Microwave radar signatures of precipitation from S band to $K_a$ band: application to GPM mission

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Abstract
Radars at different frequencies have been used over five decades for observing precipitation. S and C bands have been employed for long range coverage observations. Dual-polarization X-band radars have been shown to be useful for networked applications. Space borne precipitation radars have been at $K_u$ band, or higher frequencies such as $K_a$, as in the GPM mission. This paper presents a comprehensive and unified view of radar precipitation observations at these bands, highlighting the advantages, limitations and the specific applications associated to them. Moreover, relationships between radar measurements at different bands in rain are illustrated. Examples of their use to predict attenuation margin and to simulate observations of the dual polarization, dual frequency $K_u$ and $K_a$ scanning radar D3R to be used in the ground validation program of the GPM mission are shown.

Keywords: Weather radar, precipitation, dual polarization, specific attenuation.

Introduction
Microwave radars at various frequencies from S to W band have been used over five decades for observing and monitoring precipitation [WMO-ITU, 2009]. The choice of system frequency is determined by a combination of precipitation physics, application and engineering requirements, and economics. In fact, aspects like attenuation effects, maximum range of measurements, sensitivity, size of the antenna, and the overall cost of the system are closely related to the radar operating frequency. Radars at S- and C-band are used extensively as part of networks of national weather services for long range coverage observations obtained through radar scans at quasi-horizontal elevations. S-band (2.700-2.900 GHz), adopted by the NEXRAD network in the US, is mostly not affected by attenuation resulting from precipitation. Exceptions are regions of wet hail or intense squall lines aligned along a radar radial. They are typically expensive because of the large antennas needed to achieve narrow beams (typically 1-deg beamwidth) and high-power transmitters to cover large areas with high space resolution. The C band (usually 5.600-5.650 GHz) is in general preferred for use in Europe and Canada, representing a good compromise between sensitivity, impact of attenuation and cost of the system, the latter resulting from both lower transmit power and smaller antennas in comparison with S-band systems with the same spatial resolution. X-band frequencies (9.300-9.500 GHz) are adopted because they allow to build more sensitive and inexpensive systems (often they are also
transportable) but, experiencing higher attenuation, they were originally limited to target short range applications. Dual-polarization weather radar were introduced at the end of 1970s [Seliga and Bringi, 1976]. Differently from a conventional, single-polarization radars that transmit and receive waves with a single, usually horizontal, polarization, dual polarization radars transmit and receive horizontal and vertical polarizations, providing essentially a set of elements of the dual-polarization covariance matrix of precipitation. Definitions of the most common dual-polarization measurements are illustrated in the section “Polarimetric radar measurements in rain”, while a description of the different configuration of dual polarization radars can be found in textbooks (e.g., Bringi and Chandrasekar [2001]). After two decades of experiments carried out at several research installations, since year 2000 most of weather services have started plans to upgrade their radars to dual-polarization with the objective to achieve more reliable precipitation estimation, hydrometeor classification, even in the presence of attenuation effects. Actually, dual polarization techniques have allowed to mitigate the impact of attenuation on radar measurements based on return powers [Bringi et al., 1990; Gorgucci et al., 2006] at C- and X- band, whereas advance in processing of differential phase shift to determine robust estimation of its derivative (namely, the specific differential phase shift) [Wang and Chandrasekar, 2009] which is nearly linearly related to rainfall rate, has determined improvement in obtaining robust quantitative precipitation estimation [Wang and Chandrasekar, 2010]. Recently, dense networks of small, low cost X-band dual-polarization radars have been pursued by the CASA (Collaborative Adaptive Sensing of the Atmosphere) engineering center to sensing precipitation close to the ground, mitigating the impact of Earth curvature on systems conceived for measurements at far distances, such as S-band systems [McLaughlin et al., 2009]. At higher frequencies the impact of attenuation resulting from precipitation needs to be resolved for successful implementation at horizontal elevation angles. Actually, radars are also implemented at the frequencies of K_a, K_s, and W band (avoiding bands of water vapor and oxygen absorption) and are typically employed for vertical profiling of clouds and precipitation [Kollias et al., 2007 and references therein]. At these wavelengths, radars have excellent sensitivity to small cloud droplets and ice crystals. Their compact size makes them deployable on aircrafts and satellites. Two missions with precipitation radars (PR) are currently on Earth orbit, namely the NASA/JAXA Tropical Rainfall Measurement Mission (TRMM) and the NASA CloudSat. The first mission uses a K_u-band radar (13.8 GHz) [Kozu et al., 2002], while CloudSat uses a more sensitive but attenuation-prone radar at W-band (94 GHz) [Tanelli et al., 2008]. The core satellite of the NASA/JAXA Global Precipitation Measuring (GPM) mission, expected to be launched in 2013, will be equipped with a dual-frequency precipitation radar (DPR) system that uses the same K_s frequency of the TRMM precipitation radar jointly with a K_a frequency (35.6 GHz) [Shimizu et al., 2006]. Concerning airborne radars, it worth mentioning the dual-frequency (K_u- and K_a-band), dual-polarization Doppler rain profiling radar, known as Airborne Precipitation Radar-2 (APR-2) developed at the Jet Propulsion Laboratory [Sadowy, 2003] as a prototype for future satellite missions such as GPM that has been employed in many campaigns around the globe. As shown, specific applications are usually associated with different frequency bands. To study emerging, non conventional, radar applications, it is convenient to build the design process upon extensive data sets of observations available at different bands. Theoretical modeling allowing to build realistic scenarios at target frequencies based on existing datasets (typically at S and C-band) can be conveniently used to define relevant parameters of the new system and to a priori verify its suitability with respect to the goals of target applications. This paper aims to present a comprehensive and unified view of radar observations of precipitation at the bands ranging from S to K_a based on the precipitation radar signatures at the different frequencies, focusing on aspects
related to the dual polarization technique. Examples of applications, namely the attenuation margin and prediction of reflectivity and differential reflectivity fields, are focused on scanning radar at frequency higher than X-band such as the D3R radar, included in the ground validation plan of the NASA/JAXA GPM mission. This system is a fully polarimetric, scanning weather radar system operating at the frequencies of 13.91 GHz and 35.56 GHz covering a maximum range of 30 km. The frequencies chosen allow close compatibility with the GPM DPR system. The D3R will operate as a scanning weather radar system to cover a maximum range of 30 km (http://pmm.nasa.gov/science/ground-validation/D3R last access November 2011).

The second section of the paper will shortly describe measurements typically provided by dual polarization radar and their relationship with parameters describing microphysical properties of precipitation. The section “Methodology” will illustrate the simulation methodologies adopted in the paper. The section “Results” is composed of three subsections, concerning the relationships between radar observables in rain collected at different frequencies as resulting from and electromagnetic simulation, and two applications. The first concerns minimum detectable signal and attenuation margin in rain for typical parameters of systems operating at frequencies up to that of the K_a band. In the second, simulations of observations of the D3R radar, part of the GPM ground validation program, based on S-band observation, are presented. The “Conclusions” section will summarize relevant outcomes of the paper.

Polarimetric radar measurements in rain

For radar meteorology applications, precipitation is described by a set of microphysical properties. The same set allows to model both relevant bulk precipitation parameters and, jointly with an electromagnetic model, main polarimetric radar measurements, namely the reflectivity factor $Z_h$, the differential reflectivity $Z_{dr}$ and the specific differential phase shift $K_{dp}$ that will be defined in the following. An important component of the microphysical model is the drop size distribution (DSD) that describes the probability density distribution function of drop sizes. A gamma distribution model has been considered as adequate for many of the natural variations of the shape of DSD [Ulbrich, 1983]. In the normalized form, it can be expressed as

$$N(D) = N_w \frac{\Gamma(3)}{3.67^3} \left( \frac{3.67 + \mu}{\mu + 4} \right)^{\frac{D}{D_0}} \exp \left[-\left(3.67 + \mu\right) \frac{D}{D_0}\right] \quad \text{(mm}^{-1} \cdot \text{m}^3) \quad [1]$$

where $D_0$ (mm) is the median volume diameter, $\mu$ is a measure of the shape of the DSD, and $N_w$ (mm$^{-1}$ m$^{-3}$) is the normalized intercept parameter and $\Gamma$ is the gamma function. Both radar and rain parameters, such as rainfall rate or liquid water content can be expressed in terms of [1]. Reflectivity factors at horizontal or vertical polarizations (indicated by subscripts $h$ and $v$, respectively) can be expressed as

$$Z_{h,v} = \frac{\lambda^4}{\pi^2 K_w} \int \sigma_{h,v}(\lambda, D) N(D) dD \quad \text{(mm}^6 \cdot \text{m}^{-3}) \quad [2]$$

where $\lambda$ is the wavelength, $\sigma_{h,v}$ is the radar cross sections at $h$ or $v$ polarizations, and $K_w$ is the dielectric factor of water. They can be expressed in dBZ units by taking ten times the
logarithm of [2]. Since falling drops assume a shape that can be approximated as that of an oblate spheroid, the symbol $D$ in [1] expresses the equivalent diameter, defined as the diameter of the sphere having the same volume of the considered drop. Several equations have been proposed in the literature to model axis ratio of the drops ($b/a$ being $b$ and $a$ the semiminor and semimajor axis of the oblate spheroid approximating a raindrop) as a function of drop equivalent diameter (often referred to as shape-size relation). Given that $N(D)$ is expressed in terms of equivolume diameter, shape-size relation does not affect precipitation parameters like rainfall rate or liquid water content. Nevertheless, it is of capital importance for interpretation of polarimetric radar measurements in rain (see the review of the many shape-size relations and related studies referred in the literature that can be found in Gorgucci et al [2009]). As a consequence of the oblateness of drops, $Z_h$ is greater than $Z_v$ and the difference decreases as the elevation angle of radar increases to nullify for vertical observations. Typical dual polarization radars can measure $Z_h$ and $Z_v$ from which a further measurement, the differential reflectivity ($Z_{dr}$), can be obtained as the ratio of $Z_h$ and $Z_v$ [Seliga and Bringi, 1976]. Dependency to drop oblateness makes $Z_{dr}$ mostly sensitive to drop median volume diameter ($D_0$). Due to the oblate shape of falling drops, $Z_{dr}$ is greater than 1 (or, equivalently, greater than 0 dB). However, drops oscillate during their fall. These oscillations have an influence on $Z_{dr}$, since, on average, drops are seen by a dual-polarization radar as less oblate than expressed by the shape-size relation. A dual-polarization measurement related to propagation is the specific differential phase ($K_{dp}$), defined as

$$K_{dp} = \frac{180}{\pi} \lambda \text{Re} \left[ \hat{h} \cdot \hat{f}(\lambda, D) - \hat{v} \cdot \hat{f}(\lambda, D) \right] N(D) dD \quad \text{(deg} \cdot \text{km}^{-1}) \quad [3]$$

where $\hat{f}$ is the forward scattering amplitude and $\hat{h}$ s $\hat{v}$ are the unit polarization vector of the scattered field for $h$ and $v$ polarization, respectively. Therefore, $K_{dp}$ is proportional to the real part of the difference in the complex forward-scatter amplitudes at $h$ and $v$ polarizations, defined as the far-field vector scattering amplitude along the polarization vector of incident field. Differently from $Z_{dr}$, $K_{dp}$ is mostly sensitive to both concentration and shape. The two-way differential propagation phase $\Phi_{dp}$ is defined as twice the integral of $K_{dp}$ computed for a given propagation path. Dual polarization radar measures a differential phase shift $\Psi_{dp}$ which actually is the sum of $\Phi_{dp}$ and the differential phase shift upon backscattering. Attenuation is not measured by a radar, but can determine both extinction of precipitation returns or a bias in the radar measurements based on power returns such as $Z_h$ and $Z_{dr}$. Attenuation is expressed by integrating along a propagation path specific attenuation at two polarization states $h$ and $v$ that are defined as

$$\alpha_{h,v} = 4.343 \times 10^{-3} \lambda \text{Im} \int f_{h,v}(\lambda, D) N(D) dD \quad \text{(dB} \cdot \text{km}^{-1}) \quad [4]$$

To express effects of attenuation in differential reflectivity measurements, it is convenient to define a specific differential attenuation $\alpha_{dp}$ as the difference between $\alpha_h$ and $\alpha_v$. 


Methodology
Several methods have been proposed to investigate the dual-polarization microwave scattering and attenuation characteristics of specified populations of drops described by a microphysical model, especially at wavelengths where Rayleigh scattering hypothesis (drop diameter much smaller than the wavelength) is not satisfied. A popular one is the transmission matrix (T matrix) method [Waterman, 1971; Barber and Yeh, 1975] that allow to treat shapes such spheroids with adequate computational effort and, for the shape of drops and frequencies considered in this study, without convergence problem. This method is applied to a precipitation described by the microphysical parameters outlined in the previous section. In particular, raindrops are assumed to be described by the normalized gamma [1], whose parameters are widely varying. The ranges of DSD parameters are \(0.5 \leq D_0 \leq 3.5\) mm, \(3 \leq \log_{10} N_w \leq 5\), and \(-1 < \mu < 5\), with the further limitations of \(Z_h < 55\) dBZ at S-band and rainfall rates lower than 300 mm h\(^{-1}\).

Further assumptions concern the shape-size relation (that of Beard and Chuang [1986] is chosen), and the temperature (20\(^\circ\)). Raindrops oscillations are taken into account by assuming that canting angle of drops is a random variable. Usually this angle is modeled as a Gaussian random variable. Here, mean and standard deviation of 0\(^\circ\) and 7.5\(^\circ\), respectively, are assumed. Measurements are obtained assuming an elevation angle of 0 degrees. The frequencies of 2.8, 5.6, 9.3, 13.8, 35.6 GHz are assumed for S-, C-, X-, K\(_u\), and K\(_a\) band, respectively. Twenty thousand DSD triplets are used and corresponding radar measurements are estimated. By fixing a microphysical model of precipitation and generating polarimetric radar measurements at different frequencies as described above, it is possible both to study the relations between precipitation parameters and radar measurements at a given frequency (a method widely used to develop precipitation retrieval procedures) and to express a radar measurement at a given frequency as a function of the same measurement (or a set of measurements) at a different frequency via simple algorithms, or, exploiting measurements at different frequencies.

A further step would be to simulate range profiles maps, or volumes of radar measurements from existing high quality dataset of radar measurements. Chandrasekar et al. [2006] proposed different methods to simulate realistic profiles starting from S-band dual polarization measurements to generate realistic range profiles of radar variables at attenuating frequencies using fundamental microphysical properties of rain, namely, size and shape distribution information of frequency mapping method. Conditioning the simulation from S band measurements maintains the natural distribution of rainfall microphysical parameters. The methodology based on frequency mapping was successfully applied to develop X-band algorithms and radar network design [Mc Loughlin et al., 2009; Junyent and Chandrasekar, 2009; Wang and Chandrasekar, 2009, 2010]. Recently methodology has been extended up to the higher frequencies of K\(_u\) and K\(_a\) and applied to develop and test a microphysical retrieval procedure to be used with the of dual polarization and dual frequency ground radar D3R of the GPM ground validation segment [Le et al., 2011] and to simulate observation of snows at K\(_u\) and K\(_a\) frequencies from C-band dual polarization measurements [Leinonen et al., 2011].

Results
Relationships between radar observables at different frequencies
Different simulated radar parameters at different frequencies obtained from the electromagnetic simulation described above, are shown by the four scatterplots of Figure 1 (for clearness of the
scatterplots, only 1000 DSDs are shown in the figure). Reflectivity factor, differential reflectivity, specific differential phase shift and specific attenuation at C-, X-, K_u- and K_a- band frequencies are shown as a function of the corresponding measurement at S-band allowing a comparison at a glance among the considered measurements at different frequencies. Reflectivity factors are shown in Figure 1a. Under Rayleigh scattering assumptions, the radar cross section of a drop depends on $\lambda^{-4}D^6$. Therefore, the reflectivity factor will not change with frequency, being essentially the sixth moment of the DSD. Using the diameter variability of the set of DSDs described above, Rayleigh scattering hypothesis is almost satisfied at S-band, but at higher frequencies, resonance effects can arise (Fig. 1a). Such effects result in deviations from the bisector of the scatterplot which, at C-band, for $Z_h > 40$ dBZ and DSDs with high $D_0$ can reach up to 3 decibels. At higher frequencies, resonance effects start at lower $Z_h$, and for the K_a band, they are evident also at low reflectivities. S-band reflectivity factors lower than 40 dBZ correspond, at K_a-band $Z_h$ values that are, on average, greater than 1 dB. Conversely, to S-band reflectivity factors 50 dBZ, correspond K_u-band values that are, on average, lower than 6 dB with respect to the values at S-band. Conversely, S-band $Z_h$ values greater then 30 dBZ correspond to K_u-band values greater up to a couple of decibels. The comparison of $Z_{dp}$ at the different frequencies as a function of that at S-band is depicted by Figure 1b. Deviations from the bisector show effects of non Rayleigh scattering that determine the difference between the differential reflectivities at the different bands. Deviations from the bisector are evident, especially for C and K_a band. At K_u band and for S-band differential reflectivities greater than 1 dB, $Z_{dr}$ become fixed. However, it should be noted that there is almost a 1-to-1 correspondence between $Z_{dr}$ at S-band and $Z_{dr}$ at the other frequencies, as resulting from the tight scatterplots. Therefore it is not difficult to convert $Z_{dr}$ at S-band to the $Z_{dr}$ at a different frequency frequencies by establish a conversion through a simple look-up table (LUT) method. If the LUT is determined by stratifying S-band $Z_{dr}$ using 0.1-dB intervals, the root mean square error between the differential reflectivity determined by the T-matrix simulation and that obtained by applying the LUT to the $Z_{dr}$ at S-band, is lower than 0.012 dB for K_a, K_u, and X-band, whereas for C-band it is 0.05 dB. It is well known that $K_{dp}$ scales with frequency under Rayleigh scattering assumption [Bringi and Chandrasekar, 2001]. Actually, the slopes of scatterplots of Figure 3c, with the exception of that concerning the K_a band that will be discussed later, are very close to the ratio between the different frequencies. Therefore, $K_{dp}$ can be expressed through by simply scaling with frequency S-band $K_{dp}$ with a normalized standard error (NSE), defined as the ratio of the root mean square error between estimated and true value and the mean of true values, of 14.3 %, 11.6 %, and 14.6 %, for C, X, and K_u bands, respectively. Using the slope of scatterplots (2.23, 3.52, and 4.90, for C, X, and K_u bands, respectively) as scaling factor, normalized standard errors of 5.1%, 10.9%, and 13.6% would be obtained. As already mentioned, the $K_{dp}$ at K_a band cannot be accurately estimated from $K_{dp}$ at S band by applying frequency scaling. This due to the fact that Rayleigh scattering hypothesis is no longer valid for K_a band for large portion of rainfall cases. Actually, a correlation coefficient greater then 0.8 can only be found for DSDs that correspond to rainfall rates lower than 7.5 mm h$^{-1}$. For the same reason rainfall rate estimation using Kdp, at Ka band, works only for light rain [Matrosov, 1999]. A parameterization that could be applied to all the DSD variability of the simulation can be expressed in terms of S-band Zh and Zdr that would provide an unbiased NSE of 52.8%. Fig 1d shows the different impact of rain attenuation at the different frequencies. Apparently negligible at C-band especially for light and moderate rainfall rates, attenuation effects become more pronounced at higher frequencies (note the use double
scale in Figure 1d to represent attenuation at K\textsubscript{a} band). Attenuation is not a radar measurement and is usually estimated from other radar measurements (in particular $K_{dp}$, $Z_h$ or combination of measurements). Following the same approach of estimating a given measurement using the same measurement at S-band, the scatterplots in Fig 1d suggests that, potentially a linear relation can be established between specific attenuation at the different frequencies. Actually, using the slope of the scatterplots (896, 174, 68, 11.4, for K\textsubscript{a}, K\textsubscript{u}, X, and C-band, respectively) to convert S-band attenuation via a linear relation, we would get unbiased attenuation estimates (the maximum normalized bias of 3.6\% is obtained for K\textsubscript{a} band), but with a quite large error (27.7\%, 23.5\%, 45.4\%, and 69.3\%, for K\textsubscript{a}, K\textsubscript{u}, X, and C-band, respectively). However, S-band specific attenuation must be estimated from radar measurements. Therefore, a more practical approach is estimating attenuation at the various frequencies directly from S-band measurements such as $K_{dp}$ or $Z_h$. For example, converting $K_{dp}$ at S-band using a linear relation, allows to obtain K\textsubscript{a}, K\textsubscript{u}, X, and C-band specific attenuation with negligible bias and NSE of 52.5\%, 16.2\%, 15.4\%, 46.9\%, respectively.

Figure 1 - Comparison between reflectivity factor (a), differential reflectivity (b), specific differential phase shift, and (c) specific attenuation at horizontal state (d) simulated at S-band with corresponding measurements simulated at C, X, K\textsubscript{u} and K\textsubscript{a}. Note the different ordinate scales in panel (d) for K\textsubscript{a}-band.
Minimum detectable signal and attenuation margin in rain

The introduction has pointed out the differences among sensitivity of radars operating at the different frequencies. Sensitivity of a weather radar is usually expressed as minimum detectable reflectivity factor at a given range $r_0$, computed at the receiver input [Bringi and Chandrasekar, 2001, eq. 6.56]

$$\min(Z_{h,v}) = \frac{1}{\pi^4} \left( \frac{2}{c^2} \right) \left( \frac{4\pi}{P G_0^2} \right) \left[ \frac{8\ln 2}{\pi \theta_1 \phi_1} \right] \lambda^2 n_0^2 N \text{ dBZ} \quad \text{[5]}$$

where $\tau$ is the pulse length, $P_t$ is the transmitter power, $G_0$ is gain of the antenna, $l_{wg}$ are the waveguide losses, $\phi_1$ and $\theta_1$ are the 3-dB beamwidth, and $N$ is the noise power referenced at the receiver input. The previous equation shows that the minimum reflectivity factor is proportional to $\lambda^2$. It implies that if all the other parameters remain the same, the improvement in sensitivity in decibels passing from one frequency to a higher one, can be expressed by taking twenty times the logarithm of the ratio of the two wavelengths. For instance, from S-band to K_a-band the improvement in sensitivity is around 22dB. Depending on application, this improvement can be exploited to detect smaller particles or to reduce the transmit power. Figure 2 shows minimum reflectivity for typical transmit power adopted at the different frequency band assuming equal noise level and antenna parameters. If minimum reflectivity is set as requirement, [5] can be solved with respect to $r_0$, to obtain the maximum range at which this requirement is satisfied. However, in the case radar uses an attenuated frequency, the attenuated reflectivity should be used in [5], and the actual maximum range before extinction of returns is determined by the total, precipitation induced, attenuation in the propagation path.

![Figure 2 - Minimum detectable reflectivity factor as a function of range for radar operating at different frequencies and with different transmit power. Noise level and antenna gain are assumed to be -110 dBm and 45 dBm, respectively for all the radars. Antenna beamwidth is 1 degree and pulse width corresponds to 150 m.](image-url)
As explained in the introduction, dual polarization has moved the interest on using weather radar at ground to higher frequencies, such as those at X-band, since attenuation effects can be compensated using dual polarization techniques and rain rate can be obtained from $K_{dp}$, which is immune to attenuation. However, when wave is extinct, there will be missing observations. This problems is typical of X-band, for which dense networks have been proposed to mitigate this problem [Junyent and Chandrasekar, 2009], but wave extinction can occur at lower frequencies, such as C-band. A typical case occurs when an intense squall line becomes aligned along a radial direction from the radar. Therefore, rain attenuation needs to be considered to determine the maximum useful range of a radar system, or in a radar network, to determine the condition to obtain a gap-free coverage even in the presence of heavy precipitation [Mc Loughlin et al., 2009]. 

It can be done by considering an extra, precipitation-induced attenuation margin to be applied to the allocation of power budget. Statistics of two-way cumulative attenuation can be drafted using attenuation statistics computed at C-, X-, K_u, and K_a frequencies based on an existing dataset of unattenuated S-band measurements. Figure 3 show statistics obtained using two months of S-band $K_{dp}$ data collected by the CSU-CHILL radar during the Severe Thunderstorm Electrification and Precipitation Study (STEPS) campaign conducted along the Colorado/Kansas border, between May 26 and July 19, 2000, [Lang et al., 2004] were used to estimate attenuation at the different bands. The dataset includes low precipitation storms, supercells, and mesoscale convective systems. For a given range, the cumulative density function of attenuation was calculated. Curves shown in Figure 3 have been obtained by determining, at a given range, the attenuation (dB) corresponding to a cumulative probability of 80%, 90%, and 95%.

Figure 3 - Attenuation margin at S-, C-, X-band (a) and K_u-K_a-band (b). Percentages are referred to the probability of the total attenuation of 80%, 90% and 95%.
Figure 4a refers to S-, C-, and X-band frequencies and the typical system parameters indicated in the figure and its label. Measurements collected with the X-band radar network during the CASA IP1 experiment in Oklahoma showed the soundness of attenuation margin predicted from the STEPS campaign data and the fact that attenuation margin can be reduced by resorting to redundant radar networks [McLoughlin et al., 2009]. Figure 4b refers to the GPM radar frequencies of K\textsubscript{a} and K\textsubscript{u} band. Differences in attenuation margin are because specific attenuation at K\textsubscript{a} is on average, more than 5 times higher than K\textsubscript{u} band. The need of a margin of almost 50 dB to assure measurement availability at a short range (5 km) is shown by the figure. However, it should be interpreted as the attenuation margin needed to have measurements in 80% of cases having the same distribution of the precipitation observed during the STEPS campaign.

![Figure 4 - Estimation of reflectivity factor maps. Shown are intrinsic measurements at 35.6 GHz (a) and 13.8 GHz (c), and corresponding attenuated measurements at 35.6 GHz (b) and 13.8 GHz (d).](image)

**Simulating reflectivity and differential reflectivity maps at the GPM frequencies**

Discussion of scatterplots of Figure 1 has shown that, at some extent, it is possible to derive measurements at a given radar range gate for a target frequency from measurements collected at S-band. To use them to simulate realistic range profiles or maps of radar measurements at different bands, the method proposed by Chandrasekar et al [2006] that has been widely
exploited during the CASA project for X-band applications. An example of application of the methodology based on frequency mapping of radar measurements to simulate $K_u$ and $K_a$ intrinsic and attenuated maps is shown. The goal is to simulate dual polarization and dual frequency ground radar of the D3R radar part the GPM ground validation segment. Figure 4 shows the results obtained starting from polarimetric measurements collected at S-band by the CSU-CHILL radar. Measurements concern an intense rain cell that determined, at S-band, maximum reflectivity factors of 50 dBZ. Parameters of $K_u$ and $K_a$ radar correspond to those used for Figure 2. Fig 4a shows intrinsic (i.e. unattenuated) measurements at $K_a$ band, while Figure 4b shows measurements obtained by considering attenuation losses. Due to high attenuation, the core of the storm is missing and power returns are extinct at short distances from the radar at Ka band (Fig. 4a and 4b). At $K_u$ band, peaks of reflectivity factor tend to be higher that at S-band (see discussion of Fig. 1a). Effect of attenuation is evident, although returns are not totally extinct (Fig. 4d). Figure 5 concerns simulation of differential attenuation maps. In Figure 5a, intrinsic $Z_{dr}$ at $K_u$ band reveals the limited dynamics of this parameter. Similarly to Figure 4a, Figure 5b shows the effect of signal extinction. Conversely, intrinsic $Z_{dr}$ shows, at $K_u$ band, a dynamic range of 3 dBs (Fig. 5c). The effect of differential attenuation is shown in Figure 5d. The reduction in differential reflectivity, which becomes negative beyond 30 km from radar, is evident.

Figure 5 - Estimation of differential reflectivity maps. Shown are intrinsic measurements at 35.6 (a) and 13.8 GHz (c), and corresponding attenuated measurements at 35.6 (b) and 13.8 GHz (d).
Conclusions
Different frequency bands have been used in radar meteorology, depending on theoretical considerations, heuristics and application requirements. Simulations of polarimetric measurements in rain reveal a dependency among measurements at different frequencies. It has been shown that, in principle, it is possible to predict radar rain parameters such as $Z_h$, $Z_{dr}$, $K_{dp}$ and specific attenuation at frequency based on measurements (or on a combination of measurements) collected at a different frequency. Methodologies to obtain realistic radar measurements at a target frequency starting from S-band measurements have been proved as successful in the design of X-band radar networks and in the development retrieval algorithms at X-band within the CASA project (see McLoughlin et al. [2009] and references therein). Two applications, extending the range of application of the methodology to the GPM dual frequency precipitation radar have been shown in the paper. They are the study of attenuation margin up to $K_a$-band frequency and the simulation of observations of the dual polarization dual frequency D3R radar to be used in the GPM ground validation campaigns. The extension of the methodology to $K_u$ - and $K_a$ and to hydrometers other than rain is not straightforward [see Leinonen et al., 2011]. The use of full volume observations collected by scanning radars at S- and C-band to be used to produce synthetic reflectivity observation at $K_a$ and $K_u$-bands is one of the main goals of the campaigns ongoing in different areas of the globe in the pre-launch phase of the GPM mission.

Acknowledgments
This work has been partially supported by the CNR Short Tem mobility programme 2010, the Italian Space Agency through the “Nowcasting” pilot Project, by the Academy of Finland (contract 128328), as well as the NASA PMM program.

References
AA.VV. (2009) - Use of Radio Spectrum for Meteorology: Weather, Water and Climate Monitoring and Prediction. WMP-ITU, Switzerland Geneva, ISBN 92-61-12841-6. (on line: http://www.itu.int/pub/R-HDB-45).
Barber P., Yeh C. (1975) - Scattering of electromagnetic waves by arbitrarily shaped dielectric bodies. Appl. Opt., 14:2864-2872. doi: http://dx.doi.org/10.1364/AO.14.002864.
Beard K.V., Chuang C. (1987) - A new model for the equilibrium shape of raindrops. J. Atmos. Sci., 44:1509-1524. doi: http://dx.doi.org/10.1175/1520-0469(1987)044%3C1509:ANMFTE%3E2.0.CO;2.
Bringi V.N., Chandrasekar V., Balakrishnan N., Zrnić D.S. (1990) - An examination of propagation effects in rainfall on radar measurements at microwave frequencies. J. Atmos. Oceanic Technol., 7: 829-840. doi: http://dx.doi.org/10.1175/1520-0426(1990)007%3C0829:AEPOEI%3E2.0.CO;2.
Bringi V.N., Chandrasekar V. (2001) - Polarimetric Doppler Weather Radar: Principles and Applications, Cambridge University Press, New York. doi: http://dx.doi.org/10.1017/CBO9780511541094.
Chandrasekar V., Lim S., Gorgucci E. (2006) - Simulation of X-band rainfall observations from S-band radar data. J. Atmos. Oceanic Technol., 23: 1195-1205. doi: http://dx.doi.org/10.1175/JTECH1909.1.
Gorgucci E., Chandrasekar V., Baldini L. (2006) - *Correction of X-band radar observation for propagation effects based on the self-consistency principle*. J. Atmos. Oceanic Technol., 23: 1668-1681. doi: http://dx.doi.org/10.1175/JTECH1950.1.

Gorgucci E., Chandrasekar V., Baldini L. (2009) - *Can a unique model describe the raindrop shape–size relation? A clue from polarimetric radar measurements*. J. Atmos. Oceanic Technol., 26: 1829-1842. doi: http://dx.doi.org/10.1175/2009JTECHA1183.1.

Junyent F., Chandrasekar V. (2009) - *Theory and characterization of weather radar networks*. J. Atmos. Oceanic Technol., 26: 474–491. doi: http://dx.doi.org/10.1175/2008JTECHA1099.1.

Kollias, P., Clothiaux E.E., Miller M.A., Albrecht B.A., Stephens G.L., Ackerman T.P. (2007) - *Millimeter-wavelength radars: New frontier in atmospheric cloud and precipitation research*. Bull. Amer. Meteor. Soc, 88: 1608–1624. doi: http://dx.doi.org/10.1175/BAMS-88-10-1608.

Kozu T., Kawanishi T, Kuroiwa H., Kojima M., Oikawa K., Kumagai H., Okamoto K., Okumura M., Nakatsuka H.,Nishik K. (2001) - *Development of precipitation radar onboard the Tropical Rainfall Measuring Mission (TRMM) satellite*. IEEE Trans. Geosci. Remote Sens., 39: 102-116. doi: http://dx.doi.org/10.1109/36.898669

Lang T.J, Miller J., Rutledge S.A, Barker III L.J., Bringi V.N, Chandrasekar V., Detwiler A., Doesken N., Helsdon J., Knight C., Krebbiel P., Lyons W.A., Macgorman D., Rasmussen E. , Rison W., Thomas R.J. (2004) - *The Severe Thunderstorm Electrification and Precipitation Study*. Bull. Amer. Meteor. Soc., 85: 1107–1125. doi: http://dx.doi.org/10.1175/BAMS-85-8-1107.

Le M., Chandrasekar V., Lim S. (2010) - *Microphysical retrievals of dual polarization and dual frequency ground radar for GPM ground validation*, Proc. of IEEE Geoscience and Remote Sensing Symposium (IGARSS) 2010, pp. 2349-2352. doi: http://dx.doi.org/10.1109/IGARSS.2010.5650077.

Leinonen J., Moisseev D., Chandrasekar V., Koskinen J. (2011) - *Mapping radar reflectivity values of snowfall between frequency bands*. IEEE Trans. Geosci. Remote Sens., 49: 3047-3058. doi: http://dx.doi.org/10.1109/TGRS.2011.2117432.

McLaughlin D., and Coauthors (2009) - *Short-wavelength technology and the potential for distributed networks of small radar systems*. Bull. Amer. Meteor. Soc., 90: 1797-1817. doi: http://dx.doi.org/10.1175/2009BAMS2507.1.

Matrosov S.Y., Kropfl R.A., Reinking R.F., Martner B.E. (1999) - *Prospects for measuring rainfall using propagation differential phase in X- and Kα-radar bands*. J. Appl. Meteor., 38:766–776. doi: http://dx.doi.org/10.1175/1520-0450(1999)038%3C0766:PFMRUP%3E2.0.CO;2.

Sadowy G.A., Berkun A.C., Chun W., Im E., Durden S.L. (2003) - *Development of an advanced airborne precipitation radar*. Microwave J., 46: 84-98.

Seliga T.A., Bringi V.N. (1976) - *Potential use of radar differential reflectivity measurements at orthogonal polarizations for measuring precipitation*. J. of Appl. Meteor., 15: 69-76. doi: http://dx.doi.org/10.1175/1520-0450(1976)015%3C0069:PUORDR%3E2.0.CO;2.

Shimizu S., Oki R., Kachi M., Kojima M., Iguchi T., Nakamura K. (2006) - *Development and validation of spaceborne dual-frequency precipitation radar for GPM*. Proc. of IEEE Geosci. and Remote Sensing Symposium (IGARSS) 2006, pp. 29-31. doi: http://dx.doi.org/10.1109/IGARSS.2006.12.

Tanelli S., Durden S.L., Im E., Pak K.S., Reinke D.G., Partain P., Haynes J.M., Marchand
R.T. (2008) - *CloudSat’s Cloud Profiling Radar after two years in orbit: performance, calibration, and processing*, IEEE Trans. Geosci. Remote Sens., 46: 3560-3573. doi: http://dx.doi.org/10.1109/TGRS.2008.2002030.

Ulbrich C.W. (1983) - *Natural variation in the analytical form of the raindrop-size distribution*. J. Climate Appl. Meteor., 22: 1764-1775. doi: http://dx.doi.org/10.1175/1520-0450(1983)022%3C1764:NVITAF%3E2.0.CO;2.

Wang Y., Chandrasekar V. (2009) - *Algorithm for estimation of the specific differential phase*. J. Atmos. Oceanic Technol., 26: 2565-2578. doi: http://dx.doi.org/10.1175/2009JTECHA1358.1.

Wang Y., Chandrasekar V. (2010) - *Quantitative precipitation estimation in the CASA X-band dual-polarization radar network*. J. Atmos. Oceanic Technol., 27: 1665-1676. doi: http://dx.doi.org/10.1175/2010JTECHA1419.1.

Waterman P.C. (1971) - *Symmetry, unitarity and geometry in electromagnetic scattering*. Phys. Rev., 3: 825-839. doi: http://dx.doi.org/10.1103/PhysRevD.3.825.

Received 17/02/2011, accepted 21/11/2011

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