The Influence of Antenna Radome on Weather Radar Calibration and Its Real-Time Assessment

E. GORGUCCI
Istituto di Scienze dell’Atmosfera e del Clima, CNR, Rome, Italy

R. BECHINI
ARPA Piemonte, Turin, Italy, and Colorado State University, Fort Collins, Colorado

L. BALDINI
Istituto di Scienze dell’Atmosfera e del Clima, CNR, Rome, Italy

R. CREMONINI
ARPA Piemonte, Turin, Italy

V. CHANDRASEKAR
Colorado State University, Fort Collins, Colorado, and Finnish Meteorological Institute, Helsinki, Finland

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ABSTRACT

Operational weather radars are usually equipped with a radome to reduce the wind load on the antenna and to allow continuous operation under bad weather conditions. The study is focused on quantifying the impact on radar polarimetric measurements due to the presence of a radome. Analysis refers to the transportable X-band polarimetric radar of the Agenzia Regionale per la Protezione Ambientale (ARPA) Piemonte (ARX), which uses a “bullet shaped” radome to provide environmental protection to the antenna and receiver apparatus system.

Radar calibration is performed using wet and dry radomes. Differential reflectivity calibration results are compared with those obtained using the sun as a radiation reference source. Estimates have comparable mean values, with their differences being within the standard deviation. The paper describes a method based on the self-consistency principle that takes into account the loss induced by radome wetting due to rain to adjust the absolute calibration of the radar in real time.

To verify how well this method overcomes the problem of excess attenuation caused by the presence of precipitation on the radome, two validation methods are presented. The first uses an empirical model to estimate the two-way wet radome losses for a qualitative comparison, with the corresponding losses obtained by the self-consistency principle. The second employs comparisons between radar and gauge rainfall accumulations with and without radome correction. This approach offers a clear understanding of the response of the correction, providing quantitative performance in a real case.

1. Introduction

Most operational weather radar systems are equipped with a radome that provides environmental protection to ensure continuous and safe operation during severe weather conditions. However, a radome presents the disadvantage of affecting antenna performance as well as affecting the outgoing and incoming microwave. For this reason, a radome is constructed using materials and shapes that minimally affect the antenna pattern. The coating of the radome is hydrophobic in order to avoid additional attenuation due to a wet radome surface as much as possible.
Verification of radome specifications can be performed both at test range and on site. So far, several papers have analyzed radome effects under controlled conditions and for different radome designs (Manz 2001; Frech et al. 2011). However, properties such as the hydrophobicity of the radome coating will degrade with time and in an operational context, the performance of a radome can be very different from expectations.

A critical situation occurs in the case of heavy rain over the radome. In general, when rain hits the radome, an unknown attenuation is added to an entire reflectivity profile that depends on the thickness of the water layer on the radome surface, which in turn is related to rain intensity (Blevis 1965; Anderson 1975; Kurri and Huuskonen 2008). The different water film thickness builds up on a radome surface are determined by the surface’s technical characteristics such as the shape, the hydrophobic properties, and the flow mechanisms, and by weather conditions such as the wind speed and the rain rate. From the attenuation viewpoint, water on a radome can be described in three different forms corresponding to different rain stages. In the form of droplets, the attenuation added to a radome is moderately weak, whereas water as a continuous film introduces a significant excess attenuation (Kurri and Huuskonen 2008). As the water film rises, it increases the radome attenuation, and intense precipitation events in a short duration can cause the appearance of narrow rivulets of water running down the radome’s surface. The influence of bias due to wet radome attenuation depends on the radome’s shape and hydrophobicity of its external surface, the latter depending also on the aging and maintenance of the radome. In general, attenuation induced by the water coating of the radome depends on the radar frequency and is more pronounced at X band where, in the case of heavy rain, it determines a considerable understimation of reflectivity measurements and a wave extinction at shorter range.

In a networked radar design, an extra attenuation margin due to radome loss needs to be considered (Chandrasekar et al. 2009). Trabal et al. (2008) report examples of radome attenuation of 7.5 dB, which were obtained comparing reflectivity measurements of the Collaborative Adaptive Sensing of the Atmosphere (CASA) X-band radars with the corresponding measurements obtained by an S-band Weather Surveillance Radar-1988 Doppler (WSR-88D). Bechini et al. (2010) describe an experiment in which an X-band dual-polarization radar is calibrated using a tethered metallic sphere. During the test, the radome was wetted using an irrigation sprinkler. With respect to dry radome conditions, they reported a two-way loss of 12–14 dB for a rain rate of 156 ± 58 mm h⁻¹, where the uncertainty of the rain rate was due to the quality of sprinkler. Schneebeli et al. (2012) obtained an X-band radome attenuation up to almost 20 dB during an intense tropical rain in Brazil. For a given rain intensity and under strong wind conditions, the radome results were not equally wet and therefore the loss may change in azimuth (Germann 1999; Bechini et al. 2006). Because radome attenuation is variable both in time and in azimuth, it is important to devise a real-time correction methodology.

One of the advantages of polarimetric radar measurements in rain is their internal self-consistency principle (Sarchilli et al. 1996). This principle, used by Gorgucci et al. (1992) to develop a procedure to determine the absolute calibration of a dual-polarization weather radar based on the properties of the rain medium, takes advantage of the synergy obtained by combining radar measurements of the reflectivity factor, differential reflectivity, and specific differential phase. It has been shown that the method can achieve radar calibration with an accuracy of 0.5–1 dB (Gorgucci et al. 1999; Illingworth and Blackman 2002; Vivekanandan et al. 2003). The importance of having accurate knowledge of the absolute radar calibration for quantitative application of radar measurements brought the need for the implementation of this procedure to be specialized for each different frequency band used by weather radars. To calibrate an operational C-band polarimetric radar based on the consistency of measurements, Gourley et al. (2006) reported a fully automated polarimetric procedure that uses paths in which the differential phase shift is limited to 10° in order to mitigate the influence of C-band propagation attenuation. Precise and continuous radar calibration obtained directly by radar rainfall estimates, which is an important task for maintaining the accuracy of radar measurements, appears to lose robustness in the presence of time-varying radome attenuation, representing a serious limiting factor for quantitative radar measurements. Thurai and Hanado (2005) and Bringi et al. (2006) implemented a method at C-band based on the self-consistency approach that is capable of taking account of additional attenuation related to rain on the radome and then correcting the measured reflectivity.

This paper describes and validates a method based on the self-consistency of polarimetric radar measurements that overcomes the problem of excess attenuation caused by the presence of water on the radome at X band. Experiments were conducted with the transportable X-band polarimetric radar that has been managed by the Agenzia Regionale per la Protezione Ambientale (ARPA) Piemonte (Italy) since 2007. Great emphasis is given to the validation of the method, which is obtained by comparing reflectivity rainfall estimation with rain gauge...
measurements and by using losses estimated using the algorithm of Bechini et al. (2010).

2. Background

Accurate calibration of radar reflectivity is essential for obtaining reliable weather radar applications such as rainfall estimations and hydrometeor classification. Gorgucci et al. (1992) fixed the basic concept of the synergistic utilization of polarimetric radar measurements, namely, reflectivity factor \( Z_h \), differential reflectivity \( Z_{dr} \), and specific differential propagation phase \( K_{dp} \). The idea arose from the fact that, in the case of polarization radars, rain rate can be independently estimated using power or phase measurements. In fact, for the same radar resolution volume, a rain estimate obtained from the algorithm based on \( Z_h \) and \( Z_{dr} \) measurements written as

\[
R_{dr} = a_1 Z_h^b Z_{dr}^c (\text{mm h}^{-1})
\] (1)

must be equal to a rain estimate using the algorithm based on \( K_{dp} \):

\[
R_{dp} = a_2 K_{dp} (\text{mm h}^{-1})
\] (2)

Any systematic deviation between (1) and (2) can be attributed, under suitable assumptions, to the radar calibration. This follows from the fact that \( K_{dp} \), obtained from a range profile of differential phase shift \( \Phi_{dp} \), is unaffected by calibration errors and \( Z_{dr} \) is a differential power measurement that can be easily corrected for any systematic bias looking vertically at very light rain conditions or in ice regions. In fact, radar and in situ aircraft-based observations show that the shape of raindrops can be approximated by oblate spheroids and that on average the raindrops are oriented with the symmetrical axis in the vertical direction. This implies that the shape of raindrops seen at an elevation angle of 90° is nearly circular and that \( Z_{dr} \) measurements performed with the vertical antenna pointing should be 0 dB (Gorgucci et al. 1999).

In the case of mechanical antenna limitations, another possible atmospheric medium that can be used for \( Z_{dr} \) calibration is dry aggregated snow, known for its small intrinsic \( Z_{dr} \) value due to its very low density (Ryzhkov et al. 2005). Otherwise, procedures based on solar radiation can be used as well (Tapping 2001; Zrnić et al. 2006).

Once the \( Z_{dr} \) bias is removed, Eq. (1) can be tuned, correcting \( Z_h \) in order to have equal values for \( R_{dr} \) and \( R_{dp} \). As a result, there follows a relation among \( Z_h \), \( Z_{dr} \), and \( K_{dp} \). From a theoretical viewpoint, when a drop-shape model is fixed to describe the form of raindrops, for each drop size distribution (DSD) the corresponding radar measurements define a space where they are constrained to stay in a three-dimensional surface defined by (Searchiilli et al. 1996)

\[
K_{dp} = a_3 Z_h^b Z_{dr}^c (\text{°} \text{ km}^{-1}).
\] (3)

In Eq. (3), \( Z_h \) and \( Z_{dr} \) are expressed in linear units. As a consequence, in that domain each variable can be found as a function of the other two. Equation (3) represents the self-consistency principle of polarimetric radar measurements. This principle was utilized by Gorgucci et al. (1992) to obtain accurate radar system calibration using the properties of the rain medium directly, and the consistency of this method has been verified. This method has been extensively used to obtain important results for different radar meteorology applications (Bringi et al. 2002; Gorgucci and Baldini 2007; Chandrasekar et al. 2008).

Applying the self-consistency principle in each range bin and integrating along the path, Eq. (3) becomes

\[
\Phi_{dp}^m (r_2) - \Phi_{dp}^m (r_1) = \Phi_{dp}^w (r_2) - \Phi_{dp}^w (r_1) (°),
\] (4)

where \( \Phi_{dp}^m \) and \( \Phi_{dp}^w \) are the measured and the computed differential phase shift, respectively, given by

\[
\Phi_{dp}^m (r_2) - \Phi_{dp}^m (r_1) = 2 \int_{r_1}^{r_2} K_{dp} (°),
\] (4a)

\[
\Phi_{dp}^w (r_2) - \Phi_{dp}^w (r_1) = 2 \int_{r_1}^{r_2} (a_3 Z_h^b Z_{dr}^c) (°).
\] (4b)

Because Eq. (4) is satisfied, polarimetric measurements must be unaffected by propagation effects. Unfortunately, the higher the frequency of a radar system, the more its measurements are affected by attenuation due to precipitation. For this reason, at C and X bands the impact of attenuation needs to be resolved for successful implementation of (4b). The extent of attenuation along a rain-filled path can be directly estimated from the corresponding amount of cumulative \( \Phi_{dp} \). This means that both copolar attenuation and differential attenuation can be expressed in terms of differential phase (Bringi and Chandrasekar 2001), as

\[
A_h = \alpha_h [\Phi_{dp}^m (r) - \Phi_{dp}^m (r_0)] (\text{dB}),
\] (5a)

\[
A_d = \alpha_d [\Phi_{dp}^w (r) - \Phi_{dp}^w (r_0)] (\text{dB}).
\] (5b)

At each range, Eqs. (5a) and (5b) represent the amounts of path-integrated attenuation to be added to \( Z_h \) and \( Z_{dr} \).
because (4) is verified. It should be noted that the important advantage of this method for estimating the attenuation amount is its independence from absolute radar calibration.

From a general point of view, the coefficients \( \alpha_h \) and \( \alpha_d \) depend on drop size distribution, on the shape–size relation describing the shape of raindrops, on water temperature, and on Mie scattering effects. As a consequence, the \( \alpha_h \) and \( \alpha_d \) variability may result in a bias on attenuation and differential attenuation estimates, which will affect the accuracy of corrected \( Z_h \) and \( Z_{dr} \), and consequently the estimation (3). To avoid this problem, it should be reasonable to impose restriction on maximal \( \Phi_{dp} \) variation. At X band, Gorgucci et al. (2006) showed that attenuation and differential attenuation are highly correlated for a widely varying raindrop size distribution. In other words, the bias due to attenuation appears to nearly cancel the bias due to differential attenuation on the right side of (3).

Following the axis ratio model of Beard and Chuang (1987), a large number of gamma-distributed DSDs are simulated, varying the corresponding parameters \( D_0 (\text{mm}) \), \( N_w \left( \text{mm}^{-1} \text{m}^{-3} \right) \), and \( \mu \) in a wide range (0.5 \( \leq D_0 \leq 3.5 \), 3 \( \leq \log_{10} N_w \leq 5 \), and \(-1 < \mu < 5 \)). Radar measurements are simulated using the constraints \( Z_h < 55 \text{ DBZ} \) and \( R < 300 \text{ mm h}^{-1} \) at X band (9.375 GHz), and computing the dielectric constant of water at a temperature of 20°C. It is also assumed that the drops are canted, with the mean and width canting angle distribution equal to 0° and 10°, respectively (Bringi and Chandrasekar 2001). Nonlinear regression is then used to estimate the coefficients \( (\alpha_3, b_3, c_3) \), \( \alpha_h \), and \( \alpha_d \) of (3), (5a), and (5b), respectively. The values of \( (\alpha_3, b_3, c_3) \), \( \alpha_h \), and \( \alpha_d \) are \( 1.48 \times 10^{-4} \), 1.054, \(-4.168 \), 0.276, and 0.042, respectively. The performance of the algorithms (3), (5a), and (5b) is evaluated in terms of normalized standard error (NSE) and normalized bias (NB), defined as the bias and the standard deviation between the simulated and the “true” values normalized with respect to the mean “true” value. Quantitative analysis of the performance of the three algorithms, with respect to the assumed DSD variability, yields a normalized standard error of about 11% for (3), and 34% and 49% for (5a) and (5b), respectively, and a normalized bias negligible for all the three algorithms.

Once \( Z_h \) and \( Z_{dr} \) measurements are corrected for attenuation, (4a) and (4b) can be applied to any path (Goddard et al. 1994; Scarchilli et al. 1996) to obtain

\[
\varepsilon_z = 10 \log_{10} \left[ \frac{\Phi_{dp}^m(r_z) - \Phi_{dp}^m(r_1)}{2 \int_{r_1}^{r_z} (a_3 Z_h^{b_3} Z_{dr}^{c_3}) \, dr} \right] \text{ (dB).} \tag{6}
\]

Under dry radome conditions, (6) gives the correction to the radar constant to obtain a calibrated \( Z_h \).

From a general point of view, the accuracy of \( \varepsilon_z \) depends on several factors, namely, radar measurement accuracy, DSD and raindrop shape–size variations, and raindrop water temperature.

Varying DSDs over the wide range described above, NB and NSE of relation (6) in linear units are 0.077 and 0.176, respectively, which translate into an uncertainty of 0.7 dB and a negligible bias on \( \varepsilon_z \).

Uncertainty of polarimetric radar measurements resulting from their measurement errors also affects the accuracy of (6). Assuming an accuracy of 2° in estimating a differential phase shift and the typical accuracies of 1 and 0.2 dB in \( Z_h \) and \( Z_{dr} \) estimates, the corresponding NSE and NB of (6) in linear units are 0.271 and \(-0.014 \), respectively, which translate into an uncertainty of 1 dB and an insignificant bias on \( \varepsilon_z \).

Unlike S- and C-band radars, the effect of ambient temperature changes on the self-consistency relation (6) cannot be neglected at X band and needs to be assessed. In this way, starting from the existing conditions of the average temperature of 20°C, measured at the radar site during the measurement campaign, the behavior of (6) as a function of temperature has been investigated.

With the same microphysical model used above, the coefficients of (6) were obtained assuming drops with water temperatures of 0°C, 5°C, 10°C, 15°C, 25°C, and 30°C. Figure 1 shows NSE and NB of values obtained from (6), at each temperature, with those obtained at the temperature of 20°C. The effect of temperature changes from 20°C causes an increase in both NSE and NB. However, for temperature variations of 5°C, the increase of NSE is less than 0.04, whereas for NB it is approximately 0.01.
3. Data description

The radar data used in this work were collected by the ARPA Piemonte polarimetric X-band radar (ARX). Its main characteristics are reported in Table 1. During the summer of 2010, ARX was temporarily deployed on the mountain pass of Colle di Tenda (1835 m MSL) on the border between Italy and France, during the Italian–French cooperative project Gestion des Cres par Intégration des Systèmes Transfrontaliers de prévision et de prévention des bassins versants Alpins (CRISTAL). This study mainly focuses on the data collected on 14 August 2010 and, limited to the mountain pass of Colle di Tenda, during the Italian–French cooperative project Gestion des Cres par Intégration des Systèmes Transfrontaliers de prévision et de prévention des bassins versants Alpins (CRISTAL). This study mainly focuses on the data collected on 14 August 2010 and, limited to calibration purposes, on 29 July and 5 and 12 August. On 14 August, a deep low pressure system was moving from the English Channel to southwestern France. The associated secondary low center within an occluded front moved across the Piemonte region, accompanied by convective rain (showers) during the morning and more widespread stratiform precipitation in the afternoon.

One of the aims of the project was to investigate the feasibility and potential use of X-band technology to improve the monitoring of small- to medium-size hydrological catchments in orographically complex regions. To cope with the limited optical visibility over several azimuth sectors, the scan strategy was designed to focus the radar observations on the Vermenagna River hydrological catchment (Fig. 2), extending in the northern sector of the radar domain. Considering the orography of the region, a volume scan including only five elevations starting at 5° was scheduled, followed by two sweeps in the elevation scan mode along the most relevant directions (340° and 359° azimuth), with elevations ranging between −1° and 95°. The reduced volume scan (compared to typical radar coverage patterns consisting of around 10 elevations or more) allowed time to also include the two sweeps in elevation mode in a 5-min loop. This strategy allows low-elevation-angle observations over the target area, avoiding the waste of time that a full 360° azimuth scan, including many blocked sectors, would cause. The two elevation scans are completely unblocked, being oriented to the direction of the two valleys that are scanned from a higher observation point.

For this study, we focus on these data only since they allow low-level observations in the rain medium. Specifically, data are considered from the 0° elevation to avoid some excess noise found in the polarimetric parameters due to sidelobe contamination at the two lower available elevations (−1.0° and −0.5°). Given the height of the freezing level for the event considered (~3200 m ASL from the Milano Linate sounding), the radar provided useful measurements in rain up to a distance of approximately 30 km. In the area of interest (Fig. 2), the rain gauges located fewer than 2.5 km from either of the two elevation scans and within 30 km from the radar are marked with crosses and are considered for comparison with the radar rainfall estimates in section 5b.

Data collected in the elevation scan mode containing polarimetric radar measurements of $Z_{hv}$, $Z_{dr}$, $F_{dp}$, and $\rho_{hv}$ were estimated at a dual-pulse repetition frequency scheme using 2400–1600 Hz, with an antenna scan rate of 3° s$^{-1}$, elevation resolution of 0.5°, and range resolution of 125 m. To ensure that there was no contamination by the melting layer, the data analyzed were confined to be below that level (2800 m ASL, approximately 400 m below the freezing level). Moreover, to ensure that radar measurements referred to rain, only the range bins from each radar ray with $\rho_{hv} > 0.9$ were selected. On the corresponding $F_{dp}$ profile, a filtering technique (Hubbert and Bringi 1995) was performed for the backscatter differential phase shift correction and then used to obtain a monotonically increasing $F_{dp}$ profile. A $F_{dp}$ profile was used for calibration only if it contained more than 20 consecutive valid range bins. The corresponding $Z_{dr}$ and $Z_{dr}$ profiles were corrected for attenuation ($A_d$) and differential attenuation ($A_d$), using (5a) and (5b), respectively.

A Thies–Clima laser disdrometer was installed beside the X-band radar. The disdrometer provides particle counts in 20 classes of diameters (from 0.16 to >8 mm) and 20 classes of velocity (from 0.2 to 20 m s$^{-1}$). The instrument has a measuring area of 46 cm$^2$ and provides the DSD integrated over a 1-min time interval. These measurements are used as a reference for the actual rain rate at the radar site.

4. Radar calibration

Absolute calibration of a weather radar is a critical task for quantitative estimation of meteorological...
This is a very difficult task, especially for beam-filling targets like precipitation. It follows that any method based on the properties of the rain medium appears suited as well to obtain accurate and time-continuous radar calibration. In fact, this technique can account for any change occurring over time on the radar system. A detailed study is conducted on estimating the influence of the radome on the radar calibration and how it affects the estimation of precipitation. More generally, the influence of the radome is addressed with significant attention paid to both reflectivity and differential reflectivity.

\[ Z_{dr} \]

One basic assumption for the successful use of the self-consistency of polarimetric radar measurements is that \( Z_{dr} \) is unbiased. In the case of rain above the radome, \( Z_{dr} \) calibration needs to be studied to verify whether it can vary depending on radome wetting conditions. The calibration of \( Z_{dr} \) has been studied using different methodologies: sun calibration, observations at vertical incidence, and observations from low-density dry aggregated snow.

1) ARX Sun Calibration

ARX is a dual-polarization radar that operates in the simultaneous transmit and receive (STAR) mode. The total power provided by a 70-kW coaxial magnetron is divided by a power splitter over two separate orthogonal channels to simultaneously transmit and receive radar signals with orthogonal polarizations \( h \) and \( v \). Both the transmitter and receiver units are located behind the antenna. This configuration provides a very low power loss due to the waveguide and prevents the use of rotary joints. However, because of a potential difference in the two channels, the effects on the differential reflectivity need to be assessed. As for the bias determined by the differences in receiving channels, this can be monitored using solar radiation. In fact, the sun emits equal amounts of spectral power density in both \( h \) and \( v \) directions and then any variation from zero decibel of \( Z_{dr} \) value is ascribed to differences from the antenna port to the \( h \) and \( v \) receiver outputs. In general, the solar calibration of \( Z_{dr} \) does not include the transmit path, which can lead to a \( Z_{dr} \) bias of a few tenths of a decibel if not considered. Figure 3 shows the \( Z_{dr} \) values obtained by

FIG. 2. Topography of the area surrounding the ARX (filled triangle) superimposed with the two elevation scan directions (340° and 359° azimuth, dotted lines) and the rain gauge locations and names. Solid contour delimits the Vermenagna River catchment. The x’s indicate the rain gauges used in the validation.
directing the antenna toward the sun. The data were collected with the antenna scanning at 1\(^\circ\) s\(^{-1}\), at the fixed elevation of 57\(^\circ\), over a time-adaptive azimuth sector centered on the sun position. The scan started in the early afternoon with the antenna pointing approximately 2\(^\circ\) below the sun position (~59\(^\circ\) elevation) and went on for about 40 min, until the sun position was approximately 2\(^\circ\) below the fixed antenna elevation (~55\(^\circ\) elevation). The azimuth resolution was held constant at 0.1\(^\circ\), while the resulting effective elevation resolution varied between 0.05\(^\circ\) and 0.08\(^\circ\) during the scan period. The data were successively corrected to account for the sun time-dependent relative position and reprojected onto a Cartesian plane with 0.05\(^\circ\) resolution both in azimuth and elevation (Fig. 3). The power-averaged value of \(Z_{dr}\), computed within the 3-dB beamwidth of the radar antenna, is 0.16 dB.

2) WEATHER TARGET CALIBRATION

Two-dimensional video disdrometer, radar, and in situ aircraft-based observations show that on average the shape of falling raindrops can be approximated by oblate spheroids as a function of diameter. Moreover, on average they are oriented with the symmetry axis in the vertical direction. These considerations imply that the shape of raindrops seen at an elevation angle of 90\(^\circ\) is nearly circular. This means equal received power from rain droplets in \(h\) and \(v\) polarizations and then any nonzero observation can be directly attributed to the radar system bias between the two polarization channels. This bias takes into account the differences in both receiver gains and bandwidths, as well as differences in transmitted powers.

Here, the results of \(Z_{dr}\) calibration as determined by sounding rain with antenna at vertical incidence are described. The radar data used to find the \(Z_{dr}\) system bias were collected on 14 August 2010. They refer to a rainstorm that started around 0930 local time and lasted for more than 10 h on the radar. Every 5 min, polarimetric radar data in elevation scan mode were recorded at the azimuths of 340\(^\circ\) and 359\(^\circ\). Following Baldini and Gorgucci (2006), an analysis was conducted to locate the melting layer. The top panel of Fig. 4 shows the time evolution of \(Z_h\) as a function of height. Moderate-intensity convective cells were embedded in the wide, long-lasting stratiform precipitation. This can be deduced by the noticeable signature of the bright band near 3.0 km MSL, clearly separating the ice from the
liquid region. The bottom panel of Fig. 4 shows the corresponding time evolution of $Z_{dr}$ with the well-known characteristic of showing $Z_{dr}$ values close to zero in both the ice region and the region containing precipitation. Within the melting layer, $Z_{dr}$ presents values with high variability (Baldini and Gorgucci 2006). During the observation period, moderate precipitation was measured on the ground. Figure 4 shows that for the vast majority of the time, the layer between 2425 and 2675 m is not affected by melting processes and that it can be considered as filled by the rain medium for the entire duration of the storm. This layer was chosen to calculate the bias on $Z_{dr}$ estimates. Figure 5 shows the frequency histogram of all the $Z_{dr}$ measurements obtained from the above-mentioned layer. A $Z_{dr}$ bias of 0.26 dB is found, with a standard deviation of 0.15 dB. This value is very close to the bias obtained using the sun, which is, however, representative of the receiving path only. The difference between the $Z_{dr}$ bias obtained using the sun and the one estimated from the rain medium is only 0.06 dB. Figure 6 shows the mean $Z_{dr}$ profile as a function of height, using the same $Z_{dr}$ data as in the bottom panel of Fig. 4. It is important to emphasize that there are two regions in the profile immediately above and below the bright band where the $Z_{dr}$ bias has a fairly constant value. This result reinforces the fact that both dry aggregated snow regions and the rain medium can be used for the $Z_{dr}$ calibration (Ryzhkov et al. 2005).

An extensive analysis of the different case studies is summarized in Table 2, where the mean and standard deviation for the three layers with a thickness of 375 m and located at 2.5, 4.3, and 6.0 km are reported. A comparison among the different days and for the different layers does not show a substantial difference in terms of the mean value and standard deviation of $Z_{dr}$.

To study the behavior of the $Z_{dr}$ bias in the presence of the dry radome from each case study, only data for which no precipitation was observed on the ground near the radar were considered. An example of such data is shown in Fig. 7. The radar data, obtained from the elevation scan with an azimuth angle of 359°, represent the $Z_h$ time evolution collected on 5 August 2010, at vertical incidence. In this case the time period chosen for the analysis was between 687 and 762 min, beginning at 0000 UTC. The overall results of the analysis for the cases of dry radome are shown in Table 3. The comparison between wet and dry radome conditions presents very similar values for the $Z_{dr}$ bias. Because bias changes were included in the standard deviation, it is difficult to establish the differences in the performance of $Z_{dr}$ in cases of dry and wet radome.

### Table 2. Mean (M) and standard deviation (SD) of $Z_{dr}$ with antenna pointing at vertical incidence for the three layers located at heights of 2.5, 4.3, and 6.0 km, having a common thickness of 375 m in the case of wet radome.

<table>
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<th></th>
<th>4.3</th>
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### b. $Z_h$ calibration

A precise and continuous absolute calibration of the radar is a critical task for maintaining the accuracy of
radar measurements. In recent years, the use of the self-consistency technique has become quite popular because radar calibration can be performed directly using meteorological echoes collected during routine observational activity and then it can account for any changes that occur. Although based on a simple concept, implementation of the self-consistency calibration is not straightforward and numerous details are important, especially for the attenuating frequencies such as those at C and X bands.

In this study, as previously mentioned, X-band radar data collected in elevation scan mode are used. For each ray, only the range bins with \( r_{pw} > 0.90 \) formed the path under analysis. The \( Z_{dr} \) profiles were corrected for the previously determined bias. The resulting reflectivity, differential reflectivity, and differential phase shift profiles were filtered using the technique of Hubbert and Bringi (1995) for radar signal high-frequency fluctuation reduction as well as for the backscatter differential phase shift correction. A procedure was then applied to obtain \( \Phi_{dp} \) profiles monotonically increasing in the range. All portions of the beam located below the melting layer and consisting of more than 20 consecutive range bins were selected. Within these constraints, the radar measurements refer to a rain medium. The corresponding \( Z_{h} \) and \( Z_{dr} \) profiles were corrected for attenuation \( (\alpha_{h}) \) and differential attenuation \( (\alpha_{d}) \) using \( K_{dp} \), and then \( \Phi_{dp}^{pw} \) profiles were obtained from \( Z_{h} \) and \( Z_{dr} \) measurements.

Comparison of the measured propagation phase shift \( (\Phi_{dp}^{m}) \), which is unaffected by absolute calibration of the radar system, with the computed propagation phase \( (\Phi_{dp}^{pw}) \) obtained from the \( Z_{h} \) and \( Z_{dr} \) measurements according to (4) can give robust information about radar calibration, once the \( Z_{dr} \) measurement is ensured to be unbiased.

5. Variability of the \( Z_{h} \) bias

The large scatter shown in Fig. 8 is an indication of a remarkable variability of \( Z_{h} \) bias during the rainfall event. This time-dependent reflectivity bias is modulated...
by the variability of the rainfall, which in turn determines an excess attenuation on the radome.

The main objective of this study is to test and validate the possibility that the correction technique of reflectivity based on the self-consistency principle can take into account the many different performances ascribed to the radome during the evolution of precipitation events. The procedure developed for this purpose is based on the use of corresponding profiles of $F_{dp}$ and $F_{pw}$ described in section 2. The profiles considered consist of all adjacent range bins containing a rain medium located as close as possible to the radar on which the measured differential phase shift reaches at least $5^\circ$. The chosen rain radar profiles all contain at least 20 range bins.

Equation (6) gives the correction to add to $Z_h$ to take account of the attenuation introduced by the wet radome. The time series of (6) give the different performance of the radome and then of excess attenuation as a function of time.

Figure 9 shows the variability of two-way losses introduced by the radome attenuation obtained using the relation (6) as a function of time expressed in minutes counted from the beginning of the day. The time series refers to the entire event, which lasted on the radar site for more than 10 h on 14 August 2010.

To verify how much the excess attenuation is related to the variability of precipitation on the radome, two methods were used. The first used the attenuation obtained from an empirical model that estimates the two-way losses due to a wet radome as a function of rainfall rate at the radar site, while the second employs rain gauge data for comparing the amount of rainfall with the corresponding $Z$–$R$ obtained utilizing reflectivity with and without bias correction.

a. Comparison with the power loss estimated from disdrometer rain rate

The first method is based on a reference wet radome loss estimated from the rain rate calculated using the DSD measured by the collocated laser disdrometer. To derive wet radome losses as a function of rain rate, the procedure proposed by Bechini et al. (2010) is followed. Disdrometer-measured DSD is used to retrieve both the rainfall rate and the horizontal radar reflectivity $Z_h$, calculated using a T-matrix code (Waterman 1979) in order to take into account possible Mie scattering effects at X band. The first valid range for the ARX (considering the far field, delays in the system, and near clutter) is around 800 m. The lack of closer measurements prevents a direct comparison with the disdrometer, which was located just several meters from the radar trailer.
compare the measurements of the two sensors, the following data selection procedure was applied:

- for every elevation scan, all radar measurements (0° to 360° in azimuth) are taken from the seventh gate (812.5-m range);
- calculate the mean $Z_h$ and standard deviation $\sigma(Z_h)$ for the obtained distribution for every elevation;
- if $\sigma(Z_h) < 3$ dB, then retain the data for the given time and elevation;
- compare with the 5-min average disdrometer reflectivity and calculate the bias (dB): $Z_h^\text{radar} (\text{dBZ}) - Z_h^\text{disdro} (\text{dBZ})$, where $Z_h^\text{radar}$ is obtained incorporating the dry radome attenuation (0.3 dB one way) in the radar constant.

The constraint on the standard deviation of $Z_h$ ensures that the precipitation is relatively uniform around the radar site. In fact, if the variability of the reflectivity on the circle with a radius of 812.5 m is low, then a similar intensity (within the observed standard deviation) can be expected all over the area enclosed by the circle, including the radar. Under the same assumption of the uniform precipitation field, the X-band path attenuation was computed with the T-matrix code from the disdrometer DSD data and used to correct the radar reflectivity on the circle. The values of the bias were calculated for every radar elevation.

It is known that the radome attenuation mainly depends on the thickness of the water film flowing on its surface, which in turn is a function of the rate of precipitation (Anderson 1975). Therefore, an experimental power-law relation was assumed to express the one-way power loss $L$ (dB) due to the wet radome, as a function of the rain rate $R$ (mm h$^{-1}$):

$$L = -\text{bias}/2 = L_0 + aR^{b/3} \text{ (dB)},$$

where the factor 2 in the bias takes into account the fact that the measured bias results from the two-way (transmit and receive) propagation through the radome. A nonzero $L_0$ may arise from the existence of a threshold under which the radome attenuation becomes negligible, and consequently the validity of (7) would be limited to values above a given rain rate. In fact, at low rain rates a water film may not form on the radome, with consequently very low expected attenuation.

To find the coefficients $a$ and $b$ in (7), a linear regression with a varying coefficient $b$ is performed until the mean square error (MSE) is minimized. The MSE reaches a minimum for $b \sim 0.3$. In the case of laminar flow, the water layer thickness for a hemispherical radome is proportional to $R^{1/3}$ (Gibble 1964). The fit to Eq. (7) with $b = 1/3$ actually shows that the observed power loss is roughly proportional to $R^{1/3}$, that is, to the theoretical water film thickness.

The obtained coefficients for $b = 1/3$ are $a = 1.75$ and $L_0 = -0.34$ dB. Substituting into Eq. (7), this becomes

$$L = -0.34 + 1.75R^{1/3} \text{ (dB)}, \quad 0.05 < R < 25 \text{ mm h}^{-1}.$$ 

(8)

Figure 9 shows the time series of the two-way radome loss computed using (8) applied to the 1-min rain rate retrieved from the DSD measured by the disdrometer located close to the radar (solid line). Superimposed are the loss estimates from the radar elevation scans using the self-consistency technique (dotted line with filled circles). The agreement between the two time series is remarkable, with the self-consistency loss values being in general higher (median value of 5.9 dB) than the disdrometer-based empirical estimates (median value of 4.8 dB). Interpolation of the 1-min disdrometer estimates to the radar scan times allows for calculation of a correlation coefficient of 0.86 between the two time series.

b. Comparison of estimated rainfall accumulation with rain gauge measurements

Another independent validation for checking the ability of the self-consistency calibration to take into account the excess attenuation due to the precipitation on the radome can be carried out by comparing rain gauge measurements with radar rainfall estimates obtained by a $Z$–$R$ relation when $Z$ is used with and without bias correction. Because of the height of the radar location, the radar beam was, of course, well below the melting layer and simultaneously without ground clutter contamination when the 0° elevation angle was used. Figure 2 shows the map with the relative location of four rain gauges with respect to the two directions of elevation mode scans. One rain gauge (S3926) is along the 340° azimuth at a distance from the radar site of 12 km and three (107, S3254, S2891) are along the 359° azimuth at a distance of 19.6, 23.6, and 25.5 km from the ARX, respectively. The distance between the rain gauges and the nearest radar bin along the elevation scan varies between 490 m ($S2891$) and 2100 m ($S3254$). The rain gauges are of the tipping-bucket type, with a time resolution of 1 min and a minimum recorded rainfall amount of 0.2 mm. The range bin closest to each rain gauge was selected as the center of a window containing five range bins spaced 125 m apart. Radar rainfall estimation obtained by

$$R = 0.196Z_R^{0.523} \text{ (mm h}^{-1})$$

(9)

was computed in each range bin of the window to give the average precipitation. A simulation was performed, for the same conditions mentioned in section 2, to find
the parameters of Eq. (9) in which the true rain rate $R$ is obtained by integrating $\nu(D)D^3N(D)$, where $\nu(D)$ is the drop terminal velocity, which can be approximated as $\nu(D) = 3.78D^{0.67}$ (Atlas and Ulbrich 1977). Once $Z_h$ is corrected for attenuation due to propagation using (5a), rainfall is estimated using (9) for $Z_h$ and for $Z_h$ corrected by the wet radome attenuation. Because elevation scans were collected approximately every 5 min, the 1-min rain gauge accumulations were aggregated and synchronized to the corresponding radar intervals.

Figure 10 shows the time series of rainfall accumulation (solid black line) for the four rain gauges used: S3926 (Fig. 10a), 107 (Fig. 10b), S3254 (Fig. 10c), and S2891 (Fig. 10d). Reported in each panel are the accumulated radar estimates obtained using $Z_h$ without (dashed gray line) and with (solid gray line) wet radome correction for the case of 14 Aug 2010.

Fig. 10. Time series of rainfall accumulation from the four rain gauges: (a) S3926, (b) 107, (c) S3254, and (d) S2891 (solid black line), with the corresponding radar accumulation obtained using $Z_h$ without (dashed gray line) and with (solid gray line) wet radome correction for the case of 14 Aug 2010.
corresponding mean rain gauge accumulations normalized to the latter.

Table 4 shows the merit factors of the comparison between radar and gauge rainfall accumulation with and without radome correction. The excellent performance of the correction based on the self-consistency principle is highlighted by the reduction in nearly a factor of 2 of the NSE between the corrected and uncorrected Z_h and the near cancellation of the bias between the two estimates.

6. Conclusions

Weather radar antennas are usually enclosed within a radome that is designed to have a minimal impact on its electrical performance. Unfortunately, this condition deteriorates in the presence of precipitation, inducing attenuation and increasing transmission losses. For this reason, radar calibration may be affected by biases.

Polarimetric weather radar can be calibrated in real time using meteorological echoes collected during routine measurements. This procedure implies that Z_h is unbiased. A detailed analysis has been conducted on Z_h measurements collected by the ARPA polarimetric radar in Piemonte, Italy (ARX), with wet and dry radome and the results are compared with those obtained using the sun as a radiation source. The different estimates have comparable mean values, with their difference lying within a standard deviation. A Z_h bias is found with a value very close to the bias obtained using the sun. An extensive analysis of Z_h bias conducted for three layers at different heights does not show a substantial difference in terms of averaged value and standard deviation. Furthermore, a parallel analysis on \( \Phi_{dp}(0) \) reveals that differential phase measurements are weakly affected by a wet radome. In the light of these findings, a calibration based on self-consistency can be performed, providing a real-time estimation of the excess attenuation due to the rainfall at the radar site. The obtained bias estimation is then used to adjust the measured reflectivity.

Validation of the method is based on the comparison between the additional attenuation obtained by self-consistency with that found with an empirical model using precipitation data obtained by a laser disdrometer at the radar site. The two profiles as a function of time show a similar variability on the time scale as well as a good agreement between estimated attenuation values. A mismatch occurs at the end of the precipitation event that can be explained in terms of the persistence of wet radome conditions.

A quantitative validation of the excess attenuation correction is obtained comparing radar and gauge rainfall accumulation with and without radome correction. The analysis based on 2-h precipitation accumulations shows an excellent performance of the self-consistency method to correct the measured reflectivity as assessed by the reduction of the normalized standard error of about a factor of 2 and by the reduction almost to zero of normalized bias.

On the whole, the analysis based on the rainfall comparison shows very clearly that the self-consistency method is an efficient real-time correction of the effects introduced by a wet radome.

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