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Abteilung Sicherheit und Strahlenschutz

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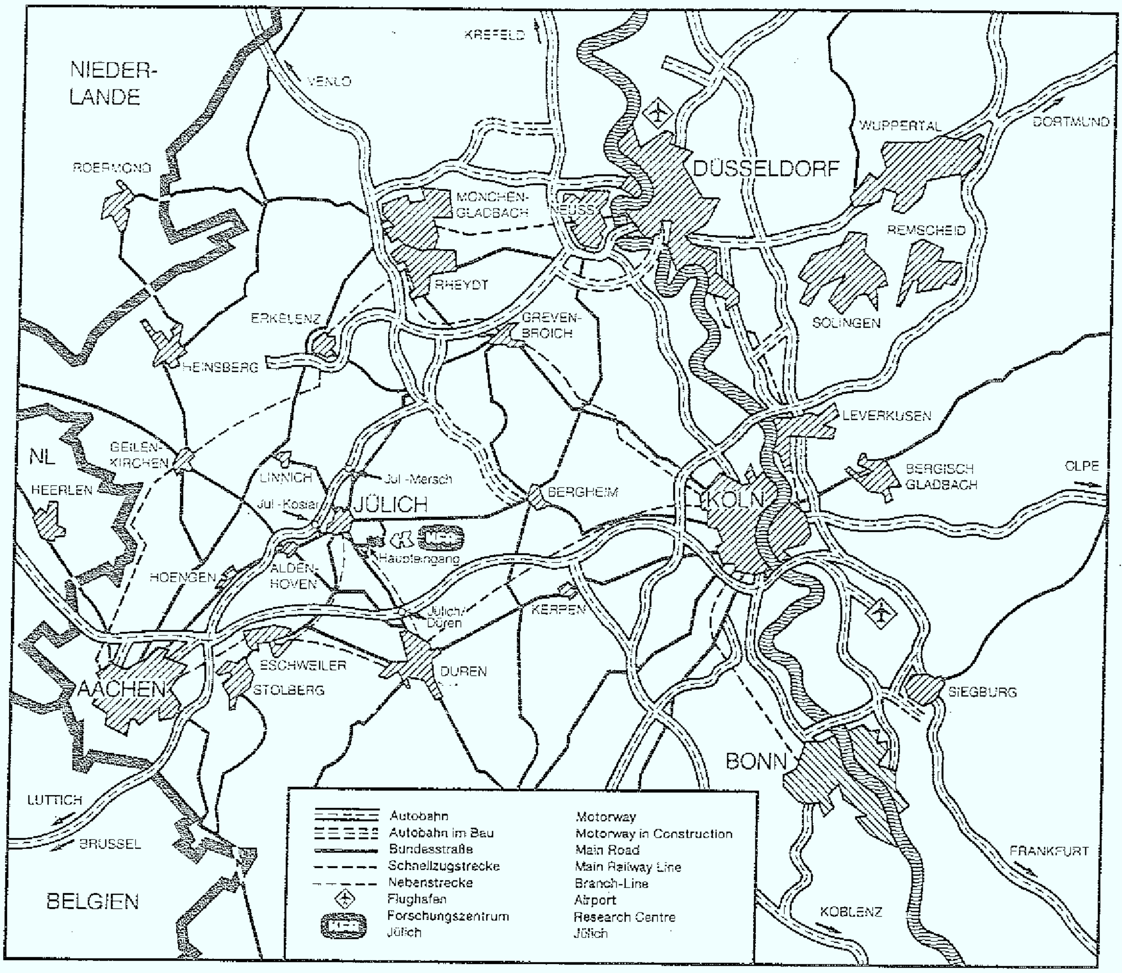


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# On the Operating Experience of the Doppler Sodar System at the Forschungszentrum Juelich

by

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## 1. Introduction

Meteorological measurement programs at nuclear installations are necessary to cope-up with an unlikely event of radioactive effluent release. Apart from the point of view of the emergency preparedness, at a nuclear facility, continuous meteorological measurements are needed to assess the impact of radioactive releases during normal operation. More realistic dispersion estimation models require meteorological inputs pertaining to the boundary layer which can not be completely fulfilled by a meteorological tower alone as the boundary layer height may extend up to 1000m. Also these models, when dealing with complex terrains, accommodate spatial variability in meteorological conditions (10).

The Sound Detection And Ranging technique known as the SODAR technique to measure vertical temperature structure in the lower atmosphere became popular since around 1970. With the advancements in the fields of electronics and computers, the Sodar technique got developed and monostatic Doppler Sodars were built by many research and commercial organizations. Around the year 1985 many commercial establishments were offering Doppler Sodars to measure three dimensional wind components up to a height of about 1000m.

At the end of 1986 a REMTECH monostatic Doppler Sodar system was procured by the KFA and since then it has been in operation in the KFA environment. The system was extensively used at the foot of the hill 'Sophienhoehe' in connection with series of tracer dispersion experiments conducted at the hill site. At other times the system was operated in the KFA premises where a 120m high meteorological tower is in operation.

Results of many specially performed tests (1,2,3,4,6,7,8,11,12) to study the usefulness and reliability of Doppler Sodars indicate that these are superior in many respects to several conventional measuring techniques though the Sodars are not yet accepted to be as basic as the conventional instruments.

In this report the description and the operating principles of the Doppler Sodar at the KFA are briefly described and outputs from the routine operation of the Sodar are compared with the concurrently measured data on the 120m high KFA meteorological tower. Three sets of data, varying from periods of ten days to 18 days, are used for the comparison.

## 2. Description of the Instrument and Operation

The Doppler Sodar system, supplied by M/S REMTECH consists of (a) a trailer carrying three antennas, (b) an electronic cabinet and (c) terminals and printers. The block diagram of the system is shown in figure 1.

### 2.1 The Antennas

The Sodar system which has been in operation since the year 1987, is a monostatic system with three numbers of fibreglass paraboloid (1.2m diameter) antennas (type AO) mounted on a trailer. The axes of antenna number 1 and 2 are tilted from the vertical by 18 degrees. The axis of the third antenna is vertical. The axes of antenna 1 and 2, when projected on the horizontal make an angle of 90 degrees. Each of the paraboloids is provided with a horn shaped shelter (1.74m high) whose inner surface is covered with foam which is a good sound absorber. At the focal points of the paraboloids compression drivers are located. Photograph of the three antenns, complete with shelters, mounted on the trailer is given in figure 2. The nominal frequency of sound to be used with these antennas is 1600 Hz. As the transmission and reception patterns of the antennas depend to some extent upon the wavelength of the emitted sound, the software of the Sodar system selects the transmission frequency so that the wavelength remains the same under different environmental temperatures.

### 2.2 The Electronic Cabinet and Terminals

The cabinet which is housed in a (mobile) wagon contains the followings.

1. A PDP11 minicomputer.
2. A transceiver for emission and reception.
3. A power amplifier for emission of sound.
4. An analog interface.
5. A microstreamer unit.

The minicomputer is of 16 bit words with 256 K bytes RAM. It has one 16 bit DIGITAL I/O parallel board and one 12 bit A/D board and has four RS232 ports. The software of the system operates on the RT11 operating system. The minicomputer has two floppy drives and 20 megabyte winchester. A VT 220 DEC video terminal with key-board functions as the master console. The terminal is associated to a dot matrix printer. The Sodar software manages the input/output, the electronic transceiver, signal processing and extraction of informations from signals.

The transceiver consists of power relays to switch power amplifier output to selected compression drivers and input relays to switch back-scattered signal received by the compression drivers to the preamplifier. The transceiver is controlled by the minicomputer. The power amplifier can deliver a peak acoustic power of 50 watts through the compression drivers.

The analog interface is used to connect analog inputs from independent sensors such as u, v and w anemometers. Signals fed through the analog inputs can be processed in the minicomputer.

The microstreamer is used to transfer accumulated data from the winchester on to magnetic tape for further processing or for storing purpose.

A colour monitor displays vector plot of wind speed (from all altitudes) obtained after each sampling period. It displays vector wind profile of the last six sampling period steps. The colour is conditioned to display mean vertical velocity.

Back-scattered echo intensity from the vertical antenna is printed on a dot matrix printer used as a facsimile recorder. (see chapter 5).

## 2.3 Operation and Principle

Under the instruction from the minicomputer the transceiver sends a sound pulse of about 150 msec duration from the power amplifier to compression driver of antenna 1. Immediately after the acoustic burst, the compression driver is electronically switched into a sensitive microphone configuration. The sound pulse, travelling along the axis of the antenna, gets scattered due to the presence of eddies in the atmosphere and the back-scattered signal is received by the microphone. This signal is amplified and passed through a band-pass filter (300 Hz width) and then mixed with the emission frequency. After that the signal is fed to the analog to digital converter board of the minicomputer.

The series of digital values against time represent the back-scattered signal corresponding to various elevations. For example, for the vertical antenna, the series of signal values during the time period between t1 and t2 (where t1 and t2 are measured from the instant of emission) correspond to a layer between heights h1 and h2 where h1=t1.c/2 and h2=t2.c/2 and the thickness of the layer (h2 - h1)=(t2 - t1).c/2 where c is velocity of sound. For the tilted antennas the relation will be h1=(t1.c/2)cos(i) and h2=(t2.c/2)cos(i) where i is the angle of tilt from the vertical. The time versus height relationship is shown in figure 4.

The minicomputer performs Fast Fourier Transform on the digital time series and produces one power spectrum for each of the time segments. These time segments correspond to different layers of the atmosphere and the altitude and thickness of the layer is governed by the above relations. Thus after the transmission of the pulse through an antenna, the back-scattered signals corresponding to definite altitude layers are processed to obtain power spectra corresponding to each of the layers. While the amplitude of the spectrum corresponds to the strength of the back-scattered signal, the frequency shift in the spectrum corresponds to the radial velocity of the air mass in the layer (ie. the velocity in the direction of the axis of the antenna). Corresponding to each transmission, radial velocities for each of the pre-assigned layers are computed and stored by the minicomputer. The small elements (of the size of half the wavelength of the emitted sound - about 10 cm) of thermal turbulence in the atmosphere are responsible for back-scattering of sound. The strength of the backscattered signal depends upon the temperature structure function definned as

$$C_T^2 = \frac{\overline{[T(x+r) - T(x)]^2}}{r^{2/3}}$$

where T(x+r) and T(x) are potential temperatures at x+r and at x and r is spatial seperation between the two points and the bar represents temporal average. Motion of these thermal elements constitute the wind speed. When these elements are encountered by the sound beam, the back-scattered signal undergoes double Doppler effect (the beam hits a moving target and again the moving target emit back). The Doppler shift Δf is very close to the approximation:

$$\Delta f = \frac{2f_0 . V_r}{c} \qquad \text{or} \qquad V_r = \frac{c . \Delta f}{2f_0}$$

where $V_r$ is radial velocity of air mass, $f_0$ is the emission frequency and c is velocity of sound. Thus from the Doppler shifts obtained from the power spectra, radial velocities corresponding to different altitudes are calculated.

After the completion of emission and reception through one antenna, the second antenna is selected and then the third. The cycle is repeated till the end of sampling time. The individual radial velocities are more or less instantaneous values. From the knowledge of the orientations of the three antenna axes and the mean radial velocities, the mean values of u, v and w components of the three dimensional atmospheric flow for each layer are computed. From the radial velocities of the vertical antenna mean and standard deviation of vertical velocity are computed. Also, the strength of the back-scattered signal (echo) and standard deviation of echo from the vertical antenna are computed for each of the layers (the strength of echo is a measure of temperature structure function). Independently of this, intensity of back-scattered echo from the vertical antenna is computed with selectable resolution for outputting on a facsimile recorder.

For a given sampling period, the following quantities are outputted to the winchester and as well as to the printer for each of the layers.

1. Echo (vertical antenna)
2. Standard deviation of echo (vertical antenna)
3. Horizontal component of wind speed
4. Horizontal wind direction
5. Standard deviation of horizontal wind direction
6. Vertical component of wind speed
7. Standard deviation of vertical wind speed

The signal received by the microphone (compression driver) can not be considered as a pure signal with a doppler shift because of the followings:

1. Presence of ambient noise
2. Imperfection of the antenna during transmission and reception
3. The back-scattering is by a volume of air determined by the beam width and range. Uneven spatial distribution of thermal velocity elements exist within a volume.

As a result, the spectrum of the received signal contains energy distribution around the Doppler shift. And in some cases, the Doppler shift corresponding to the radial velocity can be completely masked by noise and fixed echos (by obstacles) reaching the microphone. Also due to the characteristics of the antenna gain, the noise component can not be considered as white noise. In the system, the following steps are taken to minimize the effect of noise.

a. Instead of monochromatic sound pulse, double frequency pulse is emitted through the antenna. With this one gets two peaks in the spectrum instead of one and the reliability is increased. Also the jitter around the mean value of the two shifts is utilized as a measurement error.

b. To take into account the antenna transfer function, which varies with temperature, the system automatically chooses the optimal operating frequency for each antenna at prescribed intervals of time.

c. Validation tests are performed by software before and after the computation of wind speeds. Signal to noise ratio and plausibility tests are performed before validating a radial speed. A chart showing the procedure of validation adopted in the REMTECH Sodar is given in figure 5.

d. At the end of sampling time, before the results are output, final checking of results is made by the software. These checks are (1) checking the number of validations for each layer and for each of the three components to see whether the number of validations are atleast equal to the required minimum, (2) checking the values of standard deviations of the three components to see whether they are reasonable and (3) looking for the presence of a plausible wind profile. If one of these tests gives a negative result, then the software will invalidate the data for that particular layer.

## 2.4 Operating Parameters

There is a large number of operating parameters which can be changed by an operator through the master console. These parameters can be grouped into three kinds : Orders, Operating Parameters and Test Parameters. The operating parameters allow one to operate the system in a flexible manner. One can choose for example the minimum height, the thickness of layers, number of layers, sampling period etc. Also one can get back earlier results for the purpose of checking or otherwise. There are parameters to set signal to noise ratio and to set minimum number of validations for the computation of means and standard deviations. Also there are parameters to control analog inputs. The test parameters allow one to have an idea of background noise and also to identify faults in electrical connections, cables and antennas.

## 2.5 Specifications

Some of the important specifications of the REMTECH Sodar with which the system operated are listed below. The Sodar was operated with a software version of May 1987.

| | |
|---|---|
| Number of antennas (AO type) | three |
| Construction of antennas | fibreglas, parabolic<br>1.2m dia |
| Tilting angle of antennas 1 & 2 | 18 degrees |
| Peak output acoustic power | 50 watts |
| Frequency (nominal) | 1600 Hz |
| Bandwidth | +/- 290 Hz |
| Pulse width | 150 msec. |
| Minimum height | 50m at site 1<br>40m at site 2 |

| | |
|---|---|
| Thickness of the layer | 20m |
| Number of layers (range gates) | 30 at site 1<br>20 at site 2 |
| Sampling period | 10 minutes |
| Signal to noise ratio for wind components | 20 |
| Minimum number of radial velocity validation requirement for wind components | 3 |
| Minimum number of validations for computing standard deviations | 5 |
| Spatial resolution for the facsimile | 5 metres |
| Minimum signal to noise ratio for facsimile validation | 5 |

## 2.6 Precedure for computation

At the end of sampling time, corresponding to a given layer, the three radial velocities from the three antennas are available. If the three dimensional total wind vector (averaged over the sampling period) has u, v and w wind speed components along x, y and z of an orthogonal coordinate system, it follows from the orthogonolity of the two tilted antennas,

$$u = \frac{V_{r1}}{\sin\alpha} - w\cot\alpha$$

and

$$v = \frac{V_{r2}}{\sin\alpha} - w\cot\alpha$$

where $V_{r1}$ and $V_{r2}$ are the average radial velocities corresponding to antenna 1 and 2 respectively. $\alpha$ is the angle of tilt from the vertical which is 18 degrees for both the antennas. The horizontal mean wind speed $V_h$ is computed using the relation :

$$V_h = (u^2 + v^2)^{1/2}$$

and the horizontal mean wind direction $\theta$ is computed using the relation :

$$\theta = arctan\left(\frac{u}{v}\right)$$

The average vertical velocity $w = V_{r3}$ where $V_{r3}$ is the average radial velocity corresponding to the third antenna which is vertical.

As mentioned earlier, the minicomputer stores the standard deviations of the three radial velocities corresponding to each layer. Also, by the use of double frequency technique, two radial velocities are obtained for each pulse and for each layer and the average of the two is taken as the instantaneous velocity. The standard deviation of the differences between the two radial velocities (due to double frequency) is also computed for each layer at the end of sampling period. This standard deviation is considered as the sigma of the measurement error and is used to correct the measured raw value of standard deviation of vertical velocity $\sigma_{wr}$. The correction is applied as follows.

$$\sigma_w = (\sigma_{wr}^2 - \sigma_{err}^2)^{1/2}$$

where $\sigma_w$ is the corrected value and $\sigma_{err}$ is the measurement error discussed above.

For the computation of standard deviation of horizontal wind direction ($\sigma_\theta$), the approach used is slightly different. It may be noted that the antennas of the monostatic Sodar see different volumes of the atmosphere and hence the instantaneous radial velocities at a layer for a given pulse can not give instantaneous wind direction. To overcome this problem, several mean horizontal wind directions are computed during a sampling period. From these smaller period (about 1 min.) mean values, standard deviation for the sampling time is computed and as done in $\sigma_w$ computation, measurement error correction is applied. However, the $\sigma_\theta$ measurements made by the system were not at all good and there appears to be some problem in the software which invalidated almost all the cases. The Karlsruhe measurements (11) of $\sigma_\theta$ with a similar system showed very poor correlation with that measured on the tower.

## 3. Description of the Measurement Locations

The site map is given in figure 3. The KFA site is about 4 kms southeast of Juelich town. The terrain of the region is flat and is characterized by agriculture. The KFA is built in the Stetternich forest ( having 20 to 30m high trees) area of about 4 square kms and within this area there are open patches where buildings and lawns are located. The position of the KFA meteorological tower, marked T in the map, is surrounded by trees of about 25m high and bushes within distances of 30m to 60m. To some extent, this influences the turbulence and wind measurements, especially at the lower heights. The Sodar was operated at two locations (at different times) within the KFA area. These positions S1 and S2 are marked in the map. Around position S1, there are some small buildings and trees and the influence of the environment on the Sodar measurements was similar to that on the KFA tower. Within a distance of about 100m around position S2, there are no tall trees or tall buildings. However, within a distance of 50m, there are small buildings and waste treatment plants with pumps whose noise might influence the performance of the Sodar. The distance between S1 and the tower was 350m and that between S2 and the tower was 900m.

On the 120m high meteorological tower continuous measurements of wind speed, temperature and humidity are made at 8 levels (2, 10, 20, 30, 50, 80, 100 and 120m) and wind direction at 3 levels (30, 50 and 120m). The details of the meteorological measurements at the station are given in reference (5).

## 4. Comparison with Tower Data

### 4.1 Availability of Sodar data and range statistics

As discussed earlier, any Doppler Sodar system has to use a validation algorithm because of the presence of noise, mostly of environmental origin. Also, in general, turbulence decreases with height above ground and the strength of the back-scattered signal depends upon the presence of small scale thermal eddies (of the order of 10 cm). Therefore, over a period of time, the availability of data up to the full range is less than

100%. The percentage of availability of data for different layers is given in figure 6. It is known that stronger winds create more noise and make the signal to noise ratio low and the validation algorithm may invalidate the data. Also, the signal to noise ratio can become low due to poor reflectivity of the atmosphere. In a statically neutral atmosphere, the potential temperature gradient is zero and the mechanical turbulence which may be present will not produce appreciable $C_T^2$ (temperature structure function). Table 1 shows the percentage availability of Sodar data during conditions of different wind speeds at 30m level (tower). Stronger surface winds drive the atmosphere to near neutral conditions. In order to see the roll of atmospheric stability and that of surface wind in invalidating the data, the bulk Richardson number $R_B$ was calculated for 10 minutes averaging times from the tower data using the following relation:

$$R_B = \left(\frac{g}{\overline{T}}\right) \frac{\Delta T}{(\Delta u)^2} \Delta z$$

where ΔT and Δu are differences in potential temperature and horizontal wind speed difference between the heights 120m and 50m respectively. $\overline{T}$ is the average of absolute temperatures at the same two heights, Δz is 70m (120-50) and g is the acceleration due to gravity. The joint frequency distribution of $R_B$ and wind speed at 30m height for the same set of data as that used in figure 6 is presented in table 2. The $R_B$ values were grouped into three categories viz $R_B \leq -0.2$, $-0.2 < R_B < 0.2$ and $R_B \geq 0.2$. The group $-0.2 < R_B < 0.2$ represents the conditions very close to neutral stability. Number of validations at 110m layer for each of the above groups is also given in the table. It can be seen from the table that for conditions when $|R_B| > 0.2$, the percentage of validations at 110 m layer is almost 100% and is almost independent of 30m level wind speed. For conditions which are very close to neutral stability, the percentage of validations decreases from near 100% for cases around 2m/s wind speed to 18% for the speed group 6-8m/s. These results indicate that when the atmosphere is neutral, there can exist some thermal eddies which are responsible for the reflectivity of the atmosphere. And when the environmental noise is low (particularly the noise generated by surface wind), the Sodar system was able to detect this small reflectivity and give the wind components. With an increased sampling period, say 30 minutes or 1 hour, the range statistics is expected to improve as during a larger period it is more likely to have more number of validations than the required minimum in the validation algorithm.

## 4.2 Comparison of wind speed and direction

Wind speed and wind direction data from the Sodar system are compared with the KFA tower data. Both the Sodar and the tower data were of 10 minutes sampling time. Mean wind speed difference between the Sodar and the tower measurements (made concurrently) and the standard deviation of wind speed differences for different wind speed groups and at different levels are given in tables 3, 4 and 5 for three different periods of observation. The data presented cover three sets of continuous periods. The first two tables correspond to site 1 and the third to site 2. The following height combinations were used as the minimum layer for the Sodar was set to 50m for site 1 and 40m for site 2. The thickness of layers was 20m for both the sites.

| | | | | | | |
|---|---|---|---|---|---|---|
| For site 1 | Sodar : | 50m | 70m | 90m | 110m | 130m |
| | Tower : | 50m | 80m | 80m | 120m | 120m |

| | | | | | | |
|---|---|---|---|---|---|---|
| For site 2 | Sodar : | 40m | 60m | 80m | 100m | 120m |
| | Tower : | 50m | 50m | 80m | 100m | 120m |

Scatter plot for wind speed (130m Sodar level and 120m tower level) is shown in figure 7. Linear regression constants and correlation coefficients for the same sets of data are presented in tables 6, 7 and 8. The following relations are used to evaluate the coefficients and constants.

$$Y = A.X + B$$

where Y is wind speed measured on the tower, X is wind speed measured by the Sodar and A and B are constants.

$$Variance(X) = \frac{1}{N} \sum_{i=1}^{N} X_i^2 - \overline{X}^2$$

$$Variance(Y) = \frac{1}{N} \sum_{i=1}^{N} Y_i^2 - \overline{Y}^2$$

$$Covariance(X,Y) = \frac{1}{N} \sum_{i=1}^{N} (X_i Y_i) - \overline{X}\,\overline{Y}$$

$$A = \frac{Covariance(X,Y)}{Variance(X)}$$

$$B = Y - AX$$

$$\textbf{Correlation Coefficient R} = A \left[ \frac{Variance(X)}{Variance(Y)} \right]^{1/2}$$

where N is the number of cases and

$$\overline{X} = \frac{1}{N} \sum_{i=1}^{N} X_i \quad \textbf{and} \quad \overline{Y} = \frac{1}{N} \sum_{i=1}^{N} Y_i$$

Similar comparisons are made for the wind direction data from the Sodar system and the tower. The following height combinations were used.

| | | | | | |
|---|---|---|---|---|---|
| For site 1 | Sodar : | 50m | 110m | 130m | |
| | Tower : | 50m | 120m | 120m | |
| For site 2 | Sodar : | 40m | 40m | 60m | 120m |
| | Tower : | 30m | 50m | 50m | 120m |

Wind direction difference statistics are presented in tables 9, 10 and 11 for the same three sets of data . The scatter plot (Sodar level 130m and tower level 120m) is given in figure 8 for wind speeds greater than 1m/s and in figure 9 for speeds greater than 3m/s. Regression constants and correlation coefficients for the wind direction data , computed using similar relations as those used for wind speed data, are presented in tables 12, 13 and 14 for the three sets of data.

The mean wind speed differences for 130m and 120m level combination were 0.2m/s and -0.3m/s for data sets 1 and 2. For the third data set, the mean difference was -0.3m/s at 120m height. The standard deviations associated with these mean differences were around 1m/s for all the three sets. Also at the height of around 120m the mean differences and and their standard deviations did not show much variation with wind speed. However at the lower levels the mean wind speed differences were as high as 1.9m/s. The correlation coefficients were between 0.85 and 0.91 for heights around 120m and it was between 0.5 and 0.6 at around 50m height. Also at lower heights, wind speeds by tower were higher than those by the Sodar.

The mean wind direction differences between Sodar and tower at around 120m height were within about 5 degrees and the associated standard deviations were within about 14 degrees for the sets of data as can be seen from the tables. The variation of mean wind direction difference with wind speed did not show any trend. At lower levels the differences were much larger. The correlation coefficient at around 120m height was 0.98 for all the three sets of data. To see the behaviour of wind direction differences with wind direction, mean wind direction difference for each of 16 compass direction (22.5 degree) sectors were computed and the results are shown in tables 15, 16, and 17. The mean differences for the 130m and 50m levels are also plotted in figure 10. The mean difference at 50m level strongly depended on wind direction while at 130 level the dependece was not so strong. At 50m level, the mean differences were more pronounced for the wind direction sectors east of northeast (ENE) through north (N) to west of northwest (WNW). However the number of cases in these wind direction sectors were small.

To see the effect of wind direction on wind speed comparison, the scatter plot shown in figure 7 is replotted in figure 11 for cases when the wind direction was between 100 and 180 degrees from north. For these directions the differences in wind directions were small and here also the spread is much less compared to that in figure 7.

To sum up, at the 120m level, the mean differences between the tower and the Sodar data were small for both the wind speed and wind direction. At the lower levels, particularly at 50m, the scatter was rather high for wind direction data. It should be noted that the distance between the tower and the Sodar was 350m for site 1 and 900m for site 2 and these are located in the region with thickly populated trees of 20 to 30m high. Probably, the effect of trees together with the shadowing effect of the tower on the sensors (the sensors are mounted on instrument arms which project out in the southwest direction from the lattice structured tower) were responsible for the large scatter in the wind direction difference at lower heights.

## 4.3 Standard deviation of fluctuations of vertical wind speed

The standard deviation of fluctuations of vertical wind speed $\sigma_w$ obtained from the Sodar outputs (10 minutes sampling time) were used to obtain standard deviation of vertical wind direction fluctuations $\sigma_\phi$ using the commonly used following relation.

$$\sigma_\phi = arctan(\frac{\sigma_w}{\overline{u}})$$

where $\overline{u}$ is the average horizontal wind speed. Mean $\sigma_\phi$ values (at various heights between 50 and 130m) corresponding to the Pasquill atmospheric stability categories A to F are given in table 19. The Pasquill stability class for each 10 minutes interval was derived from temperature lapse rate (120m - 20m) and wind speed (30m) data from the tower. Table 18 gives the pre-established criteria, which is in use at the site. The average $\sigma_\phi$ value for a given stability class, in general, decreased with height. There were very few cases in the stability classes A and B as the observation period was in the midst of winter. The mean $\sigma_\phi$ value of 4 to 6 degrees given by the Sodar for neutral (D) category is rather low compared with the value of about 9 degrees obtained from the vector vane measurements at a height of 50m on the tower. Also, the standard deviation of $\sigma_\phi$ values was nearly as high as the mean value itself (table 19) in any stability category.

Vector vane measurements of $\sigma_\phi$ values representing 10 minute sampling time were not available for the three periods examined in this report. Therefore a direct comparison of $\sigma_\phi$ was not possible.

## 5. Facsimile Records

The facsimile record gives the average intensity (averaged over 5 pulses) of the echo (from vertical antenna) as a function of height. A sample copy of facsimile record is given in figure 12. The darkness of the record depends upon the intensity of the echo. The darkness is a measure of intensity of thermal turbulence in the length scale of about 10 cms and as such this is not of any direct use in the estimation of atmospheric turbulence/dispersion. Because, in a near neutral atmosphere the echo strength is much weaker than that in a stable stratified atmosphere and the intensity of atmospheric diffusion in the two cases is just the opposite. However in the facsimile record, though subjective, it is possible to identify thermal plumes during convective conditions and the presence of ground based inversions. The facsimile record shown in figure 12 is of about 5 hours period in the night of 20/21-2-90. The thick layer in the figure corresponds to ground based inversion which had extended upto a height of about 150m from ground. Above this layer also the strength of the echo was strong right upto the full range of the Sodar (420m). Corresponding to this period vectorial plots of wind in the 420m layer are given in figure 13. The length of vector is proportional to horizontal wind speed and the orientation indicates the wind direction. Each of these profiles is of 10 minute averaging time. It can be seen from this figure that during the entire period, within the 420m layer, the atmosphere was characterized by strong wind shear, both in horizontal speed and direction. It is interesting to observe that such strong wind direction shear (upto about 90 degrees) could persist for several hours. Under such conditions dispersion estimates based only on surface measurements are likely to be highly unrealistic.

## 6. Conclusions

The range statistics discussed in the report shows that it is very essential to choose a proper site for the Sodar system where the environmental noise level is minimum. Otherwise, during near neutral conditions when the atmospheric reflectivity is small, the range statistics will be poor because of the validation algorithm. The presence of both man made and wind created noise are to be considered while selecting a site.

The comparison of Sodar data with the tower data showed good agreement at heights around 120m both for wind speed and wind direction. The mean wind speed difference at this level was about 0.2m/s with a standard deviation of 1.2m/s. The mean wind direction difference was within about 4 degrees with a standard deviation of about 10 degrees. The correlation between the Sodar and tower measurements for both wind speed and direction was found to be good at around 120m level. In view of the fact that the measurements with both the tower and Sodar were of routine nature, the agreement can be considered as good. That is to say that there were no special preperations which are generaly made before a test run. The comparison showed that there was more scatter at the lower levels both for wind speed and wind direction. This was probably due to both the terrrain and tower induced effects.

The mean values of standard deviation of vertical wind direction fluctuations ($\sigma_\phi$) derived from $\sigma_w$ values corresponding to Pasquill stability categories (derived from $\Delta T$ and wind speed) were lower than that obtained on the tower using vector vane. Also the associated scatter about the mean values corresponding to a stability category was of the same order as the mean value. (However in the data sets used in this analysis there were not many unstable conditions). Thus if a scheme is used to descriminate stability classification using $\sigma_w$ values, the scheme is bound to give unsatisfactory results (when compared with any other standard scheme to descriminate stability classes). Some studies sited in literature (9) show certain success in obtaining approximately the same frequency distribution of stability classes as that obtained by any other standard scheme ($\sigma_\phi$ or $\Delta T$ & u or synoptic observations). It is desirable to make further studies on the $\sigma_w$ values obtained from the Sodar with different sampling times and in different seasons and then to compare with $\sigma_w$ values obtained from a standard instrument such as sonic anemometer.

The operation of the Doppler Sodar system indicates that it is possible to make continuous measurements of wind speed and wind direction in the boundary layer on a routine basis with minimum maintenance. This remote sensing technique is valuable in making site studies and in studying the characteristics of a site where air flow within the boundary layer undergoes modifications due to local effects such as land and sea breeze or flow modifications induced by hills and ghats. It can also provide some informations on the diurnal and seasonal variations of the dispersive capacity of the atmosphere at a site (informations such as wind profile, $\sigma_w$ height of boundary layer, presence of elevated inversions). Mobility of the system makes it possible to study characteristics of a region to detect the presence of any systematic spatial variability in the air flow. All these informations are required as inputs to many air pollution models which treat longer range atmospheric dispersion more realistically even in complex terrains. For such purposes a

Doppler Sodar can supplement the data obtained by a conventional meteorological tower.

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## References


1. Beljaars A.C.M., 1985, 'Verification of Doppler Sodar Measurements.' Scientific Report W.R. 85-2. Koninklijk Nederlands Meteorologisch Institute,

2. Gaynor J.E. and Kaimal J.C., 1983, 'Evaluation of Wind Parameters by Four Acoustic Doppler Systems.' Fifth Symposium, Meteorological Observations and Instrumentation, AMS, Toronto, Ont. Canada.

3. Kaimal J.C., Gaynor J.E., Finkelstein P.L., Graves M.E. and Lockhart T.J., 1984, 'An Evaluation of Wind measurements by Four Doppler Sodars.' Report No. 5, Boulder Atmospheric Observatory.

4. Peters, G and Kirtzel H.J., 1985, 'On Doppler Sodar OPeration.' Meteorological Institute, University of Hamburg.

5. Polster, G.,Geiss, H. and Heinemann, K. 1986, 'Der meteorologiche Turm der Kernforschungsanlage Juelich', Jul-2095 KFA.

6. Salomonsson S., 1985, 'The Performance of the Sodars Used in the Oeresund Experiment.' Technical Report, Meteorologiska Institutionen, Uppsala Universitet.

7. _____1985, 'Doppler Sodar for Wind Measurements.' Fl8 - 2, Swedish Space Corporation.

8. Thomas P. and Vogt S., 1989, 'Sodar - Windmessungen waehrend ausgepraegter bodennaher Temperaturinversionen.' KfK 4520 Kernforschungszentrum Karlsruhe.

9. Thomas P., 1986, 'Stability Classification by Acoustic Remote Sensing.' Atmospheric Research 20(1986) 165-172.

10. Thuilier R.H., 1987, 'Real-time Analysis of Local Wind Patterns for Application to Nuclear-Emergency Response.' Bulletin of American Meteorological Society, Vol. 68, No. 9, 1987.

11. Von Holleuffer-Kypke R.,Huebschmann W. and Thomas p., 1985, 'Testbericht Ueber das monostatische Doppler - Sodar B.' KfK 3928, Kernforschungszentrum Karlsruhe.

12. _____1985, 'Testbericht ueber das monostatische Doppler - Sodar R' KfK 3929, Kernforschungszentrum Karlsruhe.

## List of Tables

**Table 1.** Percentage of Sodar validations according to surface wind speed (at 30 m) for the period from 14-12-87 to 31 12-87.

| | Wind speed class (m/s) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Height(m) | 1 | 1-2 | 2-3 | 3-4 | 4-5 | 5-6 | 6-7 | > 7 |
| 50 | 70.8 | 81.8 | 80.9 | 71.1 | 48.6 | 26.7 | 21.6 | 0.0 |
| 70 | 98.5 | 96.5 | 96.8 | 82.9 | 63.7 | 34.0 | 33.3 | 23.5 |
| 90 | 99.3 | 97.5 | 87.7 | 62.4 | 36.3 | 19.3 | 31.4 | 35.3 |
| 110 | 99.3 | 98.6 | 90.4 | 68.3 | 41.3 | 26.0 | 39.2 | 35.3 |
| 130 | 97.8 | 96.8 | 90.5 | 70.3 | 41.6 | 27.7 | 41.8 | 29.4 |
| 150 | 97.1 | 94.4 | 85.6 | 72.9 | 57.7 | 41.1 | 43.8 | 17.6 |
| 170 | 94.2 | 91.6 | 93.2 | 88.5 | 70.7 | 46.0 | 45.1 | 41.2 |
| 190 | 89.1 | 90.5 | 94.9 | 88.8 | 72.8 | 53.0 | 52.3 | 47.1 |
| 210 | 83.9 | 88.8 | 92.1 | 91.9 | 74.5 | 52.3 | 41.8 | 35.3 |
| 230 | 75.9 | 83.9 | 88.2 | 89.2 | 70.7 | 44.9 | 28.8 | 17.6 |
| 250 | 63.5 | 81.1 | 84.6 | 86.9 | 66.6 | 38.2 | 24.8 | 35.3 |
| 270 | 51.8 | 76.5 | 78.6 | 83.4 | 62.0 | 33.3 | 20.9 | 0.0 |
| 290 | 44.5 | 73.0 | 72.8 | 79.1 | 54.3 | 27.7 | 17.6 | 5.9 |
| 310 | 40.1 | 64.9 | 67.5 | 71.6 | 52.9 | 20.0 | 13.7 | 11.8 |
| 330 | 33.6 | 61.1 | 65.3 | 67.0 | 43.0 | 16.8 | 11.8 | 0.0 |
| 350 | 29.9 | 56.8 | 60.2 | 59.3 | 44.5 | 12.6 | 12.4 | 0.0 |
| 370 | 30.7 | 52.6 | 55.4 | 52.8 | 37.7 | 8.1 | 2.6 | 0.0 |
| 390 | 22.6 | 48.8 | 50.0 | 44.0 | 27.6 | 9.1 | 2.0 | 0.0 |
| 410 | 21.9 | 43.2 | 45.3 | 35.4 | 26.0 | 7.4 | 0.7 | 0.0 |
| 430 | 14.6 | 40.0 | 39.1 | 31.3 | 19.5 | 3.9 | 1.3 | 0.0 |
| 450 | 12.4 | 34.7 | 33.9 | 22.5 | 19.5 | 4.9 | 2.0 | 0.0 |
| 470 | 18.2 | 33.0 | 30.9 | 17.2 | 15.1 | 3.2 | 1.3 | 0.0 |
| 490 | 19.7 | 26.0 | 21.8 | 14.0 | 11.8 | 2.5 | 0.0 | 0.0 |
| 510 | 22.6 | 22.1 | 17.0 | 12.4 | 10.3 | 2.5 | 2.0 | 0.0 |
| 530 | 24.8 | 17.9 | 13.7 | 8.3 | 8.7 | 2.1 | 0.7 | 0.0 |
| 550 | 29.2 | 18.6 | 12.6 | 4.6 | 6.5 | 1.4 | 2.0 | 0.0 |
| 570 | 31.4 | 16.5 | 8.4 | 5.3 | 4.3 | 0.7 | 0.7 | 0.0 |
| 590 | 36.5 | 13.7 | 7.4 | 3.0 | 3.6 | 0.4 | 0.7 | 0.0 |
| 610 | 28.5 | 7.7 | 5.1 | 1.9 | 1.4 | 0.4 | 0.7 | 0.0 |
| 630 | 13.1 | 3.2 | 1.9 | 1.9 | 1.7 | 0.0 | 0.0 | 0.0 |
| Total cases | 137 | 285 | 570 | 627 | 416 | 285 | 153 | 17 |

**Table 2.** Frequency distribution of bulk Richardson number and wind speed at 30m. Bulk Richardson number is for the 50 - 120m layer. N is total no. of cases and Nv is no. of validations from Sodar at 110m layer. The data set used is from 14-12-87 to 31-12-87.

| Wind speed m/s (30m) | Bulk Richardson number | | | | | |
|---|---|---|---|---|---|---|
| | < -0.2 | | -0.2 to +0.2 | | > 0.2 | |
| | N | Nv | N | Nv | N | Nv |
| < 2 | 3 | 3 | 81 | 80 | 299 | 296 |
| 2 to 4 | 13 | 12 | 823 | 602 | 346 | 338 |
| 4 to 6 | 2 | 1 | 657 | 196 | 77 | 74 |
| 6 to 8 | 0 | 0 | 141 | 25 | 47 | 45 |
| All cases | 5 | 4 | 1702 | 903 | 769 | 753 |

**Table 3.** Wind speed differences between tower and Sodar measurements during the period from 14-12-87 to 31-12-87 at site 1.

| Heights(m) Tower | Sodar | | Wind speed class (m/s) <2 | 2-4 | 4-6 | 6-8 | 8-10 | 10-12 | >12 | all cases |
|---|---|---|---|---|---|---|---|---|---|---|
| | | N | 155 | 543 | 622 | 195 | 33 | 0 | 0 | 1548 |
| 50 | 50 | D | -0.2 | 0.8 | 1.8 | 2.8 | 3.0 | 0.0 | - | 1.4 |
| | | SD | 0.7 | 0.9 | 1.2 | 1.7 | 2.7 | 0.0 | - | 1.4 |
| | | N | 148 | 403 | 694 | 471 | 162 | 21 | 0 | 1899 |
| 80 | 70 | D | -0.2 | 1.0 | 2.0 | 2.7 | 2.9 | 2.5 | - | 1.9 |
| | | SD | 0.6 | 0.8 | 1.1 | 1.4 | 2.1 | 2.2 | - | 1.5 |
| | | N | 152 | 403 | 586 | 301 | 101 | 22 | 0 | 1565 |
| 80 | 90 | D | -0.2 | 0.4 | 0.8 | 1.0 | 1.0 | 0.9 | - | 0.7 |
| | | SD | 0.7 | 0.8 | 1.0 | 1.2 | 1.5 | 1.2 | - | 1.1 |
| | | N | 137 | 263 | 576 | 378 | 155 | 53 | 3 | 1565 |
| 100 | 90 | D | 0.0 | 0.7 | 1.3 | 1.7 | 2.1 | 1.5 | 2.3 | 1.3 |
| | | SD | 0.6 | 0.8 | 0.9 | 1.1 | 1.6 | 1.0 | 1.0 | 1.1 |
| | | N | 139 | 264 | 581 | 432 | 186 | 67 | 3 | 1672 |
| 100 | 110 | D | 0.0 | 0.5 | 0.8 | 0.6 | 0.8 | 0.6 | 1.1 | 0.6 |
| | | SD | 0.6 | 0.9 | 1.1 | 1.2 | 1.5 | 1.2 | 0.8 | 1.1 |
| | | N | 137 | 250 | 530 | 428 | 218 | 97 | 12 | 1672 |
| 120 | 110 | D | 0.0 | 0.5 | 0.9 | 1.1 | 1.3 | 1.2 | 2.1 | 0.9 |
| | | SD | 0.6 | 1.0 | 1.1 | 1.2 | 1.4 | 1.4 | 0.6 | 1.2 |
| | | N | 134 | 248 | 525 | 432 | 226 | 111 | 12 | 1688 |
| 120 | 130 | D | -0.2 | 0.3 | 0.4 | 0.2 | 0.0 | 0.3 | 0.9 | 0.2 |
| | | SD | 0.5 | 1.1 | 1.1 | 1.3 | 1.5 | 1.8 | 0.8 | 1.2 |

N is number of cases each of 10 mins. averaging period.
D is mean difference in wind speed (m/s) (Tower - Sodar).
SD = standard deviation of wind speed differences (m/s).

**Table 4.** Wind speed differences between tower and Sodar measurements during the period from 04-01-88 to 13-01-88 at site I.

| Heights(m) Tower | Sodar | | Wind speed class (m/s) <2 | 2-4 | 4-6 | 6-8 | 8-10 | 10-12 | >12 | all cases |
|---|---|---|---|---|---|---|---|---|---|---|
| | | N | 18 | 266 | 285 | 148 | 21 | 6 | 0 | 744 |
| 50 | 50 | D | -0.4 | 0.3 | 1.2 | 1.9 | 2.5 | 2.6 | - | 1.0 |
| | | SD | 0.7 | 0.8 | 1.3 | 1.7 | 2.5 | 2.0 | - | 1.5 |
| | | N | 2 | 167 | 386 | 227 | 99 | 25 | 5 | 911 |
| 80 | 70 | D | 0.2 | 0.4 | 1.3 | 2.1 | 2.5 | 2.5 | 3.7 | 1.5 |
| | | SD | 0.1 | 0.7 | 1.0 | 1.3 | 1.7 | 2.6 | 3.3 | 1.4 |
| | | N | 2 | 169 | 367 | 202 | 69 | 8 | 0 | 817 |
| 80 | 90 | D | -0.5 | -0.2 | 0.2 | 0.7 | 1.1 | 1.3 | - | 0.4 |
| | | SD | 0.1 | 0.6 | 0.8 | 1.2 | 1.2 | 1.7 | - | 1.0 |
| | | N | 0 | 103 | 291 | 272 | 129 | 21 | 1 | 817 |
| 100 | 90 | D | - | 0.2 | 0.6 | 1.2 | 1.9 | 2.1 | 1.9 | 1.0 |
| | | SD | - | 0.6 | 0.8 | 1.0 | 1.3 | 1.3 | - | 1.1 |
| | | N | 0 | 101 | 296 | 275 | 130 | 34 | 3 | 839 |
| 100 | 110 | D | - | -0.2 | 0.0 | 0.3 | 0.7 | 1.0 | -1.8 | 0.2 |
| | | SD | - | 0.7 | 0.9 | 1.1 | 1.1 | 2.2 | 0.6 | 1.1 |
| | | N | 0 | 111 | 252 | 264 | 156 | 51 | 5 | 839 |
| 120 | 110 | D | - | -0.3 | 0.1 | 0.6 | 1.0 | 1.6 | -0.1 | 0.2 |
| | | SD | - | 0.8 | 1.0 | 1.1 | 1.1 | 1.9 | 1.5 | 1.2 |
| | | N | 0 | 113 | 256 | 261 | 170 | 54 | 5 | 859 |
| 120 | 130 | D | - | -0.7 | -0.5 | -0.3 | 0.1 | 0.3 | 0.3 | -0.3 |
| | | SD | - | 1.0 | 1.1 | 1.2 | 1.2 | 1.3 | 1.8 | 1.2 |

N is number of cases each of 10 mins. averaging period.
D is mean difference in wind speed (m/s) (Tower - Sodar).
SD is standard deviation of differences(m/s)

**Table 5.** Wind speed differences between tower and Sodar measurements during the period from 22-12-89 to 30-12-89 at site 2.

| Heights(m) Tower | Sodar | | Wind speed class (m/s) <2 | 2-4 | 4-6 | 6-8 | 8-10 | 10-12 | >12 | all cases |
|---|---|---|---|---|---|---|---|---|---|---|
| | | N | 40 | 121 | 110 | 8 | 9 | 1 | 0 | 289 |
| 50 | 40 | D | -0.3 | -0.1 | 1.7 | 2.7 | 4.2 | 2.2 | - | 0.8 |
| | | SD | 1.7 | 2.0 | 2.2 | 1.6 | 2.8 | 0.0 | - | 2.4 |
| | | N | 112 | 405 | 417 | 74 | 18 | 1 | 0 | 1027 |
| 50 | 60 | D | -0.2 | 0.3 | 0.9 | 2.7 | 5.0 | 1.0 | - | 0.7 |
| | | SD | 0.7 | 0.8 | 1.2 | 2.5 | 1.9 | 0.0 | - | 1.5 |
| | | N | 57 | 302 | 399 | 171 | 23 | 5 | 0 | 957 |
| 80 | 80 | D | 0.0 | 0.3 | 0.7 | 0.5 | 1.2 | 3.3 | - | 0.5 |
| | | SD | 0.6 | 0.9 | 0.9 | 1.1 | 2.2 | 1.1 | - | 1.0 |
| | | N | 32 | 273 | 393 | 221 | 60 | 8 | 3 | 990 |
| 100 | 100 | D | -0.6 | -0.1 | 0.1 | -0.2 | -0.4 | 0.3 | 4.1 | -0.1 |
| | | SD | 0.5 | 0.8 | 0.9 | 0.8 | 1.8 | 2.8 | 2.6 | 1.0 |
| | | N | 38 | 257 | 359 | 206 | 100 | 28 | 3 | 991 |
| 120 | 120 | D | -0.4 | -0.2 | -0.3 | -0.4 | -0.9 | -0.2 | 0.1 | -0.3 |
| | | SD | 0.6 | 0.9 | 0.9 | 0.9 | 1.3 | 2.3 | 2.4 | 1.0 |

N is number of cases each of 10 mins. averaging period.
D is mean difference in wind speed (m/s) (Tower - Sodar).
SD is standard deviation of wind speed differences (m/s).

**Table 6.** Correlation between wind speeds measured on the tower and by Sodar during the period from 14-12-87 to 31-12-87 at site 1.

| Heights(m) | | | | | |
|---|---|---|---|---|---|
| Tower | Sodar | N | A | B | R |
| 50 | 50 | 1548 | 0.48 | 0.74 | 0.59 |
| 80 | 70 | 1899 | 0.60 | 0.16 | 0.72 |
| 80 | 90 | 1565 | 0.86 | 0.03 | 0.88 |
| 100 | 90 | 1565 | 0.78 | -0.09 | 0.88 |
| 100 | 110 | 1672 | 0.94 | -0.30 | 0.90 |
| 120 | 110 | 1672 | 0.87 | -0.14 | 0.89 |
| 120 | 130 | 1688 | 0.99 | -0.18 | 0.90 |

**Table 7.** Correlation between wind speeds measured on the tower and by Sodar during the period from 04-01-88 to 13-01-88 at site 1.

| Heights(m) | | | | | |
|---|---|---|---|---|---|
| Tower | Sodar | N | A | B | R |
| 50 | 50 | 744 | 0.58 | 0.93 | 0.62 |
| 80 | 70 | 911 | 0.64 | 0.60 | 0.72 |
| 80 | 90 | 817 | 0.76 | 0.97 | 0.81 |
| 100 | 90 | 817 | 0.70 | 0.85 | 0.82 |
| 100 | 110 | 839 | 0.85 | 0.70 | 0.84 |
| 120 | 110 | 839 | 0.77 | 1.04 | 0.83 |
| 120 | 130 | 859 | 0.86 | 1.17 | 0.85 |

**Table 8.** Correlation between wind speeds measured on the tower and by Sodar during the period from 22-12-89 to 31-12-89 at site 2.

| Heights(m) | | | | | |
|---|---|---|---|---|---|
| Tower | Sodar | N | A | B | R |
| 50 | 40 | 289 | 0.36 | 1.61 | 0.28 |
| 50 | 60 | 1027 | 0.50 | 1.19 | 0.56 |
| 80 | 80 | 957 | 0.88 | 0.03 | 0.83 |
| 100 | 100 | 990 | 0.98 | 0.15 | 0.88 |
| 120 | 120 | 991 | 1.05 | 0.08 | 0.91 |

$Y(i) = A.X(i) + B$ $\quad$ Y(i):- Tower data $\quad$ X(i):- Sodar data.

$i = 1$ to N

Wind speeds in m/s

N is number of cases - each of 10 mins averaging period

R is correlation coefficient

**Table 9.** Wind direction differences between tower and Sodar measurements for the period from 14-12-87 to 31-12-87 at site 1.

| wind speed class(m/s) | Tower 50m / Sodar 50m N | D | SD | Tower 120m / Sodar 110m N | D | SD | Tower 120m / Sodar 130m N | D | SD |
|---|---|---|---|---|---|---|---|---|---|
| 0 to 1.9 | 155 | -8.1 | 58.9 | 137 | 8.7 | 43.4 | 134 | 3.9 | 29.3 |
| 2.0 to 3.9 | 543 | 6.5 | 31.7 | 250 | 4.6 | 22.7 | 248 | 1.3 | 20.2 |
| 4.0 to 5.9 | 622 | 16.5 | 29.5 | 530 | 1.2 | 9.2 | 525 | -1.0 | 10.0 |
| 6.0 to 7.9 | 195 | 22.1 | 39.2 | 428 | -0.2 | 10.3 | 432 | 1.9 | 9.9 |
| 8.0 to 9.9 | 33 | 17.9 | 24.8 | 218 | 0.7 | 10.0 | 226 | -0.2 | 8.3 |
| 10.0 to 11.9 | 0 | 0.0 | 0.0 | 97 | -0.4 | 7.7 | 111 | -2.6 | 8.5 |
| 12.0 to 13.9 | 0 | - | - | 12 | -0.5 | 3.0 | 12 | -5.8 | 4.4 |
| > 13.9 | 0 | - | - | 0 | - | - | 0 | - | - |
| All cases | 1548 | 11.3 | 36.4 | 1672 | 1.8 | 17.6 | 1688 | 0.4 | 14.2 |

N is number of cases each of 10 mins. averaging period.
D is mean difference in wind direction (degrees) (Tower - Sodar).
Sd is standard deviation of wind direction differences (deg.).

**Table 10.** Wind direction differences between tower and Sodar measurements for the period from 04-01-88 to 13-01-88 at site 1.

| | Tower Sodar 50m 50m | | | Tower Sodar 120m 110m | | | Tower Sodar 120m 130m | | |
|---|---|---|---|---|---|---|---|---|---|
| wind speed class(m/s) | N | D | SD | N | D | SD | N | D | SD |
| 0 to 1.9 | 18 | -5.9 | 20.6 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| 2.0 to 3.9 | 250 | -1.7 | 19.2 | 111 | 0.7 | 10.4 | 113 | -4.8 | 9.9 |
| 4.0 to 5.9 | 246 | 1.2 | 32.8 | 252 | -2.1 | 8.3 | 256 | -6.2 | 9.7 |
| 6.0 to 7.9 | 99 | 3.4 | 35.1 | 264 | -0.4 | 8.5 | 261 | -2.1 | 9.6 |
| 8.0 to 9.9 | 20 | 11.3 | 20.6 | 156 | -3.6 | 7.7 | 170 | -6.2 | 7.4 |
| 10.0 to 11.9 | 6 | 24.8 | 30.0 | 51 | -2.3 | 8.8 | 54 | -5.8 | 8.5 |
| 12.0 to 13.9 | 0 | 0.0 | 0.0 | 4 | 7.0 | 10.6 | 5 | 8.0 | 9.7 |
| 14.0 to 15.9 | 0 | 0.0 | 0.0 | 1 | -5.0 | 0.0 | 0 | 0.0 | 0.0 |
| > 15.9 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 |
| All cases | 639 | 0.7 | 28.2 | 839 | -1.5 | 8.7 | 859 | -4.7 | 9.4 |

N is number of cases each of 10 mins. averaging period.
D is mean difference in wind direction (degrees) (Tower - Sodar).
SD is standard deviation of wind direction differences(deg).

**Table11.** Wind direction differences between tower and Sodar measurements for the period from 22-12-89 to 30-12-89 at site 2.

| wind speed class | Tower Sodar (30m) (40m) | | | Tower Sodar (50m) (40) | | | Tower Sodar (50m) (60) | | | Tower Sodar (120m) (120m) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| (m/s) | N | D | SD | N | D | SD | N | D | SD | N | D | SD |
| <2 | 60 | -52.5 | 63.3 | 40 | -65.4 | 59.0 | 112 | 0.6 | 26.2 | 38 | 2.7 | 17.7 |
| 2- 4 | 189 | -18.8 | 46.8 | 121 | -26.5 | 45.2 | 405 | 4.9 | 20.4 | 257 | -1.1 | 14.2 |
| 4- 6 | 32 | 4.0 | 40.2 | 110 | -20.1 | 50.3 | 417 | 10.4 | 15.9 | 359 | 5.2 | 8.4 |
| 6- 8 | 8 | 19.0 | 35.7 | 8 | 0.3 | 35.0 | 74 | 19.0 | 32.7 | 206 | 7.0 | 6.9 |
| 8-10 | 0 | 0.0 | 0.0 | 9 | 7.2 | 34.5 | 18 | 11.6 | 30.5 | 100 | 10.0 | 6.6 |
| 10-12 | 0 | 0.0 | 0.0 | 1 | -5.0 | 0.0 | 1 | -6.0 | 0.0 | 28 | 9.0 | 6.5 |
| >12 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 | 3 | 10.3 | 11.9 |
| All | 289 | -22.2 | 52.9 | 289 | -27.6 | 51.5 | 1027 | 7.8 | 21.4 | 991 | 4.5 | 10.9 |

N is number of cases each of 10 mins. averaging period.
D is mean difference in wind direction (degrees) (Tower - Sodar).
SD is standard deviation of wind direction differences (deg.).

**Table 12.** Correlation between wind directions measured on the tower and by Sodar during the period from 14-12-87 to 31-12-87 at site 1.

| Heights(m) Tower | Sodar | N | A | B | R |
|---|---|---|---|---|---|
| 50 | 50 | 1548 | 0.83 | 23.84 | 0.88 |
| 120 | 110 | 1672 | 1.01 | -2.70 | 0.97 |
| 120 | 130 | 1688 | 0.96 | 7.87 | 0.98 |

**Table 13.** Correlation between wind directions measured on the tower and by Sodar during the period from 04-01-88 to 13-01-88 at site 1.

| Heights(m) Tower | Sodar | N | A | B | R |
|---|---|---|---|---|---|
| 50 | 50 | 639 | 0.73 | 50.18 | 0.91 |
| 120 | 110 | 839 | 0.96 | 9.53 | 0.99 |
| 120 | 130 | 859 | 0.90 | 23.44 | 0.99 |

**Table 14.** Correlation between wind directions measured on the tower and by Sodar during the period from 22-12-89 to 30-12-89 at site 2.

| Heights(m) Tower | Sodar | N | A | B | R |
|---|---|---|---|---|---|
| 30 | 40 | 289 | 0.78 | 43.27 | 0.58 |
| 50 | 40 | 289 | 0.82 | 39.09 | 0.60 |
| 50 | 60 | 1027 | 0.97 | -2.83 | 0.93 |
| 120 | 120 | 991 | 0.94 | 3.40 | 0.98 |

$Y(i) = A.X(i) + B$ Y(i):- Tower data X(i):- Sodar data
Wind Directions in degrees.
N is number of cases each of 10 mins. averaging period.
R is correlation coefficient.

**Table 15.** Wind direction differences between tower and Sodar measurements for the period from 14-12-87 to 31-12-87 at site 1.

| wind direction sector | Tower 50m Sodar 50m | | | Tower 120m Sodar 110m | | | Tower 120m Sodar 130m | | |
|---|---|---|---|---|---|---|---|---|---|
| | n | D | SD | n | D | SD | n | D | SD |
| N | 27 | -6.7 | 39.8 | 17 | 14.6 | 23.1 | 17 | 16.3 | 18.5 |
| NNE | 17 | -81.8 | 32.7 | 4 | -18.0 | 13.2 | 4 | -7.0 | 11.2 |
| NE | 16 | -58.3 | 29.1 | 9 | -30.1 | 42.4 | 8 | 3.8 | 15.3 |
| ENE | 16 | -42.9 | 25.2 | 12 | 8.1 | 34.3 | 11 | 5.5 | 17.0 |
| E | 57 | -11.7 | 47.4 | 55 | -0.4 | 21.9 | 55 | -1.0 | 12.7 |
| ESE | 261 | -2.9 | 26.6 | 296 | -2.6 | 8.1 | 298 | -6.9 | 6.1 |
| SE | 86 | -8.5 | 35.4 | 177 | 0.9 | 8.2 | 176 | -7.2 | 6.6 |
| SSE | 26 | 14.1 | 30.2 | 51 | 7.3 | 19.5 | 50 | -5.5 | 17.3 |
| S | 26 | -7.7 | 38.9 | 27 | 11.7 | 18.4 | 26 | -0.5 | 14.1 |
| SSW | 15 | 7.5 | 21.9 | 65 | 3.8 | 23.1 | 64 | -0.3 | 23.0 |
| SW | 138 | 22.3 | 25.8 | 318 | 1.1 | 9.7 | 342 | 4.0 | 7.8 |
| WSW | 438 | 24.5 | 30.2 | 444 | 2.0 | 16.8 | 445 | 3.7 | 13.7 |
| W | 337 | 20.3 | 31.6 | 108 | -0.1 | 11.4 | 108 | 0.8 | 10.1 |
| WNW | 51 | 23.1 | 39.0 | 23 | 0.7 | 23.9 | 18 | -7.3 | 7.1 |
| NW | 12 | 21.3 | 46.8 | 16 | 22.8 | 47.6 | 17 | 17.1 | 38.8 |
| NNW | 25 | 17.1 | 21.3 | 50 | 21.7 | 41.0 | 49 | 16.9 | 30.2 |
| All Sectors | 1548 | 11.3 | 36.4 | 1672 | 1.8 | 17.6 | 1688 | 0.4 | 14.2 |

n is number of cases each of 10 mins. averaging period.
D is mean wind direction difference (degrees) (Tower - Sodar).
SD is stanard deviation of differences in wind direction (deg.).

**Table 16.** Wind direction differences between tower and Sodar measurements for the period from 04-01-88 to 13-01-88 at site 1.

| wind direction setor | Tower 50m | Sodar 50m | | Tower 120m | Sodar 110m | | Tower 120m | Sodar 130m | |
|---|---|---|---|---|---|---|---|---|---|
| | n | D | SD | n | D | SD | n | D | SD |
| N | 3 | -105.7 | 6.2 | 0 | - | - | 0 | - | - |
| NNE | 3 | -98.0 | 6.2 | 0 | - | - | 0 | - | - |
| NE | 6 | -60.2 | 30.3 | 0 | - | - | 0 | - | - |
| ENE | 11 | -48.5 | 11.9 | 0 | - | - | 0 | - | - |
| E | 31 | -31.8 | 15.1 | 0 | - | - | 0 | - | - |
| ESE | 45 | -13.6 | 10.0 | 141 | -4.6 | 5.7 | 142 | -10.0 | 5.4 |
| SE | 144 | -8.4 | 13.5 | 168 | -5.6 | 5.2 | 172 | -11.9 | 5.5 |
| SSE | 34 | -6.5 | 10.3 | 117 | -2.5 | 6.6 | 119 | -8.7 | 5.8 |
| S | 29 | -0.8 | 16.1 | 53 | 1.7 | 8.6 | 53 | -4.7 | 8.4 |
| SSW | 39 | 3.3 | 22.4 | 54 | 5.3 | 5.9 | 57 | 1.4 | 6.0 |
| SW | 98 | 17.0 | 23.1 | 117 | 4.2 | 10.6 | 119 | 4.1 | 9.5 |
| WSW | 81 | 18.1 | 27.3 | 110 | -1.0 | 10.4 | 109 | 1.9 | 8.4 |
| W | 107 | 15.9 | 25.9 | 78 | -1.6 | 9.8 | 87 | -0.5 | 8.6 |
| WNW | 8 | 8.8 | 20.5 | 1 | 5.0 | - | 1 | -7.0 | - |
| NW | 0 | - | - | 0 | - | - | 0 | - | - |
| NNW | 0 | - | - | 0 | - | - | 0 | - | - |
| All sectors | 639 | 0.7 | 28.2 | 839 | -1.5 | 8.7 | 859 | -4.7 | 9.4 |

n is number of cases each of 10 mins. averaging period.
D is mean difference inwind direction(degrees) (Tower - Sodar).
SD is standard deviation of wind direction differences(deg.).

**Table 17.** Wind direction differences between tower and Sodar measurements for the period from 22-12-89 to 30-12-89 at site 2.

| | Tower 30m | Sodar 40m | | Tower 50m | Sodar 40m | | Tower 50m | Sodar 60m | | Tower 120m | Sodar 120m | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Wind Direc -tion Sector | n | D | SD | n | D | SD | n | D | SD | n | D | SD |
| N | 0 | - | - | 0 | - | - | 0 | - | - | 0 | - | - |
| NNE | 0 | - | - | 0 | - | - | 0 | - | - | 0 | - | - |
| NE | 0 | - | - | 0 | - | - | 0 | - | - | 0 | - | - |
| ENE | 0 | 0.0 | 0.0 | 0 | 0.0 | 0.0 | 5 | -37.2 | 54.4 | 7 | 17.6 | 8.2 |
| E | 22 | -77.3 | 69.9 | 73 | -59.5 | 67.7 | 306 | 9.2 | 16.2 | 213 | 0.7 | 10.9 |
| ESE | 130 | -28.3 | 56.6 | 92 | -26.2 | 41.5 | 321 | 7.5 | 13.1 | 326 | 4.0 | 8.8 |
| SE | 55 | -19.5 | 30.9 | 44 | -29.7 | 36.4 | 94 | -2.2 | 20.2 | 100 | 2.0 | 16.6 |
| SSE | 34 | -27.1 | 27.6 | 30 | -13.9 | 24.9 | 71 | -8.6 | 27.9 | 73 | 2.5 | 11.8 |
| S | 7 | 21.4 | 36.3 | 10 | 2.2 | 36.2 | 34 | 4.7 | 13.1 | 82 | 5.6 | 8.9 |
| SSW | 6 | 8.3 | 32.0 | 6 | 15.7 | 20.6 | 28 | 7.1 | 15.1 | 57 | 8.7 | 7.3 |
| SW | 6 | 33.3 | 12.9 | 11 | 15.3 | 22.3 | 48 | 18.8 | 20.6 | 64 | 9.5 | 7.5 |
| WSW | 8 | 18.0 | 22.6 | 7 | 8.4 | 32.6 | 60 | 30.6 | 29.1 | 41 | 12.9 | 7.0 |
| W | 13 | 27.6 | 41.4 | 11 | 15.3 | 38.3 | 31 | 19.7 | 35.8 | 17 | 14.0 | 5.6 |
| WNW | 7 | 6.3 | 14.2 | 5 | -3.4 | 7.7 | 22 | 5.8 | 29.1 | 9 | 8.8 | 6.5 |
| NW | 1 | 10.0 | - | 0 | - | - | 7 | -5.9 | 9.5 | 2 | 15.0 | 3.0 |
| NNW | 0 | - | - | 0 | - | - | 0 | - | - | 0 | - | - |
| All Cases | 289 | -22.2 | 52.9 | 289 | -27.6 | 51.5 | 1027 | 7.8 | 21.4 | 991 | 4.5 | 10.9 |

n is Number of cases each of 10 mins. averaging period.
D is Mean difference in direction (Tower-Sodar) in degrees.
SD is standard deviation of differences in degrees.

**Table 18.** Criteria for determining Pasquill diffusion categories using temperature gradient and wind speed at KFA. Temperature difference is between 120m and 20m levels of the KFA tower.

| Temperature difference (K) | Wind speed (m/s) at 30m 0.0 to 1.9 | 2.0 to 2.9 | 3.0 to 3.9 | 4.0 to 4.9 | 5.0 to 5.9 | 6.0 to 6.9 | 7.0 to 8.9 | > 8.9 |
|---|---|---|---|---|---|---|---|---|
| < -1.5 | A | A | B | B | C | C | C | D |
| -1.5 to -1.4 | A | B | B | C | C | C | D | D |
| -1.3 to -1.2 | A | B | C | C | C | D | D | D |
| -1.1 | B | B | C | C | D | D | D | D |
| -1.0 | B | C | D | D | D | D | D | D |
| -0.9 | C | D | D | D | D | D | D | D |
| -0.8 to -0.7 | D | D | D | D | D | D | D | D |
| -0.6 to 0.0 | E | D | D | D | D | D | D | D |
| 0.1 to 2.0 | F | E | E | E | E | D | D | D |
| > 2.0 | F | F | F | E | E | E | E | D |

**Table 19.** Values of standard deviation of fluctuations of vertical wind direction calculated from Sodar outputs at site 1.

Period : 14-12-87 to 31-12-87

| Height (m) | | A | B | C | D | E | F |
|---|---|---|---|---|---|---|---|
| | | Pasquill Stability Class | | | | | |
| | N | 2 | 23 | 47 | 871 | 321 | 67 |
| 50 | M | 6.8 | 5.5 | 6.0 | 5.9 | 3.8 | 3.9 |
| | S | 1.3 | 4.4 | 4.7 | 5.3 | 3.5 | 3.9 |
| | N | 2 | 41 | 76 | 1143 | 385 | 94 |
| 70 | M | 10.4 | 7.8 | 6.9 | 6.8 | 3.3 | 3.7 |
| | S | 1.7 | 4.6 | 4.7 | 4.1 | 2.2 | 3.2 |
| | N | 2 | 34 | 70 | 830 | 386 | 101 |
| 90 | M | 10.6 | 7.4 | 6.6 | 4.9 | 2.9 | 2.8 |
| | S | 2.2 | 3.5 | 3.2 | 2.6 | 2.0 | 2.4 |
| | N | 2 | 35 | 76 | 951 | 383 | 101 |
| 110 | M | 13.9 | 8.6 | 6.7 | 4.0 | 2.7 | 2.8 |
| | S | 2.9 | 4.5 | 3.4 | 2.3 | 2.0 | 2.2 |
| | N | 2 | 40 | 83 | 974 | 377 | 101 |
| 130 | M | 17.5 | 7.6 | 5.6 | 3.2 | 2.5 | 2.7 |
| | S | 4.3 | 3.4 | 3.3 | 1.9 | 1.9 | 2.1 |

Stability class was determined by tower data - wind speed(30m) and temperature difference(120m-20m).
N is number of cases - each of 10 mins. averaging period.
M is mean value of sigma-phi(deg.) derived from sigma w and wind speed.
S is standard deviation of sigma phi values.

## List of Figures

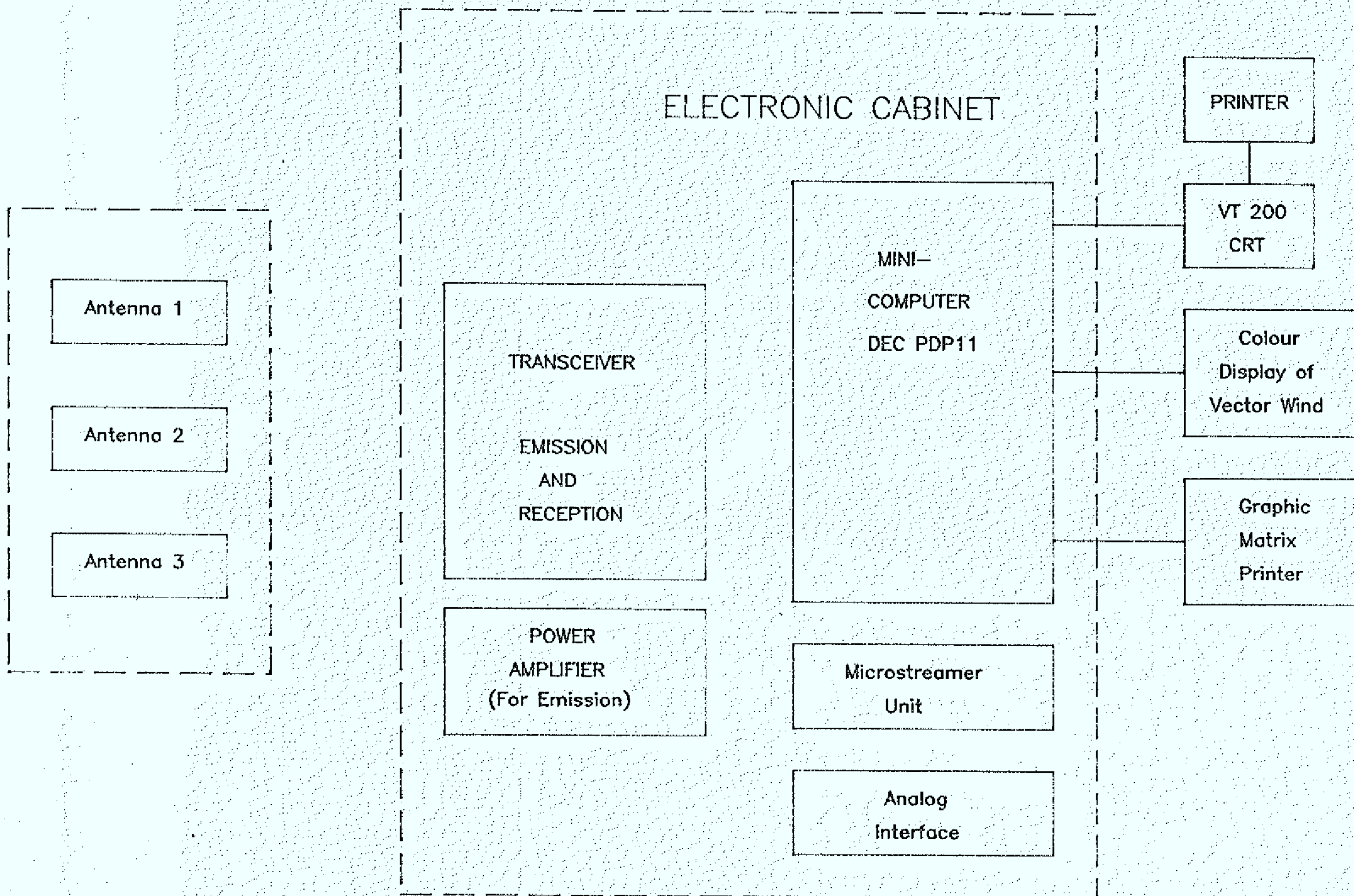



Figure 1. Block diagram of the Doppler Sodar system.

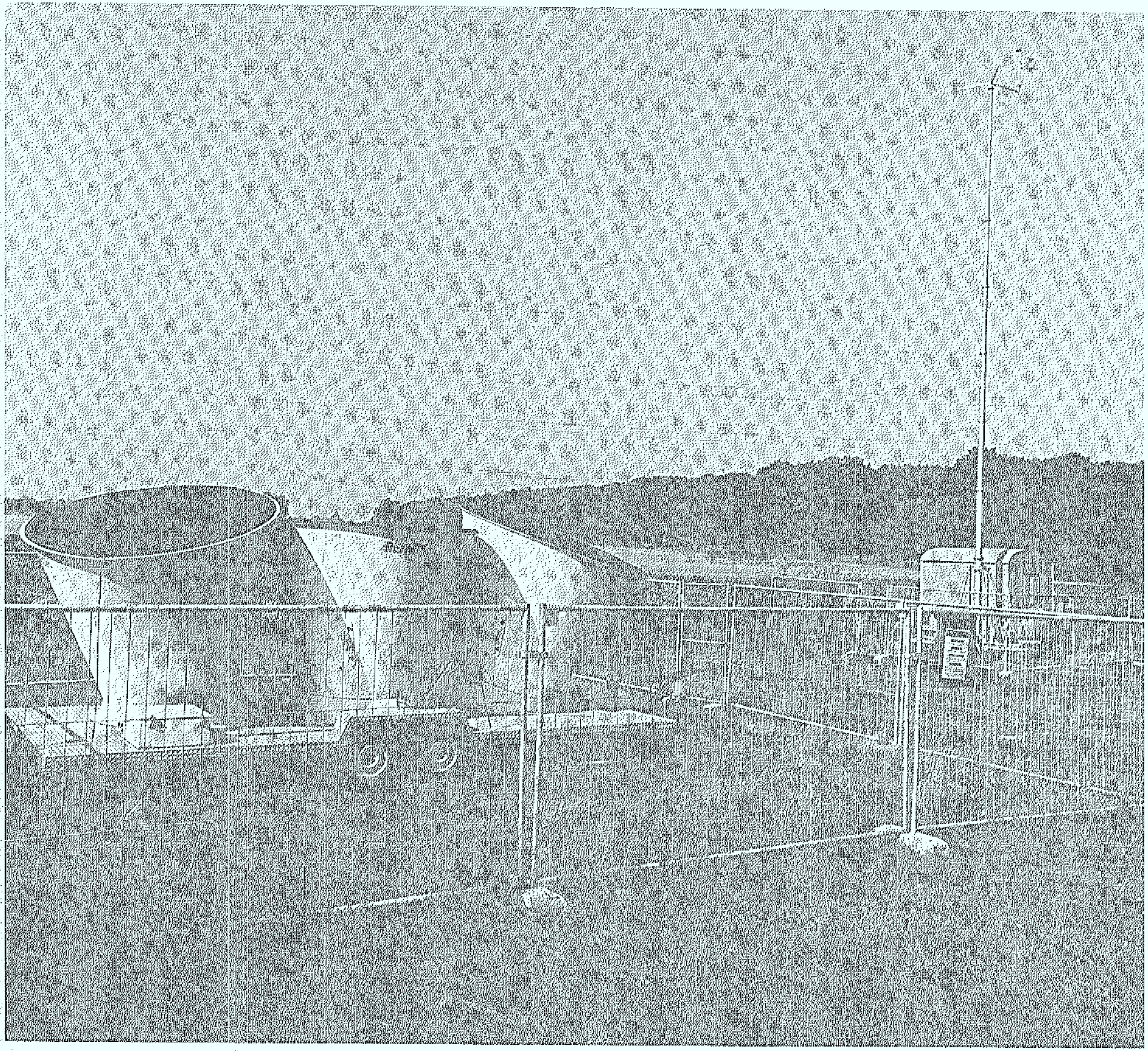


**Figure 2.** Photograph of the antennas mounted on the trailer.

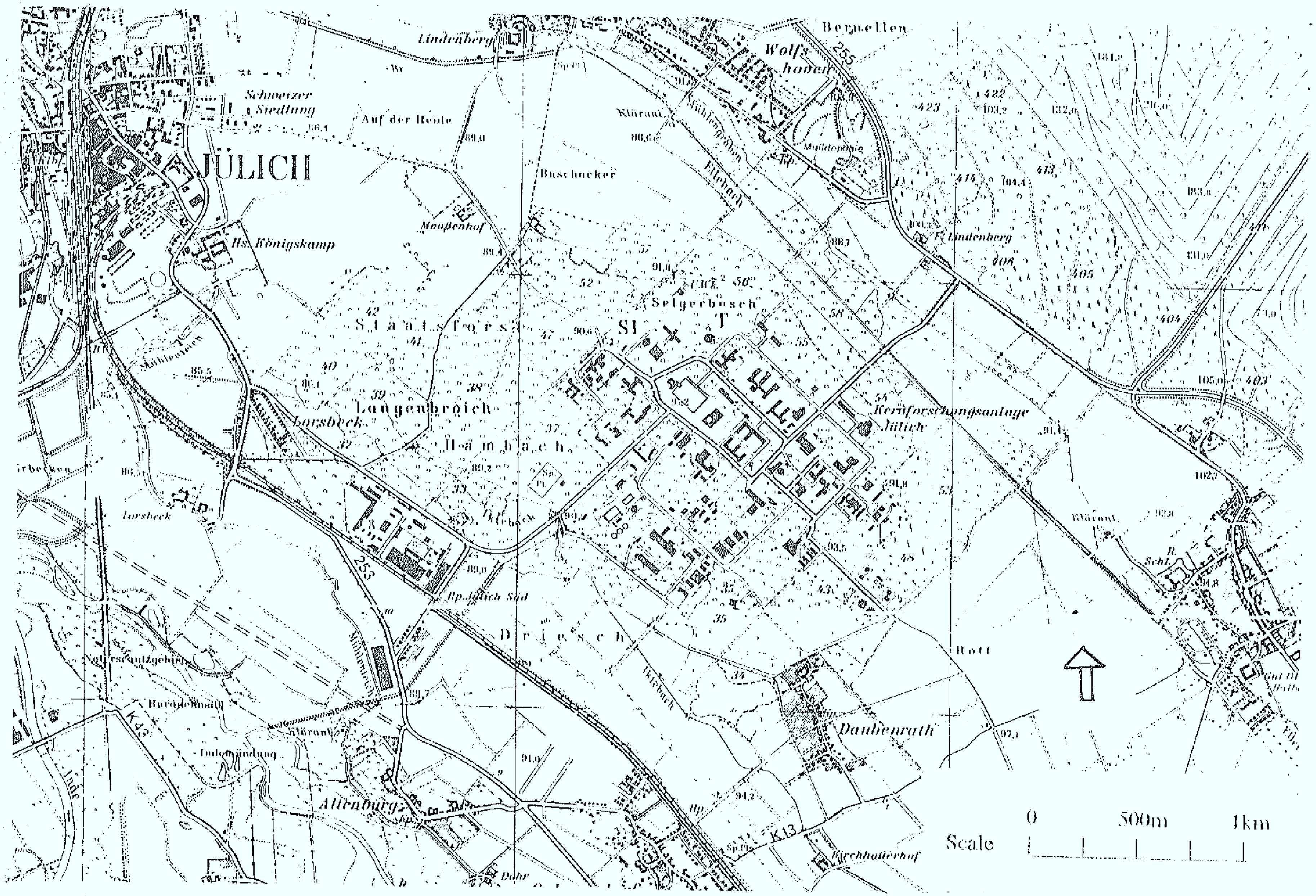
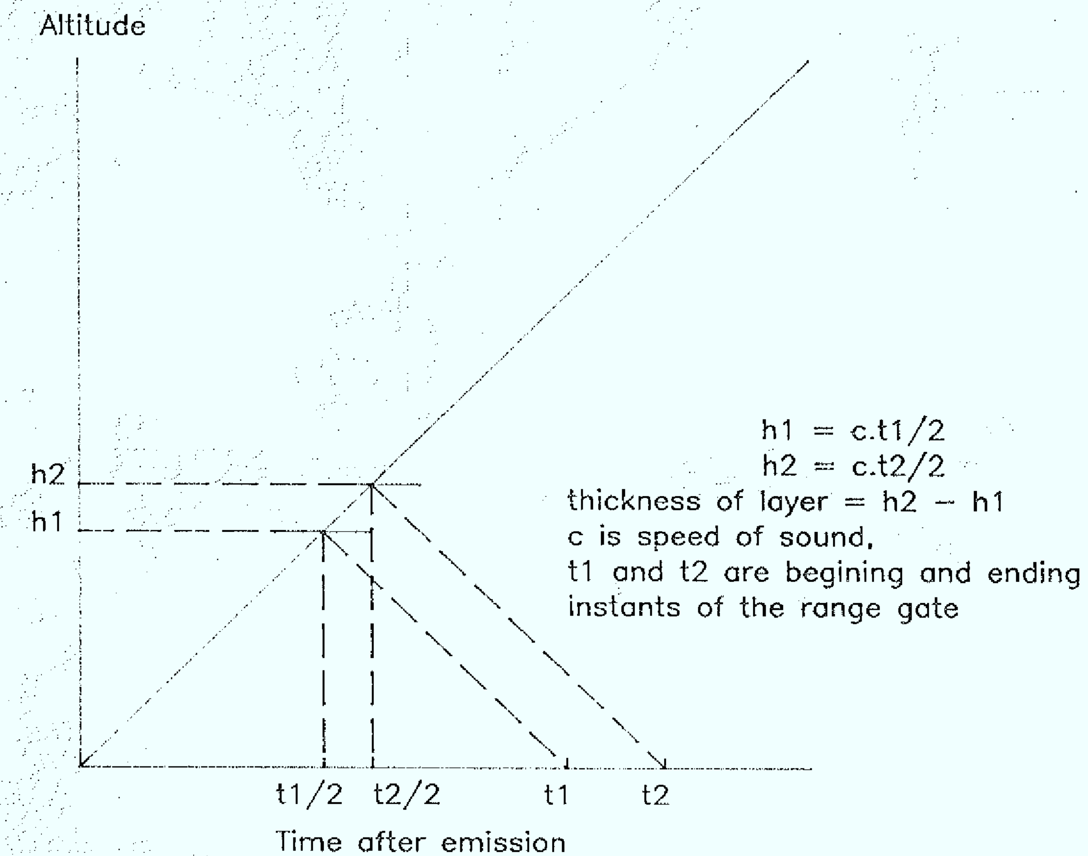



Figure 3. Site map showing the positions of the Sodar (S1 and S2) and the KFA meteorological tower (T).

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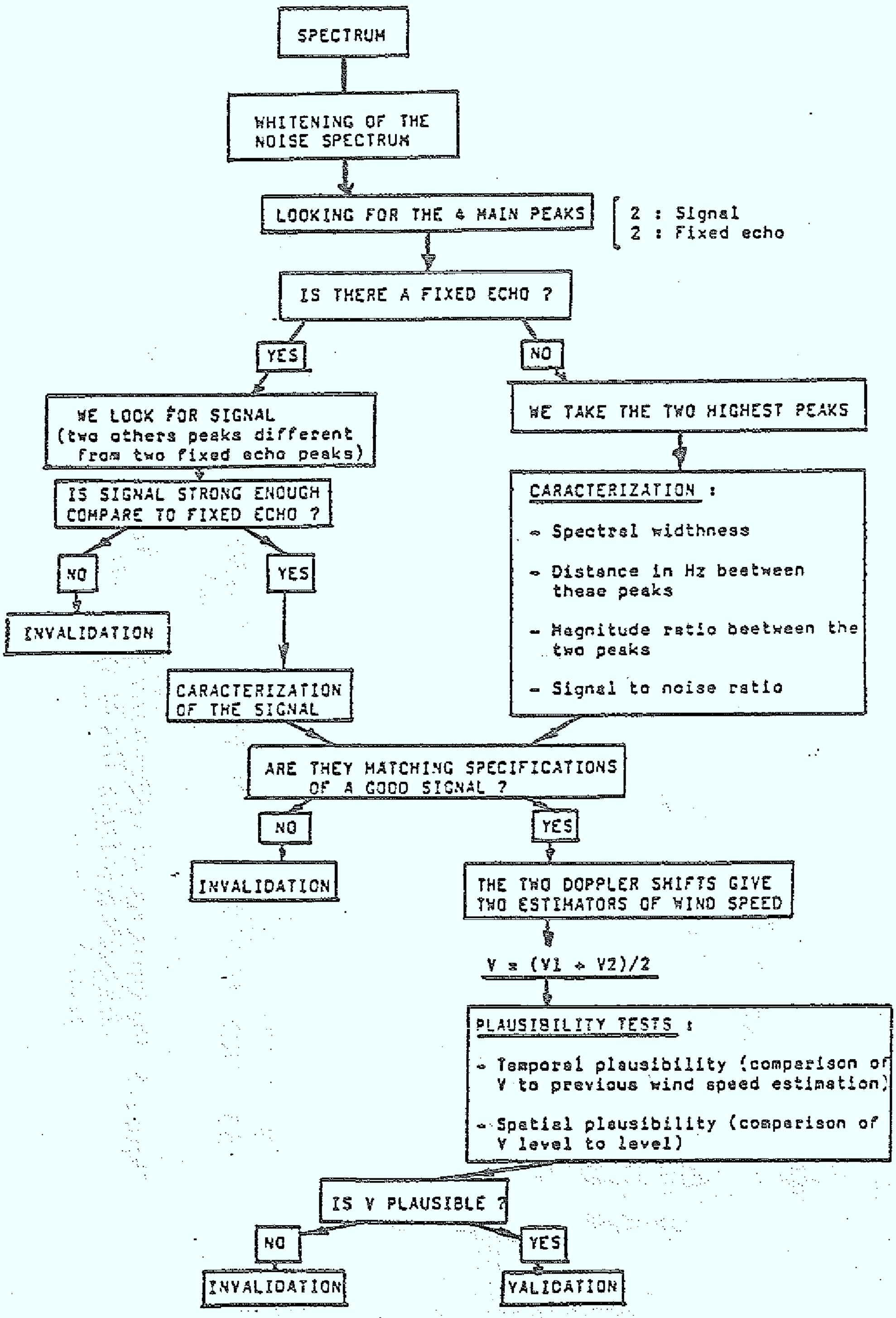



**Figure 5.** Validation algorithm used in the REMTECH Sodar during the processing of signal.

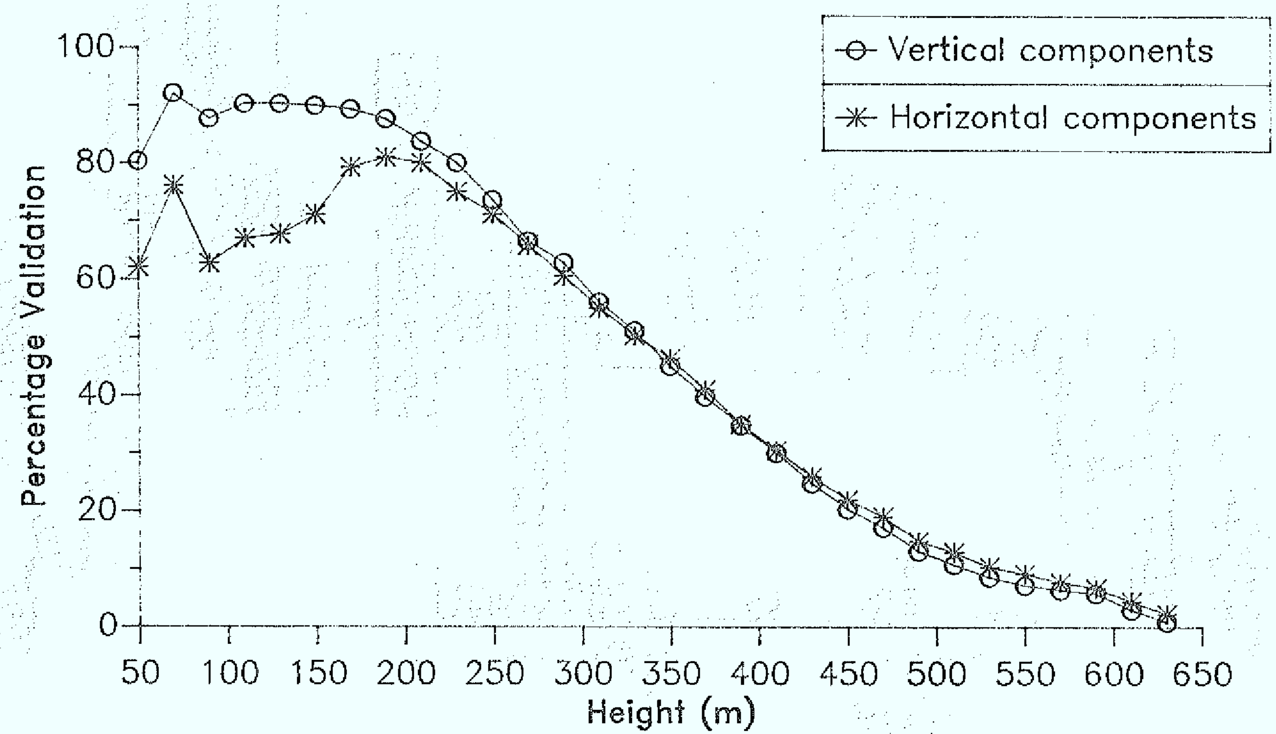



Figure 6. Percentage of validations for the horizontal and vertical components from Sodar outputs.
Period : from 14-12-87 to 31-12-87.

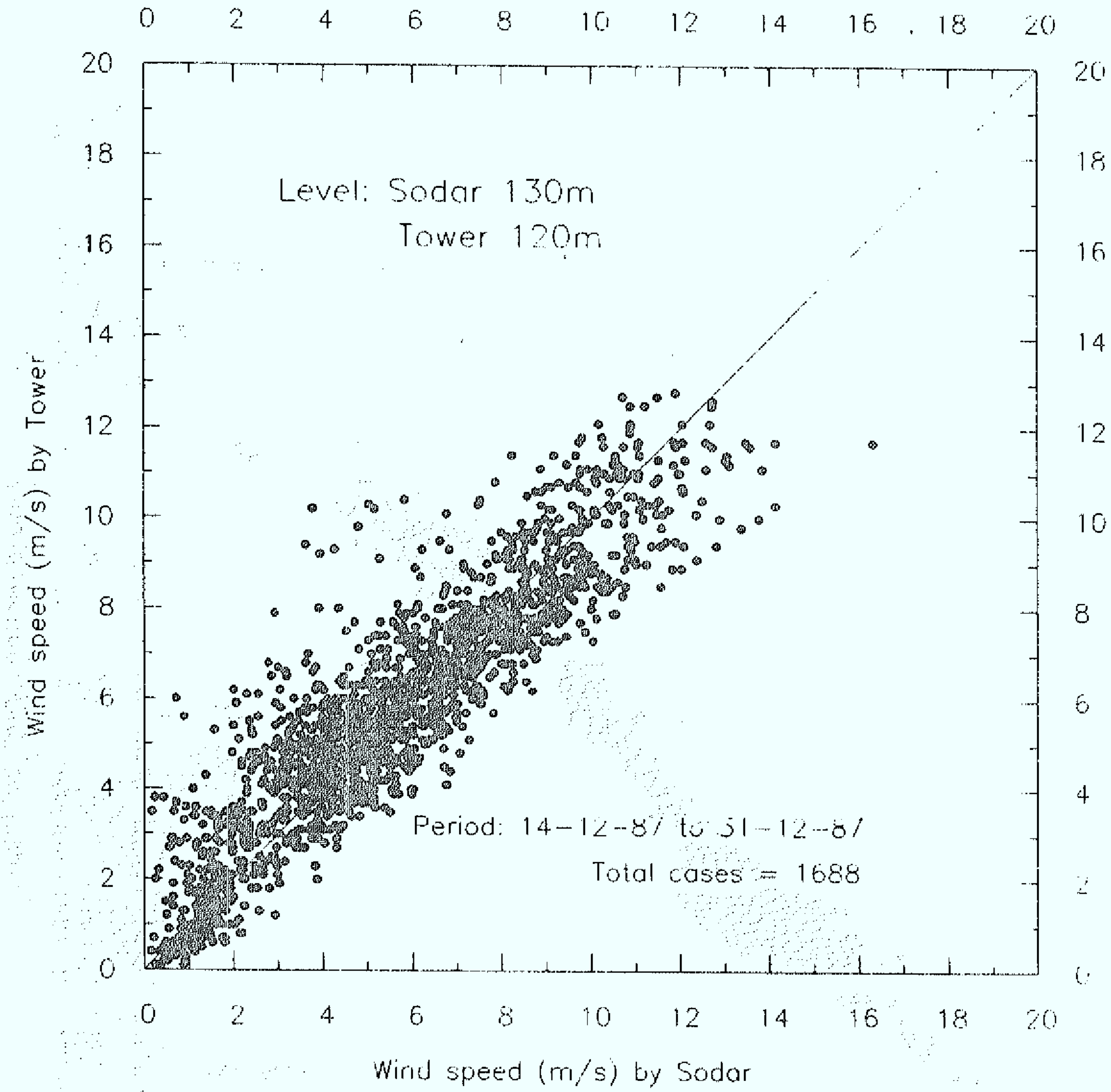
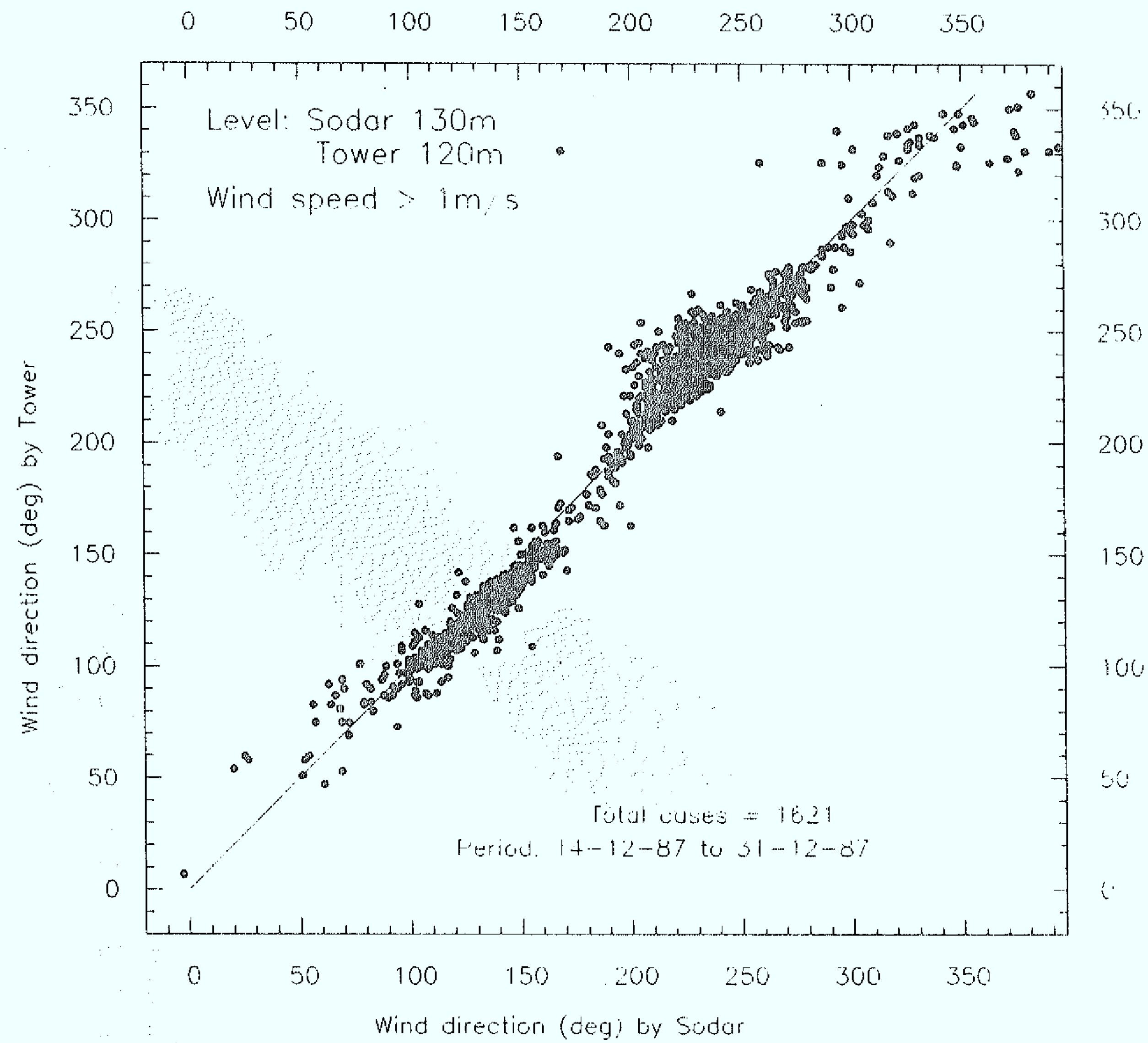



Figure 7. Scatter plot of wind speed – Sodar versus tower speeds

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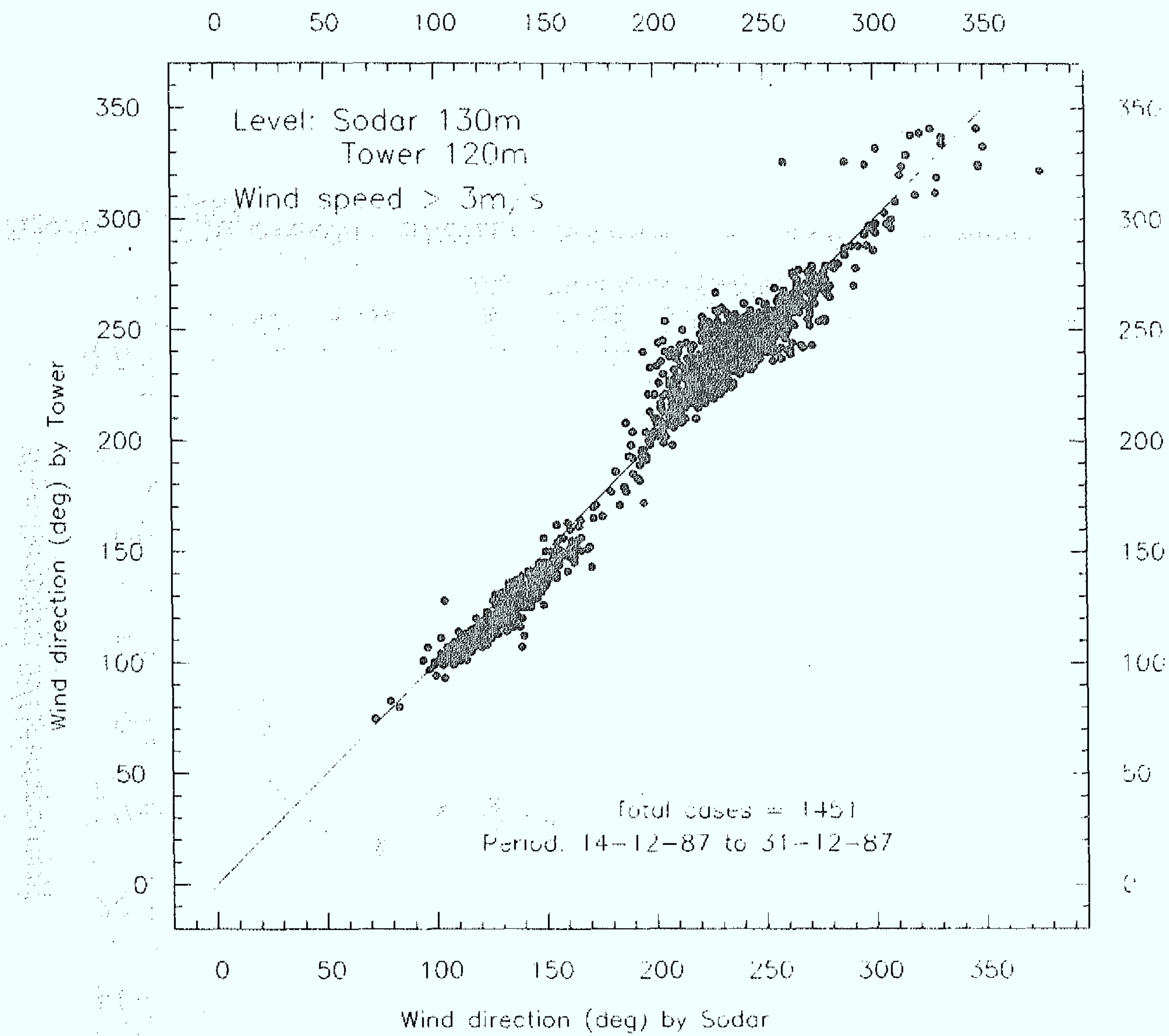



Figure 9. Scatter plot of wind direction – Sodar versus tower.

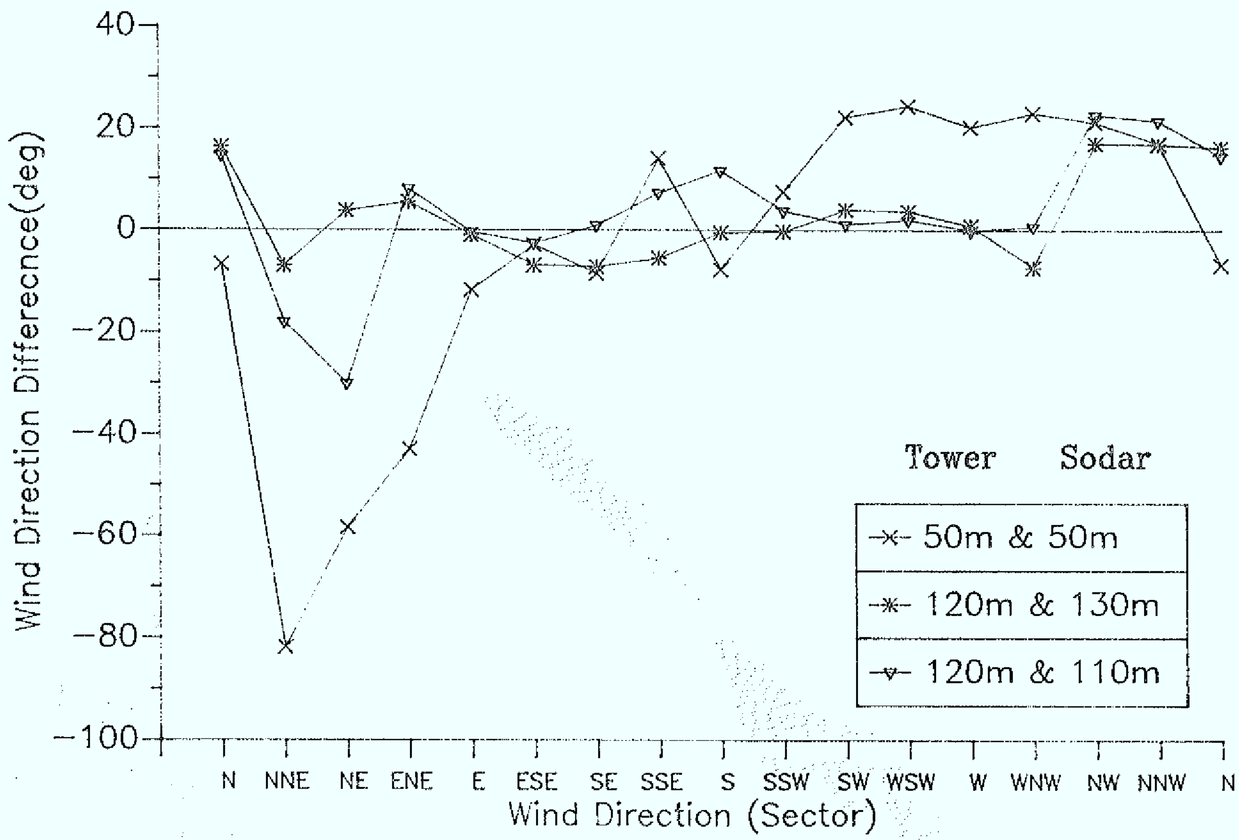



Figure 10. Wind direction difference between tower and Sodar measurements during the period from 14-12-87 to 31-12-87

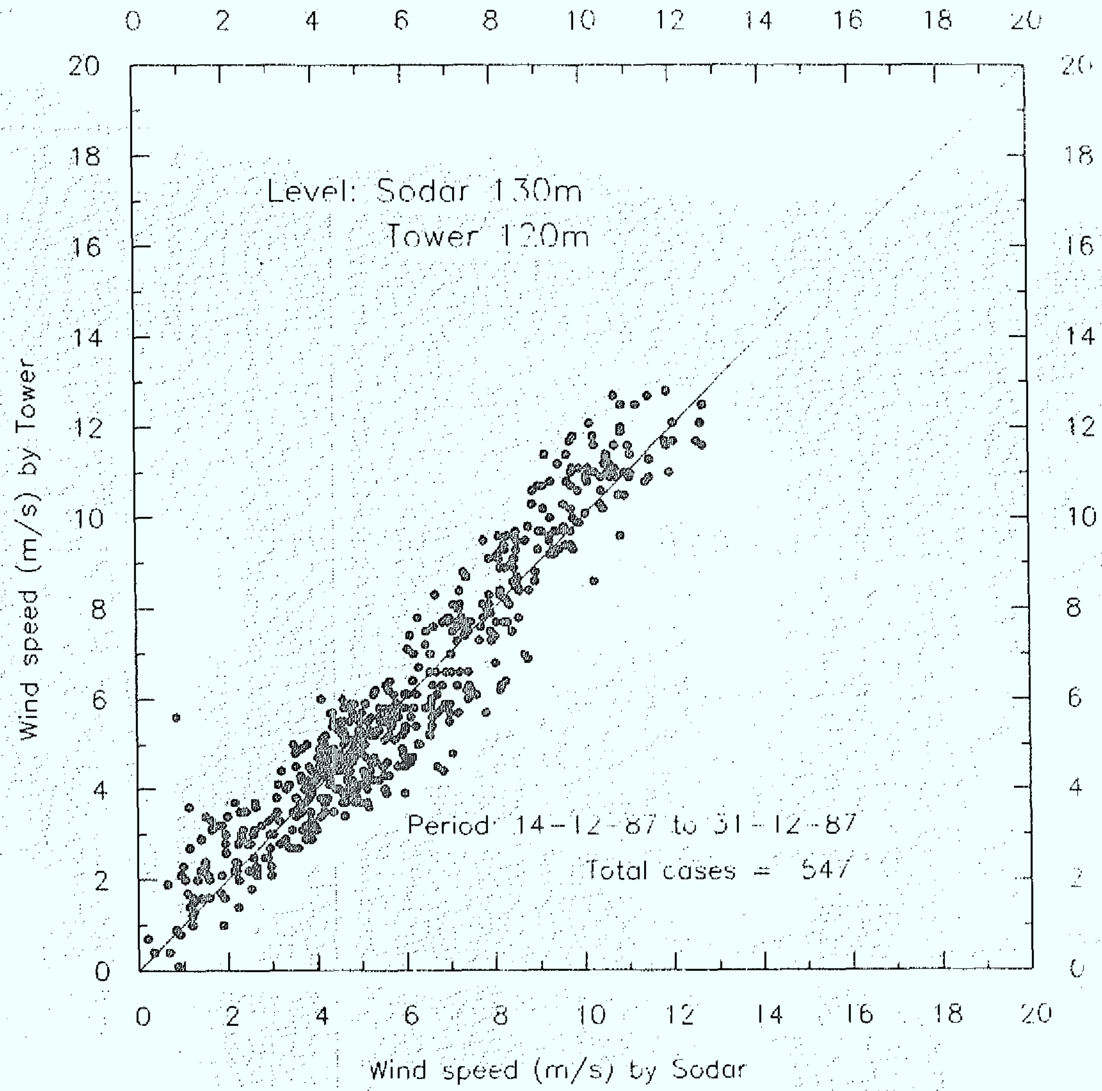
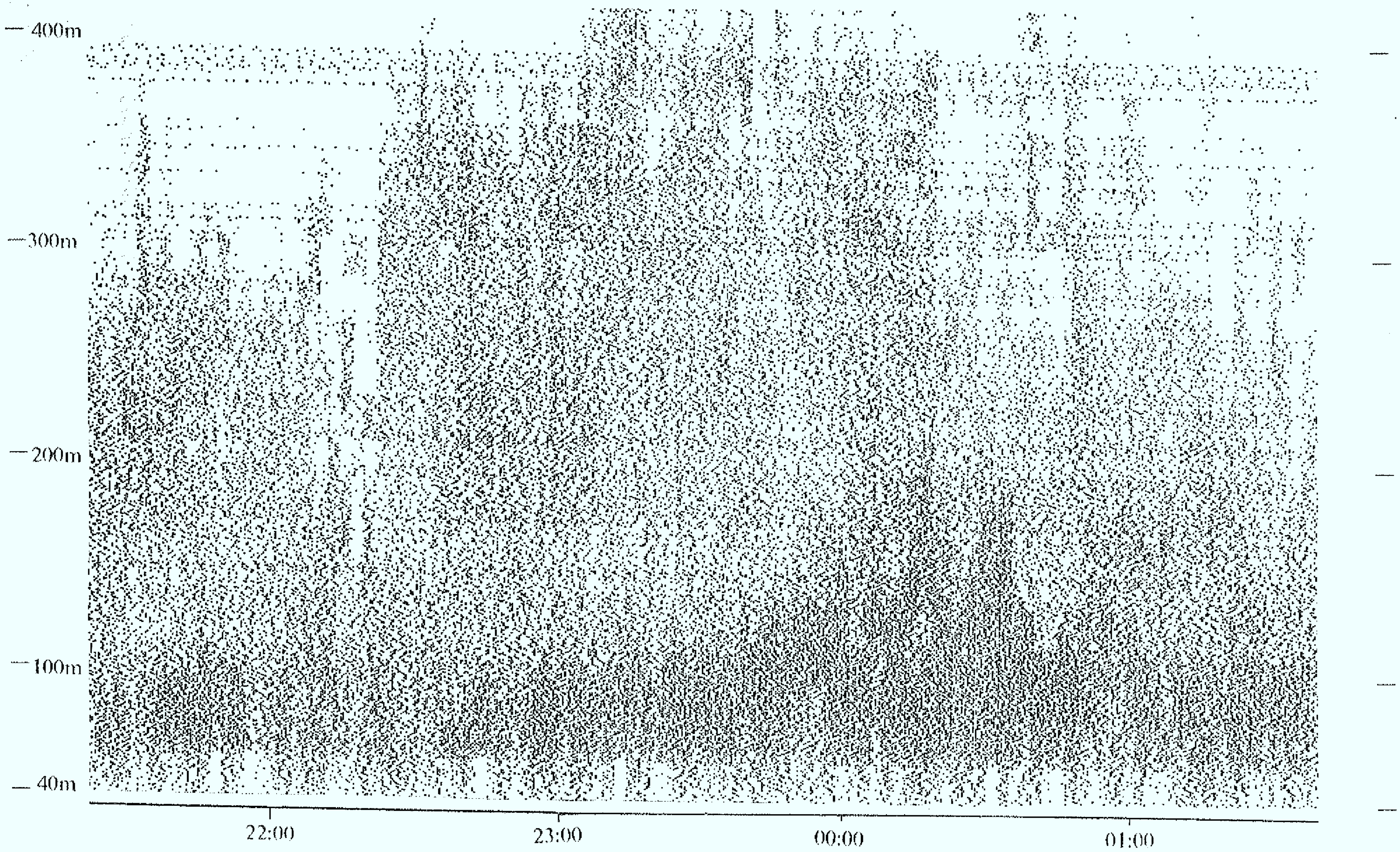



Figure 11 Scatter plot of wind speed – Sodar versus tower speeds
The wind direction was between 100 and 180 deg from North

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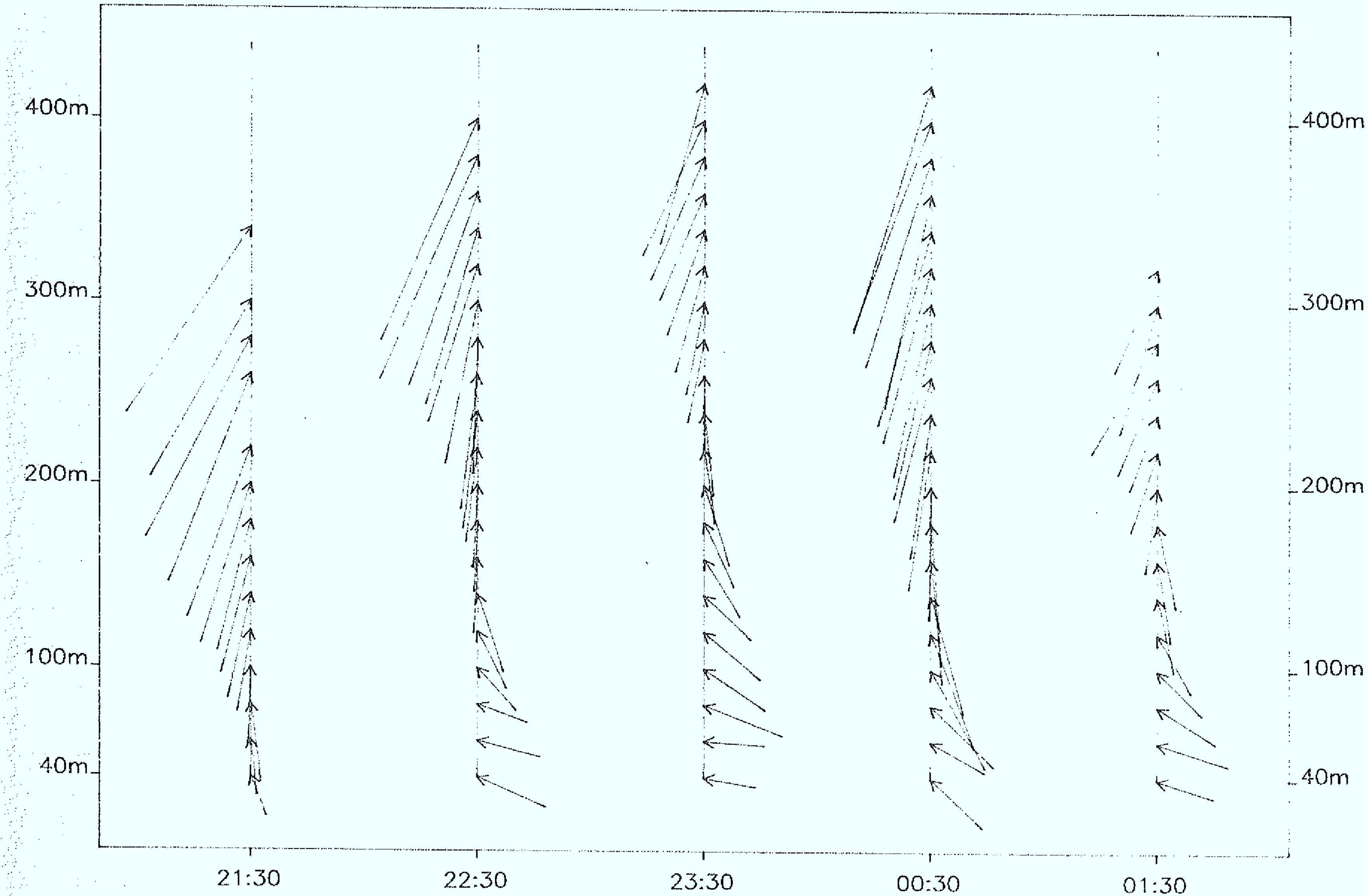

Figure 13. Vectorial plot of wind plotted from Sodar outputs of 10 min. sampling time on 20/21-2-90. Scale: 4 m/s :