Report No. CDOT-DTD-R-97-4

Avalanche Detection Using Atmospheric Infrasound

A.J. Bedard Jr.
United States Department of Commerce
National Oceanic and Atmospheric Administration
Environmental Research Laboratories
Boulder, CO. 80303-3328

Final Report
April 1997

Prepared in cooperation with the
U.S. Department of Transportation
Federal Highway Administration

REPORT DOCUMENTATION PAGE

FORM APPROVED
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	April 1997	Final Report Winter 1994 - 1995

4. TITLE AND SUBTITLE
Avalanche Detection Using Atmospheric Infrasound

5. FUNDING NUMBERS

6. AUTHORS(S)
A.J. Bedard Jr.

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(S)
United States Department of Commerce
National Oceanic and Atmospheric Administration
325 Broadway, Boulder, Co. 80303-3328

8. PERFORMING ORGANIZATION REPORT NUMBER
CDOT-DTD-R-97-4

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(S)
Colorado Department of Transportation
4201 E. Arkansas Ave.
Denver, Colorado 80222

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
CDOT-DTD-R-97-4

11. SUPPLEMENTARY NOTES
Prepared in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

12a. DISTRIBUTION/AVAILABILITY STATEMENT
No Restrictions: This report is available to the public through the National Technical Information Service. Springfield, VA 22161

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

This report describes the phenomena that snow avalanches produce sounds in the 0.5 to 5.0 Hertz range. It also documents testing of an infrasound detection system to detect snow avalanches in the southwest mountains of Colorado. Two infrasound sensors were installed so the direction of the sound could be determined by comparing the phasing and arrival times.

Avalanche detection was sometime obscured because of the high mountains nearby diverting the sound and causing clear-air turbulence.

Linking sound events with avalanche events was hampered by the fact that the time of actual avalanches could only be determined within a 12-hour period. Results were encouraging, but further testing is necessary to better define the sound patterns produced by avalanches before such a system can be used in conjunction with a motorist warning system.

Synergistic use of these detectors may be possible because of their ability to detect tornados and worldwide nuclear bomb testing.

14. SUBJECT TERMS
Infrasonic, Sound,
Snow,
Acoustic,

15. NUMBER OF PAGES
25

16. PRICE CODE

17. SECURTITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT

AVALANCHE DETECTION USING ATMOSPHERIC INFRASOUND

REPORT

A. J. Bedard, Jr.
NOAA/ERL/Environmental Technology Laboratory

TOPICS COVERED: Testing program in Silverton, Colorado, during the winter of 1994–1995 and subsequent progress and developments.

1. BACKGROUND

This report focuses on the experiment performed at Silverton, Colorado, from January through April 1995. Subsequently, we have continued to improve and test hardware and software. Currently, we continue to operate an infrasonic observatory near Boulder, Colorado, and are collecting data. A plan exists to operate a second observing system at Colorado Springs as a component of another program. This second observatory should provide some data for testing triangulation. The relationships between our avalanche work and parallel efforts to detect other geophysical phenomena are also described. Finally, recommendations are made for future work. Table 1 summarizes efforts to evaluate infrasonic avalanche detection.

2. THE SILVERTON, COLORADO, WINTER 1994–1995 EXPERIMENT

2.1 Overview

Silverton, Colorado, is located to the south of Red Mountain pass in southwest Colorado. This is a region of quite frequent natural and controlled avalanche activity. The control crews report avalanche activity to the Silverton Avalanche Prediction Center where the details are recorded. We located the system at the offices of the Avalanche Prediction Center, where we were given support for day-to-day operations. Many avalanche-related signals recorded during the experiment continue to indicate the potential value of the system. We also operated new hardware and software, testing the integration of GPS and a new algorithm designed to identify avalanche signal types while rejecting other signals. A naturally generated infrasonic signal frequently was present in this region, and the details and implications of this signal are discussed.

Silverton, Colorado, Winter 1994–1995 Experiment

This experiment was designed to operate an infrasonic observing system under more operationally oriented conditions. As shown in Fig. 1, Silverton is located in the vicinity of numerous identified avalanche paths near main roads. In this region, there are also more remote areas prone to avalanches.

TABLE 1. Summary of efforts to study and apply low-frequency sounds from avalanches.

Program	Approach	Key Results
Harrison (1976)	Measured sounds below about 0.5 Hz.	No sound detected.
Bedard *et al.* (1988)	Correlated sounds with avalanches in a 0.5–2.5 Hz passband.	Observed signals with bearings and times matching times of controlled avalanches and corresponding to episodes of enhanced regional avalanche activity.
Bedard (1989)	Attempted to measure sounds from controlled avalanche releases using a mobile observatory.	Demonstrated that control measures were not producing significant energy in the 0.5–2.5 Hz passband. No controlled avalanches were produced.
Bedard (1994)	During the winter of 1993–1994, deployed an observatory at Gothic, Colorado, to monitor sounds in the frequency range from 0.5 to 5 Hz in a region of frequent avalanches.	A large avalanche on Gothic mountain provided a clear example of an acoustic signal at the source region and a pattern of high-frequency acoustic signals matched a pattern of regional avalanche activity.
Silverton, Colorado, experiment	Installed observing system during winter of 1994–1995. Focused on improved analysis and display methods, and was more operationally focused. Also, a Global Positioning System (GPS) to get precise time was used.	Test of on-site analysis and automatic data transfer was successful. Experiment details are covered in this report.
Thermal Acoustic Wave Experiment	Operated two systems during the summer of 1995 to test hardware and software by triangulating on severe weather.	Successfully tested systems and documented infrasonic radiation from a tornado.
Mountain-Induced Clear-Air Turbulence experiment (MCAT97)	Operating two systems at Colorado Springs and the Boulder Atmospheric Observatory during February and March 1997.	Will be searching data obtained for avalanche signals, as well as turbulence-related signals, which are the focus of the study.

2.2 Hardware and Processing

The system uses two computers networked together, as shown in Fig. 2. The data from the four sensors were sampled at 20 Hz per channel by an analog-to-digital converter and fed to the acquisition computer. A GPS automatically logged the geographical position of the site and kept the system time accurate to better than 1 s. Each of the four sensors of the array was equipped with a wind noise reducer consisting of twelve 25-ft lengths of porous irrigation hose, radiating outward from a central sensor. Figure 3 shows a version of this wind noise reducer. The sensors are configured in a roughly square array, usually spaced from 50–100 m on a side. The sensor outputs were fed over cables to the central computers.

Processing was performed by the second computer, which provided information on the signal-to-noise ratio, azimuth, horizontal phase speed, dominant frequency, and power for each block of data processed. This information, in addition to the original raw data, was periodically archived to tape.

2.3 Goals of the Experiment

The primary goals of the experiment were the following:

(a) To test the new hardware and software developed under conditions that are similar to envisioned future operational installations.

(b) To compare signals recorded with observations and times of avalanches. This should increase our database of signal characteristics known to originate from avalanches.

(c) To obtain preliminary experience with an algorithm designed to discriminate between avalanche signals and sounds from other sources. This software requires that the sound be in a passband that our past experience indicates avalanche acoustic energy occurs. It also uses information about duration and signal-to-noise ratio. Any signals passing these criteria cause the processing computer to beep and flag the characteristics of the significant signal on the screen.

(d) To demonstrate the feasibility of sending the processed data to a remote location over phone lines and monitor signal activity. A part of this effort will be to test a triangulation program that will potentially provide the locations of avalanche-related signals.

(e) To record data at lower frequencies to further develop an archive to be used to test algorithms for detection and discrimination.

3. MEASUREMENT METHODOLOGIES

During the period of the experiment, many avalanches were reported by control road crews. Typically, the times of occurrence were identified to within about 12 h. Usually, a precise time was not available because observations often involved natural avalanches that occurred either at night or during a snowstorm. Within a 12-h time block, the locations and sizes of reported avalanches were plotted on a regional map together with infrasonic signal azimuths detected during this time period. Class 2 avalanches are indicated using a small circle with class 3 and class 4 avalanches indicated by progressively larger circles.

The infrasonic signals plotted were those showing characteristics associated in the past with avalanches [i.e., short-duration (usually less than 2 min), acoustic-phase velocities, large correlations, and a sharp spectral peak in the range of 0.5–5 Hz]. The experiment covered from late January to late April 1995. The following section focuses on an interval of high avalanche activity in early March 1995, which captures the key lessons learned from this experiment. All data from the experiment were processed and reviewed. Data processed in real time and sent over phone lines were found identical to post-processed data from archived magnetic tapes.

4. RESULTS AND IMPLICATIONS

The locations of avalanche activity and the bearings of infrasonic signals are compared in the following set of figures. In these figures, class 2, 3, and 4 avalanches are indicated by the sizes of the solid circles on the plots (the largest circles indicating class 4). Infrasonic signals are indicated by straight lines radiating from the location of the Silverton observatory to the direction of the source of infrasound.

March 2, 1995 (0000–1200 MST). During this time period, three class 3 and two class 2 avalanches were reported. Three infrasonic signals occurred from bearings corresponding to the two class 3 and one of the class 1 avalanches. (Figure 4)

March 2, 1995 (1200–2400 MST). Although one class 2 avalanche and one class 3 avalanche were reported to the northwest, neither of these were detected. Two infrasonic signals from the north did not correspond with any reports in the region. (Figure 5)

March 4, 1995. Another infrasonic signal from the north corresponded to a class 3 avalanche. There was no other local avalanche activity reported on this day. (Figure 6)

March 5, 1995 (1200–2400 MST). Three class 2 avalanches were reported to the west and southwest of Silverton. For two of these, the infrasonic signals correspond in bearing. One avalanche was not detected, and two additional infrasonic signals had no matching avalanche and could have originated at more distant locations. (Figure 7)

March 6, 1995 (0000–1200 MST). On this day, there were nine class 2 and seven class 3 avalanches reported, as well as numerous infrasonic signals. However, there was poor correspondence between the avalanche bearings and the signal locations. (Figure 8)

March 6, 1995 (1200–2400 MST). During this interval, there were four class 3 and three class 4 avalanches. Infrasonic azimuths were at the bearings of the class 4 avalanches and near several of the class 3 avalanches. (Figure 9)

The data indicate numbers of cases where a bearing originated from the bearings of reported avalanches. However, there were also avalanches reported with no infrasonic signals reported. Furthermore, it is notable that no signals having the characteristics of avalanche-related infrasound originated from the quadrant centered on east. A combination of the complex terrain in the region and propagation effects can explain these results. Silverton is located in a valley with mountains surrounding on all sides. In addition, many of the avalanche paths follow low ground between higher terrain. Thus, our infrasonic observatory was sheltered from direct acoustic propagation paths from many avalanches. On the other hand, diffraction of sound at the tops of mountains and refraction by atmospheric wind and temperature profiles can permit propagation into acoustic "shadow" zones. The zonal winds above mountain-top height during the winter months are usually from west to east, increasing with height. This favors trapping sound waves that are propagating from west to east, and may explain the lack of avalanche-type infrasonic signals from the east. Figure 10 summarizes these processes and indicates why it may be best to locate infrasonic observatories well to the east of the region you wish to monitor and not paradoxically at a location centered near numerous avalanche paths. This comment does not apply to an avalanche path where a clear acoustic "line of sight" is available.

An unusual signal was present almost continuously at the Silverton observing site and complicated the detection of avalanche-related signals. While larger-amplitude avalanche-type signals could be readily identified in the presence of this background, it is probable that many weaker avalanche signals were masked. Figure 11 shows that this signal seems to show two distinct bearing sectors during March 1995. It usually has a low correlation coefficient (~0.4) with sporadic increases (>0.6). Figure 12 shows histograms of azimuth and horizontal trace speed covering a 20-h interval. Figure 13, based upon the histogram of azimuth, indicates the two sectors from which the signal originated. The fact that the histogram of horizontal trace speed showed many arrivals at higher than acoustic velocities means that the signal frequently came from aloft.

Past measurements have related infrasound to airflow over mountains and regions of aircraft turbulence (Bedard, 1978). It is probable that this background signal is related to winds interacting with regional mountain peaks. This seems to be another reason for locating infrasonic observing systems at a distance from the region of high mountains you wish to monitor for avalanche activity. This dataset indicates that the sound source is usually relatively weak unless you are in the immediate vicinity. In addition, because it is probably of large areal extent, it will probably decorrelate rapidly at longer ranges. However, we note that detecting this signal type could be valuable for other missions (e.g., warning of regions of clear-air turbulence).

5. OTHER PROGRESS SINCE THE SILVERTON 1994–1995 EXPERIMENT

Since the Silverton 1994–1995 experiment, we have continued to make progress on evaluating and improving avalanche detection using infrasound while other geophysical studies were being pursued. Specifically, experiments during the summers of 1995 and 1996 resulted in further evaluation and improvements of hardware and software. An experiment currently in progress to study infrasound related to turbulence is providing further opportunities to collect avalanche signals and study their statistics and characteristics. Just as the avalanche program has provided support in the past for improving and evaluating hardware and software, other programs (severe weather and aircraft turbulence studies) now enable us to continue evolving infrasonic detection methods. We anticipate that this synergism can continue.

6. COMPARISONS WITH OTHER AVALANCHE MEASUREMENTS

A comparison with recent avalanche measurements (Nishimura and Izumi, 1996) provides some important insights into potential infrasonic source mechanisms. Previously, Bedard *et al.* (1988) noted that avalanche roll waves would pass a fixed point with the same frequency as infrasonic waves detected from avalanches. Nishimura and Izumi measured an avalanche on February 5, 1991, with wind speeds in excess of 60 m s^{-1} accompanied by impact pressure spikes occurring at slightly less than 1-s intervals (near the typically measured infrasonic frequencies). They also documented power spectra showing seismic energy as a function of time, indicating that most of the seismic energy occurred at frequencies between 5 and 30 Hz.

They measured wind speed and static pressure changes associated with an avalanche on January 29, 1996. The details of their instrumentation were not documented in their report, but the static pressure changes were quite significant. These fluctuated between -5 and +15 mb at dominant frequencies above 1 Hz. If these pressure changes are true static pressure changes, the measurements could reflect the near-field infrasonic pressure levels.

Nishimura *et al.* (1989) suggested that ordered, vortex-like structures may be a component of the snow cloud. Kawada *et al.* (1989) provided additional impact force data, again in the same frequency range as our infrasound measurements. They contrasted two avalanche types. One of these had sharp peaks on the force gauge record separated by intervals of about 0.5 s, while the other produced rounded spikes separated by about 0.2-s intervals.

7. INFRASONIC SOURCE MECHANISMS

This section discusses a possible source mechanism hinted at in the paper by Bedard *et al.* (1988). An analysis using semi-empirical information showed the frequencies of avalanche roll waves passing a fixed-point wave in the same frequency range as recorded infrasonic waves. The previous section provides additional experimental evidence for these frequencies. The wavelengths of the rolls on average are about 18 times the height of the avalanche body (which is often in the range from 1 to 3 m). This approach indicated frequencies in the range between 1 and 3 Hz, with the stronger, faster-moving avalanches producing the lower frequencies. But how is the acoustic energy produced? Since merely moving a mass from one point to another at low Mach numbers is not a very efficient sound-producing mechanism, there certainly are other important factors. Turbulence within the avalanche could produce quadrupole or dipole sound generation processes that are also relatively inefficient.

From the Gothic, Colorado, experiment, we can make an estimate for the sound pressure levels at the source, which can be used to examine sound generation processes. The observing system was about 1.5 km from the base of Gothic mountain, and on February 24, 1994, it observed an infrasonic signal that shifted from the upper regions of the mountain to the base. We associated this with a large (class 4) avalanche that occurred during the night. The pressure amplitudes were greater than 100 μbars from peak to peak. If we presume a decay of amplitude as a function of distance proportional to the inverse range because of geometrical spreading of the sound wave, we can make an estimate of the pressure levels in the source region. If we assume the source dimensions are about 50 m, the pressure amplitudes will be about 3 mb. Such pressure amplitudes should be felt by those in the vicinity of avalanches and also cause nearby structures to vibrate.

But what process can cause such large pressure changes? One feature of many avalanches is that the slab (which is initially at a temperature below freezing) is warmed by friction as it descends and then rapidly refreezes. These heating and cooling processes will be controlled by the dynamical processes of the avalanche and can produce significant pressure changes.

Snow of an average temperature of -4 °C is warmed by friction as the avalanche progresses, and some snow is melted. As the water drops mix with cold air, they become supercooled and can rapidly refreeze. This warming and refreezing is modulated by the avalanche dynamics with releases of heat as changes of state occur.

McClung and Schaerer (1993) pointed out that snow from dry avalanches can be mistaken for moist or wet snow avalanches because of frictional rubbing of particles during descent. Releases of heat over a region of the avalanche can represent an efficient monopole sound-source generation mechanism. In fact, it will only take an average temperature rise or fall of less than 1 °C in a region of the avalanche to produce the signal pressure levels observed near Gothic mountain.

Thus, we suggest as a working model for the sound generation process a system where the roll wave dynamics control the frequency of releases of heat associated with frictional rubbing of particles, as well as refreezing. In this picture, the infrasonic dominant frequency indicates the roll wave frequency and, indirectly, the avalanche height, while the amplitude is an index of the amount of heat released. If this model is correct, we would expect relatively little infrasound from wet snow slab avalanches where frictional melting and refreezing does not occur.

8. OTHER USES FOR INFRASONIC OBSERVATORIES

There are other potential uses for infrasonic observatories, and a number of these applications could provide capabilities serving multiple missions, in addition to avalanche detection missions including:

(a) clear-air turbulence detection and warning,
(b) tornado detection and warning,
(c) detection of meteors and space debris, and
(d) detection of nuclear explosions.

(a) We have past evidence relating infrasonic source locations to regions of clear-air turbulence reported by pilots (Bedard, 1978). The experiment at Silverton indicated that there were often sources (sometimes directly overhead) radiating continuously for periods of hours. The indications are that the source passbands and observatory locations for turbulence detection may also be ideal for avalanche detection. We currently are evaluating turbulence detection capabilities.

(b) There is an extremely important potential for detecting and tracking severe weather vorticity, including tornadoes and mesocyclones. We hope to do testing in Oklahoma in the near future and hope to demonstrate capabilities to improve tornado and mesocyclone detection and warning. Our vision is that infrasonic observatories could be located at NEXRAD sites in the future.

(c) We have shown capabilities for detecting meteors and space debris, which could be valuable for obtaining statistics on objects of various sizes entering the atmosphere. We are working to document these data.

(d) The Nuclear Test Ban Treaty includes an agreement on the details of an international monitoring system. This system includes infrasonic observatories to be deployed in large numbers on a world-wide basis. Many of these will also be well positioned to help with avalanche warnings, as well as other geophysical missions. The plan is that data from all sensors will be made available to the international community.

Because of the potential of multiple missions for infrasonic observations, there is a need to be sensitive to these possible alternate applications when locating observatories.

9. RECOMMENDATIONS FOR FUTURE WORK

We recommend that the following steps be taken to provide the final pieces of information we need to optimize infrasonic observing systems for avalanche detection and warning:

1. Apply a rapid deployment version of the infrasonic system (plans are to create such a system for tornado studies) and make measurements near controlled avalanches.

2. It will be critical to document the avalanche characteristics for comparison with the infrasonic signatures obtained. The measurements should include a mobile Doppler radar, video, and an infrared radiometer to measure temperature fluctuations.

3. The measurements should cover different types of avalanches, sizes, and include fall, winter, and spring.

4. Review data being recorded during the winter of 1997 at Boulder and Colorado Springs to test regional detection of avalanches from the east of the Front Range. This approach will reduce the possibility of sound sources from mountain-caused turbulence above mountain sites making avalanche detection more difficult.

5. East of the Front Range, monitoring will also exploit the fact that the upper-level winds will trap the avalanche sounds and guide them to the surface to the east. Recommend we analyze the effects of upper-level winds for improved detection.

6. The sound pressure levels measured at Gothic were so large (100 μbars) that a single sensor might be used effectively to activate road warning signs or gates for this class of avalanche (estimated at class 4). Recommend we analyze this approach.

The results of recommendations 1–4 above will create the data needed to define the strengths and weaknesses of infrasonic avalanche monitoring and guide future applications. The emerging concept is that there may be two areas of use for infrasonic sensors in helping with the avalanche problem:

1. Observing sites to the east of the Front Range that monitor large regions of the mountains. These should be spaced so that triangulation is possible. If the hypothesized source mechanism is correct, avalanche location and size range can be identified.

2. For specific locations, roads can be equipped with single infrasonic sensors and road warning signs or gates activated when a large avalanche is occurring.

ACKNOWLEDGMENTS

We are greatful for the support of the Colorado Department of Transportation, especially Dave Woodham, Neil Lacey, and Richard Griffin. We also thank Don Bachman and Denny Hogan of the Silverton Avalanche detection program for their help with the installation and operation of the Silverton Infrasonic Observatory.

REFERENCES

Bedard, A. J., Jr., 1978. Infrasound originating near mountainous regions in Colorado. *J. Appl. Meteor.* **17**, 1014–1022.

Bedard, A. J., Jr., 1989. Detection of avalanches using atmospheric infrasound. Proc., *Western Snow Conference*, Ft. Collins, CO, April 18–20, 1989, 7 pp.

Bedard, A. J., Jr., 1994. An evaluation of atmospheric infrasound for monitoring avalanches. Proc., *7th Int. Symp. on Acoustic Remote Sensing and Associated Techniques of the Atmosphere and Oceans*, NOAA/ERL/Environmental Technology Laboratory, Radian Corp., and AeroVironment, Inc., Boulder, CO, October 3–5, 1994, 10 pp.

Bedard, A. J., Jr., G. E. Greene, J. Intrieri, and R. Rodriguez, 1988. On the feasibility and value of detecting and characterizing avalanches remotely by monitoring radiated sub-audible atmospheric sound at long distances. Proc., *A Multidisciplinary Approach to Snow Engineering*, Santa Barbara, CA, July 11–14, 1988, 4 pp.

Harrison, J. C., 1976. Avalanche release and snow characteristics, San Juan mountains, Colorado. In *Seismic Signals from Avalanches*. Final Report, San Juan Avalanche Project, Institute of Arctic and Alpine Research, Univ. of Colorado, Boulder, CO. R. L. Armstrong and J. D. Ives (eds.), chapter 7, pp. 145–152.

Kawada, K., K. Nishimura, and N. Maeno, 1989. Experimental studies on a powder-snow avalanche. *Annals of Glaciology* **13**, 129–134.

Marshall, J., and J. Roberts, 1992. *Living (and Dying) in Avalanche Country*. J. Marshall, 204 pp.

McClung, D., and P. Schaerer, 1993. *The Avalanche Handbook*. The Mountaineers, Seattle, WA, 271 pp.

Nishimura, K., and K. Izumi, 1996. Seismic signals induced by snow avalanche flow. (Personal communication.)

Nishimura, K., H. Narita, N. Maeno, and K. Kawada, 1989. The internal structure of powder-snow avalanches. *Annals of Glaciology* **13**, 173–178.

FIGURES

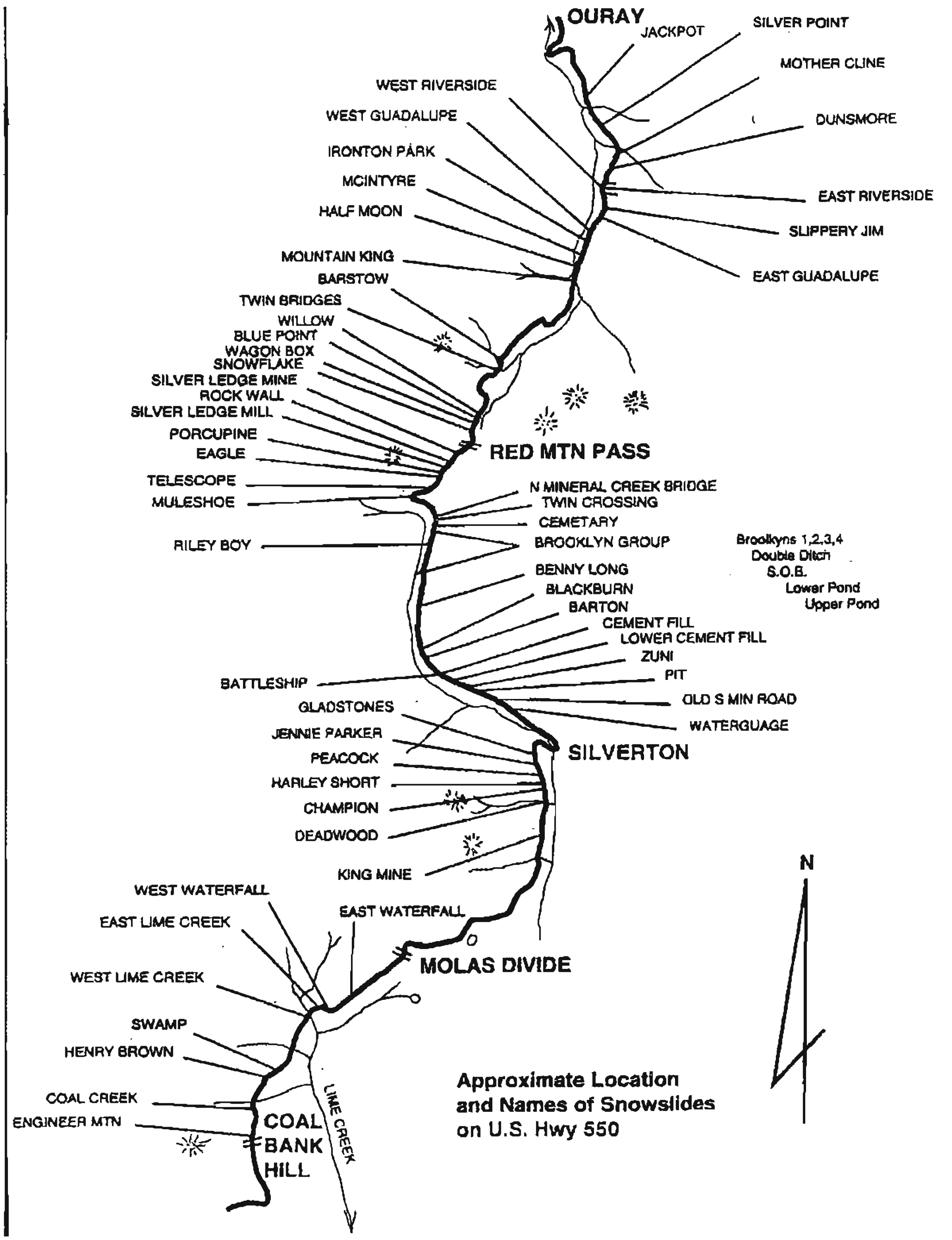

Figure 1. Avalanche paths in the vicinity of Silverton, Colorado. (After Marshall and Roberts, 1992)

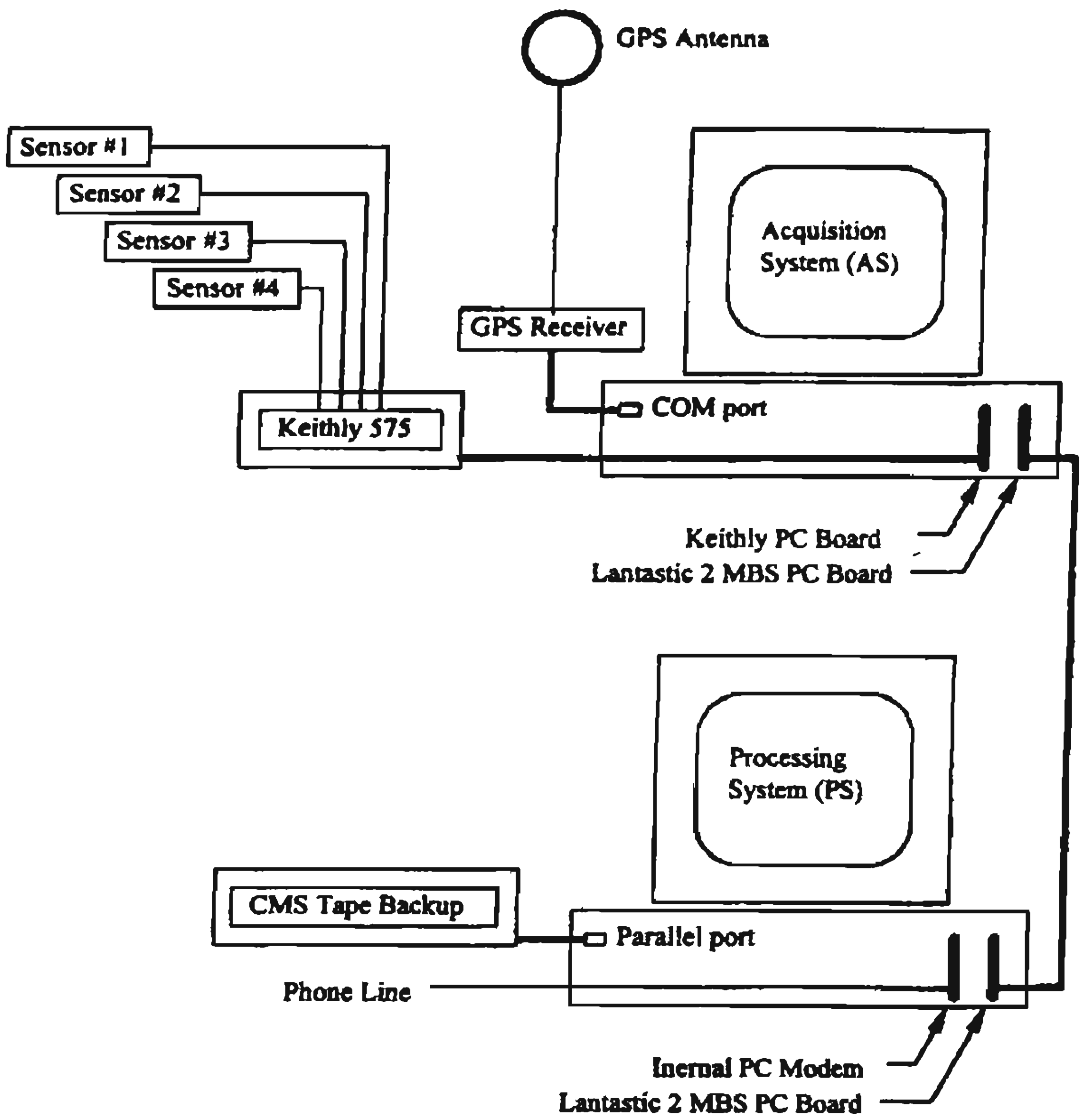

Figure 2. Block diagram of the data acquisitiion and analysis system.

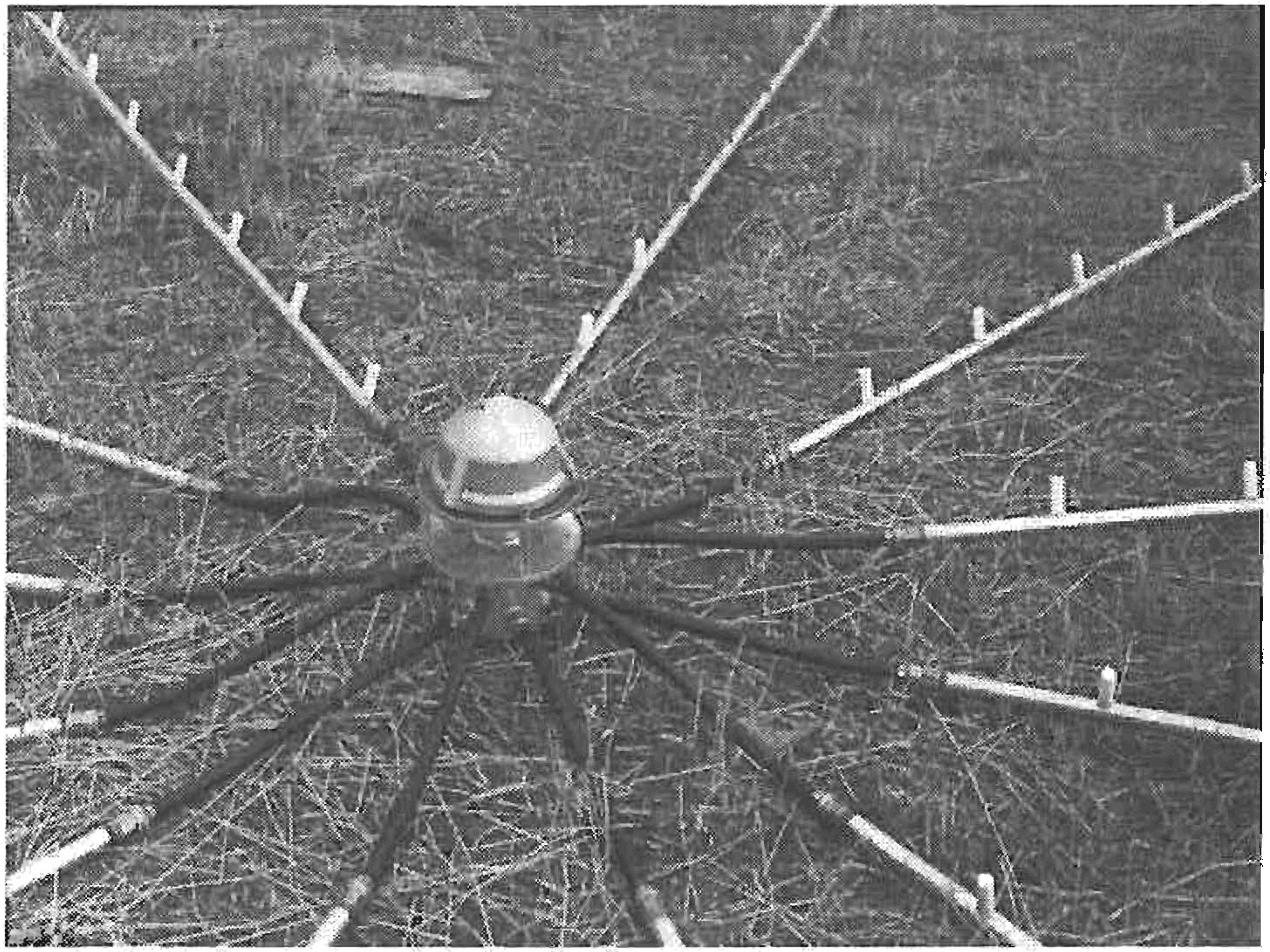

Figure 3. Photograph of a prototype wind noise reducing device.

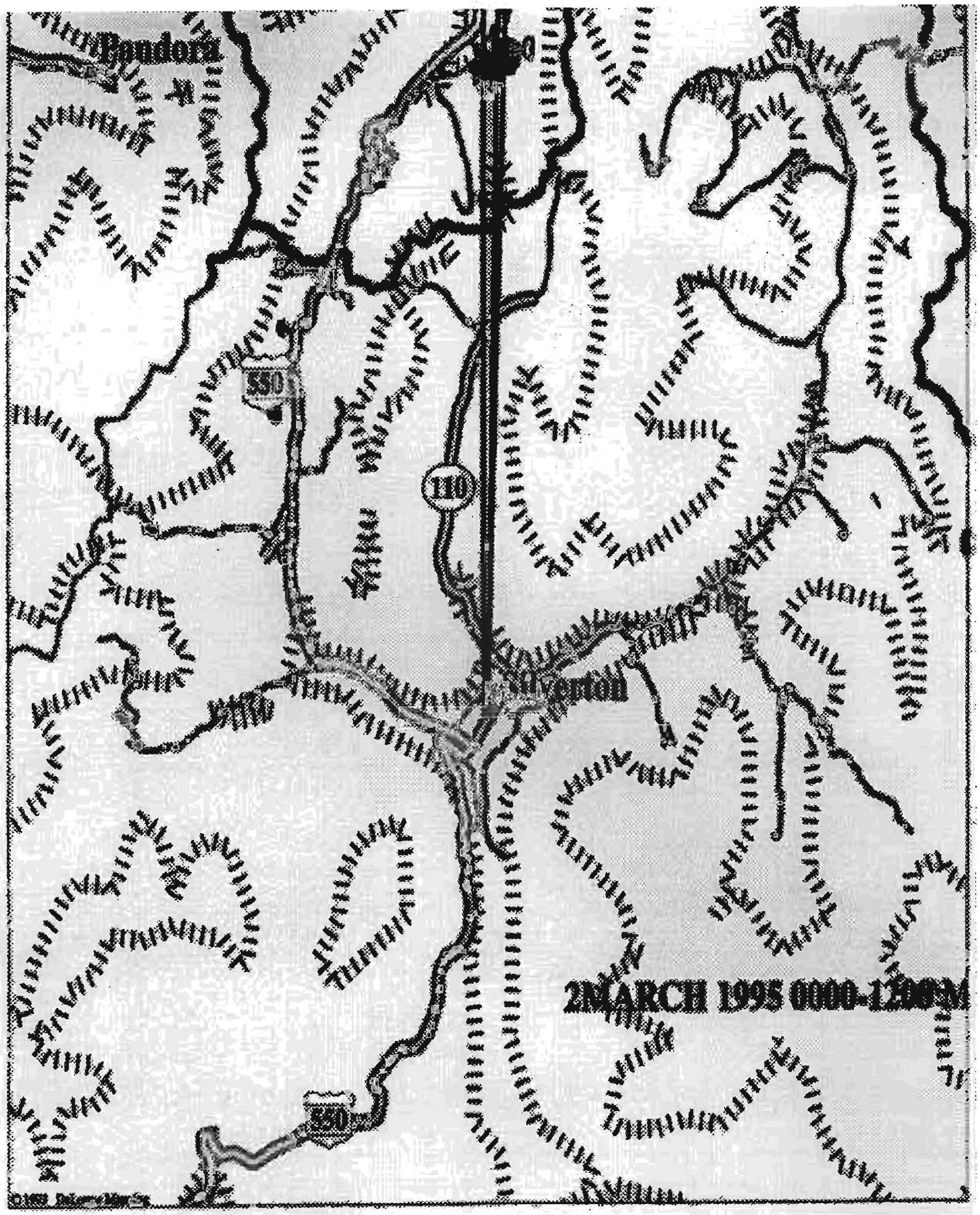

Figure 4. Comparison between avalanche reports and infrasonic data for March 2, 1995 (0000-1200 MST)

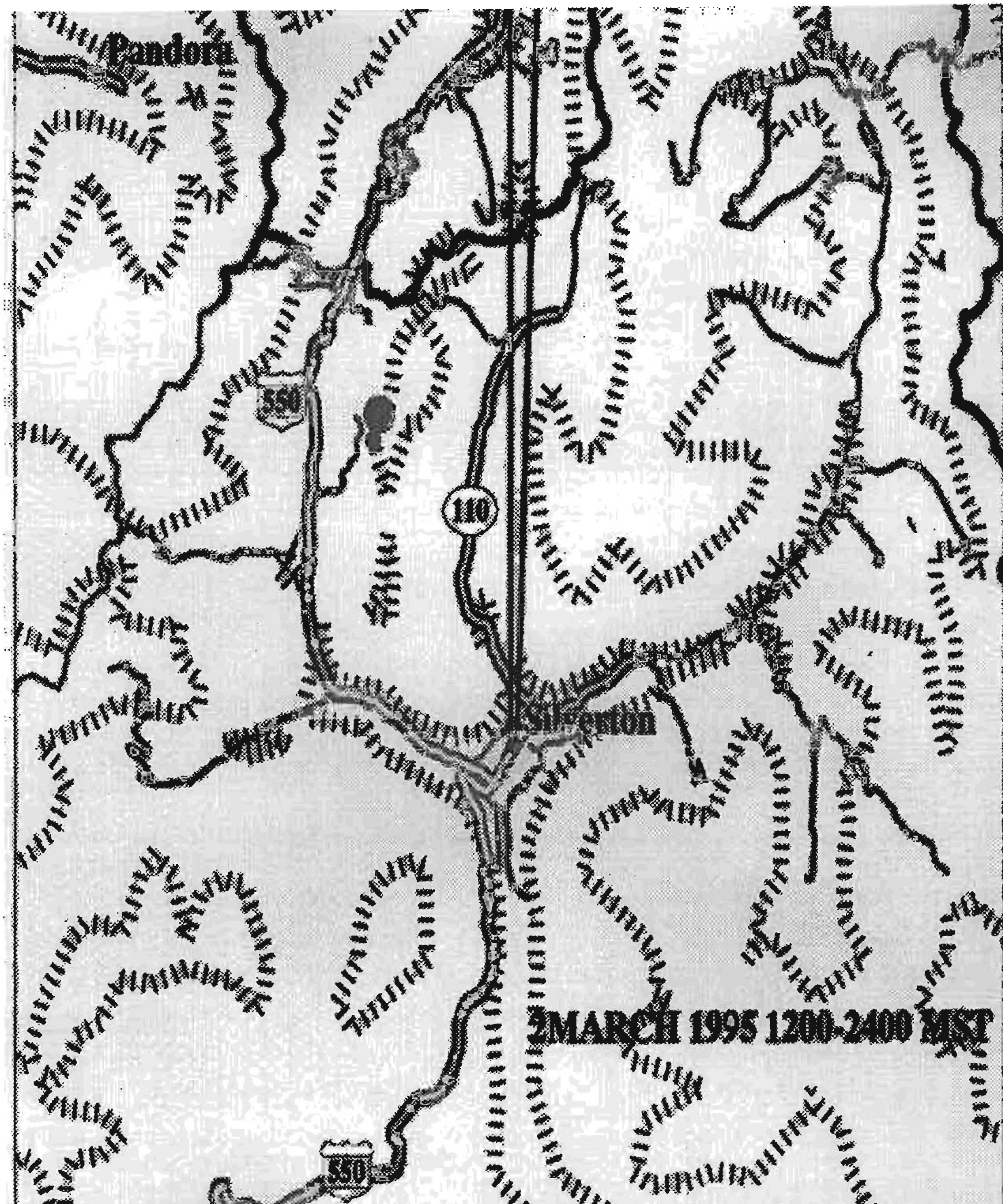

Figure 5. Comparison between avalanche reports and infrasonic data for March2,1995 (1200-2400 MST)

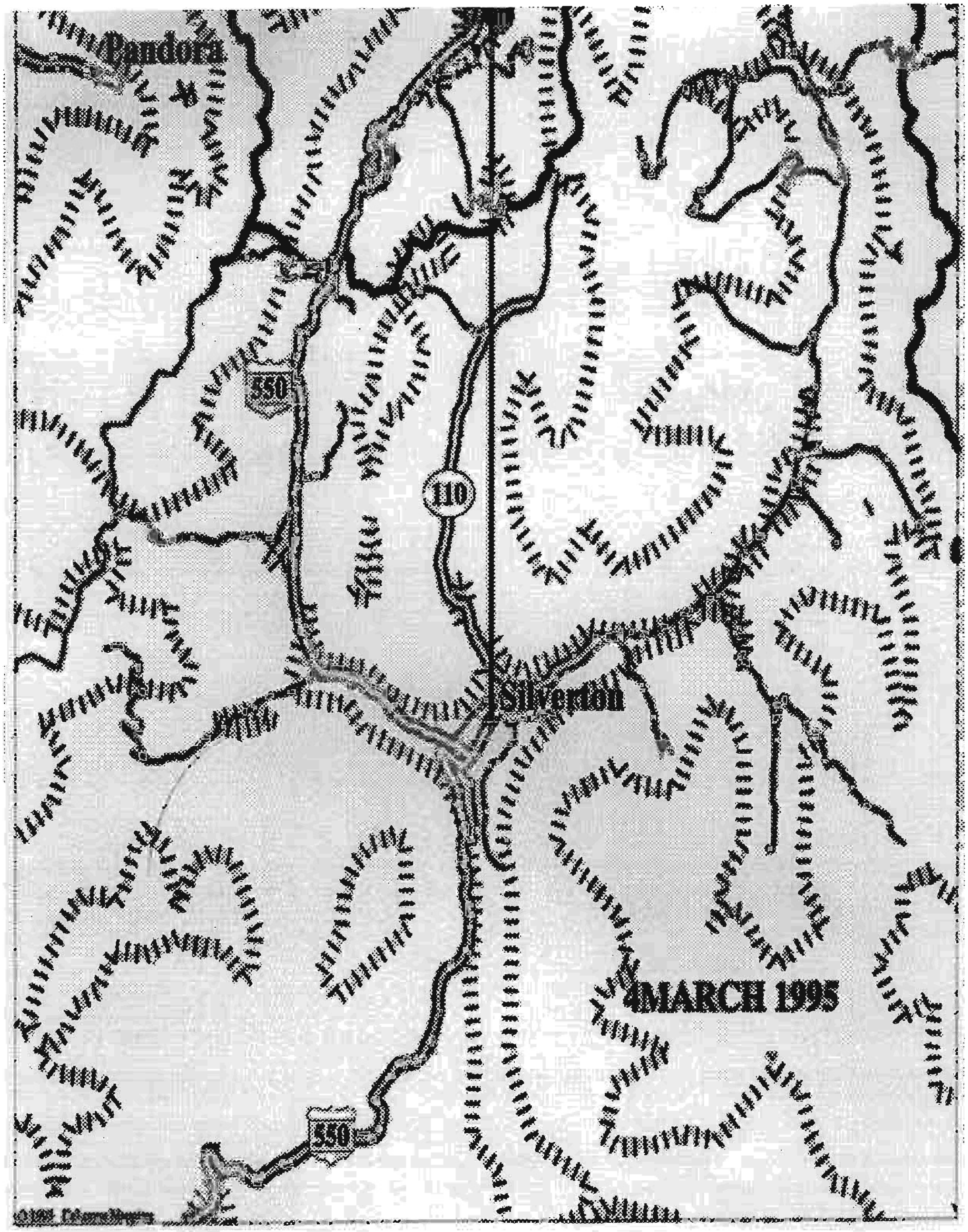

Figure 6. Comparison between an avalanche report and infrasonic data on March 4, 1995.

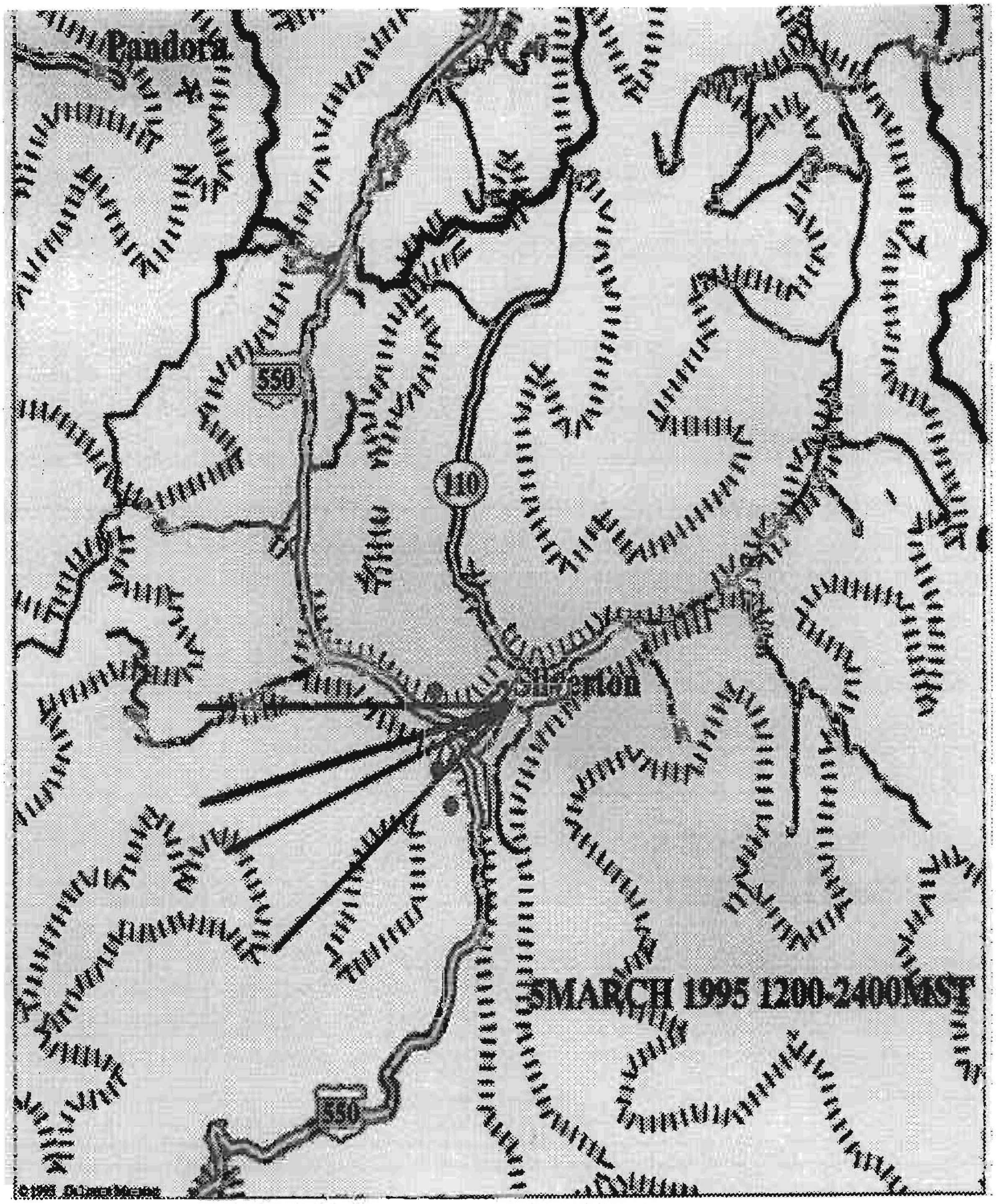

Figure 7. Comparison between avalanche reports and infrasonic data for March 5,1995 (1200-2400 MST).

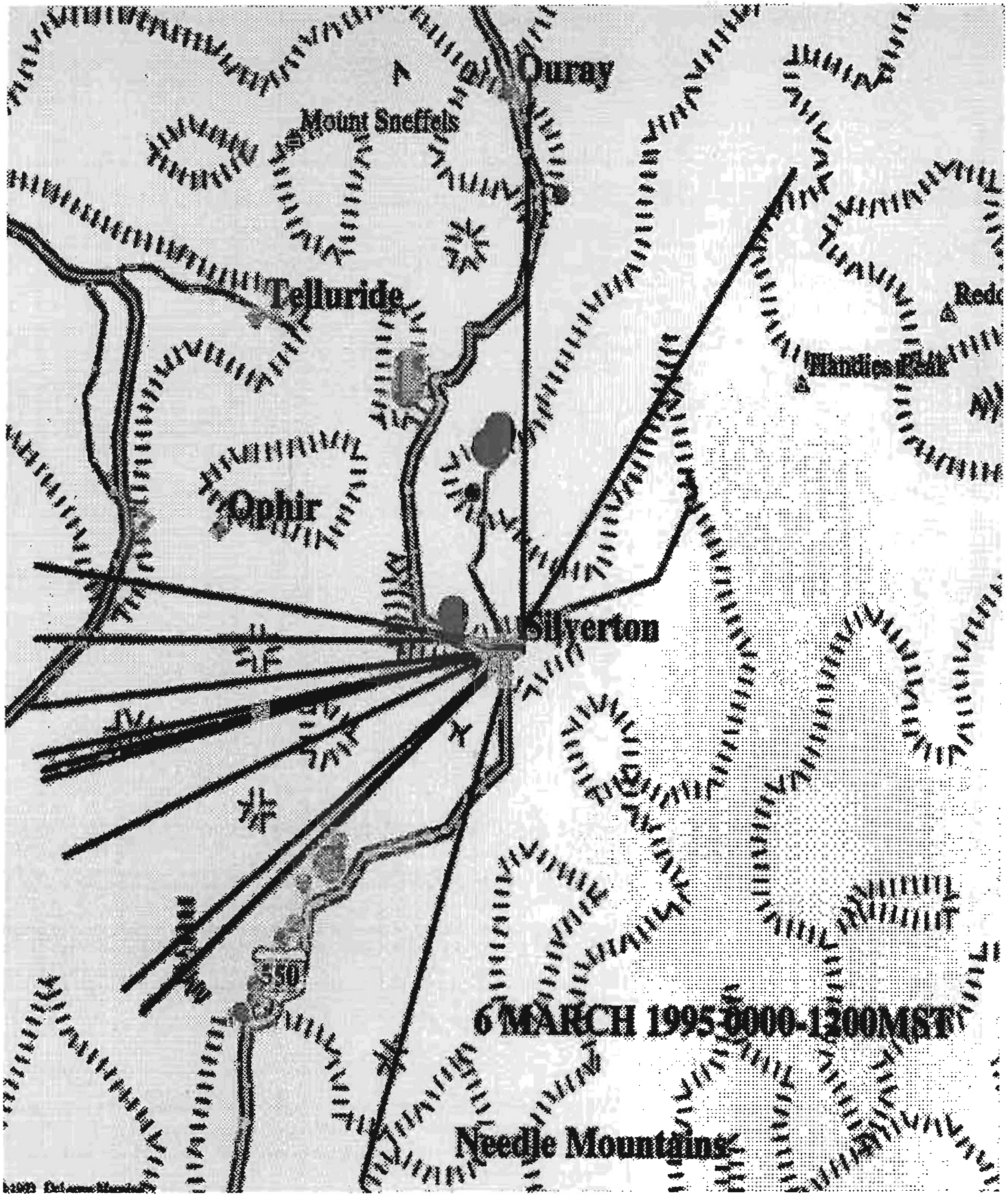

Figure 8. Comparison between avalanche reports and infrasonic data for March 6, 1995 (0000-1200)

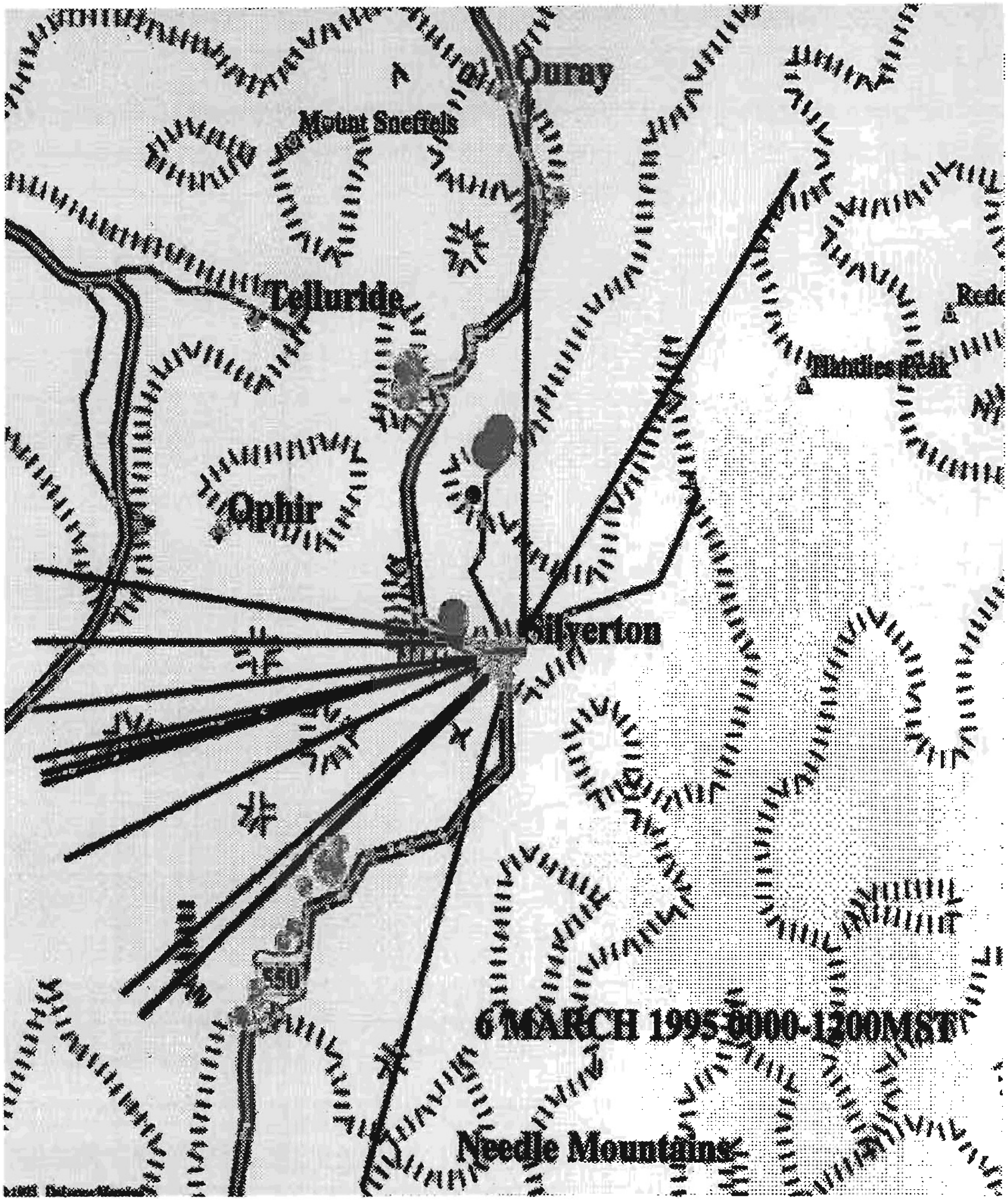

Figure 9. Comparison between avalanche reports and infrasonic data for March 6, 1995 (0000-1200)

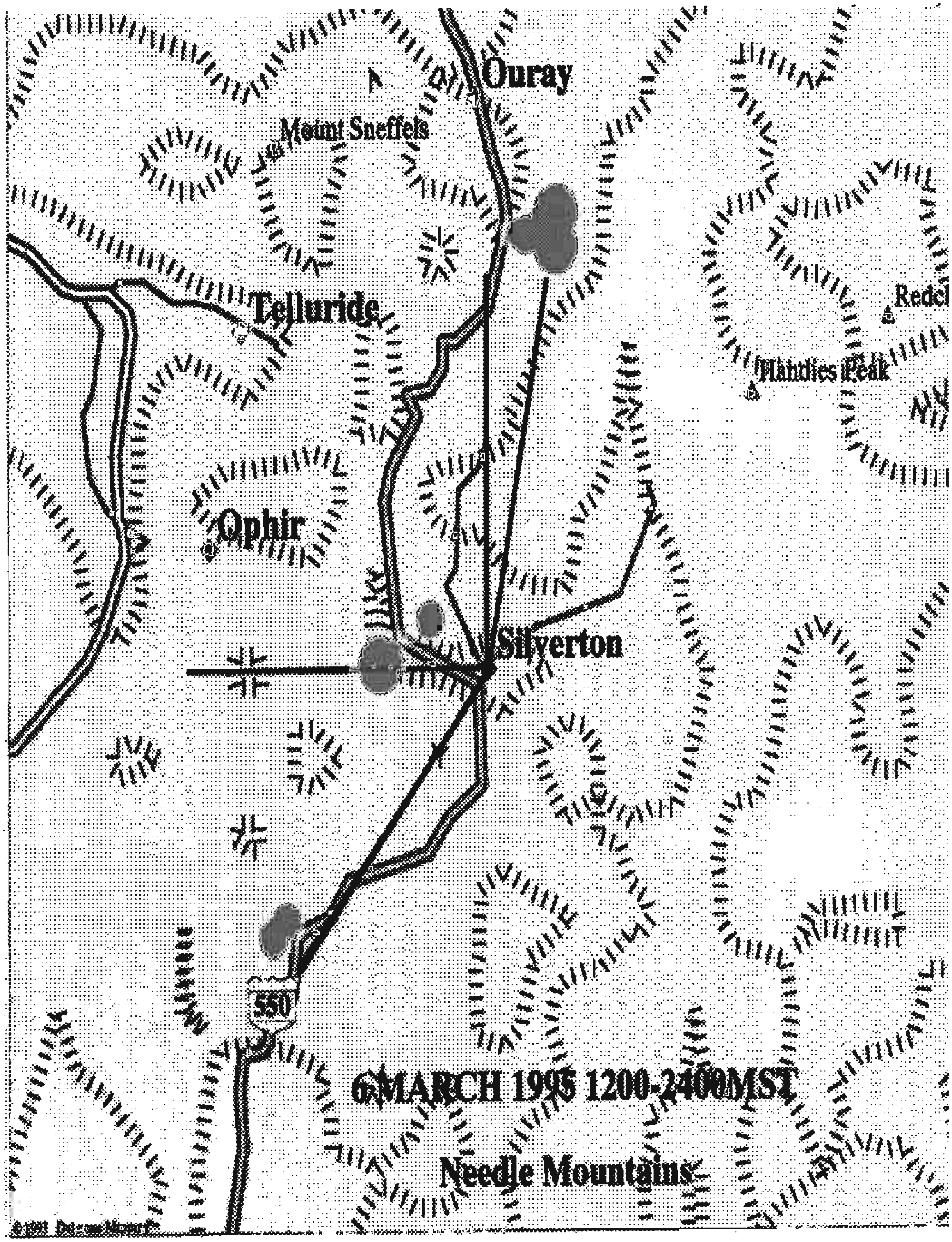

Figure 10. Comparison between avalanche reports and infrasonic data for March 6, 1995 (1200-2400 MST)

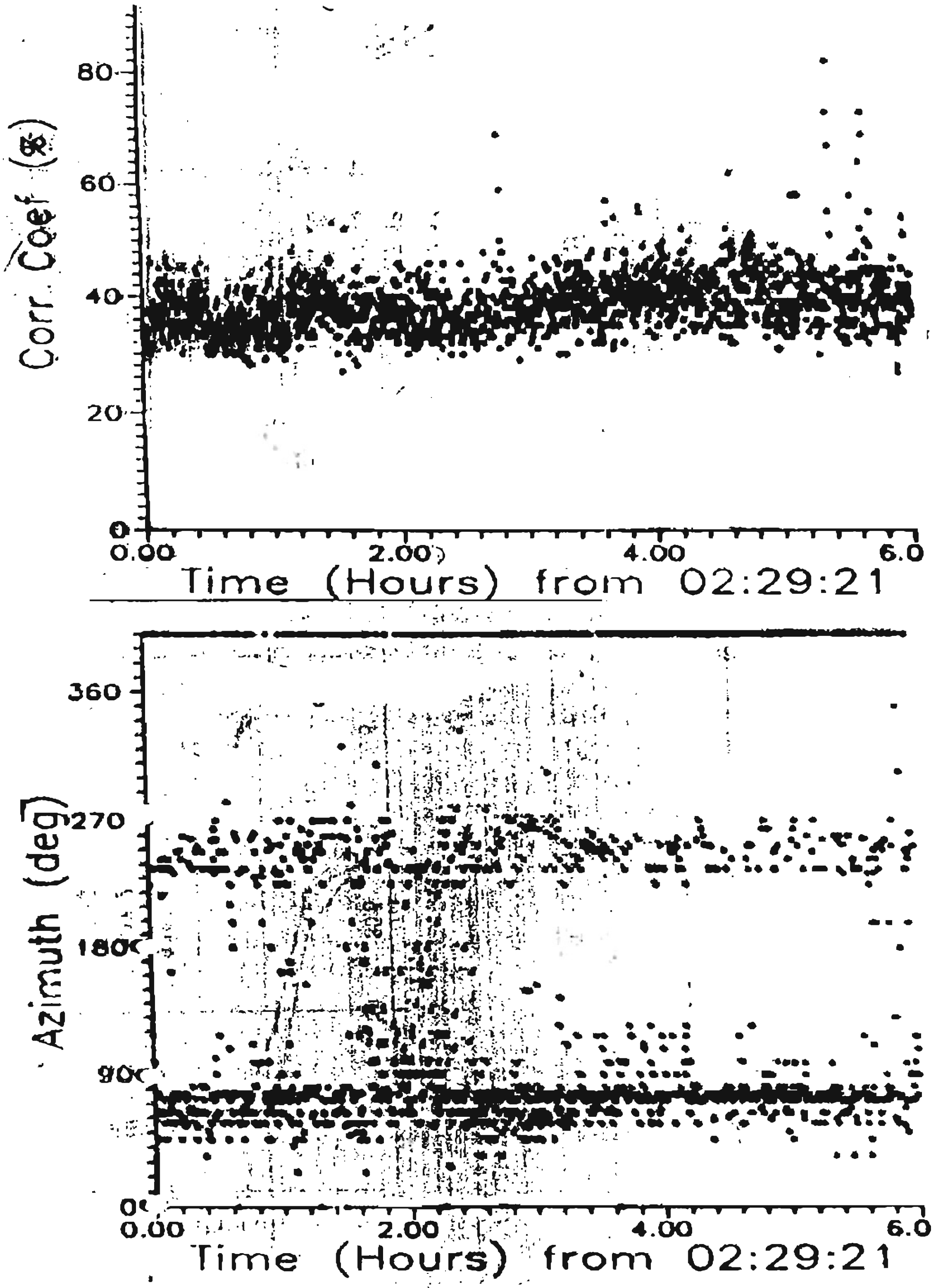

Figure 11. Correlation coefficient and azimuth as a function of time showing the existence of a low-level background signal with two diistinct directions of arrival.

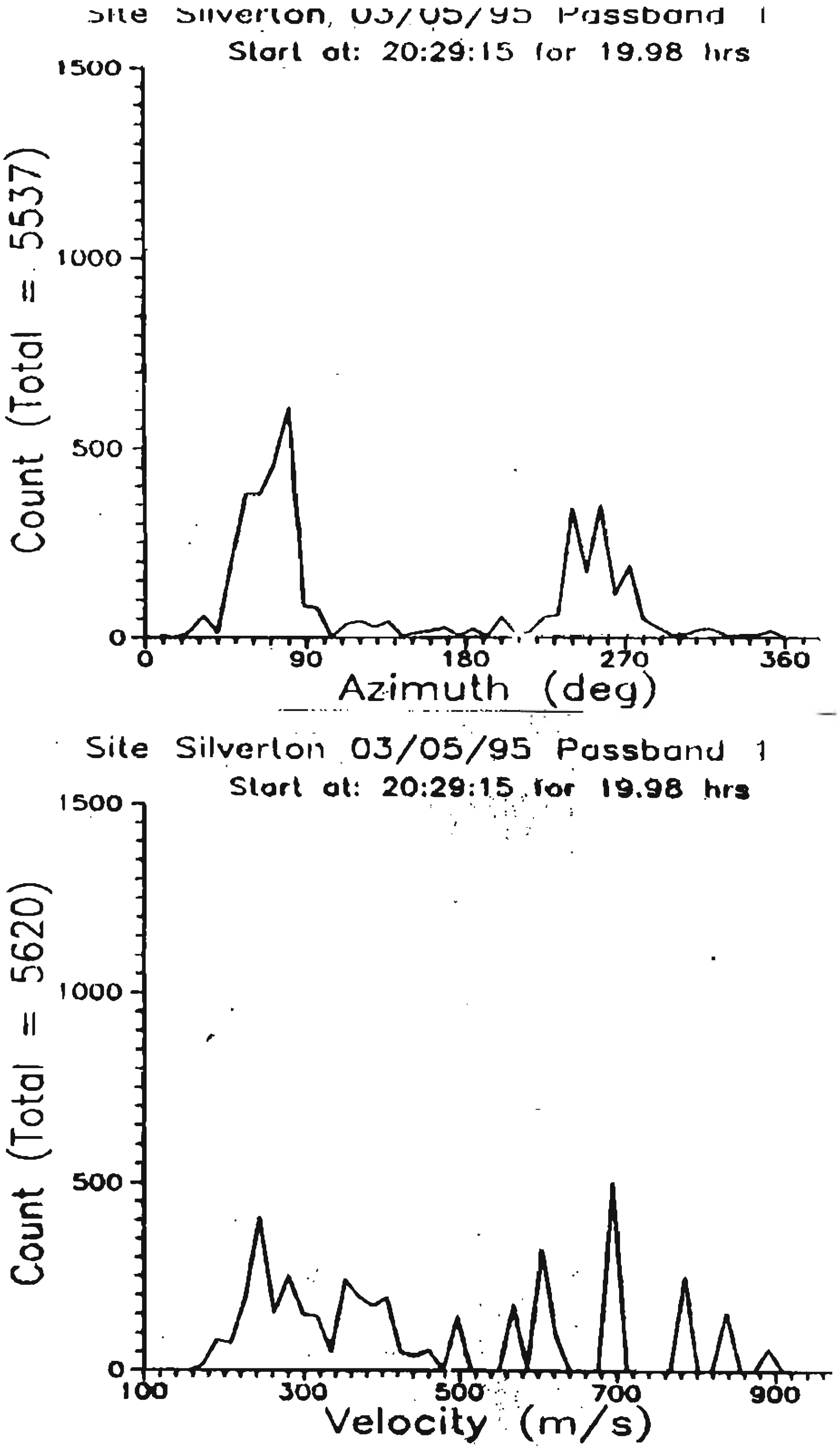

Figure 12. Histograms showing the distributions of azimuth and horizontal phase speed measurements for the background signal covering about a 20-h period.

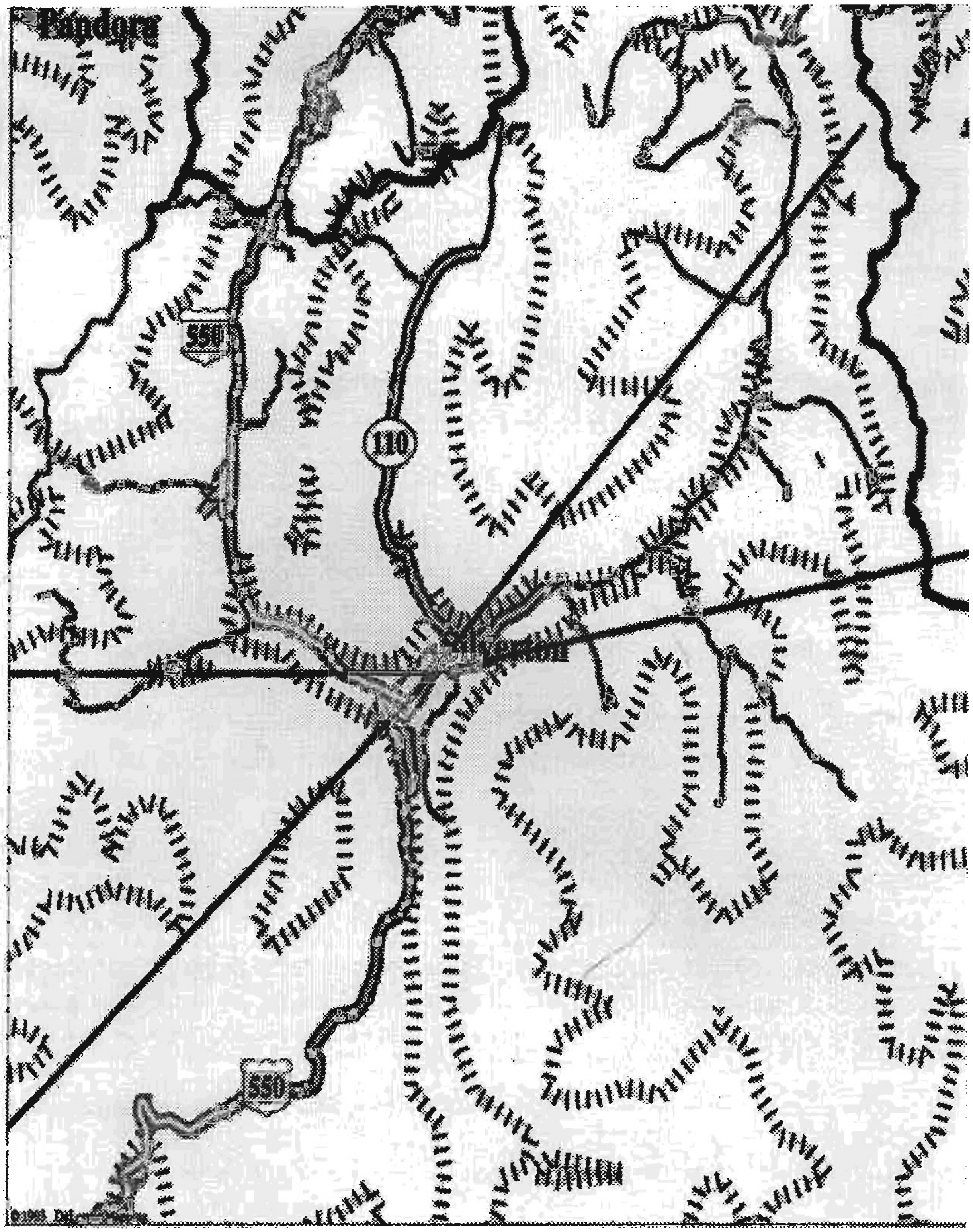

Figure 13. Bearing sectors showing the directions from which the background signal arrived.