Summary of Research (Final Technical Report)

Project Title:

“Development and application of new methods to retrieve vertical structure of precipitation above the ARM CART sites from MMCR measurements”

Type of report: Summary of Research (Final Technical Report)

PI: Dr. Sergey Matrosov

Period covered:

12/01/2004 – 11/30/2010

Institution:

Cooperative Institute for Research in Environmental Sciences (CIRES),
University of Colorado, Campus Box 216, Boulder, CO 80309-0216

Grant number: DE-FG02-05ER63954

PI contact information: Tel.: (303)-497-6393, sergey.matrosov@noaa.gov

Project Objectives:

The main objective of this project was to develop, validate and apply remote sensing methods to retrieve vertical profiles of precipitation over the DOE ARM CART sites using currently available remote sensors. While the ARM Program invested very heavily into developments of remote sensing methods and instruments for water vapor and non-precipitating cloud parameter retrievals, precipitation retrievals and studies lagged behind. Precipitation, however, is a crucial part of the water cycle, and without detailed information on rainfall and snowfall, significant improvements in the atmospheric models of different scales (i.e., one of the ARM Program’s main goals) is difficult to achieve. Characterization of the vertical atmospheric column above the CART sites is also incomplete without detailed precipitation information, so developments of remote sensing methods for retrievals of parameters in precipitating cloud condition was essential. Providing modelers with retrieval results was also one of the key objectives of this research project.

Project milestones:

Year 1:

Initial developments of the rain rate profile retrievals in stratiform rainfall from ground-based vertically pointing 8 mm wavelength cloud radar. Estimating retrieval uncertainties using theoretical considerations and comparisons with rain gauge data. Developments of a microphysical model for calculating backscatter and attenuation properties of non-spherical hydrometeors.

Year 2:

Further developments of the gradient remote sensing method for retrievals of rain rate profiles. Applications of the method to radar measurements collected at the Southern Great Plains (SGP) and Tropical Western Pacific (TWP) sites. Comparisons of retrievals from 8 mm-wavelength vertically pointing radars with results obtained from polarimetric scanning radars.

Year 3:

Developments and applications of the snowfall retrievals methods using 8 mm-wavelength ground-based vertically pointing radars. Developments of pristine and aggregate snowflake models for mm-wavelength radar remote sensing. Validation of the snowfall retrievals with snow gauge measurements.

Year 4:

Developments of the technique for simultaneous retrievals of cloud liquid water, rain rate and ice water content in stratiform precipitating systems using vertical measurements from Ka-band and W-band ground-based radars. Modeling radiative transfer in a layer of melting hydrometeors. Incorporating the melting layer model in the retrieval technique.

Year 5:

Applications of the remote sensing method for simultaneous retrievals of cloud liquid water, rain rate and ice water content in stratiform precipitating systems to measurements conducted during the warm period at the SGP site. Compilation of the data base containing the retrieved microphysical parameters of clouds and precipitation for modeler needs. Studies of interrelations among ice and liquid hydrometeor parameters in stratiform precipitating systems.

Year 6:

Modifying the method for remote sensing of precipitating clouds for applications at the Darwin TWP site by incorporating the C-POL scanning polarimetric radar measurements in the retrieval algorithm. Comparisons of ground-based radar retrievals with estimates of precipitating cloud parameters from satellite remote sensors.

1. Brief description of accomplishments for Year 1.

ARM standard instruments lack longer wavelength scanning radars that are traditionally used for precipitation studies. The 8-mm (Ka-band) wavelength cloud radar (MMCR) is one of the most important instruments deployed at the ARM CART sites. Though it was originally designed for observing cloud parameters, it can also be used for precipitation studies. Because of the high rate of the signal attenuation due to rain at Ka-band, standard precipitation radar approaches are not applicable and new methods that make use of attenuation effects need to be developed.

At the initial stage of the project, the relation between the Ka-band attenuation coefficient and the rainfall rate was developed. It was shown that the, the attenuation coefficient and the rainfall rate are proportional approximately to the same moment of the rain drop size distribution (DSD) which results in a linear relation between these two parameters. This linear relation is very stable and depend on the nature of rain (e.g., convective versus stratiform), temperature and raindrop shape model very little. The linearity of this relation is a unique feature of the Ka-band radiation, and it is a corner stone of the attenuation-based rainfall rate retrieval method.

MMCR reflectivity measurements in rain change along the vertical coordinate due to attenuation and due to variability in nonattenuated reflectivity. When the reflectivity changes are considered at a relatively large height interval, the changes due to attenuation typically dominate because of the relatively large attenuation coefficient at Ka-band. An estimator was developed to calculate rainfall rate as a range derivative of the measured (i.e., attenuated) MMCR reflectivities. This estimator is based on the least square method and considers the reflectivity trend over a height interval which has a length of 1 -2 km. The use of “sliding window” technique allows calculations of rainfall rate profiles with an apparent resolution that corresponds to the vertical resolution of the MMCR measurements, though the effective resolution is equal to the aforementioned height interval.

An analysis of uncertainties for rainfall rate retrievals was performed using an approach that considers different contributions from potential sources of errors. The sources include deviations from the linearity in the attenuation-rain rate relation and uncertainties in the nonattenuated vertical profile of Ka-band reflectivity. The latter source typically dominates the former one. The retrieval uncertainties decrease with increasing rainfall rate, and they depend on the effective vertical resolution of the retrievals (i.e., on the vertical interval used in the least square estimator). For a 1 km resolution interval and a 1 dB uncertainty in the nonattenuated reflectivity profile at this interval (which is typical for stratiform rains), rainfall rate retrieval errors are about 35% for 5 mm/h, 20% for 10 mm/h, and 15% for 30 mm/h. If the uncertainty in the nonattenuated reflectivity at the 1 km interval is about 2 dB (which is typical for convective rains) the corresponding retrieval errors are 55% for 5 mm/h, 35% for 10 mm/h, and 20% for 30 mm/h.

In cases when the higher cloud reference reflectivity is known with an acceptable degree of certainty just prior and after the rain event and this reference reflectivity can be measured for the periods when the rain is present (as for passing short convective rain shafts), an average rainfall rate for the rain layer can be estimated. The retrieval error for whole rain layer in this case is mostly determined by the ratio of the uncertainty of the nonattenuated reference reflectivity during the rain event and the magnitude of the higher cloud reflectivity dip due to rain attenuation. The estimates of mean layer rainfall rates in convective shafts of warm rain were successfully performed during the field experiments in Florida, where the NOAA ETL owned copy of the MMCR was deployed.

For successful applications of the MMCR attenuation-based retrievals it is necessary that radar echoes are in the linear range of radar receivers. This requirement limits the vertical range interval where retrievals are available. Signal linearity thresholding is best to be performed in terms of uncalibrated radar power expressed in dBm. The dBm limits were established for the SGP and TWP Darwin MMCRs. These two radars were chosen first because i) the SGP site is the best instrumented ARM CART site, it has the longest measurement record and the most sensitive MMCR, and ii) the TWP Darwin site has the Australian Bureau of Meteorology's C-Pol radar which is a very valuable tool for validations of MMCR-based retrievals. The attenuation-based rainfall rate estimator was tuned to the specific parameters of both radars (for the precipitation MMCR modes) taking into account different data system processors. Additional thresholding scheme based on vertical Doppler velocities was introduced to remove non rain echoes.

The first ARM retrievals of rainfall rate vertical profiles were performed using the SGP MMCR data. It was instructive to see how the MMCR method would work in stratiform events with light-to-moderate rainfall rates. Such events are quite common at the SGP site during spring and fall. The freezing level is usually observed at 2 to 3 km above the ground and it is identifiable using the reflectivity and vertical Doppler velocity data. It was shown that for rainfall rates as small as 4 mm/h, the proposed attenuation-based retrieval method can be successfully applied. The vertical variability of rainfall rates in stratiform events is rather modest though it is not unusual that this rate varies within one profile as much as a factor of 2 or even more. Attenuation-based retrievals were used to calculate time series of rainfall rate and accumulations at different altitudes above the ground. The comparisons of radar derived accumulations with tipping-bucket rain gauge data showed a reasonably good agreement with the radar retrievals extrapolated toward the ground. Figure 1 shows an example of MMCR-based retrievals for a stratiform rain event observed on 11 October 2004. Retrievals were made using the effective resolution of 1 km. Given the linear receiver dynamic range limitations, the MMCR retrievals of rainfall rate profiles are only available from about 0.7 km to 2.8 km.

Figure 1. Time-height cross sections of MMCR measured reflectivity (a), vertical Doppler velocity (b), and retrieved rainfall rates (c) for 11 October 2004.

Other notes for Year 1:

It was suggested that the ARM Program purchase an impact Joss-Waldvogel disdrometer (model RD-80) and install it at the SGP CART site. This instrument will enhance the surface meteorology measurements by providing raindrop size distributions and estimates of instantaneous rainfall rates and reflectivities at the ground. It will help to validate MMCR-based retrievals and other ARM activities will benefit from this new instrument as well. The current tipping-bucket rain gauge provides accumulation estimates only and does not provide rainfall rates and DSDs. A computer code was developed to provide estimates of radar reflectivity from the disdrometer DSD using the non-spherical drop model.

2. Brief description of accomplishments for Year 2.

During the FY06, an enhanced estimator for retrievals of vertical profiles of rain rates was developed. This estimator uses vertical profile of reflectivity measurements in the MMCR precipitation and /or general operation modes and calculates the reflectivity gradient as a slope of the least mean square (LMS) liner fit. A threshold technique was introduced to reject noisy data points and the data affected by saturation. Corrections for radar signal attenuation in liquid water clouds and atmospheric gases were introduced. The rainfall rate estimates from the retrieval method are obtained at each resolution bin in the MMCR precipitation mode (i.e., 90 m), while the effective resolution due to the choice of the LMS interval is typically 1 km. The 1 km effective resolution interval of the retrievals corresponds to 12 reflectivity points used to estimate a mean gradient of observed reflectivity at this interval. An additional correction factor that accounts for changes of air density with height has been introduced to the estimator. Retrievals uncertainties due to variability in the rain drop size distribution details and due to the choice of the effective resolution interval were estimated.

The attenuation based MMCR-based method to retrieve vertical profiles of rainfall rate was applied to the data set collected at the ARM Darwin Tropical Western Pacific (TWP) site. The test of the method using the TWP data presented a particular interest because nature of rainfall at this site is often convective and the freezing level is high (i.e., ~ 4.5 km, on average), which allows better evaluations of rain rate profile shape retrievals. In addition, this ARM site is complemented by the scanning Australian Bureau of Meteorology C-POL (5.5 cm wavelength) polarimetric precipitation radar, which is a valuable tool for technique validation. Convective rains are characterized by stronger vertical variability compared to stratiform rains. Since the variability of non-attenuated K_a -band reflectivity presents the major source of uncertainties in attenuation-based retrievals, testing the retrievals in convective rains provided a good opportunity in assessing the retrieval approach.

Figure 2 shows an example of the MMCR attenuation-based retrievals during a convective rain event observed at the TWP Darwin site on 11 January 2003. The upper and lower frames show the time-height cross section of the measured reflectivity (which is used as input information for the remote sensing method) and the retrieved rainfall rates, respectively. For reference, the middle frames show the vertical Doppler velocity measurements which provide information on the vertical extend of rainfall echoes. While the left frames depict the whole duration of the event, one hour worth of information is presented in the right frames for a detailed look of the retrieval features. The retrievals were not available at altitudes lower than 0.8 km due to saturation of the radar signals at close ranges and above 3.8 km because of the effective retrieval resolutions of 1 km (i.e., estimates at the higher levels were likely to be affected by the melting hydrometeors).

Figure 2. Attenuation-based MMCR measurements (upper frames) and retrievals of rainfall rates (lower frames) in convective rain observed at the ARM TWP site on 11 January 2003.

The ARM TWP Darwin site presented a unique opportunity to compare MMCR retrievals with conventional precipitation scanning radar estimates. The polarimetric C-band (C-Pol) radar is located 25.5 km away from the MMCR and regularly performs vertical plane elevation scans over the MMCR site. Both conventional (i.e., based on the reflectivity, Z , – rainfall rate relations) and polarimetric (e.g., based on the specific differential phase between horizontally and vertically polarized radar signals, KDP) estimates of rainfall rate are available from the C-Pol radar.

As an example, the vertically resolved MMCR retrievals for decimal 13.82 UTC on 11 January 2003 (a time for a C-Pol vertical scan over the MMCR site) is shown in Figure 3. This figure also depicts a corresponding profile of C-Pol and MMCR reflectivities. Note that due to non-Rayleigh scattering effects, an about 20 dB attenuator in the MMCR precipitation mode, and wet radome issues, MMCR K_a-band reflectivities are significantly smaller than C-band reflectivities. MMCR data also show very distinct attenuation effects manifested by the rapid decrease in observed reflectivities as the altitude of radar echoes increases. The KDP- and Z-based retrievals from C-Pol are shown together with MMCR retrievals. It can be seen that MMCR rainfall estimates are within uncertainties of precipitation C-Pol radar estimates using the two common C-band radar approaches. It indicates that MMCR measurements can be effectively used to estimate vertical profiles of rain rates in convective rains that result in heavy rain rates. The MMCR based rain rate retrieval uncertainties are rather comparable with precipitation radar uncertainties in rainfall retrievals.

Figure 3. Comparisons of the attenuation-based MMCR retrievals of rainfall rates with the results from scanning polarimetric precipitation radar (C-POL).

3. Brief description of accomplishments for Year 3.

The 2007 activities were mostly focused on developing and an initial application of remote sensing techniques for snowfall retrievals. As in case of rainfall retrievals, the technique development was performed for the intended use with the ARM 8-mm wavelength vertically pointing cloud radar (MMCR). The ARM remote sensing approaches developed earlier for retrievals of ice cloud parameters are not transferable to solid precipitation retrievals because precipitation size particles (i.e., snowflakes) exhibit significant non-Rayleigh scattering effects and snowflake fall velocities show very little variation with their size, thus limiting the use of Doppler velocity information for retrievals. Due to these factors, a new technique development specifically tailored to snowfall observations was needed.

Available experimental data on snowflake size distributions and new theoretical and observational studies on snowflake shapes, mass - size and fall velocity – size relationships were used to model reflectivity (Z_e) – snowfall rate (S) relations at K_a -band. It was shown that the snowflake shape affects the backscatter cross sections at K_a -band frequencies significantly stronger than for cm wavelengths. Modeling was performed for the “dry” snow conditions that are often observed at the ARM North Slope of Alaska site. The mean Z_e - S relation for the MMCR frequency was found to be $Z_e = 56 S^{1.2}$. The variability of the coefficients in this relation to uncertainties in the mass - size and fall velocity – size relationships is, however, significant and may result in about a factor two (or even greater) snowfall rate retrieval error. Overall uncertainties of snowfall retrievals at K_a -band were shown to be comparable to the errors of radar observations at precipitation radar frequencies.

The possible use of Doppler velocity measurements, V_D , for snowfall retrievals was studied. It was shown that V_D values do not significantly change for “dry” snowfall and they are approximately in the range 1 - 1.5 m s⁻¹. V_D measurements, however, can effectively be used for separating dry and wet snowfalls. Wet snowflakes fall significantly faster due to their higher density. Quantitative estimations in wet snowfall conditions remain to be a challenge. K_a -band signal attenuation in “dry” snowfall was studied and the relation for snowfall attenuation coefficients have been developed for the use in ARM snowfall rate retrievals.

Since a vertically pointing W-band radar (WACR) has been recently deployed at the Southern Great Planes ACRF site, modeling and derivations of Z_e - S relations were also performed for W-band. The dynamic range of snowfall reflectivity changes at W-band is, however, significantly less than for K_a -band due to very strong non-Rayleigh scattering effects at the higher frequency. The signal attenuation in “dry” snowfall at W-band is about one order of magnitude stronger than at K_a -band. These factors make W-band measurements of snowfall rate less preferable than at K_a -band, though the potential of using dual-wavelength radar measurements of characteristic snowflake size should be explored in more detail.

Figure 4 shows the results of deriving mean Z_e - S relations for K_a - and W-bands. Experimental snowflake size distributions for aggregate snowflakes and dendrites were used for modeling. It can be seen that single crystal snow (i.e., dendrites) and aggregate snow results are consistent, although single crystal snowfalls typically produce much smaller values of S and thus accumulations compared to aggregates.

Figure 4. Scatter plots of radar reflectivity at vertical incidence and snowfall rate at K_a - (a) and W- (b) bands.

Figure 5 shows an example of snowfall retrievals for the event observed with the NSA MMCR on September 27, 2004. For the most part of the event, typical values of V_D were smaller than 1.3 m s^{-1} which is indicative of “dry” snow with no significant riming. The high temporal variability of V_D observed in the lowest 1.5 km layer is explained by the turbulence which is also consistent with larger Doppler spectral width values. Retrieved snowfall rates for this event did not exceed 1 mm h^{-1} . The event of 27 September 2004 is one of typical “dry” snowfall events which are often observed in the Arctic. Note that scope of the events observed with the ARM NSA MMCR during 2005-2006 was rather limited due to the radar calibration problems.

Results of MMCR snowfall retrievals allow getting insights into solid precipitation processes. While typical vertical changes in snowfall rates, S , were not very significant in the lowest 400–500 m layer, there was a gradual decrease of S with height for $h > 500$ m. These changes reflect solid precipitation formation processes and the retrieved information can be used for model validations. Due to radar signal saturation issues, the lowest gate where retrievals were possible was at a height of about 300 m. The times series of snowfall accumulations estimated from the radar retrievals at the lowest gate were found to be consistent with the Climate Reference Network (CRN) surface snow gauge which was deployed nearby.

Figure 5. Time-height cross sections of MMCR reflectivity (a), vertical Doppler velocity (b), Doppler spectral width (c), and retrieved snowfall rate for 27 September 2004 (NSA ACRF).

4. Brief description of accomplishments for Year 4.

The 2008 activities were mostly focused on developing and testing a remote sensing approach to simultaneously retrieve cloud and rainfall parameters in the atmospheric column using the ARM and auxiliary remote sensors. Such an approach was suggested for the use with the ARM vertically pointing radars operating at 8 mm and 3 mm (i.e., MMCR and WACR) with the additional use of the NEXRAD KVNx radar (i.e., the WSR-88D radar which is the closest to the SGP ACRF site).

At the first stage of this approach, the MMCR and WACR measurements are used to retrieve cloud liquid water path (LWP) and the mean rainfall rate, R_m , in the liquid hydrometer layer observed between the ground and the melting layer, which is identified from the MMCR Doppler and WACR polarization measurements. These retrievals are based on the spectral differences between the attenuations in the cloud and rain components of the liquid hydrometer layer. The retrievals are immune to the absolute calibration of the ARM radars. While the Ka-band attenuation in both rain and clouds is more or less insensitive to the variations in drop size distributions, the surface based measurements of raindrop size distributions from an impact Joss-Waldvogel disdrometer (JWD) are used to constrain the W-band attenuation coefficient in rainfall.

After LWP and mean rainfall rate are estimated, the MMCR measurements are used at the second stage of the approach to retrieve ice water content (IWC) and then ice water path (IWP) of the ice part of a precipitating cloud system. Unlike for the liquid phase below the melting layer, the retrievals above this layer are based on the absolute radar measurements. The low-resolution data from the KVNx radar obtained from the ice cloud parts are used to correct the MMCR signal attenuation suffered due to propagation through the liquid and melting layers and also due to a wet radome. The KVNx radar is located at a distance of 60 km from the SGP ACRF facility and regularly performs scans thus providing reference measurements above this facility. The absolute calibration of the KVNx radar, which is operated at a non-attenuated frequency of about 3 GHz, is verified by comparing its measurements in rain with the reflectivities calculated from the JWD rain drop spectra.

A frequency difference between the MMCR and KVNx radars is accounted for during the process of the attenuation correction. The IWC retrievals using the corrected MMCR measurements are based on relations between reflectivity and ice water content. These relations were specifically tailored for the use at Ka-band. As a result of the application of the suggested remote sensing approach, cloud LWP and mean rainfall rate and also cloud IWP are retrieved for the same vertical column. The temporal resolution of the retrievals is 6 min, which is dictated by the KVNx scanning measurements repetition time and also by a desire to suppress high frequency variability in the retrieved parameters.

Figure 6 shows an example of radar measurements during a precipitation event observed on 1 May 2007 at the SGP ACRF. The liquid and ice parts of this system are separated by a melting layer which is characterized by enhanced reflectivities in MMCR data and also by a sharp gradient in Doppler velocity measurements.

Figure 6. Time-height cross sections of MMCR (a) and WACR (b) reflectivity, and MMCR Doppler velocity (d) measurements observed on 1 May 2007. The KVNIX reflectivity cross section (c) was reconstructed from the WSR-88D radar scans.

Retrieval results for the case shown in Fig. 6, are depicted in Fig. 7, where the time series of IWP, LWP and R_m are presented. LWP values are reported only for the regions below the melting layer, and the supercooled water, which might be present in some limited quantities above the freezing level, cannot be retrieved using this approach. Independent observations, however, indicate that in stratiform precipitation systems, the amounts of supercooled liquid are relatively small.

Figure 7. Retrievals of IWP, LWP and mean rainfall rate for the 1 May, 2007 precipitation event.

It can be seen that IWP values, as a rule, are significantly larger than LWP values in the same vertical column. Over the course of the event, both LWP and IWP vary rather significantly. The rainfall was mostly light-to-moderate, which is customary for stratiform events. Estimates uncertainties of the retrievals are about 30 % for the mean rainfall rate (when $R_m \sim 2\text{-}6\text{ mm/h}$), about 200 g m^{-2} for LWP and about a factor of 2 for IWP.

The validation options for the suggested remote sensing approach are few, because no other technique allow simultaneous retrievals of rain cloud parameters from ground based measurements. The retrieved rainfall, however, can be compared to estimates from JWD. Such comparisons are shown in Fig.8.

Figure 8. Comparisons of rainfall rates retrieved from radar measurements and surface estimates from JWD data.

While the use of the NEXRAD WSR-88D radar measurements provides a constraint for correction of MMCR measurements for attenuation in the liquid and melting layers, there could be periods when NEXRAD data are not available. In this case, the attenuation can be estimated theoretically. For the liquid hydrometer layer, the total two-way attenuation can be easily calculated using the retrieved values of LWP and R_m . The specific attenuation in the melting layer, however, is generally stronger than that for the rain layer. A melting layer model was developed to relate the total two-way attenuation in this layer and the resultant rain rate, R_m .

Figure 9 shows the verification of this model when the MMCR reflectivity measurements are compared to the modeled results with and without accounting for the melting layer attenuation. One can see that the melting layer model data describe observations well.

Figure 9. Comparisons of modeled and measured Ka-band reflectivities in a melting layer (ML) and stratiform rain

5. Brief description of accomplishments for Year 5.

The 2009 activities were focused on applying the multi-radar wavelength remote sensing method to simultaneously retrieve cloud and rainfall parameters in the atmospheric column using the ARM and auxiliary remote sensors. This method uses vertically pointing reflectivity measurements from the MMCR (a 0.86 cm wavelength) and WACR (a 0.32 cm wavelength) radars, operating at attenuating frequencies, and scanning measurements from the KVNIX radar, which is the closest to the Southern Great Plains ACRF site precipitation WSR-88D radar operating at an S-band frequency (a 10 cm wavelength). The KVNIX measurements are practically not attenuated in the atmosphere for most meteorological conditions. The collocated with MMCR and WACR measurements of the rain drop size distributions from an impact Joss-Waldvogel disdrometer (JWD) are also used in retrievals.

The suggested remote sensing method is applicable to stratiform precipitating events and represents the first attempt to provide separate retrievals of cloud and rainfall water which co-exist in the same volume. The retrievals were performed for the 2007 warm season precipitating events observed at the SGP ACRF site. Overall 11 qualifying precipitation events were observed during the May-June period. Most of the rest of the 2007 warm season retrievals were not possible due to the fact that WACR was not operational. The selection criteria also included thresholding on the lowest and highest rainfall rates. Time intervals with rainfall rates less than 0.5 mmh^{-1} and greater than $10\text{-}15 \text{ mmh}^{-1}$ were excluded because cloud parameters in such conditions could not be reliably estimated due to high retrieval uncertainties and instrument limitations.

The May –June 2007 period, for which retrievals were performed, was the wettest on recent record in the Northern Oklahoma. This period also presents a special interest to the ARM Program because the Cloud and Land Surface Interaction Campaign (CLASIC) Intensive Operational Period was conducted during this time. Figure 10 shows ARM radar measurements for a typical precipitation event during this period. During this event, which was observed on 24 May 2007, the brief convective rain was trailing the trailing stratiform rainfall was observed for about four hours.

Figure 10. Time-height cross sections of MMCR and WACR observations in different measurements mode during the event of 24 May 2007.

The “ice part” of the precipitating system is separated from the liquid layer containing rain and liquid water clouds by the reflectivity bright bands, which are clearly visible in Fig. 10a. The brief convective period at around 9:30 UTC causes total attenuation of cloud radar signals and retrievals are not available during this period. The corresponding retrievals of mean rain rate R_m and cloud liquid and ice water paths (LWP and IWP) are shown in Fig.11.

Figure 11. Retrievals of rainfall and cloud parameters for the observation case of 24 May 2007.

The simultaneous remote sensing retrievals of cloud and rainfall parameters were used for assessing statistical relations between these parameters. These relations can provide information on the precipitation formation processes and the water cycle, and also to develop different model parameterizations. Figure 12 shows the best power-law fits IWP- R_m and LWP- R_m derived for all 11 observational cases, which qualified for the retrievals.

Figure 12. Best fit power law IWP- R_m and LWP- R_m relations for the SGP precipitating events

For a given atmospheric vertical column IWP values in precipitating events are usually significantly higher than LWP values. There usually is a positive correlation between IWP and R_m , although situations when IWP is decreasing with rain rate were also observed. The correlation between LWP and R_m is usually very low. Figure 13 shows the combined scatter plots between cloud and rainfall parameters. The correlation coefficient between IWP and R_m is 0.31,

for IWP and R_m it is only 0.1 and a typical LWP for the observed precipitating events was about 400-500 gm^{-2} .

Figure 13. Combined IWP- R_m and LWP- R_m scatter plots for precipitating cases observed at the SGP ACRF in 2007.

Simultaneous retrievals of rainfall and cloud parameters from ARM measurements were compared with available retrievals from the spaceborne CloudSat radar. While CloudSat does not pass directly over the SGP site, such comparisons can be conducted in a statistical sense when both ARM and CloudSat radars observe the same precipitating system when the satellite ground track is at its closest to the ARM sensors (~ 56 km). Figure 14 shows CloudSat and ground-based IWP and mean rain rate retrievals comparisons for 2 systems (note that LWP retrievals are not available from CloudSat measurements). Overall, there is a decent agreement between both sets of retrievals and comparable correlations between IWP and R_m were obtained (i.e., both sets of retrievals show negligible correlations for the event of 27 May 2007 in Fig. 14a and the relations for the case of 28 June 2007 in Fig. 14b are $\text{IWP} = 1260 R_m^{0.55}$ for the ARM data and are $\text{IWP} = 1350 R_m^{0.30}$ for the CloudSat data).

Figure 14. Comparisons of the IWP and R_m retrievals from CloudSat and ARM measurements. The error bars in the lower left corner of Fig. 14a represent estimates of retrievals uncertainties.

The comparisons of ARM and CloudSat retrievals of columnar estimates of rainfall and ice water parts for the SGP precipitating events are mutually consistent. Both data sets occupy approximately the same area in the IWP- R_m plane and their mean values are within retrieval uncertainties. This fact is reassuring because both ground-based and spaceborne estimates use independent measurements.-

6. Brief description of accomplishments for Year 6.

The 2010 activities were mainly focused on developing and testing radar based remote sensing approaches to simultaneously retrieve cloud and rainfall parameters in the atmospheric column using the instruments available at the Tropical Western Pacific (TWP) Darwin ACRF. This ACRF has an advantage over other ACRFs because vertical profile measurements (from range – height indicator observations over the Darwin ACRF) are available from the scanning precipitation C-Pol radar located at a distance of about 24 km. These measurements give an opportunity to estimate the vertical profile of non-attenuated reflectivity over the TWP Darwin ARM Ka-band millimeter wavelength cloud radar (MMCR).

The remote sensing approach specifically developed for the TWP Darwin ACRF uses combination of C-Pol and MMCR measurements for retrievals of ice water path (IWP), cloud liquid water path (CLWP) and rain rate in the vertical atmospheric column above the ACRF. Rainfall retrievals constraints are provided by data from a surface impact Joss-Waldvogel disdrometer (JWD) and a tipping bucket precipitation gauge. This approach is applicable to stratiform precipitating cloud systems when a separation between the liquid hydrometeor layer containing rainfall and liquid water clouds and the ice hydrometeor layer is provided by the radar bright band. Under this approach, absolute C-band reflectivities and Ka-band vertical reflectivity gradients in the liquid hydrometer layer are used for estimations of the mean layer rain rate and CLWP. C-band radar reflectivities are also used for retrievals of IWP in cloud regions located above the bright band. The retrieval uncertainties of CLWP and IWP for typical stratiform precipitation systems observed at the TWP Darwin site are about 500-800 g/m² (for CLWP) and a factor of 2 for (for IWP). The CLWP retrieval uncertainties increase with rain rate, so retrievals of cloud component for heavy rainfalls may be impractical. The expected uncertainties of the mean layer rain rate are rather low (around 20%) which, in part, is due to constraints available from the JWD data.

The suggested remote sensing approach was applied to a number of case studies observed at the TWP Darwin ACRF. The thickness of the liquid hydrometeor layer during these events was about 4 km. Mean layer rain rates for these events were typically between 2 and 4 mm/h, although periods of heavier rainfalls were observed. Examples of the retrievals for two characteristic events observed on 27 January 2007 and 27 February 2007 are shown in Fig. 15.

Figure 15. Retrievals of cloud IWP, CLWP and mean layer rain rate in the vertical column above the ARM TWP Darwin site during the 27 January 2007 (a) and 27 February 2007 (b) events.

The retrievals indicated IWP changes in an approximate range between 1000 and 10000 g m^{-2} . Average CLWP values were approximately 1000-1500 g m^{-2} . Retrievals of lower CLWP values could be compromised by high uncertainties. In future, the suggested remote sensing approach can be applied for longer data sets at the TWP Darwin ACRF. The accuracy of the retrievals could be improved when new radars will be deployed at this site as part of the American Recovery and Reinvestment Act at the end of 2010. The use of new radar frequencies, however, will require some additional technique development.

Another focal point of the activities during the 2010 period was comparing precipitating cloud retrievals from the Southern Great Plains (SGP) ACRF with retrievals from the spaceborne W-band radar aboard of the CloudSat satellite. The CloudSat retrievals in the vicinity of SGP ACRF revealed the range of variability in IWP in precipitating systems from a few 100s of g m^{-2} to about 10000 g m^{-2} while the resultant rain rate was varying from 0.5 mm/h to about 12 mm/h. The comparisons indicated a general consistency between results from the ground-based ACRF measurements and from CloudSat. Both types of retrievals showed a moderate correlation between IWP and mean rain rate pointing to the dominance of melting processes in forming stratiform rainfall. Fig. 16 shows IWP- R_m scatter plot for stratiform events observed by CloudSat in the vicinity of the SGP ARM site. It qualitatively agrees with the ARM retrievals in Fig. 13a.

Figure 16. A scatter-plot of all CloudSat retrievals near SGP ARM site.

Journal publications resulted from the research under the project DE-FG02-05ER63954
(listed chronologically)

Matrosov, S.Y., A.J. Heymsfield, and Z. Wang, 2005: Dual-frequency radar ratio of nonspherical atmospheric hydrometeors. *Geophys. Res. Lett.*, **32**, L13816, doi:10.1029/2005GL023210.

Matrosov, S.Y., 2005: Attenuation-based estimates of rainfall rates aloft with vertically pointing Ka-band radars. *J. Atmos. Oceanic Technol.*, **22**, 43-54.

Matrosov, S.Y., P.T. May, and M.D. Shupe, 2006: Rainfall profiling using atmospheric radiation measurement program vertically pointing 8-mm wavelength radars. *J. Atmos. Oceanic Technol.*, **23**, 1478-1491.

Matrosov, S.Y., 2007: Modeling backscatter properties of snowfall at millimeter wavelengths. *J. Atmos. Sci.*, **64**, L13816, 1727-1736.

Matrosov, S.Y., M.D. Shupe, and I.V. Djalalova, 2007: Snowfall retrievals using millimeter wavelength cloud radars. *J. Appl. Meteor. Climatol.*, **47**, 769-777.

Matrosov, S.Y., 2008: Assessment of radar signal attenuation caused by the melting layer. *IEEE Trans. Geosci. Remote Sens.*, **46**, 1039-1047.

Matrosov, S.Y., 2009: A method to estimate vertically integrated amounts of cloud ice and liquid and mean rain rate in stratiform precipitation from radar and auxiliary data. *J. Appl. Meteor. Climatol.*, **48**, 1398-1410.

Matrosov, S.Y., 2009: Simultaneous estimates of cloud and rainfall parameters in the atmospheric vertical column above the Atmospheric Radiation Measurement Program southern Great Plains site. *J. Geophys. Res.*, **114**, D22201, doi:10.1029/2009JD012004.

Matrosov, S.Y. 2010: CloudSat studies of stratiform precipitation systems observed in the vicinity of the Southern Great Plains Atmospheric Radiation Measurement site. *J. Appl. Meteor. Climatol. Technol.*, **49**, 1756-1765. doi:10.1175/2010JAMC2444.1

Matrosov, S.Y., 2010: Synergetic use of millimeter- and centimeter-wavelength radars for retrievals of cloud and rainfall parameters. *Atmos. Chem. Phys.*, **10**, 3321-3331.

Matrosov, S.Y., 2011: Feasibility of using radar differential Doppler velocity and dual-frequency ratio for sizing particles in thick ice clouds. *J. Geophys. Res.*, **116**, D17202, doi:10.1029/2011JD015857.