COMET Partner's Project

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Partners or Cooperative Project: Partners project

Project Title: Vertically pointing radar reflectivity and rainfall measurements at different heights and comparison with a tipping bucket rain gauge and WSR-88D Level II reflectivity.

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Section 1: Summary of Project Objectives

The main objective of the project is the study of rainfall variation in an atmospheric column by using a vertically pointing radar called Micro Rain Radar (MRR); this radar differs from the regular weather radar (WSR-88D) in its frequency of signal (Ka band radar with 24 GHZ frequency), its temporal resolution (10-second scans and 1-minute averages), and its spatial resolution and sampling (e.g., WSR-88D is primarily a horizontally pointing beam with elevation tilts, whereas the MRR has a fixed vertically pointing beam).

The MRR measures the backscattered signal from the raindrops to calculate different microphysical parameters at different heights. Thus, the MRR provides drop-size distribution (DSD) information by converting measured Doppler spectra into drop diameters by a known relationship. Various microphysical parameters can thus be reliably estimated without any assumption to the DSD shape including rain rate (RR), liquid water content (LWC), and radar reflectivity (Z). Mean fall velocity (W) is calculated directly from the measured Doppler spectrum.

The MRR radar provides reflectivity and rainfall profiles in an atmospheric column. In our case settings, this atmospheric column starts from 35 m to 1050 m above the site; the column is divided into 30 steps, with a resolution of 35 meters. The measurements obtained from the MRR are compared against the Level II 0.5 degree base reflectivity product provided by the New Braunfels, TX (KEWX) WSR-88D radar, and the MRR rainfall estimates are compared to rainfall estimates from a high accuracy tipping bucket rain gauge collocated with the MRR at ground level (1 meter apart). The Level II reflectivity product is transformed to rainfall rate using the standard Z-R relationship ($Z = a R^b$), where a = 300 and b = 1.4.

Section 2: Project Accomplishments and Findings

We collected data from May 2009 to present, and developed three Python scripts for processing the raw MRR averaged (over one minute for all MRR parameters) data output into a spreadsheet (i.e., Microsoft Excel) for analysis. We also collected the collocated rain gauge data from December 11, 2009, to December 19, 2011;

The MRR data collected from May 18, 2009 to December 19, 2011 was quality controlled, processed, and used in the current report. Data were averaged over 1-minute interval for all four output parameters, and MRR records were separated into individual rainfall events. In order to separate between rainfall events and non-rainfall, we used a simple algorithm as follows:

1. The MRR radar reflectivity must ≥ 20 dBZ for least 10 consecutive gates (heights).

2. The rain rate must reach at least 10 mm/hr for one level, and the first 10 consecutive height levels (gates) must have a rainfall rate of 1 mm/hr or greater.

(Note: Although both years 2010 and 2011 were drier than usual, some rainfall events were missed in April, May, June, and September 2010, and a few in 2011, due to data logger and/or instrument problems. From March 25 to November 7, 2010, the data logger for the rain gauge was out of service because of electrical breakdown. The data logger was reinstalled on November 8, 2010, after repair, recalibration, and testing by the manufacturer. The MRR instrument stopped working from February 21, 2011 to November 22, 2011, because of corrosion problems of the data cable, the control box and the electrical connectors. A first attempt was made to repair the MRR locally at the UTSA Electrical Engineering Department, but this repair was not successful. We had to send the MRR back to the manufacturer in Germany for repair and recalibration. The repair took longer than usual because of administrative procedures to ship the radar outside the United States and to pay for it.)

2.1 Comparison between Gauge and MRR

From all resulting storms we selected six different rainfall events that satisfied the conditions above, with statistics shown in Table 1, including transforming 1-minute rain rates to 1-minute rain accumulation for all storm events. Note that during the storm events between March 25 and November 7, 2010, the rain gauge (TB4) was out of service, thus no rainfall records were available to compare with the MRR rainfall measurements at these dates.

In Figure 1, rainfall accumulation at one minute resolution is plotted for a storm event that started on January 14, 2010, at 18:23 CST and ended on January 15, 2010, at 21:44 CST, (about 27.5 hours) with a maximum rain rate of 28.48 mm/hr for all the 30 heights were the rain rate was measured (from 35 m to 1050 m above sensor level). This plot shows clearly how the rainfall accumulation varies through the atmospheric column during the storm.

We matched three storms from the MRR rainfall measurements to the gauge rainfall records, these storms are shown in Table 2. These storms were defined from the MRR data only, and then paired with the gauge rainfall records for the corresponding periods of each storm event.

We also downloaded and processed the WSR-88D Level II reflectivity data for the some of the rainfall events (as seen in Table 1). The data processing was done through GIS, Python scripts, and VBA macros. We selected nine radar bins to extract the reflectivity values for comparison with the MRR reflectivity as shown in Figure 2.

The rain gauge data produced some 22 storm events during the entire study period (including interruptions), the storms were defined if 1) at least three tips had occurred and 2) the no rain period between two consecutive tips should be less or equal to thirty minutes, the resulting storms are shown in Table 3. The total accumulated rainfall recorded by the TB4 was 2.057 times the total rainfall measured by the MRR for the same events. We also note that for the first 11 events, the MRR did not detect rainfall or the measured accumulations were close to 0 mm, and this is very clear for small events in particular. This means that MRR had a serious truncation problem when averaging rainfall measurements at the one minute time resolution, and MRR showed a severe underestimation of rainfall in respect to the rain gauge measurements. The correlation between the gauge and the MRR (second gate centered at 70 m) yielded an R^2 of 0.56 (Figure 3), which is lower than what we were expecting. For the large three storms shown in Table 2, the agreement between the two sensors is much higher and the underestimation is lower, it is around 3 % for the storm event of January 14-15, 2010, 22% for the February 2-3 2010 event, and only 1% for the March 20, 2010 event. The question is to understand why the underestimation has such a large range of variability, and if it is related to the physics of each rainfall event, such that reflectivity, mean fall velocity, and liquid water content can be determined.

At this stage of the research there is no indication on how and why the agreement between the gauge and MRR is different from one storm event to another. The results shown in Table 1 show similar values for the maximum recorded Z and W for the five storms, but the LWC maximum values are different. The events of October 26, 2009, February 2-3, and September 7, 2010 show unusually high liquid water content with respect to the other storm events. More analysis is needed to investigate this issue.

Figure 4 shows the cumulative rainfall for both sensors for January 14-15, 2010, February 2-3, 2010, and March 20, 2010, events. During the January14-15, 2010, event, at the beginning of the storm the MRR (at the second gate centered at 70 meters) had higher cumulative rainfall, then both sensors had similar cumulative rainfall for the next two hours, after that the gauge will have higher cumulative rainfall by 4 to 15 mm difference than the MRR for the next 22 hours, but at the end of the event the difference between the two sensors is largely decreased.

For the February 2-3, 2010 event, both sensors start with almost the same cumulative rainfall during the first two and half hours of the storms, and then the gauge cumulative rainfall starts increasing in a faster paste than the MRR all the way until the end of the storm, which resulted in the big difference in the total cumulative rainfall at the end of the storm. For the storm of March 20, 2010, the MRR starts with lower cumulative rainfall almost through the entire period of the storm; the MRR cumulative rainfall reaches the gauge cumulative rainfall value around the last 30 minutes of the storm. What is different during this storm is the fact that there is a time shift between the two sensors when both curves changes slopes, in fact the MRR preceded the gauge. The second curve inflexion around the time 5:48 was followed by a smooth and steady increase in rainfall for the MRR, but the gauge curve was following a stairway shape; this is because the gauge is recording the rainfall by the number of tips increment, while the MRR have a different approach and a better resolution.

The comparison between the gauge and the MRR cumulative rainfall is higher at the hourly resolution, as shown in Figure 5, with an R^2 of .92. This demonstrates that time integration reduces the differences between the gauge and the VPR.

2.2 Comparison between MRR RR rainfall and MRR rainfall derived from the Z-R relationship (Rz).

The MRR measures reflectivity in the Mie regime and has built-in software that calculates the Rayleigh reflectivity through derived DSD parameters. The reflectivity in the Rayleigh regime (such for the weather radar) is proportional to the sixth moment of drop diameter and is expressed as:

$$Z = \int_0^\infty D6\ N\ (D) dD \quad (1)$$

The coefficients and exponents in operational Z-R relations range between 75 and 300 and between 1.2 and 2.0 respectively; in our case the coefficients used by the National Weather Service (NWS) for WSR-88d default settings are a = 300 and b = 1.4.

The measurement of rainfall by the MRR is function of drop spectra, i.e. it is function of the number of drops in a volume, drop size, drop shape, and fall velocity (see Equation 1). The weather radar (WSR-88D) estimates rainfall by transforming backscattered reflectivity values to rainfall rates through the Z-R relationship; this is the primary difference between the MRR and WSR-88D.

The plots in Figure 6 shows the cumulative rainfall of the MRR as derived from the Z-R relationship, compared to the gauge cumulative rainfall, the curve shows a similar trend as in the case of the MRR cumulative rainfall from the RR, but underestimation is larger in the case of the Rz cumulative rainfall with respect to the TB4.

In Figure 7 we plotted the total cumulative rainfall for the MRR RR and the MRR Rz, for all three events of 2010 (January, February and March). The plots show that in the case of Rz, the total cumulative rainfall decreases with increasing gate height, while for the total cumulative rainfall as defined by the MRR RR there is also a decrease of total rain only for the January and February events, while the March events show a totally different trend.

2.3 Comparison of Reflectivity between MRR and WSR-88D

The reflectivity above the MRR site is measured at an average height of 874.68 meters above ground level (from 742.23 to 966.61 m), while the MRR can measure reflectivity from 35 m to 1050 or from 100 m to 3000 m above ground (depending on settings of radar). The preliminary results showed that MRR and WSR-88D best agreement in reflectivity measurement occurred at the MRR height measurement of 980 meters (centered at 980 m) with an R^2 of 0.42 (Figure 8) the best reflectivity agreement was for the last three heights (MRR gates), and if the average of these three heights is taken, then the correlation will be of R^2 of 0.50. The correlation between MRR reflectivity and WSR-88D's increased with increasing height to reach it maximum at the second last gate (980 m).

The MRR reflectivity comparison to the WSR-88D weather radar, as shown in Figure 9, (upper panel), shows the variability of the correlation coefficient with height, unlike rainfall comparison, the best agreement between MRR and WSR-88D reflectivity occurred at the height centered at 980m. But the lower panel of Figure 9 shows the variability of the correlation coefficient between MRR Rz and WSR-88D Rz, which is also variable by gate height, but the best agreement did not occur at 980m, it was at 875 m above ground level. This is mainly due to the nature of the Z-R relationship rainfall estimates and its associated errors.

2.4 Comparison between MRR and WSR-88D rainfall measurement

The comparison of rainfall measurement by the WSR-88D and the MRR , was best at the first MRR gate (35 m), with an R^2 = 0.16 followed by the second MRR gate (70 m) with an R^2 = 0.13, while the scatter plots of the MRR Rz and WSR-88D Rz showed the best agreement was for the second MRR gate (875 m) with an R^2 = 0.18, followed by the gate at 1015 m with an R^2 = 0.16, and the first MRR gate in this case had an R^2 = 0.13.

Table 1: Selected rainfall events statistics are given for the third gate at 105 m above the sensor.

Start Local Time	End Local Time	Duration In Hours	Max RR	Total RR	Max Z	Max W	Max LWC
			(mm/Hr)	(mm)	(dBZ)	(m/s)	(g/m^3)
1/14/2010 18:23	1/15/2010 21:44	27.35	15.01	74.27	41.9	9.06	1.63
2/2/2010 21:52	2/3/2010 16:30	18.63	8.35	27.36	37.2	7.82	0.76
3/20/2010 5:08	3/20/2010 6:59	1.72	282.64	22.16	43.4	8.58	47.77
9/7/2010 3:14	9/7/2010 17:50	14.60	115.77	101.26	46.7	9.09	20.15
10/26/2009 5:01	10/26/2009 17:22	12.35	244.76	89.80	49.3	7.46	23.76
5/14/2010 3:06	5/14/2010 13:50	10.73	97.46	53.57	47.9	9.18	6.27

Table 2: Selected rainfall events from the gauge (TB4) data and MRR corresponding rainfall statistics are given for the second gate at 70m above ground. The RR is the rain rate as directly produced from the drop spectra by the MRR and the Rz is the rainfall obtained by applying the Z-R relationship ($Z = 300\ R^{1.4}$) from the reflectivity measurements of the MRR radar.

Start Local Time	End Local Time	Duration In Hours	Total rainfall (mm)		MRR Rz	MRR RR
			TB4	MRR	(mm)	Maximum (mm/hr)
1/14/2010 20:37	1/15/2010 21:59	25.18	65.53	63.76	62.01	10.62
2/2/2010 23:06	2/3/2010 16:59	17.80	43.18	25.67	20.10	8.43
3/20/2010 5:08	3/20/2010 6:59	1.72	22.35	22.16	10.76	140.73

Table 3: Rainfall events defined with respect to the TB4 rain gauge from December 18, 2009 to December 19, 2011.

event	Beginning Time		Ending Time		rainy	total rainfall (mm)	
	UTC	Local	UTC	Local	minutes	TB4	MRR
1	12/4/2011 22:40	12/5/2011 4:40	12/5/2011 0:02	12/5/2011 6:02	82	1.5	0.0
2	12/2/2011 12:43	12/2/2011 18:43	12/2/2011 16:34	12/2/2011 22:34	231	3.0	0.0
3	12/4/2011 6:22	12/4/2011 12:22	12/4/2011 8:26	12/4/2011 14:26	124	3.0	0.0
4	12/29/2009 17:22	12/29/2009 23:22	12/29/2009 19:16	12/30/2009 1:16	114	2.0	0.0
5	12/5/2011 1:41	12/5/2011 7:41	12/5/2011 4:23	12/5/2011 10:23	162	7.9	0.0
6	12/3/2011 2:45	12/3/2011 8:45	12/3/2011 8:18	12/3/2011 14:18	333	7.9	0.0
7	12/29/2009 14:32	12/29/2009 20:32	12/29/2009 16:49	12/29/2009 22:49	137	5.1	0.0
8	1/13/2010 15:07	1/13/2010 21:07	1/13/2010 17:21	1/13/2010 23:21	134	2.3	0.0
9	1/13/2010 19:07	1/14/2010 1:07	1/13/2010 21:20	1/14/2010 3:20	133	3.0	0.0
10	4/16/2010 18:01	4/16/2010 23:01	4/16/2010 19:26	4/17/2010 0:26	85	11.2	0.0
11	5/17/2010 21:34	5/18/2010 2:34	5/17/2010 22:06	5/18/2010 3:06	32	1.5	0.0
12	3/8/2010 2:11	3/8/2010 8:11	3/8/2010 3:04	3/8/2010 9:04	53	0.8	0.1
13	4/15/2010 10:48	4/15/2010 15:48	4/15/2010 11:46	4/15/2010 16:46	58	4.3	0.1
14	4/15/2010 2:14	4/15/2010 7:14	4/15/2010 2:33	4/15/2010 7:33	19	0.8	0.1
15	12/17/2009 4:21	12/17/2009 10:21	12/17/2009 11:06	12/17/2009 17:06	405	7.1	11.8
16	1/14/2010 17:30	1/14/2010 23:30	1/14/2010 19:37	1/15/2010 1:37	127	1.5	4.9
17	1/15/2010 0:34	1/15/2010 6:34	1/15/2010 0:40	1/15/2010 6:40	6	0.8	0.1
18	1/15/2010 1:37	1/15/2010 7:37	1/15/2010 11:41	1/15/2010 17:41	604	39.1	28.6
19	1/15/2010 1:37	1/14/2010 20:37	1/16/2010 2:59	1/15/2010 21:59	1523	65.5	63.8
20	1/15/2010 12:22	1/15/2010 18:22	1/15/2010 20:51	1/16/2010 2:51	509	17.5	7.1
21	2/3/2010 4:06	2/2/2010 23:06	2/3/2010 21:59	2/3/2010 16:59	1074	43.2	26.8
22	2/4/2010 1:18	2/4/2010 7:18	2/4/2010 4:10	2/4/2010 10:10	172	4.3	0.5
23	2/4/2010 7:46	2/4/2010 13:46	2/4/2010 8:15	2/4/2010 14:15	29	1.3	0.3
24	2/11/2010 8:23	2/11/2010 14:23	2/11/2010 14:22	2/11/2010 20:22	359	12.2	8.7
25	3/16/2010 2:01	3/16/2010 8:01	3/16/2010 4:47	3/16/2010 10:47	166	7.9	0.8
26	3/20/2010 11:08	3/20/2010 5:08	3/20/2010 12:59	3/20/2010 6:59	111	22.4	23.3
27	4/14/2010 19:15	4/15/2010 0:15	4/14/2010 20:40	4/15/2010 1:40	85	3.6	0.3
28	4/15/2010 7:30	4/15/2010 12:30	4/15/2010 9:37	4/15/2010 14:37	127	3.3	5.3
29	4/15/2010 13:14	4/15/2010 18:14	4/15/2010 23:51	4/16/2010 4:51	637	25.4	1.7
30	4/17/2010 4:49	4/17/2010 9:49	4/17/2010 14:38	4/17/2010 19:38	589	25.4	8.3
31	5/14/2010 4:46	5/14/2010 9:46	5/14/2010 13:34	5/14/2010 18:34	528	68.3	11.5
32	11/26/2011 1:08	11/26/2011 7:08	11/26/2011 10:56	11/26/2011 16:56	588	23.4	9.7
33	12/10/2011 14:26	12/10/2011 20:26	12/11/2011 2:54	12/11/2011 8:54	748	15.5	1.7
34	12/13/2011 23:35	12/14/2011 5:35	12/14/2011 11:27	12/14/2011 17:27	712	5.1	2.4
35	12/15/2011 4:57	12/15/2011 10:57	12/15/2011 11:58	12/15/2011 17:58	421	3.0	1.7
36	12/18/2011 23:49	12/19/2011 5:49	12/19/2011 8:03	12/19/2011 14:03	494	7.4	2.8
					Total Accumulated Rainfall	**457.5**	**222.4**

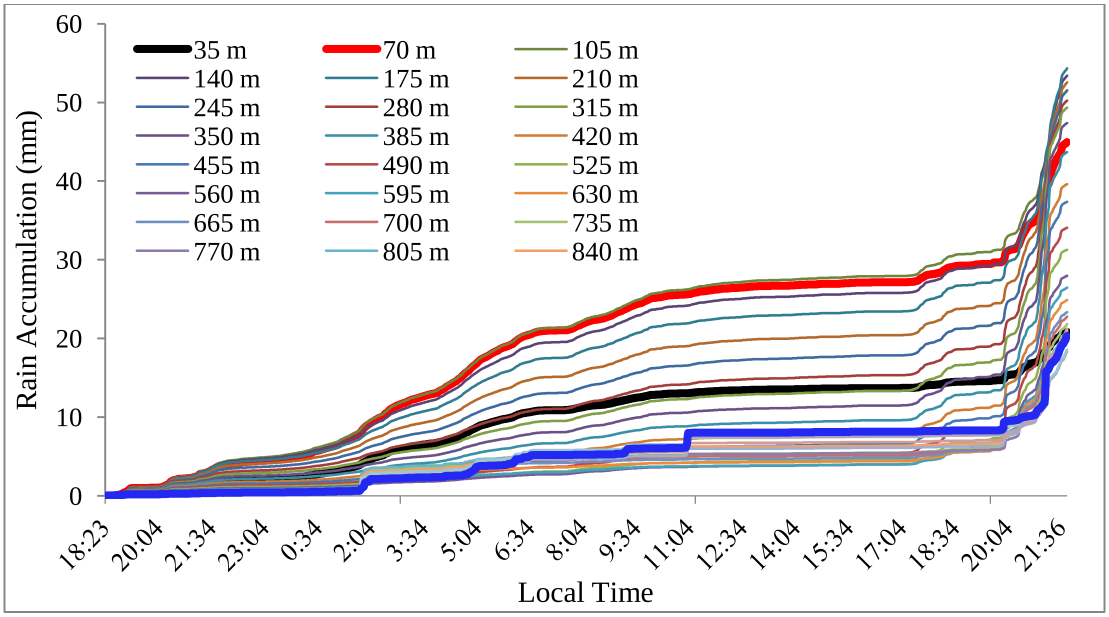


Figure 1: Time series of rainfall accumulation at one minute resolution for a rainfall event that occurred from January 14, 2010, at 18:23 CST to January 15, 2010, at 21:44 CST. Rainfall accumulation is shown for all 30 heights were the rain was measured by the MRR. The black bold line is the rainfall accumulation at the lowest elevation which is 35 m above ground level, and the red line for the second height (70 m).

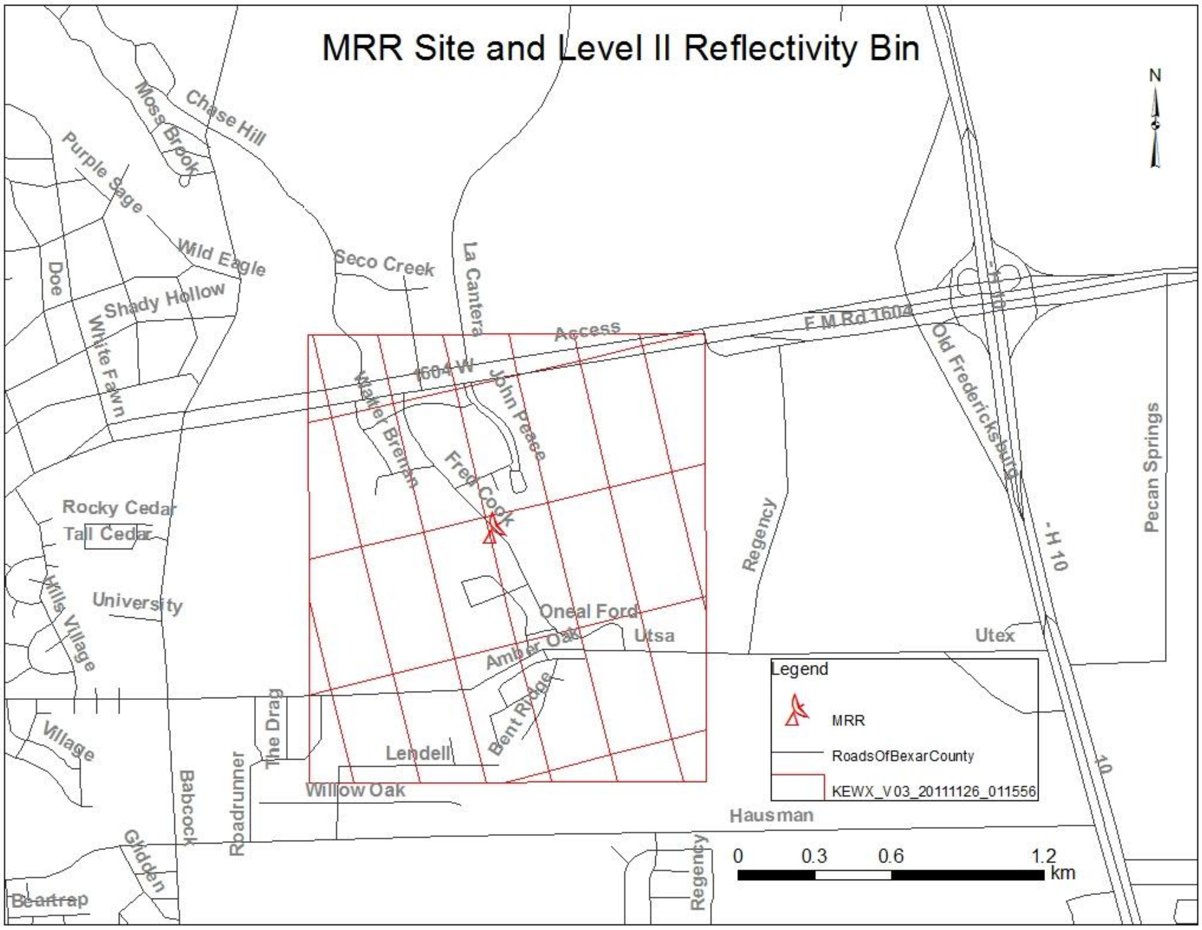


Figure 2: MRR site and Level II reflectivity Bins (WSR-88D), the dots represent the centers for each bin, these centers are used to extract the reflectivity value for each collocated bin.

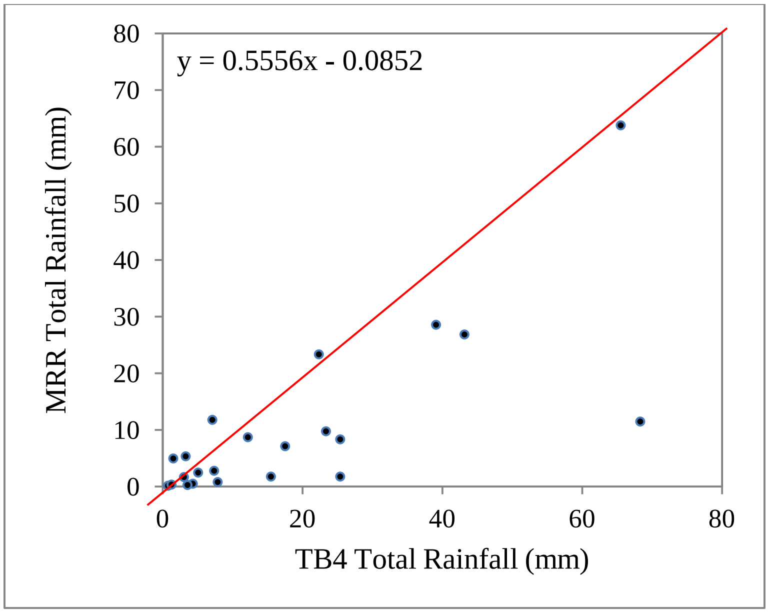
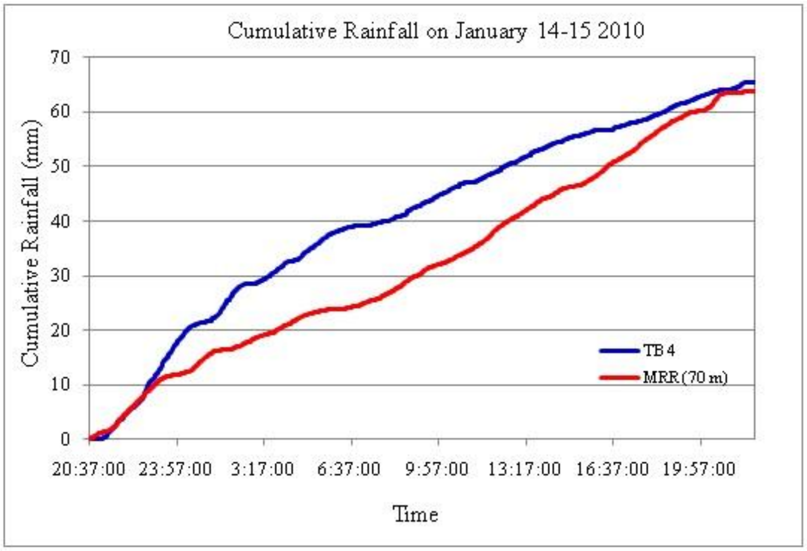
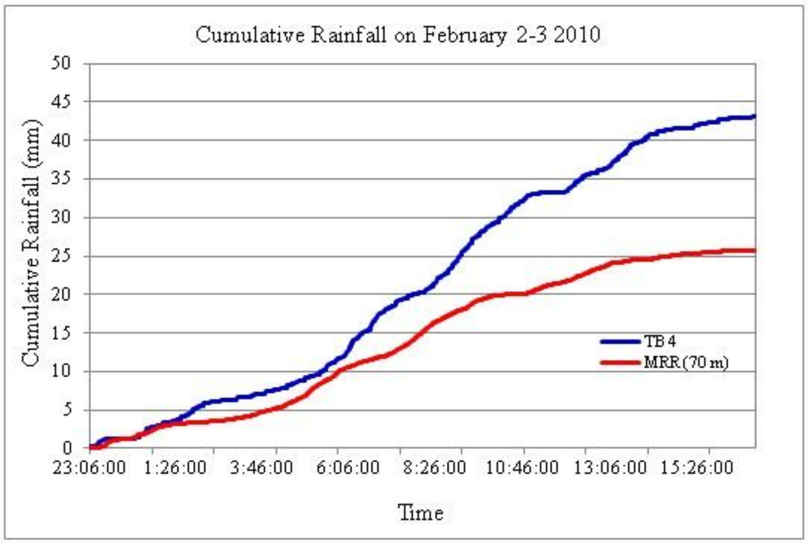


Figure 3: Scatter plot of total rainfall events between the gauge and the MRR**,** the storm events were defined from the gauge records. The plot is showing all events with total rainfall greater than 7mm as measured by the TB4. MRR rainfall is shown for the gate centered at 70 meters above ground level.


Cumulative Rainfall on January 14-15 2010
Cumulative Rainfall (mm)
0
10
20
30
40
50
60
70
20:37:00
23:57:00
3:17:00
6:37:00
9:57:00
13:17:00
16:37:00
19:57:00
Time
TB4
MRR (70 m)


Cumulative Rainfall on February 2-3 2010
Cumulative Rainfall (mm)
0
5
10
15
20
25
30
35
40
45
50
23:06:00
1:26:00
3:46:00
6:06:00
8:26:00
10:46:00
13:06:00
15:26:00
Time
TB4
MRR (70 m)

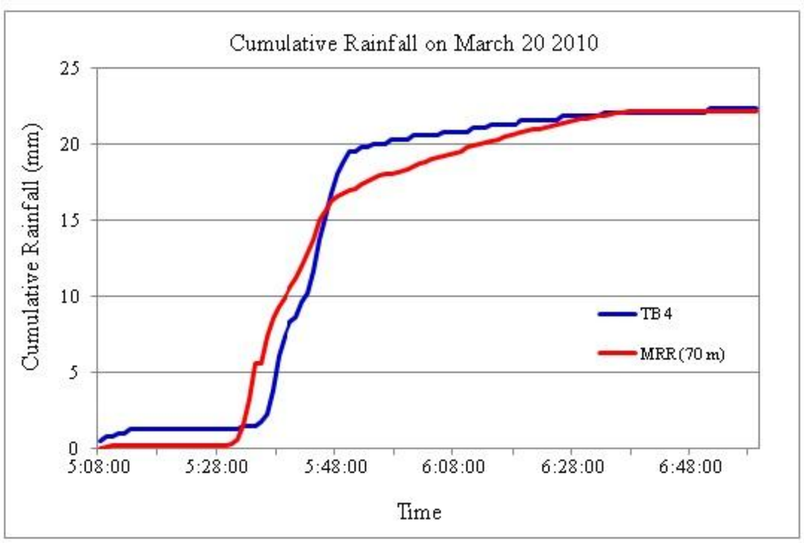

Cumulative Rainfall on March 20 2010
Cumulative Rainfall (mm)
0
5
10
15
20
25
5:08:00
5:28:00
5:48:00
6:08:00
6:28:00
6:48:00
Time
TB4
MRR (70 m)

Figure 4: Cumulative rainfall for the storm events of January (upper panel), February (middle panel) and March (lower panel) 2010.The blue line represents the gauge rainfall accumulation and the red line the MRR cumulative rainfall. MRR rainfall is shown for the gate centered at 70 meters above ground level.

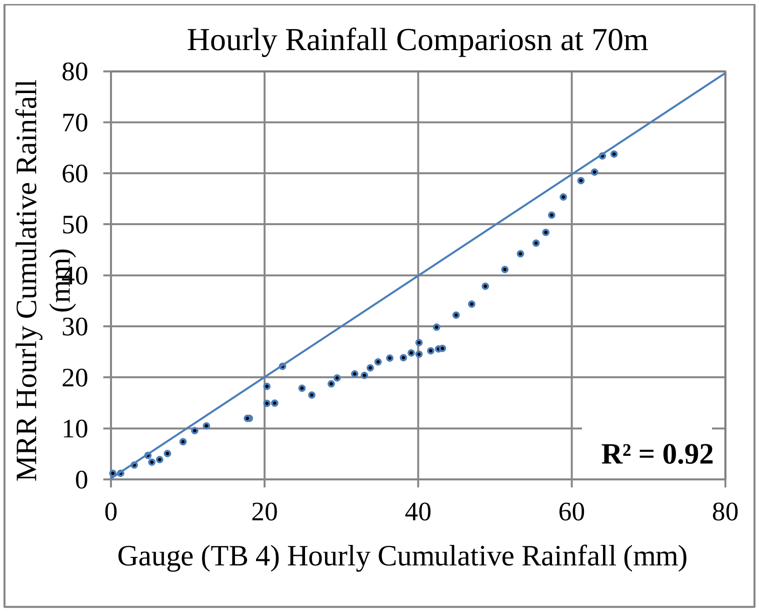


Figure 5: Scatter plot of total hourly cumulative rainfall for both gauge and MRR. The MRR rainfall is shown for the second gate centered at 70m above ground level.

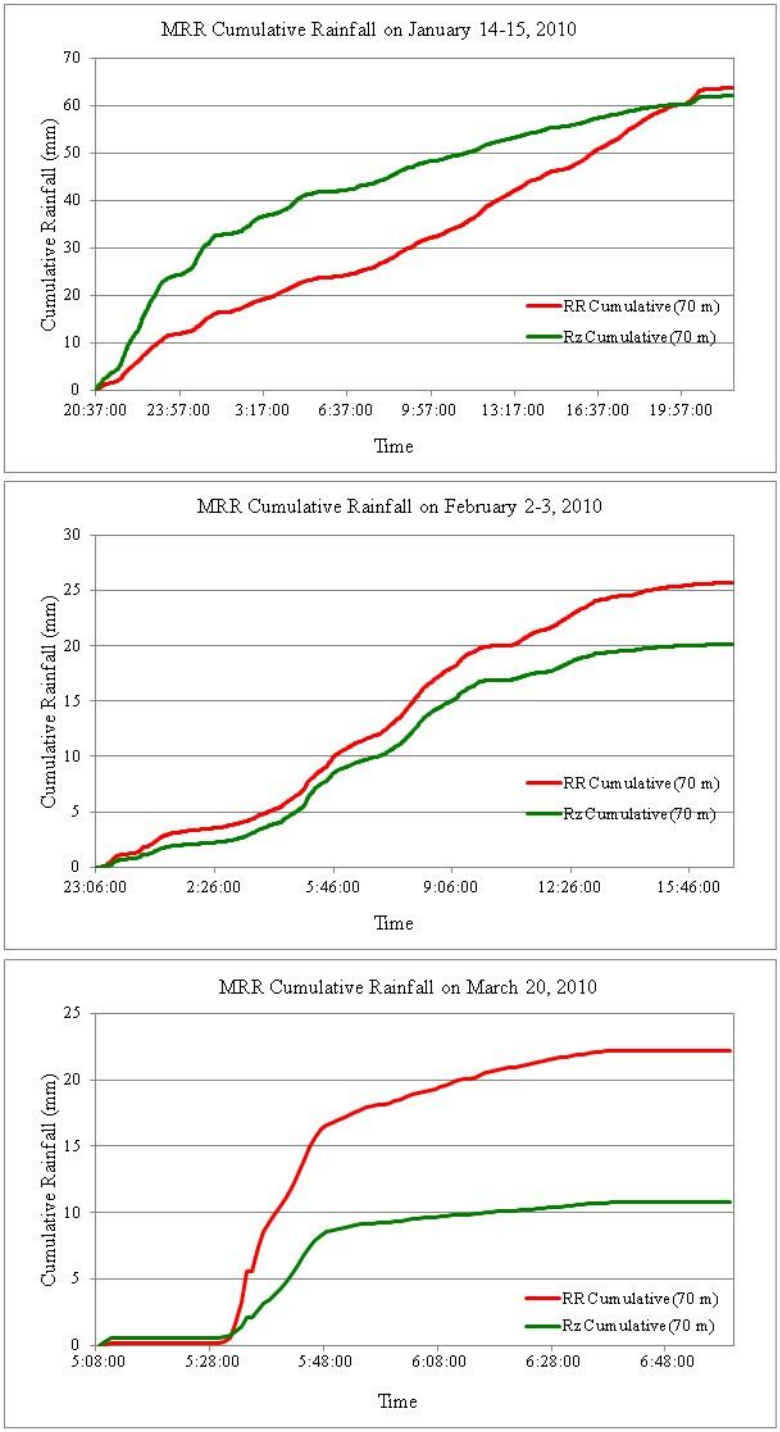


Figure 6: Cumulative rainfall for the three storms of 2010, January (upper panel), February (middle panel) and March (lower panel). The red line represents the MRR rainfall cumulative measurements as derived directly from the MRR one minute rainfall rate (RR). The green line represent the cumulative rainfall (Rz) derived from the MRR reflectivity using the Z-R relationship as used by the New Braunfels WSR-88D precipitation processing system.

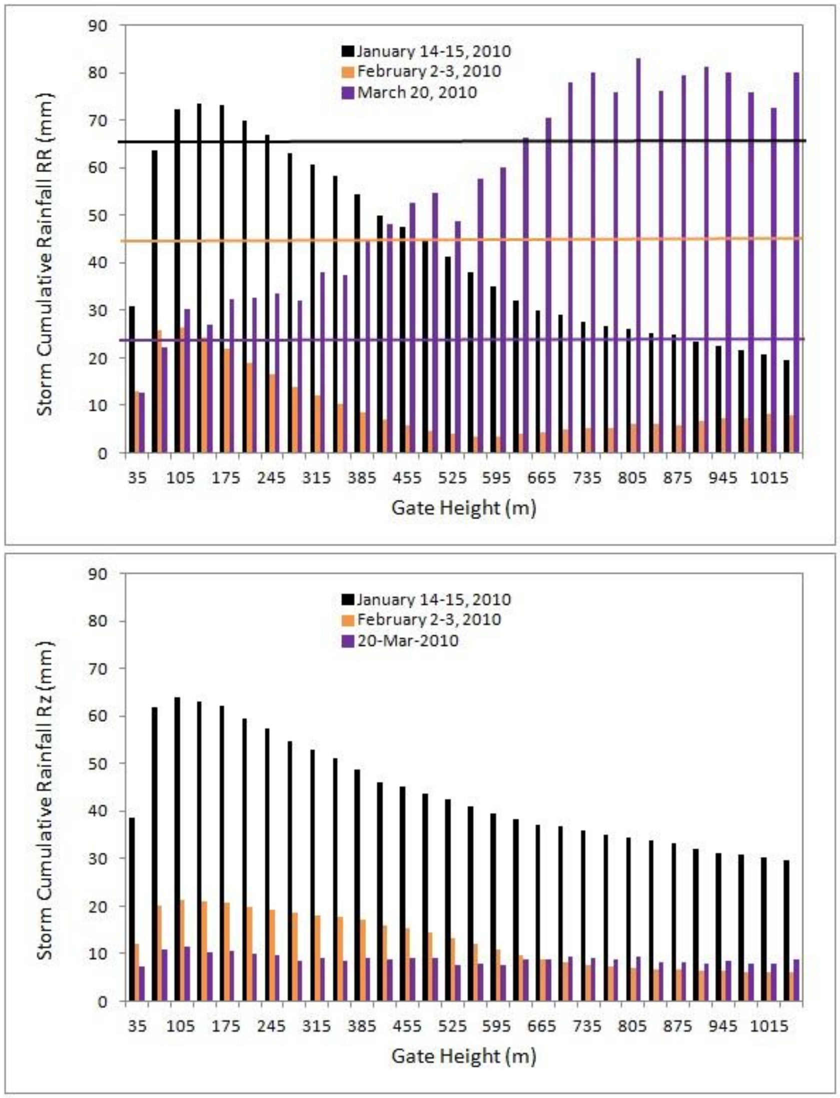


Figure 7: Total cumulative rainfall variability with height for January, February and March events. First panel shows the total rainfall from the MRR RR at all heights, and the lower panel shows the total cumulative rainfall derived using the Z-R relationship.

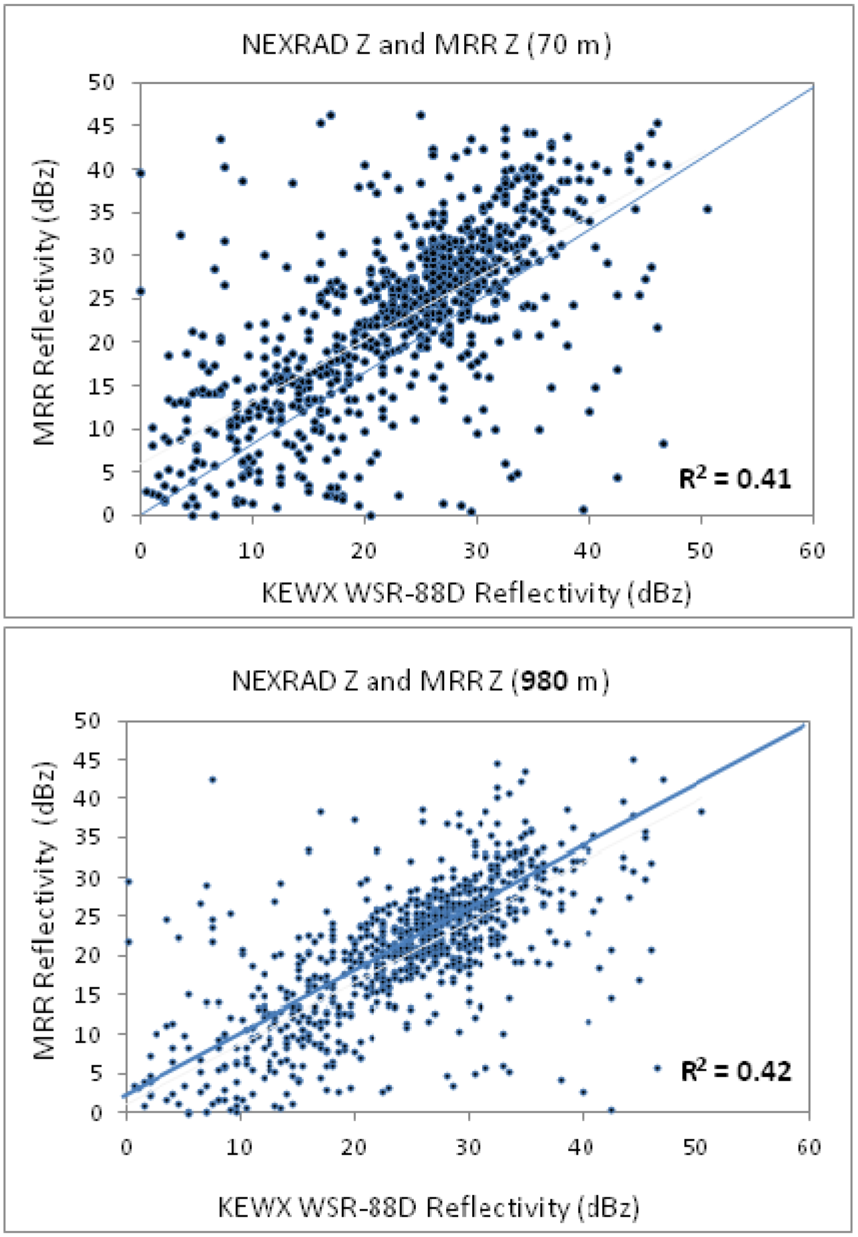


Figure 8: Comparison Plots of WSR-88D and MRR reflectivities at the gates centered at 70 and 980m above ground level.

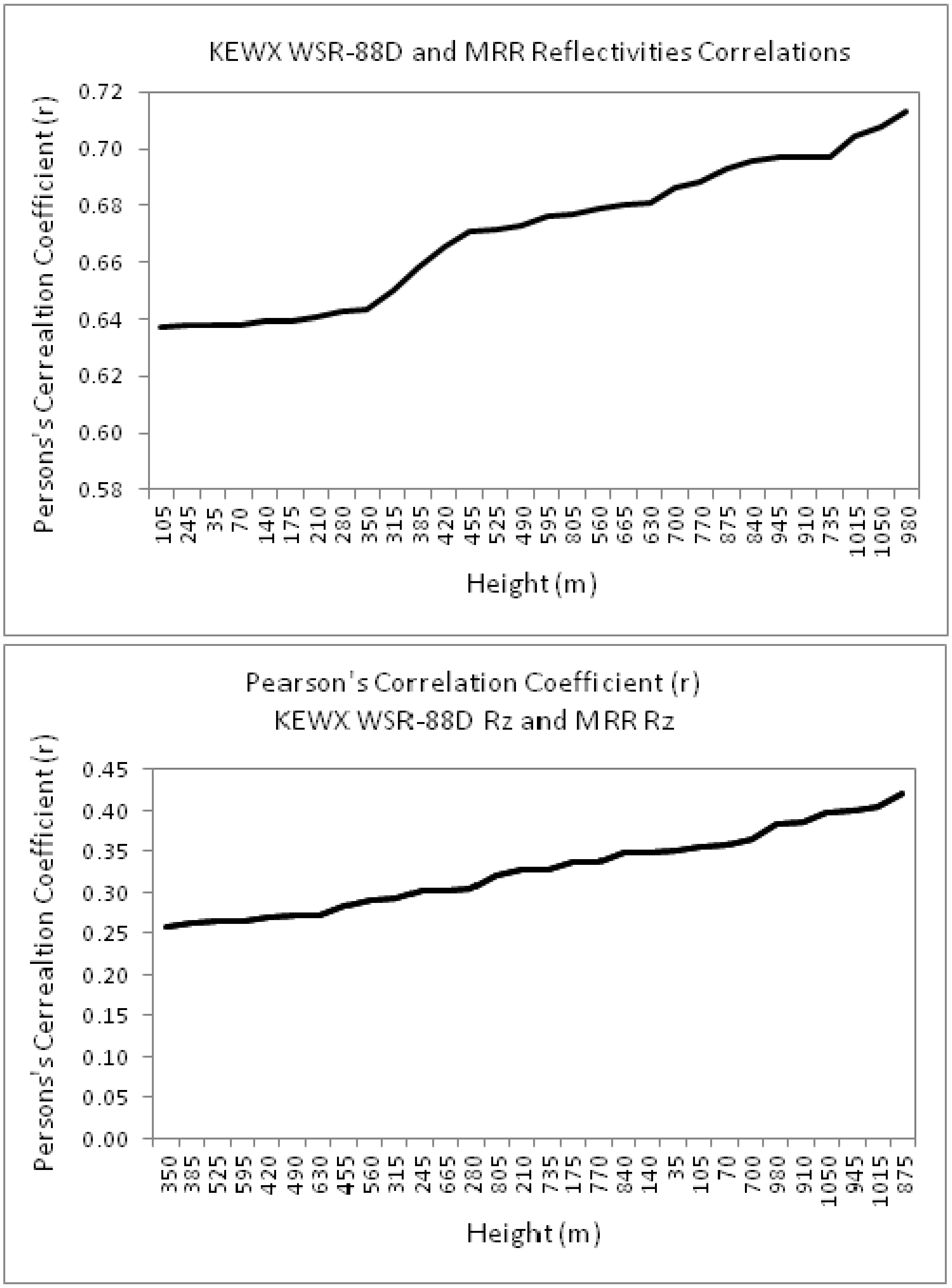


Figure 9: Variability of the correlation coefficient (r) with height, between the WSR-88D and the MRR reflectivities (upper panel) and between the WSR-88D and the MRR Rz rainfall total measurements.

Section 3: Benefits and Lessons Learned: Operational Partner Perspective

The major benefit for the NWS is the use of a vertically pointing radar to compare with WSR-88D and a gauge, We believe that this type of comparison has not been done before. Such a study will give more insight into the variability of rainfall in an atmospheric column. This kind of research could help the NWS adjust the Z-R relationship and therefore to reduce the bias in rainfall measurement as measured by the WSR-88D. The coming addition of Dual-Polarization and a new precipitation processing system may lead to continued research of this type.

Section 4: Benefits and Lessons Learned: University Partner Perspective

The project provides training to students in the use of new hydrologic tools, such as the MRR, the training includes radar (MRR) installation and setup, data processing and analysis, along with derivation of statistical and analytical methods to compare MRR results with the WSR-88D measurements and with a tipping bucket rain gauge. The research aspect of this project is to improve our understanding of rainfall processes and their variation in an atmospheric column, to capture the size distribution of raindrops and their relationship to the rainfall rate (RR) and radar reflectivity (Z).

Section 5: Publications and Presentations

The project results were presented at the American Geophysical Union Conference of December 4 to 9, 2011 at San Francisco, California. Ongoing analysis and data mining are still on the way. Also the project will be included the in a student Ph.D. dissertation, with the prospect of publishing the results in a scientific journal.

Mazari, N., H. Sharif, H. Xie, J. Zeitler, 2011. Vertical Variability of Radar Reflectivity and its Impact on Radar Rainfall Estimation. AGU Fall meeting, San Francisco, CA, December 5-9.

Section 6: Summary of University/Operational Partner Interactions and Roles

Drs. Hongjie Xie and Hatim Sharif advised one Ph.D. student (Newfel Mazari) on the installation and calibration of the MRR, data collection, and processing. Mr. Jon Zeitler provided expertise in the processing and use of WSR-88D Level II radar data used to compare with the MRR data, and it overall project design.

Mr. Zeitler, Drs Xie and Hatim, and the students worked on data analysis and interpretation, and the manuscript is in preparation for submission to a peer-reviewed journal. We held two meetings at the NWS Austin/San Antonio Forecast Office, one lecture was given by Mr. Zeitler to Dr. Xie's remote sensing class, and ad hoc discussions about the project occurred at other local meetings.