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NASA Contractor Report 4421

Recommendations for a Wind Profiling Network To Support Space Shuttle Launches

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Recommendations for a Wind Profiling Network To Support Space Shuttle Launches

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NASA

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CHAPTER 1

INTRODUCTION

A wind profiling network should be capable of helping scientists and engineers predict the evolution of the wind profile over Cape Canaveral less than 6 hours before Space Shuttle launch from November through February. The vertical resolution of the network must allow detection of vertical wind shears greater than or equal to 1 km. In addition, the network should provide Kennedy Space Center (KSC) forecasters with real-time estimates of vorticity, divergence and vertical motion.

Atmospheric motions are composed of many different time and length scales that continuously interact. Therefore, it is not possible to design a single network capable of detecting and predicting the evolution of weather phenomena on all the possible scales of motion present at a particular location. In this report we use the climatology of the KSC winds aloft, the performance of the existing 50 MHz radar located at KSC during the 2 December 1988 shuttle launch, and the results obtained by the National Oceanic and Atmospheric Administration (NOAA) Wave Propagation Laboratory (WPL) wind profiling networks to help design the KSC wind profiling network. In addition we suggest strategies that utilize radar network data to forecast vertical wind shear.

CHAPTER 2

DESIGN OF THE WIND PROFILING NETWORK

A. SPATIAL SAMPLING

During winter, air-mass thunderstorms are observed infrequently. Therefore, thunderstorms occurring during this time should be tied to the advance of mesoscale and synoptic-scale weather systems in the vicinity of KSC. This allows one to increase the station spacing within the network beyond that required to resolve individual thunderstorms (≈ 10 km). This is advantageous since wind profilers located within 50 km of one another may cause the radars to interfere with each other. Furthermore, Smith and Rabin (1989) show that divergence estimates from wind profilers placed 10 km apart can be in error by 42%, whereas errors near 6% are possible using a 100 km separation. Zamora and Shapiro (1989) show that a wind profiler network with an average station spacing of 150 km was able to resolve the synoptic and mesoscale forcing in the wind field that prepared the atmosphere for a severe convective outbreak over northeastern Colorado on 23 July 1987. Zamora et al. (1987) demonstrated that a wind profiling network with an average station spacing of 400 km was not capable of resolving mesoscale wind structure in the vicinity of the jet stream as a strong baroclinic wave passed over the network.

Sampling theory tells us that we must make at least four samples of a given wave to discern both the phase and the amplitude of the wave. If the wind profiling network station spacing is 100 km, then spatial wavelengths smaller than 400 km are not resolved unambigously and only scales greater than 400 km are resolved well. The operational rawinsonde network used by the National Weather Service (NWS) can resolve scales larger than 1600 km. A wind profiling network with stations 100 km apart has four times the resolution of the conventional rawinsonde network. Winter weather patterns are dominated by large synoptic-scale waves (1600 km) and embedded short wavelength systems (≈ 400 km). Furthermore, NASA forecasters are interested

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in using profiler data to initialize numerical weather prediction models. Kuo and Guo (1989) show that profiler station spacings smaller than 240 km are needed to provide adequate initializations for mesoscale forecast models. However, choosing a 240-km separation implies that weather systems having a length scale of 940 km will be resolved by the network. This horizontal length scale corresponds to meso-alpha scale weather systems. Smaller mesoscale systems that produce strong vertical wind shear would be undersampled. Therefore, a 100 km separation is suggested by the previous wind profiling network results and the structure of winter synoptic-scale weather systems. If the weather systems are translating across the network in a linear fashion, then space-time conversion will be possible. This conversion would allow forecasters to examine spatial scales smaller than 400 km.

B. NUMBER OF STATIONS

The wind forecasting requirements at Cape Canaveral require accurate knowledge of the winds upstream of the range and at the launch site. The range weather prediction group has also expressed interest in having the capability to compute vorticity, divergence, and vertical motion from the wind profiling network data. The minimum number of wind observations needed to compute the kinematic properties of the wind are three, as shown by Bellamy (1949). Schaefer and Doswell (1979) and Zamora et al. (1987) demonstrate alternate methods for computing the kinematic properties of the wind field. This number assumes that the important spatial variations in the wind field between any two points in the radar network are linear. Most atmospheric flow fields are nonlinear. Vorticity and divergence computed using three wind profilers may contain a significant error because the nonlinear part of the wind field must be neglected. If six stations are operating, then estimation of the nonlinear variation in the wind field at the center of the network is possible using the Taylor series method introduced by Zamora et al. (1987). Doswell and Caracena (1988) examined this question in detail.

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C. ORIENTATION OF THE NETWORK

The orientation of the network should make use of the existing profiler site at KSC and give the forecasters useful information about changes in the velocity field upstream of KSC. We used the statistics of the mean wind published in the Cape Canaveral Range Reference Atmosphere and similar data compiled by the NWS for the Tampa, Florida, rawinsonde station to estimate the average wind directions found over central Florida during November, December, January, and February.

According to the Cape Canaveral Range Reference Atmosphere, the average winds aloft in the layer from 1 to 17 km (MSL) during winter are from the west at an azimuth of 265 degrees relative to true north. We found similar results for the Tampa observations. Synoptic and mesoscale weather systems will most likely approach the launch site from this direction. Therefore, placing the axis of the observing network along the 260 radial (relative to KSC) will maximize the chances of observing significant changes in the wind field before they affect the shuttle launch area.

Figure 2-1 shows the orientation of the recommended wind profiling network using six stations. Schaefer and Doswell (1979) and Doswell and Caracena (1988) showed that equilateral triangles provide optimum estimates of vorticity and divergence. The inner triangle, formed by the existing KSC wind profiler and the profiling sites labeled 2 and 3, show the smallest radar network capable of computing the kinematic properties of the wind field. Stations 4, 5, and 6 can be added or subtracted in response to scientific or budgetary considerations. The full network will allow the users of the data to compute the wind field diagnostics using the linear wind field model for four triangular regions in the vicinity of KSC. Divergence estimates at the center of the inner triangle can be computed using the Taylor series method outlined in Appendix A. These calculations will include the nonlinear variations in the wind field. The network can be expanded to the north, south, or west by adding additional stations.

D. SITING CONSIDERATIONS

Although the ideal geometry for the wind profiling network favors equilateral triangles, other factors must be considered when siting the radars. They include radio interference from nearby sources, ground clutter (in particular moving ground clutter such as cars on busy highways), and air traffic corridors. We suggest that the radar network locations maintain the equilateral triangle geometry and avoid air traffic routes, busy highways, and powerful sources of radio waves.

E. RADAR DESIGN CONSIDERATIONS

Wind profiling radars have been designed that operate at 50, 405, and 915 MHz. Only 405 and 50 MHz radars have demonstrated the capability to measure winds routinely to heights near 17 km (MSL). Frisch et al. (1986) published a study that examines the height coverage demonstrated by clear-air radars operated by WPL at 50, 405, and 915 MHz. A radar designed with an operating frequency near 225 MHz might also be able to measure winds at these heights. Frequency allocation in this region of the radio spectrum is controlled by the Department of Defense. Thus, radar development has not been undertaken at 225 MHz. Recently, the Department of Commerce accepted the first of thirty 405 MHz radars that will be used for research and operational weather analysis. This radar measures winds from 500 m above ground to 16.25 km. However, the current design of this radar limits its vertical resolution above 9 km to 1000 m. Vertical wind shears of 1 km would not be well sampled above 9 km.

50 MHz radars such as the KSC radar can measure winds at 150 m intervals to heights well above 9 km but are unable to measure winds in the lowest kilometer above the radar. This limit makes estimation of vertical motion using the divergence of the horizontal wind difficult.

Meteorologists have inferred vertical motion in the atmosphere by integrating the continuity equation,

$$w(z) = w(z_0) - \int_{z_0}^{z} \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} dz, \tag{1}$$

where u, v, and w are the east-west, north-south, and vertical wind components and x, y, and z are the Cartesian spatial coordinates. Integration of (1) requires one to measure the full divergence profile as a function of height for an upward integration or to assume that w is zero at a height of 17 km for a downward integration. One could also use profiler-observed vertical motions. Figure 2-2 is a time-height cross section of hourly averaged vertical motions obtained using the vertical beam of the WPL Platteville VHF radar. Note that the vertical motions are nonzero for any single 1-h period at the upper observation heights. The vertical motion averages to zero at these heights only for periods greater than or equal to 12 hours. If the radar measurements are reliable, then the traditional boundary condition used to integrate the continuity equation may not be representative of the true vertical motions present at 17 km. Further research will be needed to verify these results.

Because the traditional boundary condition may be in question, we recommend that calculations of vertical motion using (1) be based on an upward integration of the full divergence profile. Thus, if 50 MHz radars are chosen for use in the KSC network, low-level windfinding capability must be added to each radar site. Radar systems operating at 915 MHz have been developed by NOAA's Aeronomy Laboratory to measure low-level winds (Eklund et al., 1988). If 405 MHz is the choice, then vertical resolution in the wind profile will be sacrificed using the 405 MHz radar design that has been demonstrated.

CHAPTER 3

RADAR PERFORMANCE

A. THE EVALUATION DATA SET

Before we discuss forecasting applications using a single profiler or a network of profilers, we can examine the performance of the KSC radar during launch conditions. This approach allows us to see strengths and weaknesses in the existing design and radar operation strategies. For this assessment we chose a 58-h wind profiler data gathering period in December 1988, when a Space Shuttle launch took place. We realize that the average radar-transmitted power was 15-dB below normal during this period. The findings of this section of the report should thus be subjected to further scrutiny when additional data sets are gathered using the full design capability of the KSC radar.

The radar data set begins at 1000 UTC 30 November 1988 and ends at 2000 UTC 2 December 1988. During this time period a large-amplitude, upper atmospheric trough passed over the eastern United States. Associated with the passage of the wave was a well-defined jet stream structure. Figures 3-1, 3-2, and 3-3 show the radar observations during the passage of the wave. Winds higher than 50 m s^{-1} were observed during the period. The radar observed winds in excess of 25 m s^{-1} at a height of 3.5 km MSL around 0000 UTC 2 December 1988. Strong vertical wind shears were generated by the passage of this weather system over Cape Canaveral.

During this time period the radar operated using vertical resolutions of 150 and 600 m. Figure 3-4 displays the number of wind observations recovered for a given range gate. Figure 3-4 indicates that the radar had difficulty recovering data between 2 and 4 and between 9 and 10 km. Near-field antenna effects or problems with the transmit/receive switch may account for the

missing data in the 2-4 km height range. Low signal-to-noise ratios (S/N) could be responsible for the data losses at other heights. Data losses caused by low S/N can be identified using low consensus numbers. Examination of the data indicates that the number of profiles passing through the consensus average test are not archived as part of the basic data set. Therefore, we were unable to use consensus data to confirm our speculations. For WPL 50 MHz radars, 12 profiles are taken during a 1-h period and passed through the consensus test. Figure 3-5 is an example printout of an hourly averaged wind profile obtained by the 50 MHz wind profiler operated by WPL at Flagler, Colorado. The sharp drop in the number of profiles passing the consensus average above 11 km was an indication that S/N was getting weaker. Data losses began appearing in subsequent range gates. We recommend that the number of wind profiles used to estimate the averaged wind at a given height be archived with the wind profiles. These consensus numbers can be used to identify radar hardware or software problems and are one indication of data quality. Frisch et al. (1986) examined the statistics of the altitude coverage of the WPL clear-air radars using the consensus numbers.

In general there is good agreement between the wind profiler observations taken at KSC and the synoptic-scale weather pattern. We did not encounter large problems with the data set at heights where the data recovery rates were high. NASA personnel have noticed a systematic problem with profiler wind observations in the 6-8 km range gates. We found an increase in the number of wind observations missing at those heights, but the statistical significance of this result cannot be determined using the December data sample.

DATA ANALYSIS AND FORECASTING APPLICATIONS

A. AUTOCORRELATION FUNCTION ANALYSIS

After checking the data set for gross errors, we computed autocorrelation functions and power spectra as a function of height from the wind profiler data at range gates where 6 or fewer hours of data were absent. The missing data points were filled by linear interpolation. Studies of the atmospheric boundary layer have used the autocorrelation functions computed from the velocity field to determine when the fluid no longer feels the influence of its initial state (Panofsky and Dutton, 1984). Thus, given the computed autocorrelations of the KSC profiler velocity field, we can determine statistically the limits of a short-term wind forecast based on a linear extrapolation of wind measurements made using the KSC profiler. The power spectra computed from the profiler observations contain important information about the noise content of the data and can be used to determine if the radar sampling times were chosen correctly.

The profiler autocorrelation functions computed for the u- and v-components of the wind at 3.2 km are shown in Figures 4-1 and 4-2. The functions indicate that the velocities become decorrelated rapidly, with the correlations becoming smaller than 50% at the third lag or 3-h time scale for the u-component. The u-component correlation goes to zero for time scales beyond 12 hours. If one used a short-term nowcast or extrapolation of KSC wind conditions for a 6-h period at 3.2 km there would be only a slight chance that it would be correct. The autocorrelation function for the u-component of the wind at 5.1 km (Figure 4-3) shows an improvement in the correlation time. At the third lag the correllation was better than 80%. At the crucial 6-h time period there was a 55% correlation. We found that the percentages were nearly the same at the 7.6-km

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profiler observing height (Figure 4-4). The 10.6- and 14.2-km u-component autocorrelation functions show good correlations for any time scale shorter than 3 hours (Figures 4-5 and 4-6).

In general, the autocorrelation functions indicate that atmospheric variability decreases as a function of height. At heights of 3.2 and 5.1 km the autocorrelation functions show a steep drop in the correlation to smaller than 30% in the 6-10-h lags. The functions do not exhibit this sharp drop in correlation in the 6-10 h lags at 10.6 and 14.2 km. Thus, single-station forecasts of wind in the upper troposphere and lower stratosphere should be more accurate in the absence of jet streaks or upper level frontal zones. Below 5.0 km, we do not expect extrapolation of wind conditions present at KSC to lead to accurate wind forecasts.

B. SPECTRAL ANALYSIS

The power spectra computed from the profiler time series suggest an additional limitation for single-station wind forecasts or nowcasts. The spectra computed from the u-component and v-component time series at 3.2 km are shown in Figures 4-7 and 4-8. The spectral estimates presented here were normalized by frequency. In this presentation, +1 and -2/3 slopes indicate a white noise and a -5/3 spectrum, respectively. Figure 4-7 indicates that the spectral estimates for time scales shorter than 3 hours contain a significant amount of noise. The spectra computed for the measured wind components at 5.1 , 7.6, 10.6, and 14.2 km are shown in Figures 4-9 through 4-16. These spectra also show signs of a noise slope at high frequencies. Which leads to the sharp drop in the autocorrelation function noted earlier. The source of this noise may be buoyancy (gravity) waves or poor radar system performance. Therefore, single-station forecasts of wind conditions based on wind profiles measured during the last observing period may be contaminated by meteorological or radar system noise. Zamora et al. (1987) noted that wind profiler measurements need prefiltering and smoothing before coherent divergence patterns can be calculated using profiler data.

C. PREFILTERING AND SMOOTHING

Wind measurements containing large errors may pass through the consensus averaging. These gross errors must be removed before smoothing the wind field in height and time. Wuertz and Weber (1989) use a nearest neighbor approach that uses past and present data to prefilter the profiler data.

Most filtering techniques need at least three measurements of the variable being filtered. Points adjacent to the point being filtered are used. If the values of wind speed and direction used in the nowcast are the values gathered during the last observing period, there will be no point after the observation because that point is in the future. Thus, three or five point recursive filtering techniques cannot be used. Wind measurements contain the estimate of the wind plus noise. It may be difficult to discern meaningful changes in the wind field from the most recent wind observation.

We can also illustrate this using the KSC profiler measurements made between 1200 and 1400 UTC 2 December 1988 and the NWS rawinsonde observations. An observer nowcasting solely from the 1200 UTC profiler observation would most likely forecast northwesterly windflow. However, the northerly wind flow associated with the frontal passage aloft passed over KSC at 1300 UTC. If a wind profiler had been located upstream of KSC, observers would have located the shear layer perhaps 6 hours earlier, and its approximate phase speed could have been estimated. The 0000 UTC 12 December 1988 NWS rawinsonde observation for Tampa is shown in Figure 4-17. The winds measured over Tampa indicate that the front has passed over that site. Thus, the NWS observation gave a clear indication that changing wind conditions were approaching, 12 hours before the 700-mb frontal zone reached KSC. Having an upstream wind profiler rather than twice a day rawinsonde observations should allow forecaster to improve their short term forecasts.

D. FORECASTING APPLICATION

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We recommend that hourly correlations be examined using wind data obtained from the KSC wind profiler and any profiling station located 100 km upstream of KSC. If the correlation is good, then nowcasts based on existing wind conditions at KSC will have a high probability of being correct. If the correlation is small, then meteorologists must direct their attention upstream of KSC and begin to monitor wind conditions closely. This approach should give forecasters some lead time before the wind change occurs at KSC as long as the scale of the weather system responsible for the change is larger than 200 km.

CHAPTER 5

USE OF NUMERICAL MODEL GRID POINT DATA

A.   COMPARISONS FOR 2 DECEMBER 1988

Numerical weather prediction models are capable of producing wind forecasts through the depth of the atmosphere with good temporal and spatial resolution. These wind forecasts may be used to improve the nowcasting capabilities of the profiler network. We compared the winds measured at KSC during the 2 December 1988 Space Shuttle launch with those forecast from the National Meteorological Center (NMC) Nested Grid Model (NGM) (Phillips, 1979).

The model was run using the initial conditions generated by NMC for 0000 UTC 2 December 1988. The run covered a 48-h period. Winds were extracted from the 16 model forecast levels at hourly intervals for the first 24 hours of the run using the grid points nearest KSC. The model forecast wind profiles are shown in Figure 5-1. The KSC profiler winds measured at the heights nearest the forecast levels for the same time period are displayed in Figure 5-2. Forecast wind profiles at 0800 UTC and 1700 UTC were not plotted because of problems with the NMC model data fields. These problems did not compromise the model results outside the 0800 and 1700 UTC forecast times. There was very good agreement between the forecast and observed winds during the first 8 hours of the experimental period, after which the difference between the forecast and observed winds increased gradually. During the period the winds at 4 km shifted from westerly to northwesterly. The strongest vertical wind shears were found at 1100 UTC, before the shuttle launch. The NGM did not forecast these events until 1700 UTC; thus, the forecast contained a 6-7-h phase error. Forecasters having access to this information would be aware of a significant change in the wind field over KSC within the forecast period. However, the exact timing of the event would have exceeded the 6-h limit imposed by KSC needs.

We also noted a bias in the forecast of the winds at 17 km. Here the wind speeds were 5-10

m s^{-1} greater than the profiler observed winds at that level. If this type of error is present at other levels in the model, then wind load calculations should not be based on the model forecast wind profiles unless the errors can be corrected using empirical techniques. Furthermore, the vertical resolution of the model is crude. Sixteen forecast levels cover the depth of the troposphere with coarser resolution in the upper troposphere and lower stratosphere. This means that wind shears layers smaller in scale than 2 km will not be forecast by the model in the middle and upper troposphere.

Since most Space Shuttle launches take place near 1400 UTC, they are too close to the synoptic rawinsonde time to take advantage of the latest numerical forecast cycle started at NMC. Thus, the latest forecast available to forecasters will be 12 hours old. The example model run we have presented here suggests that the forecast accuracy will be degraded after 8 to 10 hours. In most cases forecasters will be forced to use winds that are 12 to 14 hours into the model run. Thus, the model runs must be used with caution.

B. INITIALIZATION

The current generation of limited area numerical weather prediction models requires wind and temperature information on at least two horizontal scales of motion. These scales represent the synoptic and mesoscale scales of motion. Limited area models need a specification of these meteorological scales in their initial state. The limited data sample that would be provided by the profiling network we have recommended will not be able to specify the synoptic scales of motions. Haltiner and Williams (1980) also showed that the lack of mesoscale details in the initial model state forces the model to generate mesoscale circulations that are consistent with the large-scale initial conditions. Tarbell et al. (1981) indicate that it takes 6 to 12 hours for models to generate realistic mesoscale circulations. Thus, numerical weather prediction models run using only the NGM initial conditions may take too long to generate a mesoscale circulation that may in fact be erroneous. Note that the NGM simulation run for 2 December showed that differ-

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ences between the forecast and observed fields began to grow in the 6 to 12 period. It may be possible to use the NGM forecasts to specify the lateral boundary conditions for a regional model that would focus its attention on the KSC area. The wind profiler network data could then be assimilated into the numerical model using the four-dimensional data assimilation techniques discussed by Kuo and Guo (1989).

APPENDIX A. WIND FIELD DECOMPOSITION

By using a Taylor series expansion, we can write the u- and v-components of the wind in Cartesian coordinates as

$$u(x,y) = u(x_0 y_0) + \frac{\partial u}{\partial x}(x - x_0)\frac{\partial u}{\partial y}(y - y_0) + \frac{\partial^2 u}{\partial x^2}\frac{(x - x_0)^2}{2!}$$

$$+ \frac{\partial^2 u}{\partial y^2}\frac{(y - y_0)^2}{2!} + \frac{\partial^2 u}{\partial x \partial y}(x - x_0)(y - y_0) \tag{A1}$$

$$v(x,y) = v(x_0 y_0) + \frac{\partial v}{\partial x}(x - x_0) + \frac{\partial v}{\partial y}(y - y_0) + \frac{\partial^2 v}{\partial x^2}\frac{(x - x_0)^2}{2!}$$

$$+ \frac{\partial^2 v}{\partial y^2}\frac{(y - y_0)^2}{2!} + \frac{\partial^2 v}{\partial x \partial y}(x - x_0)(y - y_0). \tag{A2}$$

This system can be cast as a system of 12 equations in 12 unknowns where the known quantities are the 12 wind components measured at six radar sites and the x and y locations of the wind measurements. The unknowns are the derivatives of the velocity field that contain the divergence, vorticity, deformation, translation, and curvature of the wind field.

For a given triangular region we can ignore the second derivatives of the velocity field. Then the linear system reduces to a system of six equations in six unknowns, as shown by Zamora et al. (1987). The recommended network of six wind profilers will allow forecasters to estimate divergence and vertical motion using the linear approximation for four triangular regions and hence the spatial variation of divergence and vertical motion near KSC. In addition, if the full linear system is solved, divergence and vertical motion estimates accurate to second order are available for the triangular region immediately upstream of KSC.

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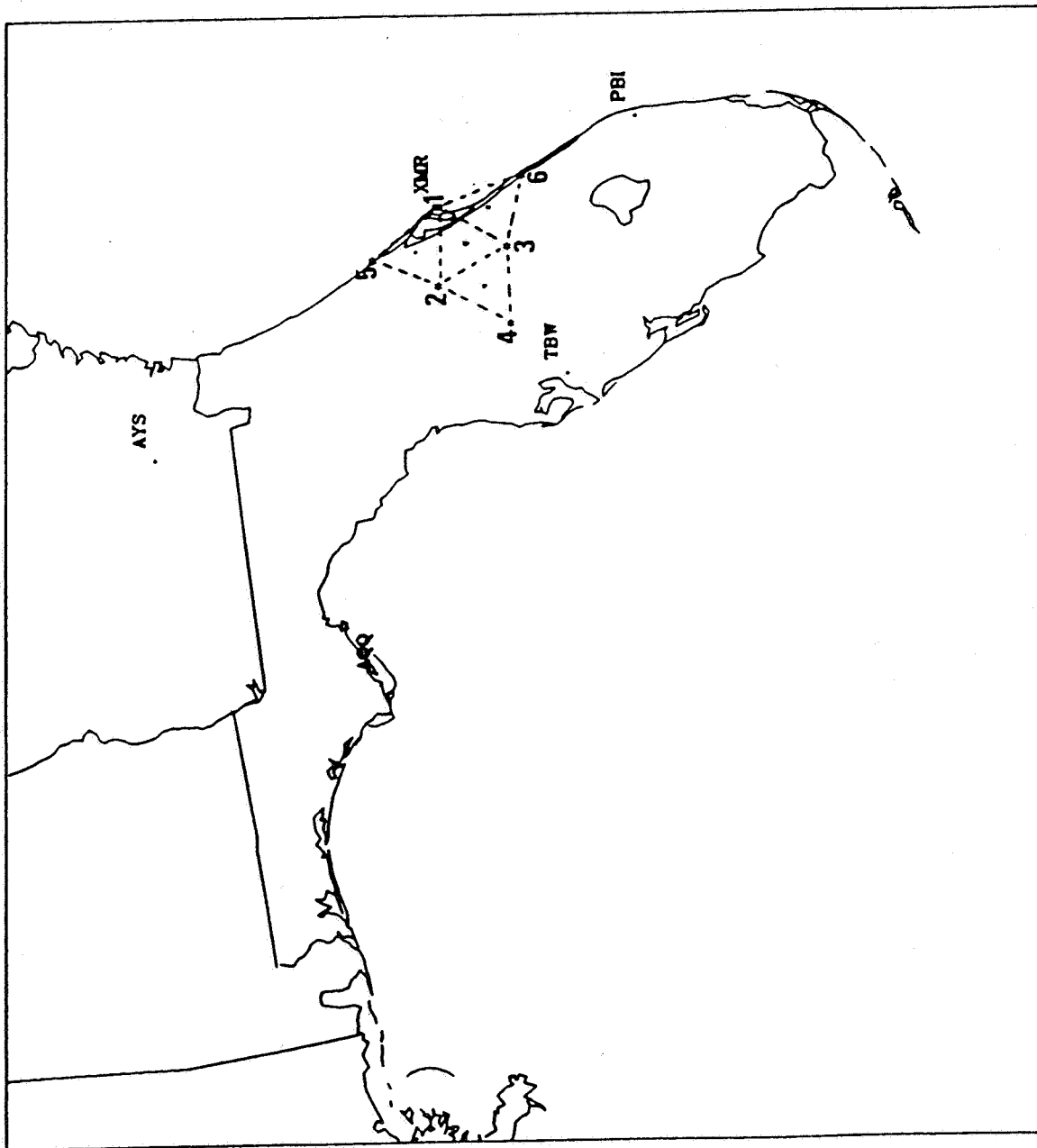
Figure 2-1. Proposed wind profiling network. Existing rawinsonde stations denoted by crosses, proposed radar sites by asterisks, and the KSC wind profiling radar by o.

PLATTEVILLE (40.10N,104.43W),el.1560m

Pressure (mb)

100.
150.
200.
250.
300.
400.
500.
600.
700.
850.
1000.

Height (km)

18.
17.
16.
15.
14.
13.
12.
11.
10.
9.
8.
7.
6.
5.
4.
3.
2.
1.
0.

24JUL87

0.   23.   22.   21.   20.   19.   18.   17.   16.   15.   14.
23JUL87
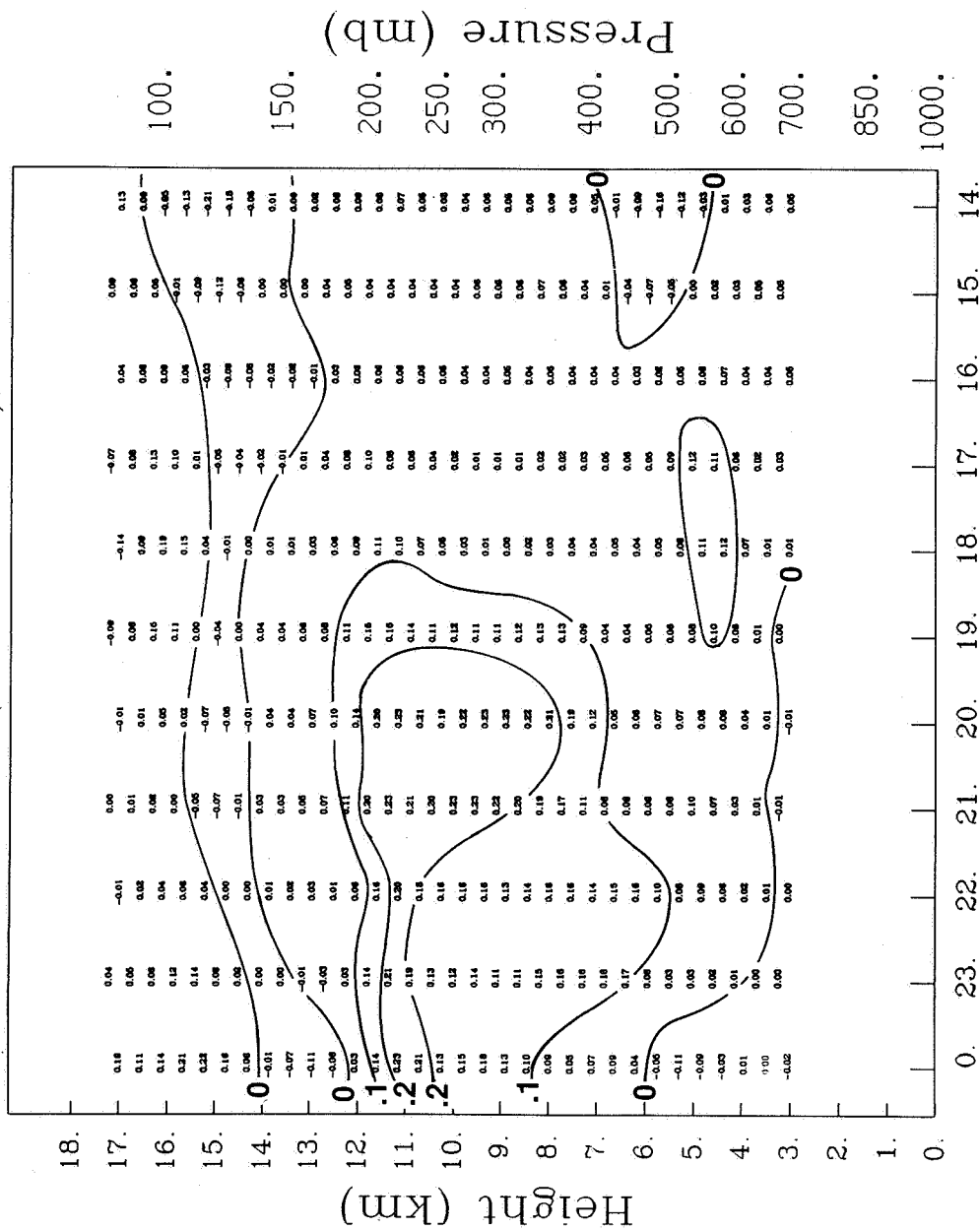
<--- Time UTC

NOAA/WPL Profiler Network

Figure 2-2. Time-height cross section of hourly averaged vertical motions measured by the WPL Platteville VHF radar in meters per second.
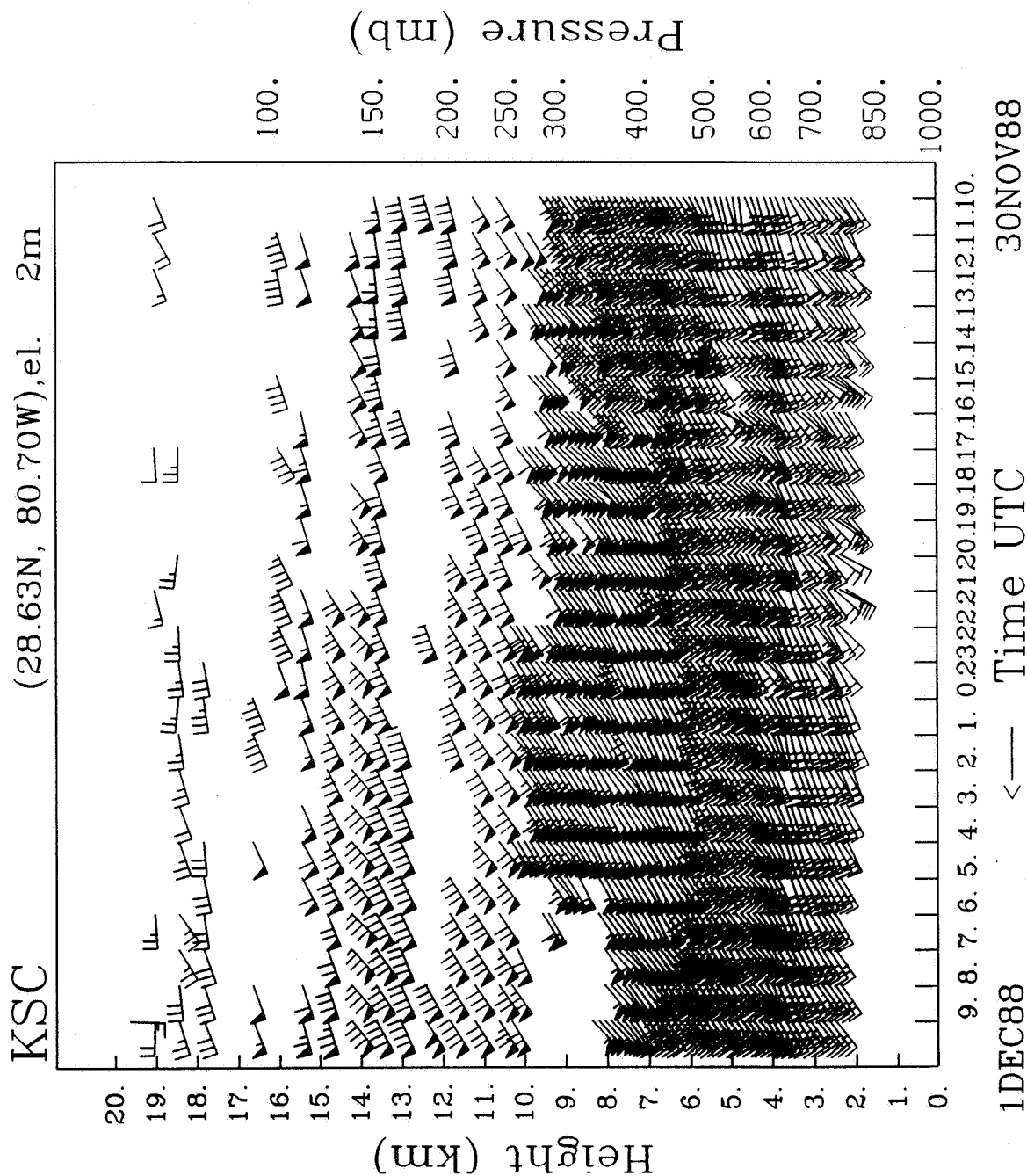
Figure 3-1. Time-height cross section of KSC profiler winds 1000 UTC 30 November 1988 to 0900 UTC 1 December 1988. Half barb 2.5 m s^{-1}, full barb 5 m s^{-1}, and flag 25 m s^{-1}.
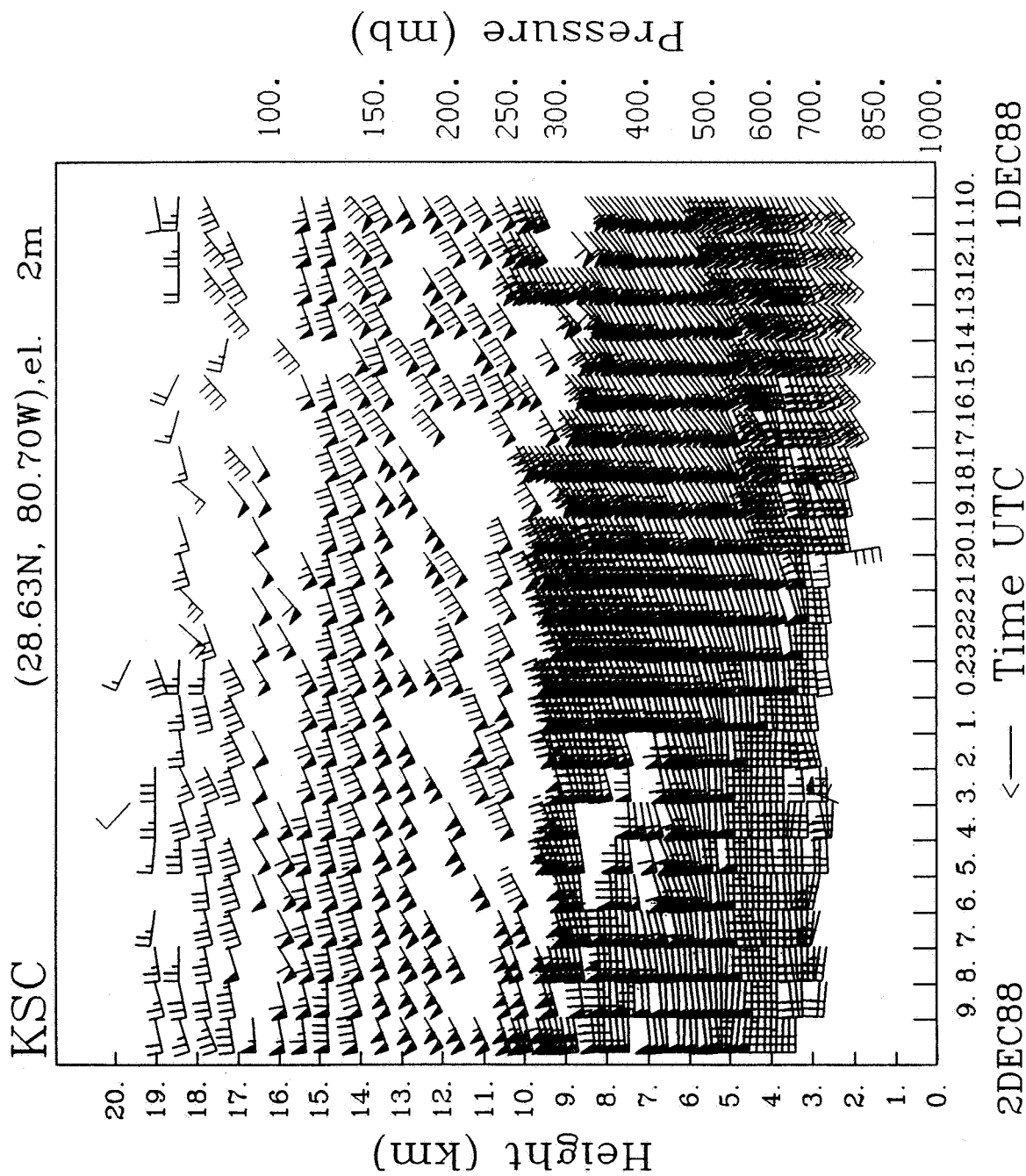
Figure 3-2. Time-height cross section of KSC profiler winds 1000 UTC 1 December 1988 to 0900 UTC 2 December 1988. Winds same as 3-1.
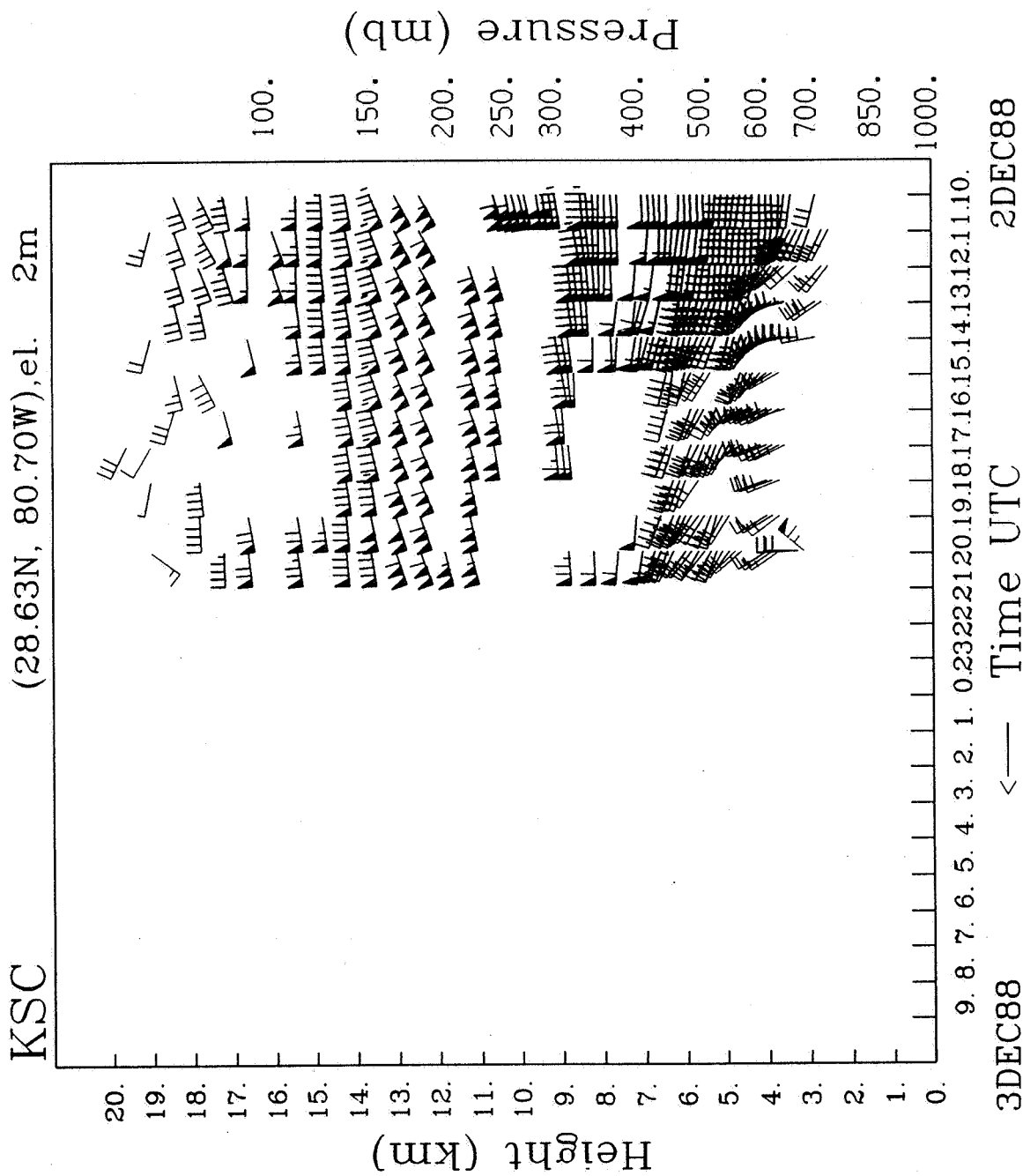
Figure 3-3. Time-height cross section of KSC profiler winds 1000 UTC 2 December 1988 to 2000 UTC 2 December 1988. Winds same as 3-1.
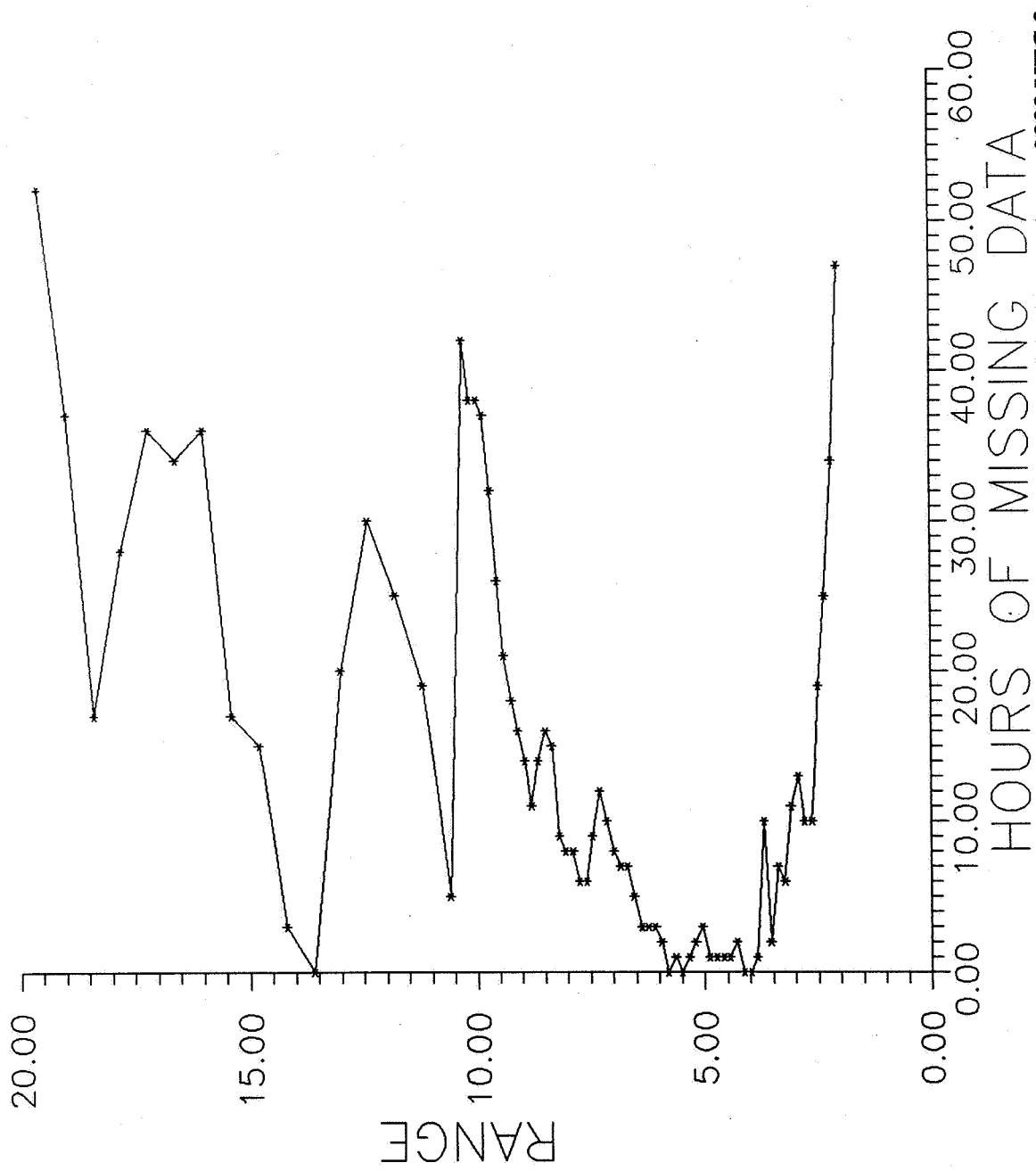
Figure 3-4. Data recovery as a function of height for 1000 UTC 30 November to 2000 UTC 2 December 1988.

```
FLAGLER
 39.12 103.90 1463.
87  7 22 1000 12. 350. 124. 13. 22.  3.67 9.67 238.00 672.00 69.8 69.8 1.64 35. 0
.29 0.87 1.
             1     5.2    245.8    3.11   12.   12.    57.7
             2     6.4    255.9    3.39   12.   12.    64.7
             3     5.0    256.8    3.68   12.   12.    66.7
             4     3.5    281.4    3.97   12.   12.    67.5
             5     3.3    300.2    4.26   12.   12.    69.6
             6     2.8    305.2    4.55   12.   12.    72.3
             7     2.3    310.0    4.84   12.   12.    72.8
             8     1.9    304.5    5.13   12.   12.    72.2
             9     3.1    280.5    5.42   12.   12.    68.1
            10     3.3    252.2    5.71   12.   12.    72.3
            11     3.0    243.0    6.00   12.   12.    74.0
            12     3.1    239.0    6.29   12.   12.    70.3
            13     3.3    232.4    6.58   12.   12.    61.7
            14     3.5    238.1    6.87   12.   12.    61.9
            15     4.0    242.9    7.16   12.   12.    62.4
            16     6.2    249.8    7.45   12.   12.    60.5
            17     8.1    253.3    7.74   12.   12.    62.1
            18     8.3    249.8    8.03   12.   12.    60.1
            19     7.2    236.7    8.32   12.   12.    54.3
            20     7.1    212.7    8.61   12.   12.    50.8
            21     8.5    207.2    8.90   12.   12.    51.2
            22     9.4    198.9    9.19   12.   12.    51.4
            23    10.9    201.6    9.48   12.   12.    50.0
            24    12.1    213.6    9.77   12.   12.    44.9
            25    10.7    214.7   10.20   12. · 12.    45.7
            26  -999.0   -999.0   11.07    6.    3.    32.2
            27  -999.0   -999.0   11.94    7.    3.    28.4
            28    11.2    223.0   12.81    5.    4.    32.4
            29  -999.0   -999.0   13.68    9.    3.    30.0
            30    13.1    227.4   14.55   10.    8.    32.3
            31    12.6    214.5   15.42   11.   11.    32.3
            32    15.4    218.1   16.29   10.    7.    32.7
            33  -999.0   -999.0   17.16   11.    2.    31.9
            34  -999.0   -999.0   18.03    5.    3.    30.7
            35  -999.0   -999.0   18.90    3.    3.  -999.0
```

Figure 3-5. Sample data printout for WPL wind profiling station showing number of profiles satisfying the consensus for a 1-h period. Column 5 shows the east antenna consensus. Column 6 indicates the north antenna consensus.
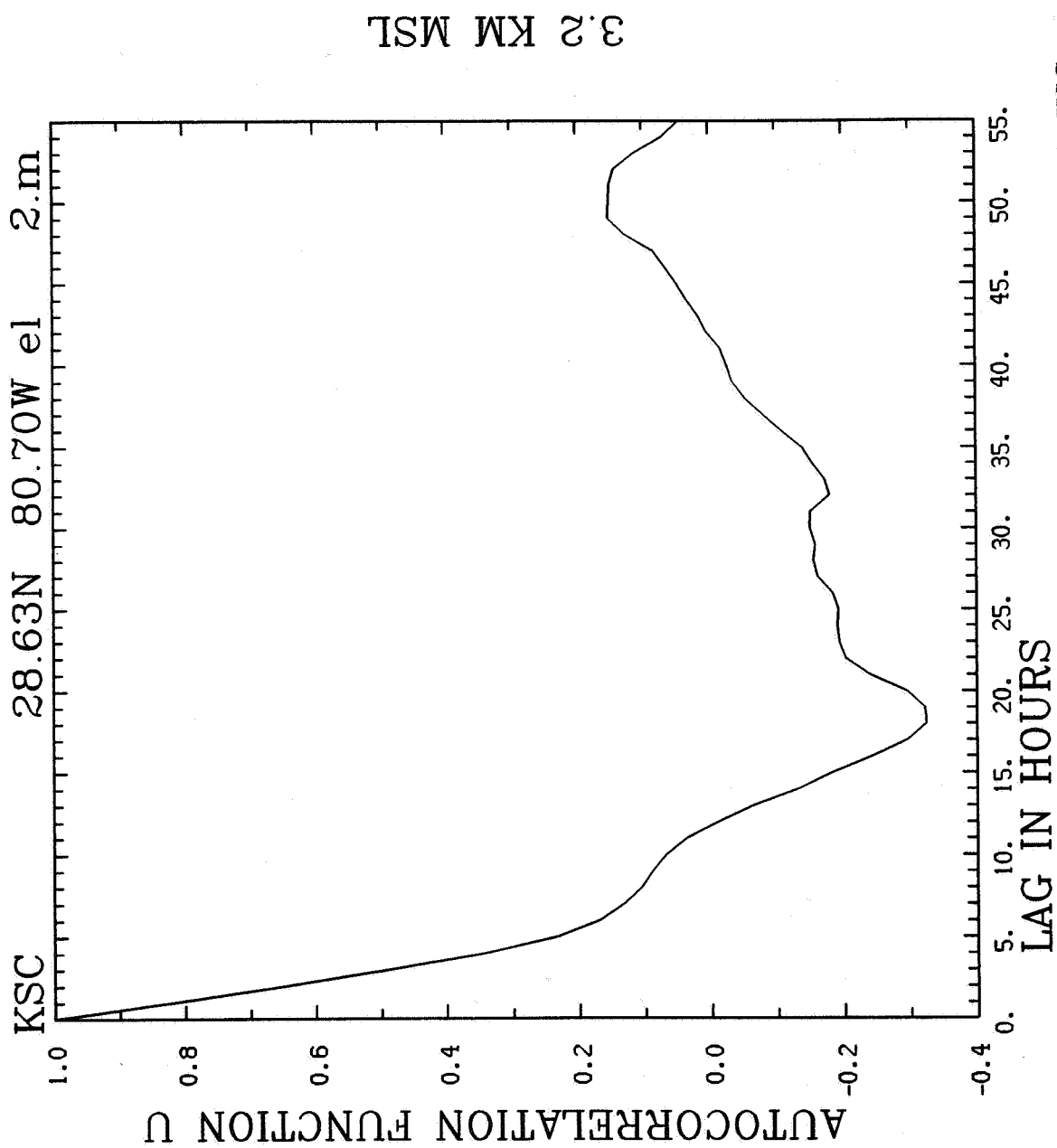
25

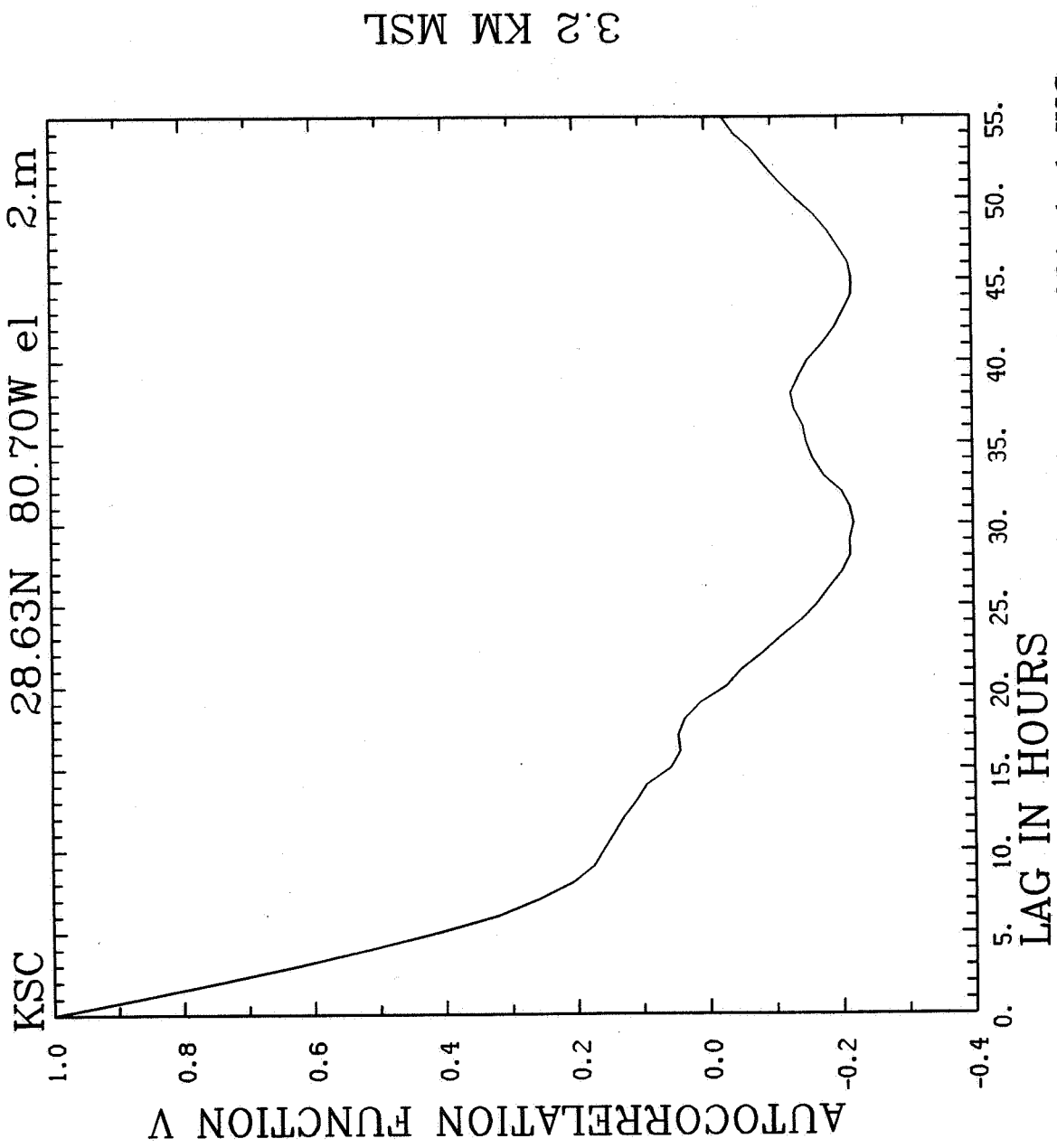Figure 4-1. Autocorrelation for the u-component of the wind measured at 3.2 km by the KSC wind profiler.

Figure 4-2. Autocorrelation for the v-component of the wind measured at 3.2 km by the KSC wind profiler.
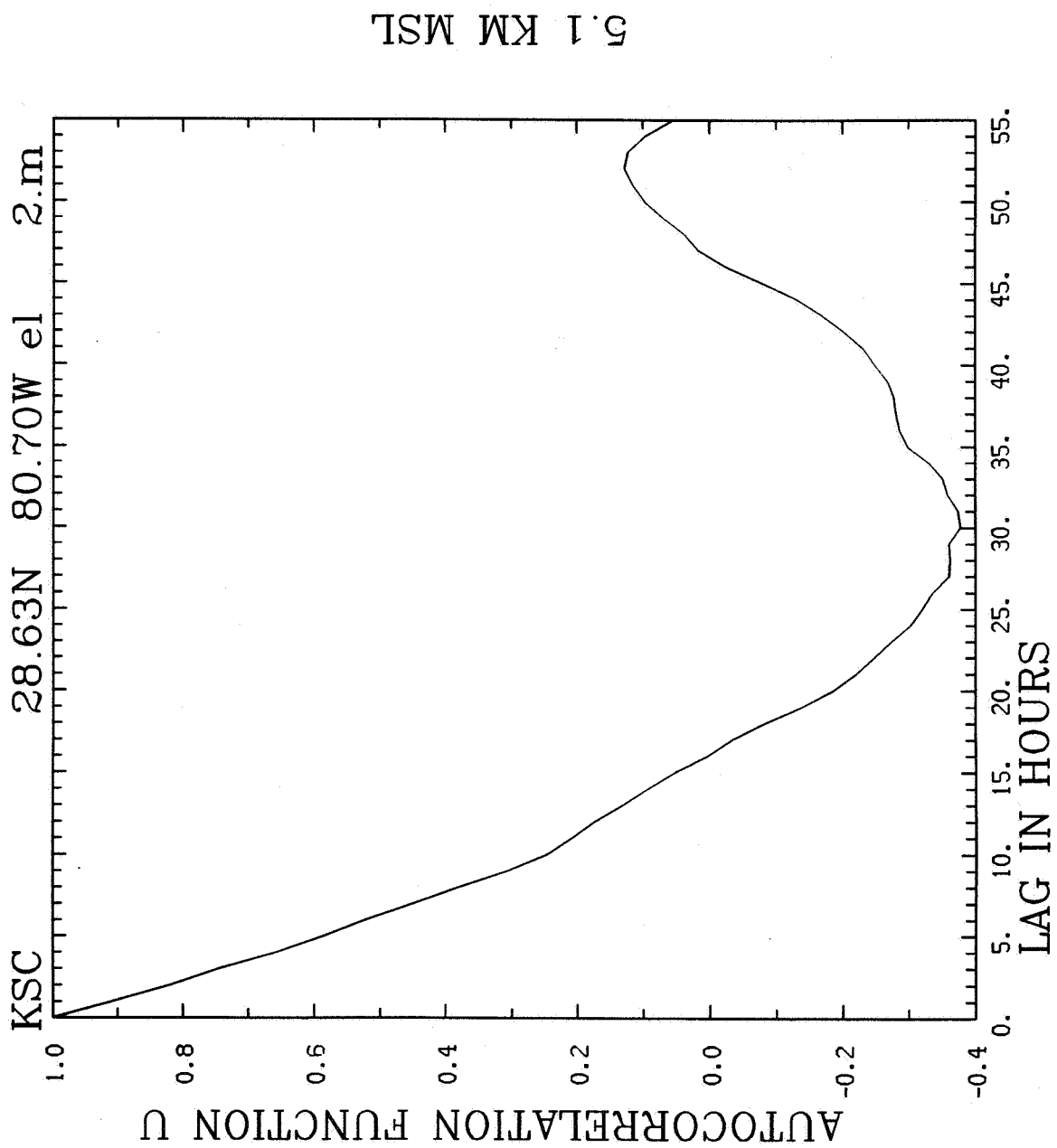
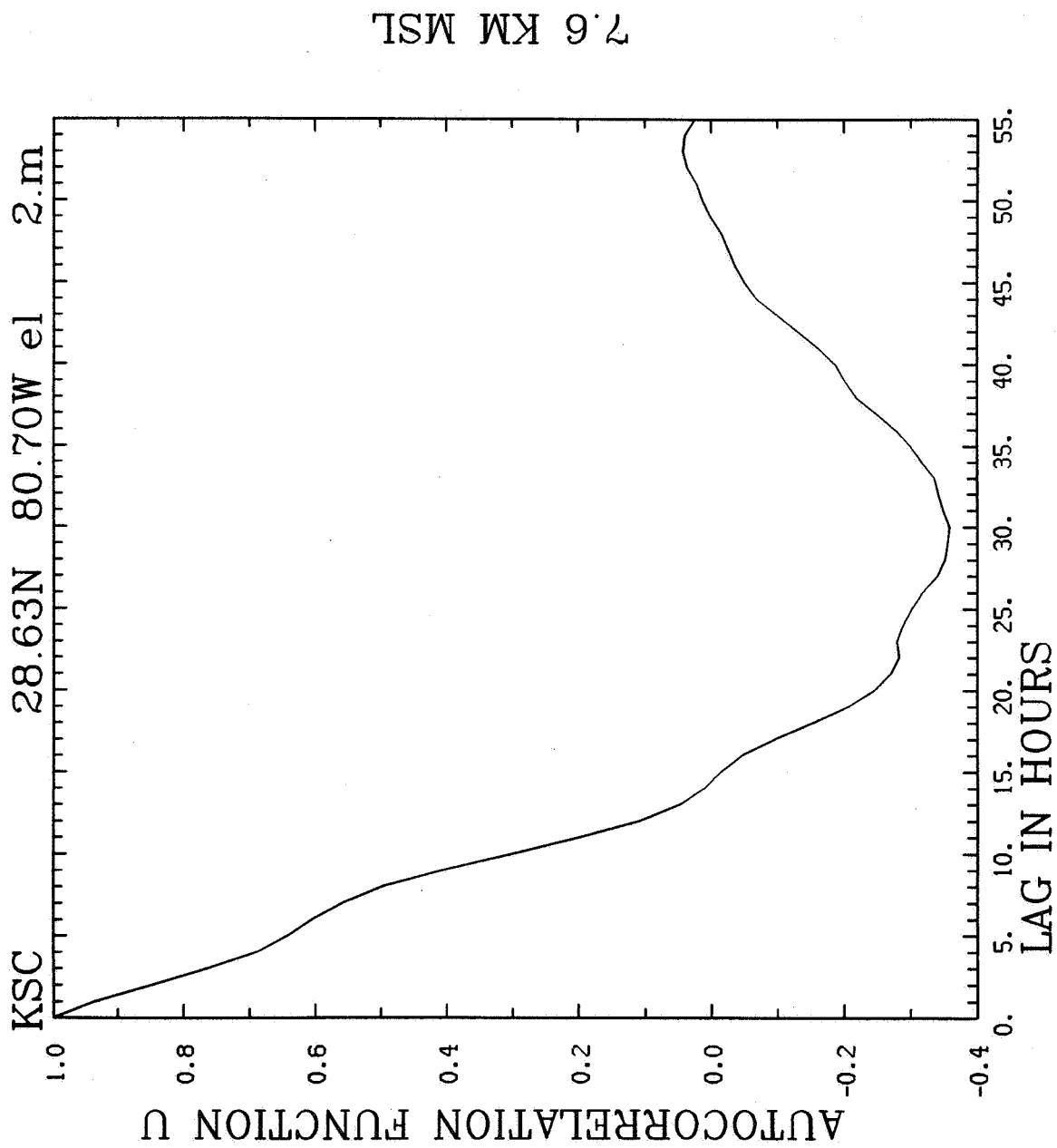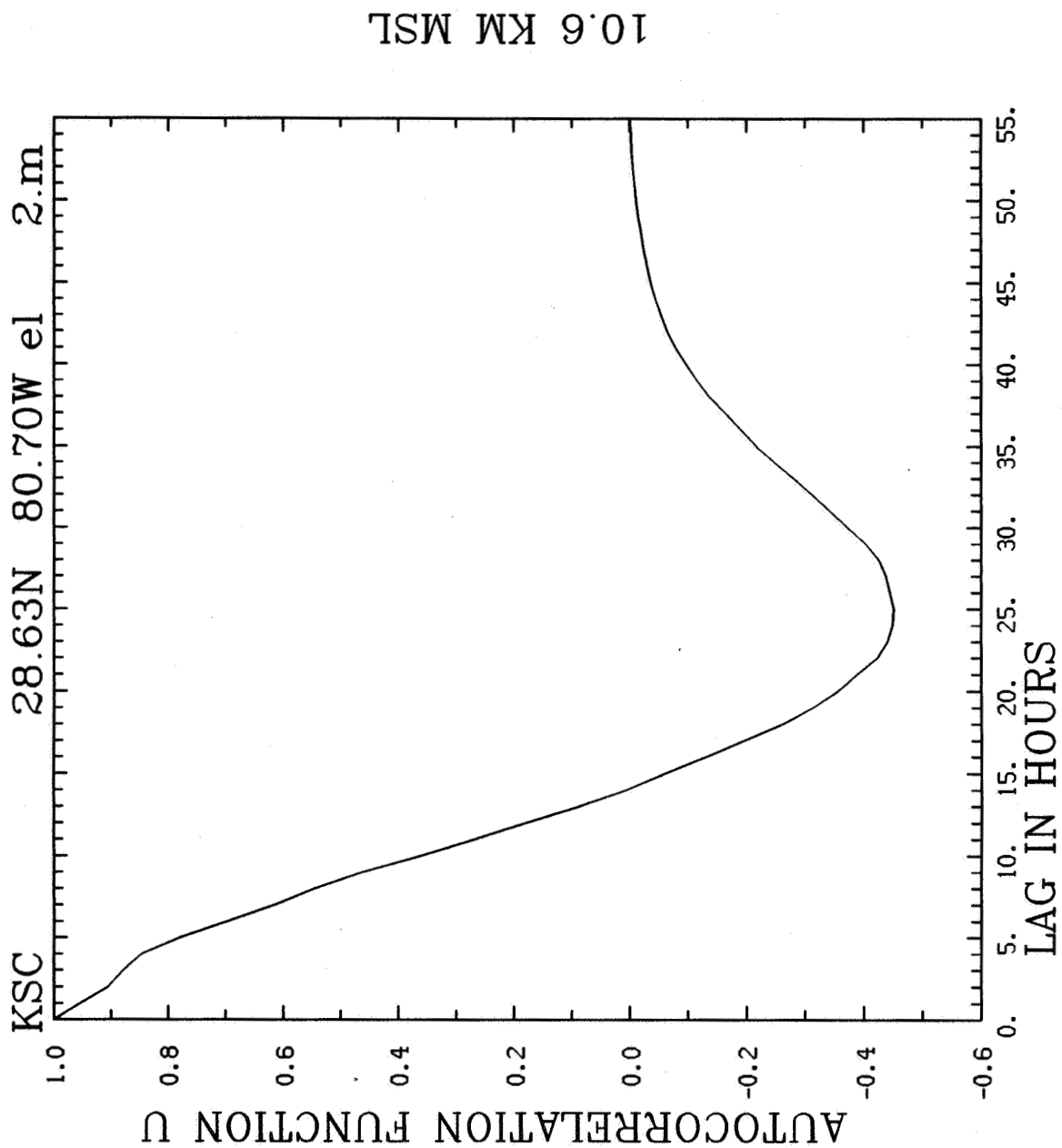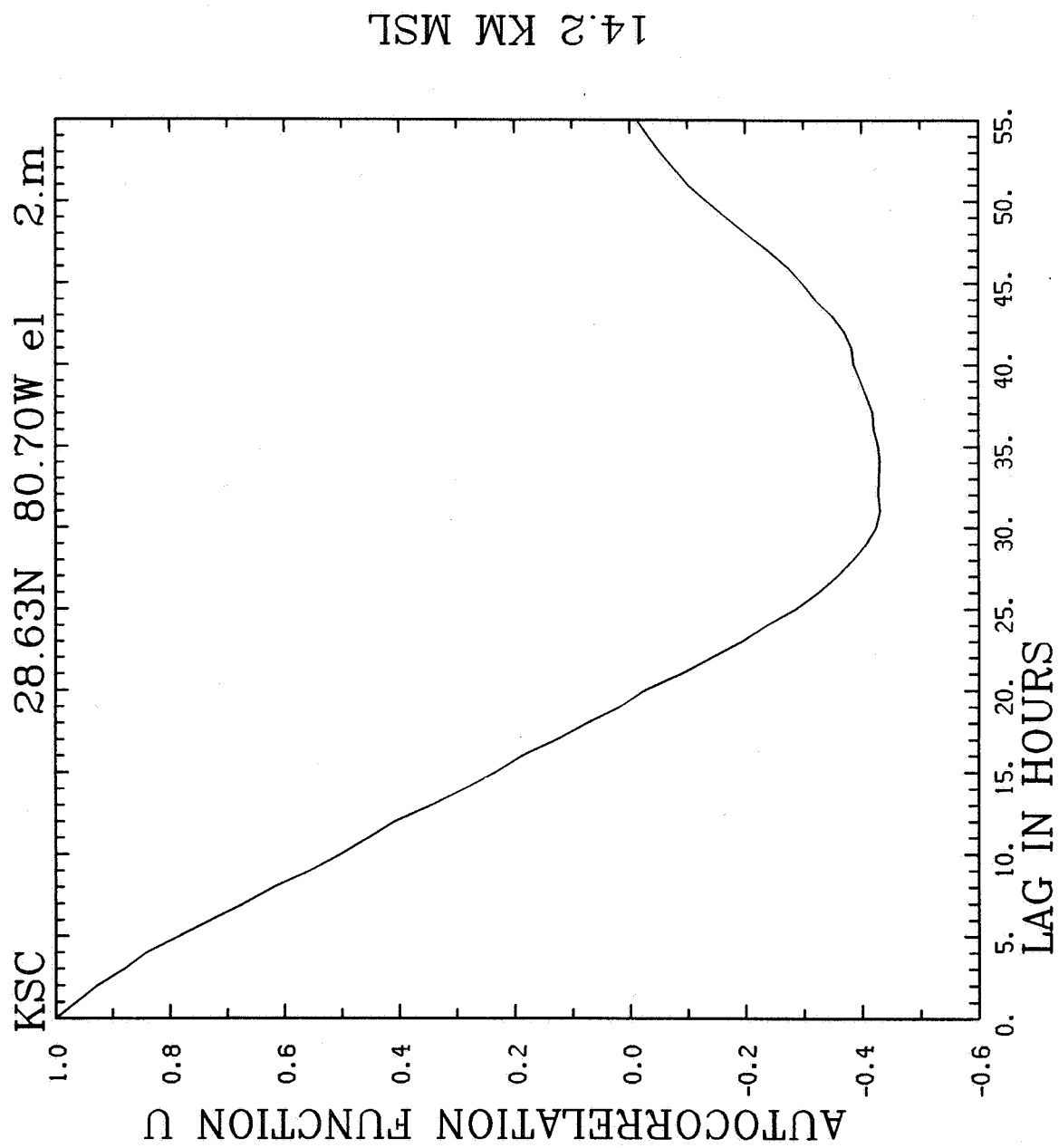Figure 4-3. Autocorrelation for the u-component of the wind measured at 5.1 km by the KSC wind profiler.

7.6 KM MSL

KSC   28.63N   80.70W el   2.m

AUTOCORRELATION FUNCTION U

LAG IN HOURS

Figure 4-4. Autocorrelation for the u-component of the wind measured at 7.6 km by the KSC wind profiler.

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Figure 4-5. Autocorrelation for the u-component of the wind measured at 10.6 km by the KSC wind profiler.

Figure 4-6. Autocorrelation for the u-component of the wind measured at 14.2 km by the KSC wind profiler.

3.2 KM MSL

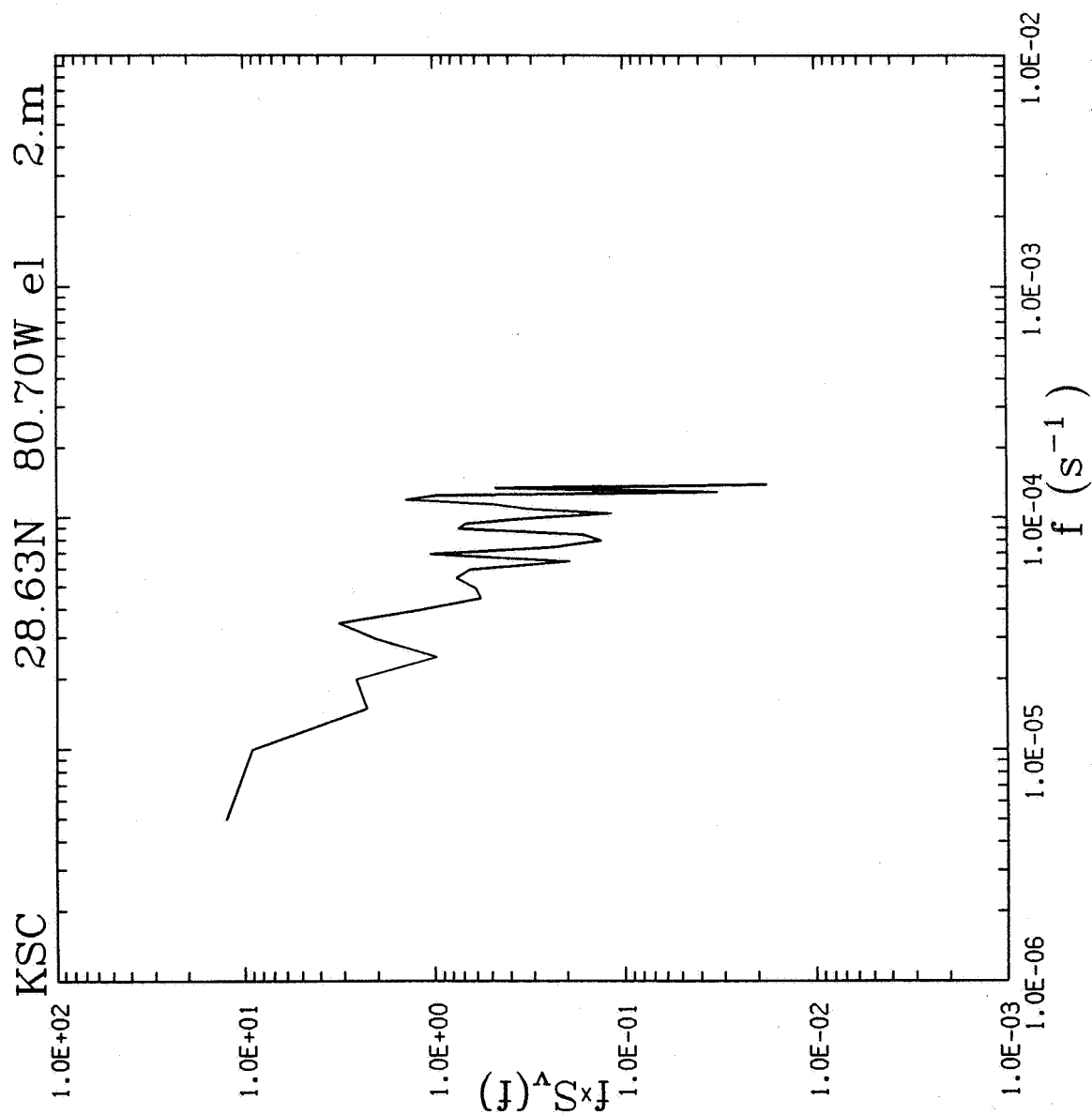KSC   28.63N   80.70W el   2.m

$f \times S_u(f)$

f (s^{-1})
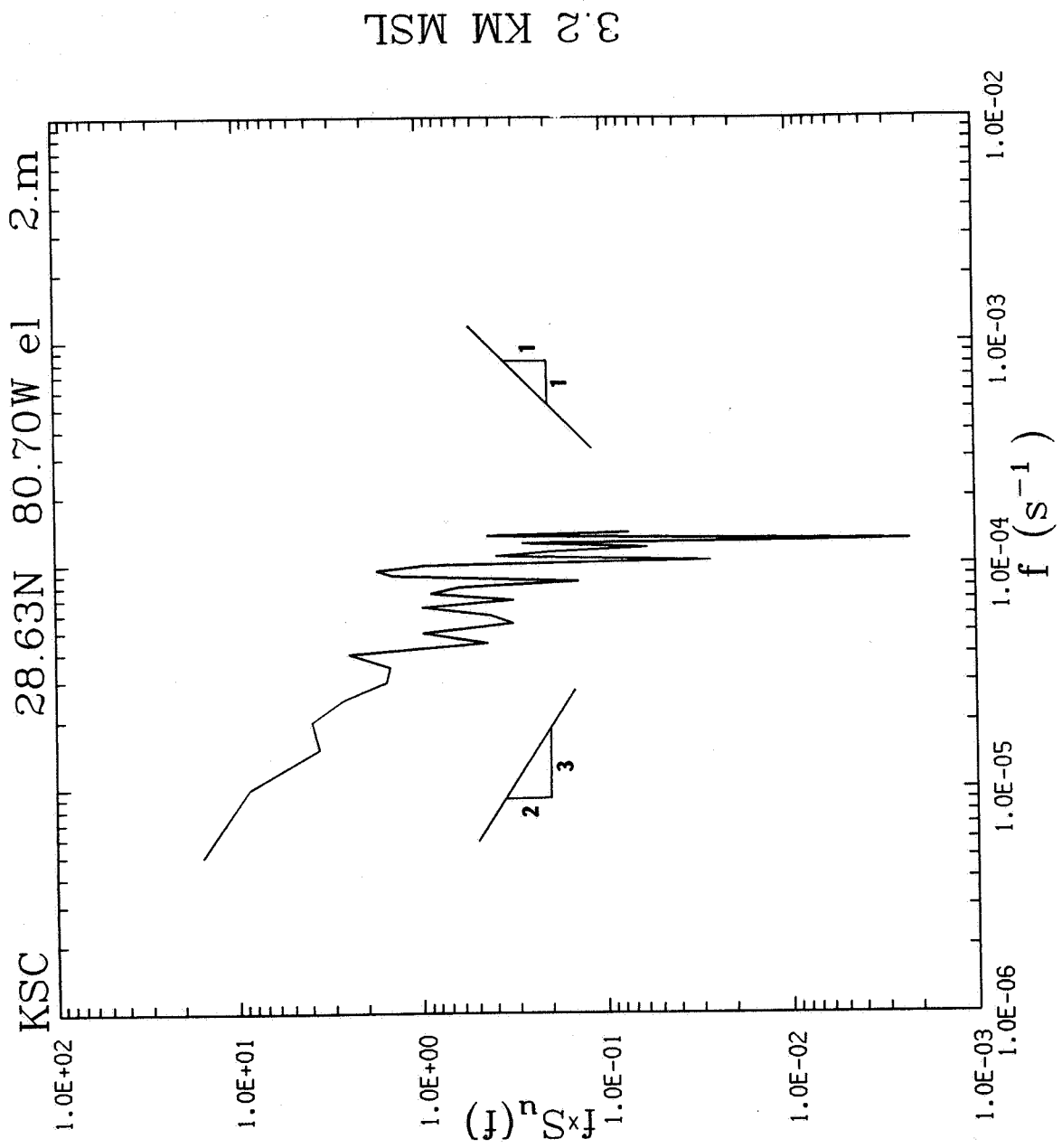
Figure 4-7. Power spectra computed for the u-component of the wind measured at 3.2 km.
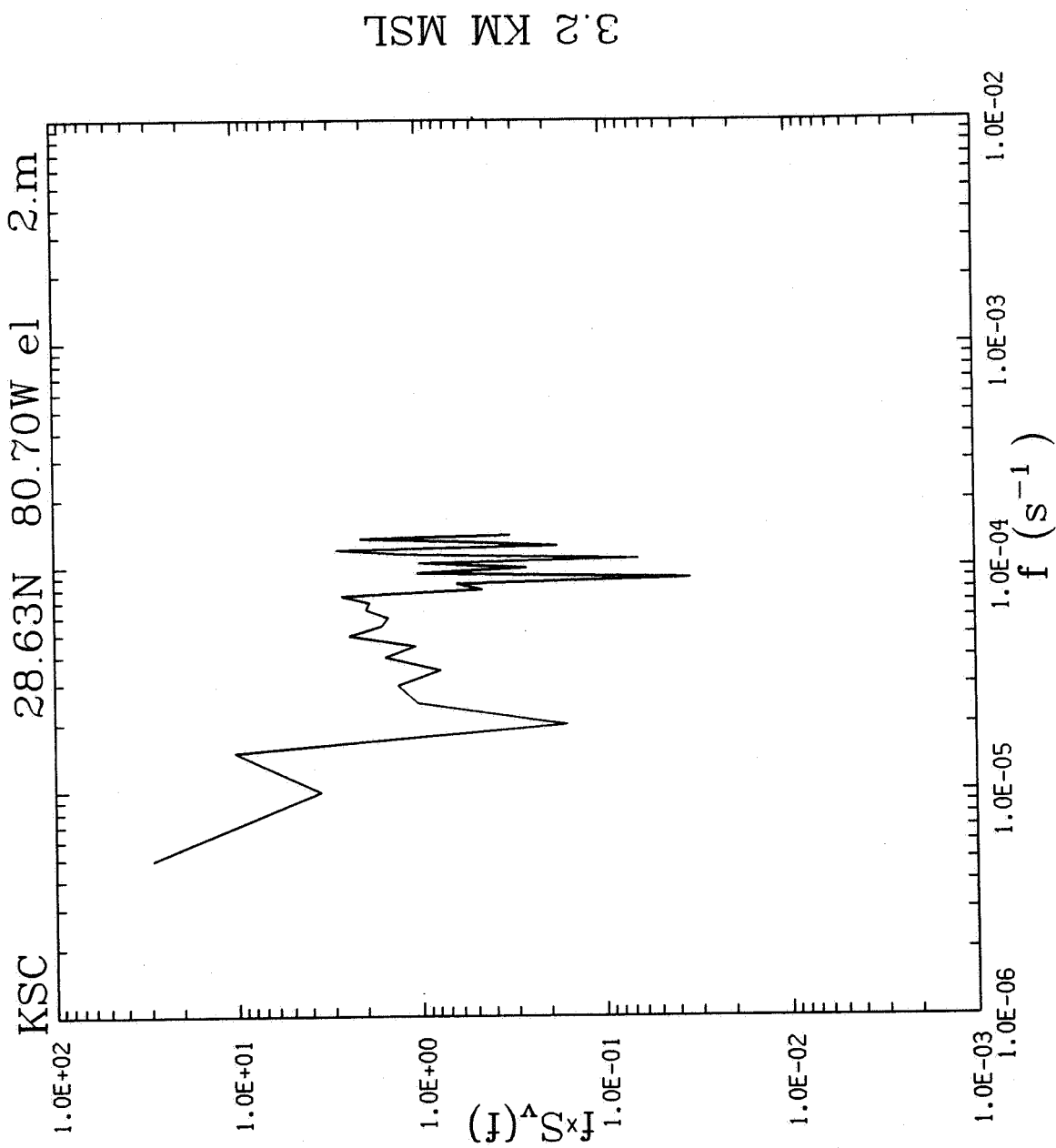
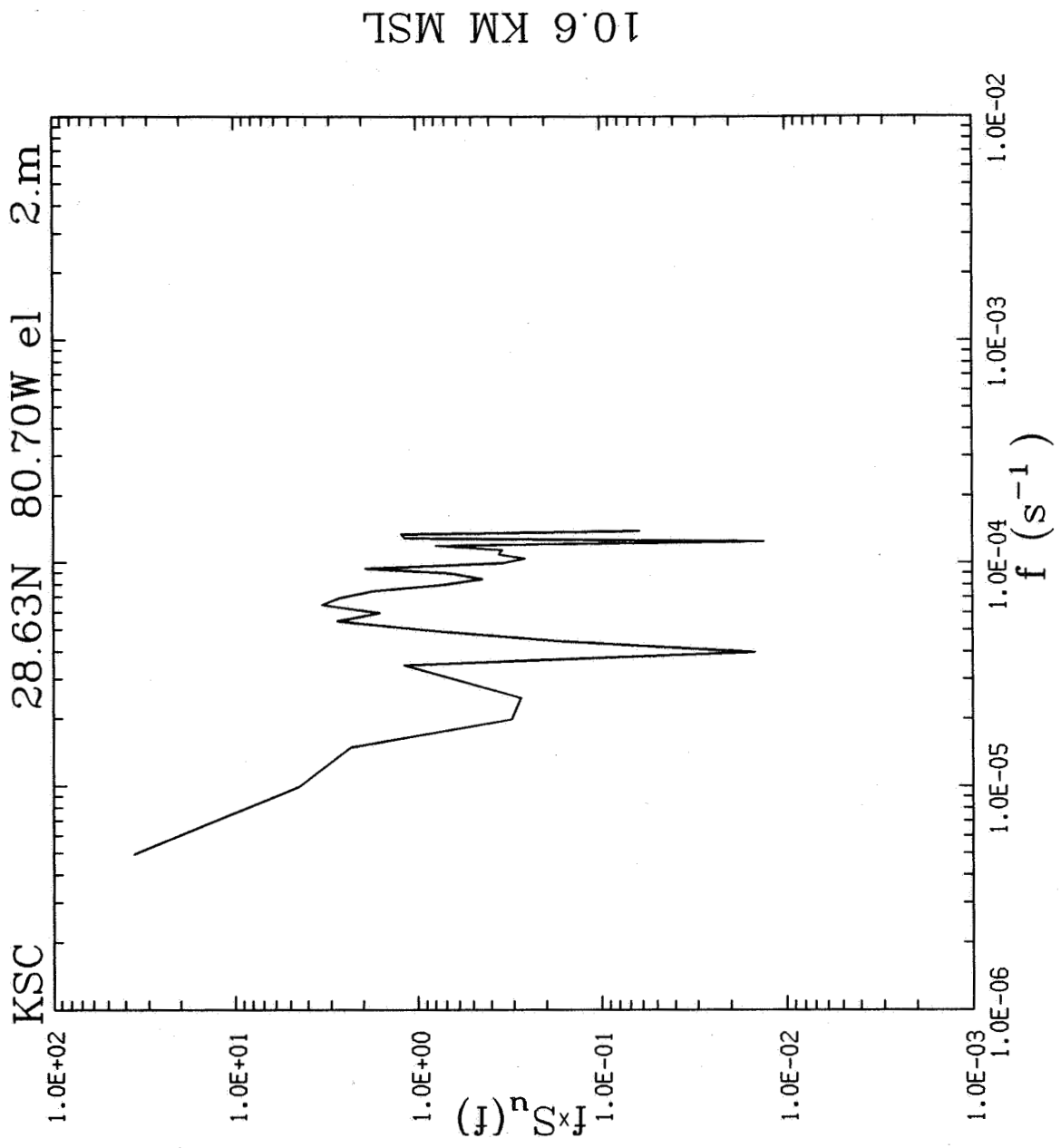Figure 4-8. Power spectra computed for the v-component of the wind measured at 3.2 km.
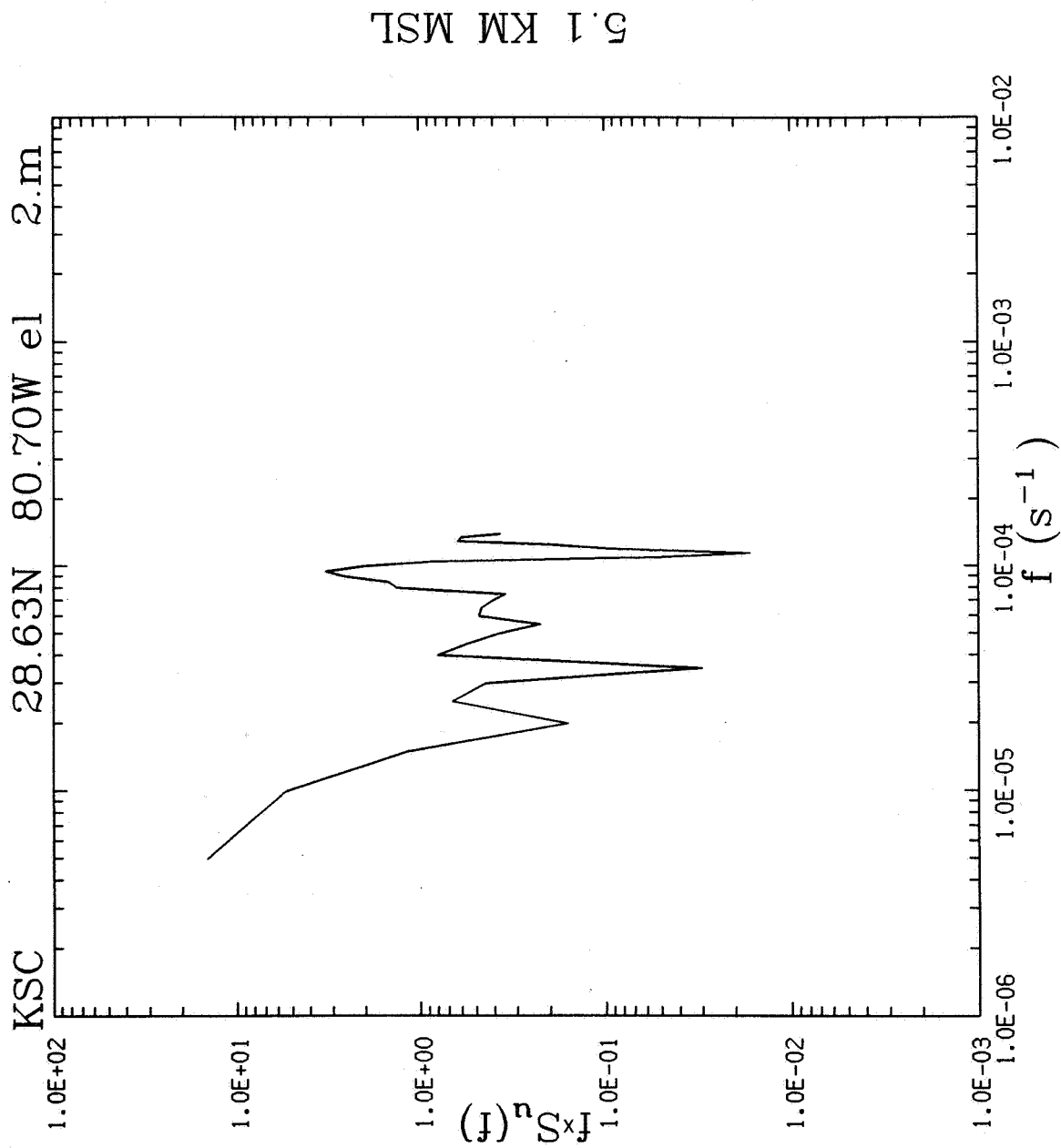
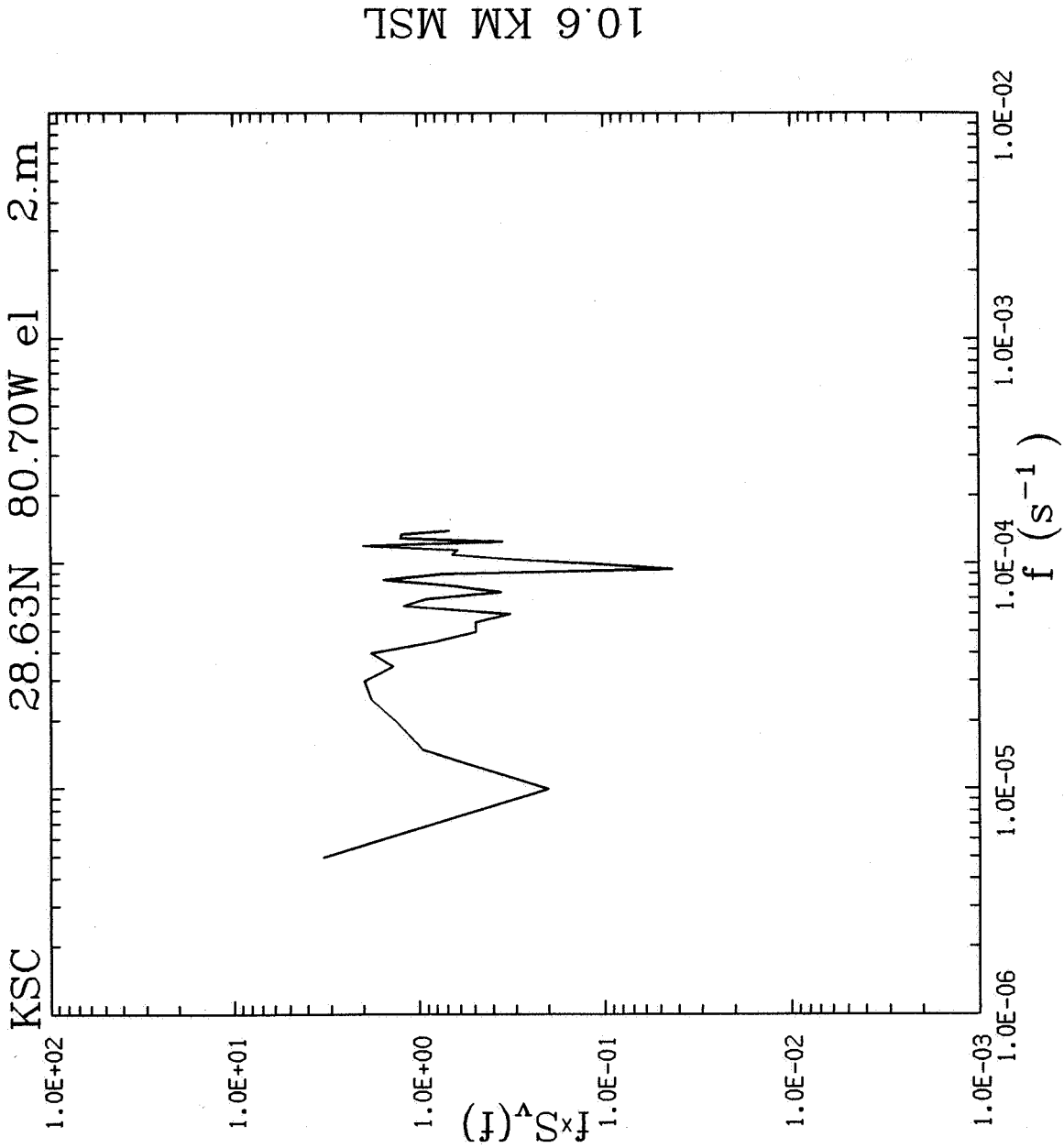Figure 4-9. Power spectra computed for the u-component of the wind measured at 5.1 km.
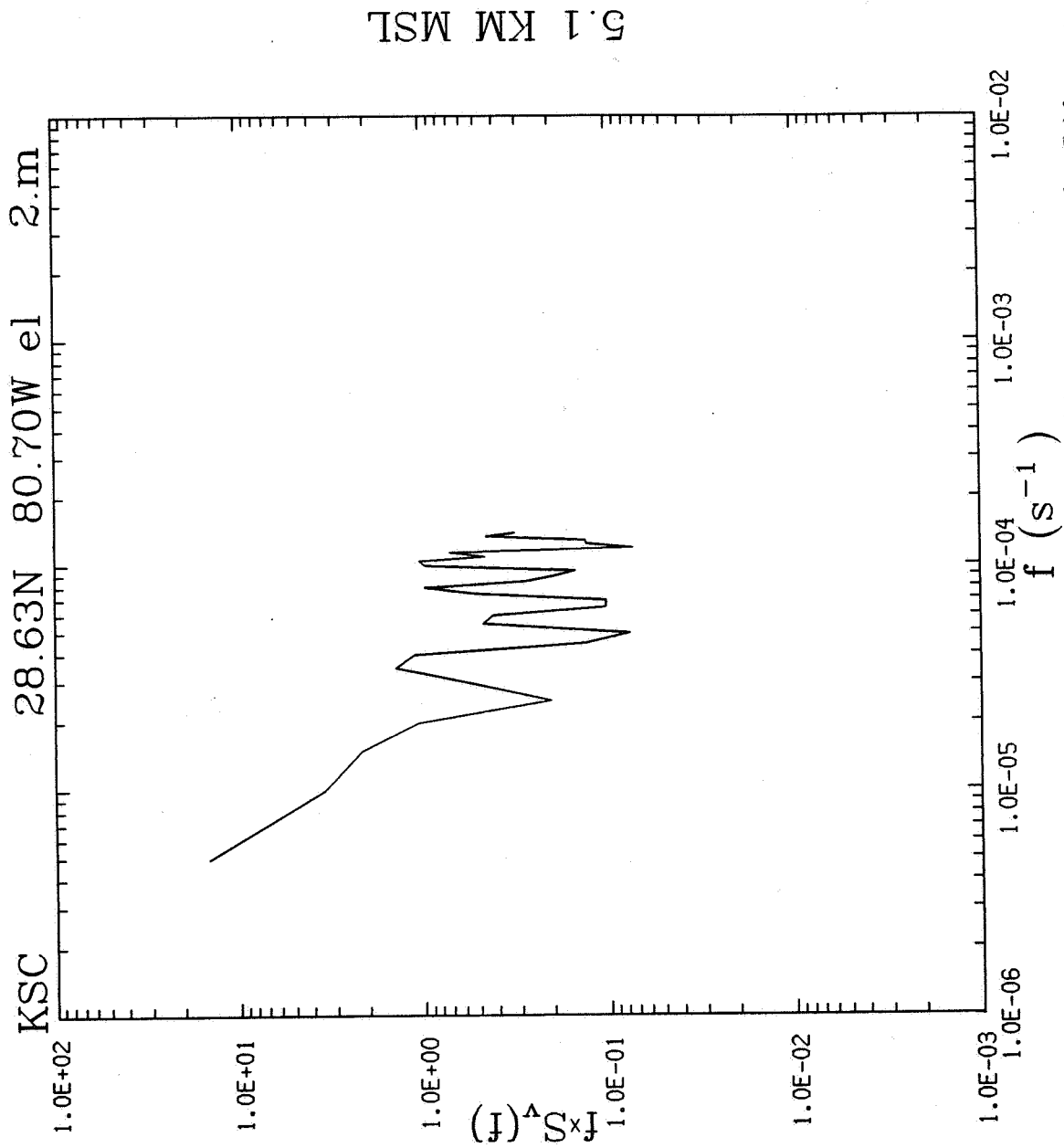
Figure 4-10. Power spectra computed for the v-component of the wind measured at 5.1 km.
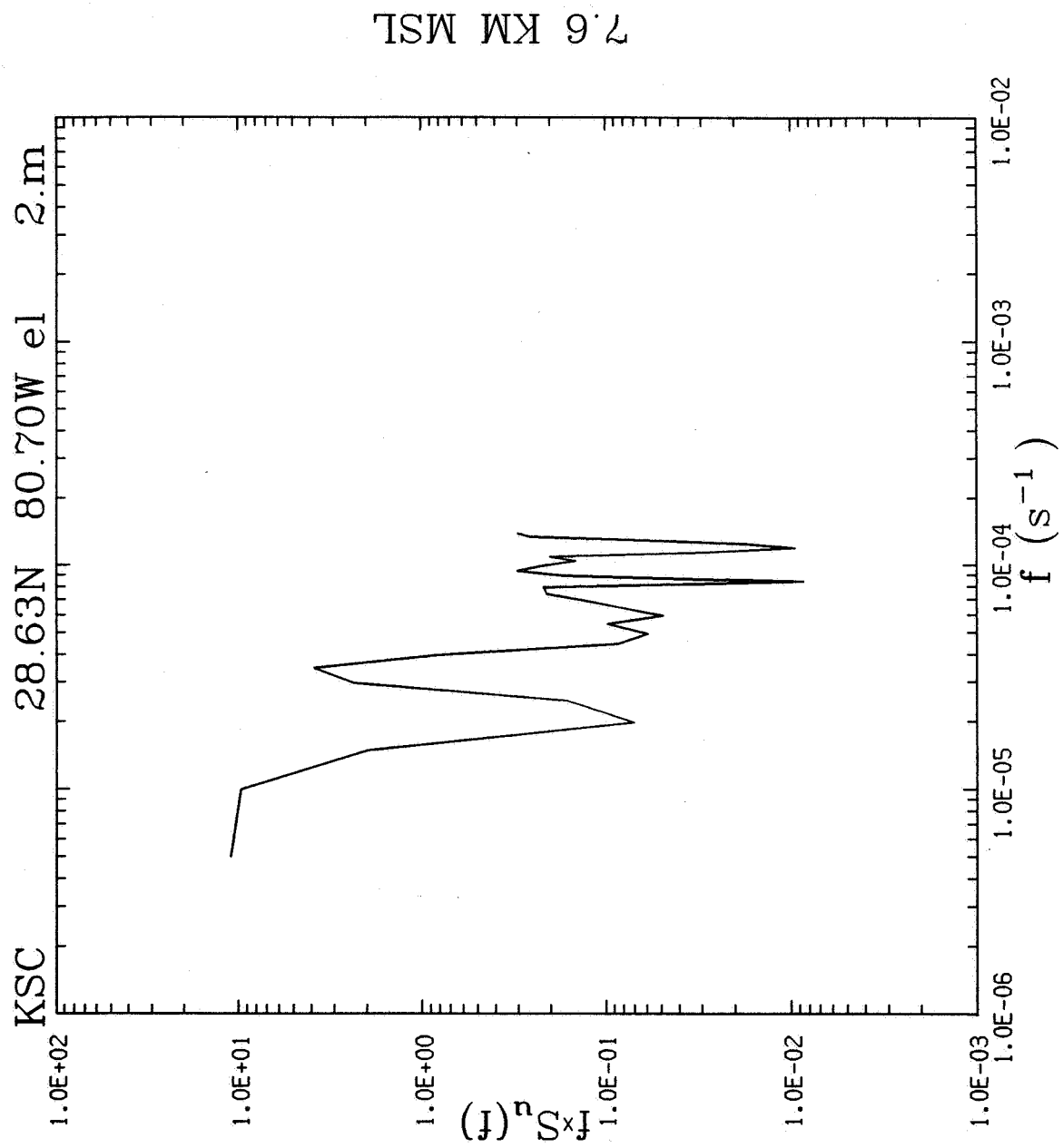
Figure 4-11. Power spectra computed for the u-component of the wind measured at 7.6 km.

Figure 4-12. Power spectra computed for the v-component of the wind measured at 7.6 km.

Figure 4-13. Power spectra computed for the u-component of the wind measured at 10.6 km.

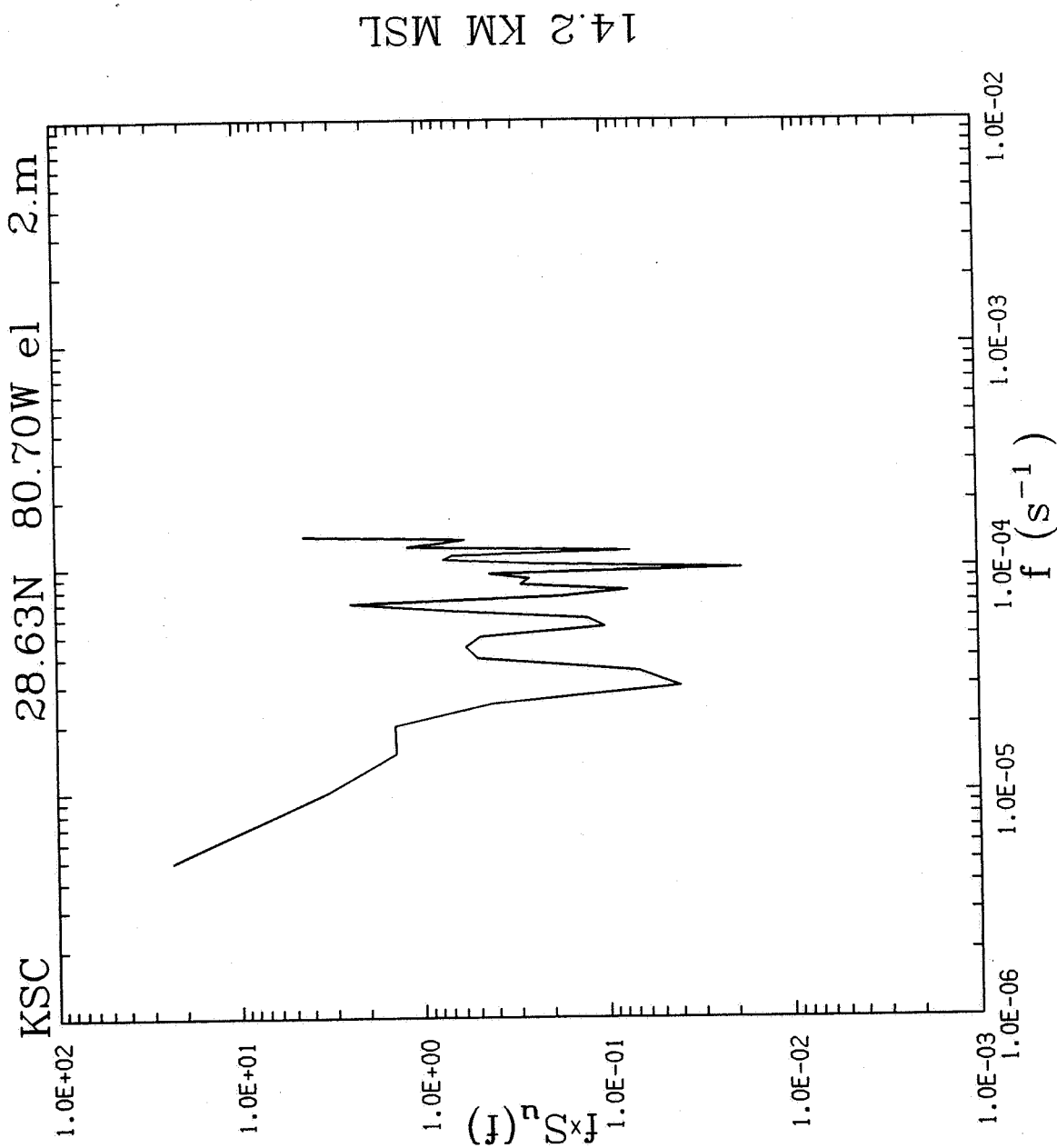Figure 4-14. Power spectra computed for the v-component of the wind measured at 10.6 km.

Figure 4-15. Power spectra computed for the u-component of the wind measured at 14.2 km.
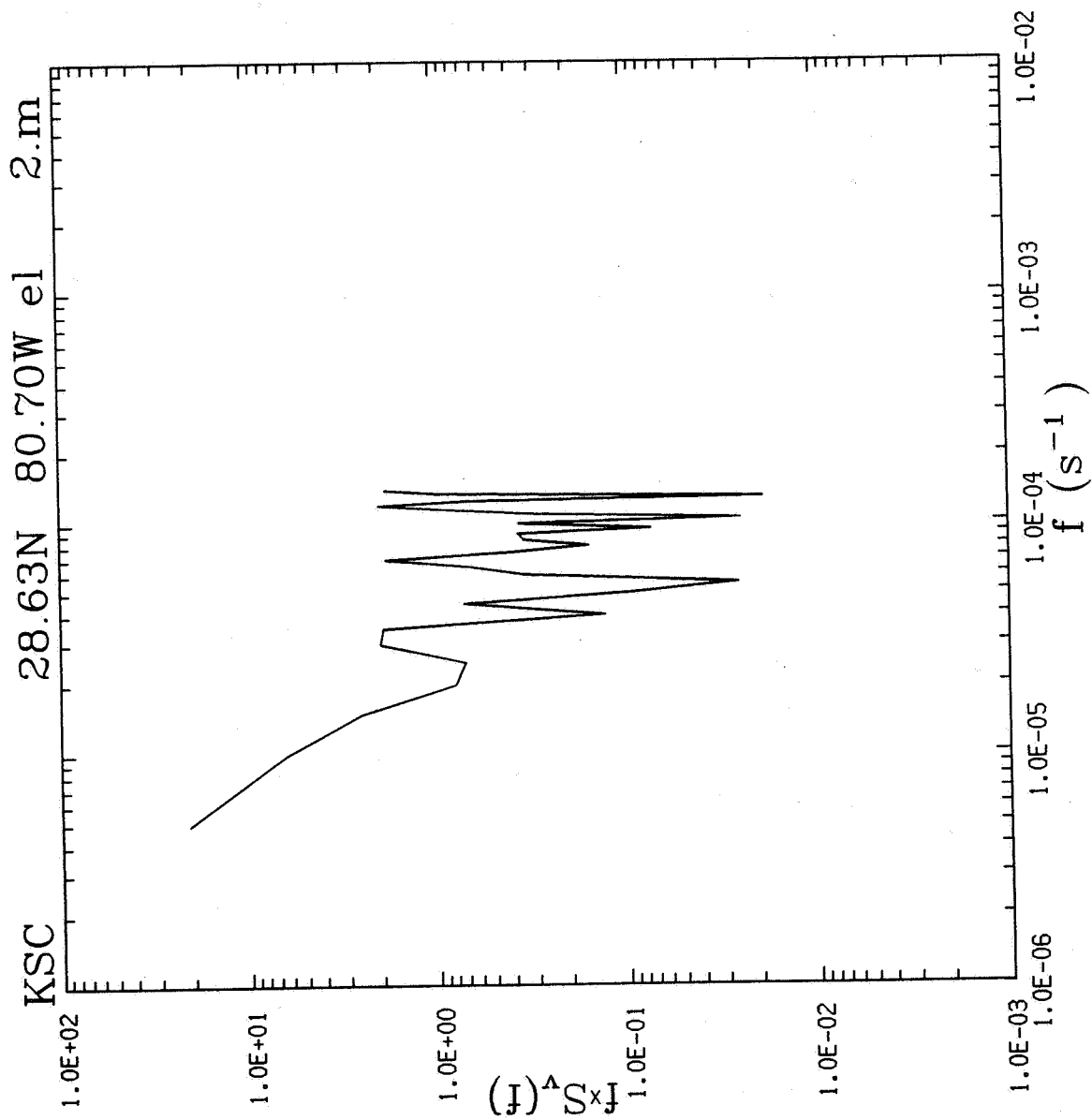
Figure 4-16. Power spectra computed for the *v*-component of the wind measured at 14.2 km.
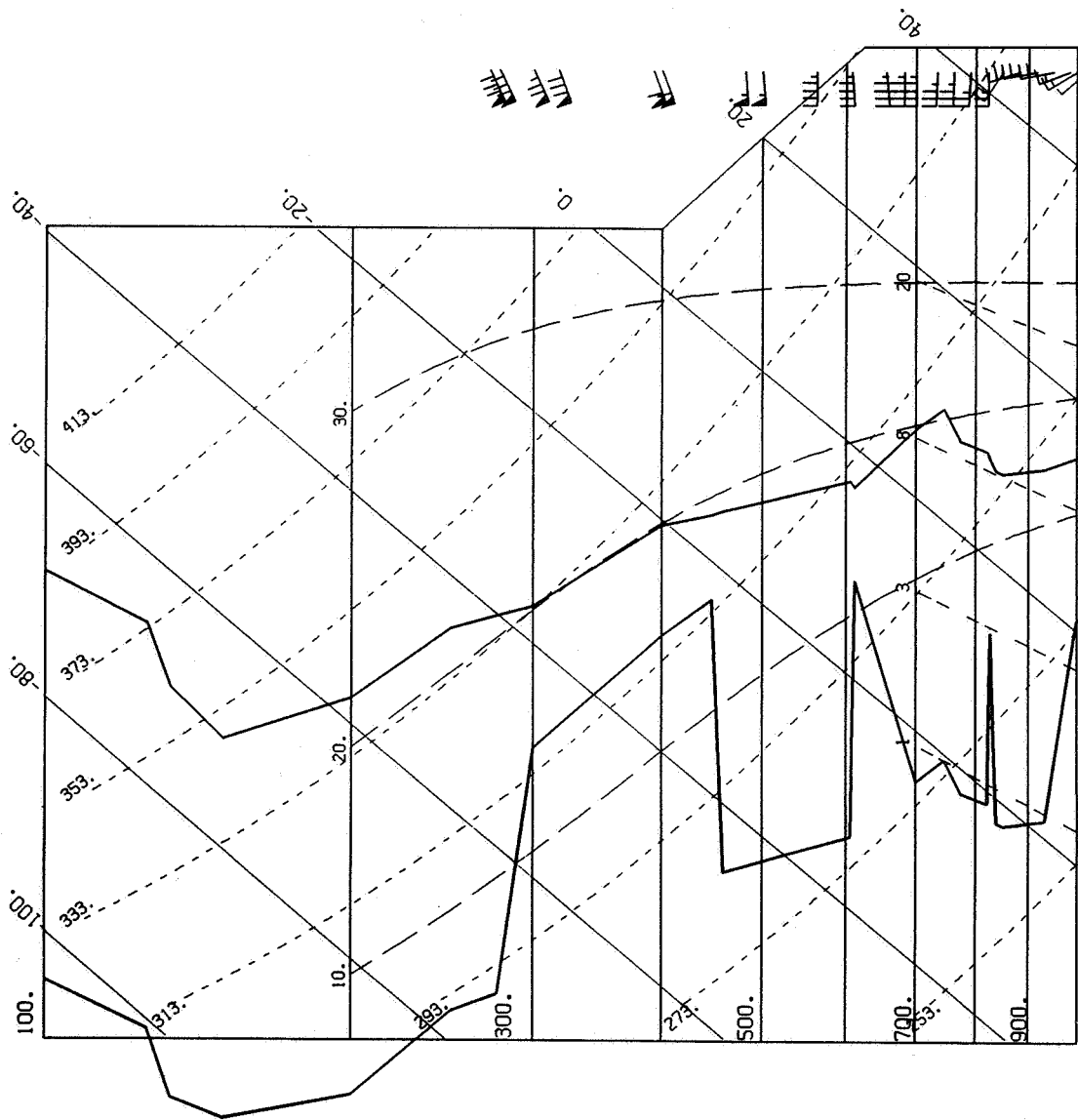
41

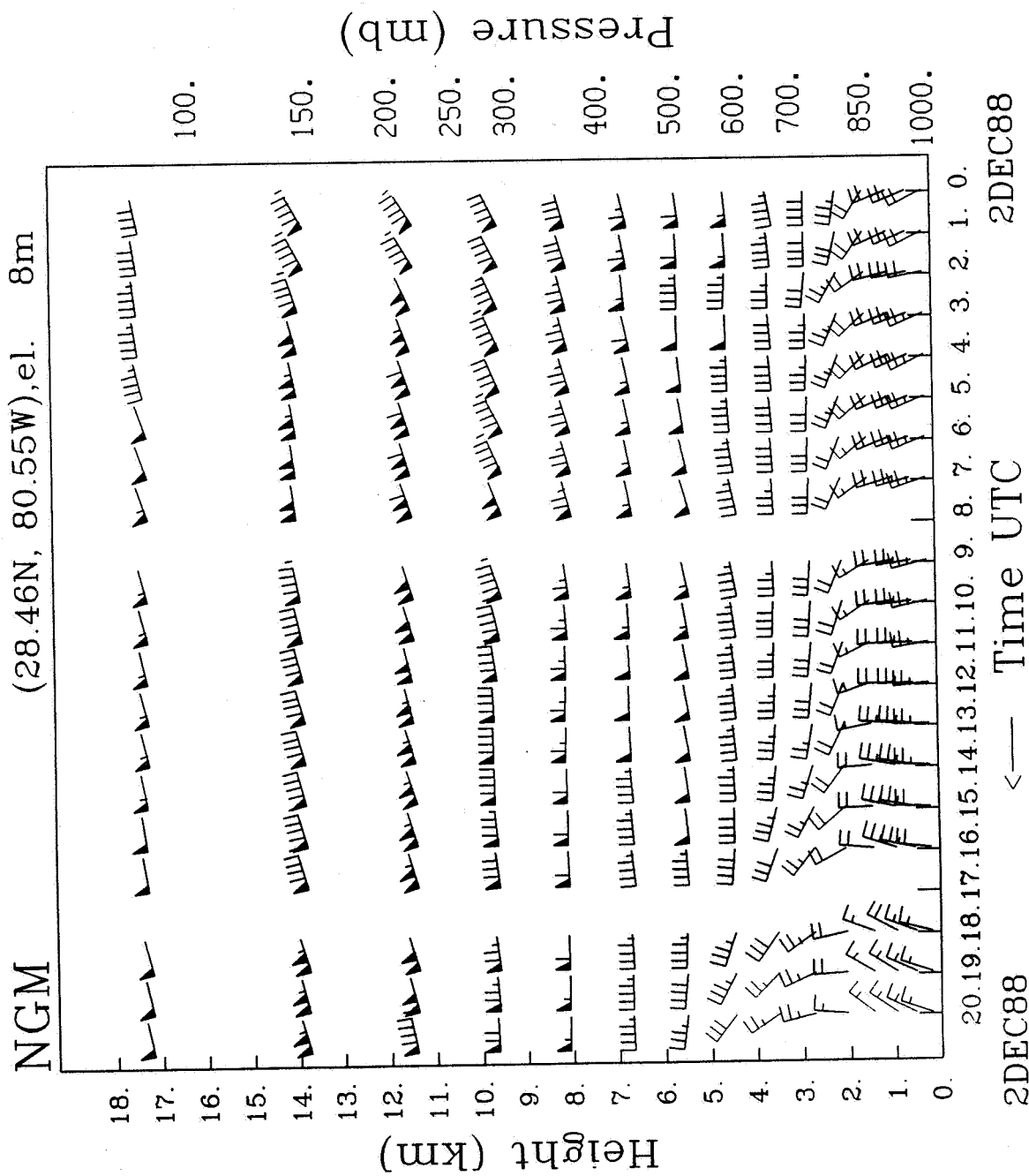Figure 5-1. NWS sounding taken at Tampa, 0000 UTC 2 December 1988. Winds same as Figure 3-1.

Figure 5-2. NGM forecast winds for KSC from 0000 UTC 2 December 1988 to 2000 UTC 2 December 1988. Winds same as Figure 3-1.
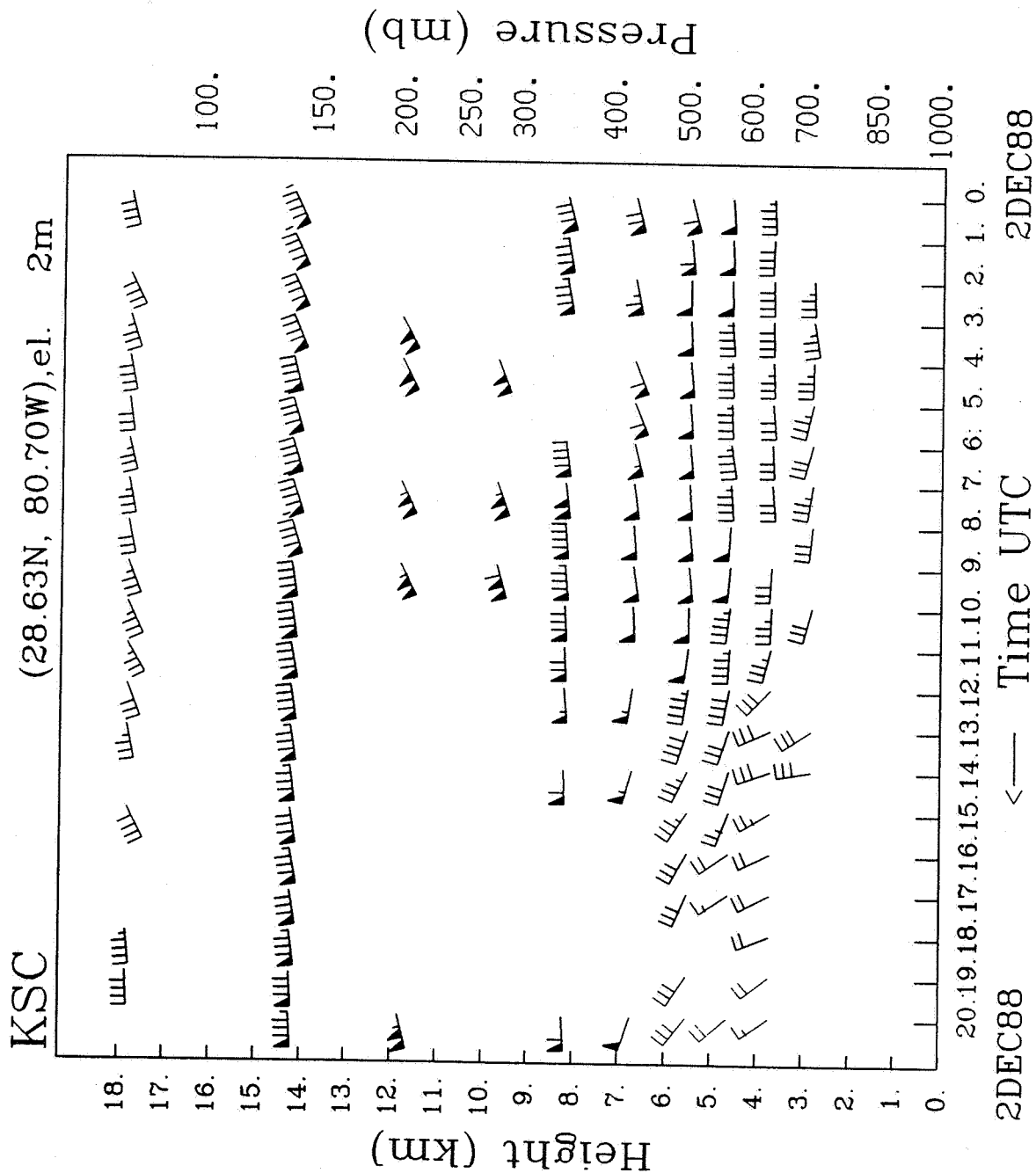
Figure 5-3. KSC profiler winds for KSC from 0000 UTC 2 December 1988 to 2000 UTC 2 December 1988. Winds same as Figure 3-1.

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13. ABSTRACT (Maximum 200 words)

This report examines the feasibility of using a network of clear-air radar wind profilers to forecast wind conditions before space shuttle launches during winter. Currently, winds are measured only in the vicinity of the shuttle launch site and wind loads on the launch vehicle are estimated using these measurements. Wind conditions upstream of Cape Canaveral are not currently monitored. Since large changes in the wind shear profile can be associated with weather systems moving over Cape Canaveral, it may be possible to improve wind forecasts over the launch site if wind measurements are made upstream. A radar wind profiling system is in use at the space shuttle launch site. This system can monitor the wind profile continuously. The existing profiler could be combined with a number of radars located upstream of the launch site. Thus, continuous wind measurements would be available upstream and at Cape Canaveral. NASA/Marshall Space Flight Center representatives have set the requirements for the radar wind profiling network. The minimum vertical resolution of the network must be set so that wind shears over depths greater than or equal to 1 km will be detected. The network should allow scientists and engineers to predict the wind profile over Cape Canaveral 6 hours before a space shuttle launch. We recommend that NASA augment its wind profiling capability with at least two additional wind profilers. These wind profilers should be located west of Cape Canaveral, approximately 100 km apart. Given our current understanding of weather systems, it is not possible to forecast all meteorological situations that may produce strong vertical wind shear over the space shuttle launch area. However, a network of wind profilers could be used to increase the accuracy of wind forecasts for the Kennedy Space Center on Cape Canaveral. Correlation and conventional synoptic meteorological techniques could be used. In addition, output from numerical weather prediction models could be used to help forecasters anticipate significant changes in the wind shear profiles during the first 4 to 6 hours of their forecast period. Chapter 1 introduces the problem of designing a wind profiling network that could be used to provide windfield forecasts in the vicinity of Cape Canaveral. Chapter 2 contains the recommendations for the proposed wind profiling network. Chapter 3 examines a data set and assesses the performance of the KSC wind profiler. In Chapter 4, power spectra and autocorrelation functions computed from the wind profiler data set and conventional weather data observations are used to assess the forecasting ability of the existing radar system and show how the recommended network could be used to forecast wind shear. Chapter 5 examines the usefulness of blending numerical weather prediction model output and wind profiler data to improve wind shear forecasts over Cape Canaveral.

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