{ws} Z_{ws}$. Finally, $\langle Z \rangle$ is obtained by averaging the previous quantity over all the profiles defined: $\langle Z \rangle = \alpha_s \langle Z_s \rangle + \alpha_{ws} \langle Z_{ws} \rangle + \alpha_r \langle Z_r \rangle$. It is worth mentioning that $\langle Z \rangle$ has been computed through a linear average using physical units ($\text{mm}^6 \cdot \text{m}^{-3}$).
- 5) With $\langle Z \rangle$ computation, a mean specific attenuation $\langle k \rangle$ is computed for each identified radar cell. Specific attenuations of rain and snow are $k_r = a_r(\alpha_r Z_r)^{b_r}$ and

$k_s = a_s(\alpha_s Z_s)^{b_s} + c_s(\alpha_s Z_s)^{d_s}$, respectively, where (a_r, b_r) and (a_s, b_s, c_s, d_s) are appropriate coefficients. Note that dry snow attenuation is characterized, at wavelengths lower than 10 cm, by two couples (a_s, b_s) and (c_s, d_s) : the first one corresponds to scattering in other directions than the backward one, and the second one corresponds to microwave absorption (e.g., [3] and [25]). At centimeter wavelengths, rain attenuation is mainly due to absorption, so that only one couple (a_r, b_r) is required (e.g., [3] and [25]). The values of these coefficients can be found in the literature. In this paper, the values (in the X-band) adopted in [22] are used: $a_r = 1.293 \times 10^{-4}$, $b_r = 0.774$, $a_s = 1.396 \times 10^{-7}$, $b_s = 1.25$, $c_s = 4.11 \times 10^{-6}$, and $d_s = 0.625$. Other k - Z relationships can be used depending on the situations considered. All such relationships are inherently uncertain since they are valid only for the conditions under which they are derived [26].

Wet snow attenuation is not so easy to compute and has received less attention than rain and dry snow. However, it is well known that wet snow attenuation is several times (factor m) higher than rain attenuation (e.g., [2]). From notably X-band radar vertical observation, Bellon *et al.* [18] have shown that bright band attenuation is three to five times the specific attenuation computed as if reflectivity of the melting layer were due to rain. The same order of magnitude, for vertical radar observations, is given in [17]. The International Telecommunication Union recommends [27] to compute wet snow attenuation by using an altitude-varying m factor inside the melting layer: below the 0°C level, m increases from 0 to about 3.53 and then decreases until 1 at the base of the melting layer where rain appears. The mean value of m over 500 m is about 2.67. Recently, Tjelta and Bacon [21] have used [27] to model wet snow attenuation on terrestrial microwave links. In this paper, the value of 3.53 is taken, which is consistent with other results in the literature (e.g., [17] and [18]). Hence, $k_{ws} = 3.53 a_r (\alpha_{ws} Z_{ws})^{b_r}$.

The total attenuation is $k = k_r + k_s + k_{ws}$, and the averaged attenuation $\langle k \rangle$ expression is thus $\langle k \rangle = \langle k_r \rangle + \langle k_s \rangle + \langle k_{ws} \rangle$.

Two tables are thus obtained: The first one is relative to $\langle Z \rangle$, and the second one is relative to $\langle k \rangle$.

- 6) These tabulated values allow to estimate the radar-cell specific attenuation k associated to the measured reflectivity Z_m : knowing Z_m , the closest value of $\langle Z \rangle$ is identified, and then, the corresponding $\langle k \rangle$ value is supposed to be k .

This six-item methodology is shown in Fig. 6 which displays radar-cell mean attenuation $\langle k \rangle$ versus mean $\langle Z \rangle$ for different values of α_s , α_{ws} , and α_r . These values are represented by small color-filled circles. For a given $\langle Z \rangle$, $\langle k \rangle$ increases with α_s [Fig. 6(a)]. The same occurs for α_{ws} [Fig. 6(b)]. Moreover, $\langle k \rangle$ decreases if $\alpha_r = 1 - (\alpha_s + \alpha_{ws})$ increases [Fig. 6(c)]. At a fixed $\langle k \rangle$, $\langle Z \rangle$ must be higher if α_s (and α_{ws}) diminishes [Fig. 6(a) and (b)]. The associated $\langle Z \rangle$ to a given $\langle k \rangle$ increases with $\alpha_r = 1 - (\alpha_s + \alpha_{ws})$ [Fig. 6(c)]. Obviously, this six-item algorithm must be repeated if z_r and z_0 are modified.

Fig. 6. Radar-cell mean attenuation $\langle k \rangle$ versus mean reflectivity $\langle Z \rangle$ for different values of (a) α_s , (b) α_{ws} , and (c) α_r .

Fig. 7. Simulation of X-band PIA at an altitude of 8 km (a) without taking into account a melting layer and (b) considering a melting layer.

IV. RESULTS

Fig. 7 shows the melting-layer influence, for an 8-km CAPPI plane, with $\theta_{3\text{dB}} = 4^\circ$. The airborne radar is looking ahead, in the local horizontal plane (elevation from aircraft direction is

Fig. 8. Z_X fields at 8 km of altitude with $\theta_{3\text{ dB}} = 4^\circ$. (a) Nonattenuated field. (b) Measured field. Corrected fields (c) by considering a melting layer and (d) without taking into account a melting layer.

zero). In Fig. 7(a), the melting layer is not considered, while it is taken into account in Fig. 7(b). For this latter case, the maximum value of PIA is about 13 dB. Comparatively, in the

former case, $PIA \approx 3.5$ dB. The same conclusion holds for other elevation angles, although the value of PIA differences can change.

Fig. 8 shows the various X-band reflectivity factors in the 8-km CAPPI plane: nonattenuated reflectivity deduced from S-band Nexrad reflectivity using the algorithm in [22], attenuated reflectivity as observed by the airborne radar (Z_m) through the algorithm in [22], corrected reflectivity by considering the melting layer, and corrected reflectivity without taking into account the melting layer. Clearly, the retrieval of the nonattenuated X-band reflectivity from Z_m is better if the inhomogeneity due to the melting layer is considered. Indeed, the high values of Z at distances greater than 150 km [Fig. 8(a)] are more in agreement with the reflectivity field in Fig. 8(c) than with that in Fig. 8(d). Although wet snow fraction α_{ws} is relatively small compared to those of rain and dry snow, high reflectivity and attenuation of wet snow contribute to increase radial cumulative attenuation in a nonnegligible quantity.

V. CONCLUSION

A method to calculate the attenuation due to the melting layer has been presented. Radar cells $\mathcal{V}_r$ are often crossed over by the layer of melting snow which separates dry snow from rain. Since these three hydrometeor classes have different electromagnetic properties, a precise correction of precipitation attenuation is applied to distinguish them. The method proposed consists first in calculating through exact formulas the fraction of $\mathcal{V}_r$ occupied by rain, that constituted exclusively of dry snow, and that filled by wet snow. Second, using several realistic reflectivity profiles involving dry snow, wet snow, and rain, a mean reflectivity $\langle Z \rangle$ is computed for radar cells containing wet snow; $\langle Z \rangle$ is obviously dependent on dry snow, wet snow, and rain fractions. A mean attenuation $\langle k \rangle$, depending as well on these three hydrometeor fractions, is also computed by determining attenuation by each class of hydrometeors using aZ_h^b relationships (Z_h is the reflectivity factor relative to a given hydrometeor class), with a and b being appropriate coefficients. It is easy for rain and dry snow; melting-layer attenuation is computed using the mean reflectivity factor over melting-layer, rain (a, b) coefficients, and introducing a multiplying factor of 3.53 in order to take into account the fact that melting-layer attenuation is much more than that of equivalent rain.

The mean quantities $\langle Z \rangle$ and $\langle k \rangle$ are thus tabulated values which permit to estimate attenuation associated with the measured reflectivity Z_m . For a fixed Z_m value, it consists in looking for the closest value of $\langle Z \rangle$ and in considering $\langle k \rangle$ as a good estimation of k . For an X-band airborne radar, the result is that attenuation is underestimated by about 10 dB in the example shown in this paper if the melting layer is not considered. This method can obviously be applied to other frequencies, and although it is presented for an airborne radar, the method can be used for ground-based radars. As a prospective, it is worth mentioning that melting snow attenuation is polarization dependent, since quasi totally melted snowflakes (i.e., at the lower part of the melting layer) present a horizontal orientation (see [28, p. 207, 473, 485–90]). Hence, melting-layer specific attenuation should be higher with horizontally polarized

microwaves. Another prospective could be the implementation into aircraft radar systems of uncertainties in k - Z relationships.

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