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ON THE USE OF A POLARIMETRIC X-BAND WEATHER RADAR FOR VOLCANIC ASH CLOUDS MONITORING

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1. INTRODUCTION

The detection and quantitative retrieval of volcanic ash clouds is of significant interest due to its environmental, climatic and socio-economic effects (Cadle et al., 1979). Ash fallout might cause hardship and damages in volcano's surrounding area representing a serious hazard to aircrafts (Casadevall, 1994). Real-time monitoring of such phenomena is crucial, also for the initialization of dispersion models. Satellite visible-infrared radiometric observations from geostationary platforms are usually exploited for long-range trajectory tracking and for measuring low level eruptions (Rose et al., 2000). Their imagery is available every 15-30 minutes and suffers from a relatively poor spatial resolution. Moreover, the field-of-view of geostationary radiometric measurements may be blocked by water and ice clouds at higher levels and their overall utility is reduced at night.

Ground-based microwave weather radars may represent an important tool to detect and, to a certain extent, mitigate the hazard from the ash clouds (Maki et al., 2001; Marzano et al., 2006b). The possibility of monitoring in all weather conditions at a fairly high spatial resolution (less than few hundreds of meters) and every few minutes after the eruption is the major advantage of using ground-based microwave radar systems. Ground-based weather radar systems can also provide data for determining the ash volume, total mass and height of eruption clouds. Previous methodological studies investigated the possibility of using ground-based single-polarization radar system for the remote sensing of volcanic ash cloud (Marzano et al., 2006a,b). A microphysical characterization of volcanic ash was carried out in terms of dielectric properties , size distribution (i.e., Gamma or Weibull functions) and terminal fall speed, assuming spherically-shaped particles (Marzano et al., 2006a). A prototype of volcanic ash radar retrieval (VARR) algorithm for sinlge-polarization systems was proposed by Marzano et al. (2006b) and applied to S-band and C-band weather radar data volumes (Marzano et al., 2010a, 2010b).

The potential benefit derived by the use of dual-polarization radar systems at X band has been tested by Maki et al. (2001) and investigated by Marzano et al. (2011) within a simulated framework. An overall algorithm, named VARR-PX (VARR Polarimetric at X band), for X-band radar polarimetric retrieval of volcanic ash clouds from measured dual-polarization reflectivity, was proposed by extending the VARR approach. VARR-PX is based on four cascade steps: i) monitoring of active volcano through a method based on analysis of reflectivity radar data time series associated with in-situ information and satellite-derived products; ii) tracking of ash plume based on a pattern matching approach applied on radar images; iii) classification of ash plume through a method based on the vectorial Bayesian theory; iv) retrieval of ash amount and fall rate from the polarimetric signatures through parametric models.

This preliminary work is aimed at 1) qualitatively verifying the microphysical and scattering model assumptions by comparing polarimetric radar signatures from simulations and observations, 2) testing the sensitivity of the retrieval algorithm with respect to input polarimetric variables. For these purposes, data from the first polarimetric X-band radar specifically devoted to ash cloud observation and installed near the Mt. Etna volcano in south Italy, are analyzed.

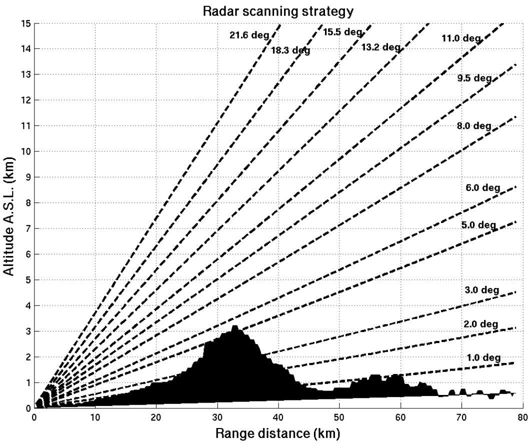

Figure 1 Scan strategy operationally adopted for the mobile X-band radar located at the Catania airport (Sicily, Italy). The profile of the Etna (3350 m a.s.l) volcano is also displayed

2. DATA SET DESCRIPTION

The observations of volcanic ash clouds through weather radars are quite limited, most of them has occasionally been carried out by meteorological radars of national weather services. During Mt. St. Helens volcanic activity of 1980-1982 there was a unique opportunity to collect observations using U.S. National Weather Service radar system at C band in Portland, Oregon (Harris and Rose, 1983). Recently, the explosive eruptions of the Icelandic Hekla volcano in 2000 (Lacasse et al., 2004), the Grimsovtn volcano in 2004 (Marzano et al., 2010a) and the Augustine volcano in Alaska in 2008 (Marzano et al., 2010b) were investigated through weather radar measurements.

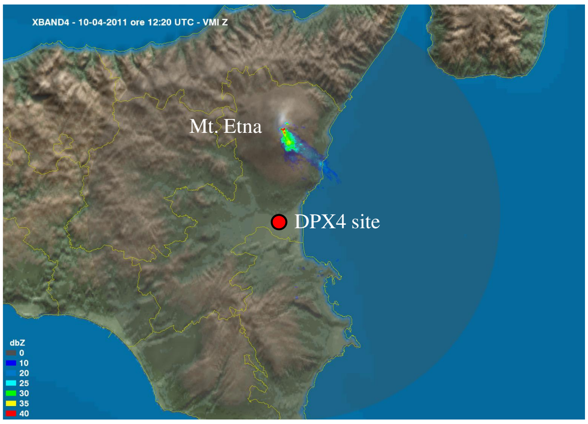

Figure 2 Volcanic ash signature at X band is quite evident from Vertical maximum intensity (VMI), observed at 12:20 UTC on 10 April 2011.

The volcanic ash cloud, generated by the Etna eruption occurred on April the 10th 2011, was clearly observed by the mobile polarimetric X-band radar (named DPX4) located inside the Catania airport (about 30-km far from the volcano vent at 40 m a.s.l.). The radar system, managed by the Italian Department of Civil protection, is operationally used either for weather or for volcanic ash monitoring, it being part of the national weather radar network.

The DPX4 system continuously operates with a volumetric scanning frequency of 10 minutes. The scanning strategy, composed by 12 elevations, is depicted in Figure 1. The adopted pulse repetition frequency (PRF) is 1875 Hz, resulting in a maximum unambiguous range of 80 km, the range resolution is 200 m. The 3-dB beam width is 1 deg.

The analyzed volcanic eruption event started on April the 8th 2011 and was characterized by an increase of the ash emission on April the 10th from 9.30 UTC to 13.00 UTC, with the maximum intensity registered around 11.00 UTC. The ash emission finished around 1600 UTC. Figure 2, depicting the vertical maximum intensity (VMI) observed at 1220 UTC by DPX4, clearly shows the south-west dispersion direction of the ash cloud.

3. DATA PROCESSING

The radar data processing can take benefit from the experience matured for the observations of weather phenomena (such as clouds and precipitation). As depicted in Figure 3, the radar data processing begins with the compensation of system offset on differential reflectivity according to the bias estimated considering the expected value of Z_{dr} in light rain conditions prior that eruption occur and for negligible rain path attenuation conditions (identified by $20<Z_{hh}<30$ dBZ) by resorting to a Z_{hh}-Z_{dr} relationship derived from scattering simulations. Next, the undesired echoes (i.e. signals due to surrounding mountains) are identified and corrected through a synergic use of clutter map, radial velocity and polarimetric texture analysis (Vulpiani et al., 2011). For volcanic ash applications the meteorological targets also belong to the class of undesired echoes and, consequently, they should be removed as well. Fortunately for the analyzed case study, clear sky conditions were observed during the eruption period making the suppression of meteorological target unnecessary.

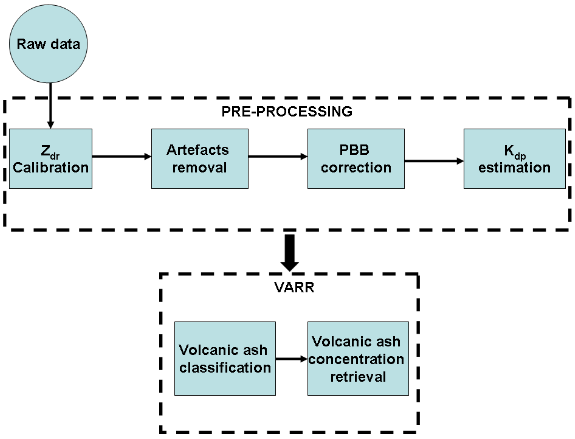

Figure 3 Block diagram showing the applied data processing chain.

The reflectivity data are then corrected for partial beam blocking effects. In this respect, an Electromagnetic Propagation Model (EPM) is used to identify the obstructed radial directions. The partial beam blockage (PBB) map, representing the occultation degree at a specific antenna elevation, is then retrieved by resorting to the simplified obstruction function proposed by Bech et al. (2003), assuming the wave propagation in the standard atmosphere (Doviak and Zrnić 1993). The estimated PBB is then compensated up to 70% as in Tabary (2007). The last step of the pre-processing is devoted to the estimation of specific differential phase K_{dp} by adapting the retrieval scheme proposed for hydrometeors by Vulpiani et al. (2011) to the typical volcanic ash signature.

The VARR-PX scheme is then applied considering all the available polarimetric measurements, i.e., Z_{hh}, Z_{dr}, ρ_{hv}, and K_{dp}. The VARR-PX algorithm consists of two main step: 1) classification of radar echoes with respect to ash particle size (fine ash: FA, coarse ash: CA, small Lapilli: SL, Large Lapilli: LL), mass concentration C_a (small: SC, medium: MC and intense: IC) and falling orientation (prolate: PO, oblate: OO, and thumbling: TO); 2) the mass concentration is estimated by applying a suitable parametric power law (i.e., $C_a=aZ_{hh}^b$)

according to the results of the classification step (Marzano et al., 2006b, 2011).

4. RESULTS

Preliminary results, obtained by applying VARR-PX to the DPX4 radar data, are discussed below.

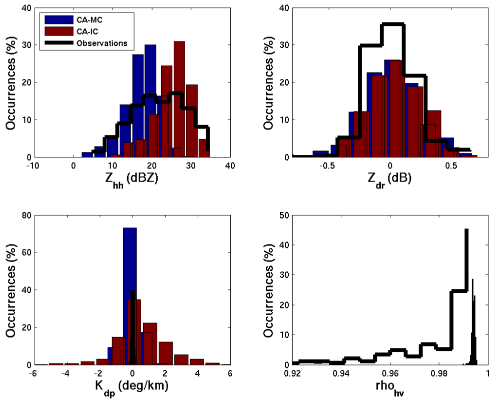

Figure 4 Histograms of polarimetric radar signatures of coarse volcanic ash particles in moderate (CA-MC) and intense (CA-IC) concentrations, respectively, as obtained from scattering simulations. Corresponding radar observations of the event of April, 10 2011 are also superimposed (as black curves).

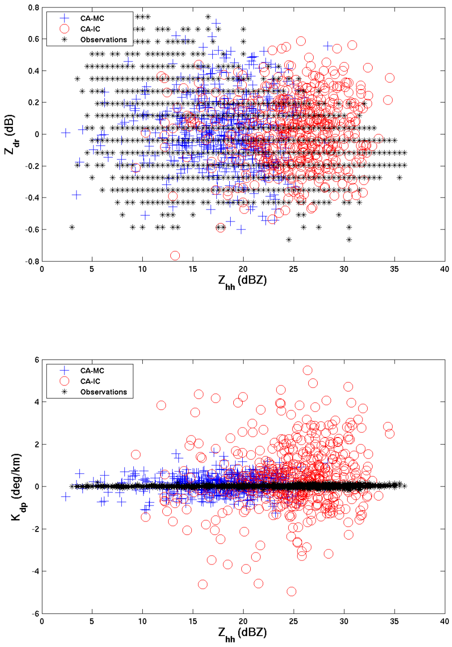

Figure 5 Scatterplots of Z_{dr} vs Z_{hh} and K_{dp} vs Z_{hh} of coarse volcanic ash particles in moderate (CA-MC) and intense (CA-IC) concentrations, respectively, as obtained from scattering simulations. Corresponding radar observations of the event dated 10 April 2011 are also superimposed.

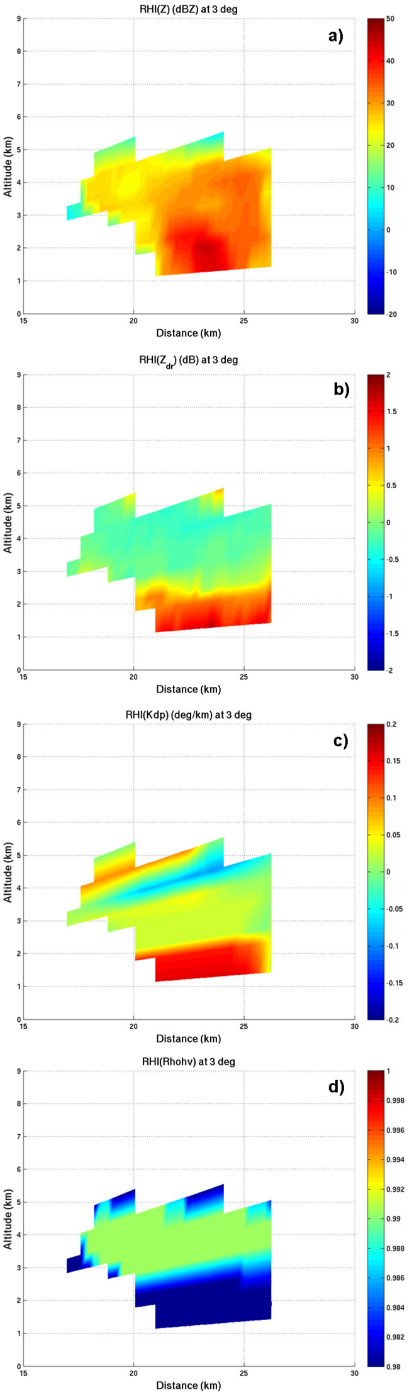

Figure 6 RHIs at 3 deg of azimuth of Z_{hh} (panel a)), Z_{dr} (panel b)), K_{dp} (panel c)) and ρ_{hv} (panel d)) as retrieved from volumetric scan at 1330 UTC on April the 10th 2011.

The echoes observed at altitudes higher than the Mt. Etna volcano peak (about 3.2 km) at medium distances (from 10 to 40 km), where lapilli are not expected due to gravity reasons, were found to be characterized by reflectivity values ranging between a few decibels to about 35 dB, while Z_{dr} was found to be symmetrically distributed between -0.5 dB and 0.5 dB with most of the values ranging in the interval $-0.25<Z_{dr}<0.25$ dB.

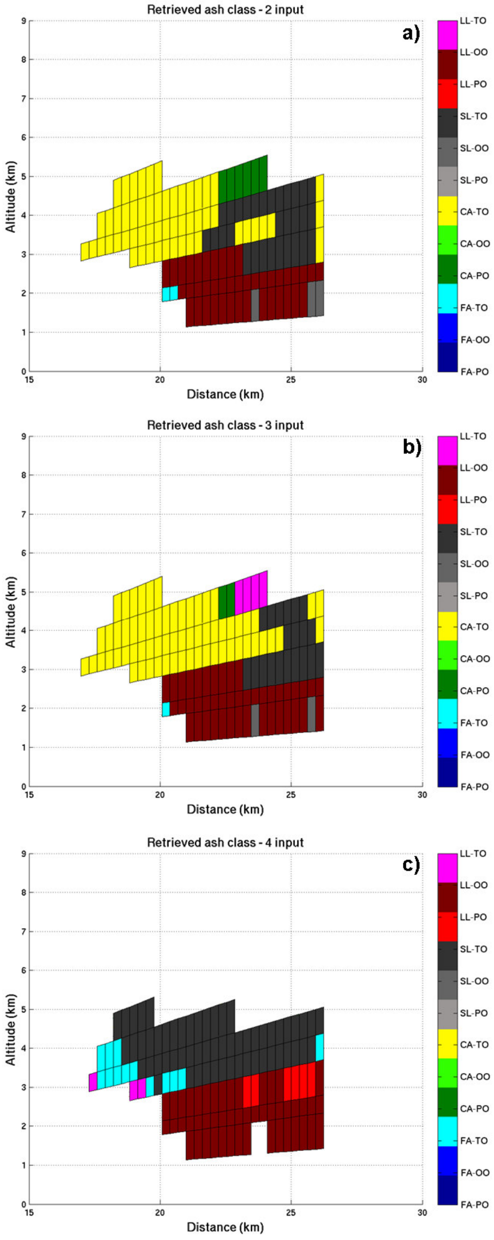

Figure 7 RHIs at 3 deg of azimuth of the classified volcanic ash particle using, respectively, 2 (upper panel), 3 (middle panel) and 4 input (lower panel), as retrieved by applying the VARR-PX algorithm.

Considering that the typical Z_{dr} accuracy is about of 0.2 dB and that the ash particle shape is generally very irregular, it can be argued that the apparent ash falling mode was thumbling. This hypothesis is also confirmed by the relatively high correlation coefficient, mainly greater than 0.98, and by approximately zero value for K_{dp}. Figure 4 shows the observed distribution of the polarimetric radar parameters (black line). Apparently, the observations match fairly well the scattering simulations of coarse ash in medium (CA-MC) and intense concentration (CA-IC), at least in terms of Z_{hh}, Z_{dr}, ρ_{hv}, while the dynamic interval of the estimated K_{dp} is significantly lower with respect to the model output.

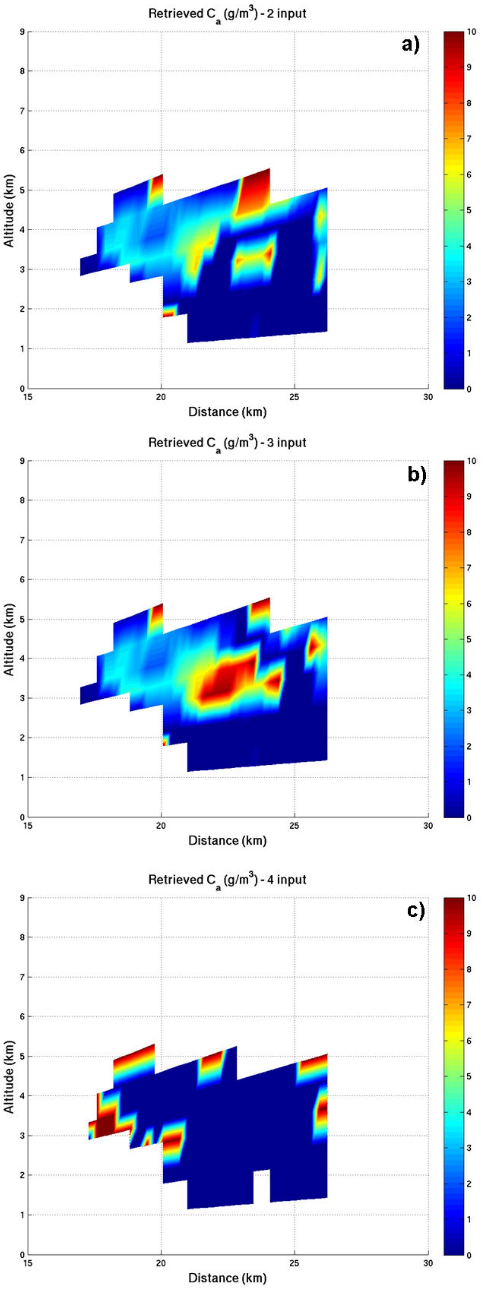

Figure 8 Same as in Figure 7 but relatively to the estimated mass concentration.

The same data are also displayed in Figure 5 in terms of scatterplot of Z_{dr} vs Z_{hh} (upper panel) and K_{dp} vs Z_{hh} (lower panel). From this Figure there is a low correlation among the polarimetric variables. This means that polarimetric observables are independent from an information content point of view, a property which should indicate the benefit of using multi-parameter relationships as in the case of rainfall estimation (e.g., Vulpiani et al., 2011).

In order to qualitatively assess the performance of the VARR-PX algorithm, the consistency between radar observables, output of the classification algorithm and estimated mass concentration is evaluated. Figure 6 shows the RHIs of the polarimetric variables at 3-deg of azimuthal angle, as derived from the volumetric scan started at 13.30 UTC. On the one hand, it can be noticed that above about 3000 m height the values of Z_{dr} are generally very close to zero, the correlation coefficient is quite high, while K_{dp} is not reliable, it being of the same order of the noise level. This suggest that at relatively high altitudes, where small (median diameter of about 10^{-2} mm) to coarse (median diameter of about 10^{-1} mm) ash particles are generally expected, the mean wind is probably responsible for the thumbling motion. On the other hand, it is clear that at lower altitudes the ash particles are generally falling with the main axis aligned in the horizontal direction, i.e. positive Z_{dr}, K_{dp}, and relatively low ρ_{hv}. The relatively high values of reflectivity are also symptomatic of relatively big particle sizes.

If the VARR-PX classification algorithm is applied to radar RHI data, it is possible to detect the ash class, as shown in Fig. 7. This step can be carried out for different input configuration of the VARR-PX algorithm, i.e. 2 inputs (Z_{hh} and Z_{dr}), 3 inputs (Z_{hh}, Z_{dr} and K_{dp}) and 4 inputs (Z_{hh}, Z_{dr}, K_{dp} and ρ_{hv}). The VARR-PX algorithm attempts to discriminate between the following classes: Fine Ash (FA), Coarse Ash (CA), Small Lapilli (SL) and Large Lapilli (LL), characterized by Oblate Orientation (OO), Prolate Orientation (PO) and Thumbling Orientation (TO), respectively.

The ash class spatial distribution in Fig. 7 closely follows the evolution of the radar reflectivity. The classified ash types are generally the same below 3000 m for all the algorithm configurations, i.e. the prevailing identified ash class is Large Lapilli with Oblate Orientation (LL-OO). The 2- and 3-input VARR-PX configurations provide similar results also at higher altitudes, except for the unrealistic detection of LL above 4500 m obtained using K_{dp} as additional input. However, considering that K_{dp} is an estimated quantity characterized by a standard deviation of about 0.05 deg km^{-1} (Vulpiani et al., 2011), it is reasonable to consider the 2-input configuration more reliable above 3000 m, in this specific case.

At relatively high altitudes and distances farther than a few km the FA and CA are more likely to be expected with respect to SL and, especially, LL. This might lead to infer that the results obtained above 3000 m with the 4-input configuration may be questionable, even if its estimated pattern is not improbable considering the Mt. Etna peak is at 3350 m. (from Fig. 7 we have SL near the vent and FA in the surrounding region).

As a further step, Fig. 8 shows the results in terms of estimated ash concentration C_a obtained by applying the VARR-PX retrieval technique to the measured reflectivity RHI data. The spatial pattern of estimated C_a does not strictly resemble that of radar reflectivity in Fig. 6a. This is due to the fact that a given reflectivity may be due either to a low concentration of bigger particles or to a high concentration of smaller particles (Marzano et al., 2006a). By applying VARR-PX classification, we can address this ambiguity by identifying regions of fine, coarse, and large ash particles. This is particularly evident below 3000 m. for all VARR-PX input configurations where the low amount of lapilli, causing high radar reflectivity, is contiguous to regions of large amount of coarse ash particles (2 and 3 input configuration) or low amount of small lapilli (4 input configuration).

CONCLUSIONS

After the emergency arisen in 2010 by the Eyjafjallajokull volcano eruption in Iceland, a renewed interest on real-time monitoring of volcanic ash cloud shows up within the international community. Among the remote sensors, weather radars might provides a partial solutions either for short to medium cloud detection and tracking or for mass concentration estimation. The X-band is generally preferable providing higher sensitivity with respect to lower frequency band typically used for weather observations.

After a few sporadic C-band radar observations of volcanic ash, one of the first documented volcanic ash cloud detection using an operational X-band polarimetric radar, is illustrated in this work. In order to assess the microphysical and electromagnetic modelling proposed in previous studies, the consistency between radar observations and simulations has been tested. A prototype of the polarimetric version of the VARR algorithm at X band, called VARR-PX, has been evaluated for distinct input polarimetric variable configurations.

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