Topographic Effects on the Reliability of Precipitation Measurement

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ABSTRACT

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The high altitude of the KMTX radar site prevents the radar from detecting most stratiform precipitation events and a significant portion of the precipitable water in low convective precipitation events. As a result, KTMX significantly underestimates precipitation for these events. Adding lower scan angles to KMTX could significantly improve the accuracy of radar-estimated precipitation.

Keywords: Rainfall Measurement, Tipping-bucket Rain Gauge, NEXRAD Radar, KMTX

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I would like to thank Dr. Summer Rupper for her mentoring not just on this project but with my education and career. I also want to thank Dr. David Tingey and Dr. Bryan Peterson for their help in the early stages of the project. I would like to give a special thanks to Kevin Rey for hiking Y Mountain with me multiple times to deploy the gauges and collect data. I would also like to thank James Raynor and Joey Haddock for hiking Y mountain with me to collect data as well. Lastly, I want to give a special thanks to my wife, Juliana, for her love, support, and patience during this project and throughout my college career.

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Chapter 1

Introduction

1.1 Overview

Various methods are used for measuring precipitation, each with its own advantages and limitations. These methods include physical precipitation gauge (known as a rain gauge) measurements of precipitation, radar estimates of precipitation, and satellite estimates of precipitation. To evaluate the effect of topography on the various methods of measuring precipitation, this study focused on rain gauges and radar estimates.

Satellites were omitted because previous studies have shown that radars and satellites have similar biases (Yilmaz et al. 2005). Radar data were selected over satellite data because radar data have more significant impact. This section also provides information regarding mountaintop radars and measurable rainfall.

1.2 Rain Gauges Versus Radar Estimates

According to Legates and DeLiberty, rain gauges may underestimate the amount of precipitation by about 5% (1993). When evaluating historical data, the error may be as high as 25% due to the effect of wind on snowfall (Groisman & Legates 1994). Groisman and Legates also found that rain gauge measurements in mountainous regions are generally less accurate, likely because of the effect of wind on snowfall as well (1994).

Further research done by Smith et al suggests that the accuracy of rain gauges depends on the rate of precipitation. They found that the maximum precipitation that a rain gauge network is capable of measuring in one hour to be 22 mm. They measured storms that exceeded 75 mm for a one hour period using radar measurements (Weather Surveillance Radar -1988 Doppler). However, for amounts less than 22 mm of precipitation in one hour, they reported no significant errors in rain gauge network data (Smith et al. 1996).

Smith et al also found that radar measurements show biases at all distances. The rain gauge network reported as much as 48% more rain than the radar measurements (as much as 100% more during the cold season). These biases are most pronounced at short range (0 – 40 km) and long range (greater than 160 km). Medium range (40 – 160 km) measurements show bias as well but it is not as significant as at close and long ranges. This study was confined to areas without significant topographical features (Smith et al. 1996).

Research done by Yilmaz et al suggests that topography affects the biases of the various methods of rainfall measurement, although the biases of specific topographic features were not identified. Their research also suggests that the biases are different for stratiform and convective precipitation patterns (Yilmaz et al. 2005).

1.3 True Rainfall Measurements

Since each measurement method has its own biases, there is no one measurement of true rainfall. These biases can be identified and accounted for in the data if multiple methods of measurement are used. For this study true rainfall is determined by combining measurements from NEXRAD radar and tipping bucket rain gauges. However, rain gauge networks do not exist in many areas, leaving only radar and satellite data.

Yilmaz found that differences between radar and satellite estimates are generally smaller than differences between radar and rain gauge or satellite and rain gauge measurements because the biases of radar and satellite based systems are similar (Yilmaz et al. 2005). With similar biases and smaller differences in measurements, it is more difficult to use satellite and radar measurements to identify and adjust for biases.

1.4 Importance of Accuracy in Radar Estimates

Because of the impossibility of having a sufficient rain gauge network, the National Weather Service (NWS) relies heavily on radar estimated rainfall in issuing flash flood warnings. The radar used in this study, (KMTX, Salt Lake City) is regularly used to estimate rainfall over specific topographic features where flash flooding is likely to occur. For example, during the course of this study, several flash flood warnings were issued for areas near the Alpine burn scar because of the rainfall over the burn scar estimated by the KMTX radar.

Since radar estimates are the primary method of issuing such warnings, accuracy in radar estimates has significant impact on public safety and on the economy. If rainfall estimates are low, public safety is adversely affected by the inability of the National Weather Service to issue warnings in a timely manner. If rainfall estimates are high, the economy is adversely affected by lost productivity and resources wasted in protecting property and evacuating people.

1.5 Radar Angles and Mountaintop Radars

NEXRAD radars sweep through the area at various angles starting at 0.5 degrees above horizontal. While this is appropriate for most radar sites, this can cause mountaintop radars such as KMTX to underestimate precipitation, especially at long range locations. Steadham and Brown suggested having additional site-specific angles for such radar sites. For KMTX they suggested adding a scan at 0.0 degrees and -0.4 degrees (Steadham & Brown 2008).

1.6 Measurable and Trace Rainfall

Rainfall is reported by NWS surface observation stations in increments of 0.01 inches. Rainfall less than 0.01 inches is not considered measurable but is reported as trace rainfall.

Chapter 2

Methods

2.1 Gauge Placement

Gauges were placed on Y Mountain near Provo, Utah, at locations reachable from the hiking trail. The gauges were placed so they were not visible from the path to prevent tampering. While not visible from the path, they were still easily accessible to minimize impact on wildlife. The gauges were deployed from early August 2013 to April 2014. However, because the gauges were not equipped with heating devices, valid data were only collected for rain events. Hence, data collected after mid-October 2013 were not considered. The latitude and longitude of the gauges is provided in table 1. A map of the gauges is included in Appendix A.

Latitude	Longitude	Radar Sector	Description
40.24610	-111.62628	Lower	Base
40.24702	-111.62261	Lower	Below Y
40.24757	-111.61907	Upper	Above Y
40.25369	-111.61098	Upper	Summit (bad data)

Table 1 Latitude, longitude, radar sector, and description of gauge placement.

2.2 Gauge Specifications

The gauges used were HOBO tipping bucket rain gauges. The gauges are rated to accurately measure rainfall within 0.1% for rainfall rates up to 2 inches per hour. When rainfall rates exceed 2 inches per hour, some rain water is lost as the bucket tips resulting in the gauge reading less rainfall than actually occurred.

The tipping bucket holds 0.01 inches of rainfall. When the bucket fills with 0.01 inches of rain, it tips, releasing the collected water. Each gauge actually contains two buckets that are attached to each other so that one bucket is collecting rain while the other bucket is emptying. This allows the gauge to measure rain falling at a faster rate without losing any water. As long as rainfall is falling at a rate less than 2 inches per hour, no water is lost during the tipping process. Because each tip is the equivalent of 0.01 inches of rain, trace rainfall is not reported by the rain gauges.

A small magnet is attached to the buckets. Each time the buckets tip, this magnet induces a small current which the data logger detects and records as a tip. The design of the buckets is such that they move at close to the same speed regardless of the rainfall rate so that the induced current is the same.

The data logger on each gauge is battery powered and is capable of logging an event every 0.5 seconds. Rainfall at 2 inches per hour is the equivalent of 18 seconds between tips so the data logger is capable of recording data much faster than the gauge is capable of measuring it. Each tip was recorded with a timestamp and then offloaded onto a computer.

The time used for the timestamp was measured from the time set when deploying the gauges. These timestamps were set based on the computer's time which was not synchronized with any universal clock. This means that the timestamps were likely somewhat time-shifted because the computer was not synchronized with a universal clock. While the rain gauge data may be time-shifed, the intervals between them are precise and accurate.

Since each individual tip was recorded with a timestamp by the logger, data reported by the rain gauges are pseudo-continuous. The data from the rain gauges can be used to construct continuous rain totals with a granularity of 0.01 inches.

2.3 Radar Reported Rainfall

NEXRAD radar reports rainfall in several ways. For the purpose of this study, 1-hour precipitation (reported using the code N1P) and instant precipitation rate (reported using code DPR) were used to determine radar estimated rainfall. N1P was used as the primary report of rainfall; DPR was only used when rainfall rates were considered as a possible cause of discrepancy between radar estimated rainfall and rain gauge measured rainfall.

N1P is reported over somewhat large areas. This is in part due to the distance from the radar site. Each sector has the same angular width so sectors farther from the radar site are wider.

DPR also uses the same angular width for each sector so sectors farther from the radar site are also wider. However, the depth of each DPR sector is significantly smaller so there is still a relatively high level of detail far from the radar site.

N1P and DPR are not reported continuously; they are reported each time the the radar scans the area. N1P is used as the primary method of rainfall measurement because it does not require continuous data.

N1P is not reported as exact amounts or in consistent increments like the radar rainfall is. The values return by NEXRAD radar for N1P are shown in Table 2 (on page 8).

2.4 Spatial Reporting Differences

Since N1P is reported over somewhat large areas (see Section 2.3), most of Y Mountain is covered by two radar sectors. For some rainfall events more than one rain gauge reported viable data for the same radar sector. The graphs and figures included only show the data for one representative gauge for each sector. Additional plots from other operating gauges are included in Appendix B.

Some difference in rainfall reported by radar and by the rain gauges may be due to the spatial differences in their reporting. NEXRAD radar reports the average rainfall for a large area while the rain gauges only report the rainfall for their specific location. Since rainfall varies in intensity over small distances, it is possible for the specific location of a rain gauge to receive significantly more or significantly less rainfall than other nearby areas that would be included in the same radar sector. While it is possible for the gauges to vary significantly from the areal average, normal variation for the storms considered would be less than the interval between N1P values (see Table 2).

To ensure that the rainfall at the gauge location was tolerably close to the areal average for the radar sector, gauges separated by a distance of approximately half the width of the sector were compared. The compared gauges did not need to be in the same radar sector (the included figures show gauges from adjacent sectors; for data from additional gauges see Appendix B).

Return	Precip (inches)	Return	Precip (inches)	Return	Precip (inches)
1	0.00 (trace)	6	0.50	11	2.00
2	0.05	7	0.75	12	2.50
3	0.10	8	1.00	13	3.00
4	0.20	9	1.25	14	3.50
5	0.35	10	1.50	15	4.00

Table 2 NEXRAD N1P Values

2.5 Temporal Reporting Differences

Precipitation totals for rain gauges are calculated continuously from the time the gauges were set up and the N1P totals are at discrete, periodic times, thus the data are not directly comparable. To compare them, I used the times from the N1P data and calculated the 1-hour rainfall totals from the rain gauges at these discrete points. All tips that happened within 1 hour before the time of the N1P data point were counted as 0.01 inches of rainfall. The new 1-hour precipitation totals from the rain gauges were compared against the N1P totals.

Additionally, because the timestamps from the gauges were not based on a universal time (see Section 2.2), the data from the gauges do not align temporally with the N1P data even after the new 1-hour precipitation totals were calculated. To correct the time-shifted rain gauge data, their times were simply aligned with the radar times such that both reached 0.10 inches of rainfall at the same time. When this was not possible (such as during events that the radar did not report more than trace rainfall), times where not adjusted. Since the purpose of this study is to determine the accuracy of radar estimated rainfall totals rather than timing, such time-shifting does not affect the results, but it does make the data easier to understand and evaluate.

2.6 Rain Gauge Error

Occasionally, the rain gauges reported a tip 0.5 seconds after the previous tip (0.5 seconds is the minimum time between tips that the logger permits). Frequently, this would only record two tips at the maximum rate the logger supports which contributes very little extra to the total. The cause of these false tips is not known; possible causes include the bucket bouncing slightly after a hard tip or the bucket tipping at exactly the right time for the logger to record it on two adjacent half-second intervals. Whatever the cause, these false tips were filtered out.

One gauge had times where multiple tips would be recorded at the logger's maximum rate for a period of several seconds or minutes. The cause of this is also unknown but a likely cause is some sort of gauge interference. Since the gauge relies on inductance which requires movement, it is unlikely that the bucket got stuck. The positioning of this gauge may have been such that significant runoff could have caused the gauge to vibrate which would cause false readings. Many of these tips were successfully filtered out providing useful data from this gauge. Any data used from this gauge was checked against the data from the adjacent gauge within the same radar sector. Plots of this data are included in Appendix B.

Both kinds of false tips were filtered out by starting with the last tip and checking to see if it was at least 1 second after the previous tip. If the tip being check was less than 1 second after the previous tip, then the tip being examined was removed. Starting from the last tip and working toward the first tip allowed multiple consecutive false tips to be removed.

While it is possible that some of these are actually legimate tips, most of them are not. Legates and DeLiberty showed that rain gauges are bias toward under-reporting rainfall (Legates & DeLiberty 1993). By removing all possible false tips, we can be sure that all rainfall reported by the rain gauges is legimate and that any errors resulted in the rain gauges under-reporting rainfall. The rain gauge data can then be used to establish a minimum actual rainfall amount. Plots with both the filtered and the unfiltered data are included in Appendix B.

Chapter 3

Results and Discussion

3.1 Overview

The results will be divided into two different kinds of rain events: stratiform and convective. Similar to the work of Yilmaz et al (Yilmaz et al. 2005), radar bias is different for stratiform and convective events. The discussion will be limited to the biases specific to KMTX as they had the largest impact on the reliability of the radar data.

3.2 Stratiform Events

Stratiform events have significant horizontal development as opposed to vertical development which characterizes convective events. The two characteristic stratiform events that occurred during the study happened in early October 2013. Figure 1 shows the first event on October 10 and Figure 8 in Appendix B.1.2 shows the second event on October 13. Only the event on October 10 is considered here in detail because the two events are very similar.

As with many stratiform rain events in this region, this storm did not produce significant rainfall. The rainfall rates recorded by the rain gauges (and filtered for false tips) are safely below the

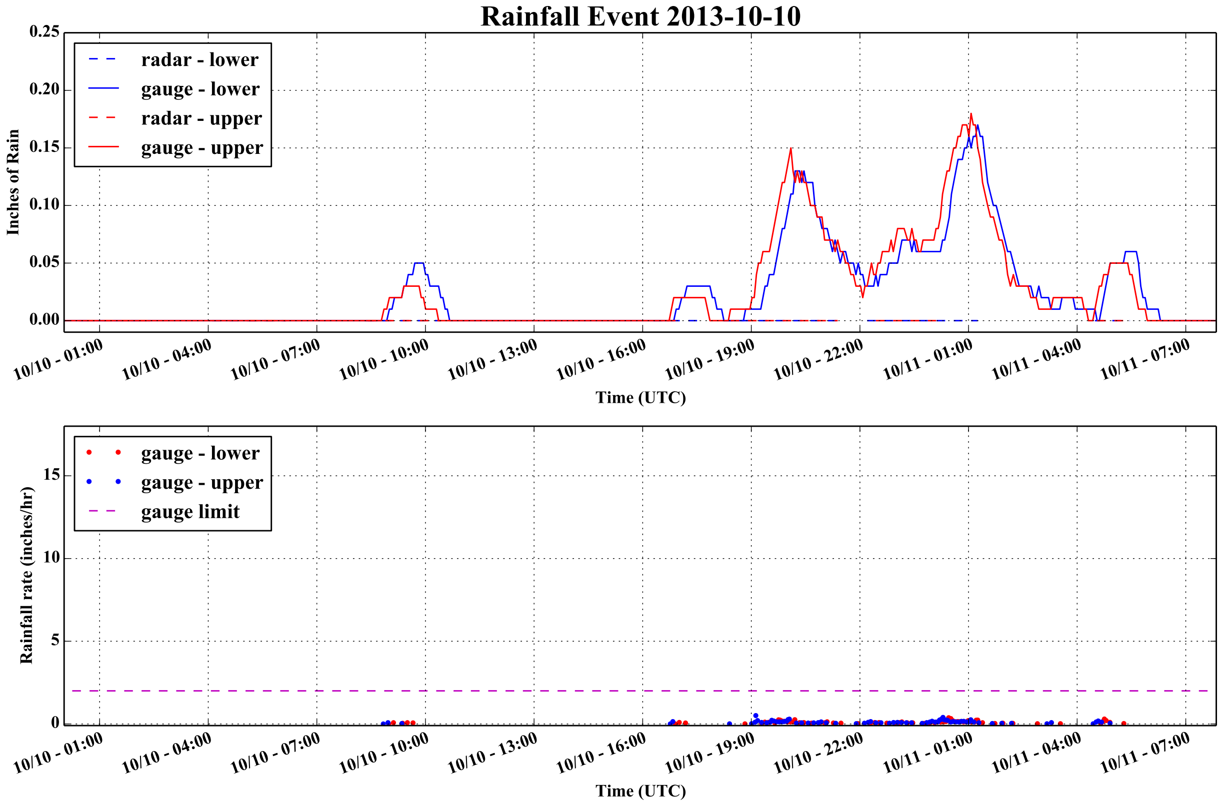

Figure 1 Radar estimated and rain gauge measured 1-hour precipitation totals for October 10, 2013

2 inches per hour limit. Based on the biases of rain gauges and the filtering, we can be sure that all rainfall reported by the rain gauges actually occurred. Consistent with what is expected for a light, stratiform rain event, all gauges reported very similar amounts of rainfall. We can have confidence that the event produced a peak 1-hour precipitation total of at least 0.15 inches. Since the event consisted of only light rain, the rain gauges did not likely under-report the total rainfall. Therefore the peak 1-hour precipitation for this event was between 0.15 and 0.20 inches.

For this event, the radar only reported trace rainfall. Since the rain gauges show that the 1-hour rainfall reached at least 0.15 inches and possibly as high as 0.20 inches the radar should have reported either 0.10 or 0.20 inches at some point during the event (see Table 2 on page 8). For both stratiform events, the radar clearly under-reported the rainfall.

Under-reporting for such light rain events is not likely to result in property damage or loss of life as such small rain totals only cause flooding under extreme circumstances. However, since these events are consistently under-reported, long-term hydrologic prediction (such as drought prediction and water use regulation) could be significantly impacted.

Under-reporting for stratiform events is not unexpected. Since KMTX is positioned at such a high altitude, its lowest angle (0.5 degrees above horizontal) likely only detects the very top of such stratiform events. The NWS can use surface oberservation stations to compensate for such under-reporting, but there are not enough surface observation stations in the area for this to be adequate. Indeed, it is the the lack of adequate surface oberservation stations that makes radar measurements so critical.

Adding scans at lower angles for KMTX as Steadham and Brown suggest would be valuable in determining total precipitation over the mountainous areas near Utah Valley. It would allow the radar to better detect stratiform precipitation events common to the area from late fall through early spring.

3.3 Convective Events

The three characteristic convective rain events that occured during the the study happened in August and early September 2013. The results of the first two events, August 17 (see Figure 12 in Appendix B) and August 28 (see Figure 2), are very similar so only the August 28 event will be discussed in detail here. The last event, which occured on September 3 (see figure 3), had significant differences and will be considered separately.

3.3.1 August 28, 2013

Both of these events produced significant rainfall. At times, rainfall rates approached or exceeded the 2 inches per hour maximum rating of the gauges. This indicates that at times some rainfall may have been under-reported by the gauges. The filtering also favors slight under-reporting by the gauges. The gauge data have good agreement for the rainfall during this event. The peak 1-hour rainfall for this event was no less than 0.45 inches of rain.

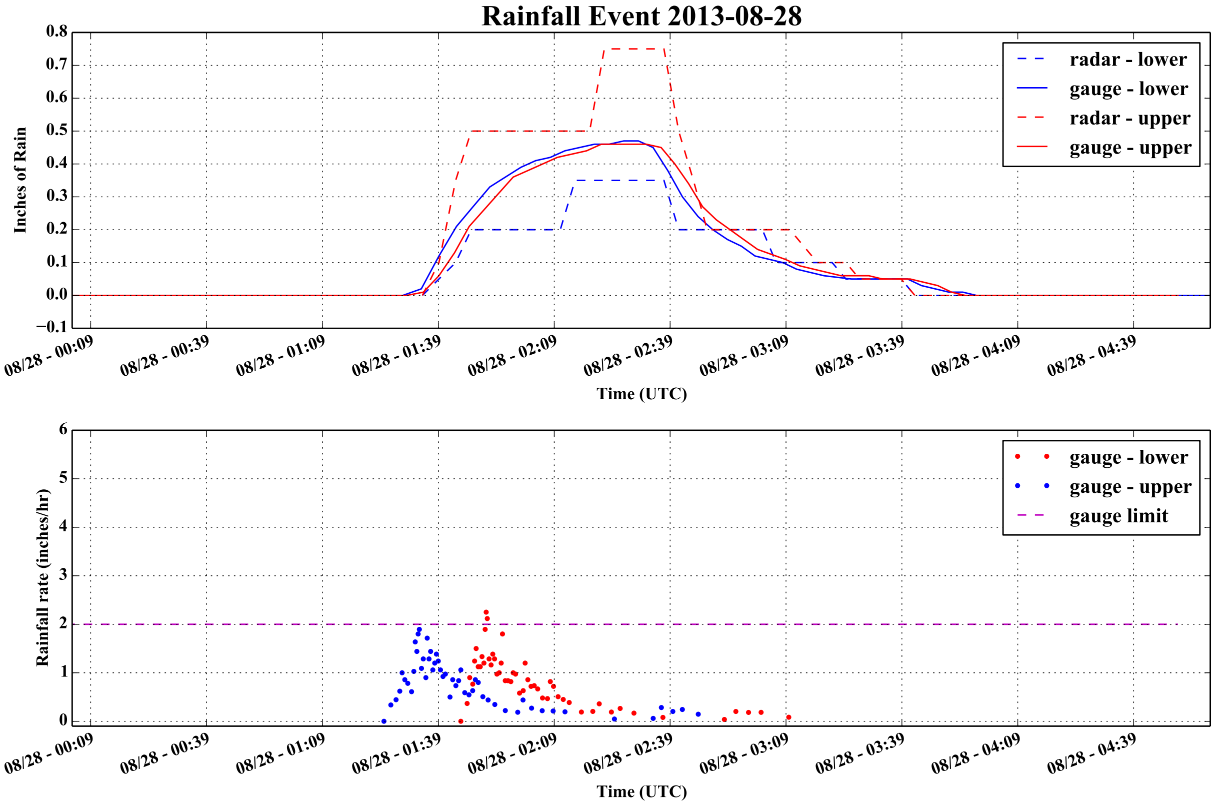

Figure 2 Radar estimated and rain gauge measured 1-hour precipitation totals for August 28, 2013

While the two rain gauges shown in Figure 2 show very good agreement with each other, the radar sectors show much more variation. Since the radar estimate is an areal average and the two rain gauges are close together (even though they are in different radar sectors), the differences in the radar estimates is likely due to spacial variation within the storm. Convective events often show significant spacial variation.

Unlike the stratiform events considered, this event (and the August 17 event) show very good agreement between the radar estimates and the rain gauge meaurements. This further confirms the assessment that the cause of the radar underestimating the stratiform events is the radar site altitude. Convective events have significant vertical development so the radar is able to detect the storm and the precipitable water correctly.

3.3.2 September 3, 2013

While the radar was able to accurately detect and estimate rainfall for the convective events on August 17 and August 28, it was not able to do so for the convective event on September 3, 2013.

This storm produced significant heavy rainfall over much of the area. Flooding was a significant issue in Provo as a result. At times, the rain gauges reported rainfall rates in excess of 5 inches per hour, more than double what the gauges are rated to measure accurately. Since the gauges under-report rainfall when rates exceed 2 inches per hour it is possible that the actual peak rainfall rate was even greater than 5 inches per hour.

The peak 1-hour rainfall total reported by the rain gauges was greater than 0.8 inches after filtering. Since the rain gauges under-reported the rainfall for this storm, the unfiltered total may be more accurate (see Figure 21 in Appendix B.2.3). The peak 1-hour precipitation from the unfiltered rain gauge data was nearly 1 inch.

Given the peak 1-hour rainfall reported by the gauges, the radar should have reported a peak 1-hour rainfall of at least 0.75 inches (see Table 2 on page 8). However, Figure 3 shows that the highest 1-hour precipitation reported by the radar for either sector was 0.50 inches. The radar underestimated the magnituby at least 50% which is significant given the high rainfall rates that accompanied this storm.

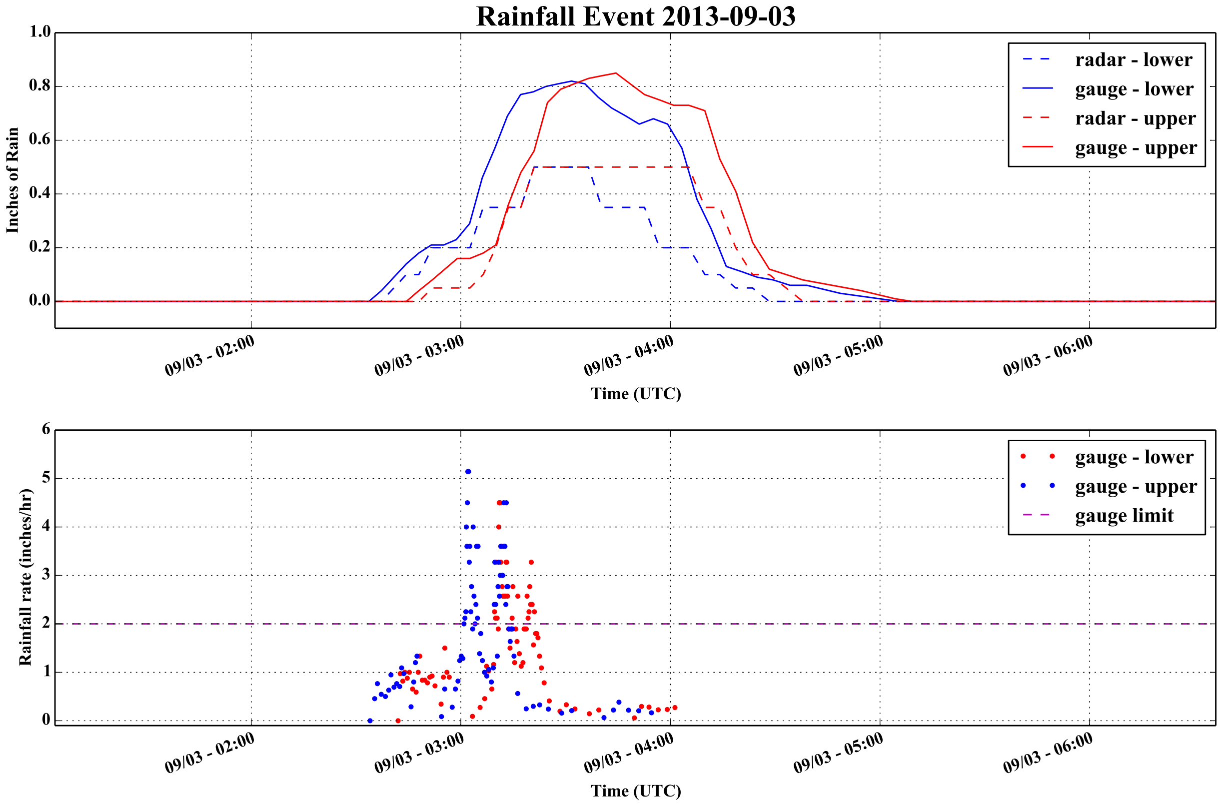

Figure 3 Radar estimated and rain gauge measured 1-hour precipitation totals for September 3, 2013

While convective events have significant veritcal development, it is still possible for the base of the storm to be low like a stratiform event. A significant portion of the precipitable water in this storm appears to have been below the lowest scan that KMTX made (0.5 degrees above the horizontal). Adding lower-angle scans to KMTX would significantly increase the accuracy of radar-estimated precipitation for low-based convective events.

Chapter 4

Conclusions

The most significant topographical feature affecting the accuracy of rainfall estimated by KMTX is the altitude of the radar site. Radar-estimated rainfall over mountainous topography is regularly underestimated by KMTX because the lowest scan is too high and does not detect a significant portion of most stratiform events and some convective events. Other NEXRAD radar sites may be affected differently by mountainous topography but the primary topographic effect on KMTX is to underestimate many precipitation events, including both convective and stratiform events.

Appendix A

Rain Gauge Map

For the latitude and longitude of each gauge, see Table 1 (on page 5). The plots shown primarily use data from the middle two gauges. Additional data from the base gauge is provided in Appendix B. None of the data from the summit gauge was viable.

Figure 4 A map of the rain gauge locations.

Appendix B

Additional Rain Event Plots

B.1 Stratiform Events

B.1.1 Additional Plots for October 10, 2013

This event was discussed in detail in Section 3.2. The plots here show data from an addition gauge as well as the unfiltered data from the two gauges shown in Figure 1.

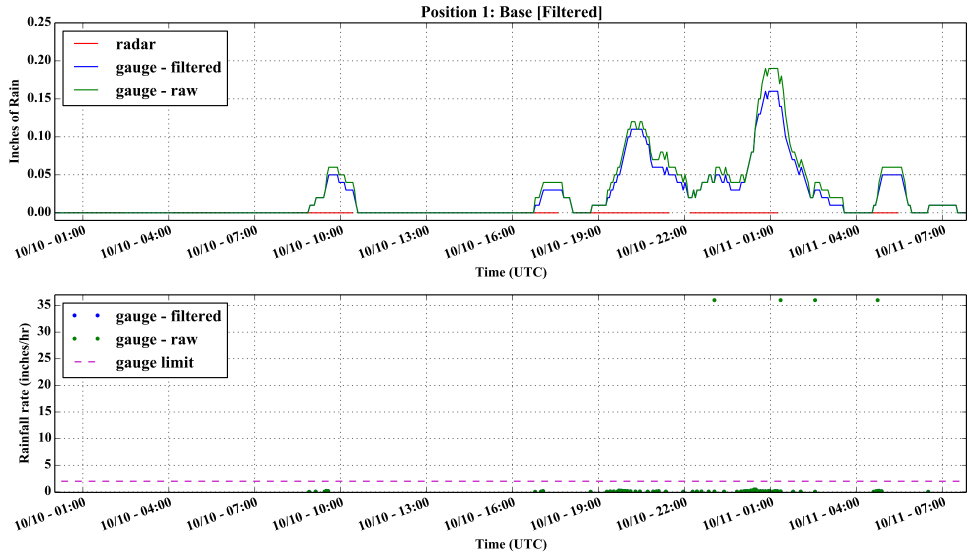

Figure 5 Radar estimated and rain gauge measured 1-hour precipitation for the lowest site (not shown in Figure 1) for October 10, 2013 including the filtered and unfiltered rain gauge data.

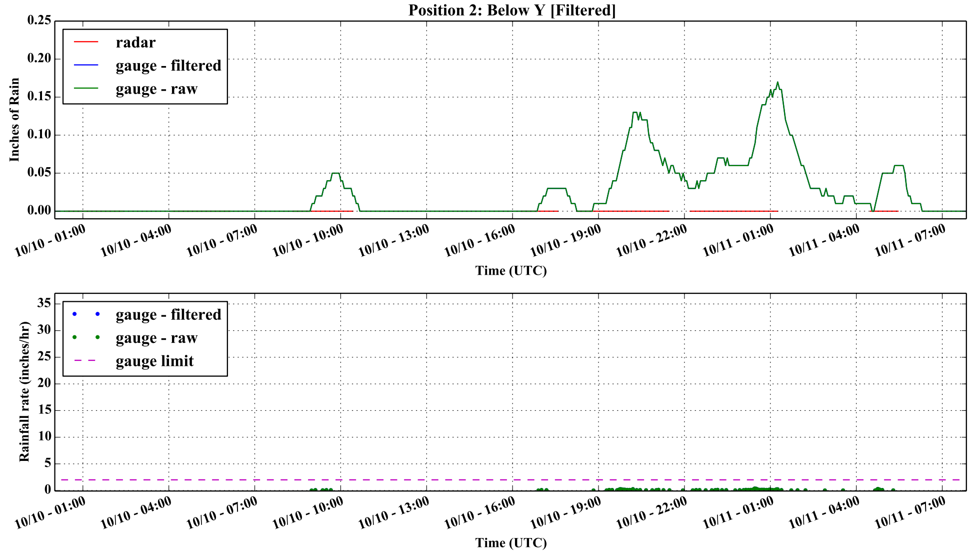

Figure 6 Radar estimated and rain gauge measured 1-hour precipitation for the lower site (shown in Figure 1) for October 10, 2013 including the filtered and unfiltered rain gauge data.

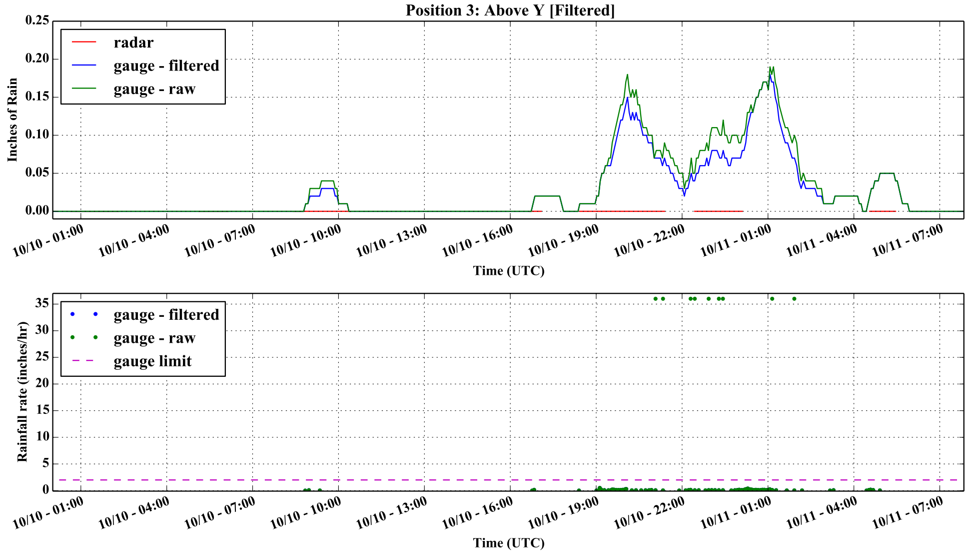

Figure 7 Radar estimated and rain gauge measured 1-hour precipitation for the upper site (shown in Figure 1) for October 10, 2013 including the filtered and unfiltered rain gauge data.

B.1.2 Additional Plots for October 13, 2013

This event produced slightly heavier rainfall than the event on October 10 which was discussed in Section 3.2. This event shows the same radar biases as the event on October 10.

These additional plots show data from an additional gauge as well as the unfiltered data from the two gauges shown in figure 8.

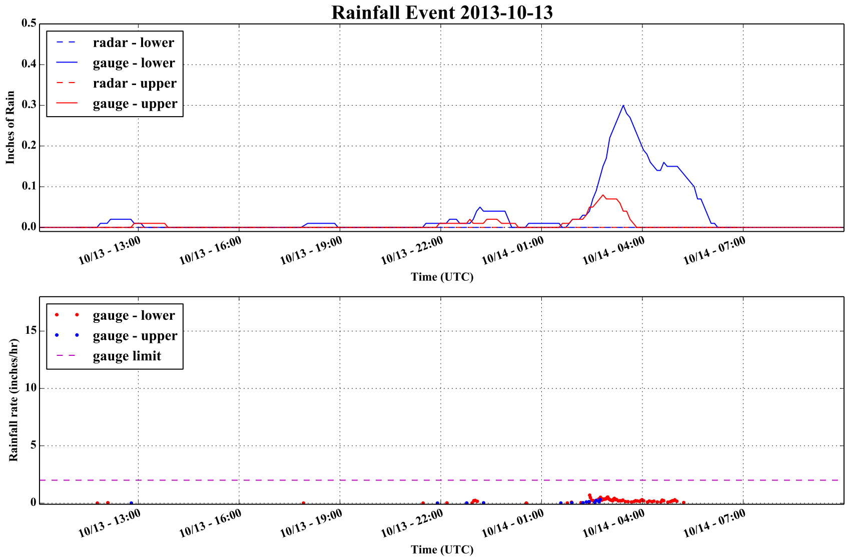

Figure 8 Radar estimated and rain gauge measured 1-hour precipitation totals for October 13, 2013

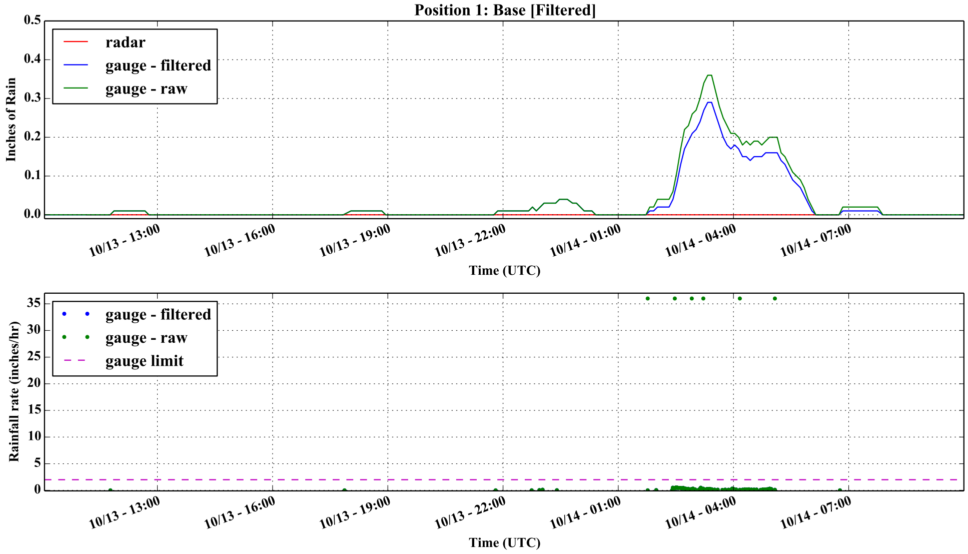

Figure 9 Radar estimated and rain gauge measured 1-hour precipitation for the lowest site (not shown in Figure 8) for October 13, 2013 including the filtered and unfiltered rain gauge data.

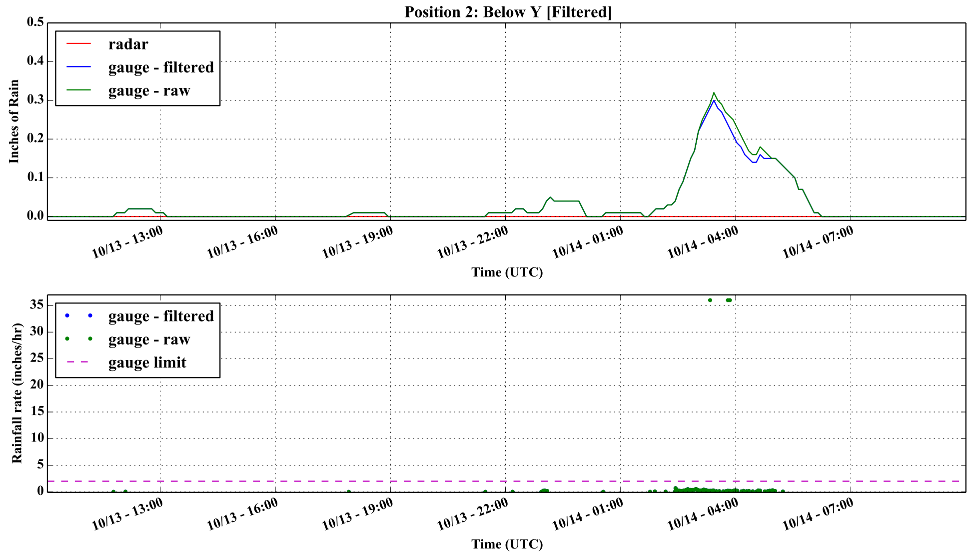

Figure 10 Radar estimated and rain gauge measured 1-hour precipitation for the lower site (shown in Figure 8) for October 13, 2013 including the filtered and unfiltered rain gauge data.

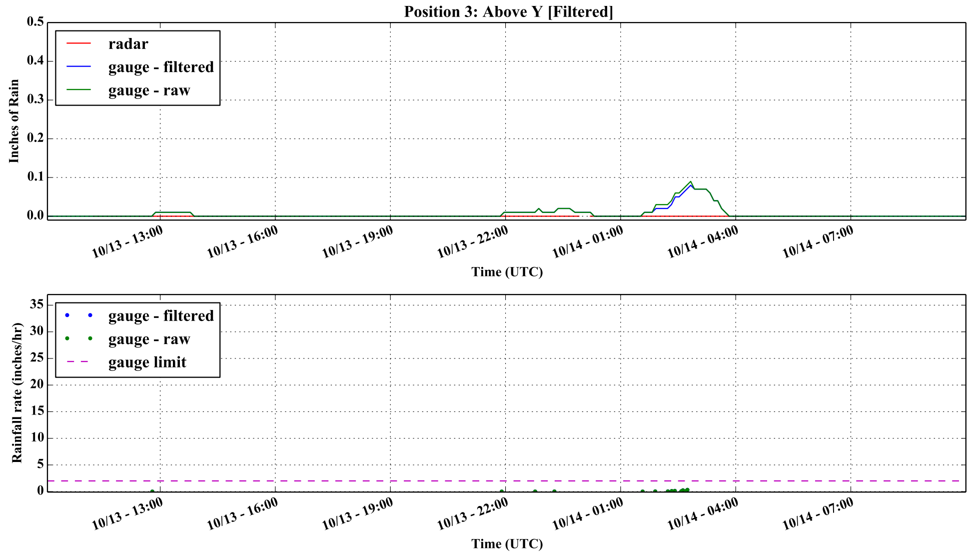

Figure 11 Radar estimated and rain gauge measured 1-hour precipitation for the upper site (shown in Figure 8) for October 13, 2013 including the filtered and unfiltered rain gauge data.

B.2 Convective Events

B.2.1 Additional Plots for August 17, 2013

This event did not produce as much heavy rainfall as the convective event on August 28 which was discussed in Section 3.3.1. The effects of heavy rainfall were not significant; it was still a convective event that shows strong agreement between the rain gauge measured rainfall and the radar-estimated rainfall.

One potential difference between this event and the event on August 28 is that the radar consistently estimated higher rainfall totals than the rain gauges reported. While this may be a result of under-reporting by the rain gauges, it may also be due to evaporation of the rain as it falls resulting in lower rain amounts on the surface than the radar estimated. Further research and study would be required to determine if this the cause.

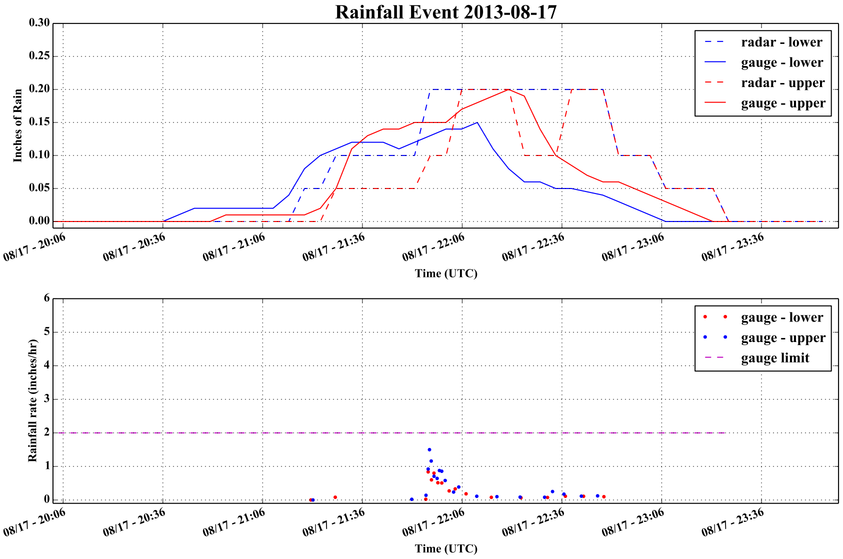

Figure 12 Radar estimated and rain gauge measured 1-hour precipitation totals for August 17, 2013

These additional plots show data from an additional gauge as well as the unfiltered data from the two gauges shown in figure 12.

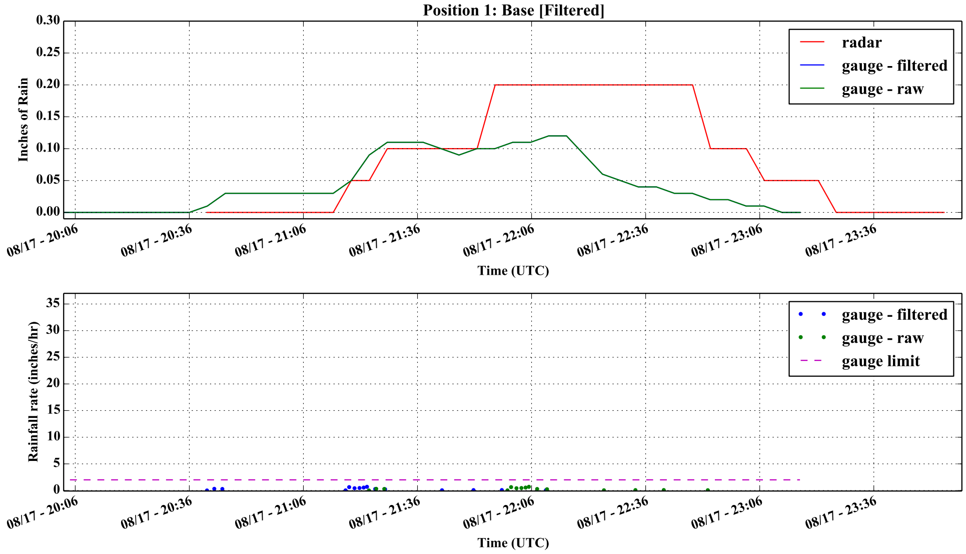

Figure 13 Radar estimated and rain gauge measured 1-hour precipitation for the lowest site (not shown in Figure 12) for August 17, 2013 including the filtered and unfiltered rain gauge data.

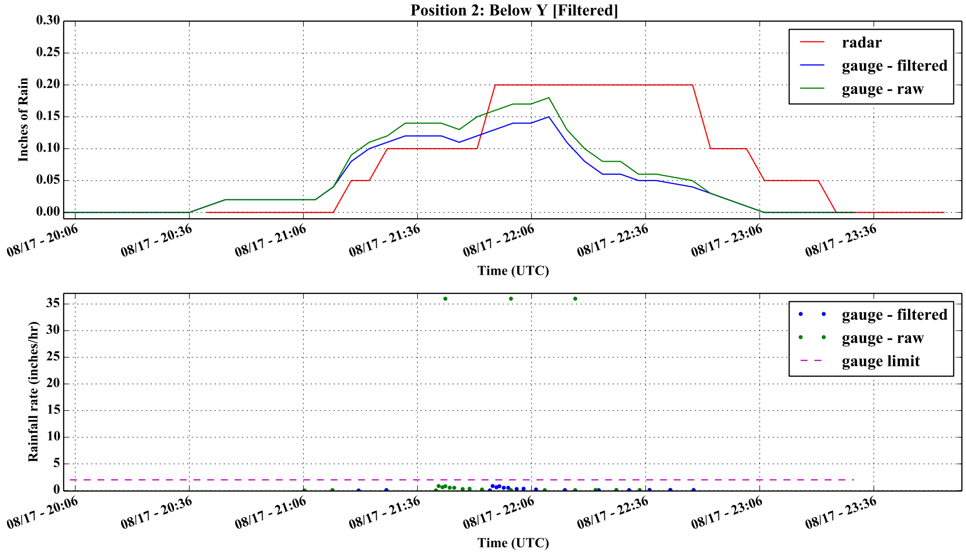

Figure 14 Radar estimated and rain gauge measured 1-hour precipitation for the lower site (shown in Figure 12) for August 17, 2013 including the filtered and unfiltered rain gauge data.

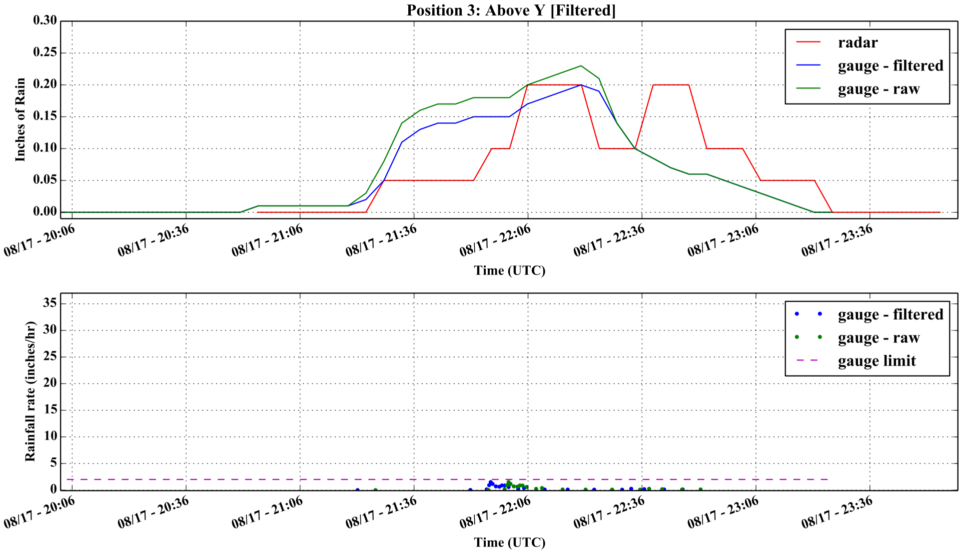

Figure 15 Radar estimated and rain gauge measured 1-hour precipitation for the upper site (shown in Figure 12) for August 17, 2013 including the filtered and unfiltered rain gauge data.

B.2.2 Additional Plots for August 28, 2013

This event was discussed in detail in Section 3.3.1. The plots here show data from an addition gauge as well as the unfiltered data from the two gauges shown in Figure 2.

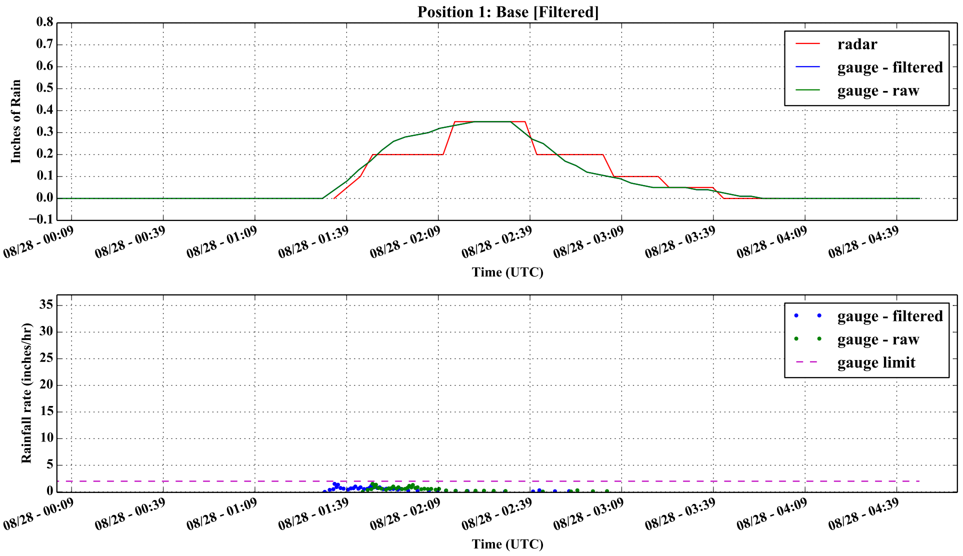

Figure 16 Radar estimated and rain gauge measured 1-hour precipitation for the lowest site (not shown in Figure 2) for August 28, 2013 including the filtered and unfiltered rain gauge data.

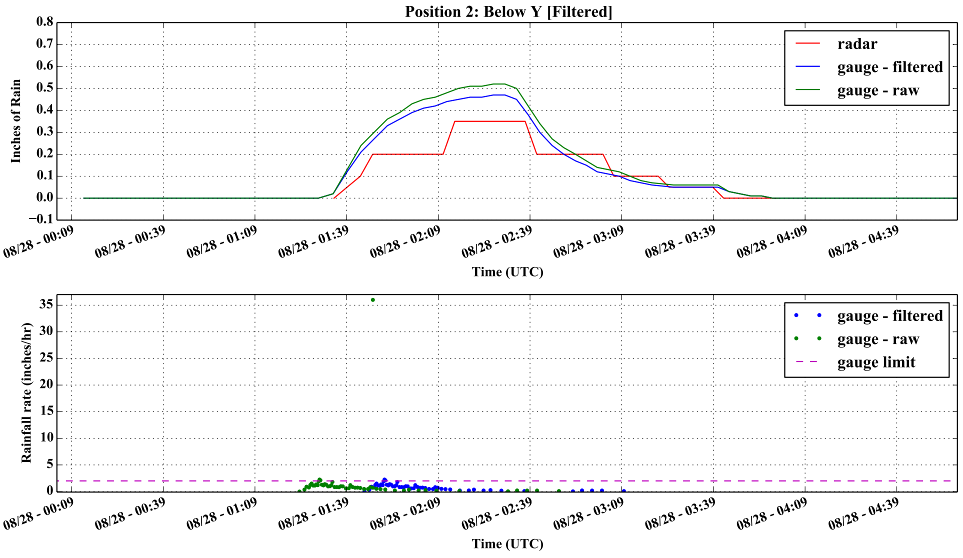

Figure 17 Radar estimated and rain gauge measured 1-hour precipitation for the lower site (shown in Figure 2) for August 28, 2013 including the filtered and unfiltered rain gauge data.

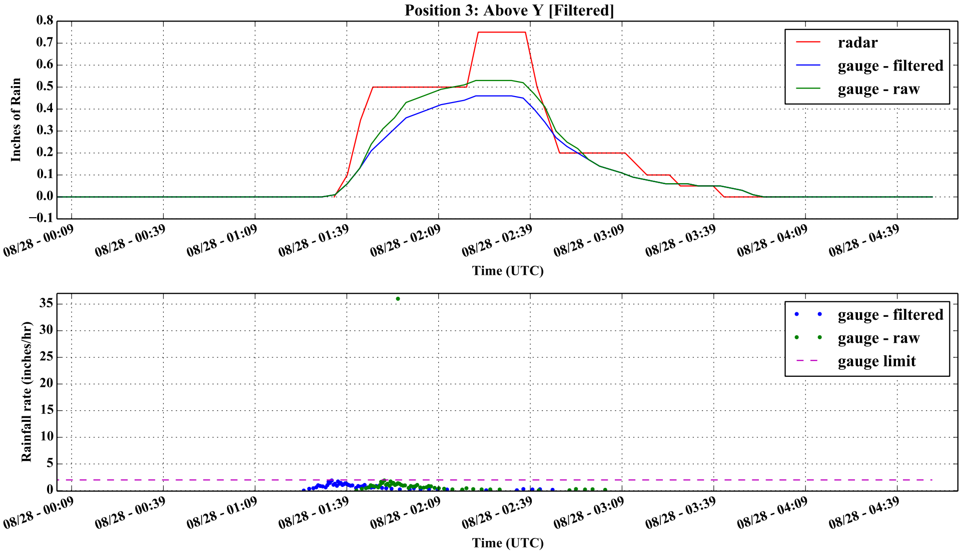

Figure 18 Radar estimated and rain gauge measured 1-hour precipitation for the upper site (shown in Figure 2) for August 28, 2013 including the filtered and unfiltered rain gauge data.

B.2.3 Additional Plots for September 3, 2013

This event was discussed in detail in Section 3.3.2. The plots here show data from an addition gauge as well as the unfiltered data from the two gauges shown in Figure 3.

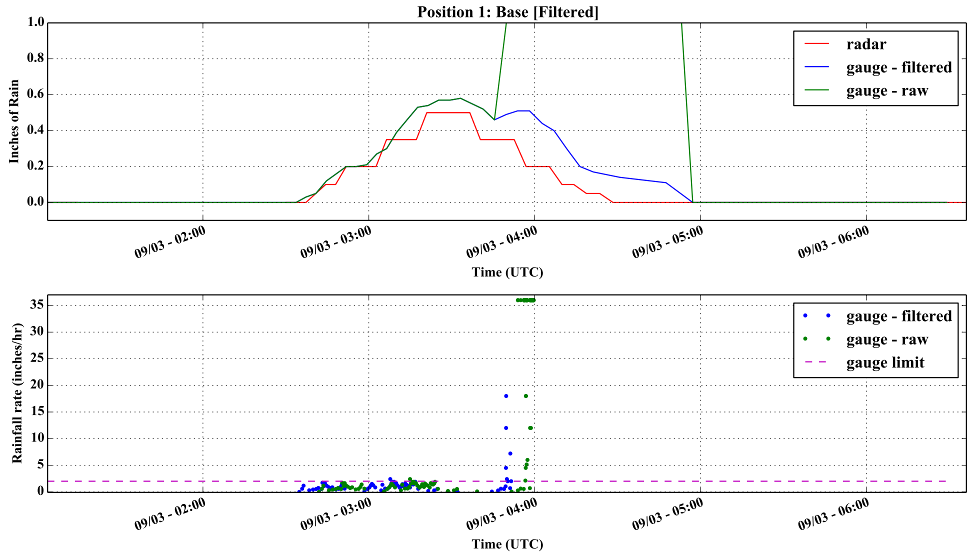

Figure 19 Radar estimated and rain gauge measured 1-hour precipitation for the lowest site (not shown in Figure 3) for September 3, 2013 including the filtered and unfiltered rain gauge data.

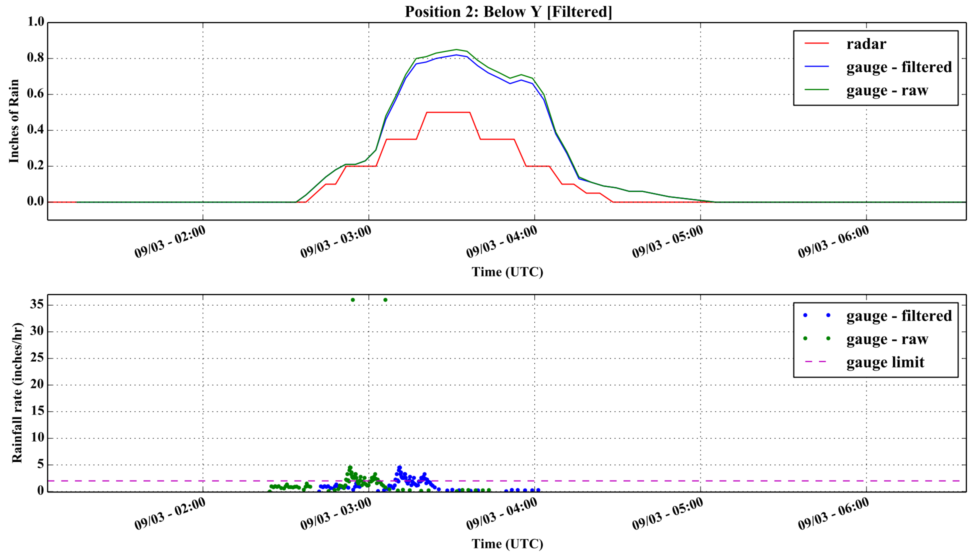

Figure 20 Radar estimated and rain gauge measured 1-hour precipitation for the lower site (shown in Figure 3) for September 3, 2013 including the filtered and unfiltered rain gauge data.

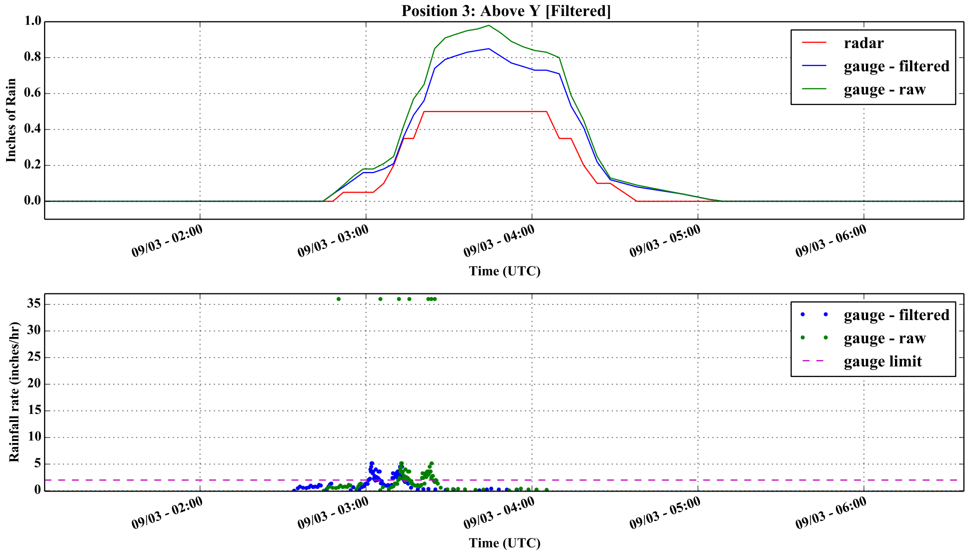

Figure 21 Radar estimated and rain gauge measured 1-hour precipitation for the upper site (shown in Figure 3) for September 3, 2013 including the filtered and unfiltered rain gauge data.

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