2010 Southwest Colorado Radar Project

Final Report
December 2010

Prepared For

Colorado Division of Emergency Management
Colorado Water Conservation Board
Southwestern Water Conservation District

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NOAA national severe storms laboratory

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Executive summary

Accurate observations of rainfall have many applications. Extreme rainfall causes damaging flash floods and debris flows. Even weak storms can impact search and rescue operations. The primary sources of quantitative precipitation estimates (QPE) are weather radars and precipitation gauges. Yet in the complex terrain of the Rocky Mountains, observations from these sensors have great uncertainty due to large gaps in radar coverage and sparse gauge networks. To better understand these uncertainties, the Colorado Water Conservation Board (CWCB) contracted with the NOAA/National Severe Storms Laboratory (NSSL) in 2009 to deploy a mobile Doppler radar near Gunnison, Colorado (Vasiloff 2009). The success of this project led to interest in using a mobile Doppler radar to monitor hazardous storms in southwestern Colorado. The target area was the infamous "black hole" in radar coverage over the Four Corners area with emphasis on the San Juan Mountains of southwestern CO during the month of August. A network of research tipping bucket rain gauges and other instruments were installed by the National Center for Atmospheric Research (NCAR) and the University of Colorado Department of Atmospheric Sciences to provide independent rainfall observations for comparison with the radar data.

A key component of the project was to assess the benefits of supplemental radar data for National Weather Service (NWS) warnings and the operations of other clients such as county search and rescue. Radar data were transmitted in near real-time to the NWS Weather Forecast Office (WFO) at Grand Junction (GJT) after being blended with other regional radars using NSSL's National Mosaic and QPE (NMQ) system. Raw base data were also displayed on web pages used by the counties, Durango - La Plata County airport and the WFO in Albuquerque, NM.

A strong Monsoon season afforded many days of data collection and remarkable insight into local storms that were under-represented by the NWS operational radars. Testimonials from various data users indicate that the additional radar data were useful even during weak storm events.

Potential solutions for a permanent Four Corners radar are discussed. Options range from low-cost used radars to high-end WSR-88D systems. Costs will include site surveys, installation and operations and maintenance. The NOAA/NWS should be consulted to ensure seamless integration of new radar data with current services.

1. Project objectives

The goal of the project was to explore the use of a research mobile Doppler radar for observing hazardous storms that had the potential for producing flash floods and debris flows, and then providing enhanced warnings to the public and emergency managers. Specific objectives were to:

- Demonstrate the utility of a gap-filling radar in the complex terrain of SW CO
- Assess benefits of local radar data for flash flood warnings and debris flows
- Document the precipitation characteristics and frequency of hazardous storms
- Develop correction factors for the KGJX radar for improved operations in the absence of the mobile radar
- Provide an advanced assessment of dual-polarization capabilities
- Document the benefits of the research radar on socioeconomic activities in the region
- Build a scientific framework for improved precipitation monitoring of regional storms

2. Reporting

This final report is pursuant to requirements in the contract between the CWCB and NOAA Exhibit D “Southwest Colorado Mobile Radar Project.” This report provides an overview of data collection including daily data summaries. The Four Corners area is home to a wide variety of populations and activities ranging from recreation to oil and gas exploration. A section is included that describes impacts of the additional mobile radar data on the population and the operations of the NWS and other data users and stakeholders. A summary section describes overall results and conclusions as well as recommendations for additional efforts. The CWCB will use the report as a final deliverable to grants from the Colorado Division of Emergency Management and the Southwestern Water Conservation District. Radar data will be made available upon request.

3. Agency responsibilities

The Colorado Division of Emergency Management is responsible for the state's comprehensive emergency management program that supports local and state agencies. Activities and services cover the four phases of emergency management: *Preparedness*, *Prevention, Response*, and *Recovery* for disasters like flooding, tornadoes, wildfire, hazardous materials incidents, and acts of terrorism.

The Colorado Water Conservation Board was created in 1937 for the purpose of aiding in the protection and development of the waters of the state. The agency is responsible for water project planning and finance, stream and lake protection, flood hazard identification and mitigation, weather modification, river restoration, water conservation and drought planning, water information, and water supply protection.

The Southwestern Water Conservation District (SWCD) was created by the State of Colorado legislation through House Bill #795 which was approved by the General Assembly on April 16, 1941. The charter of the District is to protect, conserve, use and develop the water resources of the Southwestern basin for the welfare of the District, and to safeguard for Colorado all waters of the basin to which the state is entitled. It is one of four Conservation Districts in the state.

NOAA's National Severe Storms Laboratory (NSSL) serves the nation by working to improve the lead time and accuracy of severe weather warnings and forecasts in order to save lives and reduce property damage. NSSL scientists are committed to their mission to understand the causes of severe weather and explore new ways to use weather information to assist National Weather Service (NWS) forecasters and federal, university, and private sector partners.

4. Project partnerships

Efforts to mitigate weather hazards are most effective given a strong partnership among private, local, state and federal entities. This project is mentioned as a recommendation for improving emergency warning systems in the 2010 Flood Hazard Mitigation Plan for Colorado (CWCB 2010). The number one goal of the plan is to reduce flood impacts to Colorado's economy, people, state assets, and the environment. 29 counties mentioned that they want to develop early warning systems as part of their local mitigation strategy. Also in the plan, a HAZUS analysis shows that 19 state assets in Montezuma, La Plata and Archuleta Counties are at risk from a 100 year flood.

Many representatives from a wide variety of organizations contributed to the project. Feedback from partners and stakeholders on the impacts of supplemental radar data for local operations and activities is provided in Section 10. This information represents a small step in emerging socioeconomic research to prioritize research-to-operation activities for improvement of local services and hazard mitigation.

Leading the sponsorship efforts were Joe Busto (CWCB), Marilyn Gally (CDEM), Bruce Whitehead (SWCD) and Patricia Gavelda (CO Department of Local Affairs). The scientific team consisted of Mike Meyers, Jim Pringle, Doug Crowley (NOAA/National Weather Service in Grand Junction), Dave Gochis (National Center for Atmospheric Research), and Katja Friedrich (University of Colorado). Project partners include Butch Knowlton and Tom McNamara (La Plata County Emergency Management), Kristina Maxfield (San Juan County Emergency Management), Drew Peterson (Archuleta County Emergency Management), Don Brockus (Durango - La Plata County Airport), Steve Whitehead (Southern Ute Indian Tribe), Cindy Hockelburg (U.S. Forest Service), and Terry Richardson (Ft. Lewis College).

5. Project domain and instrumentation

While the primary area of interest was the San Juan Mountains, maximum coverage of the Four Corners region was desired (Fig. 1). This region is a complex blend of various socioeconomic and environmental resource activities that are subject to potential weather hazards. For instance, there are several Native American Indian tribes, the San Juan Mountains, and the famous Four Corners area. Major economic engines include recreation and tourism along with oil and gas extraction. Rivers that flow out of the San Juan Mountains supply a significant amount of water to the Colorado River (Fig. 2). The Durango – La Plata County airport is a significant regional hub and access point for the region. Durango is also home to Ft. Lewis College. Further discussion of socio-economic impacts due to weather is provided in section 10.

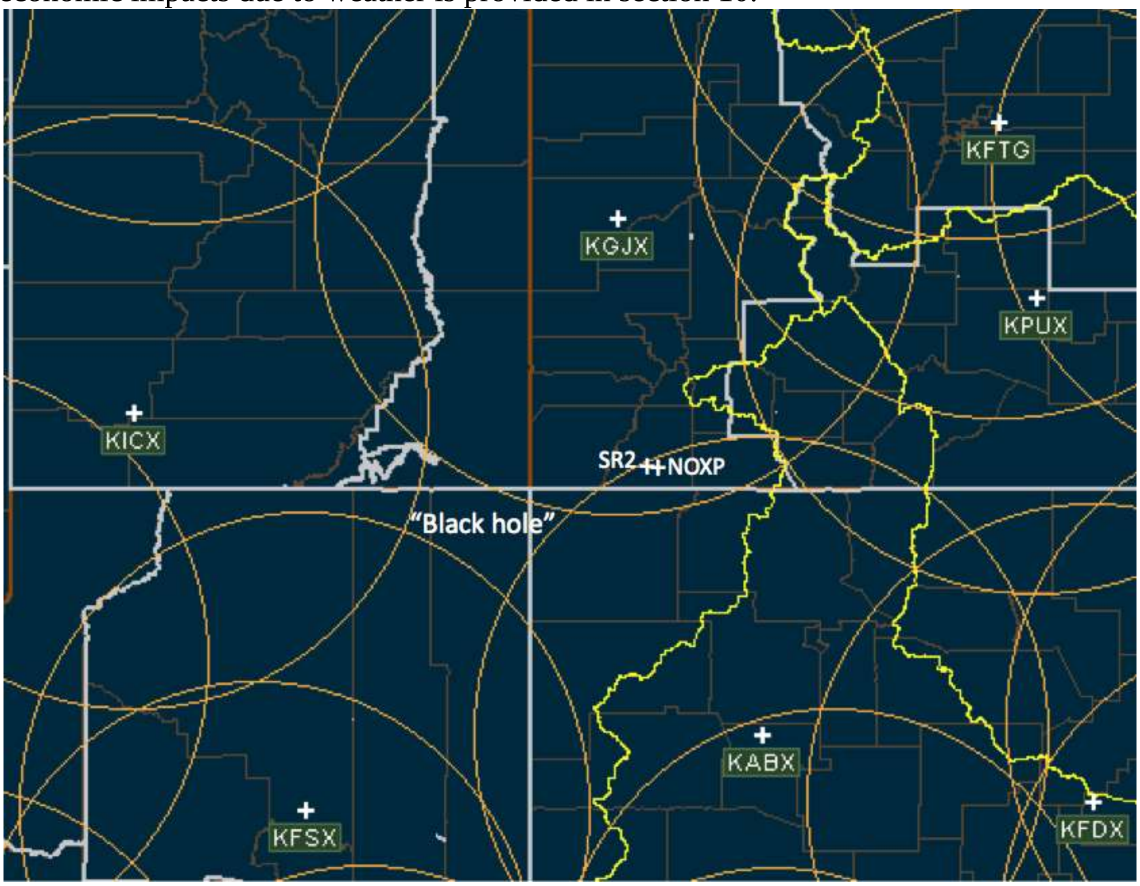

Figure 1. Project domain with regional WSR-88D radars and mobile radars indicated. Range rings are 250 km. NWS County Warning Areas are outlined in white and River Forecast Center areas of responsibility in yellow.

5a. Mobile Doppler radars

Two mobile radars were deployed at different times during the project. The initial radar was a Shared Mobile Atmospheric Research and Teaching Radar (SMART-R or SR2 (Biggerstaff et al. 2005) that had been recently upgraded to dual-polarization (DP) (http://www.nssl.noaa.gov/smartradars/). The SR2 was operated on Bridge Timber Mountain (BTM) through a special scientific data collection permit issued by the Southern Ute Indian Tribe. During the project the SR2 computer failed and the NSSL X-band Polarized (NOXP) radar was used for the remainder of the project at the Durango – La Plata County Airport. Comparative characteristics of the SR2, NOXP, and Weather Surveillance Radar – 1988 Doppler (WSR-88D) systems are provided in table 1. All three radars have different beam characteristics that are governed by the antenna size, frequency, and transmitter power. The WSR-88D is the largest and most powerful (and most expensive) of the three. Higher frequency results in greater attenuation caused by heavy rain and hail. The X-band has the highest frequency and more signal attenuation. The various attributes of radar systems dictate applications with smaller, less expensive systems more suitable to local solutions (McLaughlin et al. 2010). Results of this project highlight these contrasting considerations.

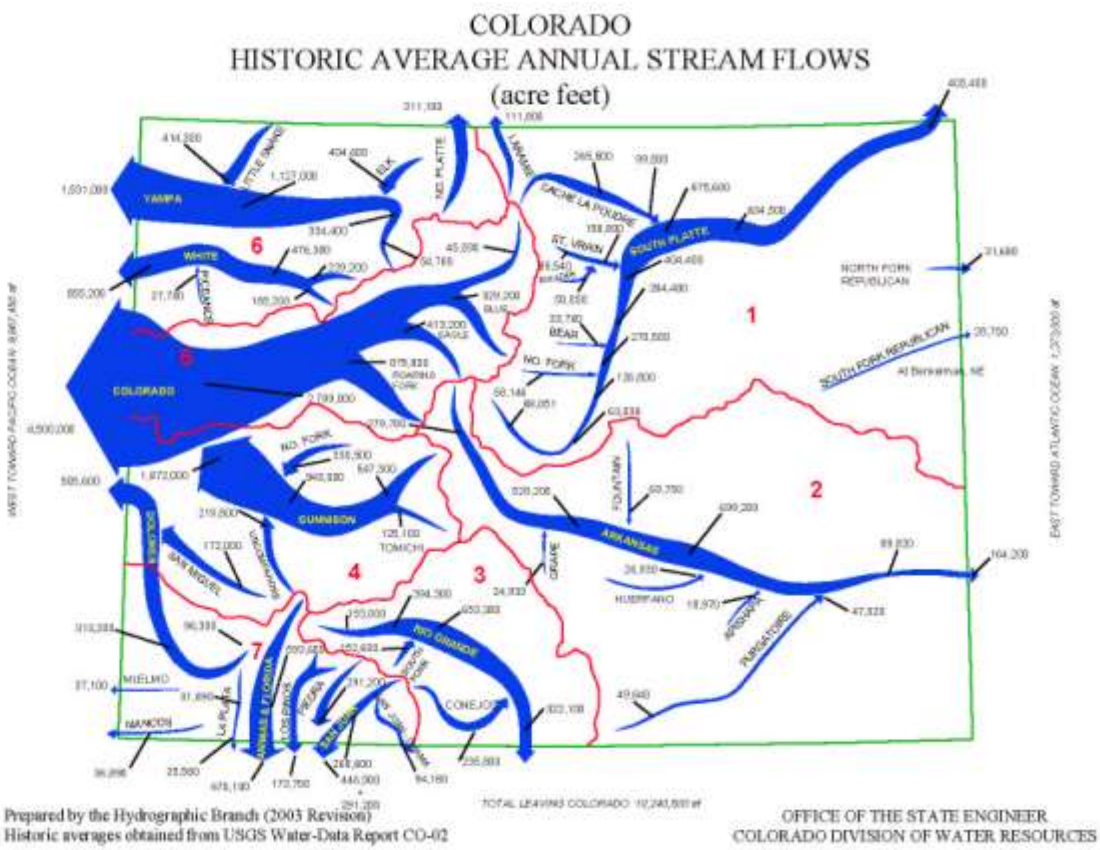

Figure 2. Historic annual stream flow for Colorado rivers.

The DP radars send radar signals in horizontal and vertical planes (http://www.roc.noaa.gov/WSR88D/DualPol/Default.aspx). Differences between the two signals are converted into the variables K_{dp} and Z_{dr}. These variables are in turn used to identify various precipitation particle types and can be used to distinguish between precipitation and ground clutter. DP variables can also be used to correct for attenuation to mitigate the shortcomings of radars with higher frequencies (Snyder et al. 2010). Finally, DP variables can be used to provide alternate methods for determining Quantitative Precipitation Estimation (QPE; see section 6b).

5b. Rain gauge network, disdrometers, and micro-radar

Seventeen portable recording tipping bucket (TB) rain gauges were deployed along drainages of the San Juan Mountains (Fig. 3). Please see appendix 1 for details of the network and data overviews. Access to U.S. Forest Service land was granted through a special land use permit. The rain gauges were provided in-kind by the National Center for Atmospheric Research (NCAR) with travel support provided by Project funds. The NCAR gauge measurements were complemented by existing hourly remote automated weather stations, (RAWS), NWS Hydrometeorological Analysis and Data System (HADS), Automated Surface Observing System (ASOS) gauge observations and 24 h totals from Community Collaborative Rain, Hail and Snow (CoCoRaHS) gauges. In addition to the gauges, two optical disdrometers and a vertically-pointing Doppler radar were provided by the University of Colorado Department of Atmospheric and Oceanic Sciences and deployed on a rooftop at Ft. Lewis College. Optical disdrometers measure raindrop distributions and can be used with gauges to calibrate radar measurements. A vertically-pointing radar provides high-resolution details of vertical storm structure at a point.

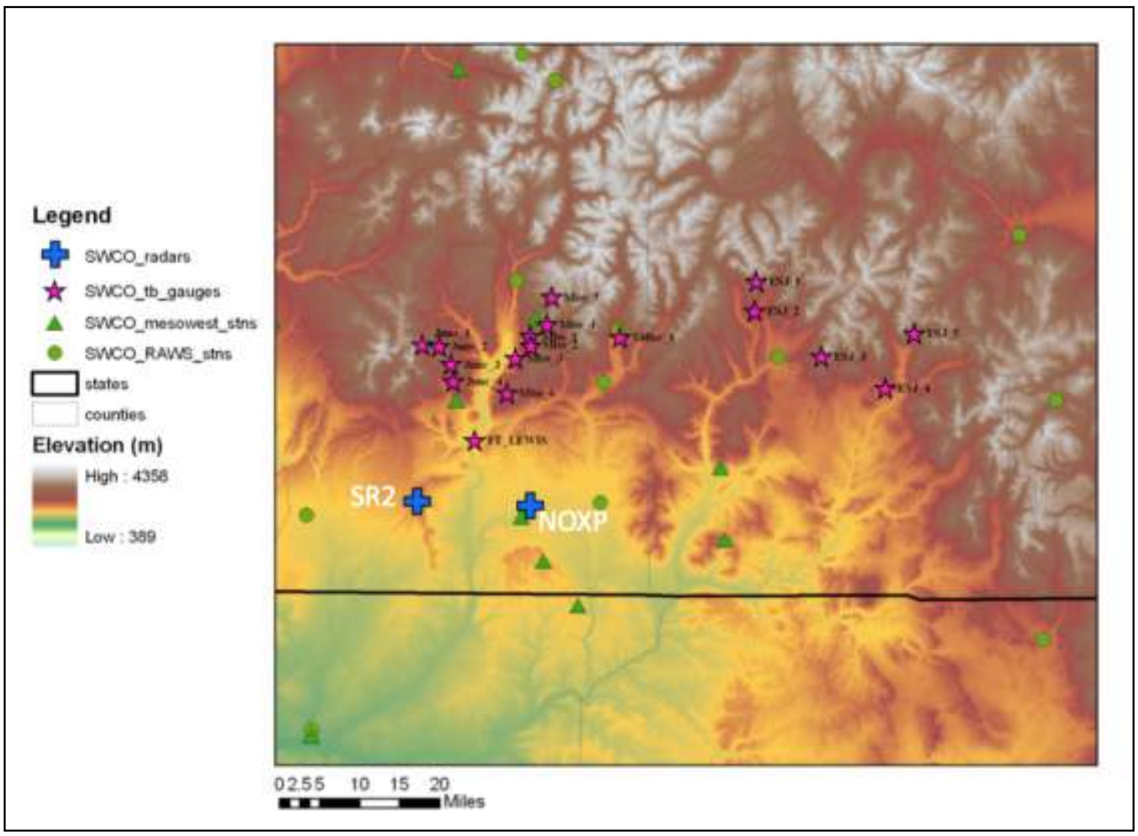

Figure 3. Locations of research tipping bucket rain gauges indicated by purple stars. Permanent gauges are indicated by green symbols. Mobile radar locations are indicated by blue + signs. Note that Ft. Lewis is in Durango. SR2 is on Bridge Timber Mountain and NOXP is at the Durango – La Plata County Airport. Terrain elevation is color coded with higher terrain in white.

6. Weather radar background

Radar-based QPE has been used for decades to estimate rainfall but has a number of uncertainties (Krajewski et al. 2010). Two key aspects of radar uncertainties are described in this section.

6a. Radar uncertainties due to range and terrain effects

This section describes basic radar principles and challenges in the Four Corners region. Many web sites provide educational material on radar principles including http://www.scribd.com/doc/28812730/Weather-Radar-Meteorology. The NEXt generation RADar (NEXRAD) program was a major step forward for storm detection in the U.S. with the installation of 158 Weather Surveillance Radar – 1988 Doppler (WSR-88D) radars. Primary considerations for radar site locations were flash floods and tornadoes in populated areas (Leone et al. 1989). As a result WSR-88Ds are more densely situated east of the Rockies. In the western U.S., the combination of widespread placement of radars, with some on mountaintops, and beam blockage severely limits the effective radar coverage. Maddox et al. 2002 and others have described significant gaps in low-altitude radar coverage with little coverage within 1 km above ground level (AGL) (Fig. 4).

There is a strong relationship between storm type and radar coverage. Confidence in radar data and specifically QPE depends on many factors including range from the radar and radar beam blockage. Tall storms are more likely to be seen by distant radars. Shallow winter storms are more likely to experience beam overshooting. Figure 5 shows the radar beam geometry associated with the 0.5 deg elevation angle from volume coverage pattern 12 (VCP-12), typically used by the NWS for rainfall monitoring. A VCP is a sequence of radar sweeps at successively increasing elevation angles. Note that the radar beam height above the ground and the beam width increase with range.

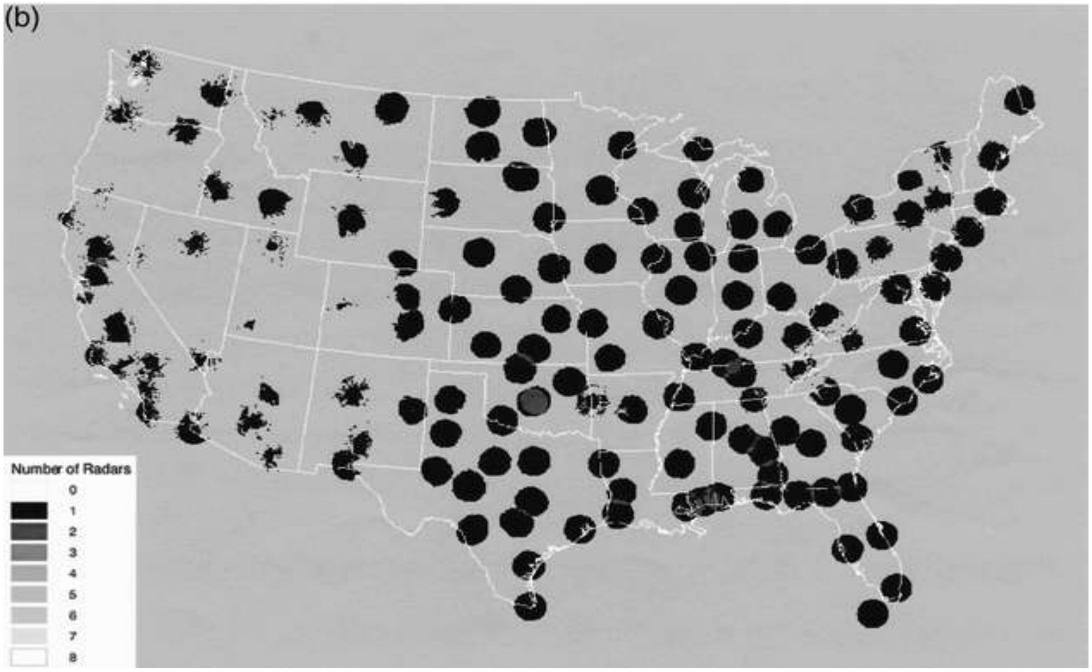

Figure 4. WSR-88D coverage below 1 km above ground level. From Maddox et al. 2002.

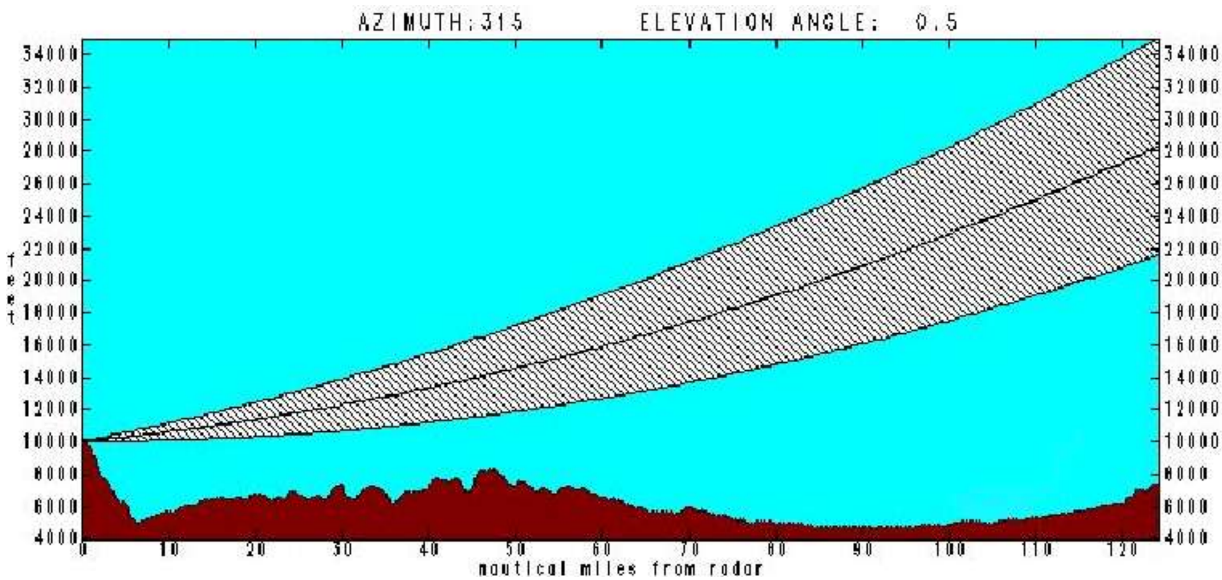

Figure 5. Schematic diagram of the 0.5 deg radar beam over complex terrain.

In the absence of terrain features, at 60 km range the 0.5 deg beam height is 500 m and the width is 1 km. At 120 km range the height and width are doubled. However, as seen in the figure, the height of the beam depends on terrain height. Wood et al. (2003) discusses the potential for improved coverage for mountaintop radars by lowering the minimum elevation angle from 0.5 deg to < 0.0 deg. Indeed, this strategy was employed when the SR2 was on BTM.

In the event of beam blockage, higher elevation angles are used to create a hybrid scan composed of different elevation angles as illustrated in figure 6. Langston and Zhang (2004) describe the automated algorithm used to create hybrid scans. In the figure, the green "bins" from the different angles/tilts are superimposed to create a single hybrid scan from which QPE is derived. Although the figure is a schematic, it is very similar to the physical situation along the south-facing slopes of the San Juan Mountains.

An image of hybrid scan beam heights for the WSR-88D network in the Four Corners is shown in figure 7. Light blue areas depict good coverage where the radar beam is closest to the ground and yellow-red areas depict poor coverage. Coverage above 3 km is quite extensive in the region. The junction of 250 km range rings shows that the red area corresponds to the so-called "black hole" area where there is actually no data from the WSR-88D system due to a 230 km range limitation for QPE. While the NWS radars are limited to 230 km range for precipitation algorithm processing, the NMQ system uses the full 460 km range. Even though the "black hole" is filled in by NMQ, extreme beam heights greatly reduce confidence in the data.

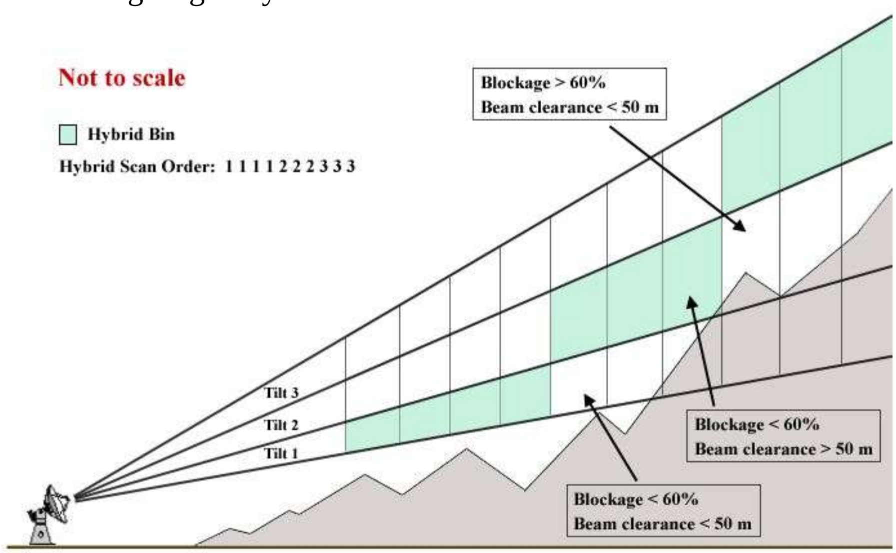

Figure 6. Schematic diagram showing how a hybrid scan is created from different elevation angles. Rules for deciding which bins to use are indicated.

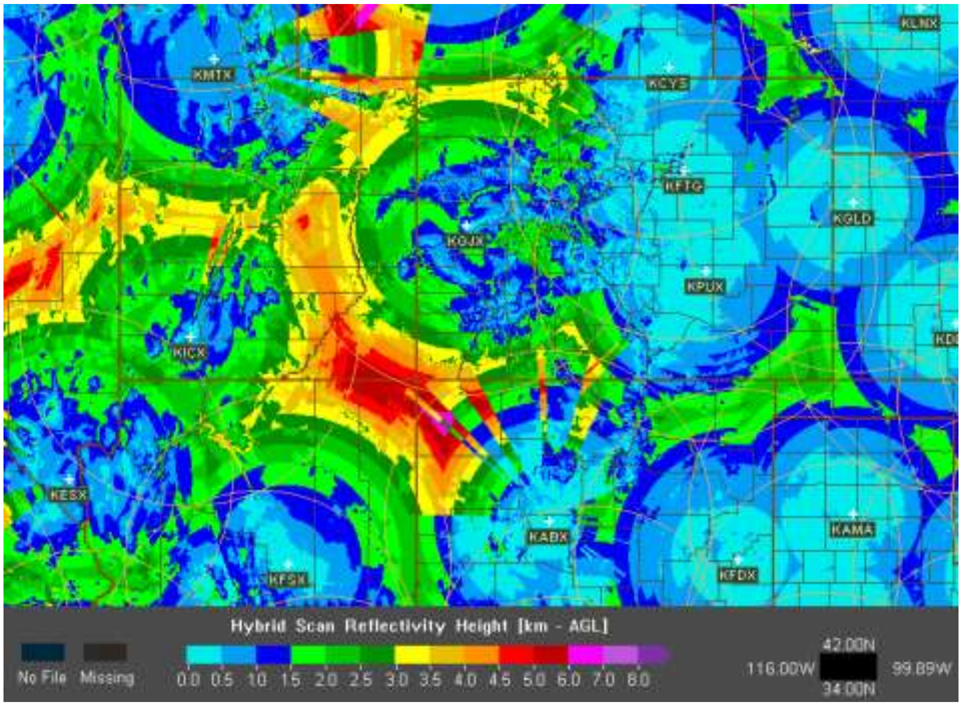

Figure 7. WSR-88D beam heights in km above ground level. Light blue indicates the best coverage.

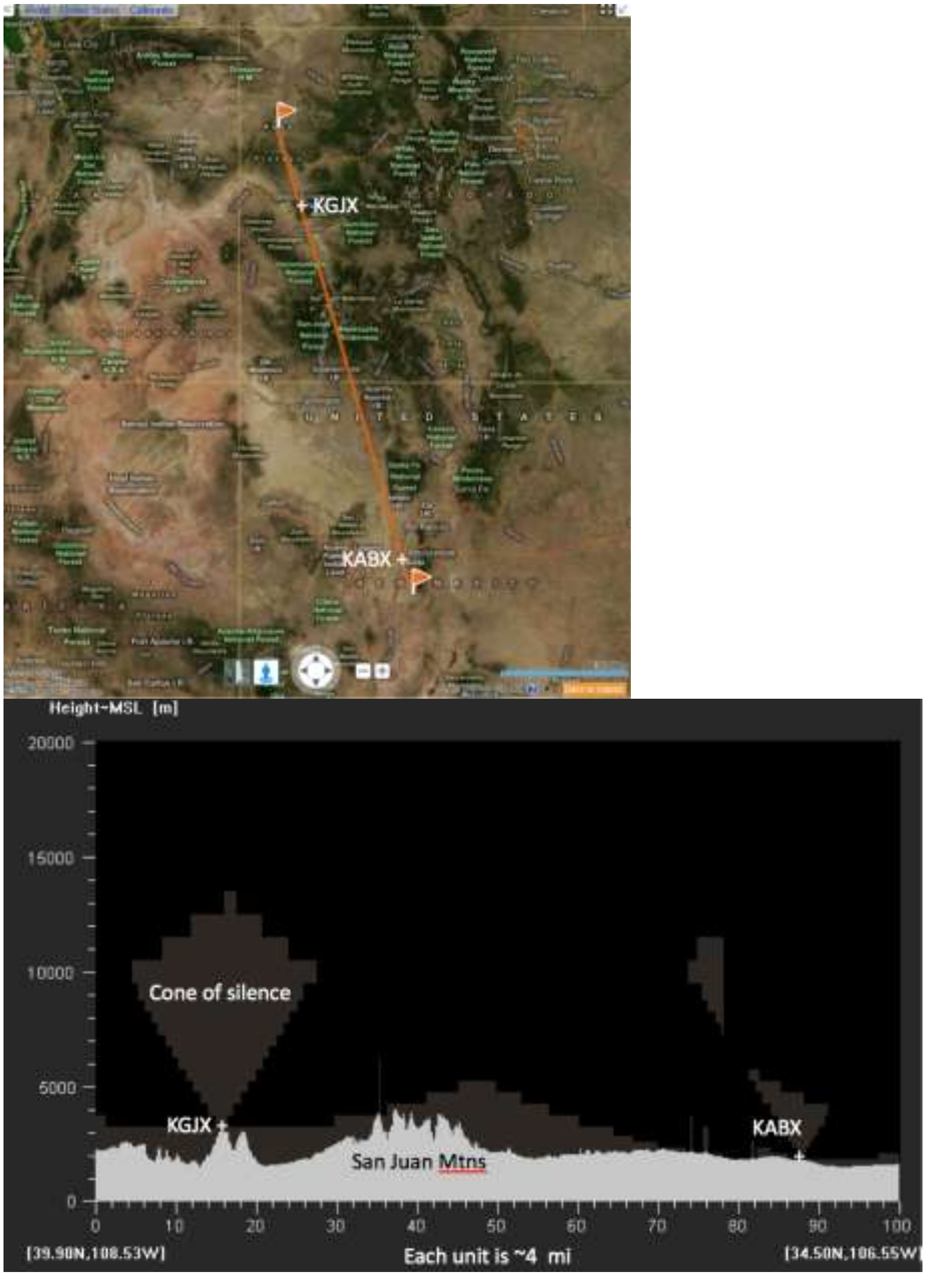

Figure 8. Top panel shows the location of the vertical cross section between KGJX and KABQ shown in lower panel. Grey shading above the white terrain indicates no coverage.

The vertical radar coverage along a line between KGJX and KABX is shown in figure 8. Each unit along the x-axis is 6.2 km (~4 mi). The cross section line begins NNW of KGJX, crosses the San Juan Mountains and central La Plata County, and ends SSE of KABX. The "cones of silence" (COS) at KGJX and KABX are due to the upper elevation angle limits. Note that a neighboring radar partially fills in the COS at KABX. The effects of blockages are evident over intervening terrain features. Moving south from KGJX, the coverage heights are low over Mt. Sneffels at 14,151 ft MSL in the northern San Juan Mountains, increase rapidly south of the San Juan Mountains and meet the KABX beam over southern La Plata County at a height of ~3.5 km AGL. Since these heights are closest to the ground on a direct line between the radars, coverage heights increase away from the axis.

6b. Rainfall estimation

Doppler weather radar data are typically described in terms of the amount of power (Z_h) reflected from cloud and precipitation particles. The relation between reflectivity and rain rate is given by the equation $Z=aR^b$. Reflectivity is expressed in terms of dBZ for scaling and display considerations; R is defined in unit of mm h^{-1}. Light rain typically has reflectivity ~15-25 dBZ with hail usually 55 dBZ or greater. Table 2 provides a range of dBZ and corresponding R values using standard NWS Z-R relations $Z_h=300R^{1.4}$ for convective storms and $Z=200R^{1.6}$ for non-convective warm season storms. For example, using this table a 50 dBZ radar echo equates to a rain rate of either 63.4 or 48.6 mm h^{-1}. Note the rapid increases in rainfall rates at reflectivity > 45 dBZ. Many studies have shown that Z-R relationships need to be tuned according to local conditions and that rain gauge data are crucial for this task (e.g., Morin et al. 2003 and Morin et al. 2005).

As previously mentioned, DP variables are expected to produce more accurate QPE (e.g., Ryzhkov 2005). As part of this project, several DP rainfall rate estimators will be evaluated as discussed by Bringi and Chandrasekar (2001) for C-band radar and will follow the approach of Silvestro et al. (2009) for combining the various relationships based on thresholds. The estimation of rainfall rate (R), using the DP radar parameters, Z_h (the horizontal channel reflectivity after attenuation correction), Z_{dr} (differential reflectivity following attenuation correction) (= 10Log(Z_h/Z_v) where Z_v is the vertical channel reflectivity), and K_{dp} (specific differential phase) are given by:

$$R\left(K_{DP}, Z_{DR}\right) = 37.9 K_{DP}^{0.89} 10^{-0.072 Z_{DR}} \quad (1)$$

$$R\left(Z_h, Z_{DR}\right) = 0.0058 Z_h^{0.91} 10^{-0.209 Z_{DR}} \quad (2)$$

$$R\left(K_{DP}\right) = 31.4 K_{DP}^{0.70} \quad (3)$$

$$R\left(Z_h\right) = 0.017 Z_h^{0.714} \quad (4)$$

Note that equation 4 is the NWS convective Z-R relation ($Z_h=300R^{1.4}$) solved for R. The equations for X-band will differ slightly due to the different scattering properties of smaller particles sensed by X-band (Anagnostou et al. 2004; Matrosov et al. 2010). While it is expected that DP will provide more accurate QPE, validation against gauges and disdrometers is needed.

Figure 9. Photograph of the NOXP radar at the Durango – La Plata County Airport. View is looking toward the La Plata Mountains.

7. Mobile radar site selection

Prior to the deployment of the mobile radar, a survey of potential sites was conducted. With coverage over southwest Colorado the primary consideration, four candidate sites were selected for further analysis with details provided in appendix 2. High-resolution digital terrain maps were used to determine beam heights above the ground where the heights were dictated by the hybrid scan tilts. Results showed that the best coverage of the south-facing slopes of the San Juan Mountains was provided at the airport site. A photo of the NOXP radar at the airport is shown in figure 9. Compared to figure 7, figure 10 shows that beam heights using the airport site are reduced from over 3 km to under 500 m for nearly all of La Plata County and under 1 km in Archuleta County. However, the airport is nearly surrounded by low ridges requiring higher elevation angles to clear them, thereby reducing effective coverage at farther ranges. Figure 11 shows terrain features observed by the NOXP at different elevation angles. Blue, green and yellow radar echoes indicate light-to-moderate rain. Except for actual storms to the SW of the radar, the red features are all ground clutter. BTM to the west and Mesa Mountain to the south are clearly visible at the lowest tilts. Note that Mesa Mountain was a location considered in the site analysis. An elevation angle of 4.0 deg was required to clear the blockages except for a remaining hint of Mesa Mountain. Results of clutter filtering of the terrain features can be seen in figure 11b.

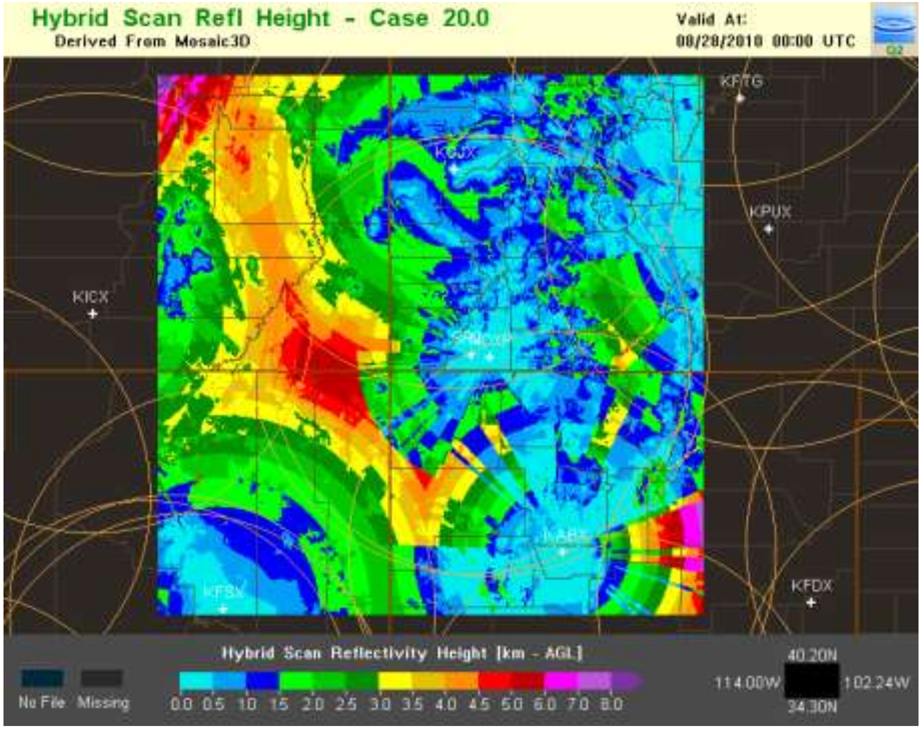

Figure 10. Radar beam heights in km above ground level as in figure 7 except with the NOXP coverage added. Light blue indicates the best coverage close to the ground.

The BTM site allowed vastly more coverage over the entire Four Corners region with minimal sacrifice in coverage over the San Juan Mountains. A photograph of SR2 on BTM is shown in Fig. 12. Figure 13 shows that, compared to the airport site, coverage was greatly improved over a substantial portion of the Four Corners region, effectively removing the infamous "black hole" and providing coverage below 500 m to a range of >200 km. The increase in coverage over that at the airport is roughly 16 times. Note that the higher beam heights to the north of the SR2 site are due to blockage by the La Plata Mountains.

8. Radar data processing and real-time display

A key project element required by the CDEM was to provide data electronically in near-real time to the NWS WFO GJT. Prior to the project the NWS Southern Region Headquarters (SRH) and Central Region Headquarters agreed to be a conduit for the ingest of NMQ data into NWS operational systems. In turn the WFO agreed to use the value added data to provide enhanced forecasts and warnings.

Mobile and regional radar data were processed with the NSSL NMQ system (http://nmq.ou.edu). NMQ provides high-resolution reflectivity and precipitation data to the Multiple-radar/Multiple-sensor (MRMS) system that was recently installed at the FAA Technical Center (see https://secure.nssl.noaa.gov/briefings/2010/11/nssl-team-completes-installation-of-weather-data-system-for-faa/). NMQ is also slated to become operational at the NWS National Centers for Environmental Prediction.

Details of the data structures and communications methods are provided in appendix 3. Briefly, SR2 data were transmitted via cell phone to a server at the NSSL. SR2 radar data were converted from polar coordinates to a 1 km x 1 km grid. A separate quality control algorithm was used to remove ground targets and other contaminates. The gridded SR2 data was merged with surrounding radars. A dynamic radar-rain rate relation algorithm uses environmental data to assign a special rainfall rate to each grid point. Note that this is a departure from the NWS systems that use a single user-defined

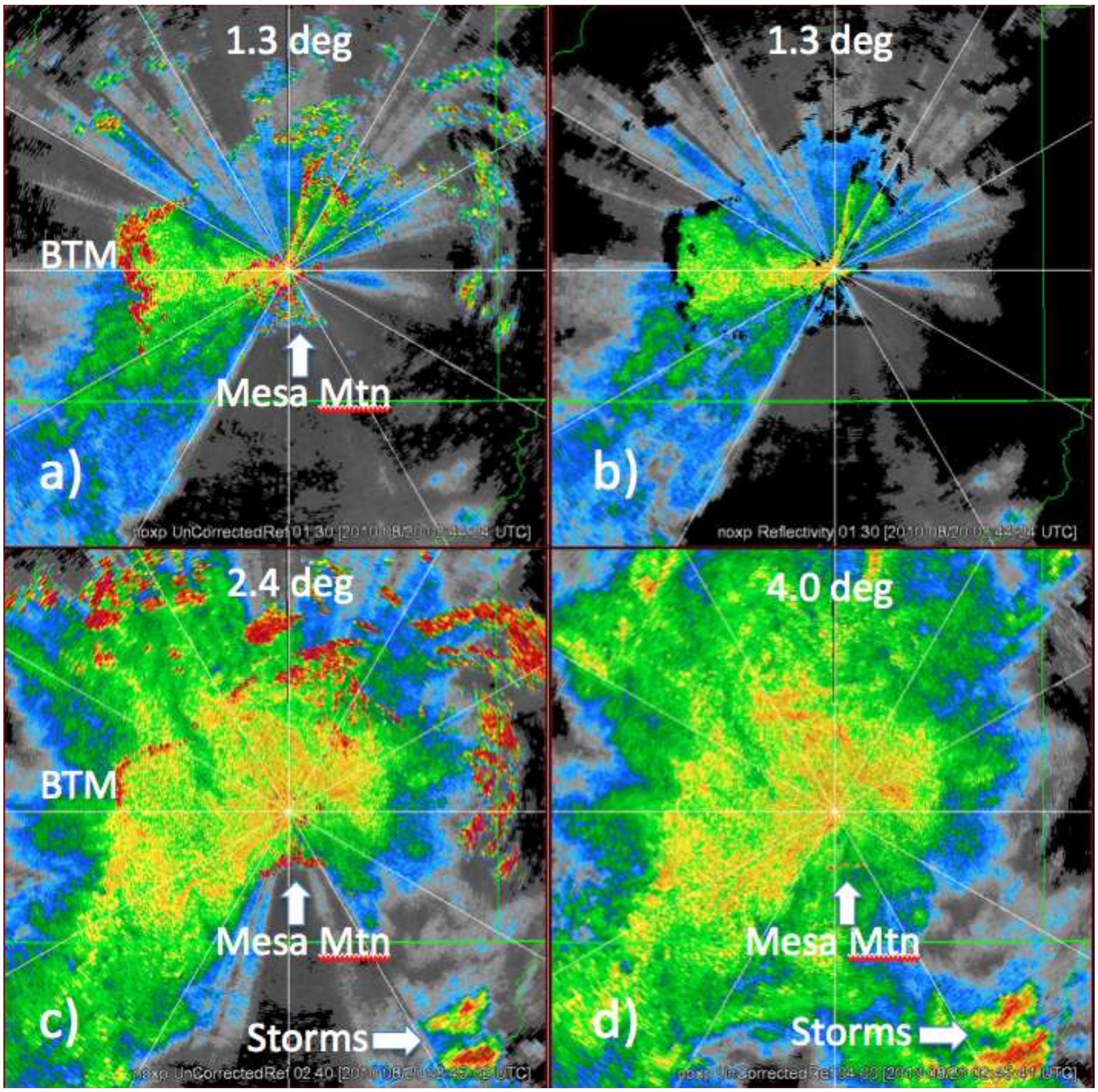

Figure 11. Reflectivity images from the NOXP at a) 1.3 deg, b) 1.3 deg with clutter filter applied, c) 2.4 deg, and d) 4.0 deg. Blue indicates light rain, yellow moderate rain, and red ground clutter except for actual storms at lower right.

Figure 12. Photograph of the SR2 radar on Bridge Timber Mountain looking north toward the San Juan Mountains.

Z-Rfor the entire data field. The final gridded field of mosaiced rain rates was provided to the WFO GJT via LDM, a standard communications protocol, for input into the Flash Flood Monitoring and Prediction - Advanced (FFMP-A) system. FFMP-A is an advanced version of FFMP that can ingest gridded data from multiple radars while FFMP ingests data from only individual radars. FFMP and FFMP-A use sub-basin rainfall rate thresholds for warnings (http://www.nws.noaa.gov/mdl/ffmp/).

A chronology of activities related to setting up data processing and communications and data transmission to the NWS is provided in table 3. The SR2 arrived at BTM on 1 August. Ingest of NMQ data into FFMP-A was completed and tested on 5 August. The video card on the RVP8 motherboard failed on 8 August and the radar was driven back to Norman. The NOXP radar was set up at the airport on 13 August. NOXP data were transmitted in a different format requiring processing with the NSSL Warning Decision Support System Integrated Information (WDSSII) system. The Internet In Motion cell phone communications system did not work initially and was operational beginning 18 August. Just after the data feed was reestablished, a major fiber cable was cut at SRH and the link between NSSL and Grand Junction was broken. The following day the National Weather Center that houses NSSL's computer systems

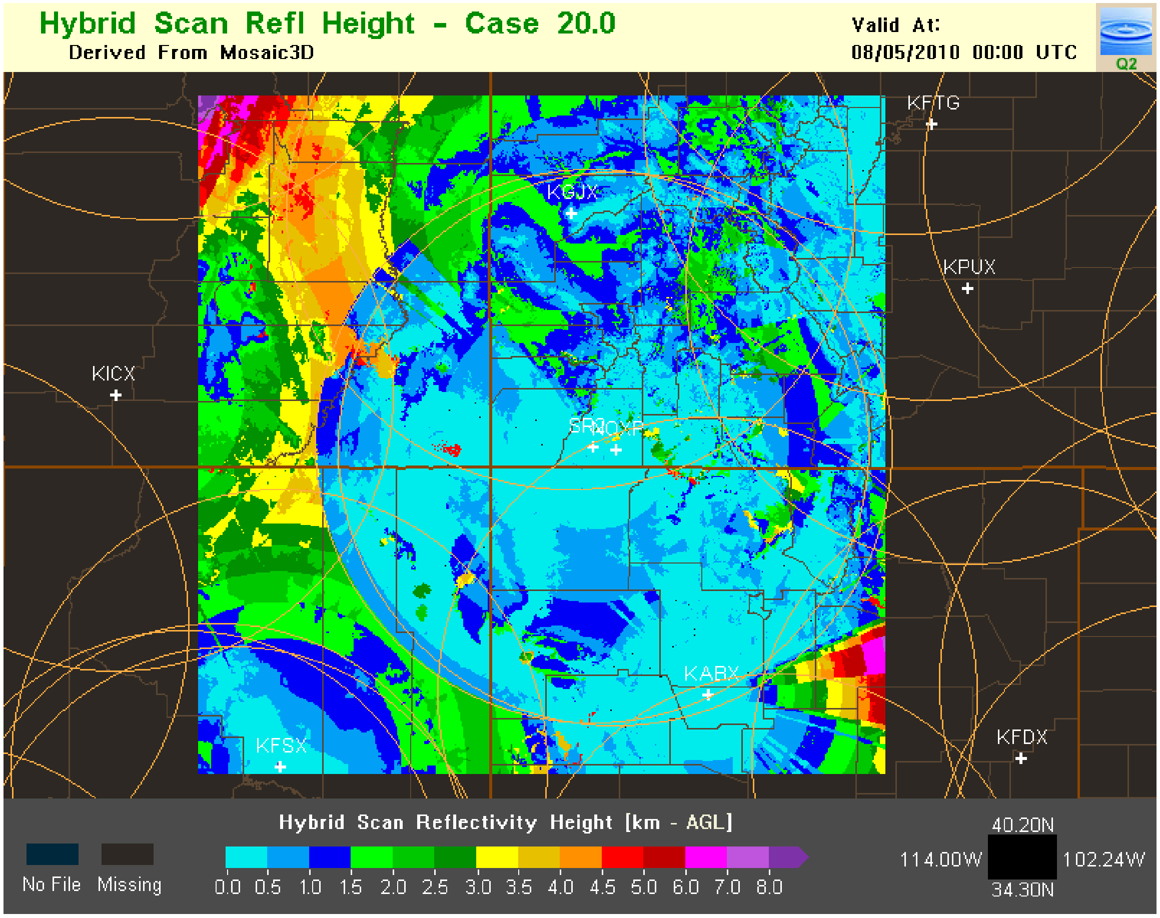

Figure 13. Radar beam heights in km above ground level as in figure 7 except with the SR2 coverage added. Light blue indicates the best coverage.

experienced a major power failure with backups failing and the NMQ system was off-line for three days. Data sets were immediately reconstructed. The NMQ processing was reconfigured for the airport site but the hybrid scan construction was not optimal and reasons are currently being explored. On 28 August the hybrid scan file was replaced by the 4.0 deg tilt that was unblocked providing a full view of the region (e.g., Fig. 11).

Images were provided over the Internet via separate web pages for each site due to different communications protocols and file formats on the radars. These web sites were used extensively by various groups and feedback on the impacts of the data, including NWS warnings, is provided below. The web site: http://smartr.metr.ou.edu/smartr2 was used for SR2. The web site http://wdssii.nssl.noaa.gov/web/wdss2/products/radar/NOXP.shtml was used for NOXP. This site provided comparisons between KGJX and NOXP. Processed data sent to the NWS was also available via a special case study web page (http://csnmq.ou.edu; case 20). This site provided instantaneous rainfall rates and accumulations in addition to reflectivity images.

9. Daily storm summaries

Table 3 lists days of operations at the two sites. The SR2 was set up on BTM on 1 August and data were collected until the main computer failed on 8 August. The NOXP radar was located at the airport beginning 13 August and remained for the project duration. While coverage was reduced at the airport site, having the radar at both locations allowed an assessment of coverage at two different sites and validated the theoretical site analysis. Please see appendix 4 for daily storm descriptions and images.

10. Project impacts

Emerging socioeconomic research points to the need for partnerships among local, state, federal, and private stakeholders in order to identify and develop optimal research-to-operations (RTO) needs for their particular interests (NRC, 2010). The Weather and Society – Integrated Studies (WAS*IS) movement emphasizes the importance of using social sciences to facilitate effective RTO (http://www.sip.ucar.edu/wasis/). Along these lines, project participants were asked to describe the impact that the additional radar data had on their operations and activities. Comments are provided in appendix 5. In summary, county emergency managers need detailed information on the location of even minor storms for operations including search and rescue, especially during nighttime. Airport operations and air traffic planning depend on weather information for efficient operations and to avoid costly flight diversions, especially during winter storms. Forecasters found the data useful in deciding when NOT to issue a warning, thus avoiding false alarms. Hydrology is another high-impact sector. The Animas and Florida rivers supply 670,100 acre-feet (AF) annually, the Los Pinos 173,700, the Piedre 291,200 AF, and 446,900 AF for the San Juan (Fig. 2). In total, the San Juan Mountains produce ~1.5 million AF of water annually. One acre-foot is 43,560 cubic feet of water, enough for one suburban family for a whole year (http://en.wikipedia.org/wiki/Acre-foot). Thus the source region of water for about four million people is not being sampled.

Steve Vasiloff provided interviews for two media events. One was for an article that appeared in the Durango Herald (http://www.durangoherald.com/article/20100826/NEWS01/708269923/Weather-wise). This article used the phrase "black hole" and described how the project was demonstrating a solution. The article was followed by an editorial reiterating the need for a permanent radar solution. The other interview was for a video segment that aired on City Span 10 as part of "Durango Sound Bytes."

11. Discussion and summary

Little research using gap-filling radars has been performed in the Intermountain region. Cotton and Knupp (1982) and Knupp and Cotton (1982) were early pioneers using a transportable radar to understand thunderstorms in the South Park area in the early 80's, well before the NEXRAD era. The 2009 Gunnison radar project and the 2010 SWCO project represent state-of-the-art science and research-to-operations using the latest technology. Mobile dual-polarized Doppler weather radars and sophisticated ground observing systems were deployed in southwest Colorado during August 2010. The primary goal was to better understand the nature of hazardous thunderstorms in an effort to provide better services to local weather data users and to reduce weather impacts on society. Comparisons between the mobile radars and the WSR-88Ds at Grand Mesa and Albuquerque showed significant benefit of the local radar in terms of filling a large radar void in not only southwest Colorado but over a significant portion of the Four Corners area, especially at the BTM location. The KGJX radar often observed storm tops but also completely missed significant storms that were observed by the mobile radars. This occurred mostly in Montezuma, La Plata and Archuleta Counties. Similar comparisons between regional WSR-88Ds and the mobile radars were noted in NW NM, NE AZ, and SE UT.

A key element of the project was to provide data to the NWS operational systems for improved flash flood warnings. This was accomplished by merging data from the mobile radars with data from regional WSR-88Ds using NSSL's NMQ system and then providing the data to the NWS FFMP-A system. Only one storm produced local flash flooding but did not meet the NWS criteria for a warning. However, a short-term forecast was issued based on the mobile radar data. The supplemental data also helped forecasters decide which storms NOT to warn on, thus avoiding false alarms. Furthermore, the additional data provided benefit to operations conducted by county emergency managers and others.

This project provides a model for conducting a field research-to-operations project by involving a number of stakeholders in order to ensure that the project goals meet local needs. For example, a legacy of the project is the installation of five real-time reporting rain gauges purchased by several counties and the Southern Ute Indian Tribe. Also, a project has been approved by the CWCB to install an ALERT gauge network in the San Juan Mountains for flash flood warnings. More on these legacy items can be found in section 14.

12. Recommendations

Data obtained during the project illustrate limitations and challenges in observing precipitation and hazardous storms due to radar coverage gaps in the West. A solution consisting of additional gap-filling radars is required to provide critical high-quality precipitation and hazardous storm observations. McLaughlin et al. (2010) discussed the need for distributed networks of radars to fill gaps in the context of the various radar characteristics mentioned earlier (e.g., transmitter frequencies). However, their analysis does not consider complications due to complex terrain, and the radars used in their study are of very limited coverage. Costs for their small low-power radars are ~$226K for the radar and ~$26K annually for operations and maintenance. This project demonstrates that improved radar coverage in complex terrain can be accomplished with a limited number of additional radars located in strategic areas. The hail storm of 16 August provided an example of attenuation due to the X-band frequency of the NOXP. A C-band radar would have experienced less attenuation. However, correction for attenuation may be accomplished through use of DP variables, thus rendering C-band a viable option at a moderate cost. A cost-benefit study should be performed to determine the economic and societal impacts of a new radar. Such an analysis should consider winter storms that may provide more benefit than during summer storms in this region. Additional discussion is provided in section 14.

Discussions with county emergency managers revealed expectations for services provided by the NWS that should be expressed through continuing outreach performed by the NWS. The Warning Coordination Meteorologist at the WFO is the primary conduit for feedback to the office for modification of or new service requirements. Further outreach by the NWS GJT office should be performed to address local concerns regarding sub-warning criteria impacts on their customers.

13. Future plans

This report provides an overview of data collected and feedback from project partners. Additional data analysis will be done and includes efforts and goals mentioned earlier.

1. Determine "legacy" correction factors for WSR-88D data. This effort has the potential to enhance the use of the WSR-88Ds by understanding relationships among the different vertical levels of data. This would enable increased confidence in the use of storm top observations from distance radars.

2. Provide QPE studies using the dual-polarization data. These studies will provide further insight into better QPE algorithms and attenuation correction methods. Furthermore, the radar data can be coupled with rain gauge and stream gauge data to better understand and predict stream flow response to rainfall.

3. Understand the formation and movement of storms based on atmospheric flow and humidity patterns. This information will help understand terrain effects on flood-producing storms and increase warning performance as well as provide validation data for numerical weather prediction models.

4. Data from this project will be made available over the Internet to facilitate local studies and societal impacts.

5. Facilitate a DP mobile radar field project during winter. A winter storm project would include coupling with distributed hydrologic models and the SNOw Data Assimilation System (SNODAS) (please see http://www.nohrsc.noaa.gov/nsa/ and http://www.nohrsc.noaa.gov/technology/pdf/wsc2001.pdf) to take advantage of the spatial observations in contrast to point observations currently provided by SNOTEL sites. In addition, a radar-snow gauge based short-term forecasting system could be employed to benefit airport snow removal and aircraft deicing operations (e.g., Rasmussen at al. 2003).

Finally, additional stakeholders should be identified and folded into future analysis and project planning. Additional users of weather information include the transportation sector (air and ground), ski areas, avalanche forecasters, cloud seeding operations, U.S. Forest Service recreation and fire weather, water and reservoir managers, and the energy sector.

14. Project legacies

Project planning discussions included local stakeholders who expressed interest in permanent rain gauges as a project legacy. As a result, San Juan, La Plata, and Archuleta Counties and the Southern Ute Indian Tribe purchased a total of five rain gauges that, with guidance from the NWS, were deployed in critical data voids. Lead by Dave Gochis, the gauges were collocated with USGS stream gauges and data are now available in Mesowest (e.g., http://mesowest.utah.edu/cgi-bin/droman/mesomap.cgi?state=CO&rawsflag=3). The data are sent over the GOES satellite data collection platform operated by the Hydrometeorlogical Automated Data System (HADS; http://www.weather.gov/oh/hads/).

A SWCO ALERT gauge project lead by Dave Gochis has been funded by the CWCB. An ALERT gauge uses wireless (e.g., radio frequency) communications and provides event-based "data bursts" as opposed to fixed-time accumulations. An example of an alert system used by the Denver Urban Drainage and Flood Control District can be found at http://alert.udfcd.org/. The SWCO ALERT system is in the design phase, again, with the assistance of the NWS.

A separate project funded by CWCB Stream and Lake Protection Section, lead by Brian Epstein, provided two radar stream level sensors that were installed over the summer. A small downward-pointing radar measures the height of the water which is converted into a flow rate by using a rating curve that is developed from discharge measurements taken at varying water levels. Temporary stations were installed on Wolf Creek at the Wolf Creek Campground Bridge and on Junction Creek at the Colorado Trail Foot Bridge. This project was coupled with the mobile radar and research rain gauge deployment in hopes of better defining the relationship between storm events and stream flow response.

This project demonstrated that a permanent radar would provide many benefits to the Four Corners community. Cost benefit studies on socioeconomic impacts of weather in the Four Corners area should be performed due to the range of potential solution costs. Appendix 6 outlines several models and contact information for a variety of radar systems.

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Jorgensen helped with radar setup and data collection. Brian Epstein of the CWCB Stream and Lake Protection Section installed the stream level sensors and assisted in rain gauge installation. Also helping with outreach to private land owners for gauge site selection and gauge installation were Pete Kasper, Water Commissioner, Division of Water Resources (DWR) Division 7, Brian Boughton, Lead Hydrographer, DWR Division 7, and David Grey, Hydrologic Technician, USGS Western Water Science Center. Les Showell transported the SR2 mobile radar. Kurt Hondl set up the WDSII web site. Larry Cedrone, HADS program manager, and Judith Pechman, University of Utah Mesowest, were instrumental in getting legacy gauge data onto the internet.

References

(R1) Anagnostou, E. N., M. N. Anagnostou, W. F. Krajewski, A. Kruger, B. J. Miriovsky, 2004: High-Resolution Rainfall Estimation from X-Band Polarimetric Radar Measurements. *J. Hydrometeor*, **5**, 110–128.

(R2) Biggerstaff, M. I., L. J. Wicker, J. Guynes, C. Ziegler, J. M. Straka, E. N. Rasmussen, A. Doggett, L. D. Carey, J. L. Schroeder, and C. Weiss, 2005: The shared mobile atmospheric research and teaching radar - A collaboration to enhance research and teaching. *Bull. Amer. Meteor. Soc.*, **86,** 1263-1274.

(R3) Bringi, V. N., and V. Chandrasekar, 2001: *Polarimetric Doppler Weather Radar. Principles and Applications.* Cambridge University Press, 636 pp.

(R4) Cotton, W. R., and K. R. Knupp, 1982: An intense, quasi-steady thunderstorm over mountainous terrain. Part I: Evolution of the storm-initiating mesoscale circulation**,** *J. Atmospheric Sciences*, **39,** 328-342.

(R5) Colorado Water Conservation Board, 2010: Flood hazard mitigation plan for Colorado.

(R6) Krajewski, W. F., G. Villarini, and J. A. Smith, 2010: Radar-rainfall uncertainties: Where are we after thirty years of effort? *Bull. Amer. Meteor. Soc.*, **91,** 87-94.

(R7) Langston, C., and J. Zhang, 2004: An automated algorithm for radar beam occultation. Preprints, *11th Conference on Aviation, Range, and Aerospace Meteorology*, Hyannis, MA, USA, American Meteorological Society, CD-ROM, P5.16.

(R8) __________, J. Zhang, K. Howard, 2007: Four-Dimensional Dynamic Radar Mosaic. *J. Atmos. Oceanic Technol.*, **24**, 776–790.

(R9) Leone, D. A., R. M. Endlich, J. Petriceks, R. T. H. Collis, and J. R. Porter, 1989: Meteorological considerations used in planning the NEXRAD network, *Bulletin of the American Meteorological Society***,** **70,** 4-13.

(R10) National Research Council, Committee on Progress and Priorities of U.S. Weather Research and Research–To–Operations Activities, 2010: When Weather Matters: Science and Services to Meet Critical Societal Needs. The National Academies Press, available at http://www.nap.edu/catalog/12888.html.

(R11) Knupp, K. R. and W. R. Cotton, 1982: An intense, quasi-steady thunderstorm over mountainous terrain. Part II: Doppler radar observations of the storm morphological structure, *J. Atmospheric Sciences*, 39, 343-358.

(R12) Maddox, R. A., J. Zhang, J. J. Gourley, and K. W. Howard, 2002: Weather radar coverage over the contiguous United States, *Weather and Forecasting*, **17,** 927-934.

(R13) Matrosov, S.Y., 2010: Evaluating polarimetric X-band radar rainfall estimators during HMT, *J. of Atmospheric and Oceanic Technology*, 7, 122-134.

(R14) McLaughlin, D. and Coauthors, 2010: Short-wavelength technology and the potential for distributed networks of small radar systems, *Bulletin of the American Meteorological Society*, **90,** 1797-1817.

(R15) Morin, E., R. A. Maddox, D. C. Goodrich, S. Sorooshian, 2005: Radar Z–R relationship for summer monsoon storms in Arizona, *Weather and Forecasting*, **20,** 672-679.

(R16) **_______**, W. F. Krajewski, D. C. Goodrich, X. Gao, S. Sorooshian, 2003: Estimating rainfall intensities from weather radar data: The scale-dependency problem, *J. Hydrometeorology*, **4,** 782-797.

(R17) Rasmussen, R., M. Dixon, S. Vasiloff, F. Hage, S. Knight, J. Vivekanandan, M. Xu, 2003: Snow Nowcasting Using a Real-Time Correlation of Radar Reflectivity with Snow Gauge Accumulation. *J. Appl. Meteor.*, **42**, 20–36.

(R18) Ryzhkov, A. V., T. J. Schuur, D. W. Burgess, P. L. Heinselman, S. E. Giangrande, D. S. Zrnic, 2005: The joint polarization experiment: Polarimetric rainfall measurements and hydrometeor classification, *Bulletin of the American Meteorological Society*, 86, 809-824.

(R19) Silvestro, F., N. Rebora, and L. Ferraris, 2009: An Algorithm for Real-Time Rainfall Rate Estimation by Using Polarimetric Radar: RIME. *J Hydrometeorol*, **10,** 227-240.

(R20) Snyder, J. C, H. B. Bluestein, G. Zhang, and S. J. Frasier, 2010: Attenuation Correction and Hydrometeor Classification of High-Resolution, X-band, Dual-Polarized Mobile Radar Measurements in Severe Convective Storms, *J. Atmospheric and Oceanic Technology*; doi: 10.1175/2010JTECHA1356.1.

(R21) Wood, V. T., R. A. Brown, S. V. Vasiloff, 2003: Improved Detection Using Negative Elevation Angles for Mountaintop WSR-88Ds. Part II: Simulations of the Three Radars Covering Utah. *Wea. Forecasting*, **18**, 393–403.

Table 1. Characteristics of the three radar systems used in this study. Shaded parameters are user-defined. *230 km maximum range limit is for precipitation algorithm processing. Long-range base data are available to 460 km range.

Parameter	WSR-88D	CPOL	NOXP
Frequency	2.7-3.0 GHz (S-band)	5.6 GHz (C-band)	7-9 GHz (X-band)
Antenna	8.54 m circular parabolic dish	2.54 m circular parabolic dish	2.54 m circular parabolic dish
Circular beamwidth	.92°	1.5°	0.9°
Peak power	500 kW	160 kW	200 kW
Signal processor	SIGMET RVP-8	SIGMET RVP-8	SIGMET RVP-8
Signal polarization	Horizontal	Horizontal & vertical	Horizontal & vertical
Polarization variables	dBZ, V_r, SW	dBZ, V_r, SW, Z_{dr}, Phi_{dp}, K_{dp}	dBZ, V_r, SW, Z_{dr}, Phi_{dp}, K_{dp}
Bin radial spacing	250 m	100 m	75 m
Maximum range*	230 km	230 km	150 km
Number of tilt scans	14	15	14 max
VCP-12 Tilts	0.5°, 0.9°, 1.3°, 1.8°, 2.4°, 3.1°, 4.0°, 5.1°, 6.4°, 8.0°, 10.0°, 12.5°, 15.6°, 19.5°	**0.0**°, 0.5°, 0.9°, 1.3°, 1.8°, 2.4°, 3.1°, 4.0°, 5.1°, 6.4°, 8.0°, 10.0°, 12.5°, 15.6°, 19.5°	0.5°, 0.9°, 1.3°, 1.8°, 2.4°, 3.1°, 4.0°, 5.1°, 6.4°, 8.0°, 10.0°, 12.5°, 15.6°, 19.5°
Volume scan time	5 min	5 min	5 min
Ground clutter cancellation	SIGMET “GMAP” notch filter	SIGMET “GMAP” notch filter	SIGMET “GMAP” notch filter

Table 2. Radar reflectivity (dBZ) to rainfall rate conversion using relations $Z=300R^{1.4}$ and $Z=200R^{1.6}$

dBZ	$Z=300R^{1.4}$ mm/hr	$Z=300R^{1.4}$ in/hr	$Z=200R^{1.60}$ mm/hr	$Z=200R^{1.60}$ in/hr
10.0	0.1	0.00	0.2	0.01
15.0	0.2	0.01	0.3	0.01
20.0	0.5	0.02	0.6	0.03
21.0	0.5	0.02	0.7	0.03
22.0	0.6	0.02	0.9	0.03
23.0	0.7	0.03	1.0	0.04
24.0	0.9	0.03	1.2	0.05
25.0	1.0	0.04	1.3	0.05
26.0	1.2	0.05	1.5	0.06
27.0	1.4	0.06	1.8	0.07
28.0	1.7	0.07	2.1	0.08
29.0	2.0	0.08	2.4	0.09
30.0	2.4	0.09	2.7	0.11
31.0	2.8	0.11	3.2	0.12
32.0	3.3	0.13	3.6	0.14
33.0	3.9	0.15	4.2	0.17
34.0	4.6	0.18	4.9	0.19
35.0	5.4	0.21	5.6	0.22
36.0	6.3	0.25	6.5	0.26
37.0	7.5	0.29	7.5	0.29
38.0	8.8	0.35	8.6	0.34
39.0	10.4	0.41	10.0	0.39
40.0	12.2	0.48	11.5	0.45
41.0	14.4	0.57	13.3	0.52
42.0	17.0	0.67	15.4	0.61
43.0	20.0	0.79	17.8	0.70
44.0	23.6	0.93	20.5	0.81
45.0	27.9	1.10	23.7	0.93
46.0	32.8	1.29	27.3	1.08
47.0	38.7	1.52	31.6	1.24
48.0	45.6	1.80	36.5	1.44
49.0	53.8	2.12	42.1	1.66
50.0	63.4	2.50	48.6	1.91
51.0	74.7	2.94	56.2	2.21
52.0	88.1	3.47	64.8	2.55
53.0	103.8	4.09	74.9	2.95
54.0	122.4	4.82	86.5	3.40
55.0	144.3	5.68	99.9	3.93

56.0	170.1	6.70	115.3	4.54
57.0	200.5	7.89	133.2	5.24
58.0	236.3	9.30	153.8	6.05
59.0	278.6	10.97	177.6	6.99
60.0	328.4	12.93	205.0	8.07

Table 3. List of radar collection periods and data communication benchmarks. Times in UTC.

SR2 at Bridge Timber Mountain

8/01 2100 – 2330; cell phone communications and the SMARTR web site were established and available
8/03 0215 – 1130; Q2 hybrid scan functional at 0400 UTC
8/04 1800 – 8/05 0140
8/05 1400 – 2000; communications via SHR>CRH > GJT's FFMP system were established
8/07 2100 – 8/08 0400

NOXP at the Durango – La Plata County Airport

8/13 2115-2140; cell service was not established
8/16 1600 – 8/17 0400
8/18 1530 – 8/19 0400; cell comms and the new WDSSII web site became available; fiber cable cut at SRH
8/19 1700 – 8/20 0400; NWC power failure - NMQ offline (data sets were reconstructed)
8/22 1730 – 8/23 0500
8/23 1700 – 8/24 0000
8/24 1900 – 8/25 0300
8/25 1930 – 8/26 0100
8/27 1730 – 8/27 2345
8/28 1830 – 8/29 0100; Q2 hybrid scans were replaced by the 4 deg tilt; comms to the WFO were reestablished
8/29 1720 – 8/30 0700
8/30 1500 – 8/31 0000