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INTERPRETATION OF RADAR DATA DURING SNOW EVENTS IN MOUNTAINOUS TERRAIN

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Introduction

During the winter months in Utah, the use of radar reflectivity (Z) is limited primarily to snow applications. Unfortunately, relationships between reflectivity and **snow**fall (S) estimates are less well understood than relationships between reflectivity and **rain**fall (R) estimates. In addition, beam blockage by mountains can hinder estimation of surface precipitation.

One of the goals of the Western Region Radar Project is to improve the use of the WSR-88D during snow events (Vasiloff 1996). The purpose of this Technical Attachment is to give an introductory comparison of data from the WSR-88D on Promontory Point in northern Utah to snowfall data collected at Snowbasin Ski Area while focusing on the influence of complex terrain. The basic questions being asked here are:

What radar reflectivity values correspond to certain snowfall amounts?

How can one tell, using the WSR-88D, if it is snowing in the mountains?

Besides NWS forecasters, there are many other potential users of radar data (e.g., avalanche forecasters and state departments of transportation). Because these "secondary" users most likely have limited training on the interpretation of radar data, an effort is made to use non-technical explanations. Thus, selected background is provided describing radar terminology and explaining what the radar measures. In addition, a short review of factors that can affect interpretation of radar data is given. Finally, data from the radar and a gage at Snowbasin are compared and used to test various Z-S relationships.

Background

What is reflectivity?

Radar reflectivity data are used to estimate local surface precipitation. The basic quantity measured by the radar is Ze, the equivalent reflectivity factor (Doviak and Zrnic' 1984).

Raindrops and/or ice particles backscatter radiation power sent out from the radar in a narrow beam pattern analogous to a spotlight. The term "echo" is often used to talk about the mass of precipitation. The quantity Ze is the amount of radiation that gets back to the radar and is theoretically related to the raindrop size diameter raised to the 6th power (and the quantity Z). Smith (1984) showed that the relationship between Z and Ze is given by

$$Z_e = 0.224Z. \qquad (1)$$

Large steel objects like trains, buildings, and cars can reflect nearly all of the radiation back to the radar antenna.

For display purposes, linear fields of dBZe are used. The quantity dBZe = 10 times the log Ze. During the warm season, 15 to 20 dBZe usually indicates light rain and 55-60 dBZe indicates heavy rain and/or small hail. Occurrences of reflectivity greater that 70 dBZe are rare and usually indicate large hail. These values are assigned various color codes depending on who creates the displays. For example, yellow and red colors are assigned the highest dBZe values; blue and green lower values.

Radar reflectivity values in winter storms are much less than during warm weather because the radar radiation pattern is interacting with ice crystals instead of water drops. Typical reflectivities during snow events range from 15 to 35 dBZe.

<u>What affects reflectivity data?</u>

Many things can degrade the radar data field. The primary factors are:

<u>1) Microphysics:</u> Crystal type, size and structure have a large effect on reflectivity.

<u>2) Mixed precipitation type:</u> Rain, snow, and a variety of precipitation types can co-exist in a cloud.

<u>3) Distance between the storm and the radar:</u> Generally, the radar beam is straight and the earth is curved. Thus, at "long" ranges, the radar beam will shoot over the top of the storm. In addition, since the beam pattern spreads apart with range, resolution decreases.

<u>4) Beam blockage:</u> In mountainous terrain, blockage of the radar beam by mountain peaks has the biggest effect on radar data. Sometimes the whole beam will be blocked and sometimes there will be only partial beam blockage. The result can be that a storm will appear to end at a mountain range.

<u>5) Type of storm:</u> Taller thunderstorms can be detected at ranges farther than shallow snowstorms.

6) <u>Location of the radar:</u> If the radar is located on a mountaintop making it higher than the surrounding region of interest, a shallow storm can be undetected or under sampled.

Complex Terrain in Northern Utah

Paramount in thinking about using radar data in the western U.S. is knowledge of the local topography. For reasons mentioned above, an important factor in Utah weather is the Wasatch Mountain range which runs north-south, and is just east of the Great Salt Lake (GSL; Fig. 1). Radar data used in this study are from the KMTX WSR-88D on Promontory Point at an elevation of 6500 ft above mean sea level (MSL).

Snowfall data for this study are from the Snowbasin Ski Area (SNB) which is about 26 nmi east of KMTX on the eastern slope of Mount Ogden (Fig. 2). Ogden Peak is about 9572 feet MSL, or 3000 ft above the radar level (ARL), and the center of the radar beam at 0.5 deg is 8300 feet MSL (1800 ft ARL). Note that the radar level is about 2300 ft above the GSL. As seen in Fig. 2, the lowest radar beam is totally blocked by the peak. A three-dimensional view of topography looking north along the Wasatch Front is shown in Fig. 3. Promontory Point is seen on the left and the 0.5 deg beam is intersecting Ogden Peak to the right.

A photograph of Ogden Peak is shown in Fig. 4a and is just to the left of center. The photograph is from the Middlebowl lift area, where the gage is located, looking southwest. (The Olympic downhill will take place on one of the slopes just to the right of the peak.) Figure 4b shows the weather station site in a view looking east. The snow depth is approximately 82 in.

Comparison of Radar Reflectivity Data And Surface Snowfall Measurements

Over a three hour period, two distinct snow bands moved over the Snowbasin area. A plot of radar reflectivity from the 0.5 deg tilt at 1637 UTC is shown in Fig. 5a. Note the black north-south data-void region associated with the Wasatch Mountains. A ground-clutter filter has removed the mountain's high reflectivities. Ogden Peak (OGP) is centered in a data-void region with Snowbasin (SNB) on the edge. An east northeast-west southwest oriented band of enhanced reflectivity is positioned just north of Snowbasin. Maximum reflectivity values range from 30 to 35 dBZe and are color-coded yellow (please note the scale along the bottom of the figure). A second band lies about 25 nm to the north. The northern band is less well-defined at 0.5 deg mainly because of beam blockage from peaks just to the north-nothwest of the radar antenna. These bands moved southward at ~8 mph. Composite reflectivity is show in Fig. 5b. (The composite is produced by displaying the highest reflectivity found at any level.) Note that the south band is nearly centered over Snowbasin with the leading edge about 5 nm south of the edge at 0.5 deg, indicating a southward slope in the band with height.

A time series plot of radar reflectivity data above Snowbasin is shown in Figure 6a. The maximum value adjacent to the surface site was used to make the plot. Vertically, it is preferable to associate data from the lowest radar tilt angle, i.e., closest to the ground, to the gage measurements. However, because the lowest 0.5 deg beam is blocked as discussed earlier, data from the 1.45 deg radar tilt are used. The center of the 1.45 deg beam is about 1500 ft above Ogden Peak.

Reflectivity above Snowbasin increased rapidly from 1600 UTC to 1615 UTC as the first snow band moved across. The maximum reflectivity of 33 dBZe occurred at 1700 UTC and decreased to a minimum of 22 dBZe at 1745 UTC. The second peak at 1830 UTC is associated with the northern band. After the northern band passed over, reflectivities hovered around 22 dBZe for over 2 hours.

Two different surface snow measurements are made: a Campbell Scientific, Inc. ultrasonic sensor gives instantaneous snow depth by bouncing an acoustic wave off of a surface; an ETI Instruments Inc. snowgage uses antifreeze to melt the snow and produces liquid-equivalent snowfall in increments of 0.01".

Actual snow depth from the ultrasonic sensor shows that snow began just after 1700 UTC and ended four hours later with a total accumulation of 6.5" (Fig. 6b). The first snowfall measurements were nearly an hour after the first snow band appeared overhead. The greatest accumulation occurred during the first one to two hours with over 2" from 1715 UTC to 1815 UTC.

Snowfall liquid equivalent accumulation (SLEA) from the ETI gage is shown in Fig. 6c. The rate of precipitation appears to be much more variable in the SLEA trace compared to the snow depth trace. The initial increase in SLEA closely matched the actual depth increase associated with the first snow band. Following a leveling-off period, the increase in SLEA from .46" to .66" from 1945 UTC to 2015 UTC was probably associated with the second band. Again, as was seen with the first band, there appears to have been about an hour delay between the band appearing overhead and an increase in the SLEA. In general, the onset and end of snow from the ETI gage matched the depth sensor. The storm total solid-to-liquid ratio (almost 10:1) agreed with readings taken by ski patrollers.

Application of Various Ze-S Relationships

Several models relating Ze to S (liquid-equivalent snowfall rate in units of mm/h) have been developed and tested. Smith found that the relation

$$Z_e = 399 S^{2.21} \qquad (2)$$

worked well for small ice crystals.

Super and Holroyd (1996) recommend the following:

$$Z_e = 330S^{2.0} \tag{3}$$

and

$$Z_e = 150S^{2.0}. \tag{4}$$

It was hypothesised that Eq. (3) was representative of lake effect storms in the Cleveland, Ohio area and (4) represented upslope storms in the Denver area. In comparison, the equation relating Ze and R (rainfall rate) currently used in the WSR-88D system is the Marshall-Palmer relationship.

$$Z_e = 200S^{1.6}. \tag{5}$$

Relationships (2), (3), and (4) were used to determine S for snowfall rates for radar observations between 1600 and 1700 UTC (Table 1). Obviously, the higher the reflectivity the higher the snowfall rate. Differences between (2) and (3) are on the order of 10%. However, relation (3) gives significantly higher results. These results are also compared to snowfall rates determined from the gage. Overall, the SLEA of 0.7 in over 4.5 hours yields a snowfall rate of 3.95 mm/h.

As seen in Table 1, this is commensurate with a constant reflectivity of nearly 34 dBZe assuming that Eq. 4 is appropriate. However, as seen in Fig. 6a, reflectivity rarely exceeded 30 dBZe.

A more detailed examination of the data provides evidence of a significant delay between radar and gage observations. Between 1700 and 1800 UTC 5.58 mm (.22 in) SLEA was observed (Table 1). The highest snowfall rates occurred 45 min to an hour after the 34 dBZe peak at 1700 UTC. The 5.58 mm/h also corresponds most closely to S derived from Eq. (4). However, Eq. (4) still falls short of estimating the high observed snowfall rate. A more appropriate relation **for this case** is determined by reducing the coefficient in (4) by half resulting in

$$Z_e = 75S^{2.0}. \tag{6}$$

Plugging S = 5.58 mm/h into (5) gives a Ze = 34 dBZ, much closer to the 32 dBZe value observed earlier.

Discussion and Conclusions

Comparison of surface snowfall data from Snowbasin and radar reflectivity data suggest approximately 45 min lag time between the radar reflectivity features and surface snowfall. The presence of mountain blockage of the lowest radar beam means that radar data from higher aloft must be used to estimate surface precipitation. However, observed snowfall rates were greater than snowfall rates determined from various Ze-S relationships. The closest match between observed S and S derived from Ze was obtained by modifying the coefficient of a Ze-S relation recommended in the literature. This indicates three possibilities for the discrepancy between observed and derived values for S:

1) Higher reflectivity information at 0.5 deg was blocked from view by the mountain necessitating the use of the 1.45 deg tilt;

2) A still different Ze-S relationship must be determined: $Ze = 75S^{2.0}$ fit these data better than previously-published Ze-S relationships;

3) Errors in the gage measurements.

Overall, many assumptions about the storm and snowfall have been made. Further data will be examined to understand short-term snowfall forecasts using data free from beam blockage problems.

Table 1. Various snowfall rates derived from observed radar reflectivity factor using Eqs. 2, 3, and 4 in the text. Gage snowfall liquid equivalent accumulations (SLEA) are given as well.

Time (UTC)	Reflectivity (dBZe)	S2 (mm/h)	S3 (mm/h)	S4 (mm/h)	Gage SLEA (mm)
1600-1615	28	1.23	1.38	2.04	-
1615-1630	26	1.0	1.10	1.62	-
1630-1645	27	1.11	1.23	1.82	-
1645-1700	32	1.87	2.19	3.24	-
1700-1715	-	-	-	-	1.01
1715-1730	-	-	-	-	.76
1730-1745	-	-	-	-	1.78
1745-1800	-	-	-	-	2.03

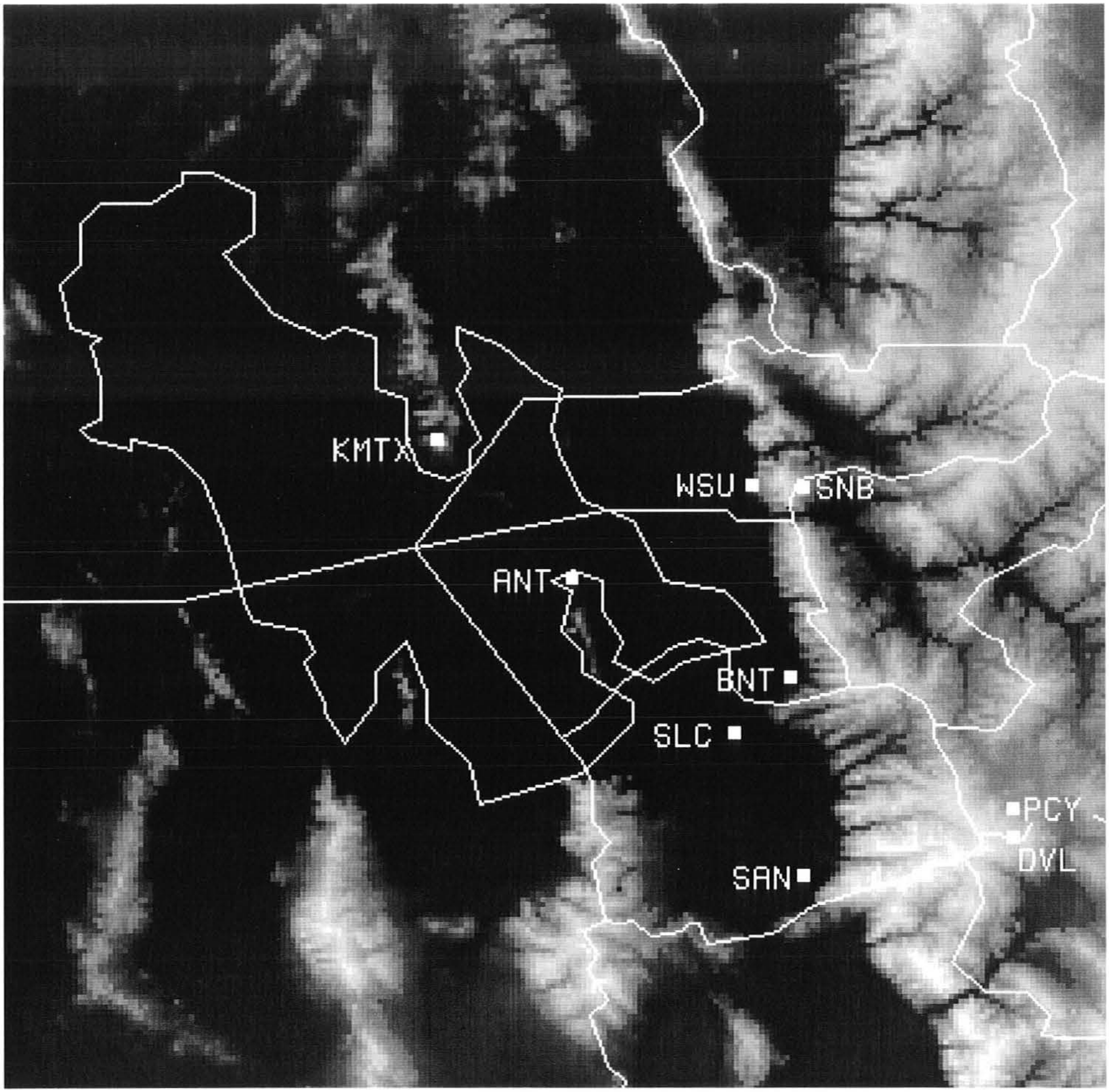


Figure 1. Layout of the 8 snowgages. KMTX indicates the location of the WSR-88D on Promontory point. Grey shades of topography are also shown with brightest shades indicating highest terrain.

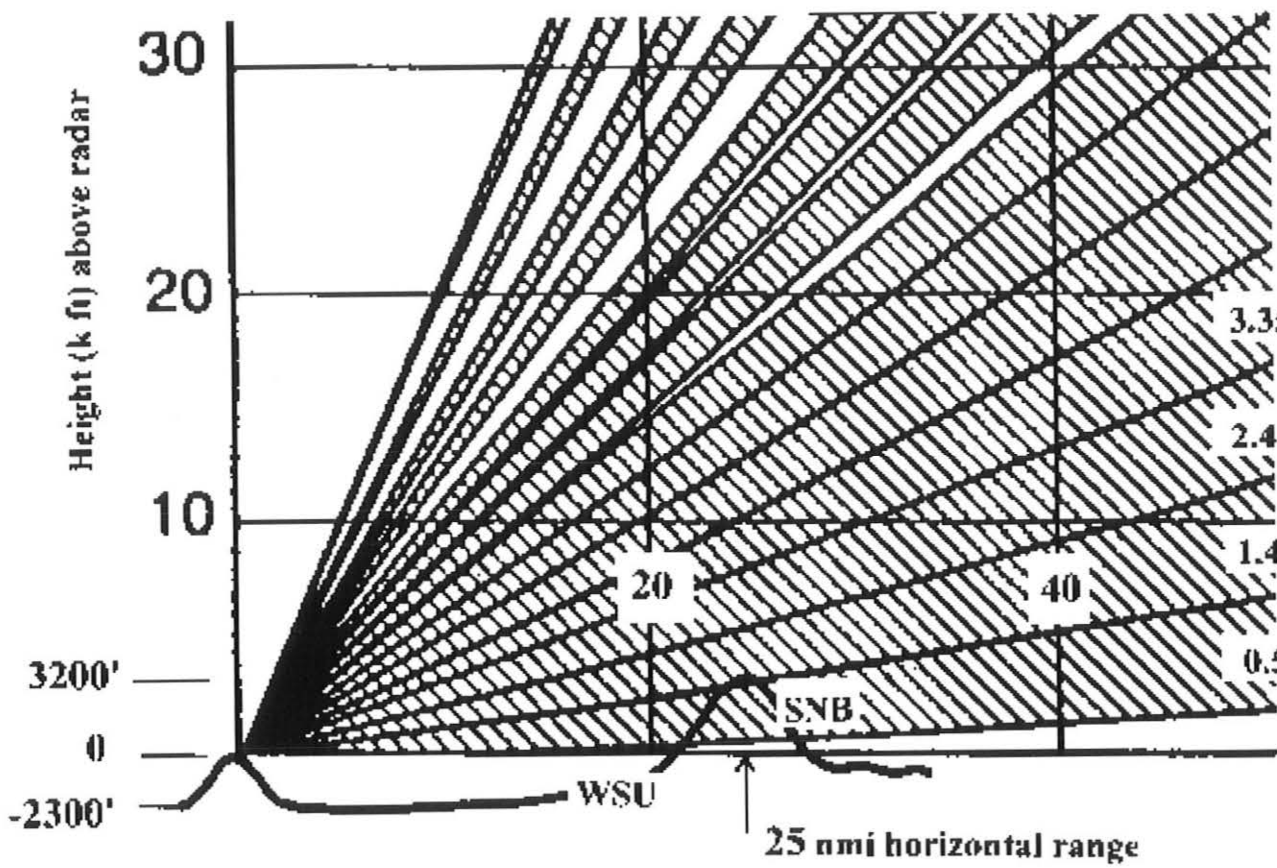


Figure 2. Side view of radar beam angles overlaid on a relief og the topography along a line from Promontory Point to Ogden Peak.

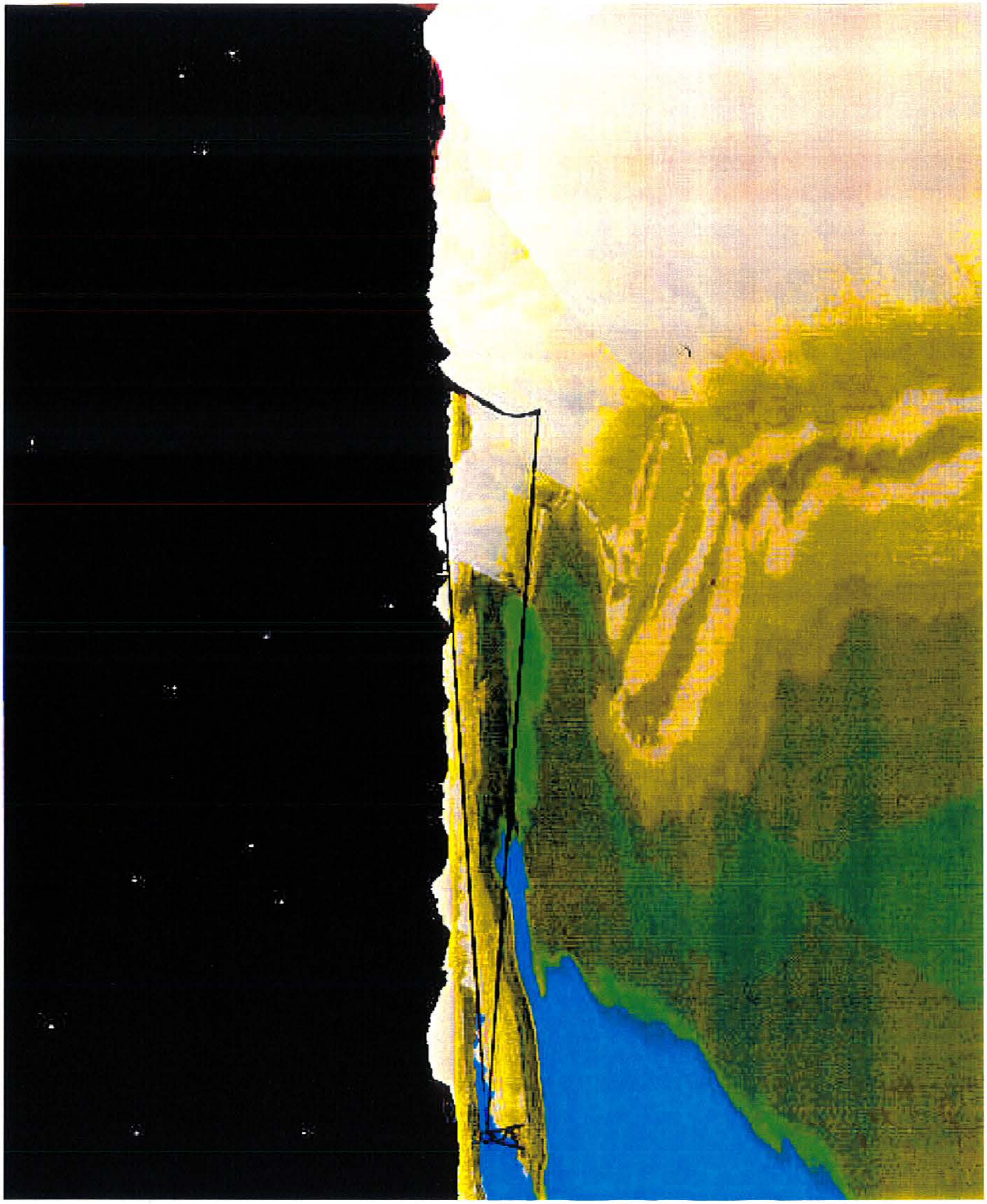


Figure 3. 3-D graphical representation of the Wasatch mountain range looking from approximately the Salt Lake City area. The KMTX WSR-88D tower is shown on Promontory Point with the 0.5 deg beam depicted intersecting Ogden Peak. The distance from KMTX to Odgen Peak is about 25 nm. (Courtesy Dan Pope, KTVX Channel 4, Salt Lake City.)

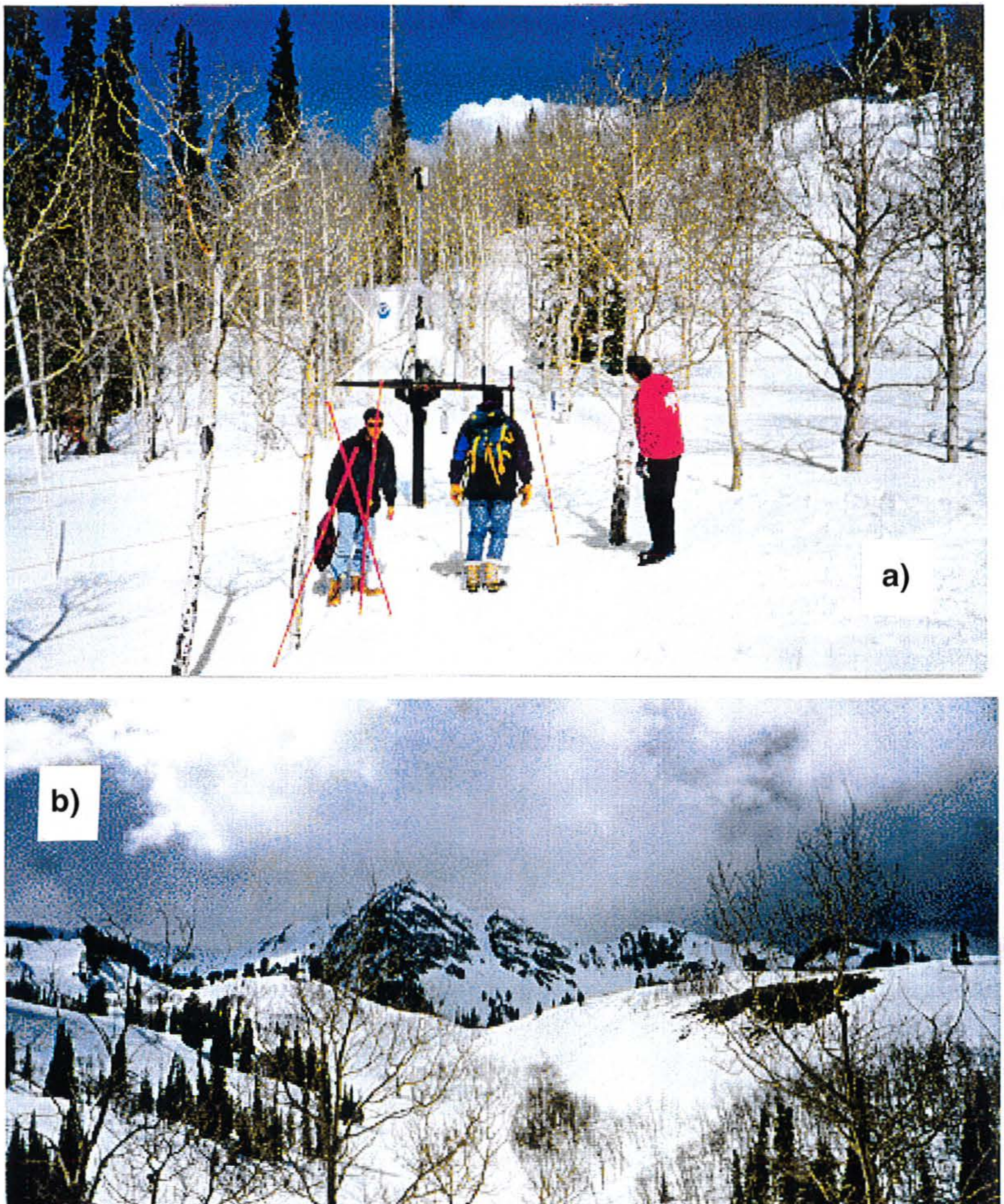


Figure 4. Photographs from the Middlebowl area at Snowbasin a) looking east toward the gage site, and b) looking west toward Ogden Peak.

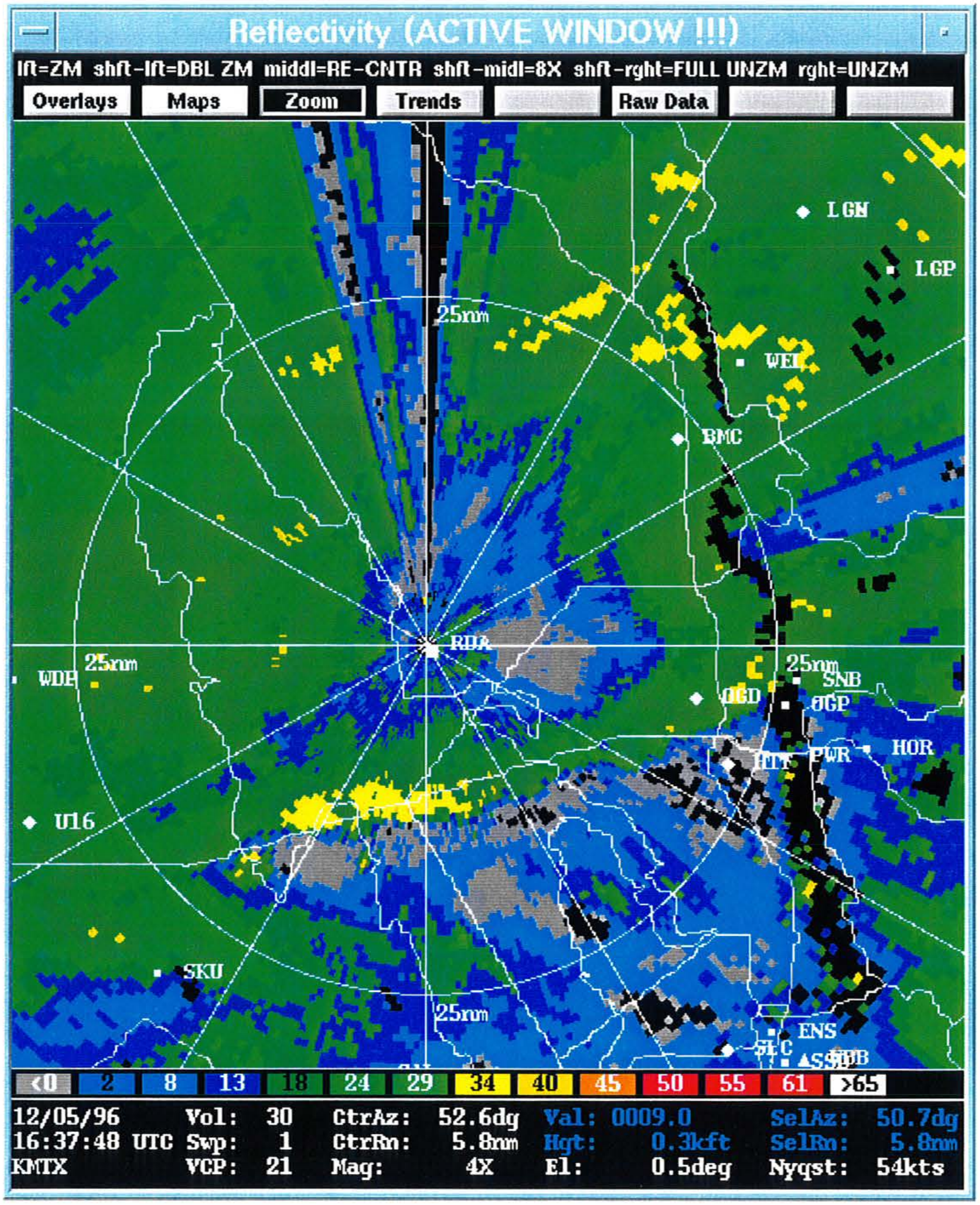
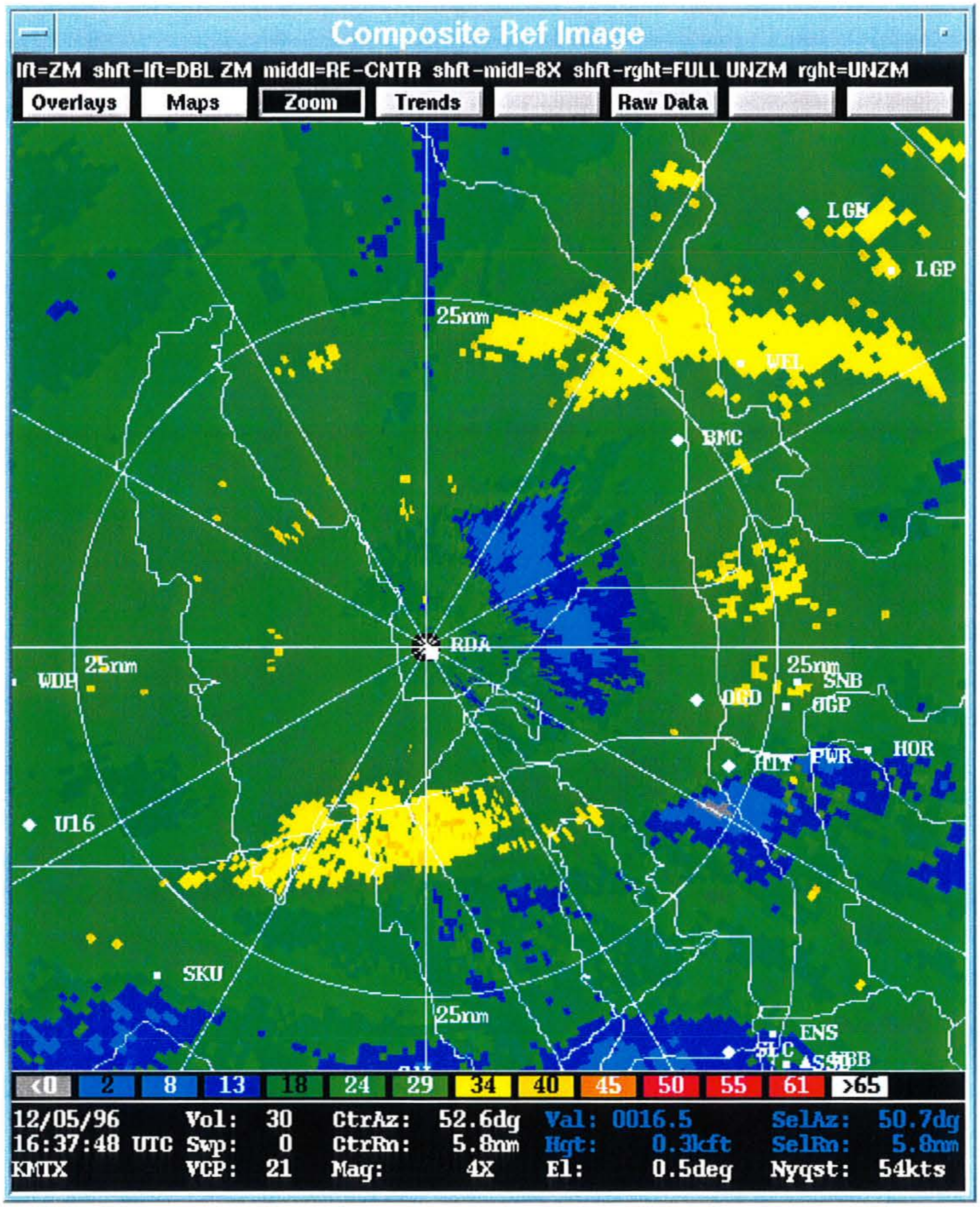


Figure 5. Plan view of reflectivity data from the KMTX WSR-88D: a) 0.5 deg tilt; b) composite reflectivity data.


Composite Ref Image
lft=ZM shft-lft=DBL ZM middl=RE-CNTR shft-midl=8X shft-rght=FULL UNZM rght=UNZM
Overlays
Maps
Zoom
Trends
Raw Data
LGN
LGP
25nm
BMC
RDA
25nm
25nm
WDP
SNB
OGD
OGP
HIF
PWR
HOR
U16
SKU
25nm
ENS
SLC
<0 2 8 13 18 24 29 34 40 45 50 55 61 >65
12/05/96 Vol: 30 CtrAz: 52.6dg Val: 0016.5 SelAz: 50.7dg
16:37:48 UTC Swp: 0 CtrRn: 5.8nm Hgt: 0.3kft SelRn: 5.8nm
KMTX VCP: 21 Mag: 4X El: 0.5deg Nyqst: 54kts

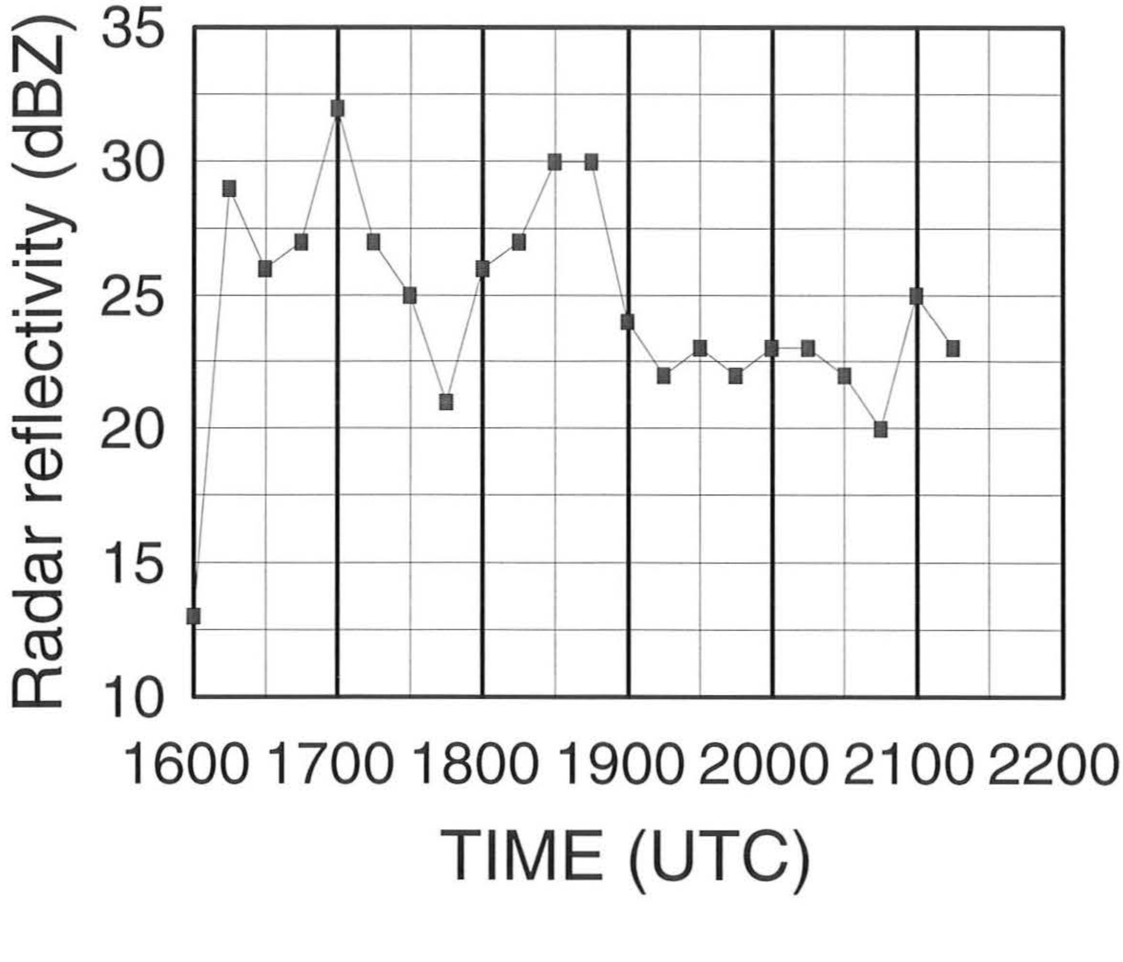
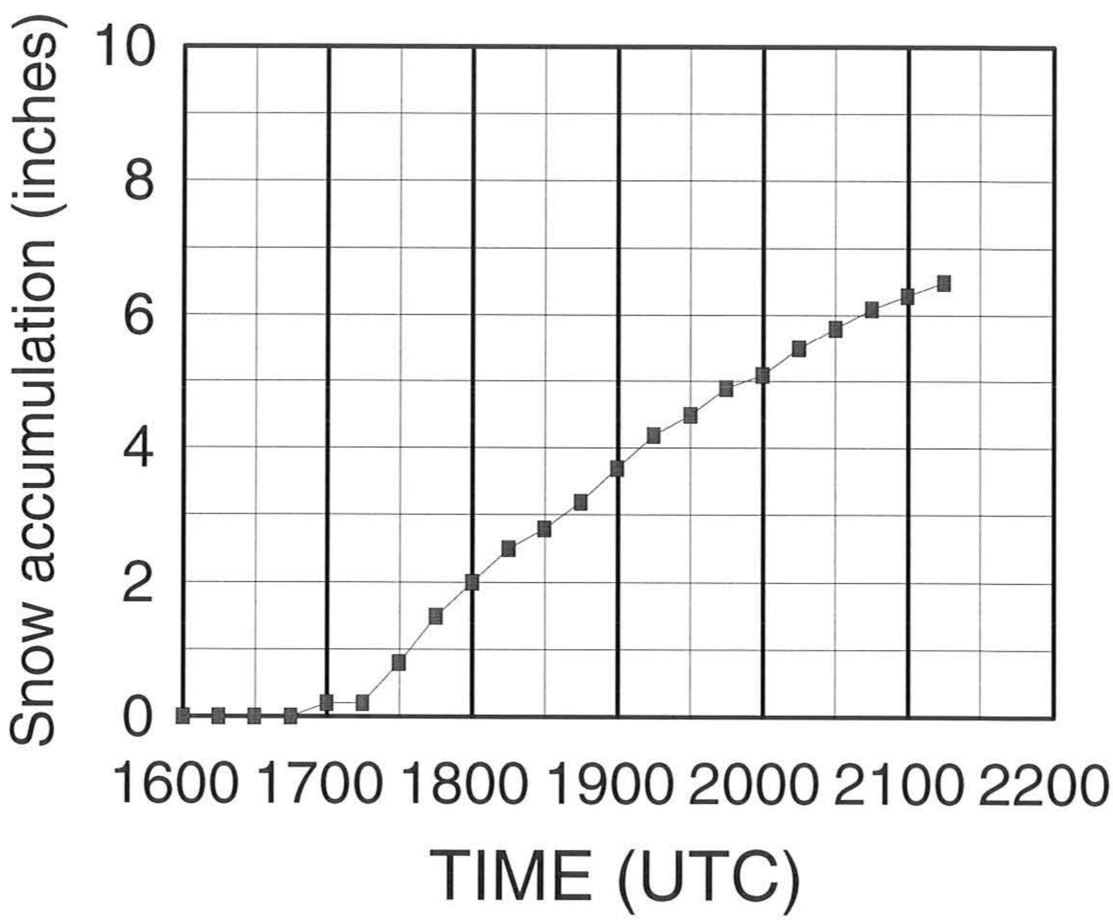
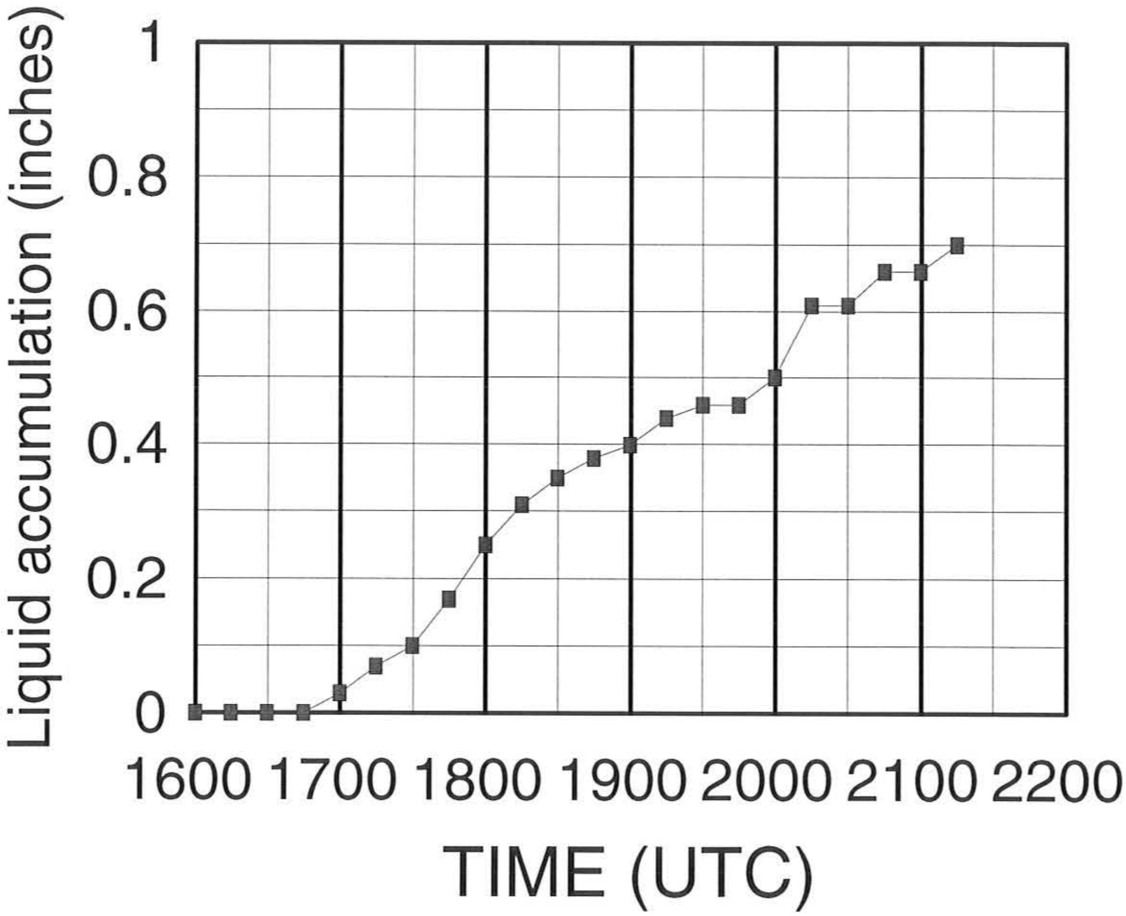


Figure 6. Time series of a) reflectivity data above the Snowbasin gage. The maximum value nearest the gage has been plotted; b) "solid" snow depth from the ultrasonic depth sensor at Snowbasin; and c) snowfall liquid equivalent accumulation.



10
8
6
4
2
0
Snow accumulation (inches)
1600 1700 1800 1900 2000 2100 2200
TIME (UTC)



Liquid accumulation (inches)
1
0.8
0.6
0.4
0.2
0
1600 1700 1800 1900 2000 2100 2200
TIME (UTC)