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AN EXAMINATION OF A DYNAMIC COLD SEASON BOW ECHO IN CALIFORNIA

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Introduction

On 1 April 1996, two distinct bow echoes developed over the northern San Joaquin Valley of California. These bow echoes moved rapidly to the east-northeast at around 40-45 mph with two distinct paths of damage reported. Both damage paths were oriented from south-southwest to north-northeast along the strongest portion of each bow echo. This Technical Attachment will investigate the WSR-88D data along with mesoscale analyses to document the development and structure of this excellent example of a cold season bow echo and explain how local topography may have forced the initial development of this complex.

Definition of Bow Echoes

Squall lines have long been recognized as producers of severe weather. Occasionally, these systems developed a bulging, convex shape (as depicted by radar) and were accompanied by stronger surface winds. Fujita (1981) described the basic morphology and evolution of this particular type of storm, which he classified as a "bow echo". Fujita documented that the highest winds tended to occur in a narrow swath corresponding to the track of the apex of the bow (Fig. 1). Surface pressure features which occasionally are observed in squall lines include a pre-squall low pressure system, a mesohigh (underneath the main downdraft), and occasionally a wake low (located behind the mesohigh). Smull and Houze (1987) documented that occasionally bow echoes develop a notch-like cavity which denotes the presence of a descending rear-inflow jet, and suggested that this mesoscale flow feature can influence the shape, intensity, and propagation of the leading convective line.

Johns (1993) observed that vigorous bow echo development associated with damaging winds can occur either with strong, migrating low pressure systems or with rather stagnant weather patterns exhibiting relatively weak synoptic-scale features. In the United States, bow echo events associated with the former pattern, classified as the "dynamic" pattern, have been observed in all seasons, while events associated with the latter pattern, the "warm season" pattern, are almost entirely confined to late spring and summer. Sometimes, the bow echo develops structures, classified as bookend vortices, on either side of the most concave portion. These vortices rotate, with the northern one rotating cyclonically and the southern vortex anticyclonically. Numerical modeling indicates that the development of bookend vortices require large amounts of CAPE and strong vertical wind shear in the environment of these systems with spin-up periods of up to 90 minutes necessary (Weisman, 1990).

Synoptic Pattern

The bow echo complex of 1 April exhibits several of the dynamic pattern characteristics, namely a strong cold frontal passage and a strong area of synoptic low pressure producing strong vertical wind shear in a weakly unstable environment. It exhibited the classic surface pressure patterns associated with strong squall lines, including a pre-squall low, a mesohigh, and a wake low. This storm also fits the "classic" severe weather pattern for California where severe weather occurs behind a weakening, mainly upper-level, front but before a secondary, and strengthening, frontal feature moves across the state. This storm also followed the typical California severe weather event with fast development to severe levels followed by fast dissipation.

As is typical with most convective weather occurrences in the Central Valley, conditionally unstable air remained in the lower levels following the passage of an upper level cold front through California early on the morning of 1 April. This allowed weak cold air advection aloft while retaining the warm and relatively moist air in the valley. Cold frontogenesis was occurring offshore of California as strong westerly winds, along with a dry push of air associated with a jet streak, caused increasing secondary circulations over the frontal zone. Due to the synoptic area of low pressure to the north of the San Joaquin Valley, a moderately strong pressure gradient had developed with south-southeast winds of 20 mph being reported at many locations by midday as the cold front approached the coast.

Satellite imagery at 1800 UTC indicated numerous breaks developing in the extensive cloud shield over the San Joaquin Valley. A broad area of light to moderate rain extended over the Sacramento Valley and an area of unorganized light to moderate convection had developed along the secondary cold front.

The breaks in the cloud cover allowed temperatures in the northern San Joaquin Valley to rise into the lower to middle 60s, with dewpoint temperatures remaining generally in the middle and upper 50s, which is quite moist for this portion of the state. Thus, as the strengthening cold front approached the coast and was forced over the Coastal Range Mountains, which extend north-south along the coast, a line of convection rapidly developed as can be seen by the 2152 UTC 0.5 degree reflectivity scan from the Sacramento WSR-88D (Fig. 2). A weak bowing eastward of the line can already be seen to the southwest of Stockton.

Development of the Bow Echoes

This initial bowing of the developing line of thunderstorms was important in the location and overall development of the bow echo complex. If one looks at the topography of the Coastal Range Mountains, one can see that there are two significant gaps in the Coastal Range Mountains, Altamont Pass leading into the Livermore Valley, and Pachenco Pass just to the west of Los Banos (Fig. 3). The initial bowing of the northern portion of the line of thunderstorms aligns perfectly with the mouth of Altamont Pass. Because of this, it is believed that the initial bowing of the line of thunderstorms was due to a deeper westerly component to the low-level wind field behind the secondary front. With much of the westerly winds blocked by topography north and south of this gap, a stronger rear-inflow developed in that portion of the line to the east of Altamont Pass causing a slight bowing of the line.

Pachenco Pass is not as broad as Altamont Pass, so the development of the southern bow echo took more time, and perhaps was enhanced by the development of the northern bow echo. However, by 2216 UTC, this second bow echo was evident as well.

Further Development of the Complex

During the next 15 minutes, the bow echo complex continued to progress to the east at around 30 mph and underwent significant mesoscale development and organization. The 2234 UTC 0.5 degree reflectivity scan indicated two well-developed bow echoes and what looked like a developing bookend vortex at the northern portion of the northern bow echo (Fig. 4). The radar beam was shooting well above the low-level structure of the southern bow echo, with little detail available beyond the well defined bow echo structure. The northern bow echo was accelerating and was now moving at approximately 40 mph to the east-northeast.

By 2245 UTC, a very well-developed bookend vortex was apparent in the 0.5 degree reflectivity scan, to the northeast of Stockton while the main portion of the bow echo itself was moving across the city of Stockton (Fig. 5). A notch in the reflectivity pattern had developed along the back edge of the bow echo on the west side of Stockton, likely indicating enhanced momentum transfer to the ground, and a more favored area of low-level convergence.

This enhanced rear notch feature was seen to accelerate rapidly to the east-northeast at speeds approaching 45 mph, moving across northwestern Stockton toward the city of Lodi. A new bookend vortex could be seen developing along the northern portion of this enhanced rear notch. The 2257 UTC reflectivity data indicated both the initial bookend vortex to the southeast of Rio Vista and the developing second bookend vortex to the southwest of the city of Lodi (Fig. 6). The storm relative velocity data for the same time period and vertical slice (Fig. 7) indicated the secondary bookend vortex plainly (located just to the north of the AN in San Joaquin). The southern bow echo continued to show the bowed structure but little mesoscale detail was evident due to the high scan angle. If a cyclonically rotating bookend vortex had developed, it would have been located to the west of Modesto, where some weak rotation could be seen in the storm relative velocity data.

A mesoscale analysis at 2255 UTC indicated the classic squall line surface pressure pattern including a pre-squall area of low pressure ahead of the bow echo, a mesohigh located behind the gust front, and a weak wake low (Fig. 8). A tight synoptic pressure gradient around this convective complex acted to increase the south-southeasterly winds ahead of the squall line with storm relative inflows reaching almost 50 mph with storm relative gusts into the storm approaching almost 60 mph. A weak area of low pressure on the front was located to the east of Sacramento with a quasi-stationary front extending to the east. A wedge of high pressure was located north of this front. Weak warm air advection over this frontal feature was producing the large area of light to moderate rain over the Sacramento Valley resulting in a weak mesohigh, produced by rain cooled air. A broad area of low pressure, located to the west of Redding and Red Bluff, was likely enhancing some of the precipitation in this region as well.

The 2303 UTC reflectivity scan showed that the secondary bookend vortex located just south of the city of Lodi was continuing to move to the east-northeast at around 45 mph (Fig. 9). The enhanced notch region remained very apparent as that portion of the bow echo continued to move faster than the remainder of the bow. The broad primary bookend vortex was now located southwest of Walnut Grove. A weak anticyclonically rotating vortex appeared to be located northwest of Modesto while the southern bow echo continued to advance east-northeastward. A cyclonically rotating bookend vortex could be seen on the northern portion of this bow echo just to the west of Modesto (Fig. 10). Echo tops with the entire bow echo complex were generally around 22000 feet during the peak of the storm.

After this period of time, both bow echoes weakened as they neared the foothills of the Sierra Nevada Mountains. Increased friction due to the foothills, along with less inflow, likely contributed to their demise.

Figure 11 shows the damage path of the northern bow echo. The damage clearly occurred very near to the enhanced notch which developed in the bow echo and furthermore almost underneath the location of the cyclonically rotating secondary bookend vortex. Many of the reports of damage have been classified as being caused by weak F0 tornadoes, likely "landspouts" produced as horizontal vorticity, generated by the cold outflow of the gust front, was stretched by developing updrafts located over the cold pool. According to Doswell (1996), "There are observations of tornadoes well away from mesocyclones in bowing squall lines. The tornadoes occur between the bowing line segment and the undercut mid-level mesocyclone, along the outflow boundary in regions of enhanced low-level cyclonic vertical vorticity. Such events have a landspout-like character, as developing updrafts along the outflow override enhanced low-level cyclonic vorticity." (Doswell's homepage). This clearly supports the areas of suspected F0 tornado occurrences on 1 April as one locates these areas in reference to the most highly bowed portion of the thunderstorm line and the cyclonic vortex feature.

Post-analysis of Storm Environment

The environment in which the bow echo complex of 1 April 1996 developed was one which was dominated by strong vertical wind shear, weak instability, and strong low-level forcing. An estimated sounding, which was created to approximate conditions at 2200 UTC near Stockton, used the 1200 UTC OAK sounding with modifications for cold air advection aloft, and weak low-level warm air advection. A surface temperature of 66 degrees with a dewpoint temperature of 58 degrees were used as average surface conditions which were then mixed to 900 mb to approximate what was likely occurring that afternoon. The lowest 50 mb were then averaged, and this value was lifted, resulting in a sounding which had modest instability (CAPE=256 J/kg) with an equilibrium level near 21000 feet (Fig. 12). These values are typical of storm environments in the San Joaquin Valley in early April.

The hodograph for this same time period clearly indicated an almost "straight-line" appearance (Fig. 13). Although observational studies indicate that moderate to strong environmental wind shear through the mid-levels is associated with the development and maintenance of dynamic bow echo activity (Johns and Doswell 1992), there has not been a thorough investigation into the nature of hodographs associated with bow echo situations (Johns 1993).

The 0000 UTC OAK sounding (Fig. 14) indicated a uniform low-shear layer of air located from 2-6 km. This layer was likely the forcing mechanism for the initial bowing of the convective line, and supported the bow echo complex across the northern San Joaquin Valley. WSR-88D VAD winds also indicated this layer (Fig. 15).

Analysis of the observations at the Stockton airport revealed interesting characteristics about this bow echo as it passed through the city. The airport was located to the south of the enhanced notch in the bow echo, thus the observations reflected those associated with the main bow echo, not within the secondary notch. Winds ahead of the squall line gusted to 34 mph as the line approached, but decreased slightly as the pre-squall low moved east of the station. As the squall line moved through the airport at 2251 UTC, a wind shift from south-southeast to southwest occurred with the peak storm gust of 38 mph recorded at this time. Pressure rose rapidly as the mesohigh built over the airport (PRJMP 5/2243/2251). In the one minute from 2256 UTC to 2257 UTC, 0.13" of rain fell indicating the strength of the downdraft with this system. From 2251 UTC to 2257 UTC, 0.29" fell. Needless to say, visibilities fell to near zero during the heaviest rainfall. Winds backed to south-southwest as the mesohigh moved eastward but remained gusty with gusts approaching 30 mph.

The wake low moved across the airport at around 2323 UTC with a pressure jump (PRJMP 3/2323/2333) occurring. Winds at the surface became northwesterly as the wake low moved east of the station. The pressure trace from that day indicated the pre-squall low, the mesohigh, and the wake low (Fig. 16).

Conclusions

A strong bow echo complex developed over the northern San Joaquin Valley during the afternoon of 1 April 1996. The development and progression of the northern bow echo was well documented by WSR-88D radar and was shown to have had the typical structures seen in bow echoes which have been documented elsewhere. As far as the authors know, this is the first WSR-88D documented case of a bow echo occurring in the Western Region. Local topography appeared to play a crucial role in the initial development and location of the bow echoes, and the mesoscale features, namely the enhanced notch region and associated secondary bookend vortex, were responsible for the production of several tornadoes along with straight-line wind damage. It is theorized that similar structures were responsible for the damage with the southern bow echo. The rapid development of the bookend vortices were surprising since numerical modeling suggests that spin-up periods of up to 90 minutes are necessary for the complete development of these features (Weisman, 1990). This rapid development and dissipation of thunderstorms in Central Valley creates one of the most challenging and difficult aspects of severe weather forecasting in California.

References

Fujita, T.T., 1981: Tornadoes and downbursts in the context of generalized planetary scales. *J. Atmos Sci,* **38**, 1511-1534.

Johns, R.H., 1993: Meteorological conditions associated with bow echo development in convective storms. *Wea. Forecasting*, **8**, 294-299.

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Smull, B.F. and R.A. Houze, Jr., 1987: Rear inflow in squall lines with trailing stratiform precipitation. *Mon. Wea. Rev.*, **115**, 2869-2889.

Weisman, M.L., 1990: The numerical simulation of bow echoes. *Preprints, 16th Conference on Severe Local Storms*, Kananaskis Provincial Park, Amer. Meteor. Soc. 428-433.

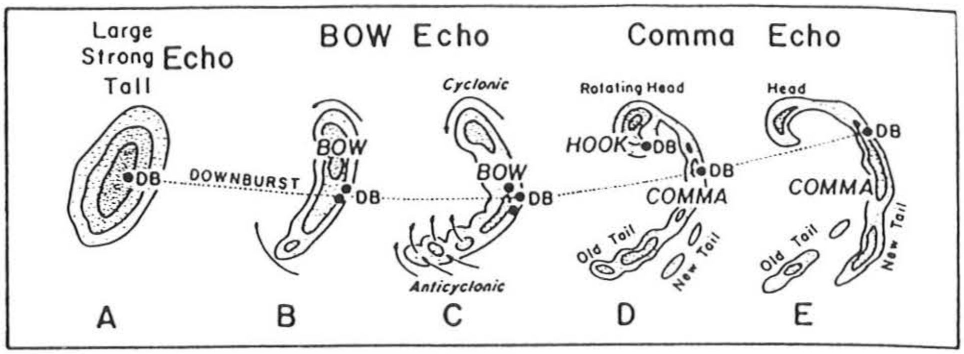


Fig 1a A typical morphology of radar echoes associated with strong and extensive downbursts. During the period of strongest downbursts, the echo often takes the shape of a spearhead or a kink pointing along the direction of motion. (From Fujita, 1978)

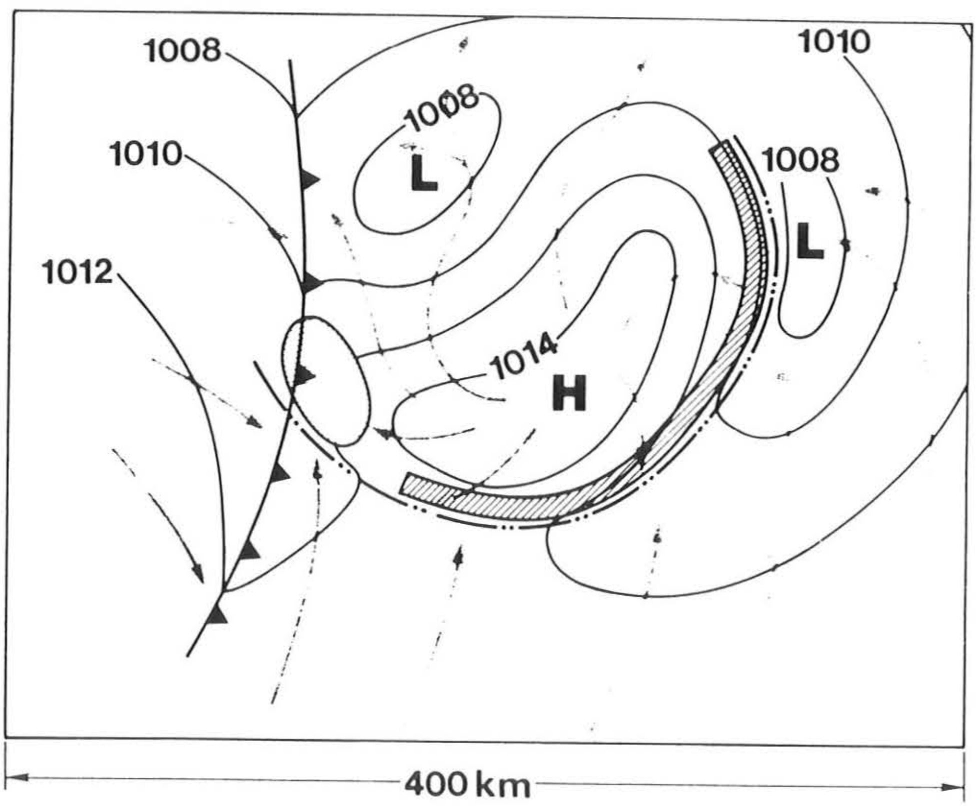


Fig 1b Schematic example of mesoscale surface pressure systems and streamlines associated with some thunderstorm outflows. Included is a pre-squall low, a mesohigh in the area of precipitation, and a wake low to the rear of the mesohigh.

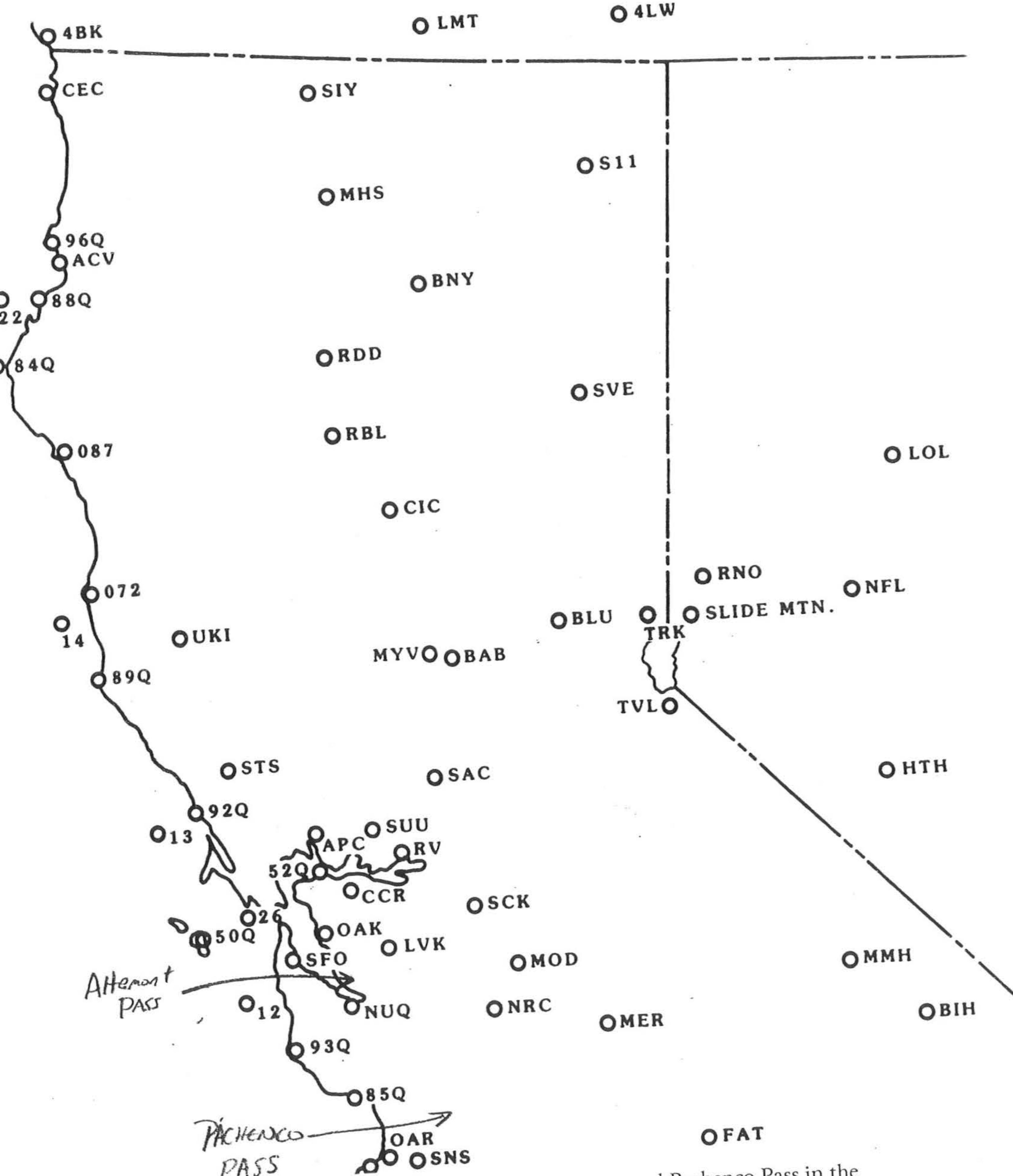
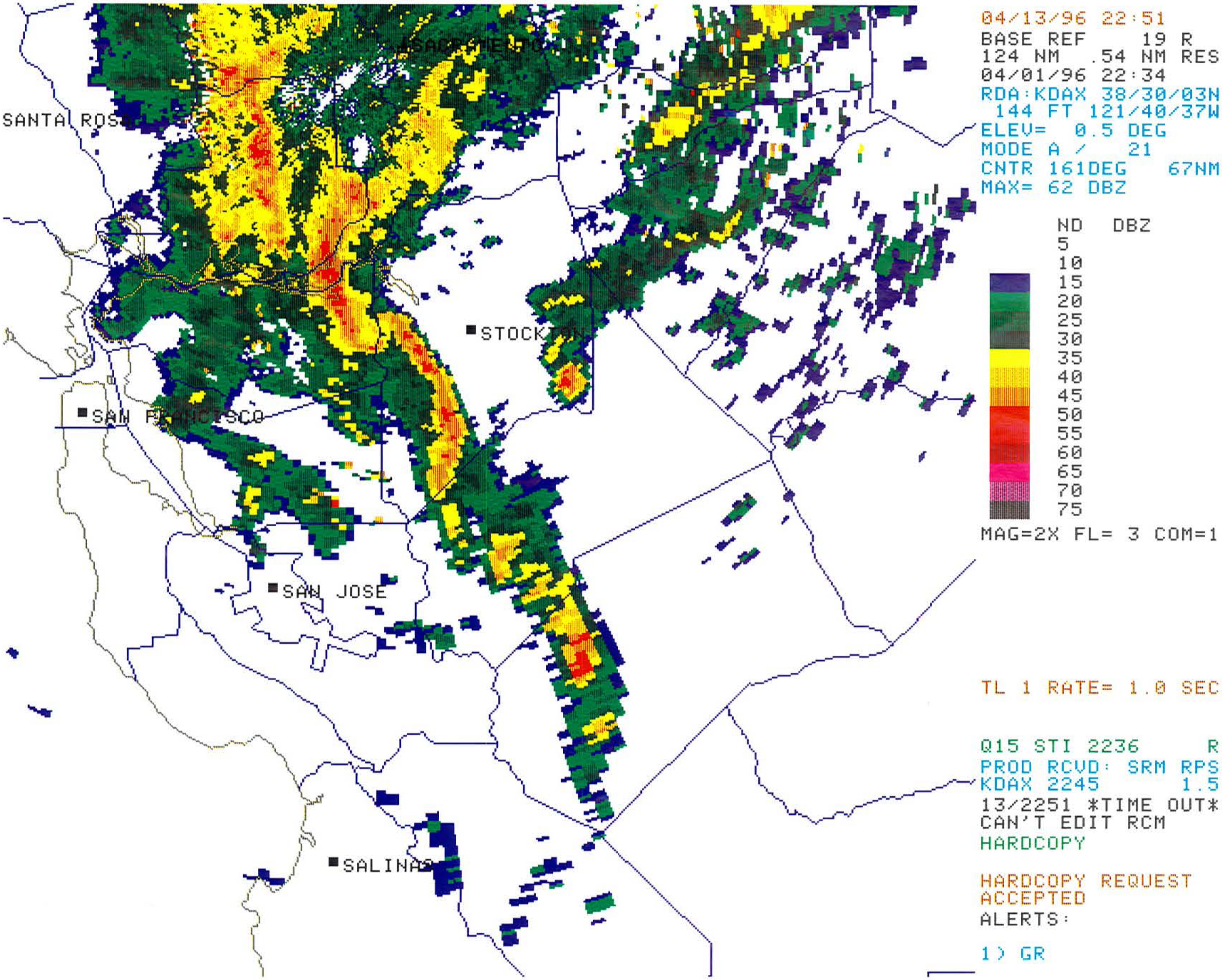


Fig 3 Map indicating the locations of Altamont Pass and Pachenco Pass in the Coastal Range Mountains.

Figure 4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STOCKTON
SAN FRANCISCO
SAN JOSE
SALINAS
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ND DBZ
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10
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MAG=2X FL= 3 COM=1
TL 1 RATE= 1.0 SEC
Q15 STI 2236 R
PROD RCVD: SRM RPS
KDAX 2245 1.5
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HARDCOPY REQUEST
ACCEPTED
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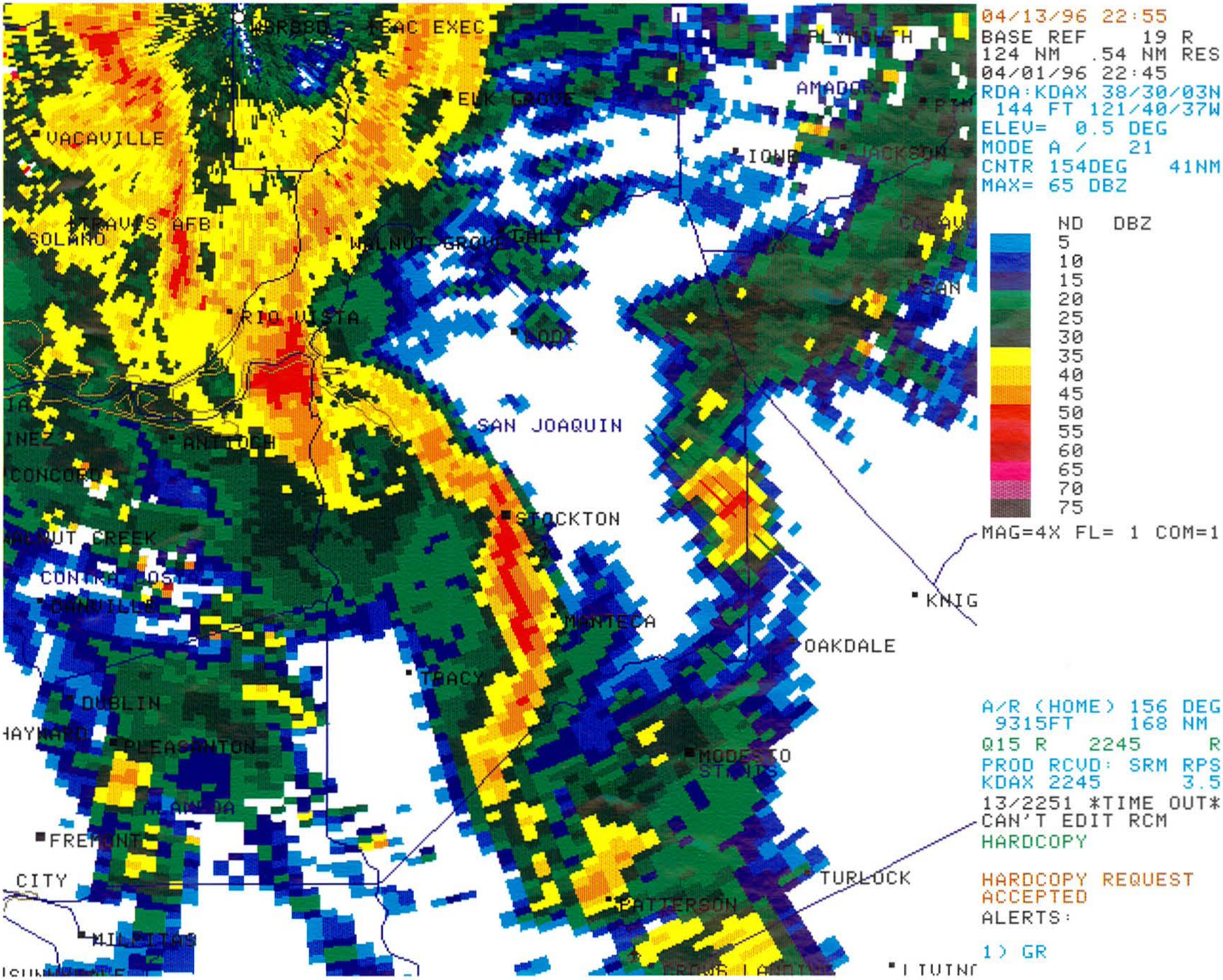
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ND DBZ
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9315FT 168 NM
Q15 R 2245 R
PROD RCVD: SRM RPS
KDAX 2245 3.5
13/2251 *TIME OUT*
CAN'T EDIT RCM
HARDCOPY
HARDCOPY REQUEST
ACCEPTED
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VACAVILLE
IONE
JACKSON
WALNUT GROVE
GALT
RIO VISTA
LODI
SAN JOAQUIN
ANTIOCH
CONCORD
STOCKTON
CONTRA COSTA
DANVILLE
MANTECA
OAKDALE
TRACY
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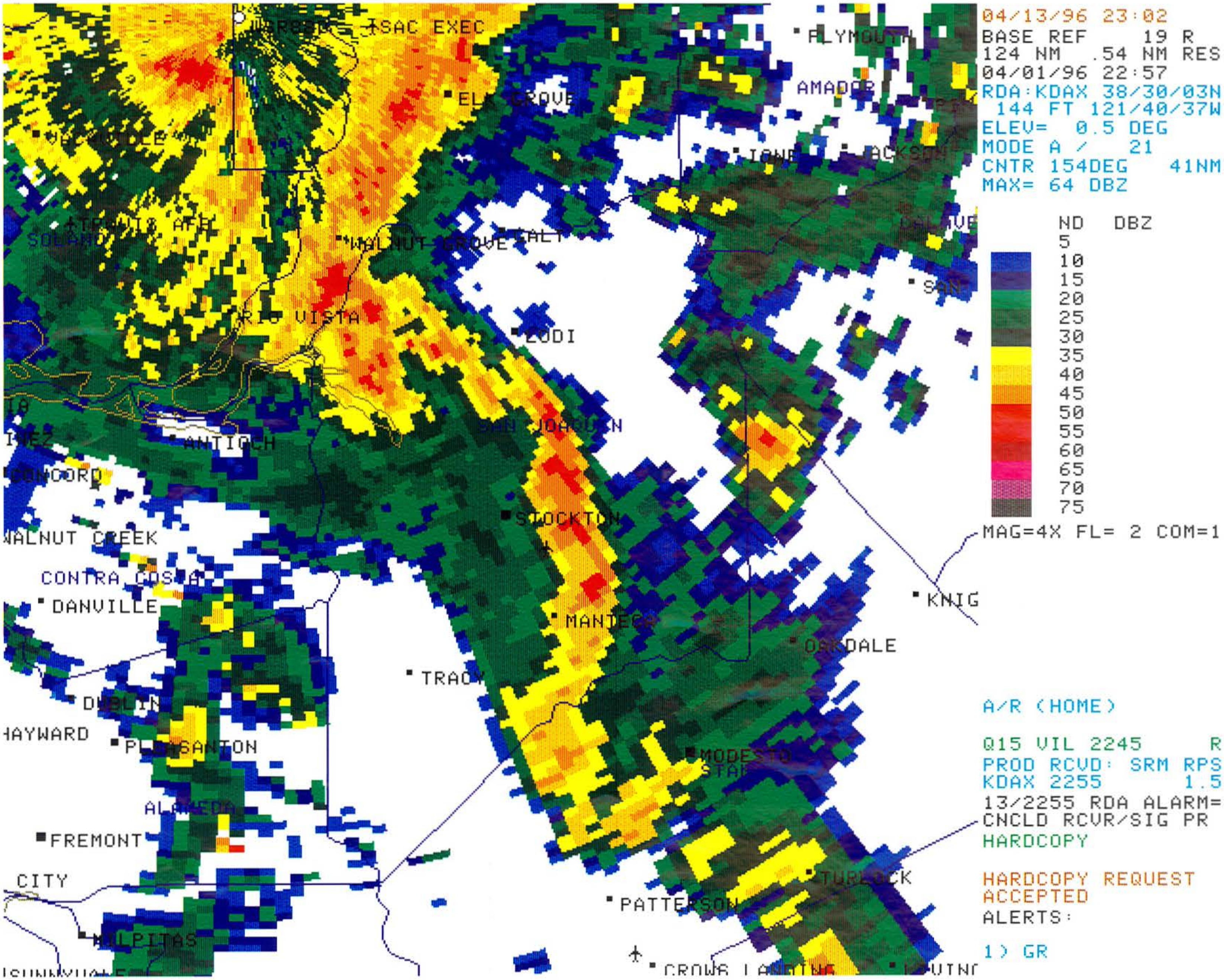
FREMONT
CITY
TURLOCK
PATTERSON
MILPITAS
KNIG

Figure 5

Figure 6



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ND DBZ
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ACCEPTED
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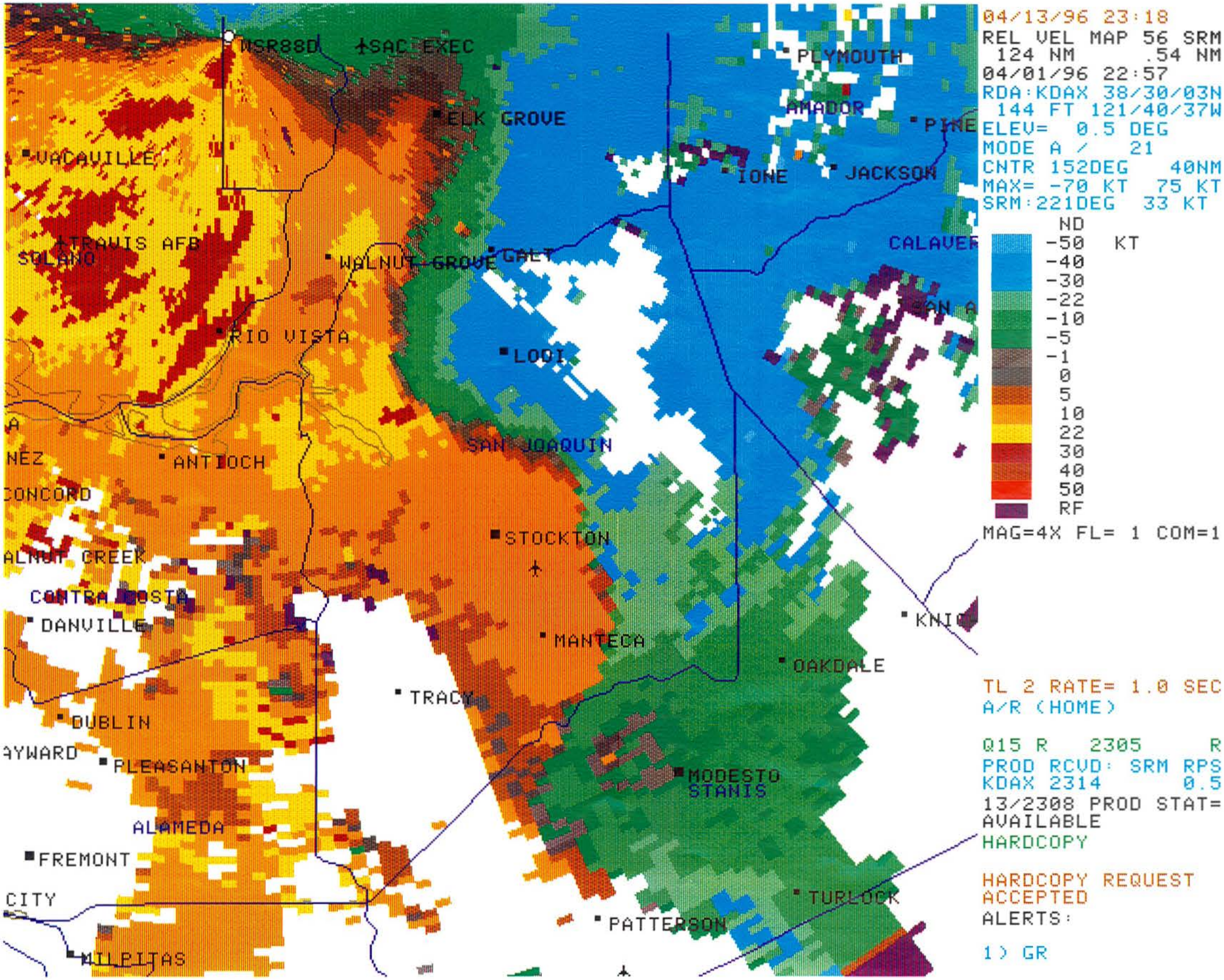
CITY
PATTERSON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MAG=4X FL= 1 COM=1
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KDAX 2314 0.5
13/2308 PROD STAT=
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HARDCOPY
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ACCEPTED
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WALNUT GROVE
GALT
CALAVER
RIO VISTA
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MANTECA
OAKDALE
TRACY
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TURLOCK
CITY
PATTERSON
MILPITAS

Figure 7

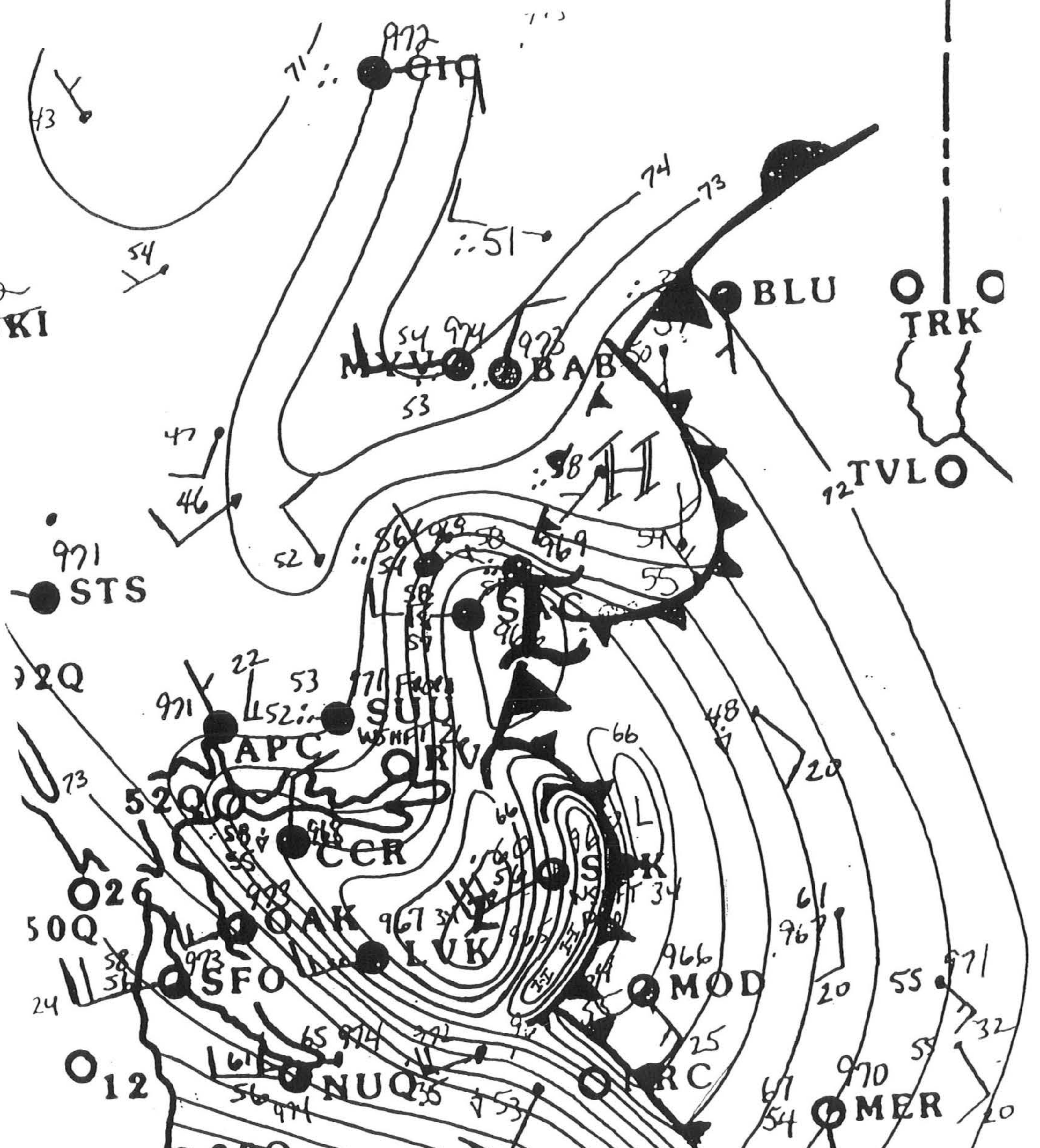
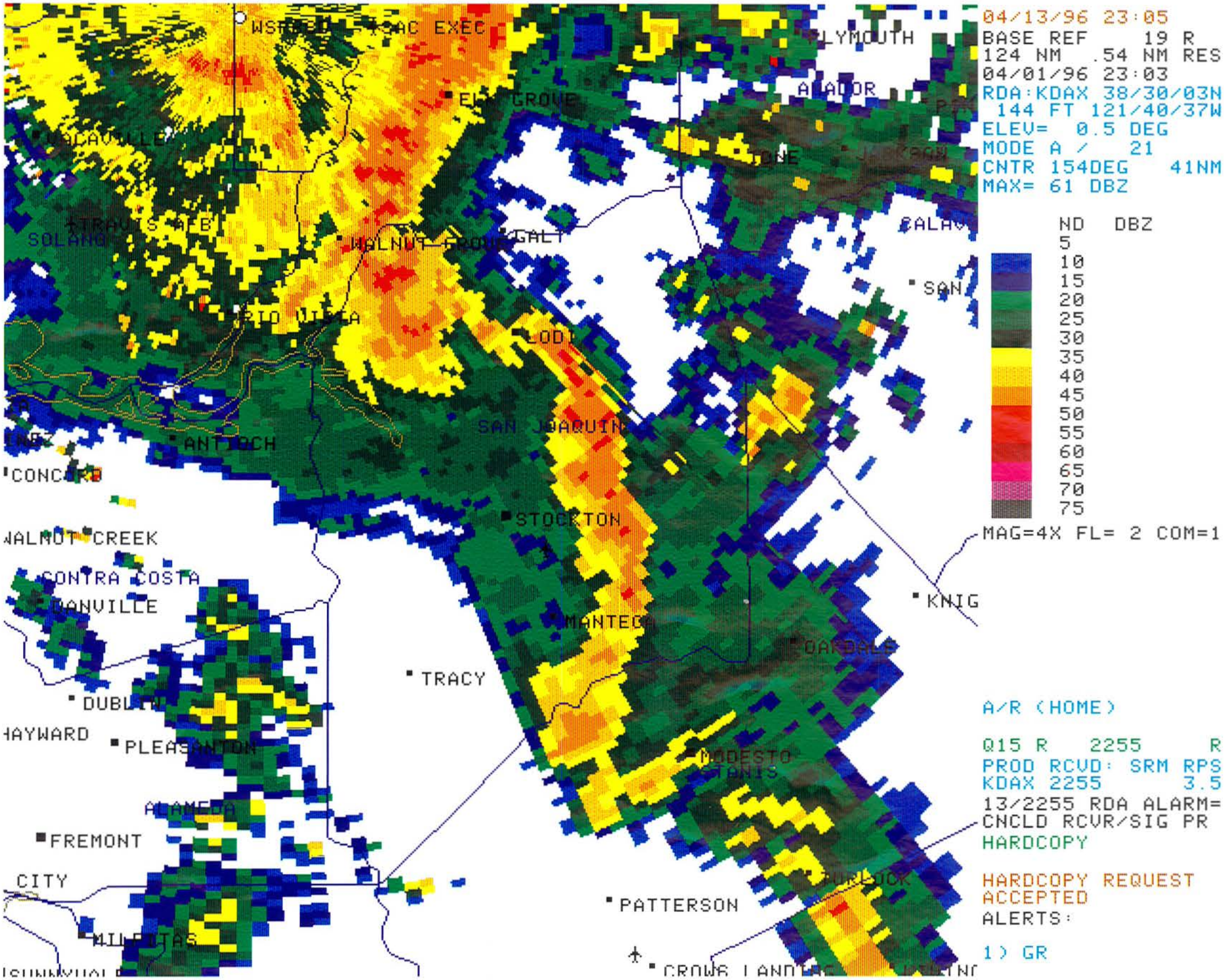


Fig. 8 Mesoscale analysis for 2255 UTC 1 April 1996. Solid lines are isobars contoured every 1 mb.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DANVILLE
MANTECA
OAKDALE
KNIG
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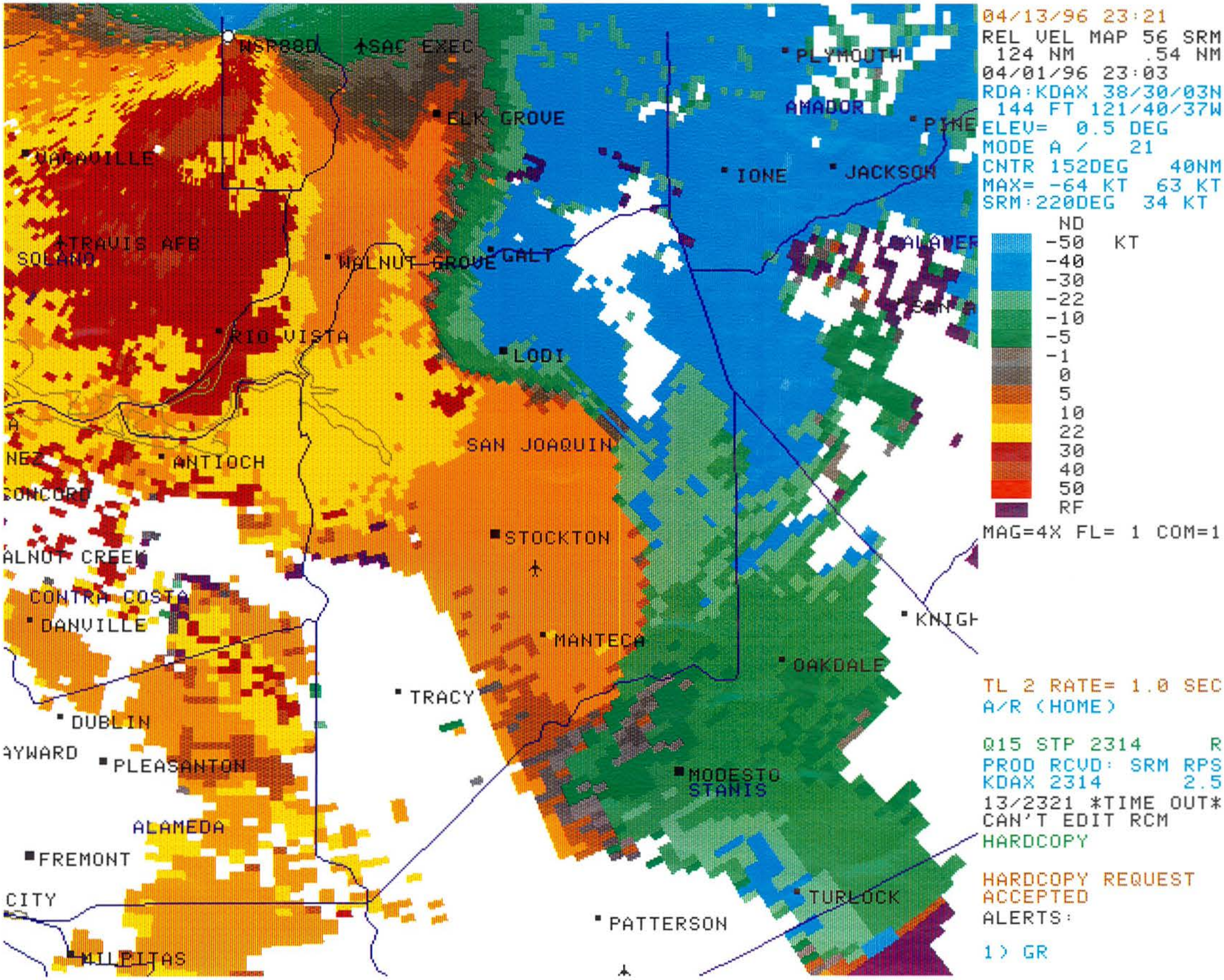
CITY
PATTERSON
CROWS LANDING

Figure 9

Figure 10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MODE A / 21
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MAX= -64 KT 63 KT
SRM:220DEG 34 KT
ND
-50 KT
-40
-30
-22
-10
-5
-1
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TL 2 RATE= 1.0 SEC
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PROD RCVD: SRM RPS
KDAX 2314 2.5
13/2321 *TIME OUT*
CAN'T EDIT RCM
HARDCOPY
HARDCOPY REQUEST
ACCEPTED
ALERTS:
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WSR88D
SAC EXEC
PLYMOUTH
ELK GROVE
AMADOR
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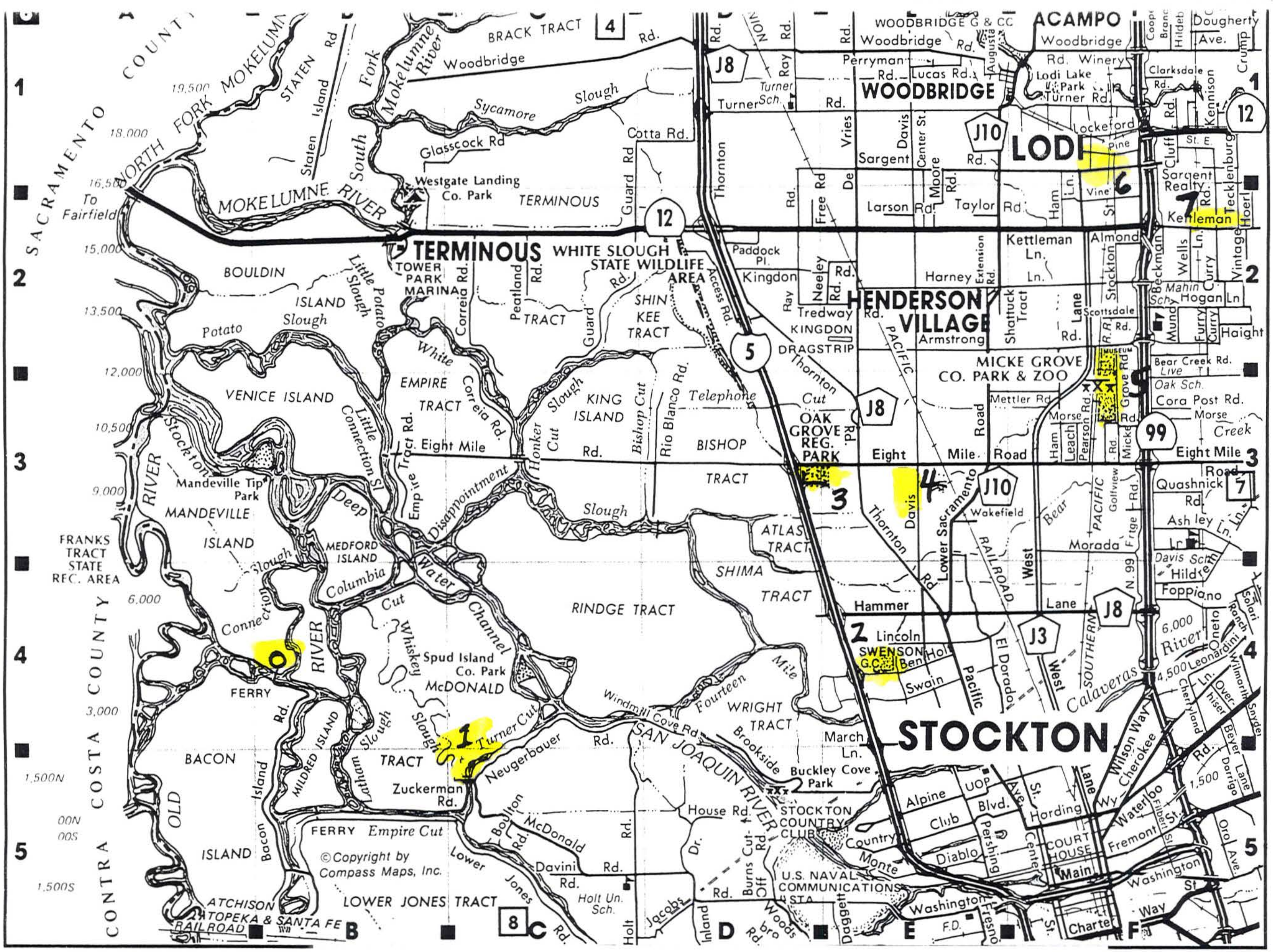
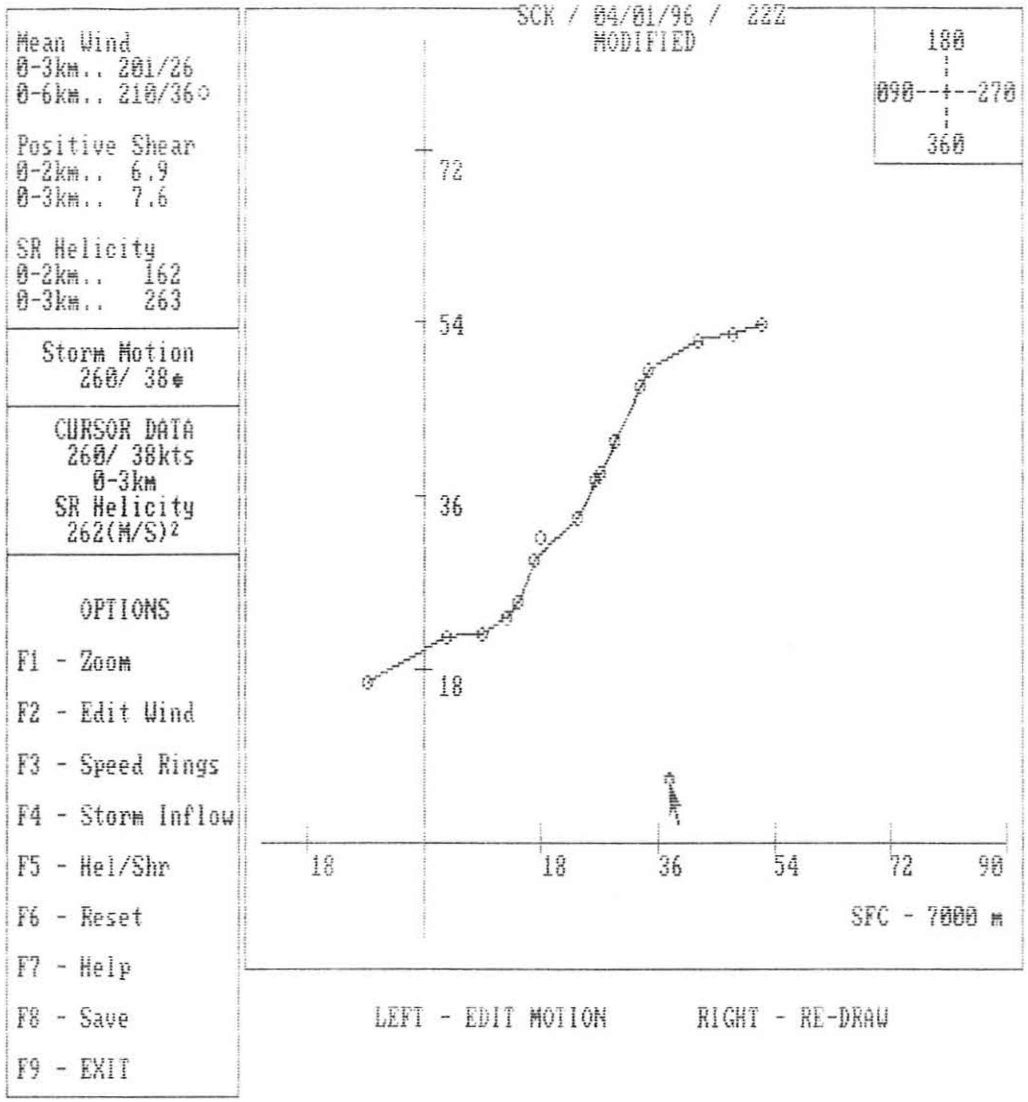


Fig 11 Locations of damage produced by northern bow echo. Reports 1,3, and 5 were determined by storm surveys to be caused by straight line wind damage with the others being produced by possible short-lived F0 tornadoes.



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0-6km.. 210/36
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0-3km.. 7.6
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0-2km.. 162
0-3km.. 263
Storm Motion
260/ 38
CURSOR DATA
260/ 38kts
0-3km
SR Helicity
262(M/S)2
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F1 - Zoom
F2 - Edit Wind
F3 - Speed Rings
F4 - Storm Inflow
F5 - Hel/Shr
F6 - Reset
F7 - Help
F8 - Save
F9 - EXIT
SCK / 04/01/96 / 22Z
MODIFIED
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090--+--270
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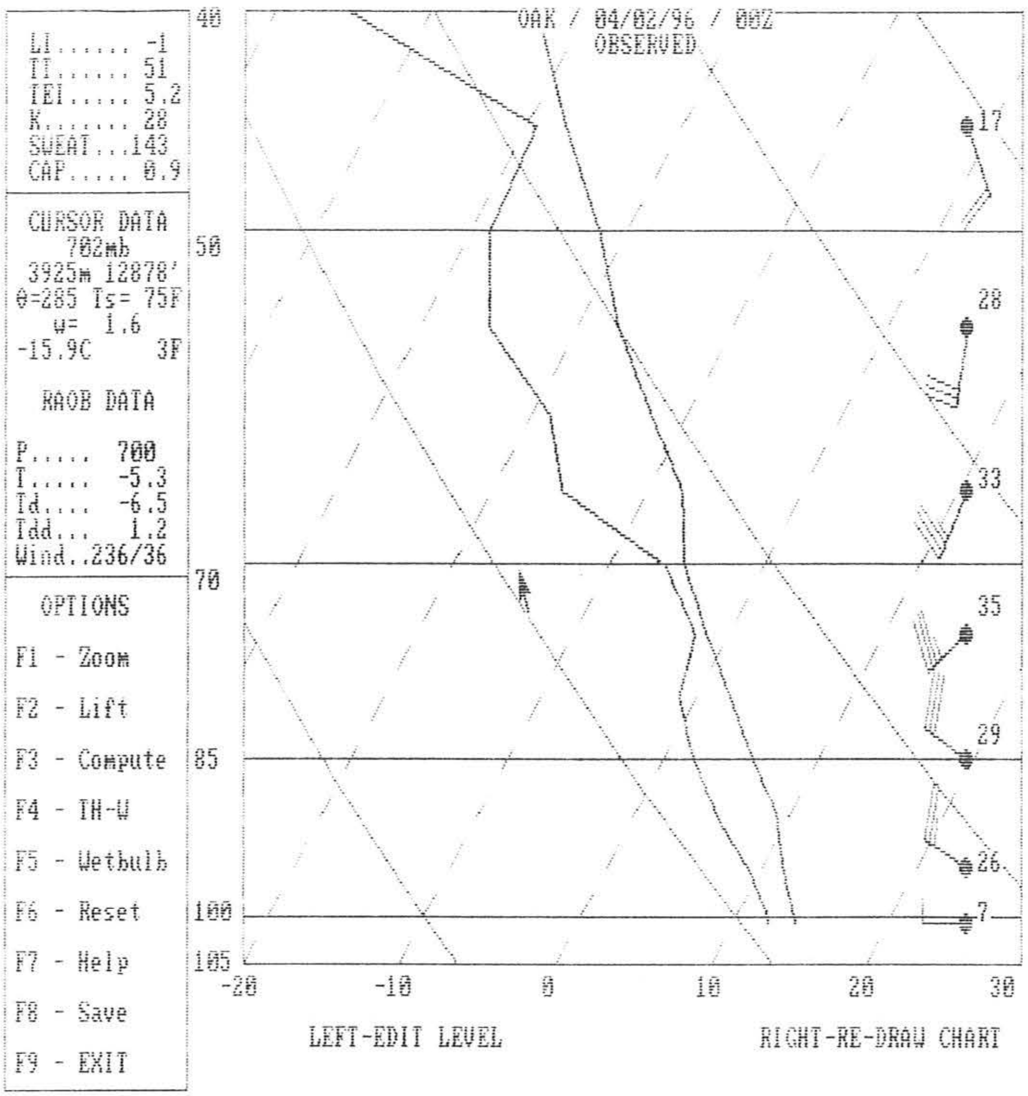
LEFT - EDIT MOTION
RIGHT - RE-DRAW

Figure 13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w= 1.6
-15.9C 3F
RAOB DATA
P..... 700
T..... -5.3
Td.... -6.5
Tdd... 1.2
Wind..236/36
OPTIONS
F1 - Zoom
F2 - Lift
F3 - Compute
F4 - TH-W
F5 - Wetbulb
F6 - Reset
F7 - Help
F8 - Save
F9 - EXIT
OAK / 04/02/96 / 00Z
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70
85
100
105
-20
-10
0
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30
17
28
33
35
29
26
7
LEFT-EDIT LEVEL
RIGHT-RE-DRAW CHART

Figure 14

Figure 15

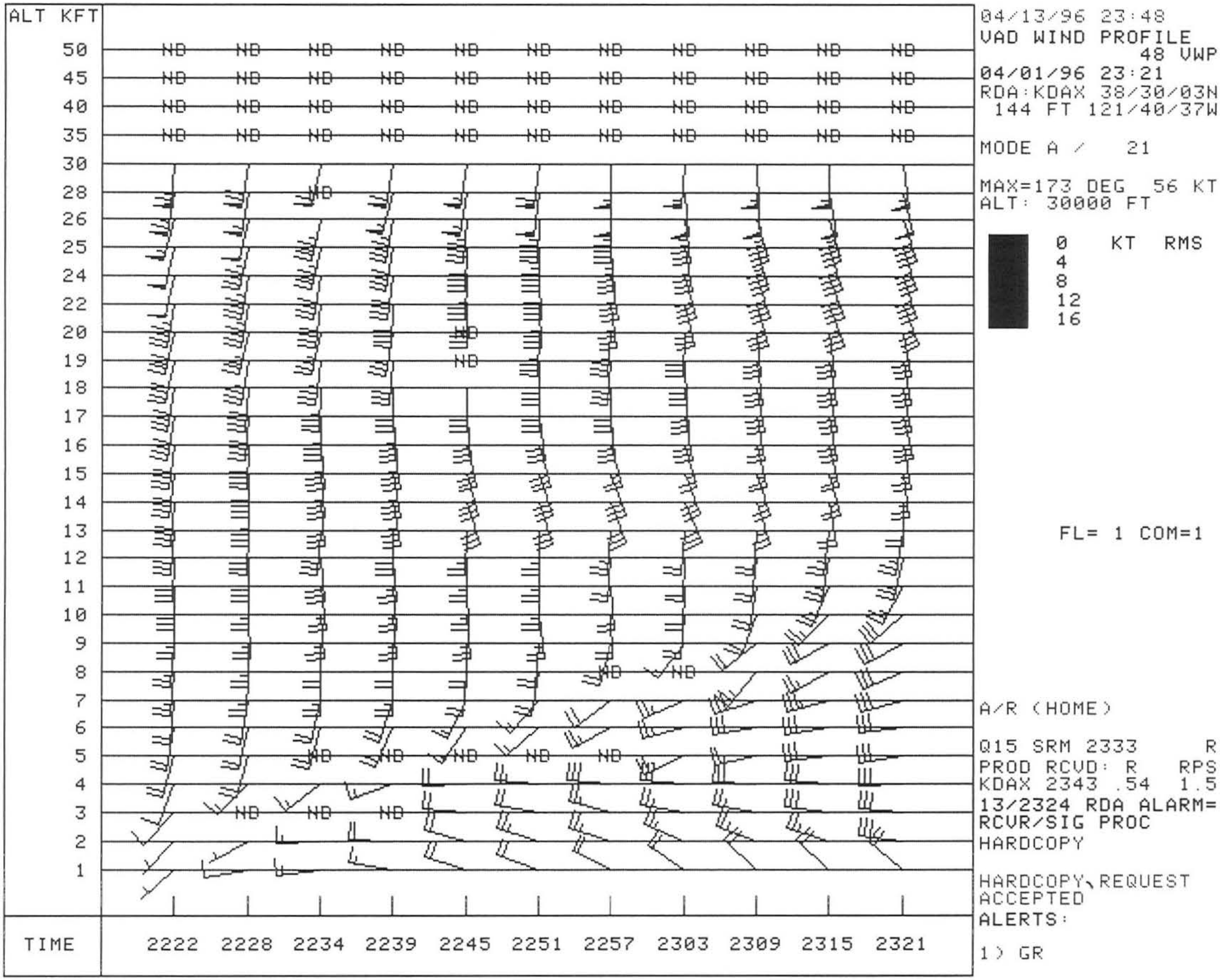
ALT KFT
50
45
40
35
30
28
26
25
24
22
20
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
ND
TIME
2222 2228 2234 2239 2245 2251 2257 2303 2309 2315 2321
04/13/96 23:48
VAD WIND PROFILE
48 VWP
04/01/96 23:21
RDA:KDAX 38/30/03N
144 FT 121/40/37W
MODE A / 21
MAX=173 DEG 56 KT
ALT: 30000 FT
0 KT RMS
4
8
12
16
FL= 1 COM=1
A/R (HOME)
Q15 SRM 2333 R
PROD RCVD: R RPS
KDAX 2343 .54 1.5
13/2324 RDA ALARM=
RCVR/SIG PROC
HARDCOPY
HARDCOPY\REQUEST
ACCEPTED
ALERTS:
1) GR

Fig 16 Pressure trace for 1 April 1996 for Stockton, CA