ALERT Network Evaluation, Final Report

Flood Control District of Maricopa County

3 July 2008

Report submitted to

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1. Executive Summary

The purpose of this project was to analyze the Flood Control District of Maricopa County's (the District's) real-time ALERT monitoring system. We used radar, theoretical path studies and ALERT data collected during quiescent and storm periods to determine the monitoring network's performance characteristics, especially its ability to provide accurate information during rainfall events.

Having accurate ALERT information during events is important because heavy rainfall can generate stream flows that have significant impacts on flood control facilities such as dams and channels. Data-triggered alarms are used to alert the on-call hydrologist to evaluate and monitor events. The data are used to create flood warnings for District observation teams, other Maricopa County departments, city emergency management departments and the National Weather Service.

The ALERT system data are also used for post-storm analyses; reconstruction of storm events to understand flooding problems, performing floodplain studies, computer modeling of watersheds, and flood control structure design are all post-storm data uses. Having accurate data is a strict requirement for all of the mission critical purposes described.

Our conclusions from this study were that the network is well-designed, well-maintained and operated correctly for its objectives. We determined the current network capacity is such that a large-scale and/or very intense rainfall event will result in an unacceptable level of data losses.

Our recommendations fall into three groups, the latter two of which are mutually exclusive options:

1) Rainfall Approach. We found that the density of the gaging network and the use of real-time gage-adjusted radar rainfall for flood operations are appropriate. We recommend the District use a higher quality of gage-adjusted radar rainfall than the real-time product for modeling and design applications.

2) ALERT System Reconfiguration. If the solution is limited to ALERT changes only we recommend a solution that entails licensing 3 new RF frequencies to incrementally improve the District's ability to receive accurate data during significant rainfall events. This solution, if implemented by the District, will require changes by ADWR and other counties to collect their data.

3) ALERT/ALERT-2 Hybrid Solution. If the District is able to move to a new technology, the capacity of the system and accuracy of the data will be improved dramatically. This solution requires that the District license 2 new RF frequencies. We recommend using ALERT/ALERT-2 concentrators at some repeater sites. This solution, if implemented by the District, will also require changes by ADWAR and other counties to collect their data.

Should the District choose to carry out one or the other of the ALERT system reconfiguration ALERT-2 hybrid solution options, the first step toward implementation will be creating a firm design based on the requirements for future data access by all entities.

2. Methods and Tools

2.1 Team approach

The project team comprised seven OneRain staff members (Jake Emerson, Ilse Gayl, Glenn Hetchler, Jim Moffitt, James Logan, Scott Pearse and Mike Zukosky) and a contract resource, Don Van Wie, from Telos Services.

Both OneRain and Telos Services have extensive experience doing network evaluations. This project was flagged from the outset as a OneRain Best Practices Training project, and the full team met on several occasions to review the methods and tools, discuss interim analytic results, and discuss potential recommendations.

Maricopa County's Flood Control District Manager, Steve Waters, and his colleagues were invaluable team members. They answered questions tirelessly and provided additional information as required to pursue elements of the project. Additional information provided included architectural outlines and charts, equipment lists, repeater sensor ID passlists, and both data from and graphical depictions of historical events.

2.2 Radar rainfall analysis

A gage-adjusted radar rainfall analysis was performed for an event for which we also had gage data records, the purpose of which was to ascertain whether the gages were performing their job of detecting rainfall according to an independent measure, the radar. We also could examine whether gaging locations actually detected the peak rainfall.

The 5-minute, 1-km x 1-km pixel radar rainfall estimates were obtained using reflectivity data from Barons Service. The radar mosaic used was constructed from several nearby NWS WSR-88D radars, enabling optimized coverage across the study area. The radar data were extracted from OneRain's radar archive covering an area bounded on the west by -113.5517° W longitude, on the east by -110.7925° W longitude, on the north by 34.7031° N latitude, and on the south by 32.5920° N latitude. This study area consisted of 62,510 radar pixels.

The time period for the analysis was November 30 (00:00 PST on November 30) through December 1 (00:00 PST on December 2), 2007. Gage data were obtained from the District's DIADvisor archive. This dataset consisted of 301 rain gages. Figure 1 (below) presents the radar rainfall study area with the locations of the District rain gages.

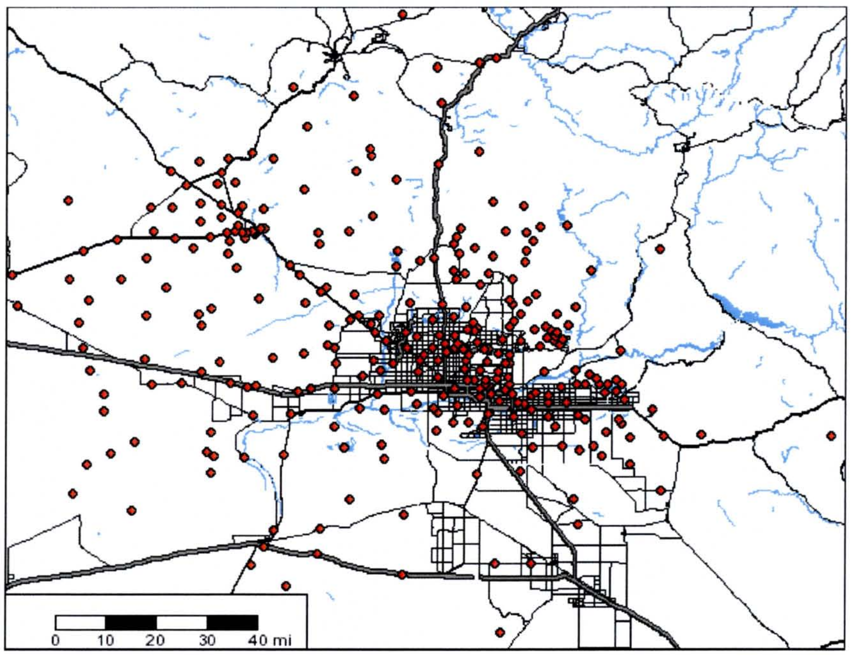

Figure 1. Radar rainfall study area with gage locations.

The methodology for this type of analysis is more extensive than the automated real-time gage-adjustment process. The rain gage data were reviewed and checked for quality using several steps. As a result of this analysis, nine gages that failed to report rainfall for the entire study period were removed from the analysis.

Scatter-plots were then generated that compare the event gage volumes with their co-located unadjusted (raw) radar pixel rainfall estimate. Using these scatter-plots, under- and over-reporting gages tended to stand out from the rest of the group.

For each gage, a time series of gage data and a time series of radar data at the pixel over each of the rain gages were collected. At each pixel containing a gage location, a gage/radar (G/R) ratio was computed by dividing the gage rainfall by the radar rainfall during each time step (time steps are chosen to match individual rainfall sub-events).

A Kriging-based interpolation technique was used to determine the appropriate geometry and distance-weighted G/R ratio for every other pixel in the domain. The G/R ratios were then multiplied by the raw/filtered radar dataset for each time period during the study to determine the gage-adjusted radar rainfall amounts. The process is shown schematically in Figure 2, below.

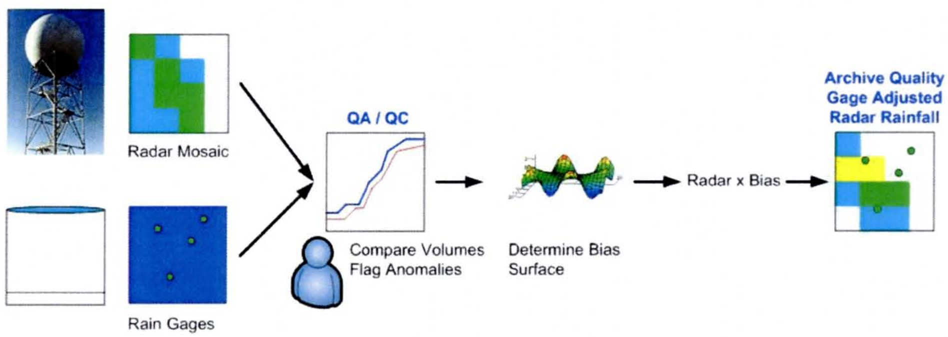

Figure 2. Schematic depicting spatially variable gage adjustment process.

2.3 Gage database preparation

The District's DIADvisor™ Base Station, Version 2.8, ALERT data collection application was set up prior to the primary analysis period (in December, 2007) to maximize the information available as input for a network evaluation.

Setup included initiating DIADvisor's port statistics. For each incoming serial port, PortStats counts 5-minute, hourly and daily incoming bytes, and it also counts how many 4-byte ALERT-compliant messages were formed for each period. Archiving was set up to save all incoming data reports, including reports from undefined sensor IDs, duplicate reports (a second report from a sensor containing the same data value and arriving within 5 seconds after first report), reports that failed validation (out of range or out of sequence), and reports from sensors flagged as out of service.

The District delivered several databases for the evaluation. The most complete data set was for the period 5/5/2008-6/10/2008, resulting in approximately 32 days of all saved types of data and port statistics. The other period studied was 8/27/2007-12/5/2007; this database contained only valid data reports and there were PortStats for the period. No data were delivered for the period between, during which there were some rainfall events. The data received were sufficient to analyze ALERT network performance characteristics.

2.4 Repeater-base station theoretical radio path analyses

Repeater site latitude-longitude values and elevations were obtained from the DIADvisor swatch2.mdb. Radio Mobile by VE2DBE software (http://www.cplus.org/rmw/english1.html) was used to compute theoretical path losses for each repeater-base station link. The purpose of this was to compare the theoretical path strengths with actual observed repeater performance, thus being able to identify problems and potential improvements.

Appendix B contains the full results of the theoretical paths analysis.

2.5 Historical events

We also acquired from the District information about rainfall rates during historical events that was useful in modeling potential data losses. We used these data to generate plausible traffic loads on the existing ALERT system, and thus to estimate the potential for data loss during events.

3. Results

There were many results computed on the way to the Results. We have summarized the significant findings in this section, in particular those used to generate Recommendations.

3.1 Radar analysis

OneRain's gage-radar adjustment procedure was able to successfully merge the data from the rain gage network and the radar rainfall data. There was minimal filtering required, and good correlation was found between the available rain gages and the filtered radar, as well as the accumulations with the adjusted radar product.

We produced a gage-adjusted radar rainfall dataset with 62,510 individual rainfall estimates (one at each radar pixel) over the Maricopa County study area for the November 30 - December 1, 2007, study period. The gage-adjusted radar rainfall estimates were approximately 35% lower than those provided by radar alone and matched well with the rain gage estimates.

RAIN GAGE PERFORMANCE

The analysis enabled us to see that the District's radar and rain gage measurements were in synch with one another, providing an independent verification of the rain gage performance.

The timing of the two measurement systems also showed a high degree of correlation. Figure 3 (below) depicts the relationship among gage, radar and gage-adjusted radar rainfall accumulation over time.

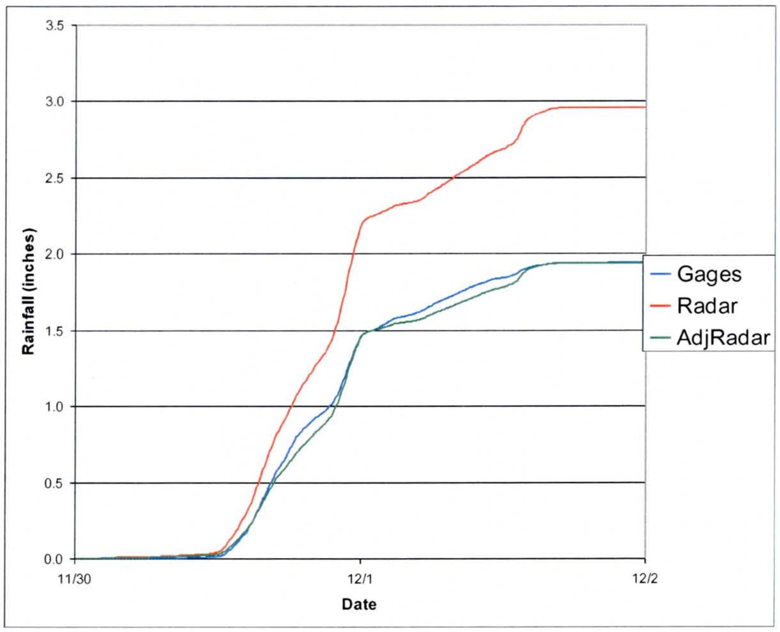

Figure 3. Average gage, radar and gage-adjust radar rainfall accumulations plot for the 11/30/2007-12/1/2007 storm over Maricopa County.

Although the amount of rainfall reported by the radar alone was a substantial overestimate compared to that detected by the gages, the similar shape and timing of the curves allowed us to conclude that both methods were detecting the same rainfall.

Figure 4 (below) shows the scatter-plot of total rainfall measured at the gages compared to the radar and adjusted radar rainfall estimates at the pixels over the rain gages for November 30 through December 1, 2007. If the gage and gage-adjusted radar rainfall estimates were identical, all points would lie on the 45-degree best fit line. However, due to scaling issues, measuring errors, natural variability and other uncertainties, these values will not always match. Nevertheless, the gage-adjusted radar rainfall data are expected to cluster around the 45-degree line.

In fact, we see that the fit was quite good both on examination of the plotted data and from the computed R^2 value of 0.88.

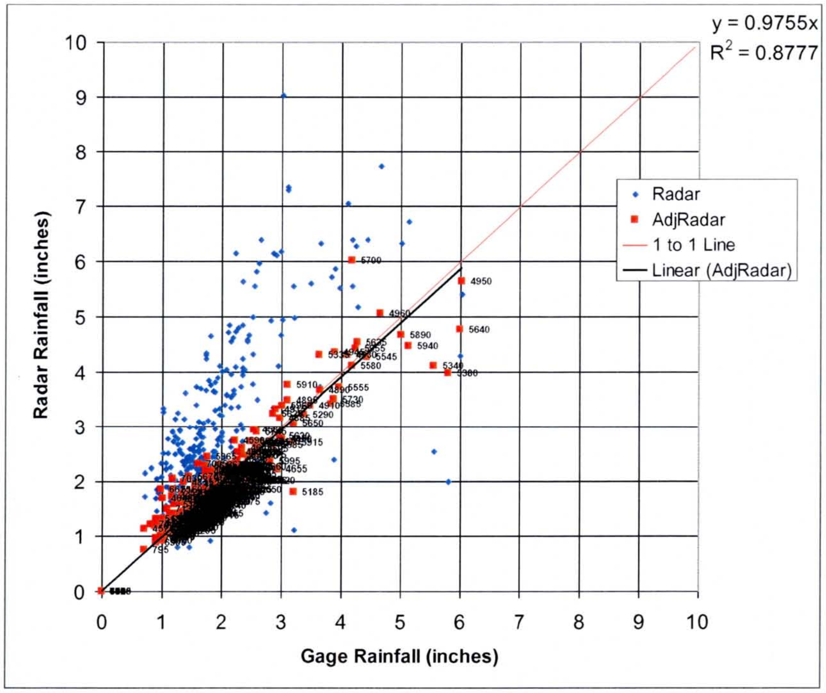

Figure 4 – Scatter-plot of radar and gage-adjusted radar rainfall totals versus individual gage rainfall totals for 11/30/2007-12/1/2007 event.

The resulting gage-adjusted radar rainfall storm total is shown below in Figure 5, below. A few radar artifacts could be observed (east southeast) but they don't appear to have been significant with respect to the rainfall accumulations in the area of maximum storm impact. There are no gages in that area so presumably it is less important to understand rainfall there.

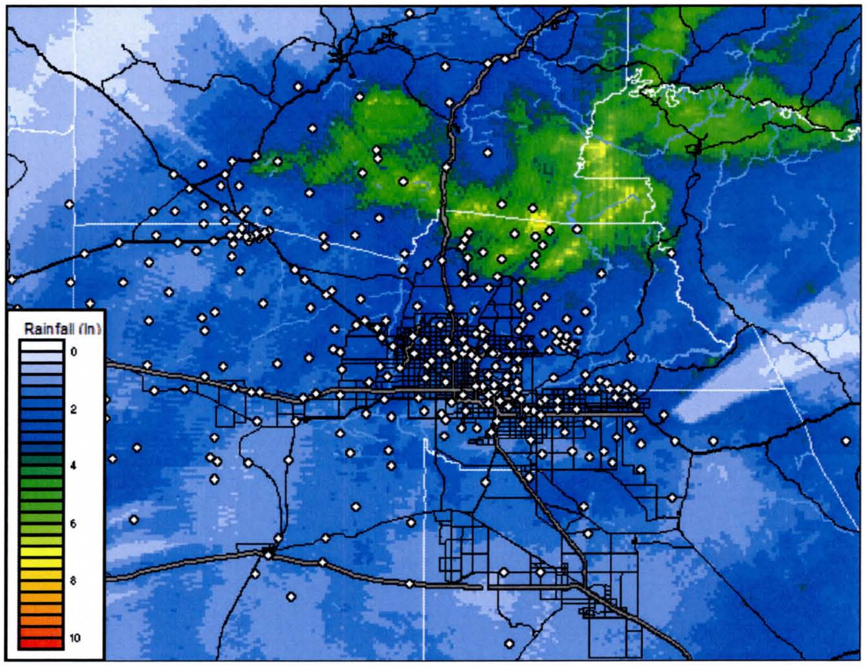

Figure 5. Storm total gage-adjusted radar rainfall accumulations for the 11/30/2007-12/1/2007 event.

RAIN GAGE DENSITY AND DISTRIBUTION

Also apparent from examining Figure 5 is the fact that the most intense rainfall occurred at locations without gages, although there were gages close by.

On the one hand, the density of gages is quite high through much of the District's area. On the other hand, it is clear from the small size of the areas receiving significantly higher rainfall that increasing rain gage network density is an expensive and hit-or-miss way to measure rainfall. Rather, using rain gages to calibrate the more complete radar coverage enabled us to see something closer to what really happened.

Appendix A contains a full report on the radar rainfall analysis, including storm accumulation graphics for the highest intensity 5-minute, 15-minute, 1-hour, 3-hour, 6-hour, 12-hour and 24-hour periods, as well as the top ten pixel accumulations for each of these periods.

3.2 Gage data overview

The DIADvisor base station received all its ALERT data from a single serial port, which is fed RS-232 serial data from an ALERT decoder. The decoder was fed audio from a receiver tuned to 171.875 MHz.

SUMMARY COUNTS: QUIESCENT VS. STORM TRAFFIC

For the period we examined, the ALERT port collected about 20,000 reports per day during quiet periods. In addition, DIADvisor was set up to compute dewpoints from reported temperature and humidity at numerous sites; these calculated reports added about 8,500 reports per day to the database. Automatically generated port statistics added another 313 reports daily.

During May and early June of 2008, about 80% of collected reports were from District gages, and slightly over 20% were from undefined sensors elsewhere on the Arizona network. During the fall of 2007, it appears that the ratio of District-defined to undefined sensors was closer to 70%-30%.

During quiet weather, the base loading of the system was made up primarily of reports from weather stations: wind, temperature and humidity, with smaller numbers of reports for barometric pressure and solar radiation. Most temperature and humidity sensors were set to report at 15-minute intervals.

Battery and precipitation sensors reported typically 4 times per day on a timed basis and contributed about 14% of the quiescent load.

Table 1 (below) summarizes identifiable traffic received by type during quiet periods in descending order of traffic percent:

Group	Records	Percent
Temperature	101696	17.3%
Humidity	100662	17.1%
Peak Wind	80066	13.6%
Wind Dir	76137	13.0%
ALERT Wind	52909	9.0%
Precipitation	45152	7.7%
Battery Voltage	41855	7.1%
Pressure	31597	5.4%
Solar Rad.	30625	5.2%
Stage	17647	3.0%
Ave Wind Speed	8841	1.5%

Table 1. ALERT traffic by Sensor Group during quiet periods.

During periods of storm activity, rain and stage gage reports increase and dominate the loading. Table 2 (below) summarizes the distribution of contributing sensors during the peak of the November 30 event in descending order of traffic percent:

Group	Records	%
Precipitation	2432	54.8%
Stage	687	15.5%
Temperature	356	8.0%
Peak Wind	275	6.2%
Humidity	235	5.3%
Wind Dir	225	5.1%
Solar Rad.	112	2.5%
Pressure	109	2.5%
Ave Wind Speed	9	0.2%

Table 2. ALERT traffic by Sensor Group at the peak of the 11/30/2007 event.

3.3 Data quality

The validation process accepted as valid (validation flag S*) 97.8% of all data received from known sensors. The proportion of duplicates was only 0.1% (validation flag ID), and all types of rejected reports based on data value (validation flag X*) amounted to 1.6%. The proportion of data carrying unknown sensor IDs (validation flag II) was about 20%.

The full distribution of ALERT reports by validation flag in the May 2008 archive is shown in Table 3, below:

Data Type	Records	%
ID	1018	0.1%
II	147604	20.1%
IO	188	0.0%
S	570480	77.6%
S1	4083	0.6%
X	16	0.0%
XH	1759	0.2%
XN	4910	0.7%
XP	4996	0.7%

Table 3. ALERT traffic by data validation flag for 5/5/2008-6/10/2008.

UNDEFINED SENSORS

In the 2008 database, undefined sensors accounted for 20.5% of all ALERT traffic. Duplicates, out-of-service sensors and reports that failed validation accounted for 1.8% of all data. In the 2007 database, only good data were saved so the undefined traffic couldn't be measured directly.

If we use a count of all data in the database compared with the PortStats count, the difference should be all I* and X* data. In the 2007 database, the difference between the PortStats count and all S* data received on the

ALERT port was 34.1%. This indicated that the undefined data category could be in the range of 32% rather than the 20.5% seen in 2008. The hourly report loading, according to PortStats, was essentially unchanged between the two periods, averaging about 850 reports per hour during non-rainy periods. There was insufficient information to comment on the reason for the large difference between the two periods.

Some of the undefined sensor reports may have come from noise on the channel or (more likely) from the corruption of the ID of a true sensor report. The proportion of these is small. IDs generated from noise or by corruption will fall somewhat randomly across the number range. By counting the number of IDs that occur once, or at most a few times in the database, we can estimate the volume. There were 418 occurrences of a sensor occurring once in a database of 316,000 reports and sensors occurring up to 10 times accounted for 577 reports, or less 0.2% of the data. It is likely that virtually all of these reports were due to corruption from contention, rather than some other source of interference.

The body of undefined sensor reports included data from nearly 450 sensors. A few reported as frequently as every 5 minutes; more than 20 reported at 15 minutes or less. It appears from the pass lists that virtually all of the undefined sensors were passed through the Sacaton and Towers Mtn. repeaters.

At least as important to understand is how the undefined sensor load responds during events. Some of the undefined gages are in areas that are affected by the same weather events as are the District's gages of interest, and thus they add to traffic loading during periods of critical performance. During the event of November 30, the proportion of S* (good) reports actually fell from 66% to 62% even as the loading from District gages tripled. In this storm, at least, traffic from undefined gages increased as District gage traffic increased.

PortStats

We used PortStats to summarize the traffic overall and to use the data from 2008 to estimate the (missing) bad reports from the 2007 database.

The hourly statistic from PortStats should equal the count of reports grouped hourly in the database. What we observed in the 2008 archive was that the number of reports in the database was usually less by an average of 1%. In the swatch2.mdb database, the disparity was 0.5%. We do not have an explanation for the observed differences and are checking our tools for future use. The observed difference is some artifact of the measurement and does not relate to performance of the ALERT network.

Because the decoder in use at the District creates finished ALERT reports that are passed to the base station serial port, no meaningful bytes-to-messages statistics were available. For systems where the decoder passes all bytes received to the serial port, the bytes-to-messages ratio (ideally 4:1) provides a meaningful measure of RF noise problems.

3.4 Repeater path study results

The results of the software analysis are summarized in Table 4, below, and the full path diagrams and statistics are available in Appendix B.

Repeater	Gages	Receive Margin (dB)	Path Length (miles)
Direct	81		
Burnt Mtn	10	10.2	57.4
Humboldt Mtn	7	27.8	42.3
Mt. Ord	8	29.0	52.1
Sacaton	15	20.1	38.6
Thompson Peak	46	54.8	33.8
Towers Mtn.	21	27.6	57.3
White Tanks	79	32.5	28.5
Yarnell Hill	33	27.2	64.7

Table 4. Theoretically derived path strengths for repeaters to District base.

3.5 System performance analyses

The ALERT protocol is designed so that losing data reports does not necessarily lead to loss of rainfall accumulation. However, if too many reports are missing, then the accumulation of rainfall can be underestimated and bad storm totals can result. On the other hand, acceptance of a bad report can falsely increment rainfall accumulation, producing exaggerated rainfall accumulation totals. Examining ALERT system performance during heavier traffic periods enabled us to better understand the risk of inaccurate rainfall.

The DIADvisor system was set to permit rain report validation for an increment of up to 10 tips. In general, this works to permit counting of rain if reports are missed in the sequence, but as described previously, both under-reporting and over-reporting can occur when erroneous reports are received.

DATA LOSSES IN NOVEMBER 30 EVENT

The peak loading during the two-day storm came between 22:00 and midnight on November 30. The rain gage raw reports were analyzed to count the missing and received reports. Based on the proportion missed, the total input load was then estimated.

During the peak two-hour period, the average received load was 2,489 reports per hour; 36.9% of rain reports were missing, indicating that the ALERT system generated approximately 3,945 reports per hour.

Approximately 1/3 of the peak traffic was from undefined sensors. Had there been a way to operate the system without this undesired traffic, the loading would have been reduced to 2,650 reports per hour, and the data loss rate would have been reduced to about 27% rather than 37%.

Data losses during large events are not uniform across the system. Repeaters are not equally loaded, so input contention levels may be much higher at some repeaters than others. Maricopa's repeater paths are also quite long, and path degradation can occur due to atmospheric conditions. Losses by repeater during the peak hours of the November 30 event are summarized in Table 5 (later in this section under Repeater Performance). Losses ranged from 24.5% at Thompson to 52.4% at Humboldt.

RAIN LOSSES IN NOVEMBER 30 EVENT

In the storm of November 30, there was only one instance in which the missed report sequence from a single gage exceeded 10; in this case, 13 tips were lost. There were 7 instances of over-count that led to the validation of 35 tips that did not occur. This happened every time a corrupted report had a data value up to 10 greater than the actual value; the report was validated and then, when 2 reports were received in the correct sequence, the count was incremented starting from a value lower than the corrupted report.

The net effect of validation errors in rainfall data was a net increase of 22 tips in about 3,000, or an over-estimation of rainfall by 0.73%.

3.6 Understanding potential data losses during rainfall events

We did not obtain data from a worst-case event and so we would like to be able to forecast data losses at higher input loadings than we have seen.

We would have liked to define a mathematical expression that related the rate of data loss to the rate of ALERT data traffic. Event-driven ALERT systems approximate an Aloha model (protocol: if you have data to send, send them), which assumes transmissions of equal length occur at random times independent of each other. The District's system deviated from a true Aloha model, however, especially during quiet weather periods, because a large part of the traffic was timer driven, with 2 to 5 or more reports issued in immediate sequence from a single source.

THEORETICAL LOSSES

A single ALERT message, such as a rain report, is sent as a 133 msec data burst preceded by approximately 200 msec of preamble tone. A status report from a weather station consists of the preamble tone followed by (for example) 5 concatenated 133 msec data packets with a short (40 msec) separation time. Five messages are thus transmitted in slightly over 1 second, whereas five individual transmissions would occupy one and two-thirds seconds. This increase in channel efficiency leads to a higher rates of data reception than we expect to see with a truly random, single-message transmission scheme. We observed this effect in the District's data record, in which a good portion of the messages received are bundled as multiple sensor transmissions.

During storm events, however, the increase in traffic over background levels is largely single message reports from rain and stream gages. While the added traffic is more truly Aloha, it is in a mixed traffic stream with longer messages, which violates the assumptions of the Aloha model. We had to combine these traffic patterns to derive the correct model for the District's ALERT system.

The Poisson equation models Aloha contention, or collisions between transmissions. In some traffic environments, one can assume that a collision results in the loss of both messages, but in the ALERT domain we have empirical evidence that, although most collision victims are lost, some messages survive intact and others survive but are corrupted. It appears that once the demodulator has "locked on" to a message, it may be able to continue to decode it in the face of interference, particularly if the interfering signal is weaker.

Survival of even a small percentage of messages has a large impact when we try to predict losses during extreme rainfall events. Loss of both messages in a collision is what causes "contention collapse" at very high loadings; at some point, attempting to add another message to the traffic stream has such a high probability of removing one that the throughput is actually reduced. If the probability that both messages will be lost is even slightly less than 1, however, the point of contention collapse is moved substantially higher.

THE DISTRICT ALERT SYSTEM'S EXTRAPOLATED LOSS BEHAVIOR

In short, based on what we have analyzed in the District's system, more reports are successfully received at higher traffic rates than would be expected from a true Aloha contention model. We don't, however, have enough information to distinguish the cause of this: Is it because reports take up on average less time than predicted because of the many bundled reports, or is it because actual message collisions have higher survival rates than the Aloha prediction that all reports in a collision are lost, or some combination of both?

We determined data losses at three different input loading rates. One was based on the average loading over quiet periods, at an input rate of about 900 reports per hour. A storm on May 22, 2008, was used to assess losses at an input rate of about 1,200 reports per hour, and the event of November 30, 2007, was used to assess losses at an input rate of 3,945 reports per hour.

A curve was fitted to the three known load/loss values and extrapolated to higher loads under a variety of conservative assumptions about message survival and effective message length. The resulting data loss function is shown in Figure 6, below.

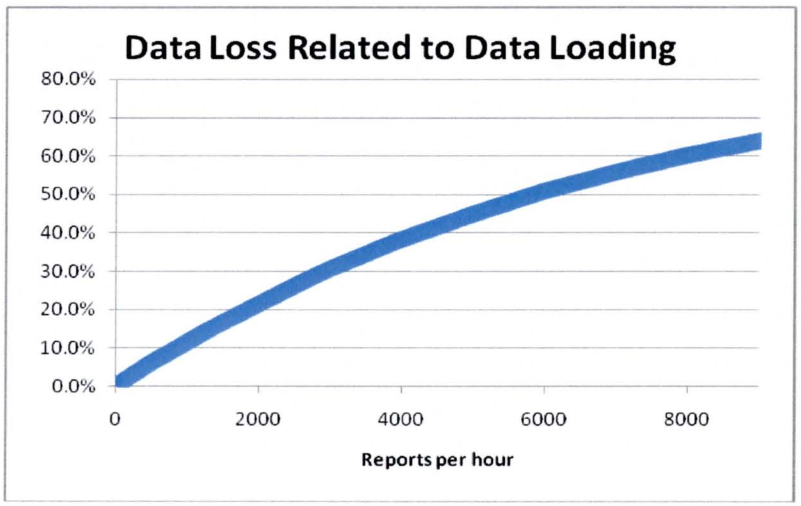

Figure 6. Derived data losses as a function of data loading for the District.

Out to 8,000 messages per hour, the various scenarios are in general agreement. At input loads of 6,000 messages per hour, we can expect data losses of 50%, and at 8,000 messages per hour these will increase to more than 60%.

STORM OF JUNE 1972 – HYPOTHETICAL LOADINGS

An intense storm in June of 1972 dumped upwards of 5 inches of rain over central Phoenix and areas to the north. About 640 square miles were included within the outline of the storm as reported by the Corps of Engineers. Within this area today, there are 66 rain gages that would have received ½ to 4 inches of rain (as always, the peak rain fell between the gages).

We estimated the peak loading this storm would produce on the ALERT network if it had occurred today. The COEmass curve of this storm indicates that up to 40% of the rain fell during the peak hour. As a first approximation, we applied a 0.4 scalar to the isohyetals, then applied the adjusted rainfall to each of the gages within each zone.

Half of the gages fell in the lowest rainfall category (0.20 inches), and no gages captured the two highest categories (1.8 inches and 2.0 inches). The total rain gage traffic generated was 820 reports.

We assumed that by the arrival of the peak hour, the hydrologic traffic response would be at or near maximum rate; our estimate for this storm was about 500 reports during the peak rainfall hour. The background traffic (timed reports, weather stations) was another 850 reports per hour. In total, the peak hour traffic load was estimated at 2,200 reports per hour, which today would result in contention losses of about 24%.

PLAUSIBLE PEAK LOADINGS

The 11/30/2007-12/1/2007 storm affected a large proportion of the Maricopa County gages, but over a relatively long storm period. The June 1972 storm had a massive impact because its peak intensity was directly over the urbanized area of Phoenix. However, its geographical extent was limited.

We would argue, largely from an intuitive basis, that neither storm approached a worst-case ALERT scenario, but development of such a model event is beyond the scope of this effort. Based on our experience, we took a shortcut approach and estimated loading from a storm that impacts half of the system's gages at a rate of ½ inch per hour, 20% at 1 inch per hour, and 1.5% of gages at 2" per hour.

Such a storm, when combined with stage gage loading, timed and weather transmissions, and reports from undefined gages would produce a peak loading in excess of 7,000 reports per hour. At this level, overall data losses would be in the range of 55%. Losses would be much worse for weaker paths, with the gages routed through the most severely impacted repeaters losing as much as 80%.

REPEATER PERFORMANCE

Timed reports – typically at 6 hours, with a few gages at 3-hour intervals – were used to send battery voltages from all sites. These reports can be used to assess the availability of individual gages, or, when we know the gages were operating, they can be used to evaluate the losses over different repeater paths. There is a high degree of availability of individual gages, and we chose to use the timer reports as a system-behavioral means to assess the efficacy of repeaters relative to each other and to gages that reported directly.

We examined over 42,000 records from 312 battery voltage sensors. About 70 of these showed indication of having been serviced (extra reports and/or a shift in report time), and 14 others had irregular clock intervals. A sample of 223 gages was analyzed to determine the ratio of received to expected data reports. These were then grouped by repeater and a composite loss rate was determined for each group.

The computed data losses from repeaters to the District base station are summarized in Table 5, below, along with the previously computed theoretical path strengths (see Appendix B for full results of theoretical path strength analysis).

		Percent Loss in		Receive
Repeater	Gages	Quiet	Peak Rain	Margin (dB)
Direct	81	10.8%	33.9%	
Burnt Mtn	10	14.4%	40.4%	10.2
Humboldt Mtn	7	21.9%	52.4%	27.8
Mt. Ord	8	14.6%	37.2%	29.0
Sacaton	15	25.6%	42.3%	20.1
Thompson Peak	46	10.2%	24.5%	54.8
Towers Mtn.	21	15.4%	42.7%	27.6
White Tanks	79	10.7%	34.1%	32.5
Yarnell Hill	33	14.0%	42.0%	27.2

Table 5. Observed data losses by repeater link and theoretical path strength.

The average data loss across the system for regular timed reports over the 32 day period was 12.5%. Losses from the gages that report directly were 10.8%, and similar losses (10.7% for White Tanks and 10.0% for Thompson Peak) were observed for the repeaters with shorter, unobstructed radio paths to base.

The observed losses were not completely in agreement with the theoretically path-modeled losses. Much higher losses were computed for Sacaton (25.6%) and Humboldt Mountain (21.9%). Path modeling software indicated the Salt River Mountains are a minor obstruction for the Sacaton path, south of East Baseline Rd. Humboldt Mountain also has a minor obstruction in the Camp Creek area, about 7 miles from the repeater. In both cases, however, the receive fade margins indicated by the model were good, and the topography does not adequately explain their weaker performance.

The relatively higher losses for Sacaton and Humboldt Mountain stand in contrast to Burnt Mountain, which shows a mid-path obstruction and a weak modeled fade margin but better performance. We believe evaluation of receiver sensitivity and antenna systems may permit tuning to more optimum performance at Humboldt Mountain and Sacaton repeaters.

4. RECOMMENDATIONS

4.1 Radar rainfall approach recommendations

There appears to be a good rain gage density over areas of population and of concern. We are unable to make judgments regarding any other gage type as those characteristics can't be generalized but rather are highly specific to local requirements. However, one can never have too many rain gages. We did observe in this report that the maximum rainfall accumulation was not detected by any of the gages, so clearly gage-adjusted radar rainfall is a better tool, and rain gaging networks can be evolved to operate as radar-calibration networks, an objective that may produce different spatial distributions of gages for the best outcomes.

For example, densely gaged areas that have excellent radar coverage could be used as donors to relatively increase the gage density of areas with poor radar coverage. A rule of thumb is that $1/10^{th}$ as many gages will provide equivalent rainfall measurement with radar than without.

OneRain provides gage-adjusted radar rainfall data both in real time and as an archive-quality historical analysis, much like the one we did for the November 20, 2007, event in this report. It is our experience that the quality and accuracy of rainfall accumulation obtainable using the automated, real-time processes is not at all comparable to the quality of QA/QC-analyzed historical data.

There are errors in both gage and radar data that cannot easily be detected in real time. In particular, for rainfall that will be used in high-impact modeling, the real-time products available do not provide the accuracy required. We recommend the District continue to use their ALERT gages and real-time gage-adjusted radar rainfall data for storm operations, and we recommend they obtain higher quality rainfall data for modeling and design applications.

4.2 District gaging network recommendations

The system is clearly well operated and well maintained. Gages have a very high level of availability, and there is ample evidence in the database that problems are quickly identified and addressed. There are no gages in the District's control that report excessively and the choice of reporting parameters appears to be carefully considered in light of the program objectives.

Besides the possibility of tuning up repeater performance at Humboldt Mountain and Sacaton, we have no recommendations in the area of operating and maintenance practices that would make significant improvements to the data collection network.

The real challenges to this system come from the sheer volume of data that it handles, and from the limitations of ALERT technology as traffic loading increases. If the system is to perform well during periods of peak loading, and particularly if the system is to grow further, it is important to consider means to limit the loss of data due to contention on overcrowded channels.

The problem is fundamentally caused by the "backbone" architecture of the Arizona system. Focusing a large amount of Aloha traffic onto a single telemetry path with very limited bandwidth assures data contention and guarantees degradation will accompany system growth.

When we refer to "gages of interest," we are referencing gages that are defined in the SensorDef table of the District's DIADvisor database. While this set obviously includes all of the District-owned gages, there may be some gages of interest that are owned and operated by other counties, and are outside the control of the District to reprogram. The recommendations will be easier to implement if all gages of interest are under the District's control.

There are over 300 gage sites defined in the District system, and possibly 300 more sites from which the system receives data that are not of interest. Every one of these gages shares the same frequency at the District's base station receiver.

The District's ALERT network operates at the hub of the statewide telemetry network and conveys much of the state data to the Arizona DWR system. It is difficult to make any change in the network architecture without impacting ADWR, NWS, Yavapai County and potentially other users. However, the problem of excessive contention data loss is also shared by these agencies and, if possible, we need to find solutions that benefit all users.

This contention problem has two components. One need is to limit the impact of traffic coming from sensors elsewhere in the state that are of no interest or benefit to the District. A second need is to reduce the contention among data reports coming from within the District system. Addressing either one impacts the backbone.

At this stage, our limited understanding of the network outside of Maricopa County makes it impossible to propose appropriate and realistic solutions that will work around the disruptions caused by upgrading the District's system. We have done our best to simply call out the impacts of changes we recommend that will improve the District's ALERT system performance for the District.

In addition to repeating District gages, Towers Mountain and Sacaton repeaters carry reports from the northern and southern parts of the state to ADWR, and are the source of data from several hundred undefined IDs in the District database. There are 6 other repeaters that transmit on the District listening frequency (171.875 MHz), all of which appear to be pass-listed only for gages of interest. All of these repeaters receive on 171.850 MHz and transmit on the adjacent frequency, only 25 kHz away.

This configuration makes it impractical to take advantage of a duplex repeater; when the repeater transmits on 171.875 MHz, it is virtually impossible to prevent it from opening or de-sensing the receiver, such that incoming messages during that time are lost. The effective "duration" of a message is therefore the time it takes to receive it, turn the repeater around and retransmit it, or about 700 msec. Since only then can the input channel be monitored effectively, the channel capacity is cut in half and the data losses increased significantly.

We believe the only way to effectively address this problem is to find an alternative frequency for the repeater output that has at least 1 MHz separation from the input frequency.

Contention in the District's system occurs among several different data streams:

1. Direct gages are in contention with all traffic coming from the eight repeaters on the single base station "listening channel."
2. District repeated gages are in contention with out-of-county gage traffic arriving at Sacaton and Towers repeaters.
3. The output of each of the repeaters has the potential for collision with traffic coming from each of the other 7 repeaters on the single output channel.

ALERT SYSTEM RECONFIGURATIONS

There are some options for the District to reduce contention using current ALERT technology. Essentially, the approach is to increase channel capacity through the addition of new frequencies, and to attempt to separate District gages of interest from backbone traffic that is not of interest.

The value of this approach is that it uses mature technology to accomplish an incremental improvement to the capacity of the system. The drawbacks are that it retains all of the ALERT vulnerabilities; double ALERT hops with two opportunities for errors and collisions, no error detection or correction at the base.

We recommend adding two new frequencies to be used on the output side of the repeaters that communicate directly to the District base. The goal would be to transfer each of the direct gages and the repeated gages of interest off of 171.875 MHz and onto one or the other of the two new monitoring frequencies. This will approximately double the capacity of the last hop link to the District's base.

If this could be accomplished, the 300 or so state gages would be left on 171.875 MHz and monitored by ADWR, while the 300+ District sites would be distributed across two channels of about equal loading. Assignments to the new frequencies would be made so as to distribute geographically related gages across both channels, i.e., traffic from any localized event would load both channels similarly.

A preliminary inspection of the FCC license database indicates that several frequencies may be available in the Maricopa County area. These frequencies should be at 171.075 MHz or below to provide good input/output separation at the repeaters; we'll refer to the output frequencies hereafter as "F2" and "F3."

A third new frequency is needed on the input side of District repeaters, to which repeated District gage transmitters would be changed. This frequency requires separation from the new output frequencies F2 and F3, as well as from 171.875 MHz. One of the frequencies at the low end of the band would be good, and 169.450 MHz may be available; for now we'll refer to it as "F1."

The best results will be obtained if the District can use F1 for all gages of interest that are directed to a repeater. This will remove the possibility of traffic from gages of interest colliding with traffic from uninteresting gages.

Towers Mountain: This site presently relays up to 150 gages from northern and western parts of the state; these come though Union repeater and are received on 171.850 MHz. There are 22 gages of interest to the District that are directed to Towers, and these are presently in contention with the undesired traffic on both the input and output side of the Towers repeater. The highest priority here is to separate these two streams.

We would leave the existing repeater as-is to repeat state traffic on 171.875 MHz and add a new repeater that transmits on F2 over a Yagi antenna directed toward the District base. If possible, all the gages of interest to the District would be reprogrammed to transmit on F1, which would be the input frequency of the new repeater. This would remove them from contention with the Union feed on both the input and the output frequencies.

If all or even some of the Towers-directed gages cannot be set to a new frequency, then the new repeater will continue to receive on 171.850 MHz and the desired gages will be filtered through a pass-list for transmission on F2. This will leave contention occurring on the input channel but still offer significant improvement by separating the output channels. In this case, it would be possible to split the audio of the existing repeater and use it to drive the new repeater (no receiver or receive antenna).

If F1 is used, the new configuration would break the existing link that feeds these 22 gages northward to Yavapai via Spruce Mountain. In our view, a non-ALERT pathway to get these data to other users is preferred; this might include IP network solution implemented at the District base (discussed later). However, if this is not available, it would be possible to drive two transmitters with the new repeater, one on F2 and the other on 171.875. The contention issues on 171.875 would be unchanged, as would be the data received at Spruce Mountain.

Sacaton: The Sacaton repeater situation is similar to Towers. It repeats about 15 gages directly, intermingled with a stream of 150 or so non-interesting gages from farther south. Our suggested solution is similar to Towers: Add a second repeater and, if possible, establish a new input frequency (F1) unique to the desired gages. If that cannot be done, then the new repeater should be fed with the audio from the existing repeater, and the desired gages filtered by pass-listing. The new repeater would transmit on F2 or F3 over a new Yagi directed to the District base.

Shifting the output frequency makes it possible to use the 50386 repeaters in duplex mode. With a dual radio and antenna, the repeater can monitor continuously and buffer incoming data while it is transmitting an earlier report. This positively impacts channel capacity.

Other primary repeaters: This group consists of White Tank, Mt. Thompson, Yarnell Hill, Mt. Ord, Humboldt and Burnt Mountain. The first three of these handle 90% of the combined load and would be the priorities for modification. We assume, based on inspection of the radio path models, that gages reporting to these repeaters are relatively free of interfering traffic from non-Maricopa gages on 171.850 MHz. This assumption needs to be confirmed, particularly at Yarnell Hill which may be affected by Mt. Union. If there is not an interference problem, input gages could be left on 171.850 MHz.

These repeaters, or at least the three busiest, should be converted to duplex repeaters to permit continuous input monitoring. This will require converting them to dual radio units with a dedicated receiver and separate receive and transmit antennas. Typically, the existing omni dipole would be used for receive, and a Yagi antenna added to direct the output to the District base. The output frequency assignment for all of the primary repeaters would be F2 or F3, chosen to interleave the load on each channel geographically.

Direct reporting gages: The gages that report directly to the base station would be moved to F2 or F3, interleaving the frequency assignments geographically to balance the loading across frequencies in any localized event.

These changes would remove all District traffic from 171.875 MHz. The District would monitor F2 and F3 and merge these two data streams at the ports of their base station computers. ADWR would continue to receive state traffic on 171.875 MHz.

An ALERT solution can be maintained for ADWR if they add monitoring of F2 and F3. To sustain an ALERT feed to Yavapai and northward, the dual transmit option discussed above for Towers Mountain could also be applied at Yarnell Hill. This would entail simultaneous repeater transmissions on the District output frequency (F2 or F3) and 171.875 MHz, so that the feed to Spruce Mountain remains the same.

From a system design standpoint, however, we believe these breaks in the ALERT backbone should be resolved not by using contention-prone RF paths, but rather by finding an alternate, error-free, higher bandwidth, non-contending pathway such as the internet protocol. Raw data received by the District could be transmitted to other users for input to their ALERT base stations. However, it may make more sense to distribute a feed of processed data from the District that can be distributed as engineering unit measurements independent of the metadata needed for validation – this removes the problem of other listeners not having direct access to the District's calibration and other metadata.

ALERT/ALERT-2 HYBRID SOLUTION

We have added this set of recommendations simply because we think the overall solution is better. Although this technology is just getting started and is not yet being implemented on a gage by gage basis, ALERT-2 already offers the opportunity to reduce contention to a much greater extent than ALERT, as well as to eliminate the introduction of errors downstream of the repeater. An ALERT-2 concentrator can receive data from two ALERT streams simultaneously, and merge these streams with *no* contention into an output whose channel efficiency increases from two to eleven-fold as traffic increases.

In addition to merging multiple incoming ALERT channels, ALERT-2 concentrators have the capacity to use time division multiple access (TDMA) to interleave transmissions from different repeater sites, thus completely eliminating output channel contention. Finally, reports that are transmitted using ALERT-2 are no longer vulnerable to being received as bad data – they are either correct as originally transmitted from the concentrator, or they are correctly rejected as having been corrupted.

The ALERT 2 solution requires obtaining two new frequencies rather than three. One would be used to add a second monitoring point at the base station that would feed a second data port on base station equipment. This frequency, (possibly 169.450 MHz) would be used by ALERT-2 repeaters for transmission. The second new frequency (possibly 171.050 MHz) would be used on the input side of the ALERT-2 repeaters. District gages directed to the ALERT-2 repeaters would be moved to this frequency.

The recommended ALERT/ALERT-2 hybrid deployment would be as follows:

1. Install dual input channel ALERT-2 TDMA Concentrators at Sacaton and Towers Mountain. One input receives and decodes a pass-listed stream from out-of-county gages on 171.850 MHz. The second input is dedicated to the pass-listed District gages. The two data streams are buffered and merged in the Concentrator, so contention between the two data streams is eliminated. Each repeater is assigned a 1.5 second time slot in which it may transmit once every 15 seconds. Sacaton will pass about 150 Pima and Santa Cruz IDs as well as 15 District gage sites. Towers Mountain will pass another 150 northern AZ IDs and 22 District sites.

2. Install single input channel ALERT-2 TDMA Concentrators at Thompson Peak, White Tanks and Yarnell Hill. The output frequency configuration is the same as Sacaton and Towers, but these monitor only the Maricopa gage input frequency. Each of these repeaters has a dedicated TDMA time slot once each 15 seconds, so output contention is eliminated. A total of 160 District sites will be distributed across these three repeaters.
3. The Mt. Oatman repeater presently transmits to White Tanks on 171.850 MHz, and passes only a few gages of interest. Unless there are reasons to approach this differently, we recommend changing its output frequency to the new White Tanks input frequency and adding it to the repeated gage load there.
4. The 84 directly reporting gages will be left on 171.875 MHz. The Burnt Mountain, Humboldt Peak and Mt. Ord repeaters would also be left as is, adding another 26 gages to this path. While they too could be converted to ALERT-2, each repeater passes between 7 and 11 sites, so their conversion is less cost effective.
5. The remaining repeaters for which the District is responsible transmit on 170.850 MHz and serve to feed data to one of the "inner ring" of repeaters. These will remain unchanged.
6. At Maricopa base, the ALERT-2 messages are decoded and the unpacked ALERT messages are reconstituted into a serial stream that can be fed directly to existing base station software.

This proposed solution still breaks the backbone connectivity in two places; the ADWR feed at the APS repeater, and the Yavapai/NWS feed at Spruce Mountain.

However, the ALERT-2 solution is significantly superior to the ALERT approach in several ways:

1. While the ALERT solution reduces contention on the output channels, the ALERT-2 TDMA approach eliminates it completely.
2. The ALERT system reconfiguration approach works by isolating the District's data collection from the rest of the state data feed. The ALERT/ALERT-2 hybrid solution incorporates *all* gages without increased contention impact, meaning that the District base station can be a single, high-quality receive point and data feed for the entire state. This makes it a logical starting point for the distribution of a data stream to all users of the state ALERT network.
3. If ADWR elects to listen to the ALERT-2 concentrator output, their data feed will be upgraded to the same extent as the District's.

Appendix A. Gage-Adjusted Radar Rainfall Analysis

Flood Control District of Maricopa County

November 30 - December 1, 2007

Introduction

Accurate estimation of the spatial distribution of rainfall is critical to successfully model hydrologic processes. Rainfall distributions are typically estimated by assuming a spatial geometry tied to point rain gage observations using, for example, Thiessen polygons, inverse distance squared weighting, or statistical Kriging techniques. Unfortunately, the spatial distributions inferred by these approaches have little connection with how rain actually falls. From a modeling perspective, these techniques too often place the wrong rain at the wrong place at the wrong time.

In recent years, improvements in technology have made radar a viable tool to improve the estimation of rainfall between the gages. Radar provides a high resolution view of the variability of rain falling over a region. Unfortunately, radar by itself has not proven to be a consistent estimator of the actual rainfall amounts.

The strength of a rain gage network is its ability to consistently estimate rain falling on a number of discrete points. Its weakness is the network's inability to estimate rain falling between the gages. On the other hand, radar's strength is its ability to see between the gages but radar is poorer than gages at estimating the rainfall volume that actually reached the ground.

By merging rain data from a gage network and rain data derived from radar, hydrologists can take advantage of the strengths of each measurement system while minimizing their respective weaknesses. Essentially, a radar image is used as an areal template for the spatial distribution of rainfall. The radar data are used to assess the rainfall timing, while the rain gage data are used to assess the rainfall volume. The net result is a gage-adjusted radar rainfall data set that combines the spatial distribution characteristics of the radar image with the scaling information from the gages.

As part of the network analysis prepared for Maricopa County, OneRain Inc. has prepared gage-adjusted radar rainfall estimates for November 30-December 1, 2007. This report summarizes these results.

Radar Rainfall Estimates

For this study OneRain used 5-minute, 1x1 km pixel radar rainfall estimates obtained from Barons Service, Inc. Each radar image is a composite prepared using data from all National Weather Service (NWS) WSR-88D radars covering the study area. The radar mosaic used is constructed from several nearby radars, enabling coverage across the study area. Nationwide, data resolution is approximately 1 km x 1 km, or about 0.4 square miles, or 340 acres.

The radar data used in this project were selected from OneRain's database of archived Barons Services reflectivity data covering an area bounded approximately on the west by –113.5517° W longitude, on the east by –110.7925° W longitude, on the north by 34.7031° N latitude, and on the south by 32.5920° N latitude. This study area consisted of 62,510 radar pixels.

Based on the gage data provided by the County, the time period for the analysis was November 30 (00:00 PST on November 30) through December 1 (00:00 PST on December 2), 2007. The final products are a dataset of gage-adjusted radar rainfall estimates every 5 minutes at 62,510 radar pixels over the study area.

Rain Gage Data

Gage data was obtained from Maricopa County's DIADvisor archive. This dataset consisted of 301 rain gages. Figure 1 presents the radar rainfall study area with the locations of the Maricopa County rain gages. The rain gage data were reviewed and checked for quality using several steps.

First, nine gages that failed to report rainfall for the entire study period were removed from the analysis. Scatter-plots were generated that compare the event gage volumes with their co-located unadjusted (raw) radar pixel rainfall estimate. Using these scatter-plots, under- and over-reporting gages tend to stand out from the rest of the group.

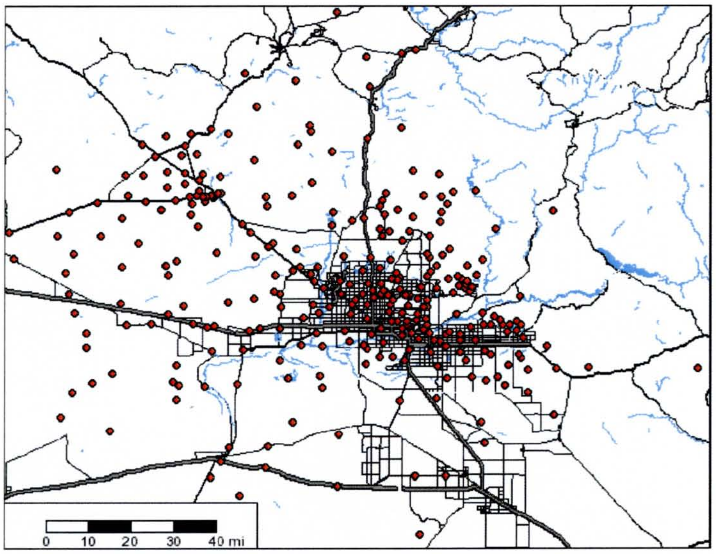

Figure 1. Background map showing gage locations.

Radar Adjustment Procedure

For each gage, a time series of gage data and a time series of radar data at the pixel over each of the rain gages were collected. At each pixel containing a gage location, a gage/radar (G/R) ratio was computed by dividing the gage rainfall by the radar rainfall during each time step (time steps are chosen to match individual rainfall sub-events).

Next, a Kriging-based interpolation technique was used to determine the appropriate geometry and distance-weighted G/R ratio for every other pixel in the domain. The G/R ratios were then multiplied by the raw/filtered radar dataset for each time period during the study to determine the gage-adjusted radar rainfall amounts. This process was repeated for each storm period during the study period. Figure 2 presents a schematic description of the spatially variable gage-adjusted radar rainfall process.

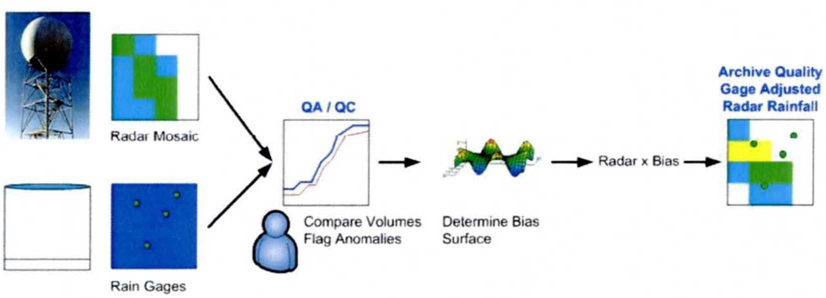

Figure 2. Schematic depicting spatially variable gage adjustment process.

Gage-Radar Analysis Results

Tables 1-7 (next 7 pages) present the ten highest rainfall intensities for time periods ranging from 5 minutes to 24 hours. These tables include pixel number, geographic coordinates and start times (in MST) for the accumulation amounts. The most intense 5-minute accumulations occurred at 6:35 am on December 1. The ten most intense one day totals occurred approximately from mid-day November 30 until mid-day December 1, 2007.

Co-presented with Tables 1-7 are Figures 3-9, each providing a graphical depiction of the storm accumulations from which the 10 top pixels were chosen.

Pixel	Latitude N	Longitude W	Start Time	Rainfall (in.)
47161	34.187	-112.737	12/01/2007 06:35	0.404
47428	34.196	-112.727	12/01/2007 06:35	0.403
46895	34.178	-112.737	12/01/2007 06:35	0.402
47162	34.187	-112.727	12/01/2007 06:35	0.401
47429	34.196	-112.717	12/01/2007 06:35	0.400
46896	34.178	-112.727	12/01/2007 06:35	0.398
47163	34.187	-112.717	12/01/2007 06:35	0.397
42700	34.034	-112.105	12/01/2007 12:10	0.393
42434	34.025	-112.105	12/01/2007 12:10	0.376
46977	34.178	-111.887	12/01/2007 02:35	0.372

Table 1. Top ten 5-minute rainfall intensities.

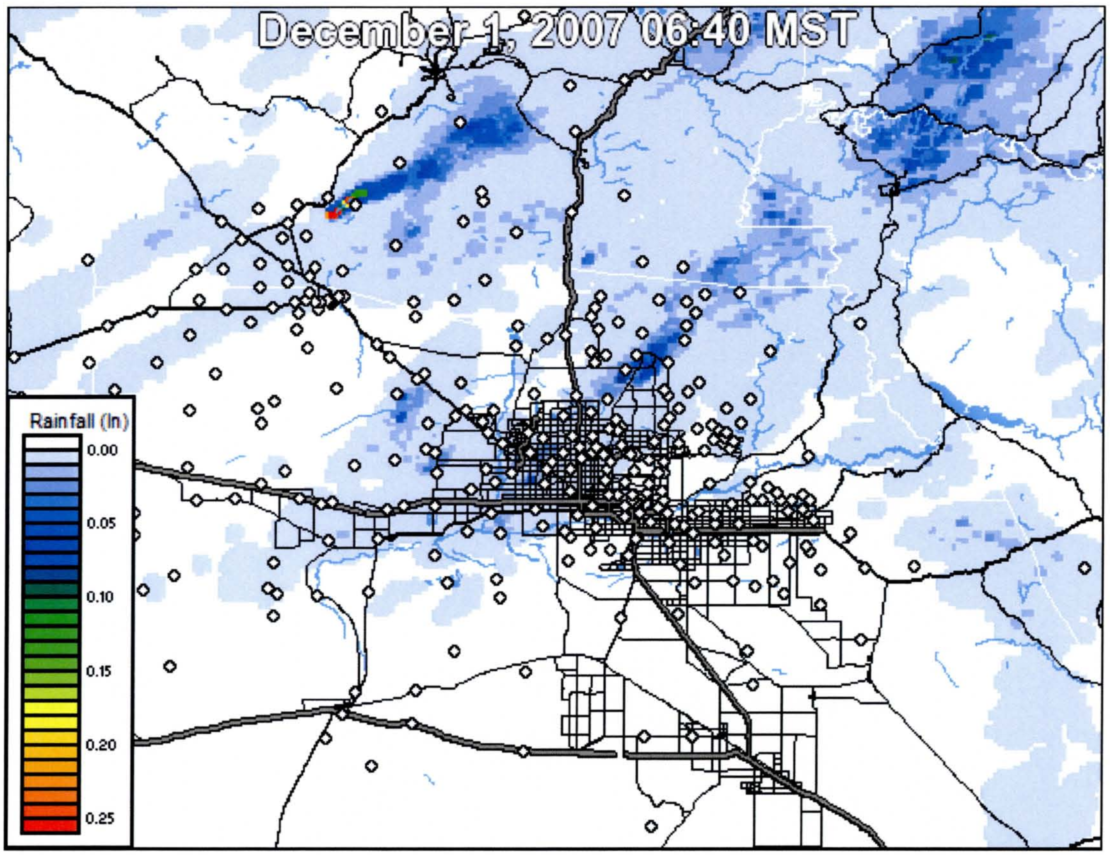

Figure 3. Top ten 5-minute rainfall intensities.

Pixel	Latitude	Longitude	Start Time	Rainfall (in.)
9032	32.893	-110.922	12/01/2007 16:20	1.053
43280	34.052	-111.607	12/01/2007 13:00	1.038
43014	34.043	-111.607	12/01/2007 13:00	0.996
43281	34.052	-111.596	12/01/2007 13:00	0.993
43815	34.070	-111.576	12/01/2007 13:05	0.979
9299	32.902	-110.912	12/01/2007 16:20	0.961
9033	32.893	-110.912	12/01/2007 16:20	0.960
42700	34.034	-112.105	12/01/2007 12:00	0.931
42213	34.016	-111.638	12/01/2007 12:55	0.906
46895	34.178	-112.737	12/01/2007 06:25	0.904

Table 2. Top ten 15-minute rainfall intensities.

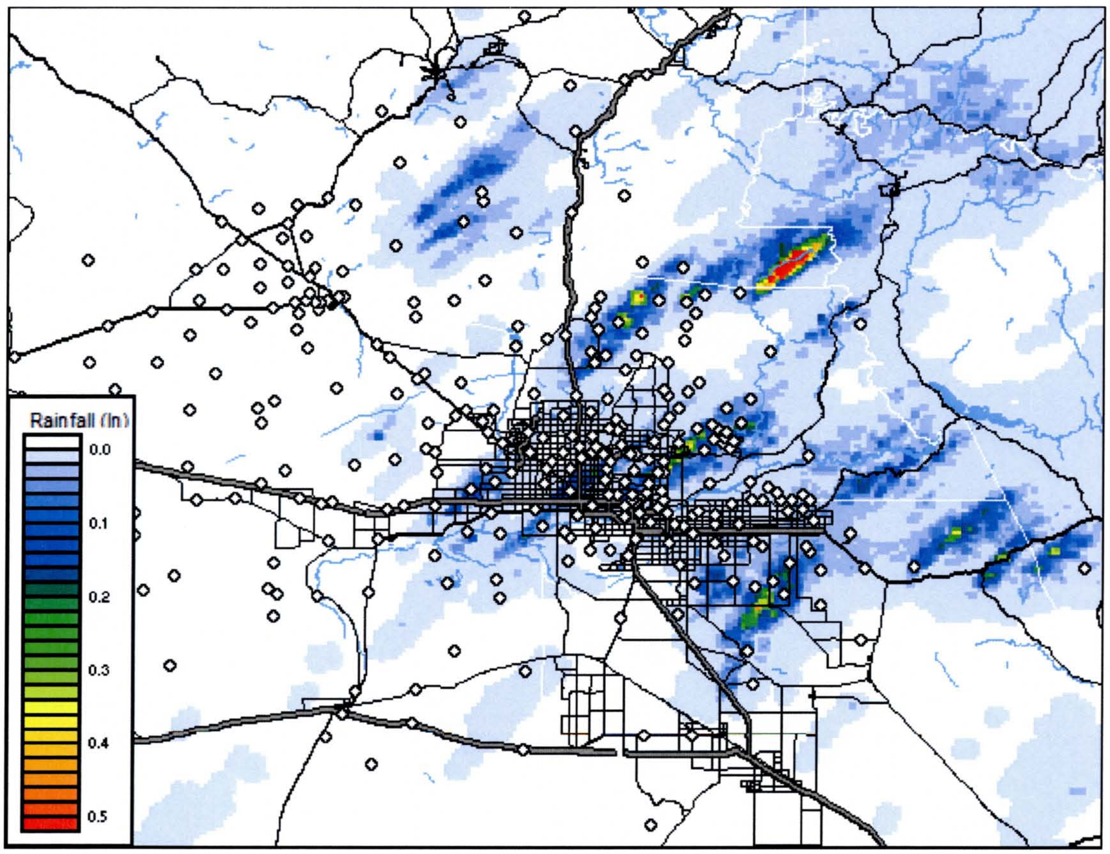

Figure 4. Top ten 15-minute rainfall intensities.

Pixel	Latitude	Longitude	Start Time	Rainfall (in.)
38208	33.881	-111.794	12/01/2007 14:05	1.657
38207	33.881	-111.804	12/01/2007 14:05	1.601
41129	33.980	-111.845	12/01/2007 12:25	1.507
47163	34.187	-112.717	12/01/2007 05:50	1.504
46896	34.178	-112.727	12/01/2007 05:50	1.498
37674	33.863	-111.814	12/01/2007 14:15	1.496
37944	33.872	-111.773	12/01/2007 14:10	1.484
40863	33.971	-111.845	12/01/2007 12:10	1.471
46895	34.178	-112.737	12/01/2007 05:50	1.446
38209	33.881	-111.783	12/01/2007 14:10	1.441

Table 3. Top ten 1-hour rainfall intensities.

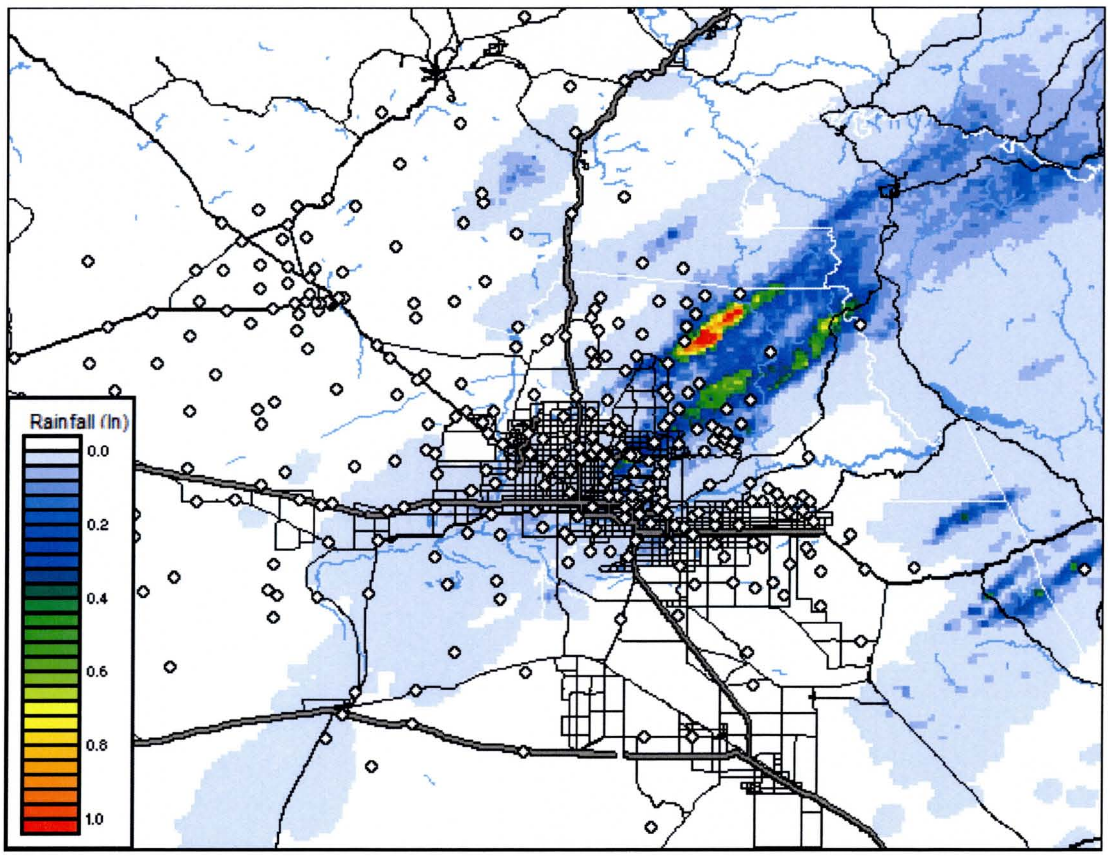

Figure 5. Top ten 1-hour rainfall intensities.

Pixel	Latitude	Longitude	Start Time	Rainfall (in.)
38210	33.881	-111.773	12/01/2007 12:35	2.361
39811	33.935	-111.721	12/01/2007 12:25	2.357
38208	33.881	-111.794	12/01/2007 12:20	2.318
40078	33.944	-111.711	12/01/2007 12:25	2.226
39812	33.935	-111.711	12/01/2007 12:25	2.220
39278	33.917	-111.731	12/01/2007 12:40	2.207
39277	33.917	-111.742	12/01/2007 12:40	2.197
39012	33.908	-111.731	12/01/2007 12:40	2.179
38209	33.881	-111.783	12/01/2007 12:20	2.177
39011	33.908	-111.742	12/01/2007 12:40	2.174

Table 4. Top ten 3-hour rainfall intensities.

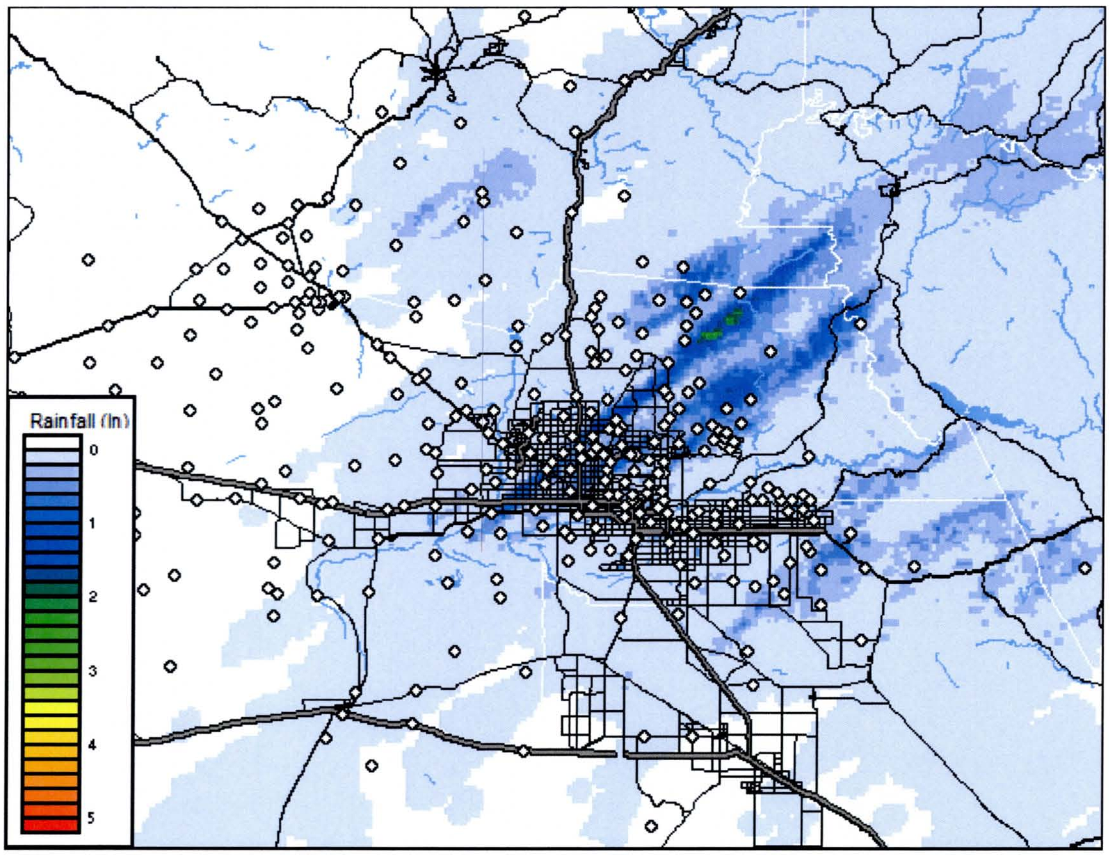

Figure 6. Top ten 3-hour rainfall intensities.

Pixel	Latitude	Longitude	Start Time	Rainfall (in.)
38458	33.890	-111.960	12/01/2007 07:25	3.277
41929	34.007	-111.825	12/01/2007 07:35	3.237
42195	34.016	-111.825	12/01/2007 07:40	3.110
49128	34.249	-111.648	11/30/2007 18:45	3.075
41129	33.980	-111.845	11/30/2007 18:45	3.069
56061	34.483	-111.472	11/30/2007 21:40	3.059
55795	34.474	-111.472	12/01/2007 07:35	3.039
55794	34.474	-111.482	11/30/2007 14:05	3.037
59526	34.600	-111.399	11/30/2007 14:05	3.034
62460	34.699	-111.316	11/30/2007 14:05	3.033

Table 5. Top ten 6-hour rainfall intensities.

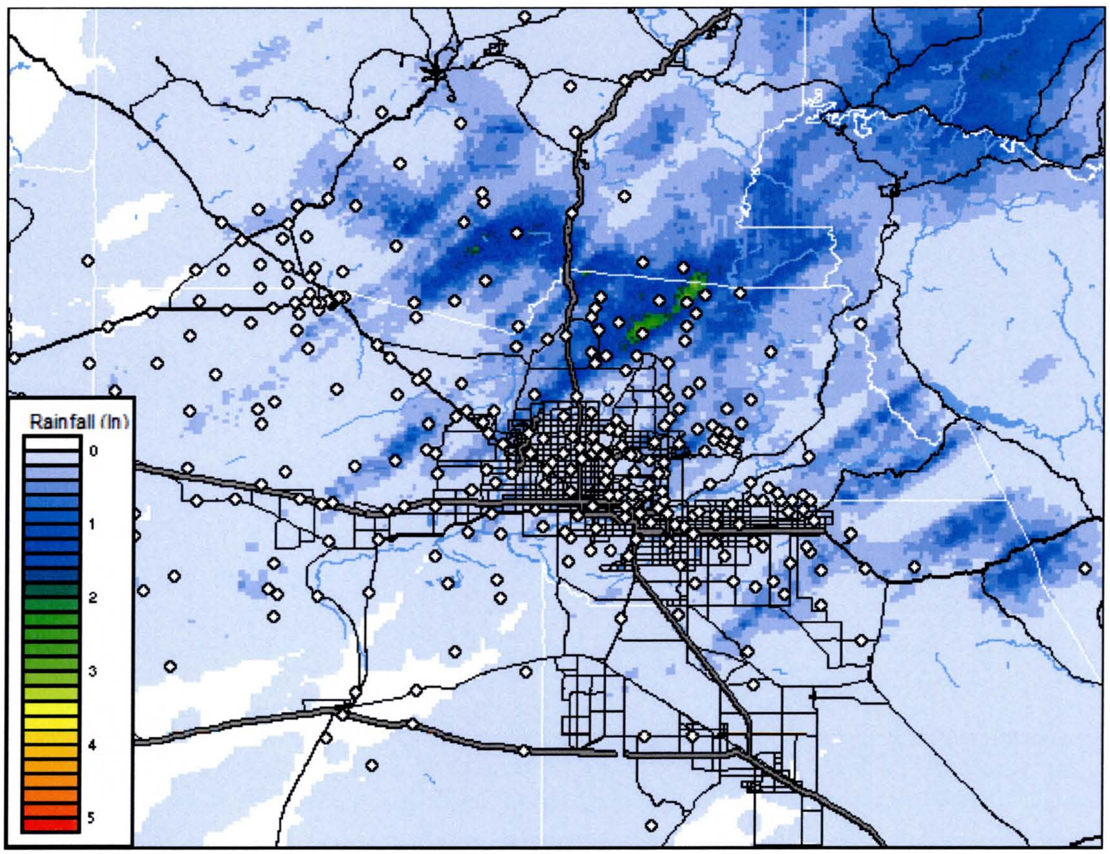

Figure 7. Top ten 6-hour rainfall intensities.

Pixel	Latitude	Longitude	Start Time	Rainfall (in.)
49395	34.258	-111.638	11/30/2007 15:40	5.145
45147	34.115	-111.555	11/30/2007 13:00	5.142
45149	34.115	-111.534	11/30/2007 13:10	5.107
49128	34.249	-111.648	11/30/2007 15:40	5.099
49129	34.249	-111.638	11/30/2007 15:40	5.017
48597	34.232	-111.638	11/30/2007 15:40	4.991
49126	34.249	-111.669	11/30/2007 15:35	4.966
44881	34.106	-111.555	11/30/2007 13:05	4.948
46203	34.151	-111.638	11/30/2007 13:10	4.945
49125	34.249	-111.679	11/30/2007 13:15	4.923

Table 6. Top ten 12-hour rainfall intensities.

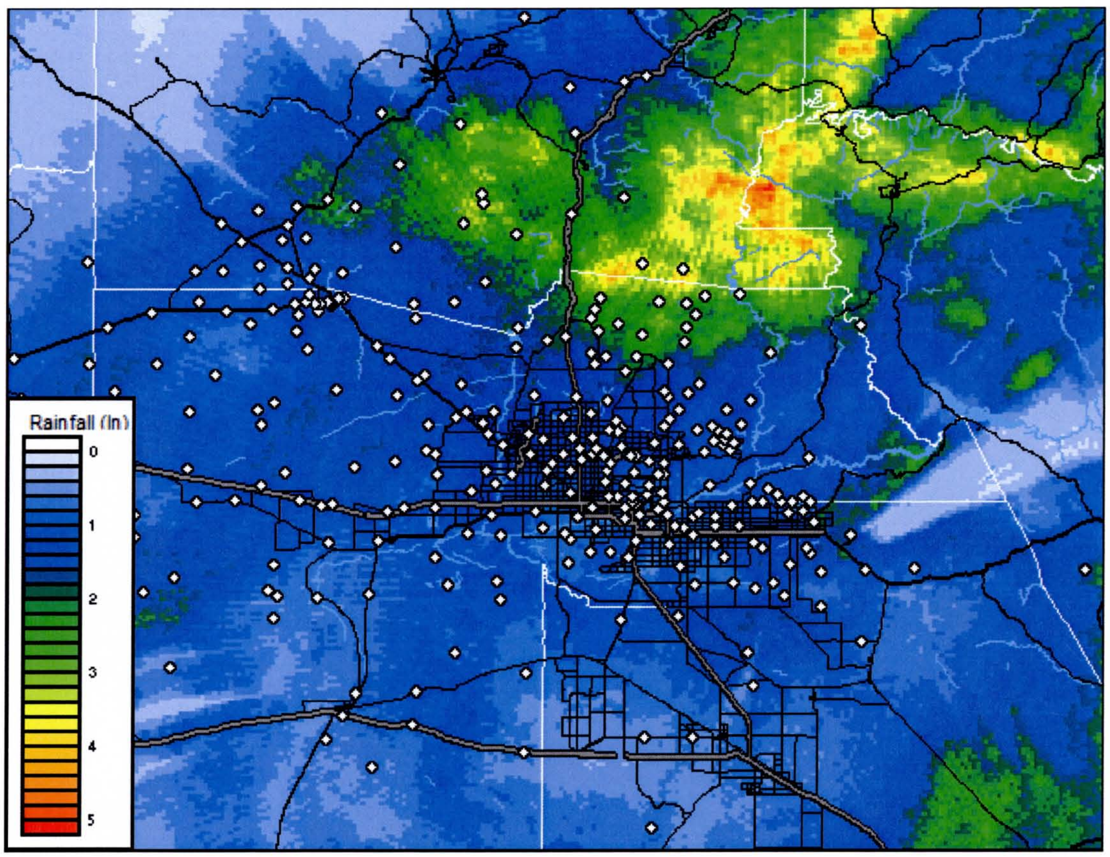

Figure 8. Top ten 12-hour rainfall intensities.

Pixel	Latitude	Longitude	Start Time	Rainfall (in.)
42461	34.025	-111.825	11/30/2007 13:50	7.514
42195	34.016	-111.825	11/30/2007 13:45	7.455
41928	34.007	-111.835	11/30/2007 13:30	7.440
41929	34.007	-111.825	11/30/2007 13:30	7.302
42727	34.034	-111.825	11/30/2007 13:50	7.194
42194	34.016	-111.835	11/30/2007 13:45	7.182
49130	34.249	-111.628	11/30/2007 13:15	7.057
48597	34.232	-111.638	11/30/2007 13:10	7.053
49129	34.249	-111.638	11/30/2007 13:15	7.005
49395	34.258	-111.638	11/30/2007 13:10	6.988

Table 7. Top ten 24-hour rainfall intensities.

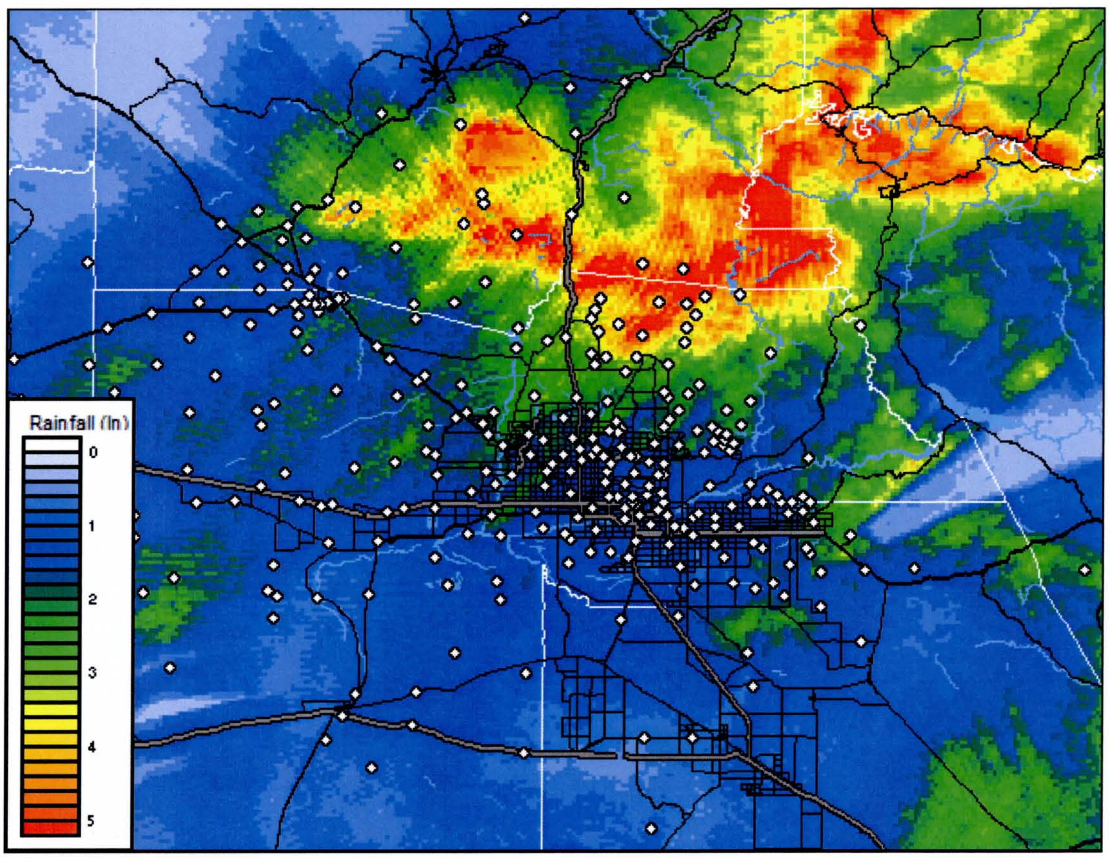

Figure 9. Top ten 24-hour rainfall intensities.

Figure 10, below, shows the result of the gage-adjusted radar rainfall adjustment procedure. A G/R ratio was determined for each pixel and for each storm period before being multiplied by all of the raw radar rainfall estimates during those time steps.

The result is a gage-adjusted radar rainfall dataset that matches the volume and timing of the rain gage network, but includes the spatial information from the radar.

The Gages line shows the average accumulated rainfall for the gages with valid rainfall data and the Radar line shows the average accumulated rainfall from the radar pixels over the valid rain gages. The AdjRadar line shows the average gage-adjusted radar rainfall estimates for the pixels at the rain gages.

In this figure, the AdjRadar line nearly matches the Gages line, indicating a good match between the rain gage and the gage-adjusted radar rainfall datasets. Overall, the gage-adjusted radar rainfall estimates were approximately 35% lower than the unadjusted radar estimates.

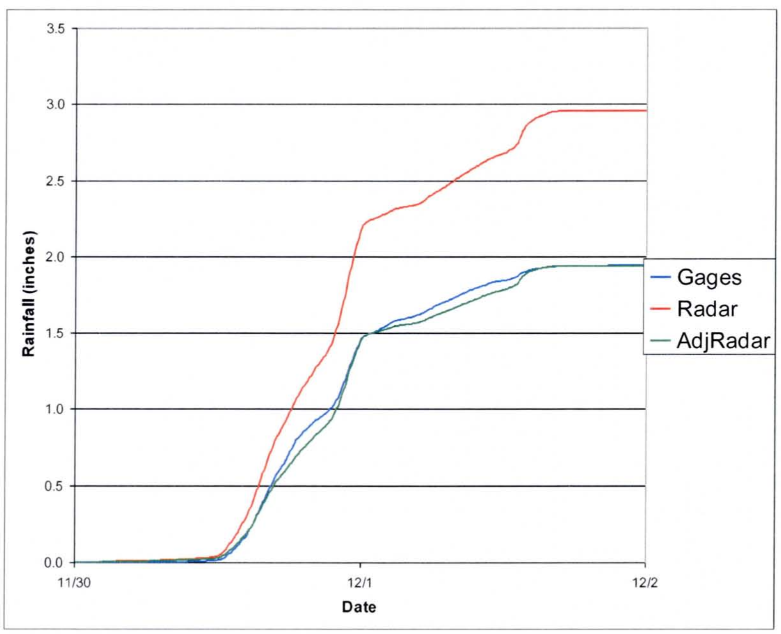

Figure 10. Average Gage, Radar, and Gage-Adjusted Radar Rainfall accumulation plot for November 30 - December 1, 2007.

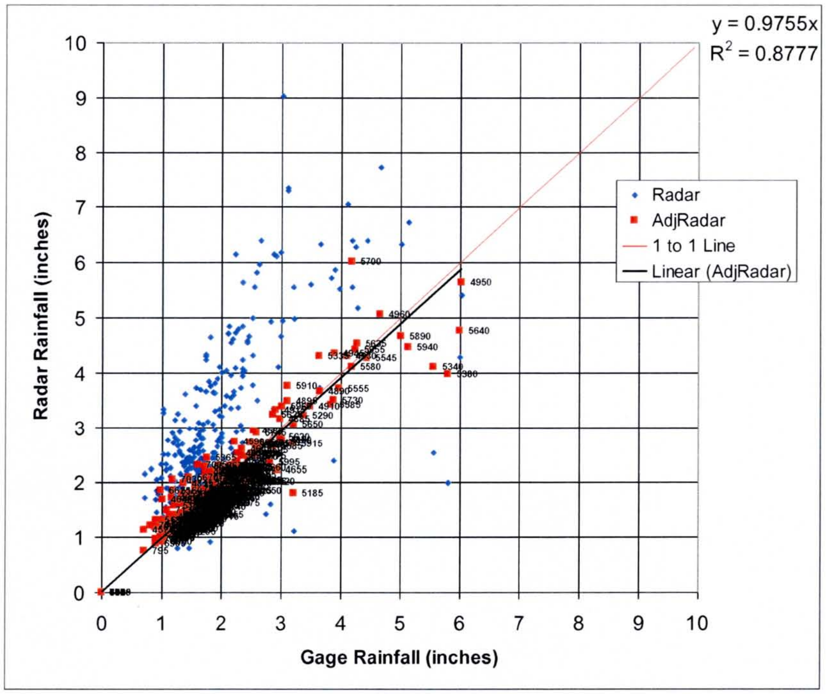

Figure 11. Scatter-plot of Radar and Gage-Adjusted Radar Rainfall totals versus Gage Rainfall for each gage for November 30 - December 1, 2007.

Figure 11, above, shows the scatter-plot of total rainfall measured at the gages compared to the radar and adjusted radar rainfall estimates at the pixels over the rain gages for November 30 to December 1, 2007.

If the gage and gage-adjusted radar rainfall estimates were identical, all points would lie on the 45-degree best fit line. However, due to scaling issues, measuring errors, natural variability, and other uncertainties, these values will not always match. Nevertheless, the gage-adjusted radar rainfall data are expected to cluster around the 45-degree line.

Conclusions

OneRain's gage-radar adjustment procedure was able to successfully merge the data from the rain gage network and the radar rainfall data. There was minimal filtering required, and good correlation was found between the available rain gages and the filtered radar, as well as the accumulations with the adjusted radar product. The timing of the two measurement systems also showed a high degree of correlation.

The result is a gage-adjusted radar rainfall dataset with 783 individual rainfall estimates (one at each radar pixel) over the Maricopa County study area for the November 30 to December 1, 2007, study period. The gage-adjusted radar rainfall estimates were approximately 35% lower than those provided by radar alone and matched well with the rain gage estimates.

Appendix B. Theoretical RF Paths (derived with Radio Mobile Software)

Introduction

Repeater site latitude-longitude values and elevations were obtained from the DIADvisor swatch2.mdb. Radio Mobile by VE2DBE software (http://www.cplus.org/rmw/english1.html) was used to compute theoretical path losses for each repeater-base station link. The purpose of this was to compare the theoretical path strengths with actual observed repeater performance, thus being able to identify problems and potential improvements.

The following Figures 1-8 show screen captures for each link in the analysis.

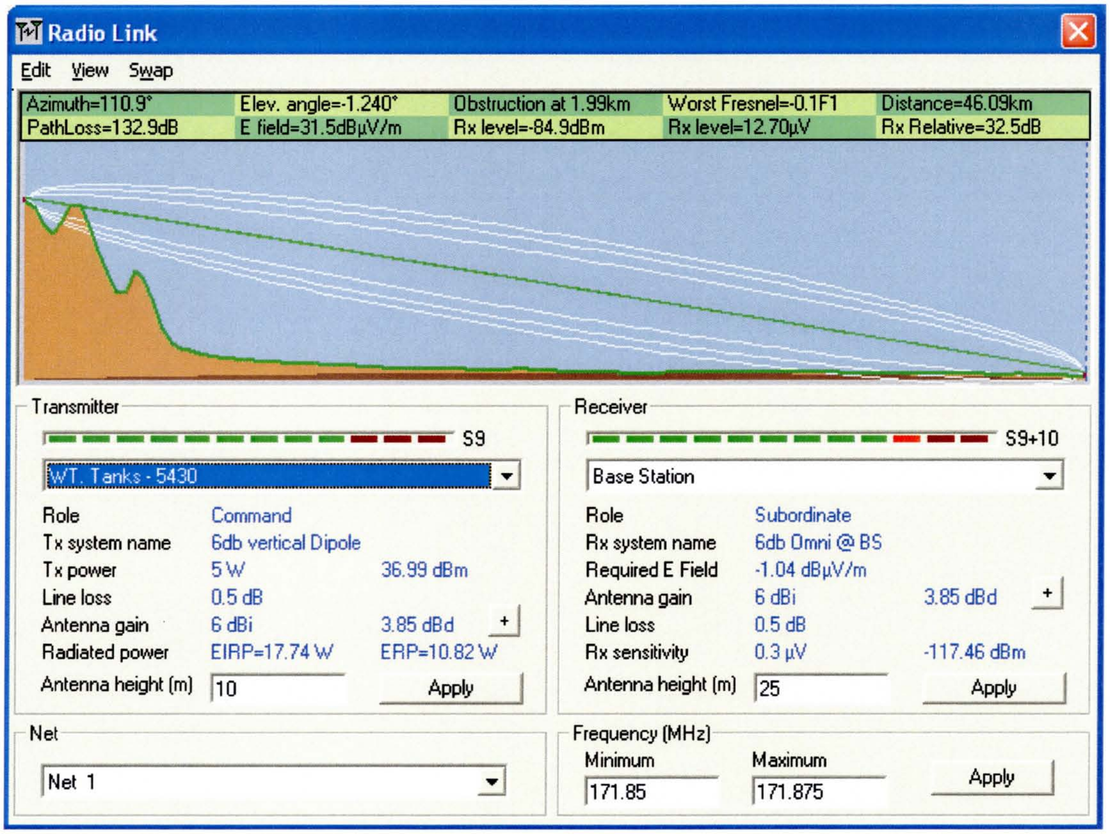

Figure 1. White Tank Peaks to District base path analysis.

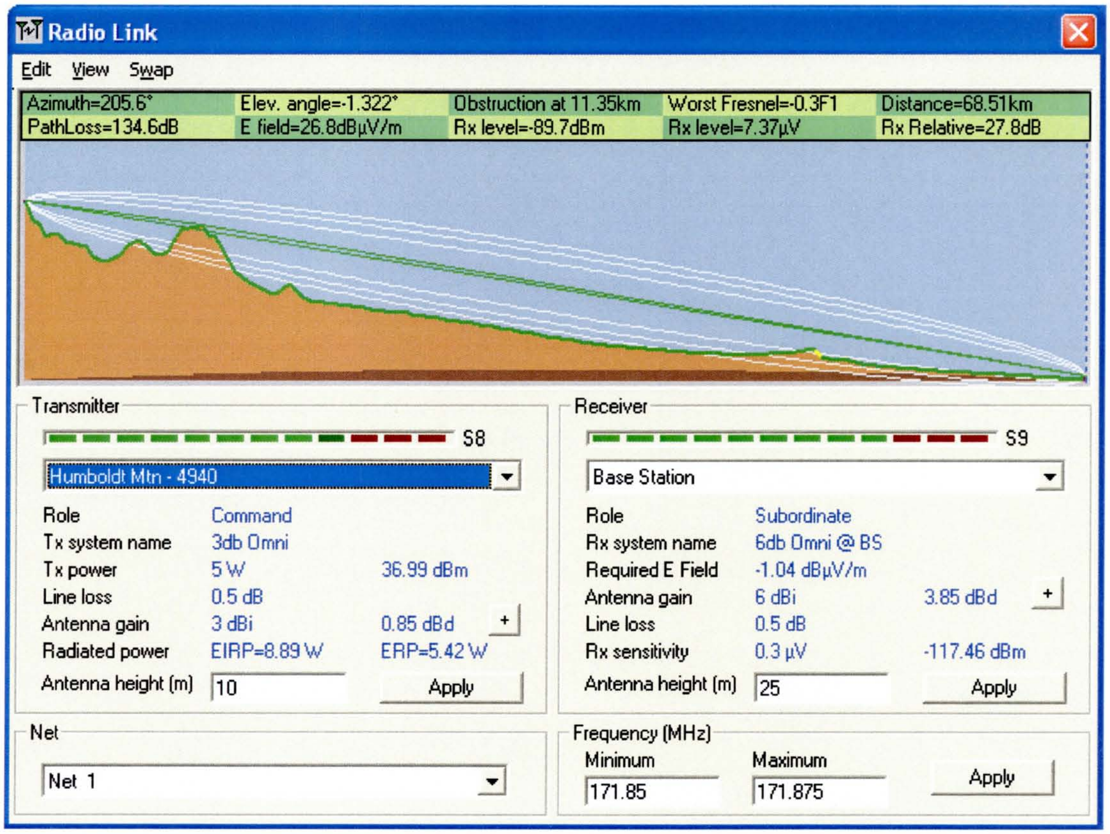

Figure 2. Humboldt Mountain to District base path analysis.

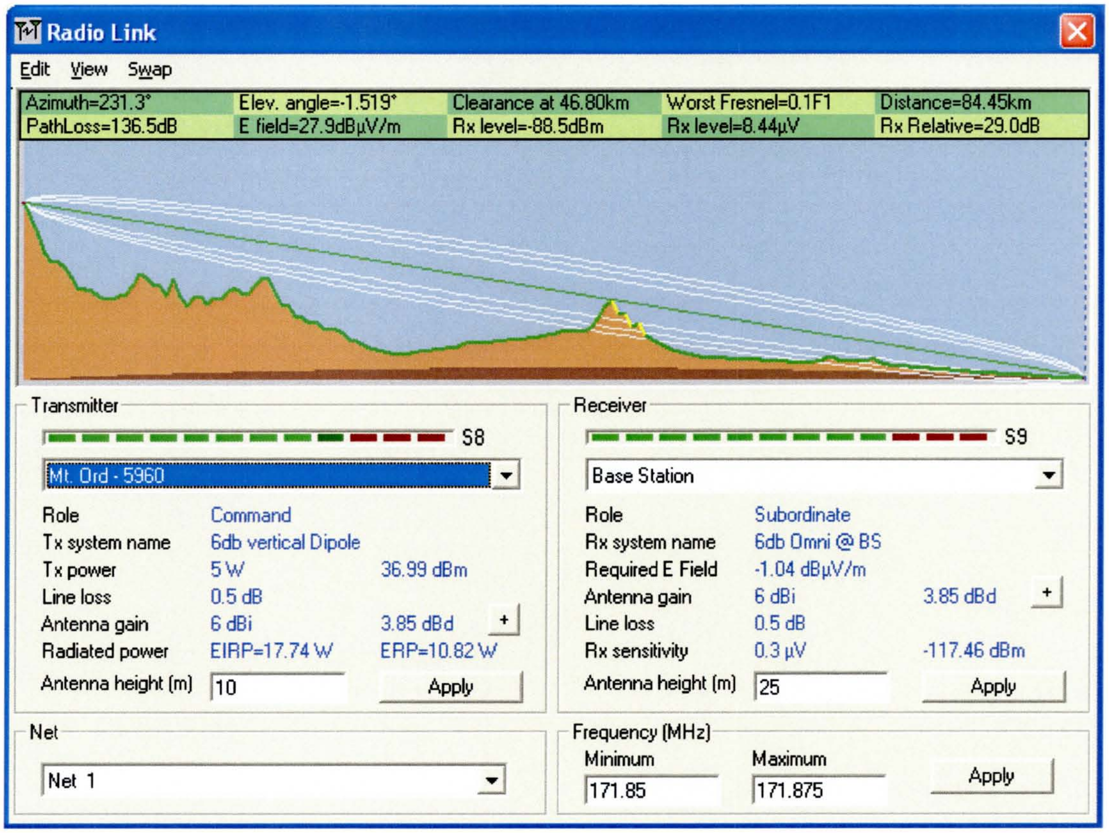

Figure 3. Mt. Ord to District base path analysis.

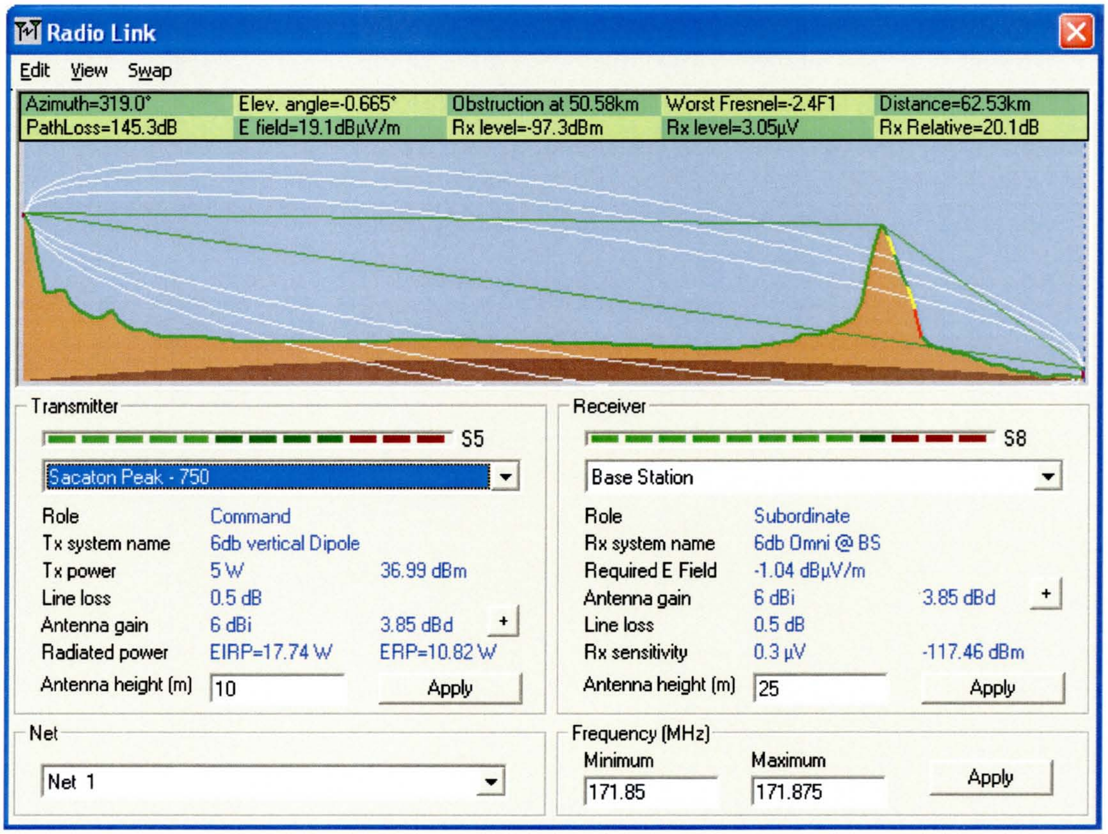

Figure 4. Sacaton Peak to District base path analysis.

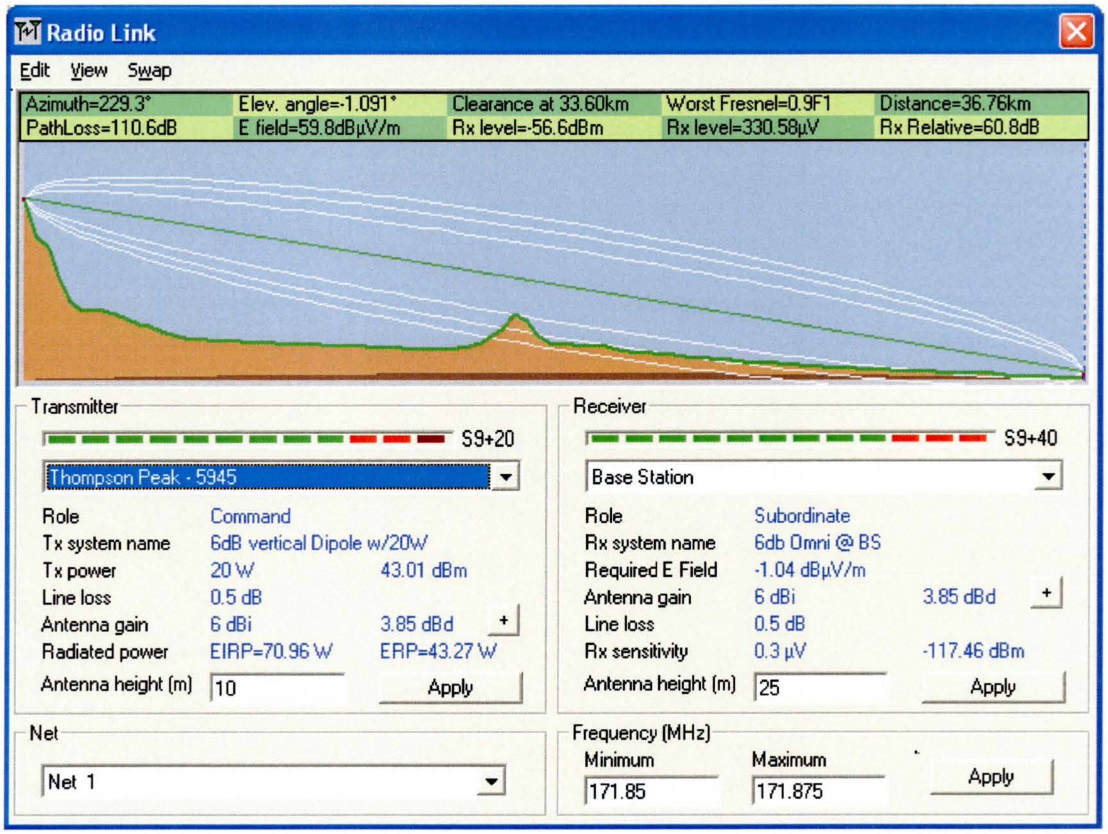

Figure 5. Thompson Peak to District base path analysis.

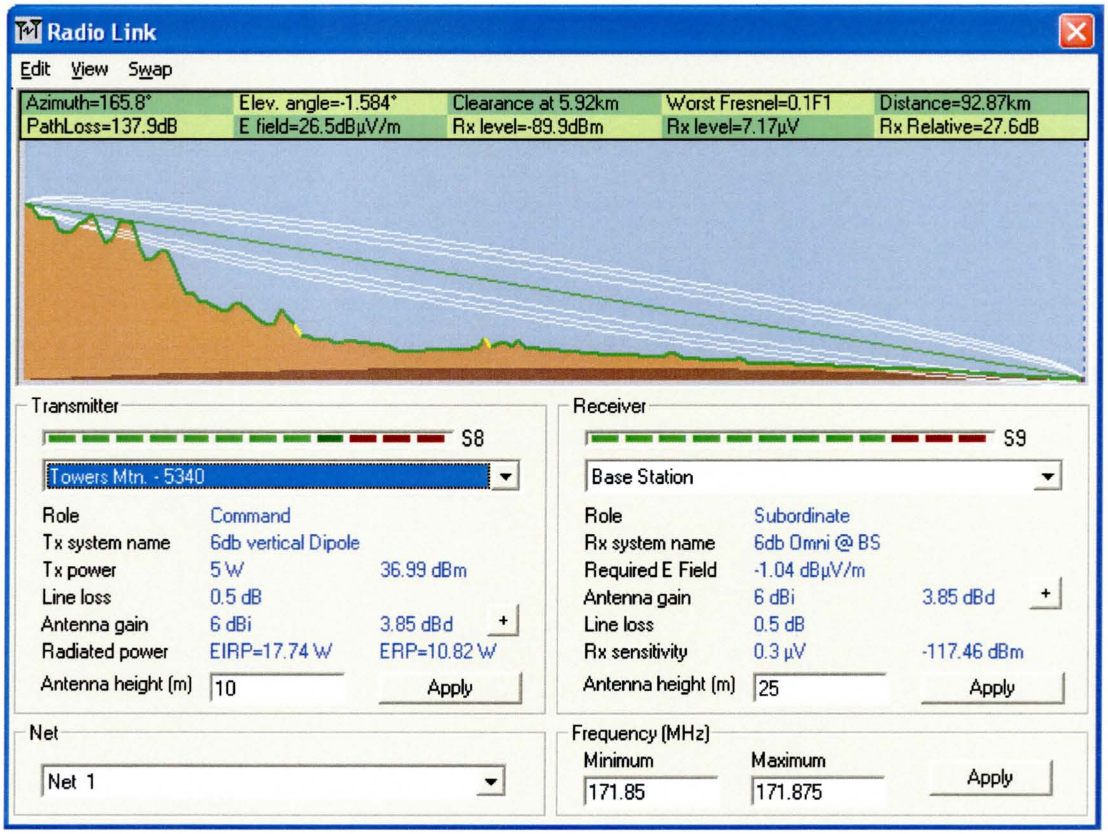

Figure 6. Towers Mountain to District base path analysis.

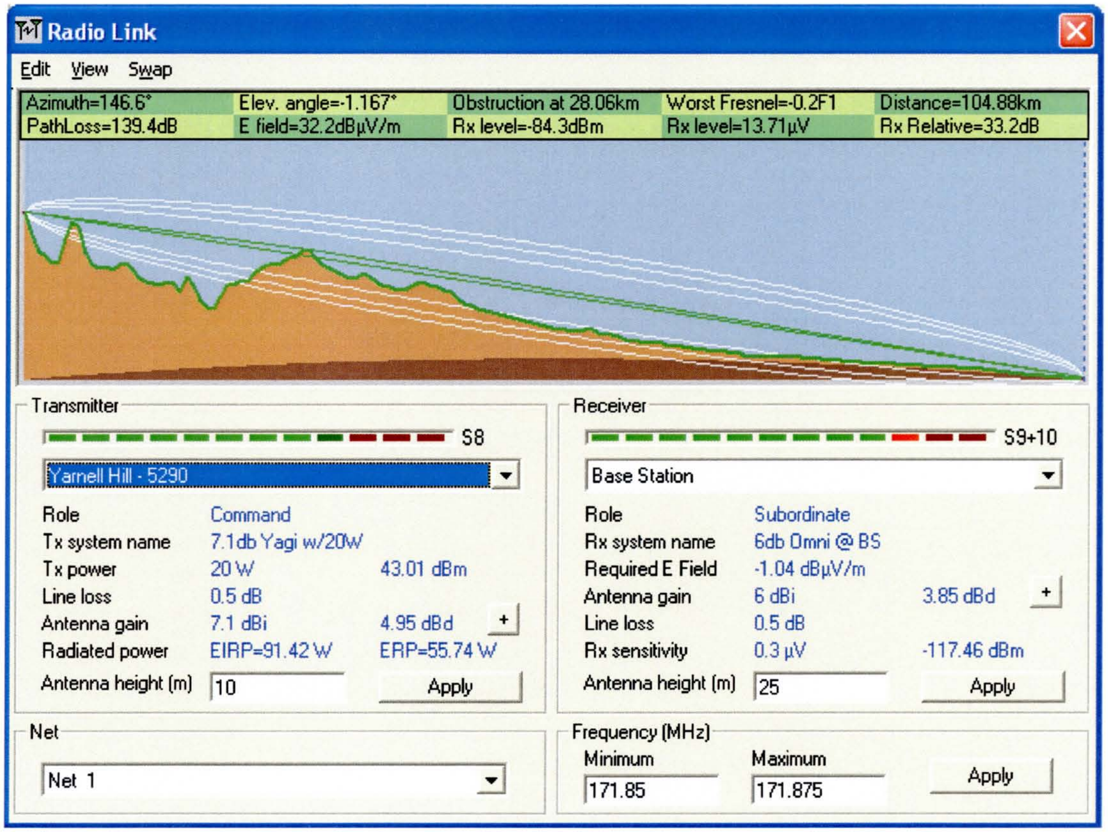

Figure 7. Yarnell Hill to District base path analysis.

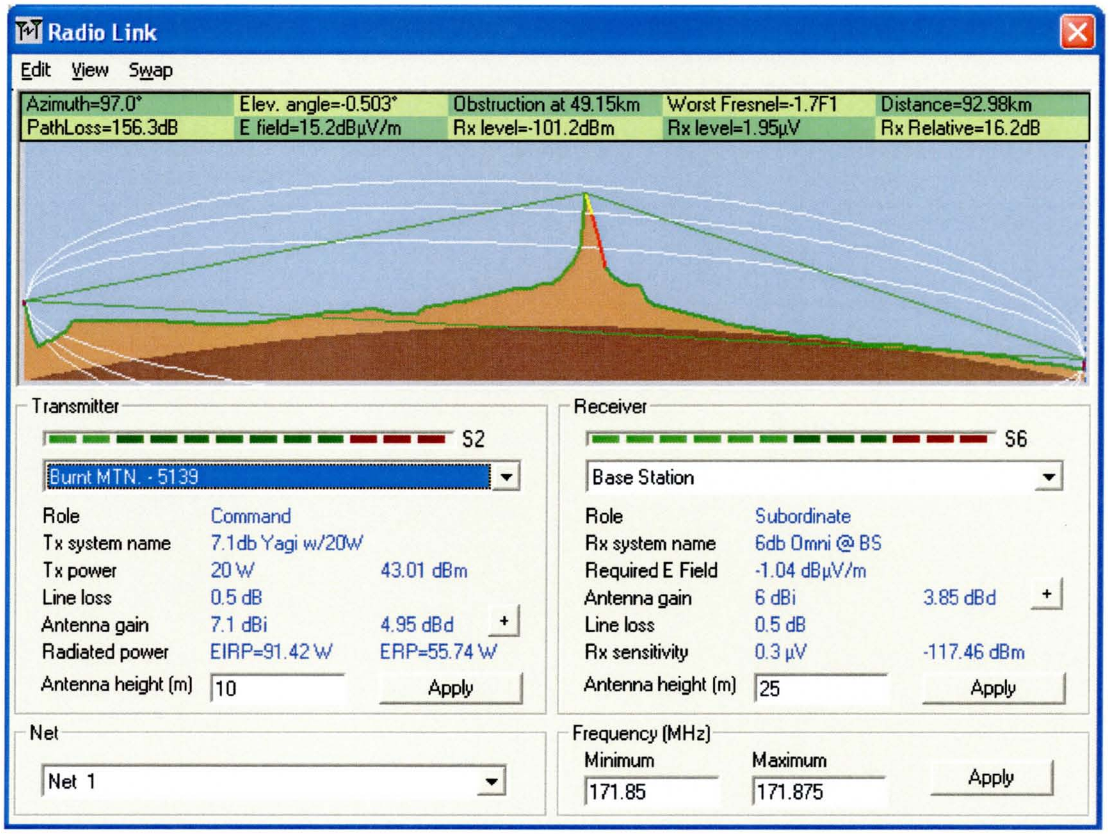

Figure 8. Burnt Mountain to District base path analysis.