Cirrus Clouds Millimeter-Wave Reflectivity Comparison with *In-Situ* Ice Crystal Airborne Data

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ABSTRACT

In an effort to evaluate scattering models for particle size distributions of ice crystals within cirrus clouds, simultaneous data was collected in March 2000 during the Department of Energy (DOE) Atmospheric Radiation Measurement (ARM) Cloud Intensive operational period (Cloud IOP) at the Cloud and Radiation Testbed (CART) site in Lamont, Oklahoma. In situ measurements of ice particles were collected using the National Center for Atmospheric Research (NCAR) Video Ice Particle Sampler (VIPS), which flew on the University of North Dakota Citation research aircraft. Ground-based vertical radar profiles were collected using the University of Massachusetts (UMass) 33GHz/95GHz Cloud Profiler Radar System (CPRS). Data from both sensors was used to retrieve and compare the equivalent radar reflectivity at Ka band (33GHz). The equivalent radar reflectivity measured by the ground-based, zenith-looking, CPRS radar at Ka band and compared to the reflectivity computed from the airborne VIPS samples of particle size distribution, *N(D)*, using Mie theory. As anticipated the equivalent reflectivity of the radar and VIPS were similar at the time the UND Citation overflew the radar.

Keywords: Cirrus clouds, millimeter wave, equivalent reflectivity, particle size distribution

1. INTRODUCTION

Cirrus clouds play an important role in the balance of Earth's energy dynamics. These clouds cover about 20% of Earth and are mainly composed of ice particles. They cool the Earth by reflecting solar radiation back to space and warm it by trapping infrared radiation emitted from the surface and lower atmosphere [1,2].

In order to evaluate the accuracy of the current climate models, precise millimeter-wavelength radar measurements of clouds microphysical properties for developing the cloud parameterization are needed. Several experiments have been done in the past two decades to improve the understanding of the relationship between microphysical and radiative properties of cirrus clouds (FIRE-I, FIRE-II and ARM). In addition, similar studies have been performed in the past where radar and in-situ measurements were analyzed and compared. Chandrasekar, Bringi and Strapp have documented comparisons for graupel and hail [3]. All of these experiments employed various types of instruments, such as radars and in-situ devices whose measurements result too expensive and also cover a limited region of the sky, which in turn reinforces the intention of validating radar data [4,5].

Appropriate radars for studying clouds such as cirrus clouds are millimeter wavelength radars like the UMass Cloud Profiler Radar System (CPRS), because they are sensitive enough to study particles smaller than one millimeter. For the in-situ measurements the NCAR Video Ice Particle Sampler (VIPS) was used. The CPRS operating frequencies are 33 and 95 GHz, which is near to the atmospheric window making it useful for studying the microphysical properties of clouds [4]. Although Rayleigh approximation is applicable at 35GHz, in this work we used the full Mie equations to calculate the backscattering from individual crystals. It is known that the shapes of the particles found in cirrus clouds are not spherical (bullets and bullet rosettes are the most common) yet for many applications the use of Mie scattering, which assumes a sphere shape for the particles is a good approximation. One of the most common methods employed to evaluate the effects of particles shape in the backscattering efficiency is

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the discrete dipole approximation (DDA). Data from both instruments were obtained on March 2000 from the ARM experiment at the Southern Great Plains (SGP) site in Oklahoma [5]; a satellite photo of the area is shown in Fig. 1; this was for March 3rd, and at that time, 3 surface radars and three aircrafts were sampling cloud layers [6].

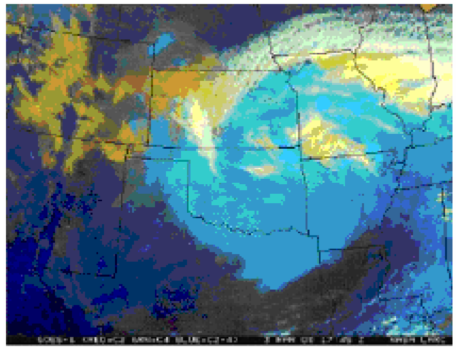


Fig. 1. GOES satellite false color image of the cloud field over the ARM site on 3 March 2000. Terra passed directly overhead of the CART central facility at 1740 UTC [6].

2. EXPERIMENT SETUP

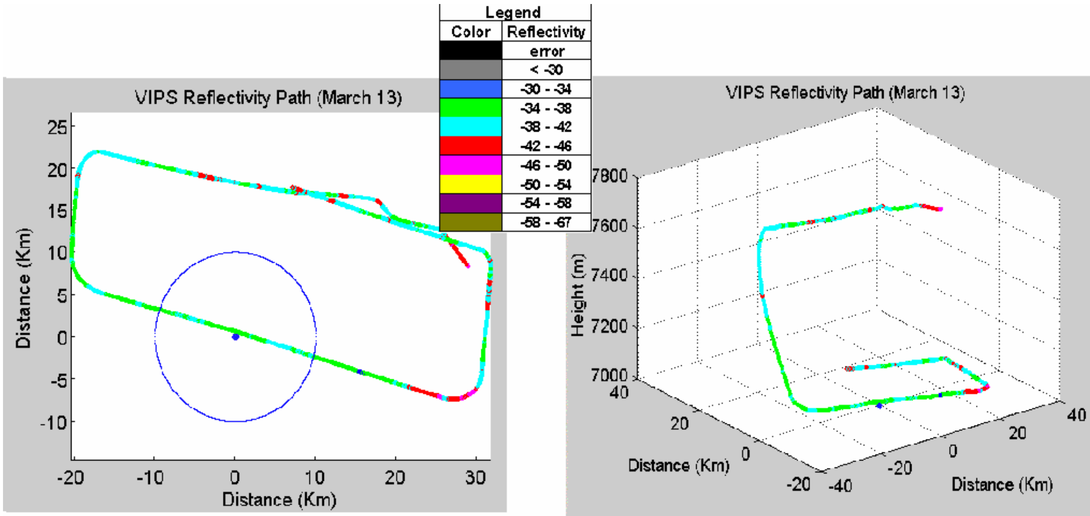
Data from March 13, 2000 was used because in that particular day cirrus clouds were present and the sensors were close in time and space. The flight pattern for that day was a series of legs at various altitudes like the portion of the flight shown in Fig. 1.b, and an overhead view of the flight is shown in Fig. 1.a. The ice particle data was collected using an instrument called Video Ice Particle Sampler (VIPS) and given by A. Heymsfield from the National Center for Atmospheric Research (NCAR). This is an airborne instrument that flies inside cirrus clouds, and takes samples of the cirrus cloud particles sizes up to 5 μm in size. The VIPS have an electro-optical and imaging unit that is in charge of collecting data, and another part designated to record data. The particles' images are recorded in two formats, one is at 30 Hz on high-resolution Hi-8 VCRs; the other format is at 1 Hz, digitized in real-time in an Apple PowerPC [7]. The colors for both Fig. 2.a and Fig. 2.b represent the equivalent reflectivity seen by the airplane's VIPS and the blue dot represent the location of the radar with the axes changed from latitude-longitude (the location of the radar was latitude 36.6011 and longitude 97.4809) to distance in kilometers. The change to distance was done to find the points of data spatially closer using eq.(1) as follows:

$$D = E * [\cos^{-1}\{(\sin(a)) * \sin(b) + \cos(a) * \cos(b) * \cos(P_1 - P_2)\}] \ \ [km] \qquad (1)$$

where E= Earth Radius=6367.3 km, a= latitude of 1st point=36.6011 , b= latitude of 2nd point, P_1=longitude of 1st point = 97.4809, and P_2=longitude of 2nd point. The match in time was done simply using the same times of data gathered for both sensors. Equivalent reflectivity obtained from data from the CPRS is shown in Fig. 3 and in this case the blue line in the mid section of the figure is the path of the plane at the same time that the radar collected the information. The matched data was compared using traditional methods such as assuming Mie backscattering from the ice bullets; the backscatter was calculated as a function of the wavelength, diameter and density. Mie theory is used to obtain the backscattering coefficient of small particles; it assumes that the particles are spherical or randomly oriented in a way that their scattering properties can be approximated by a spherical shape. But this assumption lead to incorrect scattering properties and also even some times, polarization parameters are neglected [8]. The equation that was used to calculate the equivalent reflectivity for the VIPS data is given by Sekelsky [4]:

$$Z_e = \frac{10^{12}\lambda^4}{4\pi^4 |K_w(\lambda)|^2} \int_0^{D_{max}} \xi_b(D,\lambda,\rho) N(D) D^2 dD \quad [mm^6 m^{-3}] \qquad (2)$$

Where ξ_b is the Mie backscattering coefficient, K_w is the dielectric factor and *N(D)* is the particle's size distribution. The density of the ice particles has been shown that have a big effect in the backscattering [9]. The density of the ice particles itself vary as a function of its dimensions and in cirrus clouds various shapes of the bullet rosettes are observed; past studies found that the dominant crystal type found in cirrus clouds is the bullet rosette, with an average of five bullets per rosette like the shown in Fig. 4.a.



a) b)

Fig.2.a) Overhead view of the VIPS flight track pattern for March 13, 2000. The blue dot at (0,0) indicates the position of the CPRS radar, the blue circle is only a reference for data that were spatially closed between sensors. b) Is the same as a) but in three dimensions to show the altitude variation.

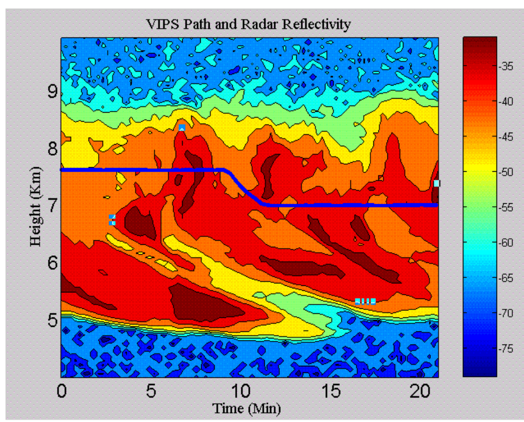


Fig. 3. CPRS reflectivity plot versus time showing the trajectory of the airplane through the cirrus cloud.

Different crystal structures are more dominating in a cirrus cloud depending of the diameter. Particles of less than a 100um are more likely to have a spherical shape [10]. Each bullet has a longitude relation, L (mm), versus wide, w (mm) (see Fig. 3.b), (twice times the apothem) for temperatures between –18º and –20 ºC given by [11]:

$$w = 0.25L^{0.7856} \quad \text{[mm]}, \tag{3}$$

for bullets with $L \leq 0.3$ mm, and

$$w = 0.185L^{0.532} \quad \text{[mm]}, \tag{4}$$

for bullets with $L \geq 0.3$ mm.

In this way the equations were determined for the bulk density, ρ, of the bullet, considering the solid ice density as 0.9 g cm-3 and using the volume of ice in individual crystals

$$\rho = 0.78L^{0.0038} \quad [\text{g cm}^{-3}] \tag{5}$$

As the Wiener's theorem states the complex index of refraction, m, depends of the bulk density when dealing with dry ice particles:

$$m = \frac{2 + n_i^2 + 2 f_i \left(n_i^2 - 1\right)}{2 + n_i^2 + f_i \left(-n_i^2 + 1\right)} \tag{6}$$

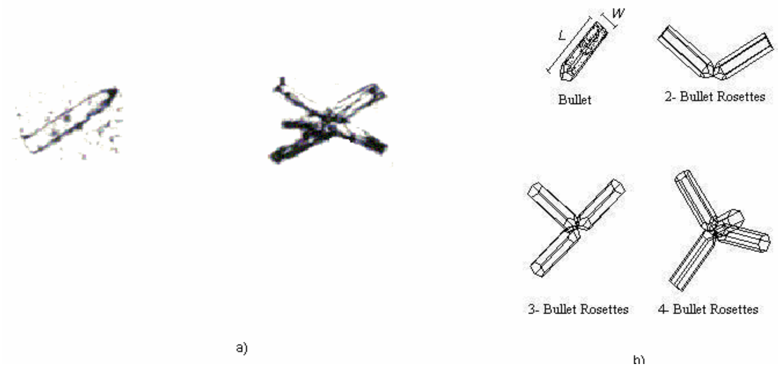


Fig. 4.a) Most common shape found in cirrus clouds: One bullet per rosette and five bullets per rosette. b) Bullet and Bullet Rosettes with different angles of junction

where f_i represents a non-dimensional fraction of the volume of air and ice and it is defined as:

$$f_i = \frac{\rho}{\rho_i} \tag{7}$$

with ρ_i as the solid ice density (0.9 g cm-3) and where n_i is the complex index of refraction of solid ice which is different for every frequency (33 and 95 GHz). Using the above equations, we obtained an index of refraction for each bullet size [9]. The new complex indexes of refraction in our case are used to calculate the backscattering efficiency using Mie theory. This was done by converting the length L of a bullet shaped particle to diameter of a sphere. Finally this backscattering efficiencies and the particle size distribution from the VIPS are used to calculate the equivalent reflectivity; which are then compared to the equivalent radar reflectivity obtained by the CPRS. In the future we are going to do the same using backscattering efficiencies obtained by particles with bullet shape.

3.DATA AND EQUIPMENT

3.1. UMass Cloud Profiling Radar System (CPRS)

CPRS operates at 33 and 95 GHz frequencies and in this experiment the radar was operating in a vertically looking position so that it was looking at zenith at all times; some of the most important specifications for the radar are shown in Table I. Although both frequency channels were on at the time of the over flight of the airborne VIPS system, it was later discovered that the 95GHz channel was not working properly during this time (see Fig. 5), so only data from the 33 channel is used for this work. The data already processed by this radar was obtained from the ARM website [5] and is in NetCDF format; these files were opened using IDL software. From this data we used the range (distance to the radar), the time of the measurement and the equivalent reflectivity. A contour plot from the CPRS data to represent the radar reflectivity is shown in Fig. 3 with the horizontal axis as time and the vertical as height.

Table I:

	Ka-band Radar	W-band Radar
Frequency	33.12 GHz	94.92 GHz
Peak Power	100 kW	1.5 kW
Average Power	120 W	15 W
PRF	200 Hz - 3 kHz	1 Hz - 80 kHz
Pulsewidth	200 - 2000 ns	50 - 2000 ns
Noise Figure	11 dB	13 dB
3 dB Bandwidth	2, 5 MHz	2, 5 MHz
3 dB Beamwidth	0.5 deg	0.18 deg

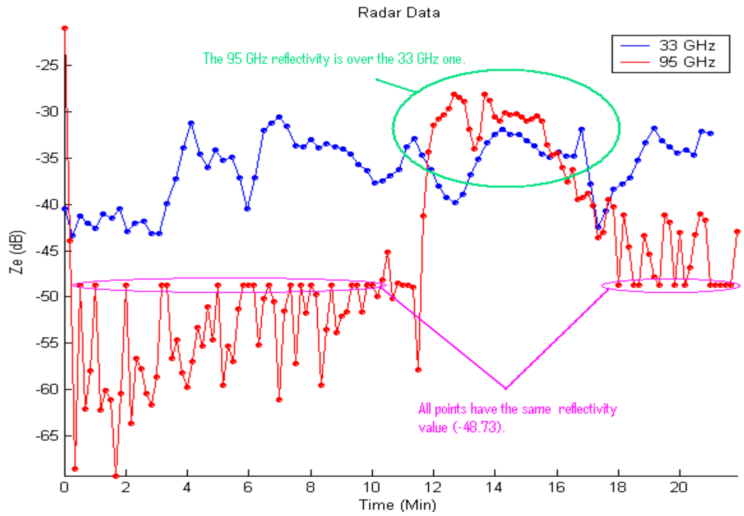


Fig 5. Time trace of the data showing the radar reflectivity of the two channels of CPRS data during the time when the airplane over flew over the radar.

3.2. NCAR Video Ice Particle Sampler (VIPS)

This device uses an electro-optical instrument used to collect and record a continuous sample of cloud particles down to 5 μm. Particles are collected continuously on a looped belt coated with silicone oil. The VIPS system is composed of two parts: (1) an electro-optical collection and imaging unit mounted in a standard particle measurement system (PMS) can, and (2) data acquisition and recording components (see Fig.6.a)[7]. Aperture width of the collection subassembly is adjustable for varying flight conditions. The CCD imaging cameras are coupled with inline, high detail video enhancers.

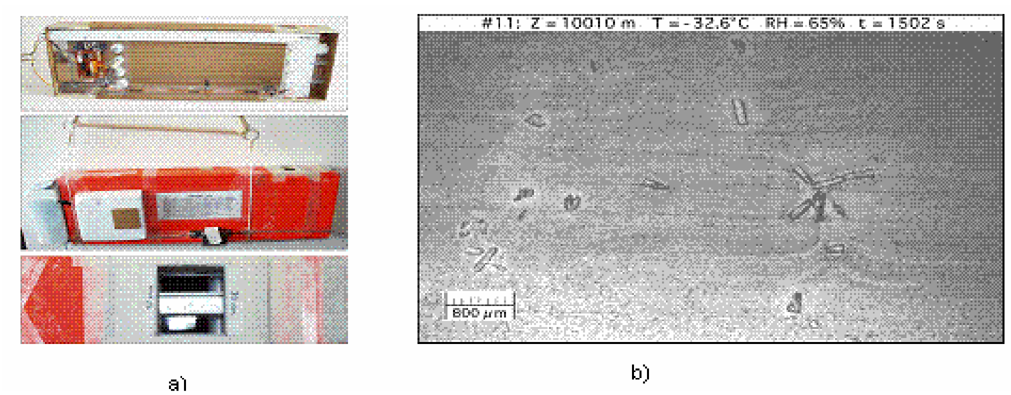


Fig. 6.a) Three different views of the in situ equipment (VIPS), b) Picture from the VIPS recorder.

The data we have from this instrument is in table format in MS Excel®. From here were used the altitude of the airplane, the diameters and concentration of particles *N(D)* per cubic meter present for this diameters. Also to compare in time and space with the radar data the times were the data was gathered and the coordinates of the airplane were used. The data of this instrument is shown in Fig.2.a and b, this figure show the device flight track and the calculated equivalent reflectivity in decibels for each point of data. Also for comparison purposes data from an instrument similar to the VIPS, the cloud particle imagery (CPI) is shown in Fig.7.a. This instrument formed part of the same campaign as the VIPS; the data was collected using the University of North Dakota Citation research aircraft, the figure show the average particle size distribution in L^{-1} μm^{-1}. This data compare positively with the one obtained by the VIPS (see Fig.7.b)[12].

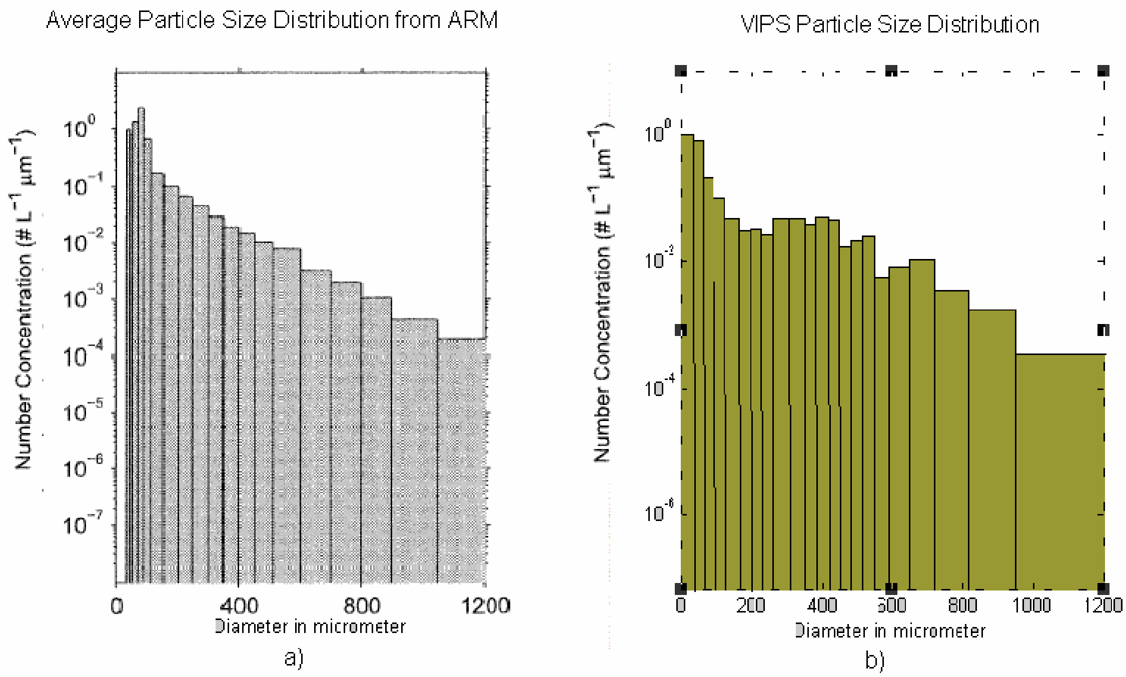
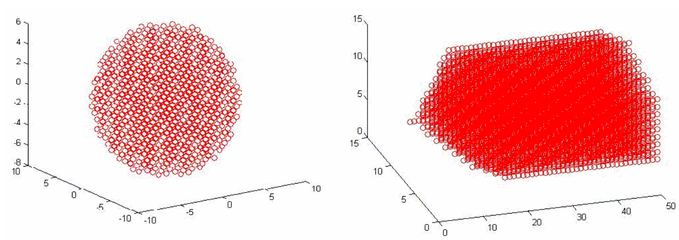


Fig. 7.a) Average particle size distribution from data collected between the 9 and 13 of March 2000, by the University of North Dakota Citation research aircraft , using a cloud particle imagery (CPI)[12] .b) Particle size distribution obtained from data of the VIPS when the plane flew very close to radar location.

3.3. Discrete Dipole Approximation (DDA)

Evans and Vivekanandan have shown that radar reflectivity is dependant of shape, size and other microphysical properties [13]. Therefore when the shape of the particles are taken into account the use of a method such as discrete dipole approximation is a good alternative to obtain the backscattering efficiencies. The basic idea of DDA is the representation of a random particle by a finite array of N dipolar subunits arranged on a cubic lattice as shown in Fig. 7.a and b. For every dipole an electric field is calculated and the backscattering is calculated from the sum of all the fields due to each dipole. As future work, we will compare the backscattering efficiencies and the equivalent reflectivity obtained using Mie theory with the equivalent reflectivity using the discrete dipole approximation [9].



a) b)

Fig. 8. Dipole representation of particles. a) Spherical shape. b) Bullet shape

4. RESULTS

The resulting backscattering using Mie theory and taking into account the change in density is shown in Fig. 9. Only diameters up to 2,250µm are used because for higher diameters the concentration of particle was in most of the cases insignificant.

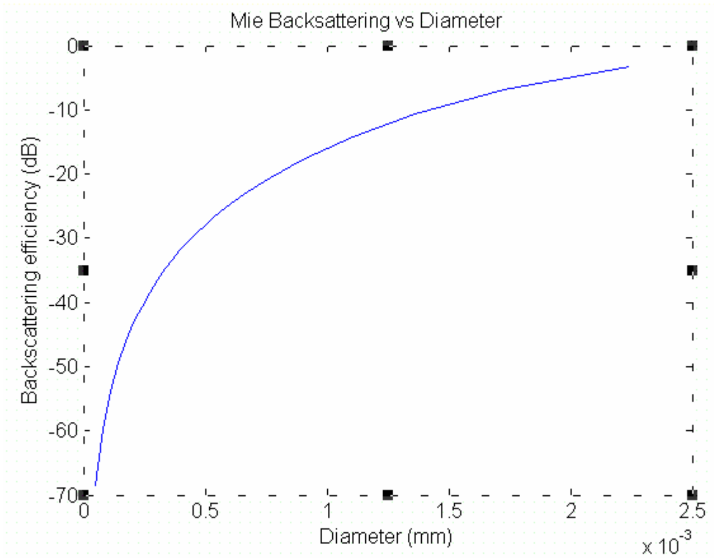


Fig. 9. Backscattering efficiency using Mie theory.

The comparison for in-situ and radar measurements is shown in Fig. 10, where the CPRS data is represented by a red line and the VIPS data is represented in blue. The data was gathered in the same interval of time, and a green line represents the distance between instruments. The root mean square (RMS) difference value for the equivalent reflectivities measured and derived from *N(D)* was calculated for data with a horizontal distance of 10 and 5km between instruments (airborne VIPS and ground-based CPRS) using the following equation:

$$Z_{e\,RMS} = \sqrt{\frac{(a_1 - b_1)^2 + (a_2 - b_2)^2 + (a_3 - b_3)^2 + \ldots + (a_n - b_n)^2}{n}} \qquad (8)$$

Where a_n is the equivalent reflectivity from the CPRS in dBZ, b_n is the equivalent reflectivity from the VIPS also in dBZ, and n is the total number of points used in the calculation. The resulting RMS difference for a distance up to 10km between instruments was 4.673 dBZ, and for a distance up to 5km, the difference was reduced to only 1.311dBZ.

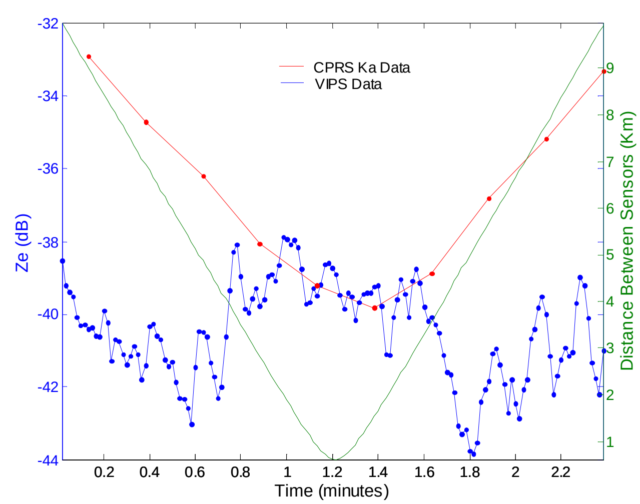


Fig .10. Plot showing on the left scale the radar reflectivity from the CPRS and the computed reflectivity from the VIPS particle size distribution and on the right the distance between the radar and the airplane position. Obviously the best agreement occurs at the center of the graph where the distance is minimum.

The equivalent reflectivity obtained for both instruments compare favorably when both instruments were close in time and space which suggests that both instruments are well calibrated., this can be seen in Fig. 10; and the RMS values obtain are more similar when the airplane flew closer to the ground radar, as expected. In the future, we intent to compare the backscattering efficiencies obtained from Mie theory with backscattering obtained for a bullet shape particle using DDA and determine which one better compares with the in-situ equivalent reflectivity derived from the VIPS data. In the future, we also intent to develop algorithms to compare Ice Water content (IWC) from for cirrus clouds using data from VIPS with the IWC derived from the average radar reflectivity at 33 GHz from UMass' Cloud Profiling Radar System.

5. CONCLUSIONS

In this work we evaluated scattering models for particle size distributions of ice crystals within cirrus clouds, simultaneous data was collected during the DOE ARM Cloud IOP at CART site in Lamont, Oklahoma, from the NCAR VIPS and UMass 33GHz CPRS from March 2000. Data collected simultaneously from both sensors was used to retrieve and compare the equivalent radar reflectivity at Ka band (33GHz). Data from the 95GHz channel of the CPRS could not be used due to an apparent failure in that particular channel during overpass. The particles that have the most impact in the equivalent reflectivity have a diameter between 100 and 1,200μm, this can be appreciated in Fig. 9 in which for diameters bellow 100μm the backscattering efficiency is very small and then it start to increase very fast before it reaches a diameter of 1,200μm and also in the Fig.7.b in which the concentration of particles for diameters higher than 1,200μm are negligible. The equivalent reflectivity obtained for both instruments compare favorably when both instruments were close in time and space which suggests that both instruments are well calibrated., this can be seen in Fig. 10; and the RMS values obtain are more similar when the airplane flew closer to the ground radar, as expected. The resulting RMS difference for a distance up to 10km between instruments (airborne VIPS and ground-based CPRS) was 4.673 dBZ, and for a distance up to 5km, the difference was reduced to only 1.311dBZ.

6. FUTURE WORK

In the future we intent to compare the backscattering efficiencies obtained from Mie theory with backscattering obtained for a bullet shape particle using DDA and determine which one better compares with the in-situ equivalent reflectivity derived from the VIPS data.

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