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A.C.M. Beljaars

Verification of Doppler sodar measurements

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Koninklijk Nederlands Meteorologisch Instituut = Royal
Netherlands Meteorological Institute,
Fysische Meteorologie = Physical Meteorology,
Postbus 201,
3730 AE De Bilt,
The Netherlands.

U.D.C.: 551.501.815 :
551.510.522 :
551.507.7
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Verification of Doppler Sodar Measurements

by

A.C.M. Beljaars

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1. Introduction

Boundary layer research at KNMI was mainly dealing with a one dimensional description of the atmosphere up to 1980. It was realised, however, that advection effects enter in many situations. For this the 200 m meteorological tower at Cabauw was not sufficient; other measuring points were needed. Doppler Sodar, by means of which wind profiles can be measured up to several hundreds of meters high, seemed appropriate. An important advantage of Doppler Sodar is that it works with equipment on the surface only which can be moved rather easily on a trailer.

In 1980 a profound market investigation was done in order to make an appropriate choice. Important information came from the Boulder Low level intercomparison Experiment (BLIE, Kaimal et al., 1980), during which different commercial Doppler Sodars were compared with tower measurements up to 300 m. Finally it was decided to buy a 3 dimensional Remtech-Sodar (Bertin at that time). One of the reasons for this choice was that the KNMI would take advantage of new developments that were going to be introduced by the manufacturer. The hardware would be updated after one year of operation and some software updates would follow afterwards.

The first system that was delivered used the "zero-counting" method with a small 8-bit micro computer. In 1982 the system has been changed to a "spectral system" with a 16-bit micro computer. Some modifications have been applied to the antennas as well.

The purpose of this paper is to report on the applicability of Doppler Sodar. Many applications have already been proposed in literature (cf. Weill,1984). In this report we limit to the parameters that are produced in the standard output as delivered by the manufacturer. Since the system has changed quite drastically during the testing period, only the last results are realy important in the context of future use. Some of the experience that was gathered in earlier stages of tests is of more general interest and will therefore be mentioned as well.

We will start with a technical description of the equipment in the next section, including the successive modifications and the main experiences with it. In section 3 we will evaluate the results of different measuring campaigns by comparing with tower measurements.

2. Technical description of Doppler Sodar

2.1 General principles

Doppler Sodar is a more sophisticated version of the well known facsimilé sodar. In stead of measuring echo intensity only, Doppler Sodar also measures the frequency of the back scattered sound.

Sodar emits periodically (about every 5 seconds) a short sound pulse (about 0.2 seconds) and then switches to reception. The received energy level at a certain time after emission is a measure for the so called structure function at the level that corresponds to the time delay (delay and height are connected by sound speed). The ratio of received and emitted power reads (Neff, 1975)

$$\frac{P_r}{P_e} = E \cdot e^{-2\alpha R} \, \sigma(R,f) \, \frac{A}{R^2} \, G \cdot C \cdot \tau \cdot \tfrac{1}{2} \qquad (1)$$

where E = efficiency of emission and reception

α = average sound attenuation (m^{-1})

R = distance or height of the scattering volume

σ = scattering cross section per unit volume

A = antenna surface area (m^2)

G = correction due to antenna directivity

C = sound speed (m/s)

τ = emission time interval (s)

Some remarks have to be made in relation to this expression:

- In general we have no absolute calibration of the equipment. This means that E is unknown.
- The attenuation of sound waves depends on frequency, humidity and temperature. The attenuation becomes more important for high frequencies. The frequency of 1600 Hz is often used as compromise

between vertical resolution and attenuation. The characteristic damping distance is of the order of 100 m at this frequency.

- In the case of backscattering towards the emission antenna, the scattering cross section is related to temperature fluctuations only.

$$\sigma = 0.0039\ k^{1/3} \frac{C_T^2}{T_o^2}$$

where k stands for the sound wave number, C_T for the temperature structure function and T_o for the absolute temperature. This means that energy will only be scattered back to the emission antenna when temperature fluctuations are present. This limits the height range for example in the nocturnal boundary layer where we do not expect temperature fluctuations above the boundary layer height.

- Most of the energy is scattered back by the fluctuations that have a length scale of the order of sound wave length. This means that turbulence scales of the order of 20 cm determine the scattering at 1600 Hz.

With Doppler Sodar, we not only measure the backscattered energy as function of height but also the Doppler shift of the signal. This Doppler shift gives information on the radial velocity of the scattering volume (cf. Fig. 1). By measuring with three antennas pointed in different directions, three velocity components are measured. After averaging over some time (at least 5 à 10 minutes) to smooth out the turbulent fluctuations, the three measured radial components can be combined to find the wind components in a rectangular coordinate system. In general it is assumed that the mean vertical velocity component is zero. The vertical antenna is only used to measure the standard deviation of the vertical velocity. It is noted that with a monostatic system (3 antennas together, emission and reception is combined in the same antenna) the different measuring volumes are separated by some distance. This makes that the velocity vectors can only be combined after averaging since it has to be assumed that the velocity field is homogeneous.

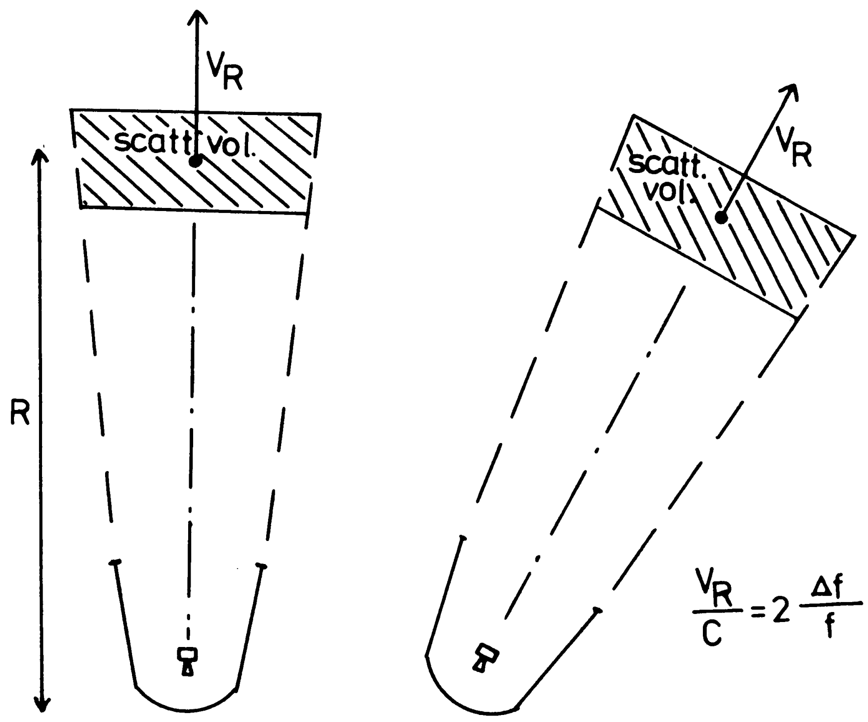


Fig. 1. Antenna configuration with one vertical antenna and one tilted antenna. The third antenna is tilted in a plane perpendicular to the plane of this figure.

2.2. The first Remtech (Bertin) system

The first version of the sodar consists of 3 antennas mounted on a trailer connected with an electronic unit with microcomputer and zero-counting electronics. The antennas have a parabolic dish with a diameter of 1.2 m and a loudspeaker with horn in the focal. The support of the loudspeaker has an hydraulic device which keeps the distance between horn and dish exactly at 2 sound wave lengths for all temperatures. By interference of the emitted and reflected wave (on the dish), the antenna shows a filter effect dependent on this distance. To keep the maximum of the filter characteristic exactly at 1600 Hz, the distance between reflector and horn has to be adjusted for temperature changes. Since the zero counting method is extremely sensitive for the filter characteristic, this effect turns out to be important.

The side lobes of the antennas are shielded by a slightly conical cylinder of about 2 m high. This cylinder is made out of resine inforced polyester in two layers with a sheet of lead in between. This isolates the antenna for background noise. Reflections at the inside are damped by ondulated foam. At a frequency of 1600 Hz the antennas have a beam width of about 10 degrees (3dB points) which makes that the scattering volume at a height of 200 m has a width of about 35 m.

The electronics consists of emission-reception logic, filtering circuits and a power amplifier (cf. Fig. 2). The filtering is done in two bands: (i) the central band around emission frequency through which the backscattered Doppler Signal is coming and (ii) two side bands which are used to monitor the magnitude of the background noise. The amplitude of the signal in both bands are measured by the microcomputer to calculate signal to noise ratio. The number of zero crossing behind the central filter is measured in order to determine the frequency of the signals. It is clear that the result of this frequency measurement is strongly related to the filter curve. The accuracy of the filter characteristics therefore is very important. The software in the microcomputer takes care of the following activities:

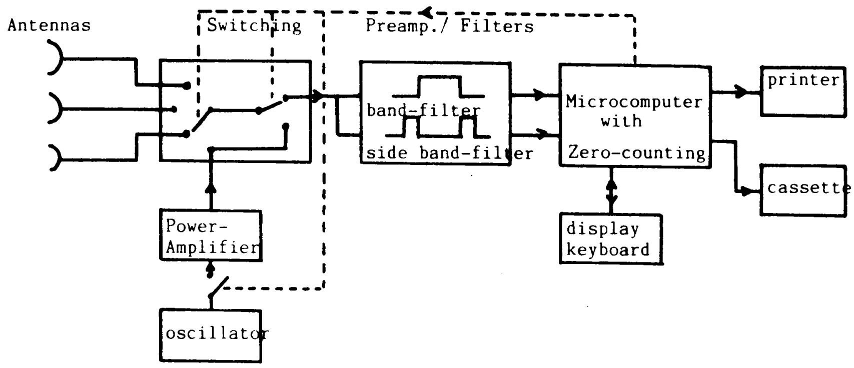


Fig. 2.a: Electronic configuration of the "zero-counting" sodar. The micro computer has been manufactured by Alcyon and contains a 8080 processor.

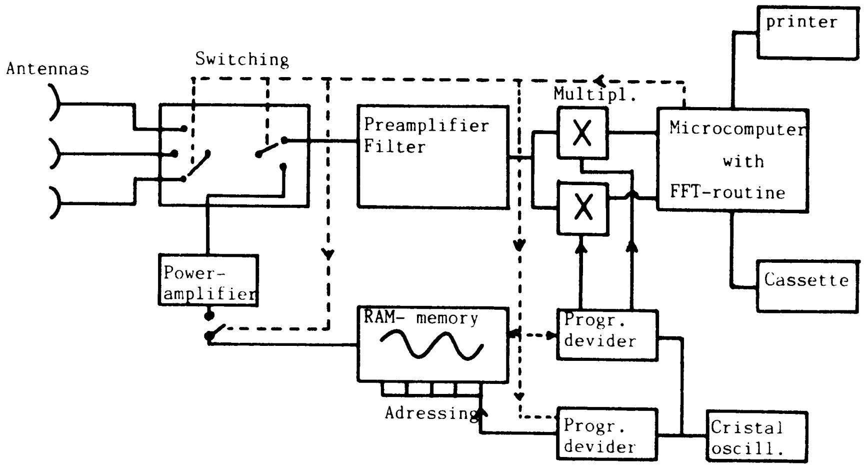


Fig. 2.b: Electronic configuration of the "Fast Fourier" sodar. The microcomputer has been manufactured by Digital Equipment corporation and contains a 11/03 processor.

- emission reception switching
- sampling of signals (2 amplitudes and 1 frequency)
- invalidation of samples with poor S/N-ratio
- correction of the frequency measurements as a function of signal to noise ratio
- averaging
- calculation of horizontal wind speed and standard deviation of the vertical component at the end of the averaging interval
- printing of the results and storage on cassette.

The first measurements with this system were done at a distance of about 200 m from the 200 m high mast at Cabauw. The emission frequency was 1600 Hz. It turned out that the connection cables between antennas and electronics were very sensitive for the electromagnetic field of power supply cables. It was necessary to seperate signal and power supply cables (several meters to be safe). The wind measurements compared very poorly with the tower measurements. The reason for this was that the echo's were dominated by returns from obstacles. The tower was one of them, some buildings at a distance of 200-300 m also contributed. From the latter one could even hear the echo's. Since fixed echo's have zero dopplershift, they have the tendency of shifting the measured velocity towards zero.

In order to avoid the problem of fixed echos the sodar was moved to a distance of about 2 km from the tower. The direct surroundings consisted of trees and some low buildings. The idea was that returns from trees would be sufficiently diffuse to avoid perturbation of measurements. In practice, however, the results were not any better than those obtained near the tower. It was clear that also trees cause important contributions to the received signal. In all these cases there was no significant difference between the three antennas in spite of different tilting. We have simply to doe with the wave that travels horizontally away from the antennas, scatters on the trees or buildings and comes back horizontally. The height/distance ratio of the obstacles is not of importance. Only their "effective cross section" counts; a large building will have the same perturbing effect whatever its position within the measuring range.

The only way of obtaining serious measurements was to shift the emission frequency to 2400 Hz which makes the antennas more directive. A disadvantage of this higher frequency is the limited height range. Acoustic waves at a high frequency damp out faster.

Since the system has been updated to a spectral system at 1600 Hz, no results are presented for 2400 Hz with the zero counting method.

2.3 The Remtech-sodar with spectral analysis

The main difference between this version of the sodar and the one described in section 2.2, is the way in which the Doppler shift is determined. Instead of characterizing the received band filtered signal by the mean frequency, the spectral distribution of the signal is calculated by means of Fourier transformation. This has the advantage that the filter electronics is far less critical than in case of the zero-counting electronics. Another advantage of the electronics as illustrated in Fig. 3, is the flexibility. Many operating parameters can be changed by software. Frequency can be changed (within the range of the filter in the preamplifier which is about 100 Hz) and the pulse can be coded by programming the RAM-memory. In the present version of the software, the emission pulse is modulated with 30 Hz such that two frequencies are present namely 1585 and 1615 Hz.

Together with the new electronics the hydraulic distance adjustment in the antennas has been removed. Obviously the exact filter characteristic of the measuring chain has become less important. We are not looking any more at the average frequency in the reception band but at spectral peaks.

Not many details are known about the software but again there are a number of tests to qualify the signal. Suspected echos are discarded, which can be due to bad signal to noise ratio or due to fixed echos.

The vertical resolution can be changed by the length of the emission pulse and by setting the thickness of the measuring layers. The resolution on the reception side is fixed however to about 30 m since time series with a length of 170 ms are taken to do spectral analysis. Different thicknesses of measuring layers are obtained by means of interpolation. Because of the fixed reception time intervals it does not make sense to choose measuring layers much thinner than 30 m.

In Fig. 3 an example is given of spectra as they are calculated by the sodar software. These spectra are not stored when the sodar is running in a standard way. They are only used to check for fixed echos. Individual spectra are used to determine Doppler shift. It is clear from fig. 3.b that the scatter is large and that it is very difficult to determine Doppler shift from this. Although two frequencies are emitted, sometimes only one spectral extreme is observed. The averaged spectra in figure 3a are only for illustration; they are not used in the on-line data reduction.

3. Results of different measuring campaigns

3.1 Turbulence measurements in 1982 with the zero-counting electronics

As far as the mean wind field is concerned we limit ourselves to the statement that the equipment behaved poorly at 1600 Hz because of fixed echo problems. It gave good results at 2400 Hz in the sense that the accuracy of half hour averages of mean horizontal wind was comparable with the accuracy found during BLIE in Boulder (Gaynor and Korrell, 1981).

Although the zero-counting electronics is not in operation any more, it is still interesting to mention some results of an experiment in which only the vertical antenna was used for turbulence measurements. All samples of the vertical velocity were stored and the standard deviation of vertical velocity was calculated afterwards. The sample frequency was 0.15 Hz, the maximum height range was 500 m, the emission pulse had a length of 200 ms, the measuring layers had a thickness of 40 m and the emission frequency was 2400 Hz.

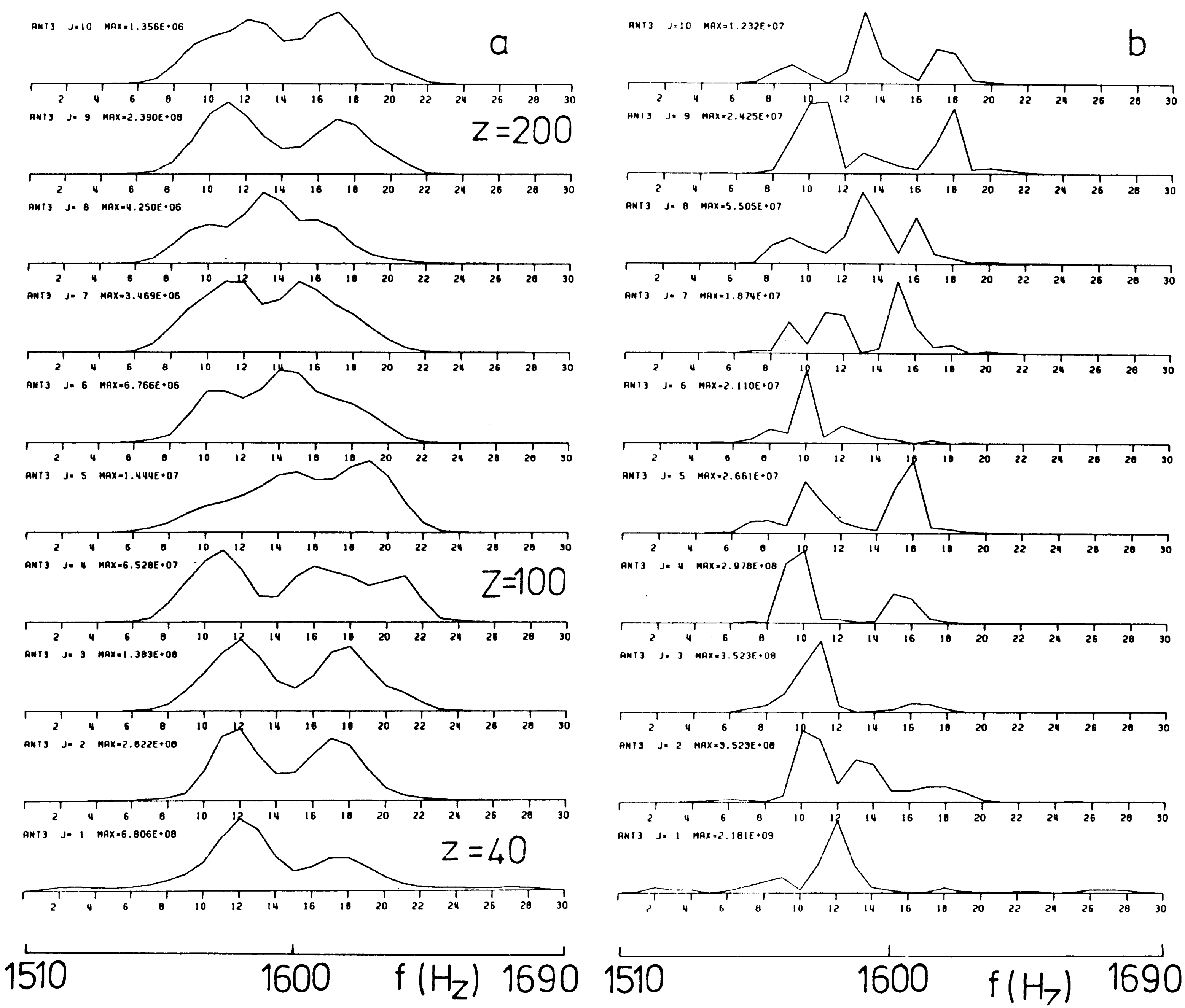


Fig. 3. Spectral distribution of the backscattered sound for antenna 3 (vertical). J = 1 to 10 range from z = 40 to 220 m. In figure a the spectra are averaged over 15 pulses. Figure b represents the spectrum of a single pulse. Emission is at the frequencies of 1585 and 1615 Hz. Spectra are calculated over 32 points. The vertical scale of the pictures is normalized on the maximum value, which is indicated by the number max.

A summary of the results is given in figure 4, where standard deviations as measured by trivanes at the tower are compared with sodar measurements. The standard deviation is derived from sodar samples in two ways: (i) By using all samples, (ii) by using the averaged values of three subsequent samples.

A clear correlation between sodar and trivane measurements is observed. The scatter, however, is large. After averaging over 3 successive samples, the resulting standard deviation becomes slightly lower due to the low pass filtering effect of this operation.

In connection with the measurement of standard deviation, we mention two error sources:

1. The beam width is rather large which introduces averaging over a volume with a size of about 35 m at 200 m height. The volume size increases with height. This effect results in underestimation of the standard deviation. This effect might be present in the data of figure 4 since sodar measurements at 200 m are systematically lower than those at 80 m (cf. Appendix B for a quantitative estimation).
2. The determination of frequency from a signal with length dt can only be done with an accuracy of the order 1/dt. The Fourier transorm of a sine wave over dt seconds leads to power spectrum that has the form of a sinc function (cf. Bendatt and Piersol, 1966). The width of the spectral peak is about 1/dt, corresponding to a σ_w of about $c/(2\ f\ dt) \simeq 0.6$ m/s.

3.2 First experiments with the FFT-sodar (february 1983)

These experiments were carried out at about 2 km from the Cabauw mast, at a place surrounded by trees and some small buildings (The zero-counting sodar at 1600 Hz was strongly perturbed by fixed echo's here). The antennas are still the same without temperature compensation and the operation frequency is 1600 Hz modulated with 30 Hz resulting in 1585 and 1615 Hz. It should be noted that the month of february had only a small number of days with strong echos. The weather was cloudy most of the time and regularly rainy. The results of this measuring period are very irregular. Sometimes the results correlate well with tower measurements. Sometimes the sodar data deviate strongly. There is no

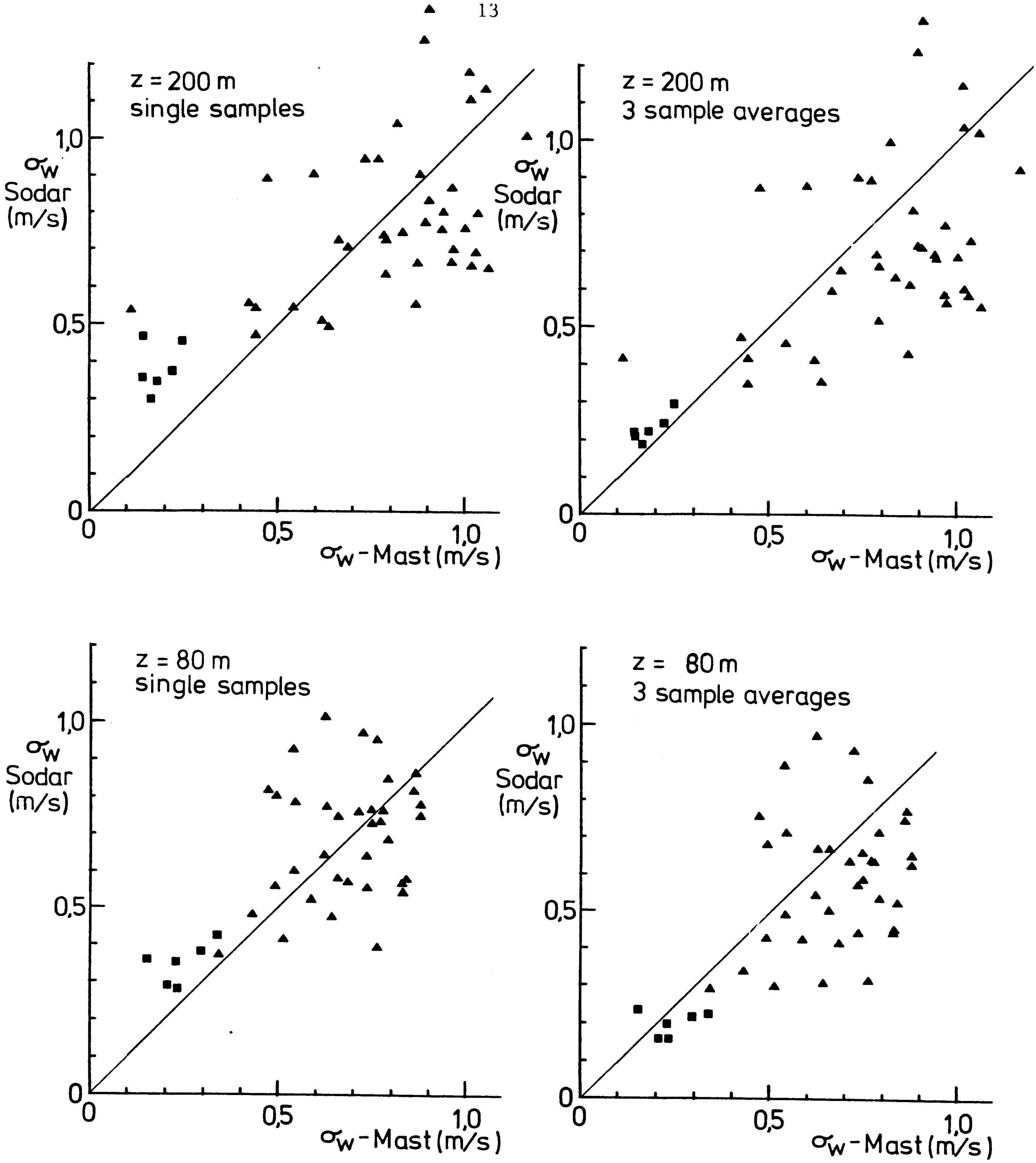


Fig. 4. Standard deviation of vertical velocity measured with sodar in comparison with trivane-measurements. For this all basic samples from the zero-counting system have been recorded. Standard deviation has been calculated with all individual smaples over half hour intervals (left hand figures) and on the bais of non overlapping averages of 3 samples (right hand figures). Situations with positive (▲) and negative (■) surface heat flux are distinguished. These measurements were done in May 1982.

clear correlation with weather conditions. It is believed that fixed echos cause the problem although the software was accounting for this. Also an error in the software should not be excluded. The results of this measuring campaign are summarized in table. 1.

3.3 Results from COAST (April-May 1983)

During the COAST-experiment, the Remtech Sodar was installed a few hundreds of meters from the Dutch coast. There were no obstacles in the direct surroundings and there were no indications for fixed echos. The measurements are compared with data from an anemometer on a tower at a height of 70 m. The results of half hourly averaged values are presented as scatterplots in the figures 5 and 6. The scatter in wind speed is larger for strong winds. This is probably due to systematic errors in the horizontal components in the direction of the antennas. This might be related to corrections that are done in the Sodar software for deflection of sound beams in a wind gradient according to Spizzichino (1972). This effects cancel however when the directivity of the antenna is taken into account (cf. Appendix A).

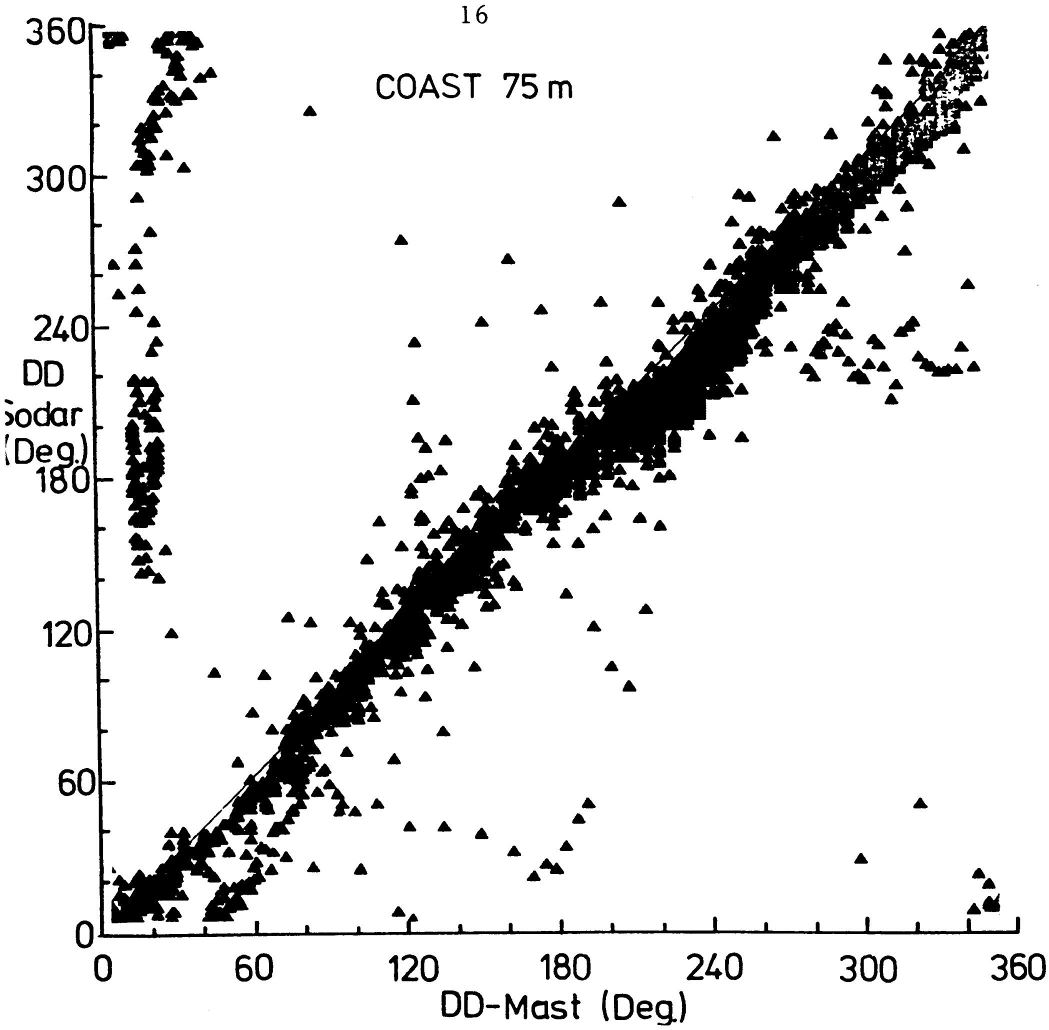
Since the standard deviation of the wind vane at 70 m height was also recorded, this particular output of the sodar could be tested as well. The results are presented in Fig. 7. It turns out that the standard deviation of wind direction is strongly overestimated by Doppler Sodar.

It should be noted that the weather conditions during COAST were very unfavourable for Doppler Sodar; The measurements contain many situations with rain, clouds and very strong winds. Heavy rain and wind above 15 m/s are hardly present in the results because of invalidation by the Sodar software.

In general it can be concluded that the results for mean wind speed are in reasonable agreement with anemometer data. The obvious erroneous results as reported in the previous section did not occur. This might have two reasons: (i) almost no obstacles were present that could cause fixed echos and (ii) Remtech changed the computer code. Although Remtech declared that only minor changes were made, I have the feeling that

Tabel 1 Comparison of sodar winds with tower measurements. February 1983. Highest measuring level 420 m.
Velocities are in m/s; directions in degrees.

		40 m					80 m					120 m					200 m				
		mean value					mean value					mean value					mean value				
	variable	sodar	mast	RMS diff	corr	nr P	sodar	mast	RMS diff	corr	nr P	sodar	mast	RMS diff	corr	nr P	sodar	mast	RMS diff	corr	nr P
0. L was not determined	U	-1.2	-0.4	1.1	0.92	24	4.7	8.7	5.1	0.94	95	4.2	8.0	5.1	0.94	81	6.2	10.8	6.0	0.89	80
	V	0.2	-1.4	1.8	0.23	24	4.2	2.5	2.8	0.93	95	5.1	2.8	3.2	0.97	81	3.4	1.2	3.2	0.96	80
	FF	1.2	1.4	1.0		24	6.3	9.0	3.5		95	6.6	8.5	3.0		81	7.1	10.8	3.6		80
	DD	99	17	96		24	228	254	24		95	219	251	25		81	242	264	23		80
	integral height range distrib. 25%: m							50%: m		75%: m		90%: m									
1. L<-500 or L>500	U	-3.5	-6.6	5.9	0.11	11	2.5	5.5	4.7	0.91	256	3.4	6.9	4.2	0.94	270	4.7	8.2	4.2	0.95	229
	V	-0.5	-2.2	2.9	0.13	11	3.2	5.5	2.4	0.90	256	4.1	2.8	2.5	0.95	270	4.2	2.5	2.7	0.96	229
	FF	3.5	7.0	5.7		11	4.1	7.0	3.7		256	5.3	7.4	2.8		270	6.3	8.6	2.9		229
	DD	82	71	52		11	218	246	32		256	220	248	22		270	228	253	18		229
	integral height range distrib. 25% = 200 m							50%: 300 m		75%: 380 m		90%: m									
2. -500<L<-100	U	-4.7	-4.7	3.9	0.27	24	-3.0	-1.5	2.5	0.94	47	-3.4	-2.5	2.1	0.94	48	-2.4	-1.2	2.4	0.94	40
	V	-1.2	-1.4	1.8	0.22	24	-1.8	-1.7	1.4	0.84	47	-1.9	1.6	1.7	0.76	48	-2.1	-2.1	1.3	0.88	40
	FF	4.8	4.9	3.7		24	3.5	2.2	2.5		47	3.9	3.0	2.1		48	3.2	2.4	2.5		40
	DD	75	74	46		24	58	41	17		47	61	57	20		48	48	29	15		40
	integral height range distrib. 25% = 220 m							50%: 280 m		75%: 380 m		90%: m									
3. -100<L<0	U	-1.5	-1.7	1.5	0.49	18	-0.9	-0.6	1.6	0.82	27	-0.9	-0.7	1.4	0.90	27	-2.3	-1.1	4.3	0.70	26
	V	0.3	-1.4	1.8	0.15	18	-1.0	-0.8	0.8	0.86	27	-0.9	-1.0	0.6	0.90	27	-1.5	-1.8	1.7	0.69	26
	FF	1.5	2.2	1.5		18	1.3	1.0	1.4		27	1.3	1.3	1.1		27	2.8	2.1	4.1		26
	DD	100	50	50		18	41	36	25		27	45	35	26		27	58	32	43		26
	integral height range distrib. 25% = 240 m							50%: 300 m		75%: 340 m		90%: m									
4. 100<L<500	U	-7.0	-5.7	4.1	0.74	24	0.1	1.9	2.7	0.96	148	0.0	2.0	2.7	0.98	156	0.4	2.5	2.5	0.99	155
	V	0.4	-2.2	5.7	0.22	24	1.0	2.7	1.5	0.93	148	1.0	0.4	1.6	0.95	156	1.0	-0.1	1.9	0.96	155
	FF	7.0	6.1	5.2		24	1.0	2.0	2.4		148	1.0	2.0	2.2		156	1.1	2.5	2.0		155
	DD	94	69	37		24	184	249	23		148	180	259	18		156	203	273	13		155
	integral height range distrib. 25% = 320 m							50%: 400 m		75%: 420 m		90%: m									
5. 0<L<100	U	-0.4	1.1	2.4	0.47	53	0.7	1.2	1.0	0.97	119	0.6	1.5	1.6	0.94	113	1.0	1.8	1.6	0.96	106
	V	-2.8	-2.9	1.2	0.85	53	0.0	0.6	1.2	0.99	119	-0.3	0.3	1.3	0.98	113	-0.4	0.1	0.9	1.00	106
	FF	2.8	3.1	1.9		53	0.7	1.4	1.2		119	0.7	1.5	1.4		113	1.1	1.8	0.9		106
	DD	70	42	46		53	331	308	13		119	2	322	22		113	356	329	12		106
	integral height range distrib. 25% = 220 m							50%: 300 m		75%: 360 m		90%: m									



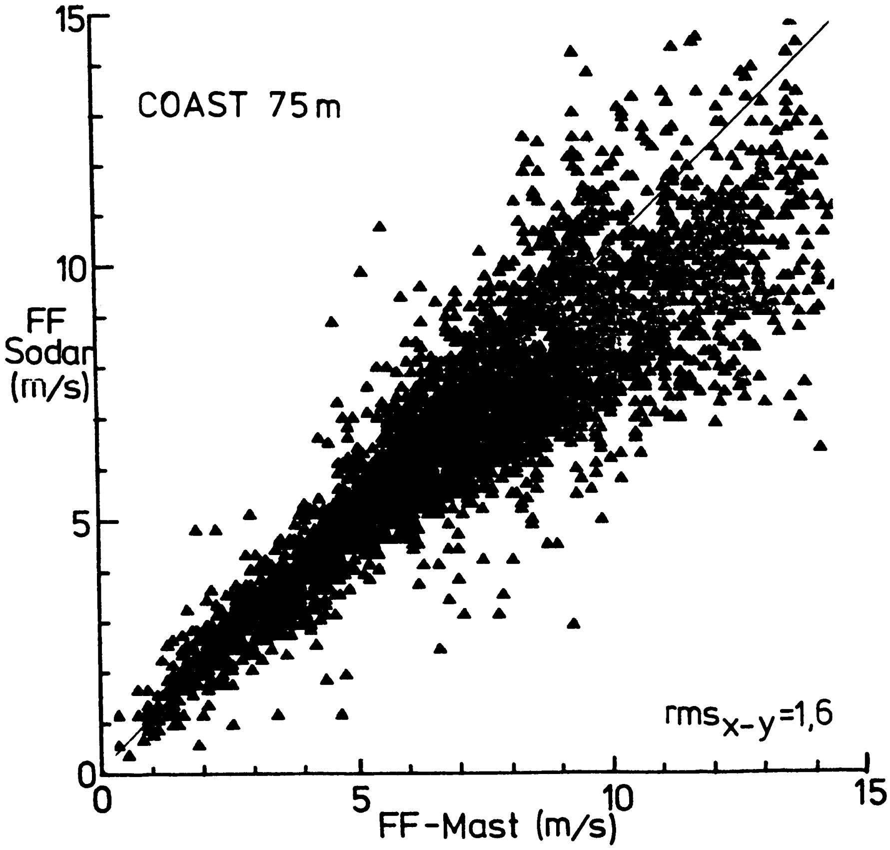


Fig. 5. Comparison of horizontal wind speed and wind direction with anemometer and vane during COAST (April-May 1983).

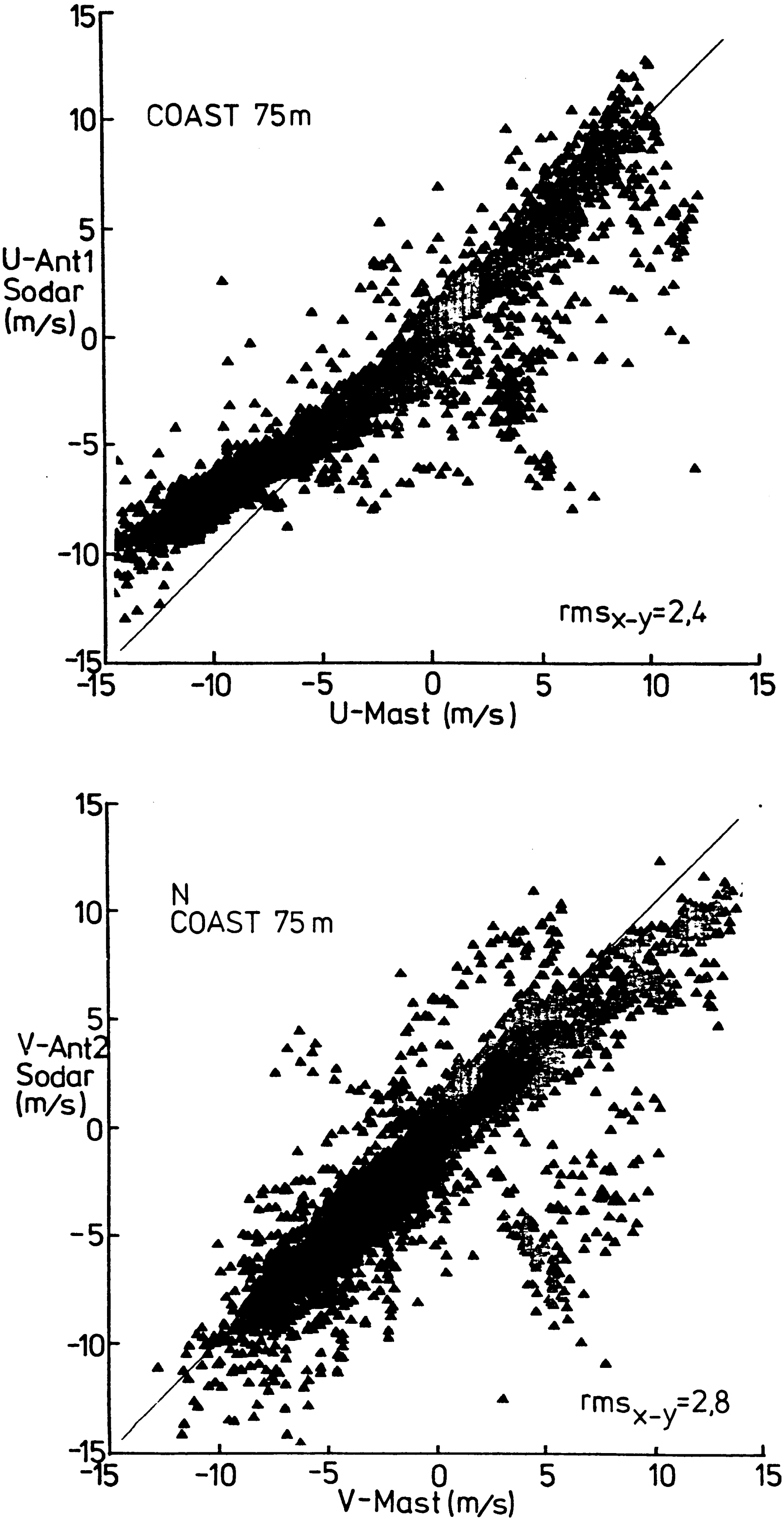


Fig. 6. Comparison of the horizontal wind components in the two antenna directions with tower measurements during COAST (April-May 1983).

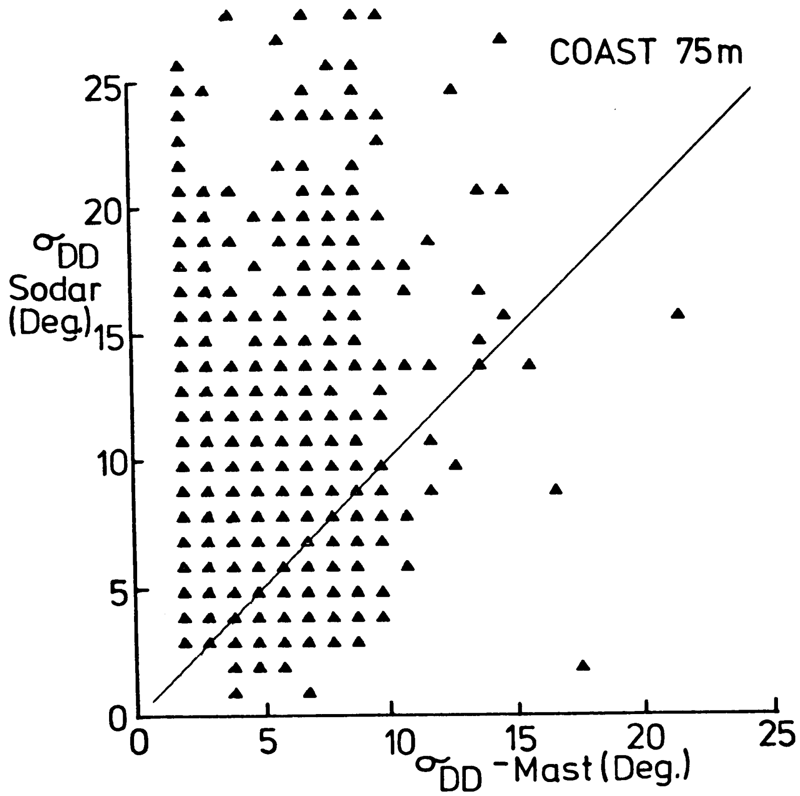


Fig. 7. Standard deviation of wind direction as measured by Sodar in comparison with wind vane measurements during COAST (April-May 1983).

there was still a bug in the previous program. In the latter case, the results of section 3.2 are not representative for the actual functioning of the Sodar.

3.4 Comparison of Sodar and tower data in summer 1983

In the period from July 2 to July 5 and from August 16 to September 2th, the Doppler Sodar has been in operation at a distance of about 200 m from the Cabauw tower. Just before this campaign the antenna foam has been replaced by a different type. The old foam had a corrugated surface and was covered with a paint coating to reduce usage by weather influences. The new foam is flat and has a thickness that is adapted to sound wave length for minimum reflection. According to the tests by the manufacturer, the new foam should reduce fixed echo problems and should improve the overall performance of the system.

Although we had fixed echo prolems with former versions of the sodar at this position, we could not observe this any more. Neither the 200 m tall tower at a distance of 200 m nor the rahter solid building at about 300 m distance caused any problem. The results of the mean horizontal wind comparison are summarized in table 2. Figures 8 and 9 illustrate the measurements for the 160 m level. The height range was above the preset highest measuring level of 420 m in most cases. The heights of the integral distribution curves (these are the heights below which the range is during the indicated percentage of the time) are given for 25, 50, 75 en 90%. It should be realized that the height range is the maximum height where the sodar software indicates that the signal to noise ratio is sufficient to determine Doppler shift. We have no idea about the accuracy above 200 m since we have no reference measurements there.

Conclusions about the horizontal wind comparisons can be summarized as follows:

- The RMS-difference between the velocity components measured by Sodar and by the tower, is very close to 1 m/s in most cases. This is comparable with other studies (cf. Gaynor et al., 1983).
- The errors increase with height which is probably due to a decreasing signal to noise ratio.

Tabel 2. Comparison of sodar and tower wind measurements during August en September 1983. Highest measuring level is 420 m. The U and V components are in the west-east and south-north direction respectively. Velocities are in m/s; directions in degrees.

		40 m					80 m					120 m					200 m				
		mean value		RMS		nr	mean value		RMS		nr	mean value		RMS		nr	mean value		RMS		nr
	variable	sodar	mast	diff	corr	P	sodar	mast	diff	corr	P	sodar	mast	diff	corr	P	sodar	mast	diff	corr	P
0. L was not determined	U	-1.0	-1.2	0.6	0.98	156	-1.6	-1.8	0.9	0.95	157	-1.9	-2.1	1.1	0.95	151	-2.3	-2.0	1.4	0.93	116
	V	-0.7	-0.6	0.6	0.98	156	-0.4	-0.2	0.7	0.98	157	-0.3	-0.2	0.8	0.97	151	0.0	0.2	1.4	0.94	116
	FF	1.2	1.3	0.7		156	1.6	1.8	0.8		157	2.0	2.1	0.9		151	2.3	2.0	1.5		116
	DD	55	61	12		156	77	83	14		157	80	84	20		151	91	95	24		116
	integral height range distrib. 25% = 260 m 50%: 340 m 75%: >400 m 90%: m																				
1. L<-500 or L>500	U	-0.2	-0.4	1.1	0.94	98	-0.4	-1.1	1.1	0.97	109	-0.3	-1.0	1.0	0.98	107	-0.2	-0.8	1.0	0.98	93
	V	-2.6	-2.6	1.4	0.96	98	-2.9	-2.6	0.7	0.99	109	-3.0	-2.7	0.7	0.99	107	-3.4	-3.3	0.8	0.99	93
	FF	2.6	2.6	1.3		98	2.9	2.8	0.7		109	3.0	2.9	0.6		107	3.4	3.4	0.8		93
	DD	4	10	11		98	7	23	10		109	6	21	10		107	3	13	7		93
	integral height range distrib. 25% = 380 m 50%: m 75%: m 90%: m																				
2. -500<L<-100	U	1.3	0.9	1.3	0.94	141	0.9	0.4	1.0	0.98	135	0.9	0.5	1.1	0.97	133	0.3	0.3	1.9	0.93	120
	V	-1.2	-1.3	1.2	0.97	141	-1.6	-1.5	0.9	0.99	135	-1.5	-1.3	0.8	0.99	133	-1.4	-1.7	1.5	0.97	120
	FF	1.7	1.6	1.4		141	1.8	1.5	0.9		135	1.7	1.4	0.8		133	1.4	1.7	1.7		120
	DD	313	326	12		141	331	346	11		135	327	340	10		133	347	349	19		120
	integral height range distrib. 25%: 400 m 50%: m 75%: m 90%: m																				
3. -100<L<0	U	-0.8	-1.0	1.1	0.91	204	-1.1	-1.1	1.3	0.91	201	-1.0	-1.2	1.5	0.90	189	-1.2	-1.0	1.7	0.88	191
	V	-0.8	-0.7	0.9	0.90	204	-0.8	-0.7	1.1	0.92	201	-1.0	-0.8	1.2	0.92	189	-0.7	-0.6	1.3	0.91	191
	FF	1.1	1.2	1.0		204	1.3	1.3	1.0		201	1.4	1.4	1.2		189	1.4	1.2	1.6		191
	DD	47	56	20		204	53	60	29		201	45	57	29		189	57	59	30		191
	integral height range distrib. 25% = 400 m 50%: m 75%: m 90%: m																				
4. 100<L<500	U	-0.7	-1.1	0.7	0.98	141	-0.9	-1.7	1.0	0.99	143	-0.9	-1.7	1.1	0.99	135	-1.3	-1.9	1.3	0.98	134
	V	-2.2	-2.3	0.6	0.99	141	-2.6	-2.5	0.5	1.00	143	-3.0	-2.7	0.5	1.00	135	-3.4	-3.4	1.1	0.98	134
	FF	2.3	2.6	0.7		141	2.8	3.0	0.5		143	3.1	3.2	0.5		135	3.6	3.9	1.1		134
	DD	19	26	7		141	19	34	15		143	18	32	9		135	22	29	13		134
	integral height range distrib. 25%: 340 m 50%: 380 m 75%: m 90%: m																				
5. 0<L<100	U	-1.6	-2.1	0.7	0.99	219	-2.6	-3.3	1.0	0.99	218	-2.8	-3.5	1.1	0.98	191	-3.4	-3.7	1.1	0.98	185
	V	-1.8	-1.9	0.5	0.99	219	-2.2	-1.9	0.6	0.99	218	-1.9	-1.5	0.7	0.99	191	-1.2	-1.1	0.9	0.98	185
	FF	2.4	2.9	0.8		219	3.4	3.9	0.7		218	3.4	3.8	0.8		191	3.6	3.9	0.9		185
	DD	43	48	7		219	49	60	9		218	56	67	10		191	71	74	11		185
	integral height range distrib. 25% = 300 m 50%: 380 m 75%: m 90%: m																				

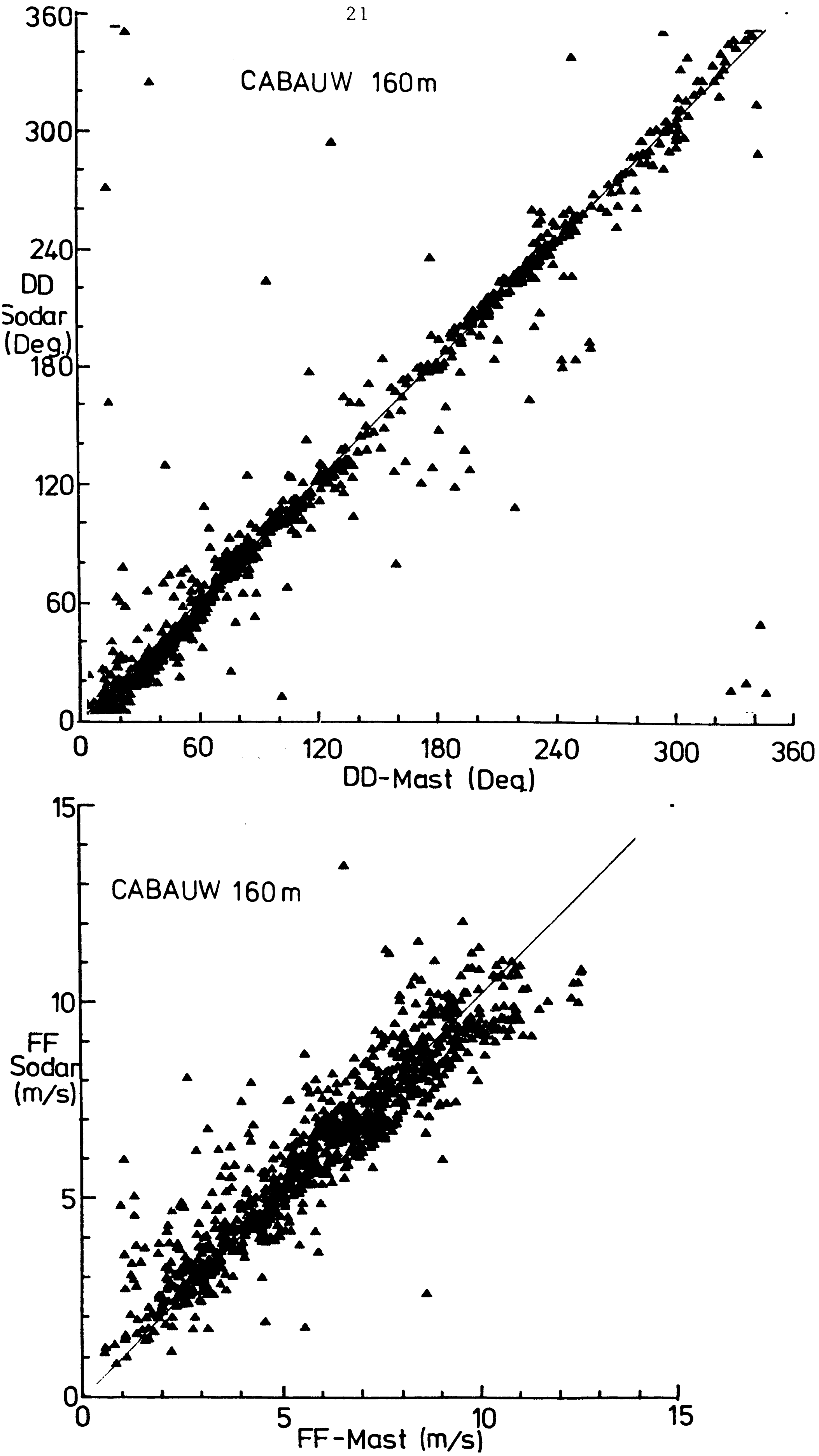


Fig. 8. Comparison of Sodar en tower measurements (Cabauw, August 1983). Horizontal wind speed and direction are shown.

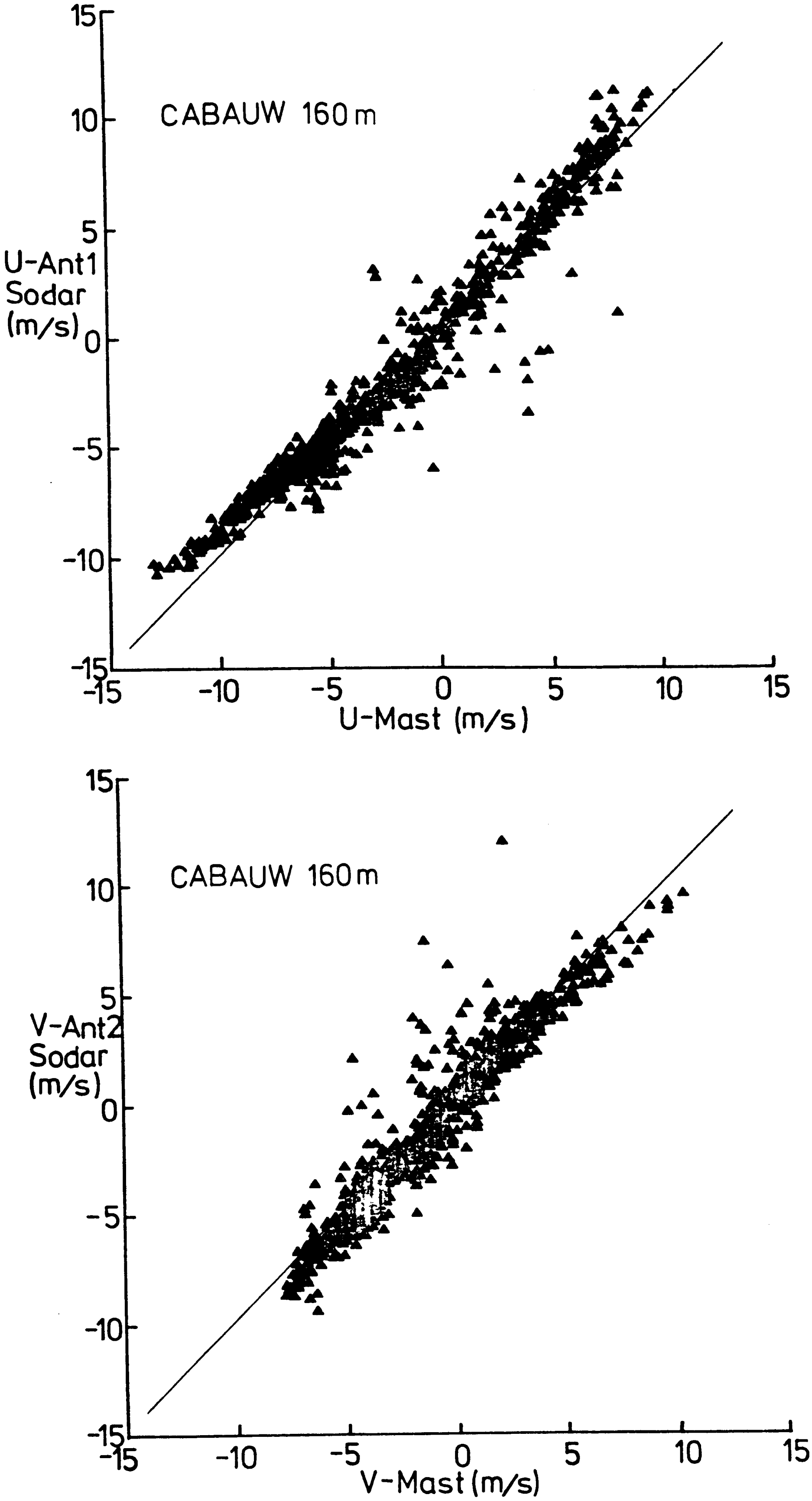


Fig. 9. Horizontal wind components in the two antenna directions. Comparison of Sodar and tower measurements (August 1983).

- The errors are slightly larger for the unstable case at the 200 m level. The reason for this is not clear. Two possibilities are mentioned: (i) for weak winds there might be an averaging problem in the sense that the tower and the sodar do not see the same convective structures and therefore also not the same winds, (ii) since the sodar software selects samples with sufficient signal to noise ratio there might be a bias towards convective cells with positive vertical velocity.
- The quality of the sodar measurements during summer 1983 is much better than during COAST (compare the figures 5 and 8). This must be attributed to the more favourable conditions in summer 1983. During COAST we had much rain, clouds and strong winds. In summer 1983 we had clear skies with convection during the day and stable nights which result in strong radar echos.

In August 1983, during the measuring period discussed above, turbulence measurements were done on selected days. In total 54 hours of measurements were done from which 36 hours under convective conditions and 18 hours during the night. Clear days and nights were selected. A comparison of half hourly averaged σ_w-values is given in the figures 10, 11 and 12. It is clear from the profiles of σ_w during the day (fig. 10) that the sodar follows the trivane measurements within about 0.1 m/s. Even the maximum of σ_w at 120 m (31-8-83) is reproduced by sodar. In the nocturnal boundary layer (cf. fig. 11) the trivane measurements are followed rather well except when the signal strength becomes too low as on 30-8-83 where σ_w measured by sodar increases above the inversion whereas the trivanes indicate that σ_w decreases.

All the half hourly averaged σ_w-measurements are compared in the scatter plots of fig. 12. The root mean square difference between sodar and trivane measurements is about 0.12 m/s at low heights and increases with height. At 160 and 200 m we observe sometimes distinct erroneous results especially during the night. This is probably due to poor signal to noise ratios. Apparently the criterion for this is not sufficiently tight. During the night with relatively low σ_w-values, the sodar produces too large numbers. The lowest σ_w-value that can be detected by sodar is about 0.2 m/s.

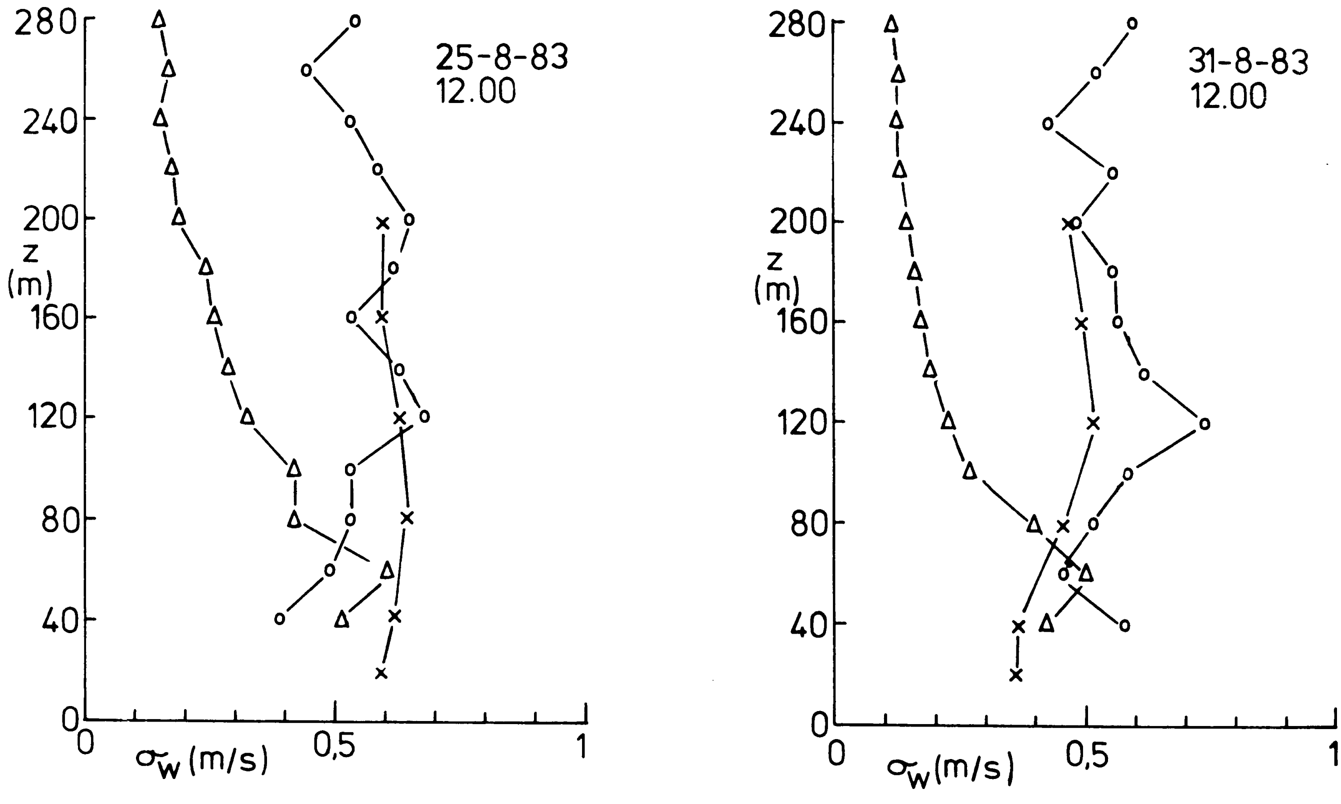


Fig. 10. Standard deviation of vertical velocity measured by Sodar (o) and measured by trivanes (x) as function of height. The figures represent a convective situation. The echo intensity is indicated as function of height by Δ in arbitrary units.

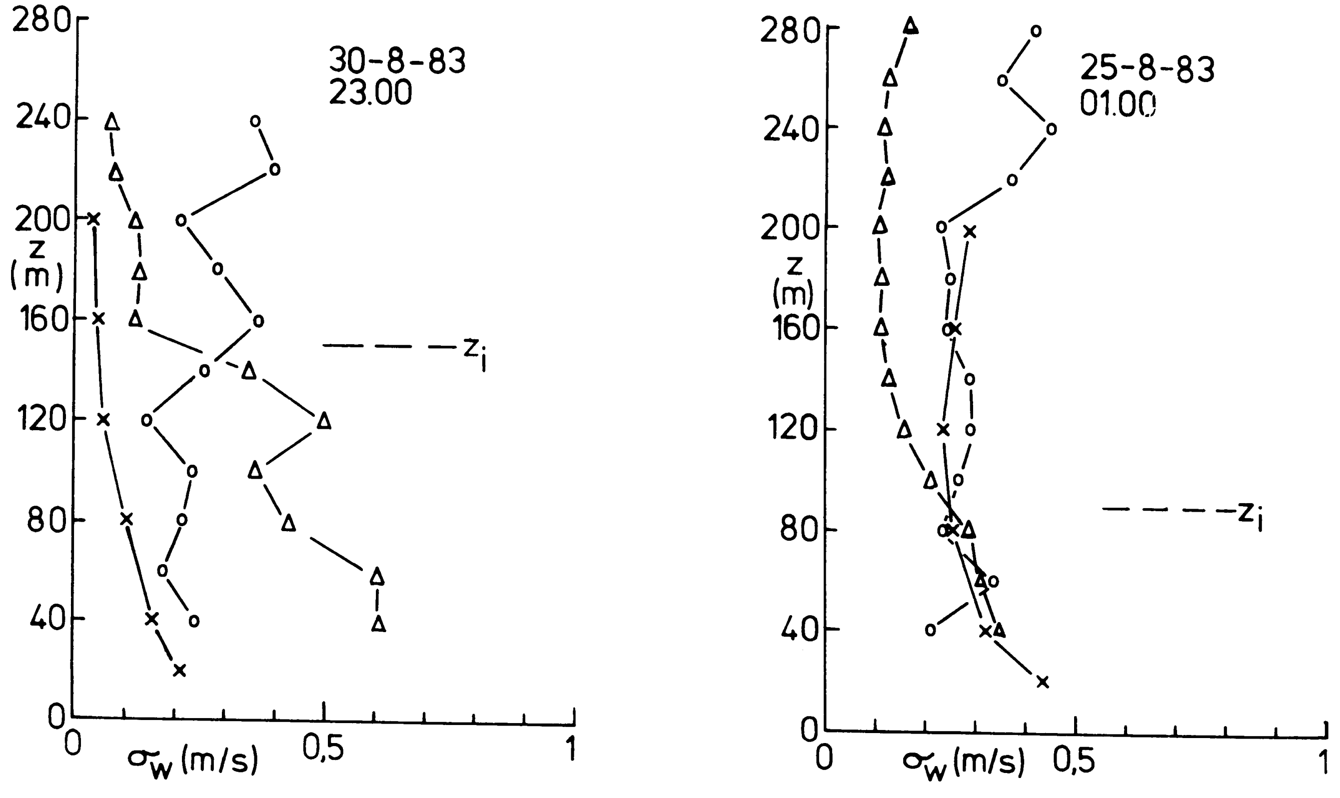


Fig. 11. Standard deviation of vertical velocity measured by Sodar (o) and measured by trivanes (x) as a function of height for two cases of a nocturnal boundary layer. Echo intensity is indicated by Δ.

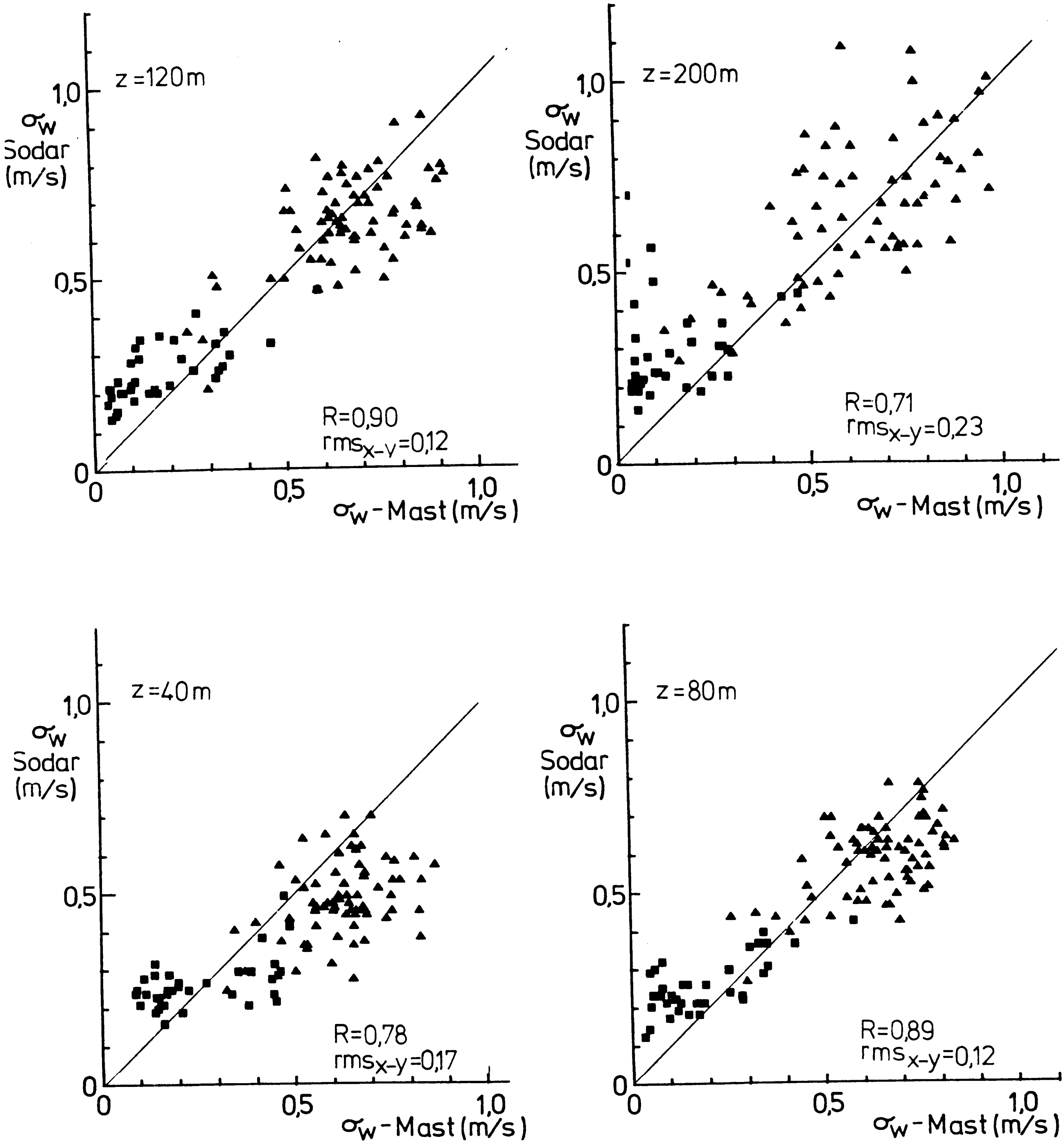


Fig. 12. The standard deviation of vertical velocity measured with Doppler Sodar (FFT-version) in comparison with Trivane data. Situations with positive (▲) and negative (■) surface heat flux are distinguished. These are half hour averages obtained in August 1983 at Cabauw.

The standard deviation measured by sodar is compared with trivane measurements in Fig. 13. In general the sodar overestimates the σ_{DD}-values. Still there is a reasonable correlation.

Finally the scattering intensity C_T is compared with surface heat flux H_0 for convective situations. Since the free convection relation $C_T \sim H_o^{2/3} z^{-2/3}$ is expected, the scatter plots are presented in this way (cf. fig. 14). A weak correlation is found, but the constant of proportionality decreases with height. This is due to attenuation of sound waves with distance. Attenuation is related to humidity according to Neff (1975). Therefore only the lowest measuring levels can be used for H_0-estimation, because here the influence of attenuation and humidity is small.

The scattering intensity is most commonly used to determine inversion height which is usually defined as the position of a sharp decrease of C_T (the border of a black area on the classical facsimile record). A plot of C_T profiles as function of time is given in figure 15. The inversion layers are determined by means of subjective interpretation.

It is important to note that by taking half hour averages, a lot of information is lost. For inversion height measurements, the classical facsimile recorder gives more information than the averaged C_T profiles. Extension of the present Doppler Sodar with a facsimile recorder would improve the determination of inversion height and the classification of atmospheric phenomena (convective plumes, nocturnal boundary layers, elevated inversions).

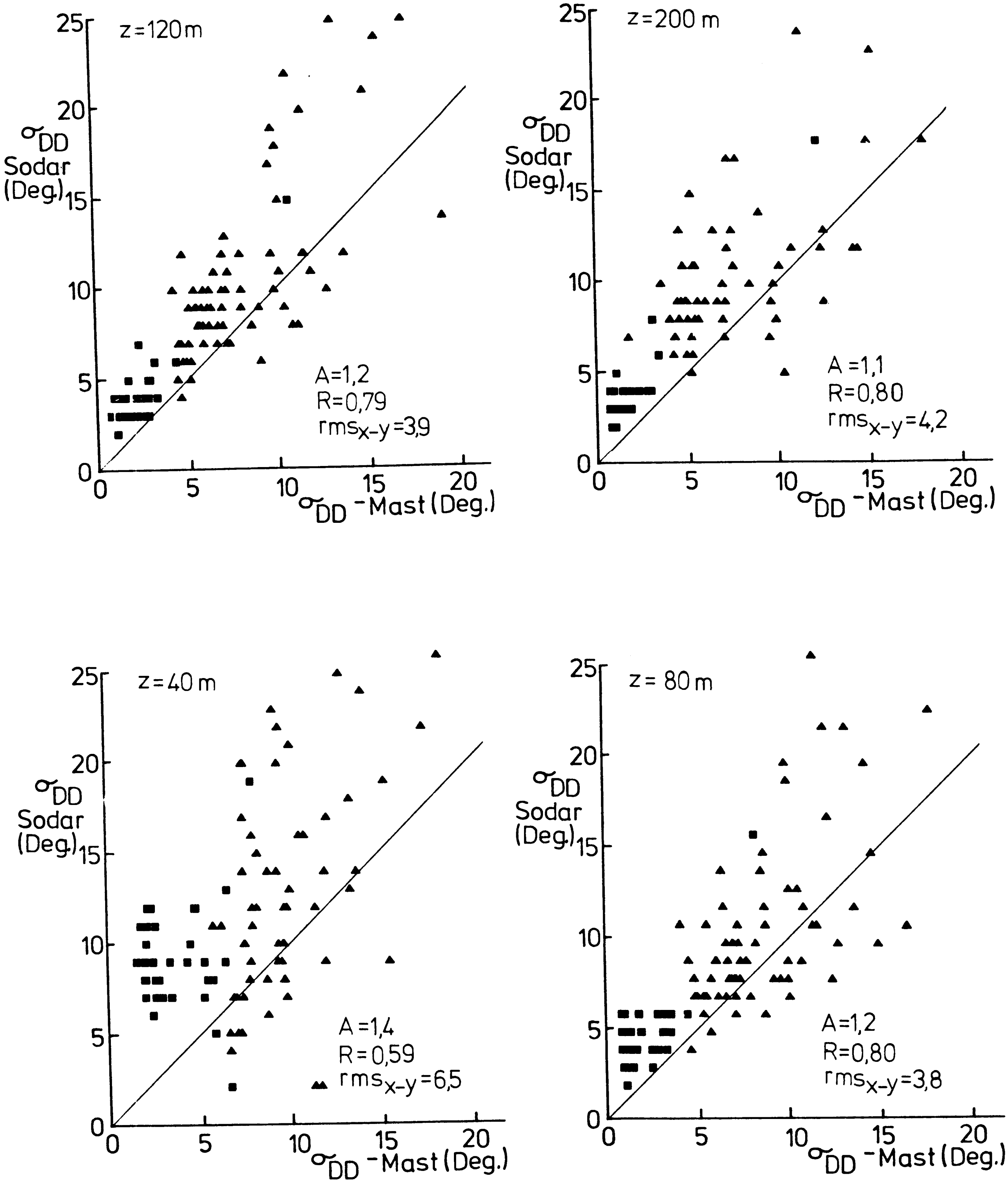


Fig. 13. Standard deviation of wind direction as measured by Sodar (FFT-version) in comparison with Trivane measurements. Measurements were done in August 1983.

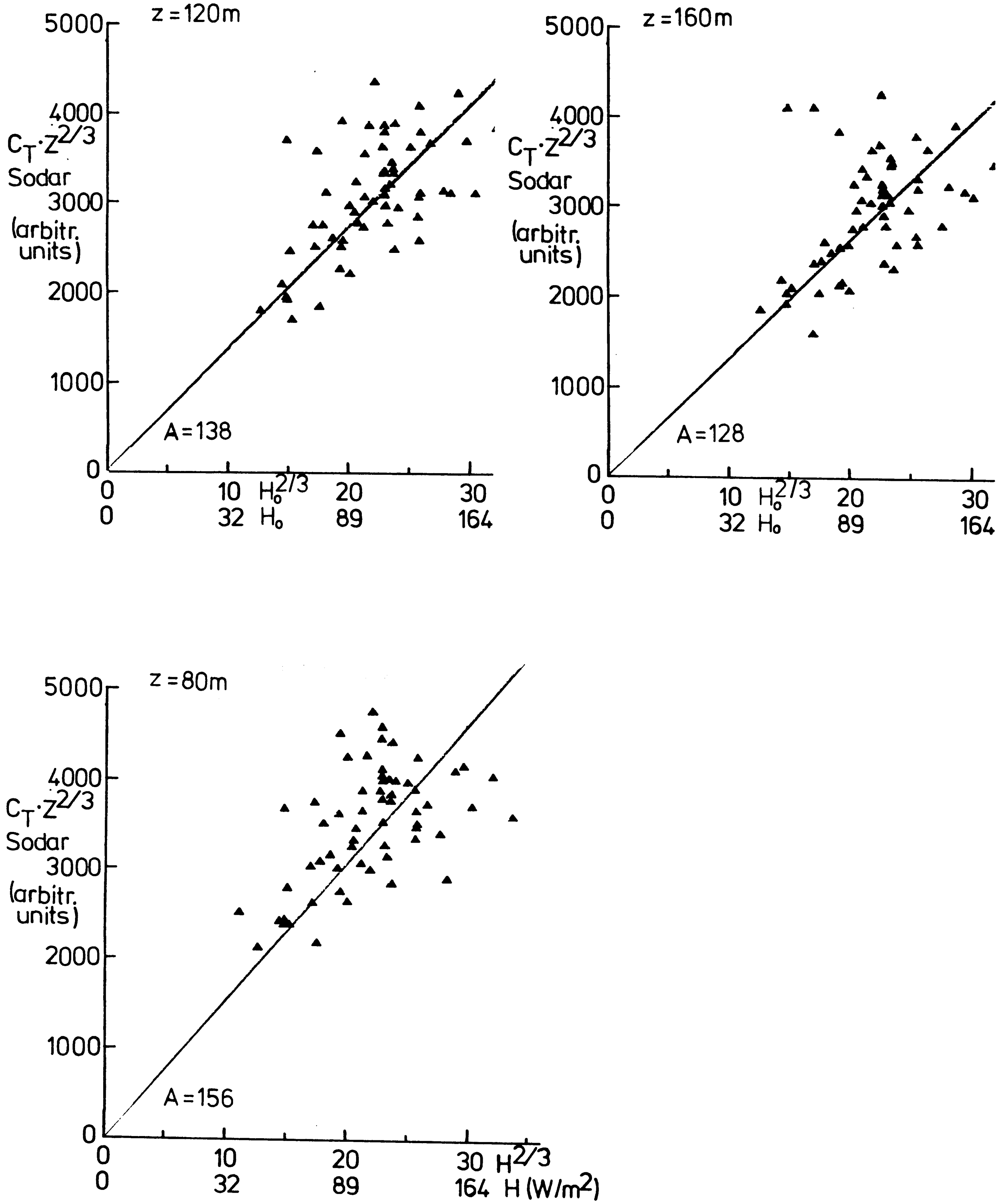


Fig. 14. Experimental check of the convective scaling relation $C_T=A.H_o^{2/3}z^{-2/3}$. The surface heatflux H_o has been determined by eddy correlation at 20 m height. The structure function C_T has been measured by Sodar. The empirical factor A turns out to decay with height. This is due to attenuation of sound.

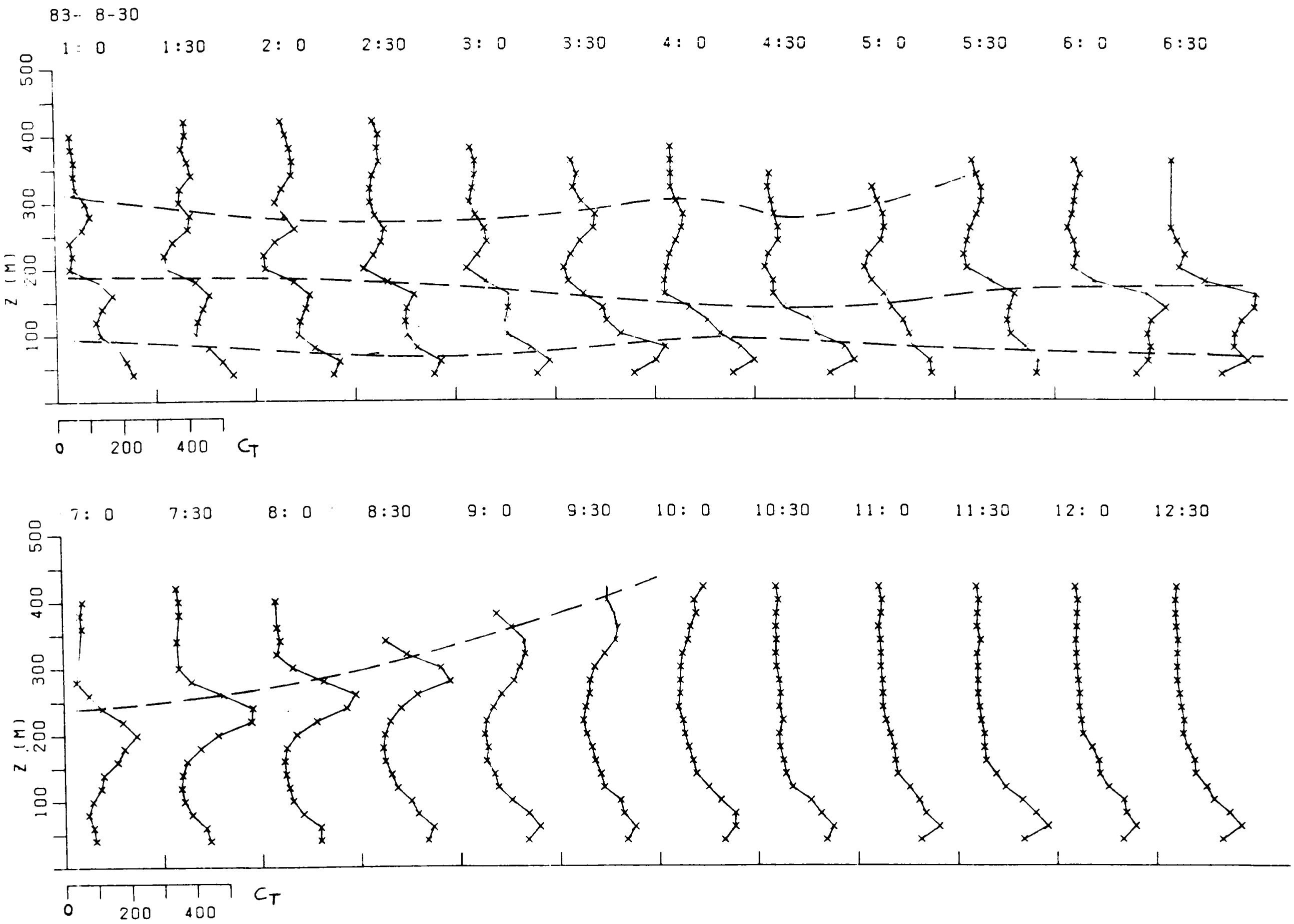


Fig. 15. Reflectivity as function of height for a 12 hour period. The dashed line is an interpolation by hand of the regions of steep gradients. These can be interpreted as inversion heights.

4. Conclusions

In this report, measurements with the commercial Remtech Sodar have been compared with tower measurements. Since the Sodar software is still developed further, these results should be seen as the state of the art in 1983. For example the routine that adapts emission frequency as function of temperature has not yet been tested. According to the manufacturer this routine should improve the antenna characterics and therefore reduce fixed echo problems. Also the newest antenna foam has not yet been tested in a comparison experiment.

Our findings with this sodar can be summarized as follows:

- Wind measurements have an accuracy of the order of 1 m/s. The R.M.S. difference of the horizontal wind components between Sodar and tower measurements is about 1 m/s.
- The height range strongly depends on circumstances. Wind measurements almost always go up to 200 m during night time and up to 500 m during the day. Strong winds (more than 15 m/s) and rainy weather (more than 1 mm/hour) reduce the height range to zero.
- Inversion height can be determined on the basis of echo intensity. Some information is lost however with respect to facsimilê recordings. For inversion height measurement and diagnostic purposes, it is useful to branch a facsimilê to the Sodar.
- Good siting of Doppler Sodar is very important. Obstacles or trees in the direct surroundings deteriorate in general the measurements. Although the software eliminates fixed echos, it is better to avoid them because the fixed echo software also reduces the number of samples. If possible, obstacles should be avoided between 50 and 200 m away from the antennas.
- Doppler Sodar results strongly depend on siting and weather conditions. To see how Doppler Sodar behaves as all weather instrument a systematic test over at least one year would be necessary.
- In spite of the rather large measuring volume, the measurement of the standard deviation of the vertical velocity component behaves quite well.
- The standard deviation of wind direction is measured rather poorly. The campaign with convection during the day and clear nights gave some correlation.

- Echo intensity relates to the surface heat flux according to convective scaling relationship. It can be used as a crude estimite for this in convective situation.

In general it can be concluded that Doppler Sodar is useful tool to determine important boundary layer parameters as: boundary layer wind, inversion height and turbulence intensity. Accuracy and height range depend on weather conditions and citing. It has been proved already that Doppler Sodar is a very useful tool in boundary layer research (for example meso scale experiments) in particular because it can be moved very easily. Time has come now to test Doppler Sodar as an operational instrument in all weather conditions, for example in a network.

Appendix A Deflection of sound beams

In the software of the Remtech Sodar a correction is applied for the deflection of sound waves in a wind gradient (according to Spizzichino, 1972, 1974). This correction is based on the assumption that the sound beam is emitted in the direction of the antenna axis (direction θ_o). The backdiffused sound that arrives at the antenna follows a different pattern which implies that the measured velocity vector has angle $\theta_o + \delta$ instead of δ (cf. fig. A.1).

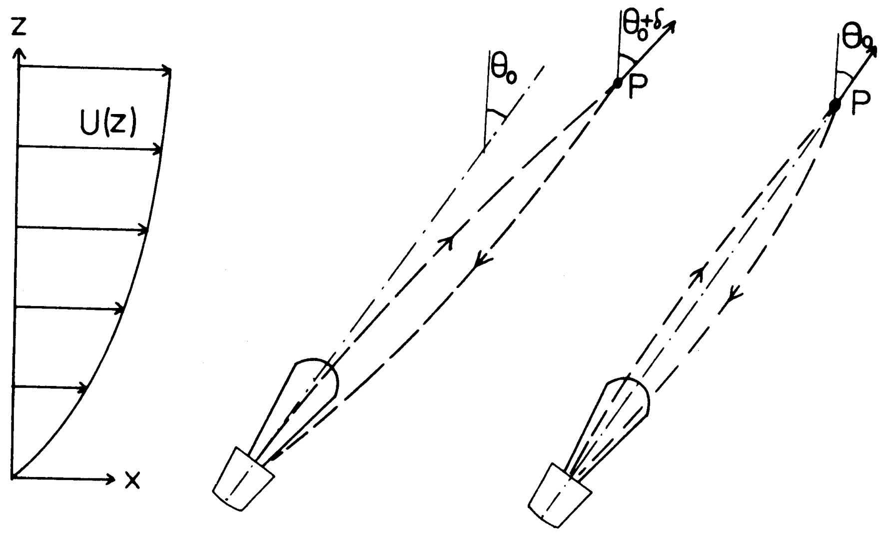


Fig. A.1 Deflection of the sound beam in a wind gradient. The dashed lines give two examples of rays that are emitted. The return of the ray in the left hand figure is the one that is considered by Spizzichino but is (in this example) outside the reception curve (solid line) of the antenna. The ray of the right hand figure contributes to the received energy.

This is only applicable when the emitted beam is very narrow and the receiver has a sufficiently wide angle to receive the backscattered sound. This is not the case in the left hand example of fig. A.1.

For a monostatic sodar where emitter and receiver are equal, the situation is quite different. We have to integrate over all emitted rays. Symmetry between emission and reception implies that the effective scattering volume is on the axis of the antenna. This makes that the correction is zero and should not be applied for a monostatic sodar.

Appendix B The effect of volume averaging on turbulence measurements

The σ_w-measurements as done by Doppler Sodar are influenced by a number of filtering effects. One of these effects is smoothing due to the finite dimensions of the measuring volume. At a height of 100 m the measuring volume is about 20 m wide and for the standard on emission pulse length about 30 m high. All small scale fluctuations inside this measuring volume are smeared out and will not contribute to the variance of the velocity samples. They will contribute, however, to the spectral broadening of the backscattered sound.

Let us assume that we know the spectrum of w as a function of the wave vector in the mean wind direction

$$F_w(k_x) = \int_{-\infty}^{\infty} R_w(x)\, e^{ik_x x}\, dx \;.$$

Where $R_w(x) = \overline{w(x_o)\, w(x_o + x)}$
In fact $R_w(x)$ is a lateral correlation function.

Since we average over a volume and we want to investigate the effect of this averaging, we need the three dimensional spectrum for this.

The effect of averaging can be expressed by means of convolution, where $h(\underline{r})$ indicates the measuring volume:

$$w'(x) = \int_V w(x-\underline{r})h(\underline{r})d\underline{r}$$

This is equivalent to a multiplication in the $\underline{k}$-vector domain

$$E'_w(\underline{k}) = E_w(\underline{k})H(\underline{k})$$

where

$$H(\underline{k}) = \| \int_V k(\underline{r})\, e^{i\underline{k}\cdot\underline{r}}\, d|\underline{r}| \,\|^2$$

Unfortunately we have no experimental information on the three dimensional spectrum. To transform from 1 to 3 dimensions and vice-versa we can use the so called isotropic relations, which is acceptable in the high frequency range far from the production scales. Also the filtering by finite measuring volumes will always take place at the high frequency side. To keep the problem isotropic we can only consider sphere symmetric scattering volumes which means that $k(\underline{r})$ depends only on (r). This implies that we can limit ourselve to the E(k) spectrum which is the three dimensional spectrum integrated over a sphere. This is only possible when H(k) depends on k only and not on the individual components.

We can write now:

$$E'(k) = E(k)\ H(k) \text{ where } k = (k_x^2 + k_y^2 + k_z^2)^{\frac{1}{2}}$$

An empirical spectrum for $E_w(k_x)$ can be used and interpreted as a lateral one dimensional spectrum. Transformation to a three dimensional spectrum, application of the formula above and backtransformation leads to a filtered one dimensional spectrum $E_w'(k_x)$.

Simple integration from 0 to infinity indicates the loss of variance by means of filtering.

The transformations from the one dimensional lateral spectrum $F_w(k_x)$ to the three dimensional spectrum E(k) and vice-versa read (Hinze, 1975)

$$F_w(k_x) = \frac{1}{2} \int_{k_x}^{\infty} \frac{E(k)}{k} \left(1 + \frac{k_x^2}{k^2}\right) dk$$

$$\frac{\partial}{\partial k}\left(\frac{E(k)}{k}\right) = \frac{1}{k} \frac{\partial F_w(k)}{\partial k} - \frac{\partial^2 F_w(k)}{\partial k^2}$$

of $$\frac{E(k)}{k} = - \int_{+k}^{\infty} \left\{\frac{1}{k_x} \frac{\partial F_w(k_x)}{\partial k_x}\right\} dk_x - \frac{\partial F_w(k)}{\partial k}$$

What we have to do now is to multiply E(k) by a filter H(k) corresponding to a measuring volume and transform back to $F_w(k_x)$. Since this leads in general to unmanagable integrals we limit to a very simple filter namely:

$$H(k) = 1 \text{ for } \|k\| < k_u$$
$$H(k) = 0 \text{ for } \|k\| > k_u$$

Backtransformation reads

$$F'_w(k_x) = \tfrac{1}{2} \int_{k_x}^{k_u} \frac{E(k)}{k} \left(1 + \frac{k_x^2}{k^2}\right) dk \qquad k_x < k_u$$

$$0 \qquad k_x > k_u$$

$$= \tfrac{1}{2} \int_{k_x}^{k_u} \frac{E(k)}{k}\, d\left(k - \frac{k_x^2}{k}\right)$$

$$= \tfrac{1}{2} \frac{E(k_u)}{k_u} \left(k_u - \frac{k_x^2}{k_u}\right) - \tfrac{1}{2} \int_{k_x}^{k_u} \left(k - \frac{k_x^2}{k}\right) \frac{\partial}{\partial k} \left(\frac{E(k)}{k}\right) dk$$

$$= \tfrac{1}{2} \frac{E(k_u)}{k_u} \left(k_u - \frac{k_x^2}{k_u}\right) - \tfrac{1}{2} \int_{k_x}^{k_u} \left(k - \frac{k_x^2}{k}\right) \left[\frac{1}{k} \frac{\partial F_w(k)}{\partial k} - \frac{\partial^2 F_w(k)}{\partial k^2}\right] dk$$

$$= \tfrac{1}{2}\left(\frac{E(k_u)}{k_u} + \frac{\partial F_w(k_u)}{\partial k_u}\right)\left(k_u - \frac{k_x^2}{k_u}\right) + F_w(k_x) - F_w(k_u)$$

$$F'_w(k_x) = F_w(k_x) - F_w(k_u) - \left(k_u - \frac{k_x^2}{k_u}\right) \tfrac{1}{2} \int_{+k_u}^{\infty} \frac{1}{k_x} \frac{\partial F_w(k_x)}{\partial k_x}\, dk_x.$$

De laatste integraal betreft altijd het -5/3 gebied. Hier vervangen we F_w door

$$\frac{F_w(k_x)}{F_w(k_u)} = \left(\frac{k_x}{k_u}\right)^{-5/3}$$

$$\int_{-k_u}^{\infty} \frac{1}{k_x} \frac{\partial F_w}{\partial k_x}\, dk_x = \int_{+k_u}^{\infty} \frac{1}{k_u} F_w(k_u) \cdot \left(-\frac{5}{3}\right) \left(\frac{k_x}{k_u}\right)^{-5/3} d\left(\frac{k_x}{k_u}\right)$$

$$= \frac{F_w(k_u)}{k_u} \left(-\frac{5}{3}\right) \int_{k_u}^{\infty} d\left(\frac{k_x}{k_u}\right)^{-2/3} \left(-\frac{3}{2}\right)$$

$$= \frac{F_w(k_u)}{k_u}\, \frac{5}{2}\, (-1) = -\frac{5}{2} \frac{F_w(k_u)}{k_u}$$

$$F'_w(k_x) = F_w(k_x) - F_w(k_u) + \frac{5}{4}\left(1 - \frac{k_x^2}{k_u^2}\right) F_w(k_u).$$

$$= F_w(k_x) + F_w(k_u)\left(\tfrac{1}{4} - \tfrac{5}{4}\frac{k_x^2}{k_u^2}\right) \qquad \text{for } k_x < k_u$$

$$= 0 \qquad \text{for } k_x > k_u$$

The rectangular filter $k(x) = \frac{1}{L_x}$ for $-L_x < x < 0$

$= 0$ for $x < -L$

$x > 0$

leads to $H(f) = \left(\frac{\sin \frac{k L_x}{2}}{\frac{k L_x}{2}}\right)^2$

We will take the first zero for k_m, which implies $k_u = \frac{2\pi}{L_x}$.

The relative error that will be observed in w'^2 due to volume averaging is

$$E_r = \frac{\int_o^\infty F_w'(k_x)dk_x}{\int_o^\infty F_w(k_x)dk_x} = \frac{\int_o^{k_u} F_w(k_x)dk_x + \int_o^{k_u} F_w(k_x)\{\tfrac{1}{4} - \tfrac{5}{4}(\frac{k_x}{k_u})^2\}dk_x}{\int_o^\infty F_w(k_x)dk_x}$$

We now adopt the universal form of the spectrum as proposed in Caughey (p. 148, 1981) with the peak wave number k_m as characteristic parameter for the quantity α.

$$\frac{k_x E_\alpha(k_x)}{\sigma_\alpha^2} = \frac{0.643\,(k_x/k_m)}{1 + 1.501\,(k_x/k_m)^{5/3}}$$

For unstable cases: $2\pi/k_m = 6\,z \qquad z/z_i < 0.2$

$= 1,2\,z_i \qquad z/z_i > 0.2$

(cf. Caughey, 1981, fig. 4.7).

For the stable cases $\frac{2\pi}{k_m z_i} = \frac{z}{z_i} \rightarrow k_m = \frac{2\pi}{z}$

(cf. Caughey, 1981, fig. 4.35)

Calculation of E_r on the basis of the spectrum above lead to

$$E_r = 1 - 0.714\,(k_u/k_m)^{-2/3}$$
$$= 1 - 0.714\,(2\pi/L_x k_m)^{-2/3}$$

where L_x is the dimension of the scattering volume.

For a beam with a width of 10° we obtain $L_x \simeq 0.175\ z$.
For the unstable and stable cases this results in:

$E_r = 0.90$ for	$z/z_i < 0.2$	unstable
$= 1 - (0.147\ z/z_i)^{2/3}$	$z/z_i > 0.2$	unstable
$= 0.69$		stable.

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