

CHAPTER 6 : SODAR Measurements

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6.1 Introduction to SODAR

Wind turbine technology has developed very rapidly over the past 20 years. One of the eye-catching consequences is the enormous increase in size of wind turbines. E.g., in Germany the *average* rated power per wind turbine installed in the year 2000 is nearly 1 MW. The hub height of MW-size wind turbines ranges from 70 to over 100 m, with rotor diameters ranging from about 65 m to 80 m. For design specifications there is a need to know the wind characteristics over the whole rotor diameter. Upscaling the wind turbines this corresponds to the layer between 60 m and 140 m. However, the costs of erecting a wind measurement mast of sizes over 30–40 m increase progressively with height, so the need for cheaper measurement techniques starts to arise. A very promising alternative for mast measurements is by making use of a (mini-)SODAR. This has been explored within the POWER-project to study the wind characteristics of the coastal zone. Some of the preliminary results have been reported [Coelingh et al. (1999)] and [Coelingh et al. (2000)]. The basic measurement principle of the SODAR will be explained in the next paragraph (for an overview also see [Crescenti, G.H.(1997)]).

6.2 Basic description of SODAR measurement principle

The acronym SODAR means **SO**und **D**etecting **A**nd **R**anging. In the case of the Aerovironment 4000, the basic principle is as follows (although, slightly different techniques are sometimes being used by other manufacturers) : A sound beam is emitted in an upward direction. Part of the signal is reflected off temperature inhomogeneities in the air. The reflected signal is then detected again by a microphone. The duration between emission and detection is indicative for the vertical distance (height) the reflected signal represents (as we know the speed of sound). The Doppler shift of the signal is a measure for the wind speed. Because one cycle consists of three beams under angles of 16° a three dimensional vector is being measured. The signal is then decomposed into the two horizontal directions and the vertical. The working frequency of the signal can be set by the user, but is usually 4500 Hz. The sampling frequency is about 1 Hz, so one cycle of three beams takes about a period of 3 s.

6.3 Features of SODAR measurements

SODAR can be used to measure the component of the wind speed in the direction of the sound beam, and thus is a wind measurement device with several distinctive advantages over conventional cup anemometry. First, it is easy to install and does not require any permits. Apart from the sound produced by the outgoing pulse no hindrance is being posed by a SODAR. The only requirements are a flat and stable surface, power supply (either by connection to the grid or a stand alone system with batteries), and (optional) a telephone connection for remote operation (either by a cable or by GSM).

Depending on the specifications of the different models from several manufacturers (mini-)SODARs can measure wind speeds up to several hundreds of meters, with a vertical resolution of 5 to 20 m and a minimum height of 10 to 30 m. The distinction between a mini-SODAR and a SODAR is the working range: a SODAR works up to the region of a km, with a resolution of hundreds of meters. They have been in use for a long period near air fields and nuclear plants. Their main function is to monitor the wind characteristics in the upper air (compared to near the surface) for either ascending and descending aeroplanes or the dispersion of plumes of nuclear material in case of accidents.

In recent years the specifications have been adapted to suit e.g. the wind energy industry with higher vertical resolutions and a lower maximum height (higher than 200 m is hardly of interest for wind energy purposes anymore). Experiences with mini-SODARs, particularly for wind energy purposes, are scarce, but increasing fast. Generally, two types of applications are of interest: one is for wind turbine manufacturers, the other is for wind project developers. The first group needs to make measurements on operating wind turbines, the second group also as part of site assessment.

The costs of operating a SODAR are mainly capital costs and labour costs for installation and removal, and also for data analysis. In contrast, costs for anemometer mast are also costs for equipment to install and remove (high) masts from a site.

Depending on the manufacturer and the model, SODARs may weigh in the order of 100 kg, and can easily be transported in a van and installed by hand by a few people within hours.

The disadvantages of a SODAR are that it is not possible to calibrate them as cup anemometers. It is not possible to put a SODAR in a wind tunnel and thus obtain a calibration curve. However, as experience is being gained with this relatively new technique more and more evidence from field experiments become available with which the results increase in quality.

6.4 Description of Aerovironment 4000

The Aerovironment 4000 mini-SODAR as used in this project is a phased-array type system. Its default operating frequency is 4500 Hz, corresponding to a wave length of about 8 cm. Several parameters can be adjusted by the user, and need to be optimised for the specific experimental conditions. E.g., the averaging time was set to 10 minutes, the vertical resolution to 5 m and the maximum height range to 200 m. The minimum height is 15 m. The system consists of an acoustic antenna, an Acoustic Signal Processor (ASP), and a computer for data storage. By using a (GSM-)modem data can be transferred to enable remote control operation. To shield the signals from ambient noise and to increase the signal-to-noise-ratio the an encasing is present, which extends to over 2 m by the hinging cuffs.

6.5 SODAR measurement campaigns

Within the POWER project three sets of SODAR measurements were performed:

- *SODAR trials at Petten (The Netherlands).*
Equipment trials were carried out by staff from Ecofys in collaboration with ECN and gave the project staff valuable experience in setting up the SODAR system and performing the measurements as well as enabling them to set up quality control and analysis systems for the observations. Full details are available in a separate report [Dam, J.J.D. van and E.J. van Werkhoven (1999)].
- *Measuring Post Noordwijk (9km off the coast of The Netherlands)*
These are the measurements used to help validate the Coastal Discontinuity Model (see Chapter 5). This work was performed by Ecofys staff and is described in Section 6.6.
- *Weybourne (UK)*
SODAR data was measured at a coastal site in eastern England by staff from UEA. This work is reported in Section 6.7

6.6 SODAR measurements at Measuring Post Noordwijk (MPN)

6.6.1 Introduction

The location MPN is an offshore platform located 9 km off the Dutch coast (see Figure 6-1). The platform is owned and operated by the Public Works Department (Rijkwaterstaat), Directie Noordzee. Permission was obtained to set up the SODAR at MPN, which was installed in January 2000.

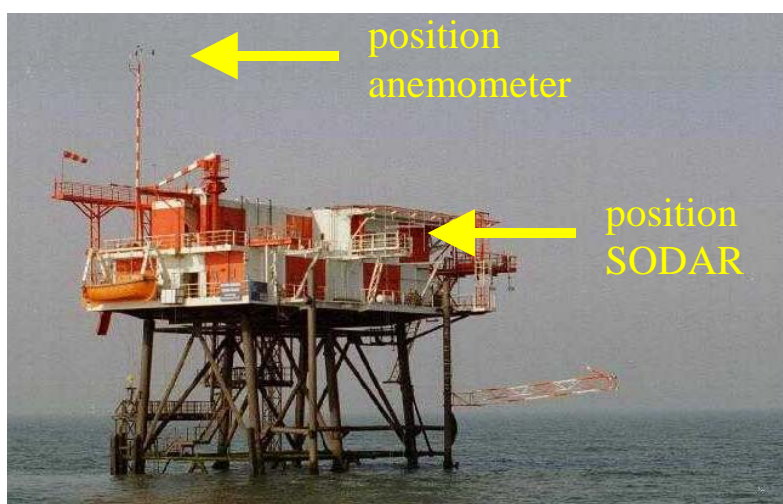


Figure 6-1: MPN platform located in the North Sea 9 km off the coast; the positions of the anemometer and of the SODAR (not installed yet) have been indicated (photograph courtesy of OCN, Delft, The Netherlands).

After initial measurements without the cuffs (see Figure 6-2), on February 23 2000 the measurements were started that were of suitable quality. The end date was June 15 2000, so about 4 months of observed data have been gathered for the validation of the CDM.



Figure 6-2: SODAR located at MPN as seen from below (without cuffs).



Figure 6-3: SODAR located at MPN as seen from above (with cuffs).

The SODAR is situated at a small platform about 15 m above MSL, which is at the level 3 m below the helicopter platform (for illustration see Figure 6-3 and Figure 6-4). This is not ideal due to possible acoustic reflections, and flow distortion by the build-up of the platform itself. However, suitable locations are restricted at the platform so there was no alternative available.



Figure 6-4: SODAR located at MPN as seen from the side (with cuffs).

6.6.2 Data processing and software

For each averaging period, the SODAR software (Doplmain) produces a so-called wind table. This is a standard output file that forms the basis for further analysis and will be explained further. For data analysis purposes, a vector with (wind speed) data is far more desirable than the wind table format. The supplier of the SODAR provides a computer programme called PADS that is able to convert wind tables to time series to be described in further detail. As this software tool did not fulfil our requirements, we decided to build a conversion software tool ourselves. Before building such a tool, the output has to be understood completely. In the final section, the features of the developed software package are described.

Wind tables

An example of a wind table produced by the SODAR software is shown in Figure 6-5. The header of the wind table contains information on date and time of the observation period and it shows the actual parameter settings of the SODAR. The meaning of each setting is given in the Doplmain manual [Aeronvironment (1998)]. Below the header, a matrix is printed. Each line gives information about one specific height including the horizontal wind speed and direction, the wind speeds split in three orthogonal directions (u and v in the horizontal plane, w the vertical direction), the number of measurements per component, the intensity of the returned signal, the signal-to-noise ratio per component and the observed gust wind speed and direction. After each day all wind tables are written to a text file (yymmddv.dat) on the PC connected to the ASP.

MPN	06/13/2000 17:30:04 TO 06/13/2000 17:40:03 VR4.56 4500 800 100 50 10 0 0										3 COMPONENT 39HTS ZENITH 16-16 ARA 000 SEPANG 090 MXHT 40 UNOISE 127 VNOISE 220 WNOISE 143 ANTENNA STATUS: OK AC									
HT	SPD	DIR	W	SDW	IW	GSPD	GDIR	U	SDU	NU	IU	SNRU	V	SDV	NV	IV	SNRV	NW	SNRW	
200	99.99	9999	99.99	99.99	15	99.99	9999	99.99	99.99	0	13	2	99.99	99.99	0	23	3	0	2	
195	99.99	9999	99.99	99.99	15	99.99	9999	99.99	99.99	0	12	2	99.99	99.99	0	23	3	0	2	
190	99.99	9999	99.99	99.99	14	99.99	9999	99.99	99.99	0	12	3	99.99	99.99	0	22	3	0	2	
185	99.99	9999	99.99	99.99	14	99.99	9999	99.99	99.99	0	12	3	99.99	99.99	0	22	3	0	2	
180	99.99	9999	99.99	99.99	14	99.99	9999	99.99	99.99	0	12	3	99.99	99.99	0	21	3	0	2	
175	99.99	9999	99.99	99.99	13	99.99	9999	99.99	99.99	0	11	3	99.99	99.99	0	21	3	0	2	
170	99.99	9999	99.99	99.99	13	99.99	9999	99.99	99.99	0	11	3	99.99	99.99	0	20	3	0	2	
165	99.99	9999	99.99	99.99	13	99.99	9999	99.99	99.99	0	11	3	99.99	99.99	0	19	3	0	2	
160	99.99	9999	99.99	99.99	12	99.99	9999	99.99	99.99	0	10	3	99.99	99.99	0	19	3	0	2	
155	99.99	9999	99.99	99.99	12	99.99	9999	99.99	99.99	0	10	2	99.99	99.99	0	18	3	0	2	
150	99.99	9999	99.99	99.99	11	99.99	9999	99.99	99.99	0	10	3	99.99	99.99	0	18	3	0	2	
145	99.99	9999	99.99	99.99	11	99.99	9999	99.99	99.99	0	9	2	99.99	99.99	0	17	3	0	2	
140	99.99	9999	99.99	99.99	11	99.99	9999	99.99	99.99	0	9	3	99.99	99.99	0	17	3	1	2	
135	99.99	9999	99.99	99.99	11	99.99	9999	99.99	99.99	2	10	3	5.57	0.25	4	17	3	1	2	
130	12.79	247	99.99	99.99	13	13.04	246	11.74	0.47	6	11	3	5.08	0.40	8	19	3	3	3	
125	12.14	246	0.04	0.37	19	14.62	239	11.09	0.45	25	15	4	4.95	0.56	23	24	4	25	4	
120	12.50	248	-0.16	0.32	28	15.80	244	11.55	0.45	58	22	6	4.78	0.37	37	28	5	54	6	
115	11.75	248	-0.08	0.36	38	15.24	242	10.88	0.45	74	30	8	4.45	0.33	61	37	7	82	8	
110	11.53	246	-0.07	0.39	49	17.92	232	10.53	0.37	113	40	10	4.69	0.35	83	44	8	113	10	
105	11.06	245	-0.06	0.37	54	14.58	238	10.04	0.38	123	45	12	4.64	0.38	97	47	8	121	11	
100	10.90	246	-0.10	0.36	53	14.96	246	9.96	0.37	136	45	12	4.42	0.39	100	46	9	120	11	
95	10.72	245	-0.09	0.35	47	14.17	228	9.75	0.39	137	41	12	4.45	0.36	95	42	8	125	11	
90	10.30	245	-0.10	0.36	41	14.53	249	9.36	0.37	134	38	12	4.31	0.33	91	36	8	130	11	
85	9.92	245	-0.12	0.36	37	14.41	236	9.00	0.36	132	34	12	4.17	0.33	79	30	7	128	10	
80	9.63	248	-0.11	0.31	31	14.12	236	8.93	0.35	127	30	11	3.61	0.31	74	27	7	114	10	
75	9.78	245	-0.11	0.30	30	13.55	235	8.85	0.34	129	28	11	4.16	0.36	87	27	8	115	10	
70	9.45	246	-0.06	0.35	28	14.25	243	8.61	0.35	124	25	11	3.89	0.35	79	25	7	119	10	
65	9.28	245	-0.07	0.34	25	14.28	243	8.43	0.35	116	23	11	3.87	0.36	80	23	7	119	10	
60	9.09	246	-0.04	0.33	22	12.75	246	8.29	0.35	125	21	11	3.74	0.32	73	21	7	110	9	
55	8.88	245	-0.05	0.34	20	12.78	233	8.04	0.31	128	19	11	3.76	0.38	72	20	8	105	9	
50	8.82	245	-0.07	0.35	19	13.11	248	8.03	0.35	125	17	10	3.66	0.34	71	18	7	105	9	
45	8.67	246	-0.05	0.37	17	12.31	233	7.92	0.37	125	16	11	3.53	0.35	76	15	7	113	10	
40	8.35	248	0.00	0.32	16	11.80	264	7.77	0.38	131	15	11	3.07	0.35	83	15	8	117	10	
35	7.92	254	0.00	0.32	16	16.47	220	7.62	0.36	141	13	12	2.17	0.46	119	17	9	136	11	
30	7.40	262	0.03	0.27	18	10.83	254	7.33	0.39	140	13	12	1.04	0.32	144	23	13	146	14	
25	7.45	261	-0.17	0.23	22	10.62	249	7.35	0.41	139	13	13	1.20	0.41	149	27	13	149	15	
20	7.67	260	-0.42	0.31	33	10.49	254	7.56	0.44	145	14	13	1.29	0.29	145	37	12	150	14	
15	5.54	274	-0.23	0.29	52	10.77	270	5.53	0.50	120	20	11	-0.40	0.55	133	45	11	143	15	
10	99.99	9999	99.99	99.99	128	99.99	9999	99.99	99.99	2	110	4	-2.83	0.13	151	200	10	0	3	

Figure 6-5: Example of a wind table as produced by the Doplmain SODAR software.

PADS

The Profiler Analysis and Display Software tool PADS is a custom made computer programme provided by the manufacturer Aerovironment that is able to convert wind tables to time series and perform some offline processing. Ecofys obtained a version of PADS in order to evaluate its performance regarding capabilities, user-friendliness. All of PADS' exporting features provide a time series of wind speeds and some user defined other quantities (like vertical wind speed, standard deviation per beam etc.). The programme can also display some typical output like

time series, wind profiles, histograms and wind roses graphically. Unfortunately, no clear description of the method of conversion is given in the manual of the software [Aeronvironment (1998a)]. Therefore it is unclear for which criteria data points were (in)validated and it was not possible to reproduce all of PADS calculated mean wind speeds. Apart from this, the version of the programme as made available to us was not very user friendly, rather slow and unstable. For these reasons, it was decided not to use PADS but to develop a specific software tool for our purposes. In this way, there is exact control over the offline processing method and adaptations can be made to preference. Besides, it is possible to define the format of the output (time series) and make it flexible. Such a flexible output file enables adding other relevant time series like rain, other wind speeds (from a nearby mast), air and water temperature to the SODAR data file. This makes further analysis of the data and adding model output results possible.

Input and output file formats

Before a conversion programme can be developed, relevant input and outputs have to be determined. In this case the input files consist of the wind tables as they are produced by the SODAR software Doplmain. The output files are being produced by the conversion programme and consist of files with time series of SODAR observations. Therefore a standard output file format was developed to store the SODAR data but also other (meteorological) data. This format enables the development of standard software to analyse the data. The requirements the format file had to fulfil were:

- flexibility in the number of quantities for which time series can be stored, including SODAR data and other quantities.
- date and time stamp referring to the observation period.
- listing of SODAR parameter settings, conversion settings and other relevant information with respect to the data during the specified observation period.
- file compatibility for easy use of Matlab and Excel.
- simple file manipulation.
- chronological file structure: all data referring to one interval have to be written to one line.
- fixed format: it has to be possible to derive the complete format (length, number of rows and columns, number of characters per quantity) from the information in the header.
- All information in one file has to refer to one location.

Based on these requirements it was decided to produce two text files for each data set: a data file with extension .wta (wind table array) and a log file with extension .log. The exact definition and an example of both data and log file are described in [Wiegerinck, G.F.M. and J.P. Coelingh (2000)].

The data file comprises the actual data: it consists of a header followed by a matrix with the data. In the header, the time of first and last interval written to the data file are shown, the averaging interval, the minimum and maximum height of which SODAR data are available, the SODAR height interval and the location the data refer to. A vector with ones and zeros indicates the quantities that are stored to the file. Above each column, an abbreviation indicating the contents of that column is also given.

The log file contains a header with the same information as the data file. In this file also the data source is stored (e.g. SODAR type) and the relevant measurement settings per period. In case of SODAR measurements, also the parameters used for offline processing are mentioned. In such a way, it is always clear in what way the original SODAR data has been processed.

MatLab routines

Several possible software environments exist suitable for programming the conversion programme like MatLab, Excel/Visual Basic and general environments like Turbo Pascal and C. Each environment was judged on relevant issues: the maximum number of measuring points, possibility to run the software under future operating systems, complexity of use, possibilities to extend the programme and the possibilities to import data from and to other applications.

Excel is generally known and is easy to use. It is very easy to import data from other applications. Major drawbacks are that Excel becomes extremely slow and unstable when a spreadsheet becomes large and the length of the time series is limited to 65536 intervals. MatLab does not have these drawbacks. It is less well known than Excel but detailed MatLab knowledge is not required once the tool is developed. The software is easy to extend. Importing other data is possible and can be standardised but is somewhat more difficult than importing data in Excel. (Note : Other environments like C and Pascal would be as suitable for this purpose as MatLab). As the analysis of the time series

will be performed by MatLab as MatLab is especially developed for working with matrices. Therefore, we have chosen to use MatLab for the conversion programme. The developed conversion programme will be discussed here in a global way. For detailed information the reader is referred to the manual [Wiegerinck, G.F.M (2001)] .

The Wind Table to Standardised AVerages file (WT2STAV) is able to convert wind tables to the standard file format from the previous section. At the start of the programme, the user can enter the desired start and stop date, averaging period and minimum and maximum height of the SODAR. The user can also set requirements on the percentage of data that has to be valid in order to produce a valid mean, the signal intensity, the signal-to-noise ratio, the standard deviation and the magnitude of horizontal and vertical wind speed. After that, the programme request the user to enter which quantities have to be written to the output file.

The software checks which wind tables are available within the entered period and checks whether the requested time and height resolution are possible. After that, per averaging interval the corresponding wind table(s) are determined. For each wind table, the data are (in)validated according to the user selected settings and if the set requirements are met, the average wind speed is calculated. For each interval, the mean values are written to a data file and a log file is composed from the input and observed problems. The programme turns out to be very stable but somewhat slow.

To analyse the SODAR data, also rain information and other meteorological quantities are of importance like wind speed and direction measured at a mast, water temperature and air temperature. Algorithms have been developed to convert these data to the standard format and add it to the file with SODAR data.

In MatLab, also standardised procedures were developed to analyse the data in a data file. This included procedures to read data from and write data to a file, select a specific period or quantity, add stability data . and procedures to make graphs and calculated mean wind speeds for the analysis as described in the next section.

6.6.3 Data analysis

According to the manufacturer's specifications the working range of the Aerovironment 4000 is between the heights of 15 m to 200 m, with a vertical resolution of 5m. An example of a time series measured by the SODAR at MPN is shown in Figure 6-6 over a period of just over 2 days. In this figure, the wind speeds at 15 m, 35 m, 55 m and 75 m with respect to the SODAR level are shown and for comparison also the wind speeds of the anemometer at 27.6 m (above MSL) sea level.

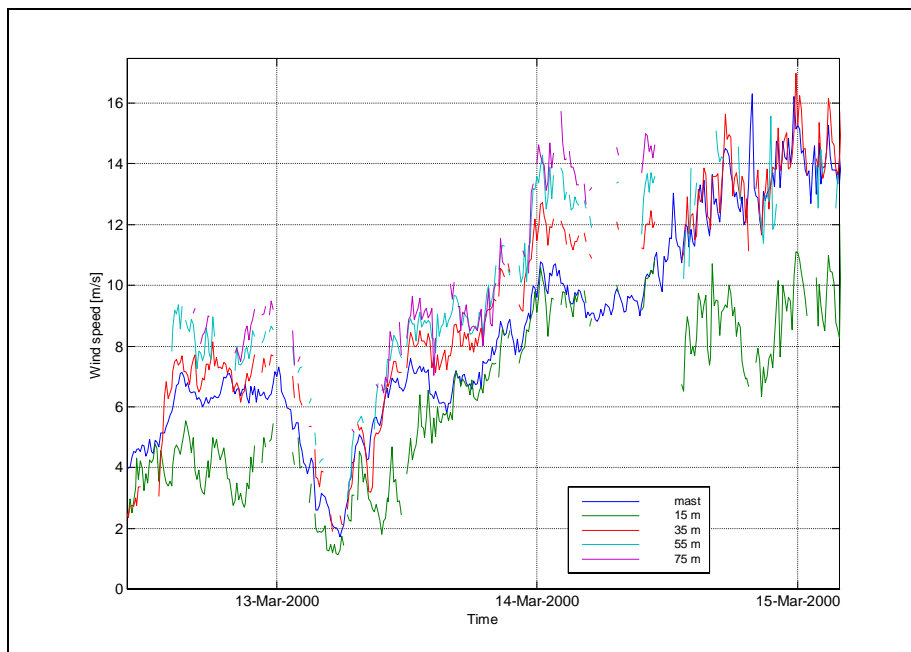


Figure 6-6: Time series SODAR measured wind speed, 15 m, 35 m, 55 m and 75 m above SODAR level.

It turns out from that for some periods, the wind speed measured by the SODAR is lower than the wind speed measured by the anemometer despite the higher height. Besides, the higher the height the lower the amount of data that is recovered. This is an intrinsic problem of SODAR: the intensity of the emitted pulse decreases with height because of absorption, scatter and increase of the area over which the beam propagates. Hence, the higher the

height, the larger the chance that the back scattered signal drowns in the back ground noise and the Doppler shift can not be determined. Figure 6-7 shows the percentage of recovered data as a function of the height relative to mean sea level.

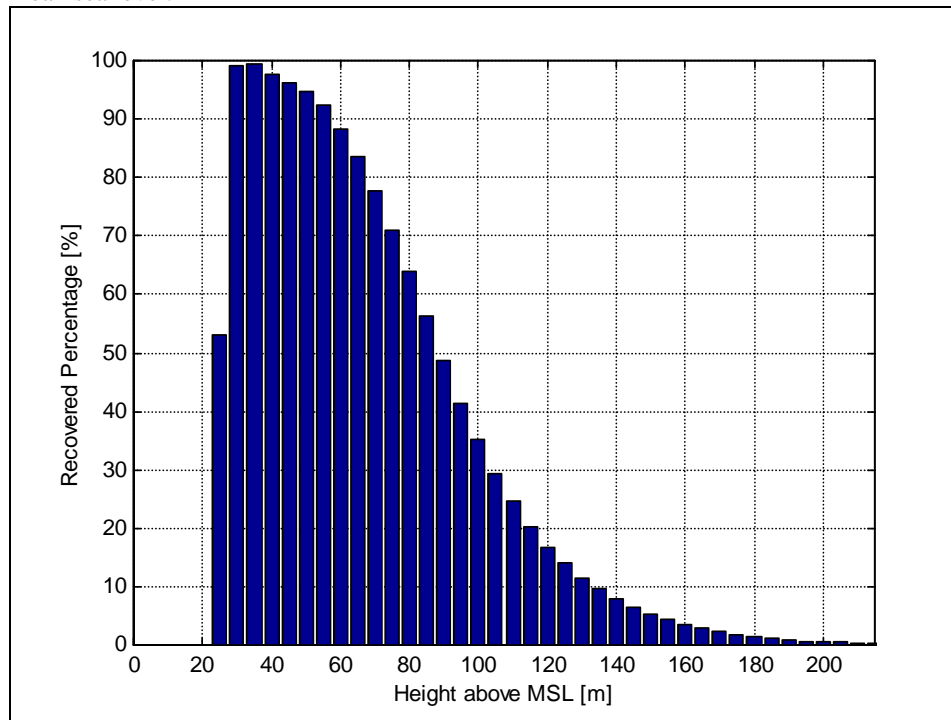


Figure 6-7: Recovered percentage of wind speed data as a function the height relative to mean sea level for the measurements at MPN from February 23 to June 16, 2000.

The height range of the SODAR at MPN is generally less than the height range the SODAR obtained at the ECN-terrain [Dam, J.J.D. van and E.J. van Werkhoven, (1999)]. Above 60 m, the availability falls more rapidly than at ECN. Low availability of data at larger heights may limit the usefulness of a SODAR because it deteriorates the quality of statistical analysis of the data. The best solution is of course to analysis the reasons for the worse performance and try to alleviate these in order to get better results. In addition, if it is understood under which circumstances results are poor theoretical modelling may help to add modelled wind speeds to replace missing or erroneous values. However, this last step may prove to be too complicated.

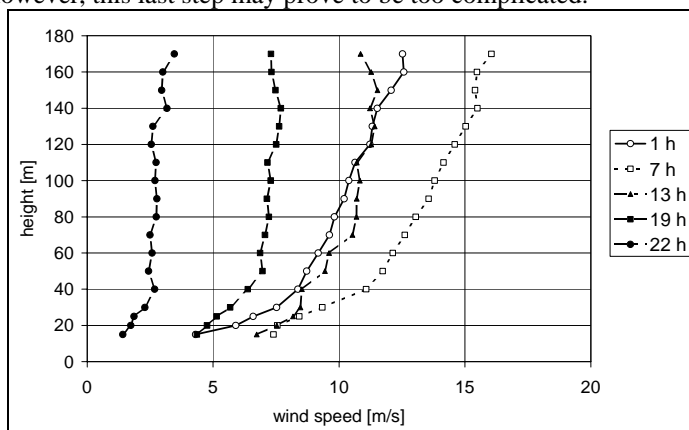


Figure 6-8: Wind speed profiles as measured with a SODAR on one day. The profiles shown are hourly averages.

One of the most powerful features of the SODAR is that wind profiles over a specific period can be determined. This gives detailed insight in phenomena that play a role in the boundary layer. Some examples of profiles averaged over one hour on one day are shown in Figure 6-8. The increase of the wind speed with height depends on stability of the atmosphere and roughness of the sea. At the moment, several theories exist, but until now it was not possible to *measure* complete profiles. Apart from the efforts to understand SODAR operation, in this chapter the SODAR measurements will also be compared to wind speeds calculated with the help of Monin-Obukhov similarity theory. The SODAR does not only measure wind speeds, but also produces quantities per height indicating the reliability of the measurement. This includes signal-to-noise-ratio, signal intensity and number of measurements within the aver-

aging period. It is a task for the user to select the criteria to (in)validate data. The requirements data had to fulfil in order to be valid for the measurement series at MPN are given in Table 6-1. These are the settings as advised by the supplier of the SODAR. The exact meaning of the requirements is explained in the manual of the conversion programme WT2STAV [Wiegerinck, G.F.M. and J.P. Coelingh, (2000)].

Table 6-1: Overview settings for offline processing SODAR data measured at MPN.

Description	Requirement
Number of accepted returns	$\geq 50 \%$
Intensity	> 4
Standard deviation	$\geq 0.02 \ \& \ \leq 10 \text{ m/s}$
Magnitude horizontal wind speed	$\leq 35 \text{ m/s}$
Magnitude vertical wind speed	$\leq 15 \text{ m/s}$
Signal-to-Noise ratio	≥ 2

Reliability and quality of SODAR data

The reliability and quality of the SODAR data is of importance. First, the problem of rain is discussed. After that, we try to identify the causes for the poor height range. With this knowledge in mind, measurements of SODAR and mast are compared with each other. The section concludes with a discussion on the reliability of the current SODAR set and recommendations for future measurements will be given. For the analysis, we will only focus on the measurements at MPN from February 23, 2000 until June 15, 2000.

Influence of rain

During the preliminary SODAR measurements at the ECN-terrain, it was found out that the SODAR does not always function well during rain. This is shown with the help of Figure 6-9 and Figure 6-10. In Figure 6-9, the 10-minute averages of the anemometer are plotted against the SODAR measured wind speed at 50 m height. The sector $110^\circ\text{--}230^\circ$ is excluded as in this sector mast and SODAR are situated in the wake of a wind turbine. Quite some points occur where the SODAR wind speed is too high. When periods with rain are also filtered from the data set (Figure 6-10) these points disappear and all points are more or less on a straight line.

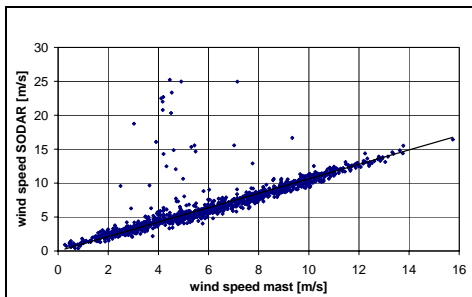


Figure 6-9: Mast wind speed versus SODAR wind speed at ECN, both at 50 m AGL including periods with rain. Wind directions from $110^\circ\text{--}230^\circ$ excluded.

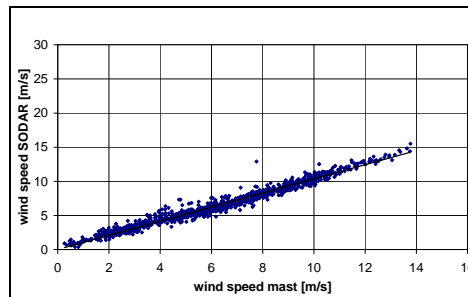


Figure 6-10: Mast wind speed versus SODAR wind speed at ECN, both at 50 m AGL. Points measured during rain and wind directions from $110^\circ\text{--}230^\circ$ excluded.

According to the supplier, the rain causes an additional (false) peak in the spectrum per height. The SODAR software searches the highest peak in the spectrum. From the corresponding frequency, the Doppler shift is determined and from that the wind speed at the specific height. So, in case the 'rain peak' is higher than the real signal peak, the wrong peak is taken to calculate the wind speed. The shape of the rain peak is more or less similar to that of the signal peak and hence the data is not invalidated by the SODAR software. The rain problem is more or less intrinsic to the SODAR principle of operation, probably depending on the frequency of operation. The supplier is currently looking for a software solution.

When looking to time series, it turns out that the SODAR performance is not disturbed during all rain showers. This probably depends on the fall down intensity of the rain: the higher this intensity, the larger the noise caused by rain. To overcome the rain problem, a rain detector was installed near the SODAR at MPN. For our further analysis periods of rain are excluded from the data set. The disadvantage of this is that also periods with good data are excluded.

Height range

A SODAR gives valuable wind profile information that can be used for a number of purposes. Unfortunately, for the measurements at MPN the recovered percentage of data decreases rapidly with height. This is a serious limitation in order to statistically analyse the data at the higher heights. Therefore, it is important to find out under what circumstances the SODAR performs well. Possible causes for the poor height range are back ground noise, the state of the weather and the magnitude of the wind speed.

First we will discuss the influence of back ground noise on the height range. After that, the influence of stability and wind speed is investigated even as other possible quantities that may play a role with respect to the SODAR height range.

Influence of background noise

A SODAR emits a pulse in a specific direction. Directly after that the SODAR records the returned signals. As explained in section 6.2, the time between emitting and receiving of the returned signal is a measure for the height. A fast Fourier transform algorithm is applied to the measured signal. In the obtained spectrum the band width with the largest signal intensity is determined and the corresponding frequency is used to determine the Doppler shift.

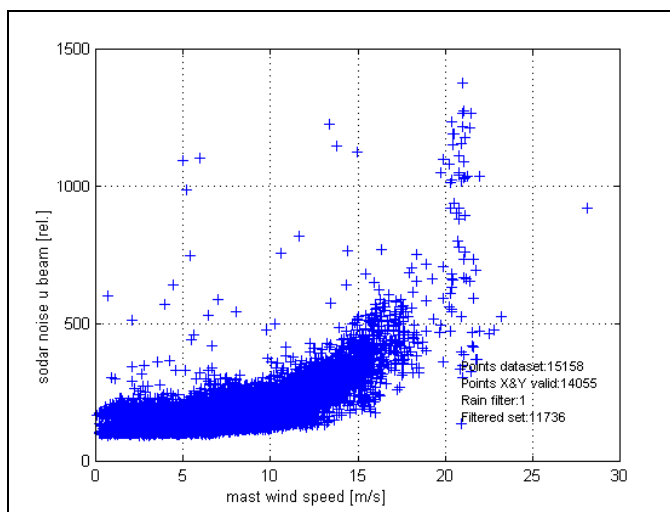


Figure 6-11: Scatter plot of wind speed versus observed back ground noise in the *u*-beam.

The signal intensity of the sent beam decreases with height because of scattering, absorption and spreading of the total signal intensity over an increasing surface. Hence, the signal reflected from high heights easily 'drowns' in the background noise, depending on the nature and frequency of that noise.

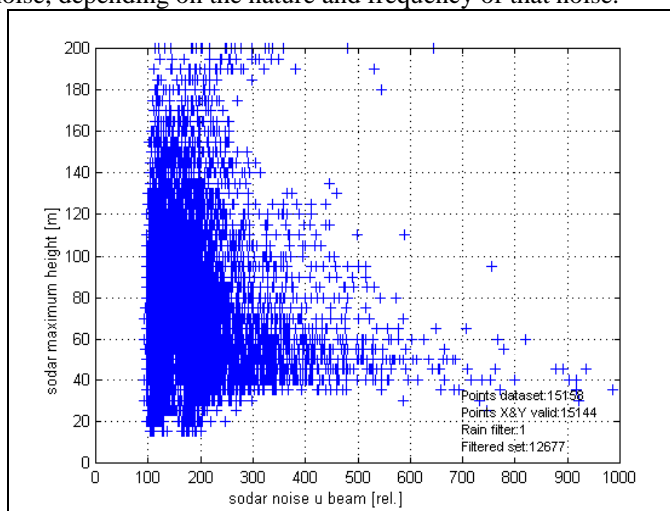


Figure 6-12: Scatter plot of noise level *u* beam versus the maximum height reached by the SODAR.

Sources of back ground noise are the noise produced by the diesel generator needed for electricity supply, noise of the waves and whistling of the wind around the superstructure of the platform. The noise produced by the diesel

generators is independent of the wind speed. The noise generated by the waves and whistling of the wind increases with the wind speed. In Figure 6-11, the noise observed by the SODAR u beam is plotted versus the mast wind speed. At low wind speeds, the noise of the beam does not go below a lower limit, most probably the noise produced by the diesel generators. Above roughly 7 m/s, the noise starts to increase with wind speed: the noise produced by waves and wind whistling around the superstructure of the platform drowns out the noise of the diesel generators. Similar patterns are observed for the v - and w -beam. The only difference is that the lower limit of the noise for the v -beam is significantly higher than for the other two beams. An explanation is that this is the beam that is sent along the diesel generators.

From the above described operation of the SODAR, one would expect that a higher back ground noise level results in a lower signal-to-noise ratio and hence the maximum height reached decreases. In Figure 6-12, a scatter plot of the noise of a beam versus the maximum height reached by the SODAR is shown. As expected, the maximum height decreases with increasing back ground noise level. When averaging the mean maximum height per noise 'bin', Figure 6-13 results. A clear decrease is observed. Similar plots are obtained for the other two beams.

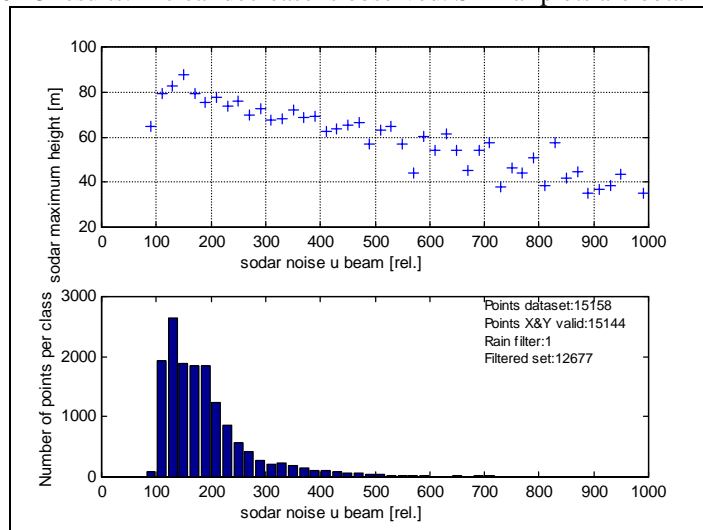


Figure 6-13: Noise of the u beam versus the maximum height of the SODAR

Hence, the back ground noise is a clear cause for the poor height range. However, because of the broad scatter in Figure 6-13 it appears that also other effects play a role.

To increase the height range, it is important to reduce the back ground noise as far as possible. A recommendation for future measurements is to position the SODAR on top of the platform. This would have the following effects:

- Less disturbance from diesel generators. On top of the platform, no sound from the diesel generators can be heard. Near the current position of the SODAR, one can clearly observe this noise. Hence, repositioning the SODAR to the top of the platform reduces the back ground noise level due to the diesel generators.
- No disturbance from reflections of the platform. At the moment, part of the sent beams is reflected by the superstructure of the platform. Positioning the SODAR on top will reduce this.
- The SODAR is positioned further away from the waves. A lower noise level may result.
- The SODAR is placed on a higher position with respect to mean sea level. This can be positive with respect to the availability of data at e.g. 100 m MSL but the wind speeds at low heights (until 30 m MSL) are not observed.
- In case the back ground noise only occurs in a limited frequency band, a shift in the frequency of operation may be helpful. It would be wise to analyse the frequency of the waves, diesels and floating of wind along the superstructure. When changing the frequency also other effects play a role. A lower frequency will result in a higher absorption rate and hence the signal intensity that returns to the SODAR decreases. Another frequency also implies another wave length and this may also affect the performance.

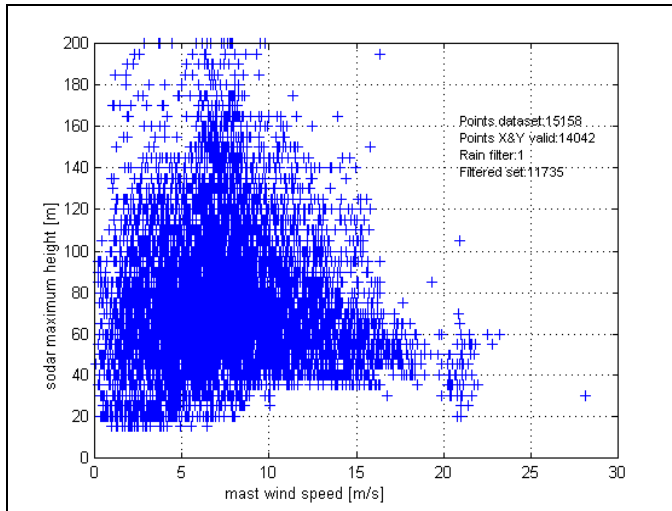


Figure 6-14: Maximum height reached by the SODAR relative to the SODAR level as a function of the mast wind speed at measuring height.

Influence of wind speed

From the previous section we know that there is at least an indirect relation between wind speed and SODAR height range: a larger wind speed causes a higher back ground noise level and hence a poorer height range. It is possible that wind speed also directly affects the height range. To investigate this, we made a plot of the mast wind speed versus the maximum height of the SODAR reached (Figure 6-14) Averaging this scatter plot per wind speed 'bin' of 1 m/s, Figure 6-15 results.

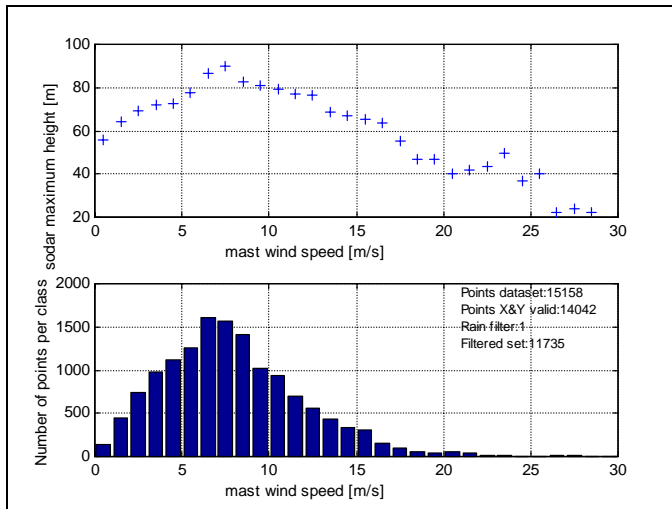


Figure 6-15: Average height reached by the SODAR per wind speed 'bin' of the mast.

For low wind speeds (< 7 m/s) the height reached increases with wind speed. For wind speeds higher than 7 m/s, the influence of noise as described above is clearly observed. The cause of the increase of the SODAR height range with wind speed is not clear. An option is that the stability of the atmosphere plays a role. The stability becomes in general important at low wind speeds which is an indication that both effects may be related.

Influence of stability

The stability of the atmosphere plays a major role for understanding the wind and temperature profile and may affect the height range of the SODAR. First of all, we will describe the several stability classes that occur and a way to parameterise the stability of the atmosphere. After that, the possible influence on the SODAR height range is discussed.

Calculation of the stability parameter:

A parameterisation of the stability does exist: the Monin-Obukhov length or stability parameter L . This parameter describes the ratio between mechanical vertical turbulence and thermal vertical turbulence. Mechanical turbulence occurs when in a rough terrain (e.g. a rough sea) the wind speed is high. By means of gust of wind, the air in the bottom tens of metres of the atmosphere is stirred intensively by movements on a very small and on a very large scale. This is caused by friction at ground level. Another cause for vertical air movements are air density differences. In case the air flowing over sea has a temperature lower than that of the sea water, the air density at the lower levels of the atmosphere will be smaller than that at higher level. Vertical mixing will occur. This is called convection or thermal turbulence. The scale of thermal turbulence is somewhat larger than that of mechanical turbulence.

Several stability classes occur: neutral, stable and unstable. In a neutral atmosphere, the mechanical turbulence is dominant. This occurs under relatively high wind speeds at ground level and under heavy cloud. The wind speed at a specific height depends solely on the roughness of the terrain and the geostrophic wind speed and can be described by a logarithmic profile:

$$u(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right) \quad (6.1)$$

Here, u (m/s) is the wind speed, u_* (m/s) the friction velocity, κ the dimensionless Von Karman constant, z (m) the height and z_0 (m) the roughness length.

For stable and unstable conditions, equation (6.1) does not hold anymore as also thermal aspects start playing a role. In an unstable atmosphere, the density of air does not decrease with height and vertical mixing results. By the vertical exchange of air also the horizontal wind speed of the air is exchanged. The exchange of wind speed downwards is very effectively and as a result, the wind speed near ground level is only slightly smaller than the wind speed at large heights.

Under stable conditions, the air density decreases with increasing height and hardly any vertical exchange of air occurs. In this case, a strong wind at higher heights can coexist with calm in the bottom tens of metres of the atmosphere.

In case of a stable or unstable atmosphere, the influence of thermal effects has to be included in equation (6.1), then

$$u(z) = \frac{u_*}{\kappa} \left[\ln\left(\frac{z}{z_0}\right) - \Psi\left(\frac{z}{L}\right) \right] \quad (6.2)$$

with Ψ the stability function and L (m) the Monin-Obukhov length. For a more detailed discussion on stability, the reader is referred to literature (e.g. [Garratt, J.R.(1994)]).

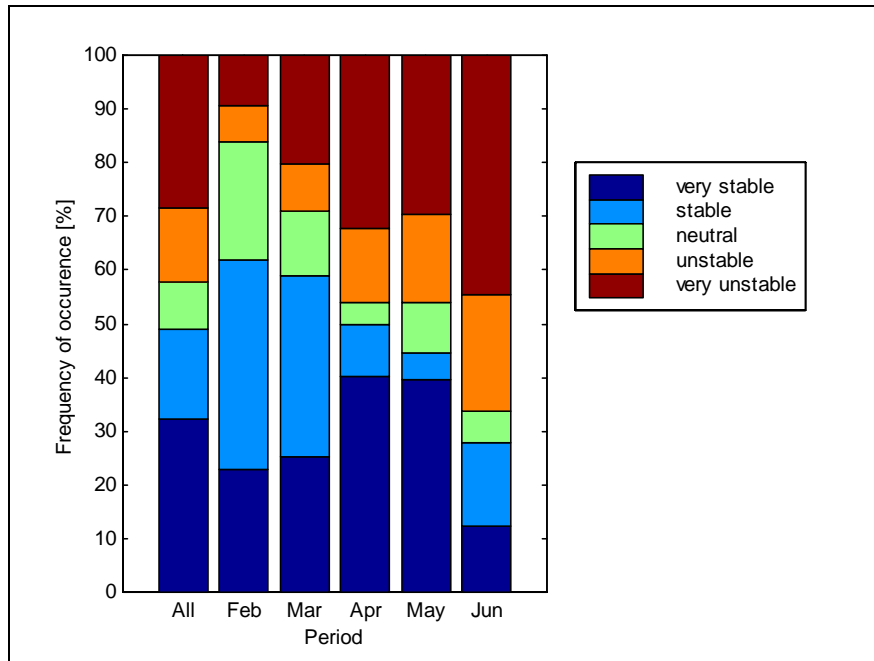


Figure 6-16: Distribution of stability conditions at the MPN platform from February 23 to June 16 2000 from very stable (bottom) to very unstable (top). The number of points for which the stability length could be determined is also given per period.

It is possible to determine the stability parameter from a single wind speed, one air temperature and the water temperature using Monin-Obukhov similarity theory. At Measuring Post Noordwijk, these quantities are measured on a routine basis. Hence, for every 10 minute mean, one can calculate the stability parameter. For the period of useful measurements (February 23 to June 15), the stability was determined per month and for the whole period. The result is shown in Figure 6-16. We have used the Monin-Obukhov length to define the five stability classes: very stable ($0 \leq L < 200$), stable ($200 \leq L < 1000$), very unstable ($-200 \leq L < 0$), unstable ($-1000 \leq L < -200$) and neutral ($|L| > 1000$). We compared the calculated distribution of stability classes with the long term mean [Coelingh et al. (1996)]. For the Spring months (March–May), very stable occurs 35% of the time, stable 14%, neutral 8%, unstable 11% and very unstable 32%. This compares well to our distribution. Because of the small number of points, the outcome for February is not representative.

Stability and SODAR height range:

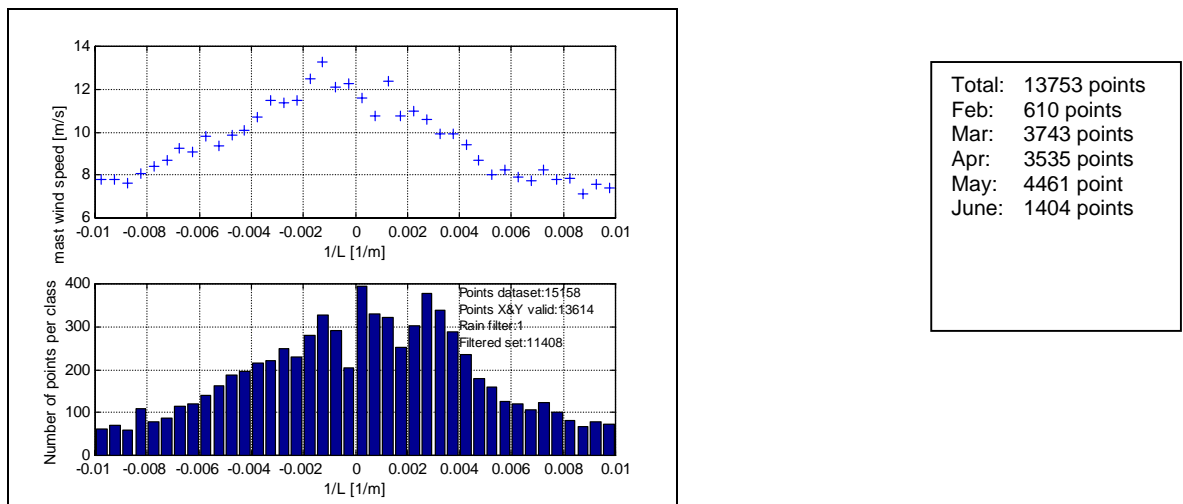


Figure 6-17: Relation between stability and mast wind speed, averaged per 'stability bin'.

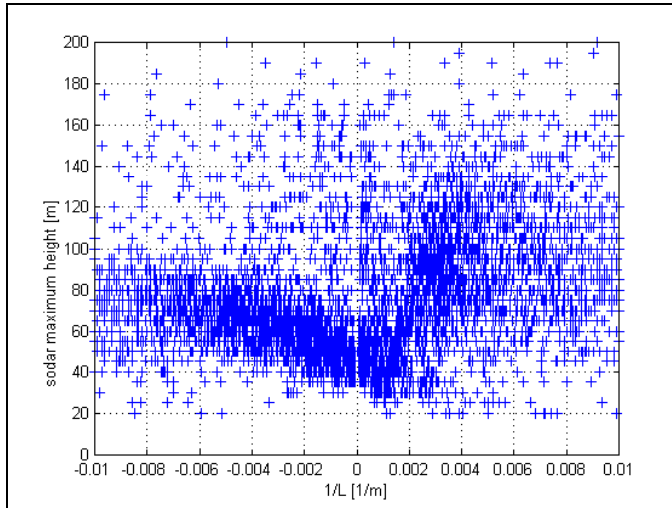


Figure 6-18: Influence of stability of the height reached by the SODAR (relative to the SODAR level).

As indicated in the description of the stability classes, stability and wind speed are related. For the considered period, we plotted the wind speed of the mast versus a measure for the stability (Figure 6-17). The highest wind speeds occur under neutral circumstances. Under very stable circumstances, there is hardly any horizontal movement of air and also hardly any vertical movement. When the wind speed increases for some reason, the influence of mechanical turbulence will increase and the atmosphere becomes somewhat less stable. This explains the increase in wind speed when the atmosphere becomes less stable. For very unstable conditions, the influence of frictional forces is limited and the wind speed near ground level is only slightly smaller than the wind speed at high heights. An increase in this wind speed implies that the influence of frictional forces becomes more important and the atmosphere will become less unstable.

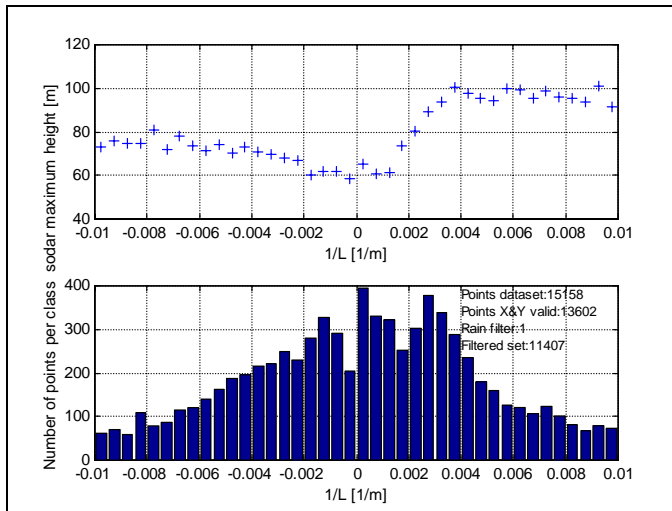


Figure 6-19: Mean maximum SODAR height per stability bin.

This relation between wind speed and stability complicates the analysis of the influence of stability on the height range. First, we will look to the overall influence of stability on the height reached by the SODAR. A scatter plot is shown in Figure 6-18, the average height reached per bin is shown in Figure 6-19. The height range is worst under neutral conditions. An obvious reason is that the wind speeds and hence the back ground noise levels are the highest under these circumstances. The more unstable the atmosphere, the higher the height reached. This also holds for stable conditions, although here there tends to be a "maximum" height range.

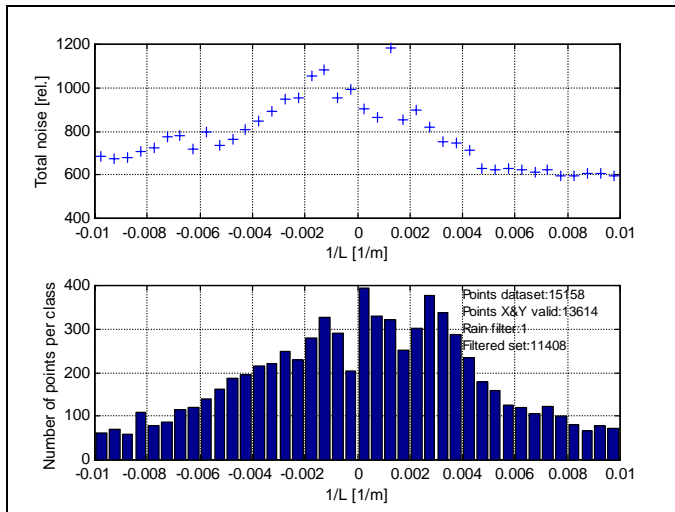


Figure 6-20: Scatter plot total noise observed versus stability.

A difference between the latter two is that under unstable circumstances the SODAR hardly ever exceeds 100 m height. Under stable circumstances, much higher heights are reached but in this case there is a broad 'scatter band' between approximately 50 m and 150 m height. From Figure 6-17 it appears that for very stable and very unstable conditions, the average wind speed is approximately 7.5 - 8.0 m/s. For stable circumstances the average height range is roughly 100m while for unstable circumstances this is only 75m. As the average wind speeds in these areas are the same, one would also expect a comparable height range for both stability classes but this does not seem to be the case. An interesting question is the noise level as a function of stability (Figure 6-20). It turns out that under stable conditions the total noise is somewhat lower (600) than under unstable conditions (650) but the difference is not very significant. It appears that apart from the wind speed related effect, the SODAR works somewhat better under stable conditions than under unstable conditions. Further analysis of the data set is needed to confirm this idea but is beyond the scope of this report.

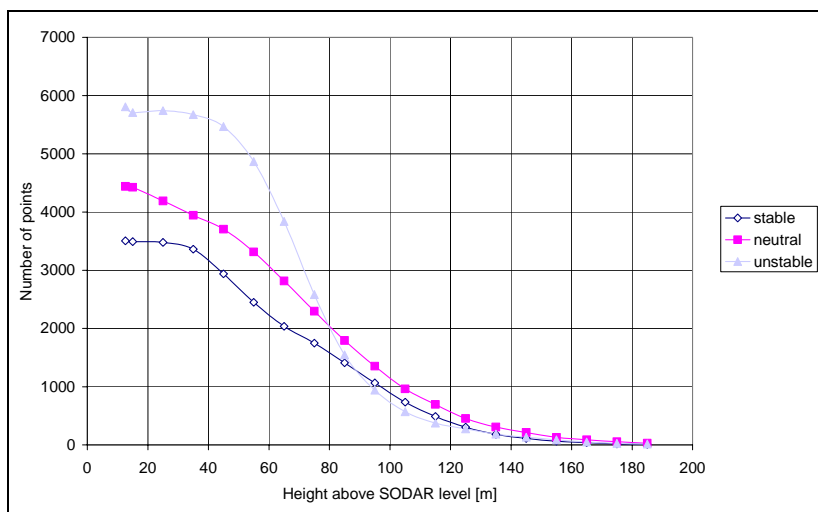


Figure 6-21: Absolute number of points of a certain stability class.

Another way to look to this is shown in Figure 6-21. For each SODAR height, the time steps for which valid data are measured were determined and the subsequent stability was looked up and summed per stability class. The number of points decreases for all stability classes with increasing height. However, the decrease is much stronger for an unstable atmosphere than for stable and neutral conditions. One explanation might be that in near neutral conditions, there are smaller (or even non-existent) temperature inhomogeneities for the SODAR beam to reflect off.

Is it now possible to explain the better height range with increasing wind speed (for low wind speeds) and/or why stability seems to improve the height range? No, a guess is the best we can do for now.

A SODAR measures wind speeds at three points. The angle between the vertical beam and the non-horizontal beams is 16 degrees. The higher the height a measurement refers to, the larger the distance between the measuring points. The vertical wind speed is used to derive the horizontal wind speed components from the two non-vertical beams. For non-laminar flows, the three measured values may not correspond to each other with an invalid outcome as result. The higher the height the measurement refers to, the larger the chance that the wind speeds measured do not correspond with each other. For very low wind speeds, the variability is high. This is also the cause under unstable circumstances. This might explain the better height performance with wind speed and the better performance under stable circumstances. A way to investigate this would be to look to the average height related to the turbulence-intensity. As no standard deviations are determined by the mast, this is not possible.

Other influences

In the above, we derived the influence of noise, wind speed and stability on each other and on the height range of the SODAR. Also other effects may play a role. The most obvious quantities that may affect the performance are the absolute air and water temperature. A scatter plot for both quantities is shown in Figure 6-22 and Figure 6-23 respectively.

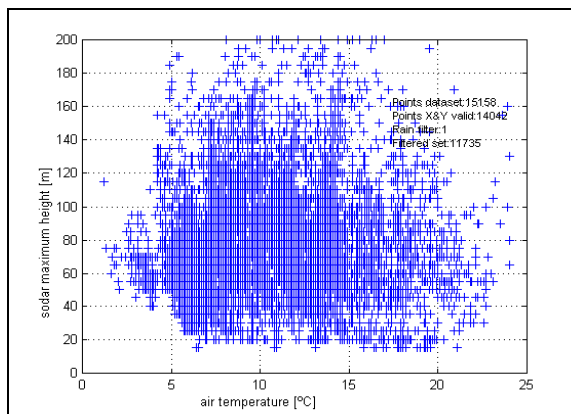


Figure 6-22: Scatter plot of SODAR height range versus air temperature.

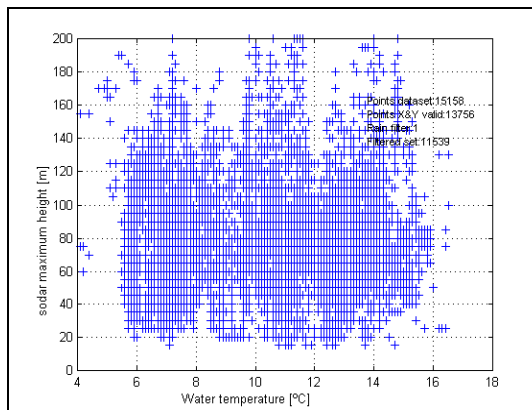


Figure 6-23: Scatter plot of SODAR height range versus water temperature.

It is clear that these quantities on its own are not related to the SODAR height range. Another important quantities are the influence of humidity and turbulence-intensity. Unfortunately both quantities are not available.

6.6.4 Conclusions

From the analysis described in this section, we can conclude the following:

- The height range of the SODAR at MPN is less than during earlier onshore measurements at ECN and should be improved.
- The back ground noise level is quite high and increases with wind speed. The base noise source are the diesel generators for the electricity supply which sets a lower limit for the back ground noise. When the wind speed increases, additional noise sources arise: the sound of the wave grows and the wind whistles along the super-structure of the platform.

- The height range of the SODAR decreases with an increase in back ground noise level; the returned signal 'drowns' in the noise.
- For wind speeds smaller than 7 m/s (measured at the mast) the SODAR height range improves with increasing wind speed. The reason may be the more laminar flow, but this is just a guess.
- For wind speeds larger than 7 m/s the height range decreases with wind speed. This is caused by the increase of back ground noise with wind speed above 7 m/s.
- Wind speed and stability are related. The wind speed is largest under neutral conditions and decreases for stable and for unstable atmosphere.
- The SODAR height performance is worst under neutral conditions. The more unstable the atmosphere, the better the height performance. This also holds for stable conditions. This is to a large extent caused by the larger noise level at higher wind speed but there may be a relation that the more stable the atmosphere, the better the SODAR height range.

6.6.5 Comparison of SODAR data with MPN measuring mast data

In the previous section the height performance of the SODAR was discussed. Of course, the produced wind speeds and directions should also be correct. In this section we use the wind speeds and directions from the mast anemometer and vane and Monin-Obukhov similarity theory to check the SODAR measurements. When comparing mast and SODAR data with each other, one has to take in mind that the platform disturbs the wind flow pattern. Hence, mast and SODAR may (under specific circumstances) measure the disturbed flow instead of the undisturbed flow which complicates the analysis.

We shall first compare the wind directions measured with the mast and the SODAR with each other. This will give some first insight into the influence of the platform. After that, the wind speed measurements will be compared.

Wind direction

In Figure 6-24, the frequency of occurrence per sector is plotted for the mast (27.6 m MSL) and for the SODAR at several heights. In order to make a fair comparison, only intervals are used for which the direction of the wind speed at the mast and at the SODAR from 30 to 120 m MSL are available ('equal statistics'). The distribution of the wind direction of the mast and that of the SODAR above 60 m MSL are roughly the same. Between 30 m and 60 m, the distribution differs considerably from that of the mast. The measure of deviation differs per sector.

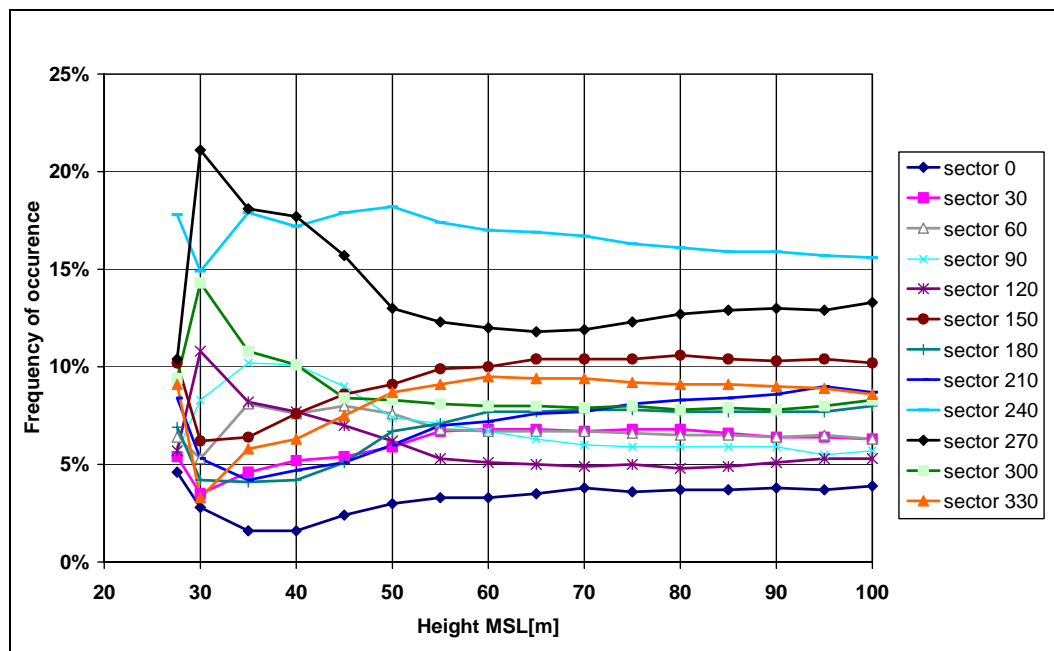


Figure 6-24: Frequency of occurrence per sector for mast and SODAR from 30–100 m above MSL with equal statistics (4472 points).

Another way to look at this is shown in Figure 6-25. In this figure, the wind direction distribution of mast and of the SODAR at 30 m, 35 m and 60 m is plotted for equal statistics from 30 m- 60 m MSL. Again the distribution of mast and SODAR at 60 m MSL compare well, while the lower heights have a different distribution compared to the mast, the wind for the lower SODAR heights has shifted from the west-south-west sector to the west sector. The North-north-east sector has shifted to the east and east-north-east sector.

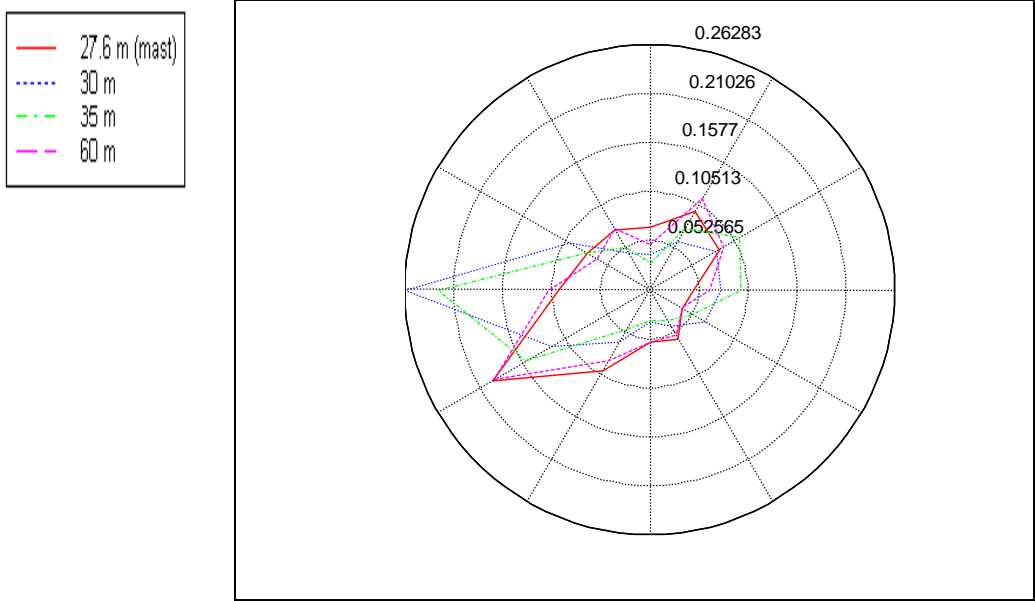


Figure 6-25: Wind rose for the mast and SODAR at 30m, 35m and 60 m MSL. Equal statistics for 30 m–60 m of the SODAR and the mast (11753 points)

A possible explanation for the observed behaviour is that the wind at the lower SODAR heights is disturbed by the platform: wind from the WSW flows along the helicopter deck and appears to flow from the west. Similar effects may occur at the east side of the platform. It is remarkable that the mast wind direction is hardly disturbed while a clear disturbance is seen at the lower SODAR heights.

We will return to this issue in the next section where the mast wind speed and SODAR wind speed are compared.

Wind speed

Wind speed profiles

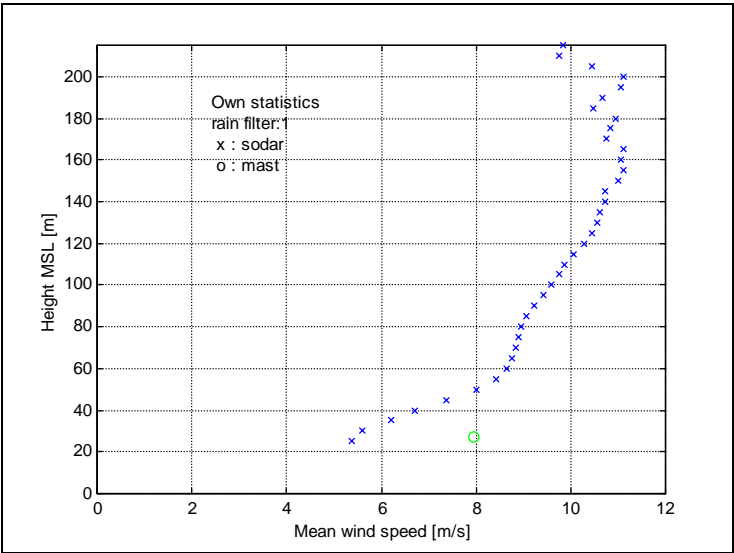


Figure 6-26: Wind speed profile based on SODAR and mast. Each mean is calculated based on own statistics. A rain filter (threshold value 1) was applied, 14055 points remain.

Figure 6-26 shows the mean wind speed for the mast and for each SODAR height. Per height, all available measurements are used to calculate the mean wind speed. For the SODAR, a rain filter with threshold value 1 is applied. The magnitude of the measured wind speeds seems fair. The mean mast wind speed is larger than that of the

SODAR measurements at the lowest heights but the difference in statistics may be the cause. A better way to compare mast and SODAR wind speed is by comparing a set for which each height has the same statistics.

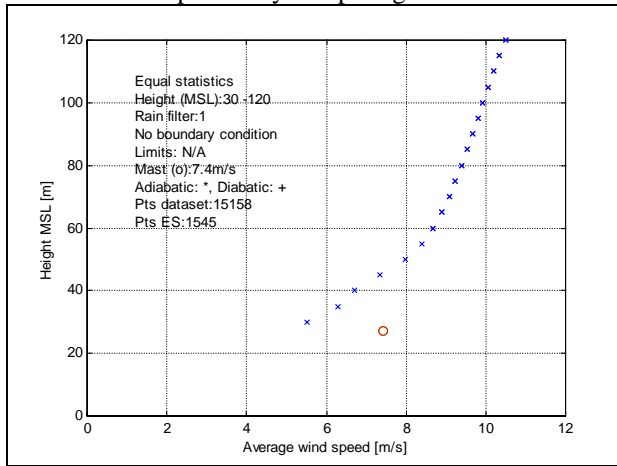


Figure 6-27: Wind speed profile with equal statistics for SODAR heights from 60–120m MSL and mast wind speed. Rain filter (threshold value 1) applied.

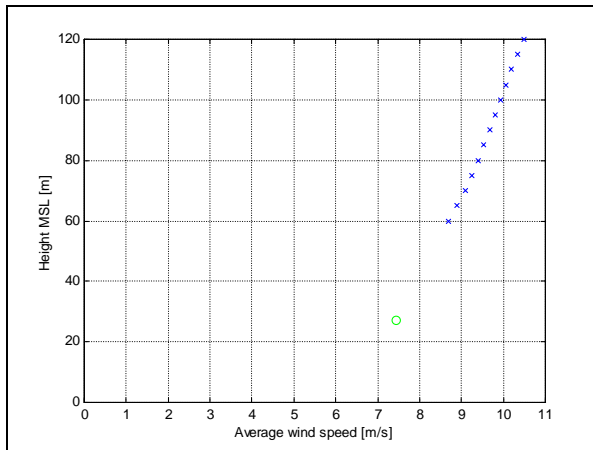


Figure 6-28: Wind speed profile with equal statistics for SODAR heights from 60–120m MSL and mast wind speed. Rain filter (threshold value 1) applied.

In Figure 6-27 such a wind speed profile is shown. An interval is only included in the calculation of the mean when for 30m to 120m MSL at *all* heights and for the mast a valid wind speed is measured. Besides, a rain filter with threshold value 1 is applied. In total 1513 of the 15158 intervals of 10minutes available are used to calculate the mean wind speed which is rather limited. Despite the fact that now the same set is used, the mast mean does not correspond to the SODAR measurements at the lower heights. When we ignore the SODAR measurements below 60 m MSL, the mean mast wind speed does correspond to the SODAR measurements at heights above 60 m MSL. The same holds for other sets. Compared to the mast, the SODAR measured wind speeds below 60 m are too low. Above 60 m, the measured wind speeds may be correct but there is no way to validate this.

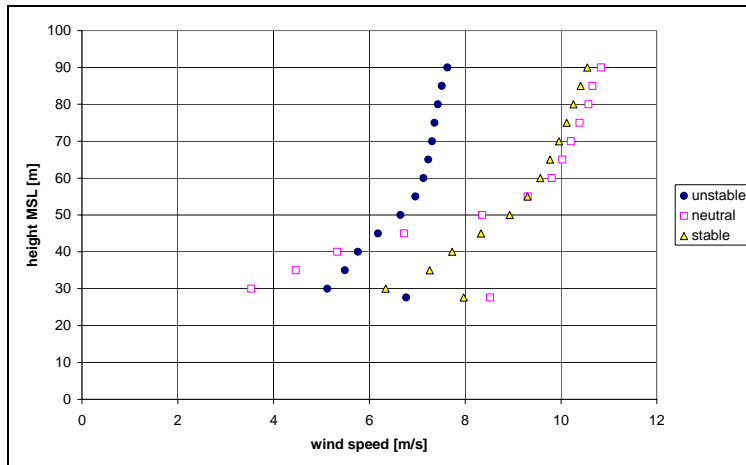


Figure 6-29: Wind speed profile for 30 – 90 m MSL (equal statistics) for several stability conditions. Neutral: 184 pts, stable: 2831 pts, unstable: 2003 pts.

We investigated whether this phenomenon does occur under all circumstances or not. First of all, we made a subdivision to stability class: stable, neutral and unstable. The resulting profiles are shown in Figure 6-29. It turns out that under all stability circumstances, the SODAR measured wind speeds below 60 m are too low compared to the mast. Under neutral conditions the underestimation is considerably larger than under stable and unstable conditions. Remarkable is the clear 'discontinuity' in the unstable and neutral profile at 60 m MSL. Similar profiles were made for several wind speed and noise classes. The too low wind speeds below 60 m was observed for all wind speeds and noise levels. Besides, it appears that for all circumstances, 60 m MSL is the lowest height with a not too low wind speed compared to the mast.

Conclusion: Above 60 m MSL, the mean wind speed of the mast and the SODAR fit in a neat profile. When the mast measurements are correct, the SODAR measured wind speeds below 60 m MSL are too low. under all circumstances. Above 60 m, it appears that the SODAR produces valid means, but there is no way to validate this. It also appears that the height from which onwards mast and SODAR profile corresponds is fixed at 60 m MSL.

Scatter plots

Until now, we have only considered mean wind speeds. Another approach is to compare the time series of the mast and SODAR in scatter plots. In Figure 6-30 to Figure 6-32 the mast wind speed is plotted against the wind speed at the SODAR from 30 m MSL to 60 m MSL. Only points are plotted for which both mast and SODAR measurements are available. A rain filter was applied.

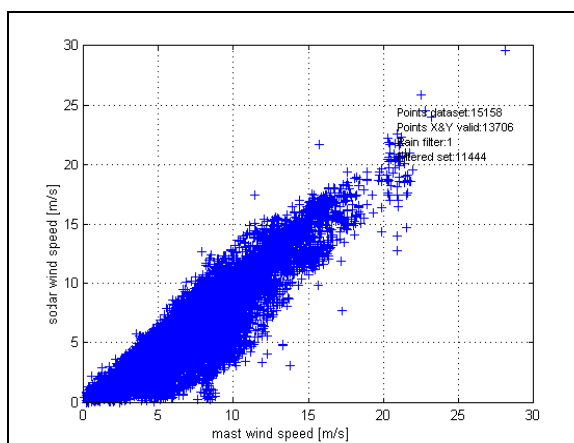


Figure 6-30: Mast versus SODAR wind speed at 40 m MSL. Rain filter (1) applied.

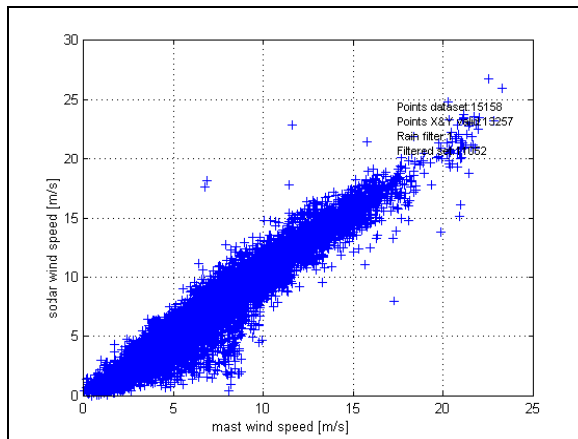


Figure 6-31: Mast versus SODAR wind speed at 50 m MSL. Rain filter (1) applied.

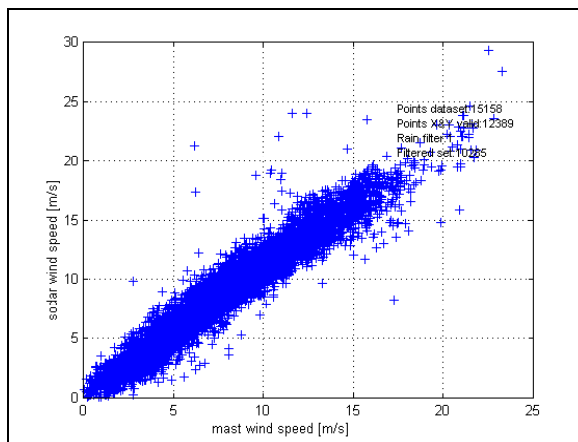


Figure 6-32: Mast versus SODAR wind speed at 60 m MSL. Rain filter(1) applied.

The scatter plot of mast wind speed and SODAR wind speed at 40 m MSL shows that below a mast wind speed of 10 m/s the SODAR wind speed varies between 0 m/s and the mast wind speed. For larger wind speeds, the underestimation by the SODAR is at maximum 5 m/s. this underestimation disappears for larger SODAR heights. At 60 m, the underestimation has disappeared but the scatter band is quite broad. the cause is most probably the variation in stability and roughness length. In Figure 6-32 still some points are situated outside the scatter band. More stringent requirements for data validation and rain filter will probably prevent from this.

From the scatter plots, we can conclude the following. At heights below 60 m MSL, the SODAR sometimes gives too low wind speeds compared to the mast wind speeds, but sometimes also the correct wind speed is measured. At larger heights, underestimation does not occur anymore. More stringent requirements for data validation will probably reduce the number of points outside the scatter band.

Monin-Obukhov similarity theory

With the help of Monin-Obukhov similarity theory, it is possible to calculate the wind speed at an arbitrary height based on one measured wind speed, the roughness length and the stability. For each time interval, we have calculated the wind speed at 60 m and 120 m MSL from the mast wind speed with the help of this theory and by applying the logarithmic profile. A scatter plot of SODAR wind speed at these heights versus the transformed wind speed is a means to validate the performance of the SODAR. A scatter plot for 60 m MSL of the SODAR and the wind speed calculated with Monin-Obukhov similarity theory is plotted in Figure 6-33. A similar plot for the logarithmic method is shown in Figure 6-34. Both plots are more or less a straight line. On average the Monin-Obukhov calculated wind speeds at 60 m MSL are somewhat lower than the SODAR measurements. The underestimation is somewhat larger when the adiabatic profile is used. Note that the scatter bands are quite broad.

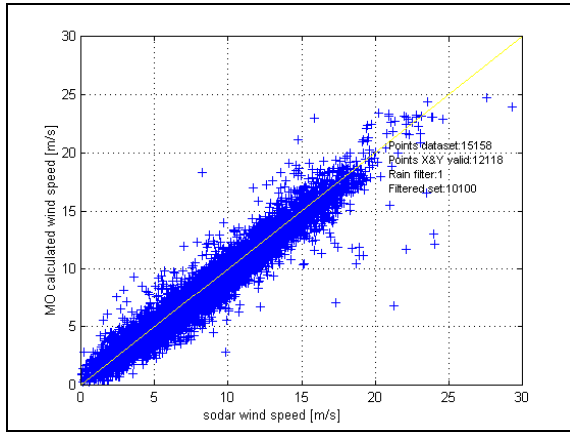


Figure 6-33: Wind speed SODAR versus diabatic wind speed at 60 m MSL. A rain filter with threshold value 1 is applied.

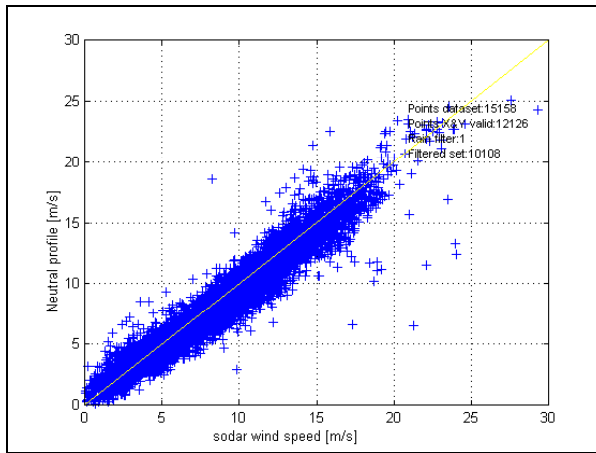


Figure 6-34: Wind speed SODAR versus adiabatic wind speed at 60 m MSL. A rain filter with threshold value 1 is applied.

For 120 m MSL (Figure 6-35 and Figure 6-36) the same is observed although the underestimation of the theory is larger, especially at higher wind speeds. This corresponds to earlier observations that the accuracy of the model decreases for increasing heights.

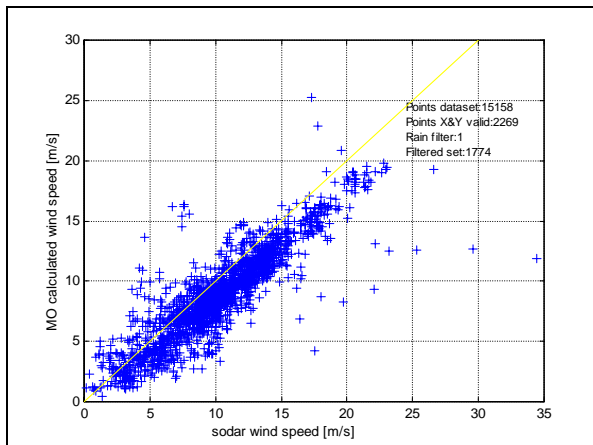


Figure 6-35: Wind speed SODAR versus diabatic wind speed at 120 m MSL.

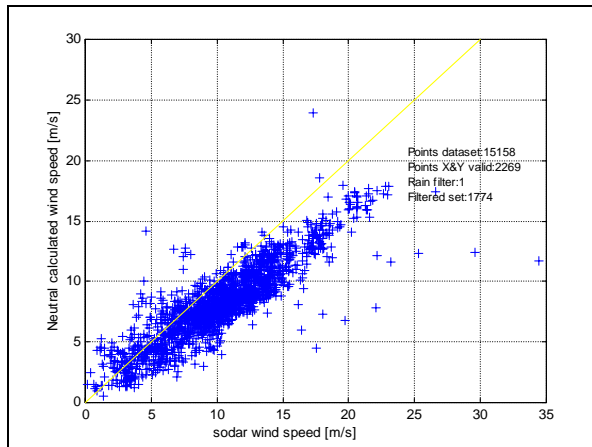


Figure 6-36: Wind speed SODAR versus adiabatic wind speed at 120 m MSL.

6.6.6 Summary of results

In summary, the following conclusions can be drawn.

Wind direction

Above 60 m MSL the wind direction distribution of the SODAR and that of the mast compare well. Below 60 m, the distribution measured by the SODAR deviates significantly from that of the mast. The measure of the deviation varies per sector.

Wind speed profiles

The mean wind speed of the mast and the SODAR observation above 60 m MSL form a neat profile. When we assume that the mast measurements are correct and undisturbed, the SODAR wind speeds below 60 m MSL are too low compared to the mast. It appears that above 60 m, the SODAR produces valid means, but there is no data available to validate this. The 60 m border seems fixed and is observed under all circumstances.

Scatter plots

From the scatter plots, it turns out that below 60 m the SODAR measured wind speeds vary between 0 m/s and the mast wind speed for wind speeds below 10 m/s. For larger wind speeds, the maximum observed underestimation is roughly 5 m/s. At larger heights, no extreme underestimation occurs. More stringent requirements for data validation will probably reduce the number of points outside the scatter band.

Comparison SODAR with Monin-Obukhov similarity theory

At 60 m MSL, the SODAR measurements correspond well with the wind speed calculated from the mast wind speed and Monin-Obukhov theory, although on average the Monin-Obukhov calculated values are somewhat lower than the SODAR measurements. At 120 m, the MO theory based calculated give larger deviations especially at the higher wind speeds.

How can these observations be explained? In case the mast gives correct and not disturbed measurements, the SODAR underestimates the undisturbed wind speed below 60 m MSL. The cause should be a mechanism that only affects the SODAR. A mechanism that may affect the SODAR measurements are reflections of the emitted SODAR pulse against waves and water. The SODAR is positioned on the platforms superstructure 15 m above the water surface. Part of the emitted pulses will reflect against the waves and the water. The speed of the waves and the water may determine the Doppler shift for this part of the beam. It is not sure whether the Dop-main software filters this data or not. This effect cannot explain all of the observed phenomena: the SODAR is positioned 15 m above MSL. Therefore this effect can only play a role until roughly 30 m MSL.

Disturbance of the wind by the platform appears a more probable explanation. Then, the mast and SODAR function correctly and the deviation is caused by the disturbance of the wind flow by the platform. In general, disturbance of wind speed by an object causes a larger turbulence intensity and a lower mean wind speed. The latter is indeed observed by the SODAR. Besides, the wind speed distribution at the lower SODAR height is shifted which can be a result from the shape of the platform. From the scatter plots it turns out that at 30 m height the SODAR measured wind speeds vary between 0 and the mast wind speed. This is also an indication that the platform disturbs the wind speed. In case the platform is the cause for the low observed wind speed by the SODAR below 60 m MSL, it is remarkable that the SODAR observes a significant disturbance as a result of the platform while this is

absent in the mast measurements. Possible explanations are the difference in measuring principle (plane versus point), the difference in position with respect to the platform or the higher level of the turbulence intensity.

The alternative is that the SODAR measures the undisturbed wind speed and the mast is not correct. This option seems not very likely. The mast directions compare well with SODAR observations above 60 m. Besides, some SODAR profiles show clear discontinuities below 60 m that are a contra-indication for the above assumption. The mast wind speed compares well with mast wind speeds from other stations [Coelingh et al. (1996)]. Further evidence is that the 60 m Monin-Obukhov calculated wind speed compares well with the SODAR at 60 m MSL. When we assume that the theory is correct, this implies that mast measurements and SODAR measurements at 60 m correspond with each other. This is further evidence for the correctness of the mast measurements.

It seems likely that the SODAR measures wind speed correctly and that the platform disturbs the wind flow. As a consequence, the SODAR measures the disturbed wind speed. Unfortunately, there is not enough data at present to validate this preliminary conclusion more thoroughly. First of all, longer data sets can give more insight. It is then possible to analyse data per sector. An alternative is to place anemometers at higher heights (preferably measuring the undisturbed wind speed) or one close to the SODAR. As we are interested in undisturbed wind profiles, it is for the given platform advisable to position the SODAR where disturbance by the platform is the least.

At 60 m MSL, the SODAR measurements are on average somewhat higher than the mast measured wind speeds transformed by Monin-Obukhov theory. The width of the scatter band is quite broad. Partly this may result from the measuring error of the SODAR but also the theory may not be suitable for small time intervals. The higher the height referred to, the larger the difference between theory and SODAR measurements. With the current information it is not possible to determine which of the two compares best with the actual wind speed.

6.6.7 Discussion

A SODAR is a very useful device to measure wind speed profiles and can help to describe boundary layer phenomena. In this section the performance of the SODAR in the period from February 23 to June 16 200 at Measuring Post Noordwijk was investigated. It turned out that the SODAR does not produce correct wind speeds during some periods of rain. For this reason, periods with rain are excluded from the data set.

The percentage of data recovered by the SODAR decreases with height. The height range of the SODAR at MPN is poor and worse than earlier onshore measurements at ECN. We tried to identify the causes.

The back ground noise level is quite high and increases with wind speed. The base noise source are the diesel generators for the electricity supply which sets a lower limit for the back ground noise. When the wind speed increases, additional noise sources arise: the sound of the wave grows and the wind whistles along the superstructure of the platform. The height range of the SODAR decreases with an increase in back ground noise level; the returned signal 'drowns' in the noise.

For wind speeds smaller than 7 m/s (measured at the mast) the SODAR height range improves with increasing wind speed. The reason may be the more laminar flow, but this is just a guess. For wind speeds larger than 7 m/s the height range decreases with wind speed. This is caused by the increase of back ground noise with wind speed above 7 m/s.

Stability and height range are also related. There is an indirect effect because wind speed and stability are related. The wind speed is largest under neutral conditions and decreases for stable and for unstable atmosphere. There is small evidence that there is also a direct effect between stability and SODAR height range. The SODAR height performance is worst under neutral conditions. The more unstable the atmosphere, the better the height performance. This also holds for stable conditions. This is to a large extent caused by the larger noise level at higher wind speed but there may be a relation that the more stable the atmosphere, the better the SODAR height range.

We also compared the SODAR measurements to the wind speed mast at MPN-platform.

Above 60 m MSL the wind direction distribution of the SODAR and that of the mast compare well. Below 60 m, the distribution measured by the SODAR deviates significantly from that of the mast. The measure of the deviation varies per sector. The mean wind speed of the mast and the SODAR observation above 60 m MSL form a neat profile. When we assume that the mast measurements are correct and undisturbed, the SODAR wind speeds below 60 m MSL are too low compared to the mast. It appears that above 60 m, the SODAR produces valid means, but there is no data available to validate this. The 60 m border seems fixed and is observed under all circumstances.

It seems likely that the SODAR measures wind speed correctly and that the platform disturbs the wind flow. As a consequence, the SODAR measures the disturbed wind speed. Unfortunately, there is not enough data at present to validate this preliminary conclusion more thoroughly. First of all, longer data sets can give more insight. It is then possible to analyse data per sector. An alternative is to place anemometers at higher heights or close to the SODAR. As we are interested in undisturbed wind profiles, it is for the given platform advisable to position the SODAR where disturbance by the platform is the least.

With the help of Monin-Obukhov theory it is possible to transform measured mast wind speeds to other heights, taking into account the stability of the atmosphere. The mast wind speed was transformed to 60 m and 120 m MSL and compared to the SODAR measurements.

At 60 m MSL, the SODAR measurements are on average somewhat higher than the mast measured wind speeds transformed by Monin-Obukhov theory. The width of the scatter band is quite broad. Partly this may result from the measuring error of the SODAR but also the theory may not be suitable for small time intervals. The higher the height referred to, the larger the difference between theory and SODAR measurements. With the current information it is not possible to determine which of the two compares best with the actual wind speed.

The SODAR functions well but because of the large back ground noise level, the height range is poor. This makes the SODAR data less valuable for statistical purposes but does not affect the usefulness for validation of the CDM-model: only the amount of available data points at the higher heights reduces. At the lower heights, enough data is present for statistical purposes. Unfortunately, it seems that below 60 m MSL, the SODAR measurements are disturbed by the platform. Therefore, below 60 m the SODAR measurements do not reflect the undisturbed wind flow and can not be used for validation of the CDM. Above 60 m MSL, the SODAR measurements seem correct and correspond with the mast measurements. These data can be used to validate the CDM.

The only identified cause for the poor height range that can be influenced is the back ground noise. Positioning the SODAR further away from the diesel generators will enormously reduce the back ground noise level. When repositioning the SODAR, it is also of importance to look for a position where the noise from waves and whistling of the wind is as low as possible. Another position of the SODAR may also reduce the disturbance of the platform on the heights lower than 60 m.

In order to further analyse the performance and correct functioning of the SODAR a longer data set is desirable. The positioning of an anemometer at a low level near the SODAR or at a larger height (> 60 m) can also give valuable information.

6.7 Analysis of SODAR data collected in the UK

6.7.1 The Weybourne site

A mini-SODAR was installed at Weybourne in August 2000 and remained on site until the end of October 2000. Weybourne is a village located on the north coast of Norfolk. The SODAR site is within the grounds of an out-station belonging to the University of East Anglia School of Environmental Sciences, where laboratory facilities are available for atmospheric chemistry measurements. The site position is 52.95°N by 1.13°W. It has the advantage of having no-one living nearby, which is a consideration with a mini-SODAR which makes a persistent 'pinging' noise. Ambient noise levels are low, which allowed high quality measurements to be taken, with few missing data. The site is well exposed to the open sea to the north (see Figure 6-37)

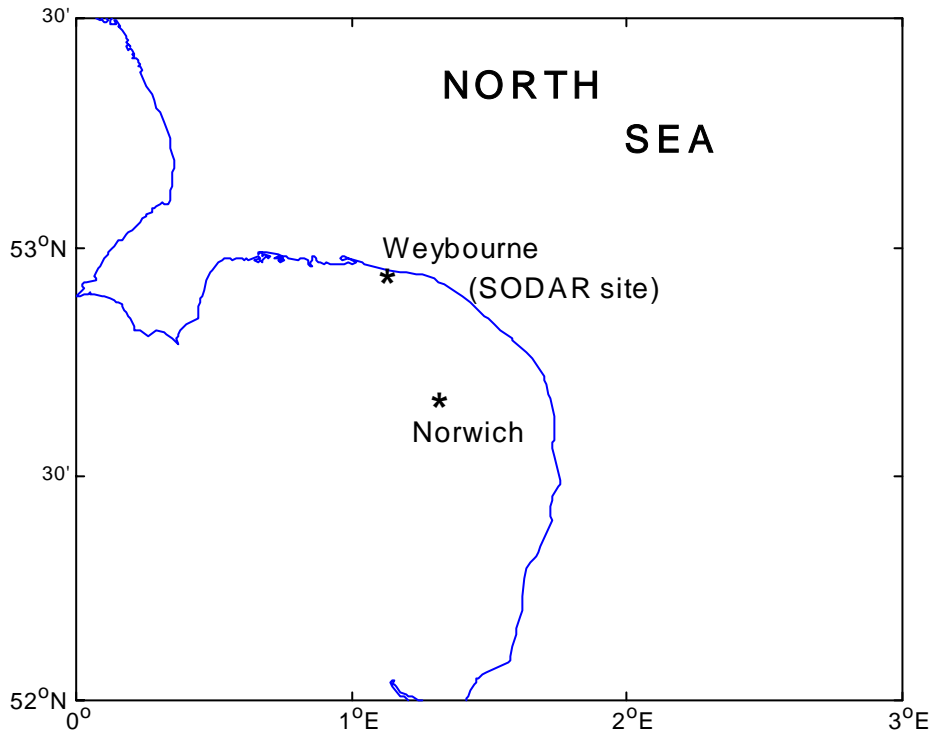


Figure 6-37: Location of the SODAR installation at Weybourne

These factors made it an ideal location for looking at the vertical profile of winds moving onshore from the open sea.

6.7.2 Data processing

High quality data for 80 days were collected, from 26th August 2000 to 22nd October 2000. The mini-SODAR was on site for a longer period, but some data were lost due to the activities of rabbits (see Figure 6-38), problems with a disk drive, and occasional erratic behaviour of the system. The rabbit problem was solved by encasing the cables in rigid plastic piping. Data were collected every 5 minutes at 5 m intervals from 10 to 200 m and the variables of main interest include wind speed and direction, gust speed and direction, vertical wind speed, and the u and v components of the horizontal wind field.



Figure 6-38: Damage to SODAR cabling by rabbits

Before analysis the SODAR data required extensive filtering to rationalise missing values and to adjust obviously incorrect estimates. In addition to the degrading of data due to destruction of the cable by rabbits, the data quality is affected by random fluctuations and systematic bias during rainfall. Error-correction software was developed using the last 57 days of measurements, where the only errors in the data were due to rainfall and apparently random “spikes”. The methodology was then applied to the less reliable part of the record. The error-correction procedure is as follows:

- Pass 1: sets all data in the current record to missing if wind speed, u, or v component is missing. The lack of any of these elements on a 5-minute time step makes it impossible to validate the remaining data and to create time-averaged wind speeds and direction.
- Pass 2: sets all data in the current record to missing if the previous and subsequent values of wind speed, u, or v are missing. This circumstance makes reliable interpolation impossible.
- Pass 3: interpolates up to three consecutive missing 5 minute timesteps, if the adjacent values form a series of smooth estimators with no spikes. It was considered that interpolation of more than three successive 5 minute timesteps could lead to unreliable estimates of hourly mean wind. Prior to interpolation, adjacent data were checked for abnormally high or low values.
- Pass 4: this stage is a subjective assessment of the time series. The data are visually “tuned” using a graphical display by interactively adjusting isolated peaks, interpolating isolated missing values, and inserting missing values when the series appears dubious.

Following error-correction, hourly and daily mean vertical wind speed and horizontal wind speed and direction, were calculated, and output to files at each 5 m level along with maximum gust and maximum gust direction.

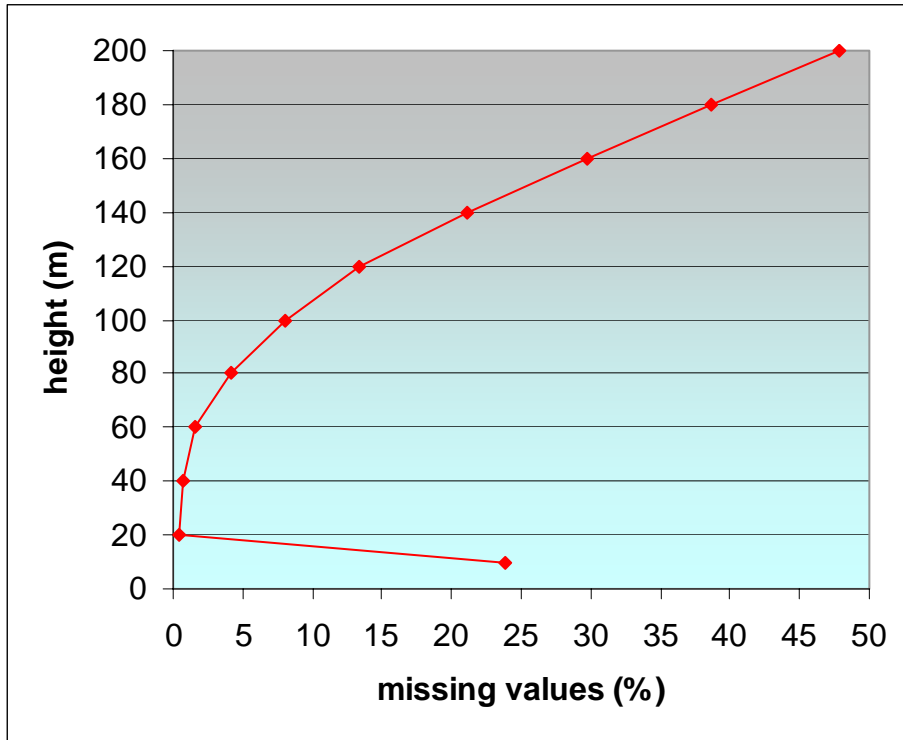


Figure 6-39 : Percentage of missing values with height

Figure 6-39 shows that, because of missing values, it would not be possible to estimate a reliable diurnal cycle above about 120 m and below 20 m. The missing values at height are not caused by a failure of the SODAR but indicate that the effective measuring height of the instrument varies with atmospheric conditions.

6.7.3 Analysis of the data

Mean wind speed profile

Figure 6-40 shows how the mean wind speed profile varies with height according to the SODAR data. An exponential curve fits the data better than a logarithmic curve, with r^2 of 0.9954. The curve is calculated from hourly mean wind speeds, averaged over a day, and then averaged over the last 57 days of recorded data.

Diurnal cycle of wind speeds

Figure 6-41 shows the diurnal cycle in wind speed, averaged over all values at each hour from 0000 to 2300, at heights from 20 to 120 m at 20 m intervals. The averaging to calculate the diurnal cycle only uses data from the last 57 days of the record, to avoid problems related to missing values in the first few days of instrumentation. Heights above 120 m are not shown because they contain increasing numbers of missing values. The diurnal cycle at all heights has a trough centred on 1800 hours. At 20 m, there is a gradual decline in wind speeds from a maximum at 1200 hours. This peak at 20 m at 1200 hours is not found aloft, where the maximum is at about 2300 hours.

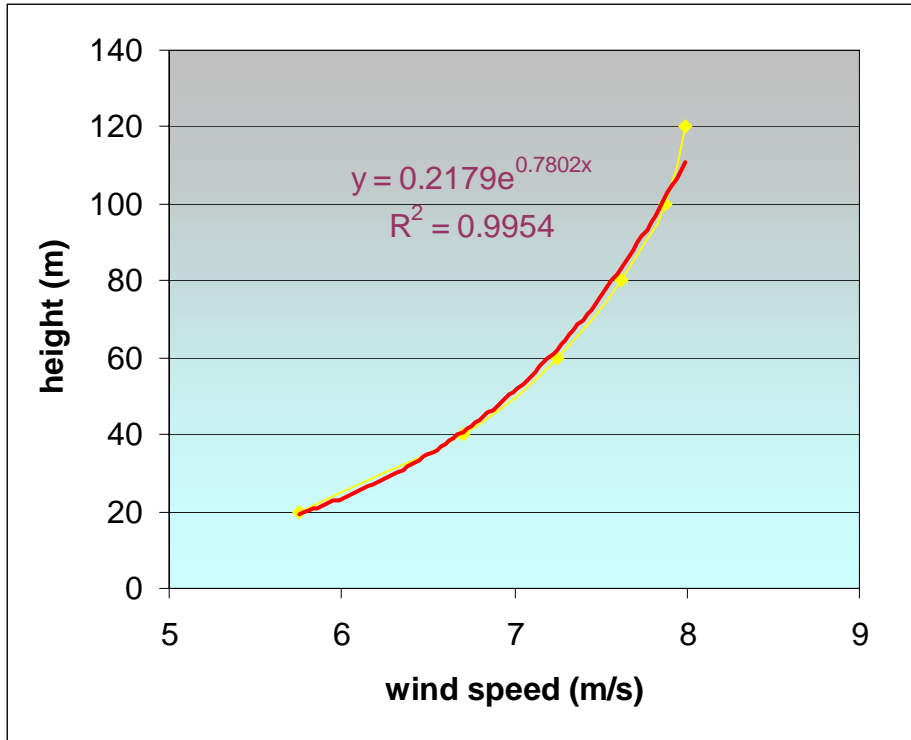


Figure 6-40 Mean daily wind speed profile

Figure 6-42 shows the daily mean wind speed over the whole 80 days. The charts are organised to display wind speeds at two heights on each plot. The dashed rectangle indicates the period when the record was disrupted by rabbits chewing through the cable. In the daily mean data, this appears to have had little effect, apart from the period when the instruments cut out entirely. Wind speeds at height above 100 m are shown in smaller plots since the vertical wind shear is much less at these heights.

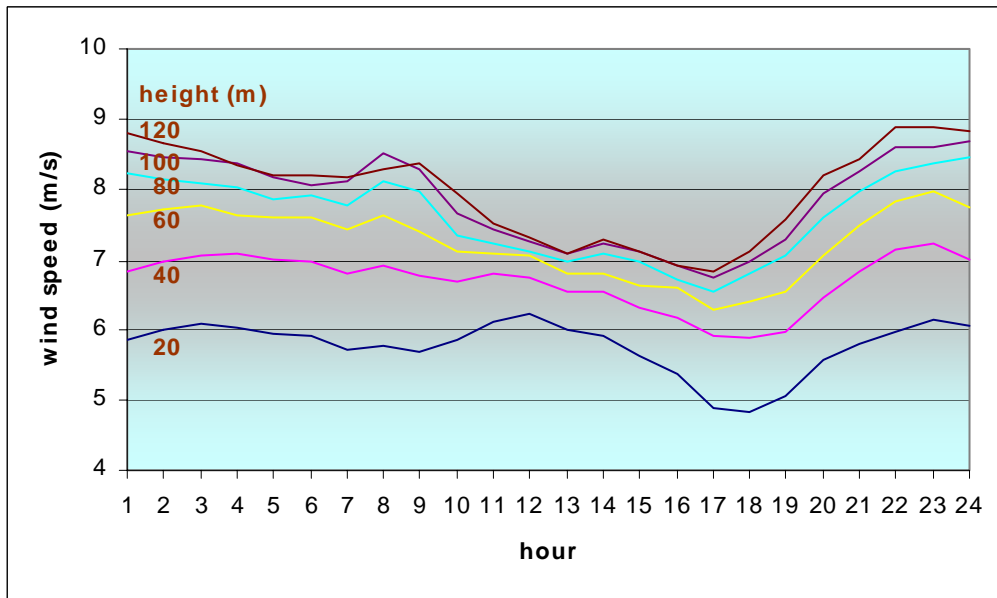


Figure 6-41 Diurnal cycle of wind speed at Weybourne

Partitioning the data into land and sea fetches

The Weybourne site is well exposed to the open sea from the north, but has a land fetch to the south. In order to understand the differences between land- and sea-fetch winds with respect to:

- the diurnal cycle of wind speeds and
- the vertical wind speed profile,

the data set of wind speeds was partitioned into land and sea subsets:

- land fetch: defined as wind directions 130°-270°
- sea fetch: defined as wind directions 310°-70°

and analysed further. The partitioning was carried out conservatively, to ensure the purity of the two subsets. Winds from the west-north-west and from the east, blowing along the coast, were rejected at this stage. Note that when the data are partitioned in this manner, there are many more land-fetch observations than sea-fetch observations. Analyses of the land-fetch wind speeds can be carried out up to 200 m above the ground, whereas for the sea-fetch wind speeds there are insufficient observations above 100 m for meaningful results to be obtained.

As shown clearly in Figure 6-39, there are many missing data from the mini-SODAR at the 10 m height (and in fact it turns out that mini-SODAR data are not reliable this close to the ground). We therefore obtained data from a standard anemometer mast located very close to the mini-SODAR. This is the Weybourne SAWS anemometer, at a standard 10m above the ground, located some 200 m south of the mini-SODAR. The data for the period during which the mini-SODAR took measurements were obtained from the British Atmospheric Data Centre (BADC). In the analyses which follow, the 10 m data is always from Weybourne SAWS.

First, we used the partitioned data to look at differences in the diurnal cycle Figure 6-43 shows the mean wind speed at each hour in the day, at heights up to 200 m for the land fetch and 100 m for the sea fetch. The diurnal cycles are quite different, as is their evolution with height.

For the land fetch, at the lower heights there is a clear peak in the middle of the day. However, by 60m the amplitude of the cycle has reduced to close to zero. As the height increases still further, wind speeds become higher at night, and reach their minimum in the early afternoon hours. This is according to theory, and has been observed by, for example, [Emeis (2001)]. At night, a low-level inversion forms as the land surface cools. The surface layer decouples from the rest of the boundary layer, giving very low wind speeds close to the ground and higher wind speeds above the surface layer. In the daytime, as the land surface warms, vertical mixing leads to small vertical gradients in wind speed.

Over the sea at the lower observation heights, wind speeds are lower in the afternoon, and higher at night, with the transitions occurring in the late morning and late evening. [Barthelmie et al. (1996)] noted that the temperature of the sea surface will tend to be lower than that of the overlying air during the day, leading to stable conditions and lower windspeeds, whereas at night the sea surface will tend to be warmer than the overlying air, leading to less stable conditions and higher wind speeds. Therefore, the diurnal cycle over the sea may be the inverse of that observed over the land. Here, we see that this pattern is not only preserved with height, but there is some indication that it becomes more intense. There are important implications here for wind turbines located in the near-shore zone, whose hub heights are expected to be of the order of 100 m above the surface.

Figure 6-44 shows the vertical wind speed profiles in the sea- and land-fetch data subsets. Sea profiles are very similar through the day. There is little variation in speed with height, suggesting well-mixed unstable conditions. Over the land, there is a diurnal cycle in these profiles. In the early hours of the morning, there is a substantial increase in speed with height, indicating stable conditions. After dawn, the profile gradually steepens until by midday there is little variation in speed with height. As evening progresses, the profiles move once more towards increasing wind speed with height. These clear differences in land-fetch and sea-fetch wind speed profiles are potentially important for developers attempting to predict hub-height windspeeds from near surface observations.

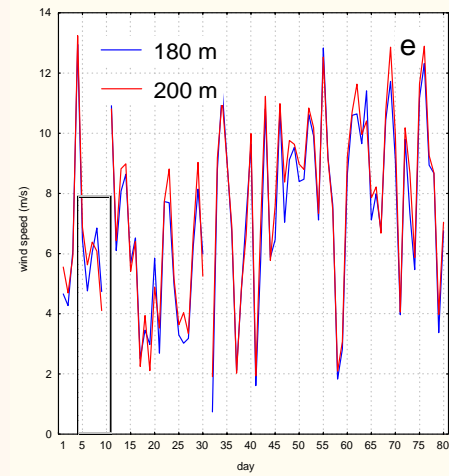
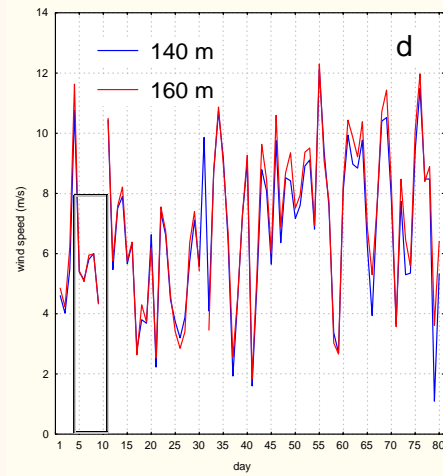
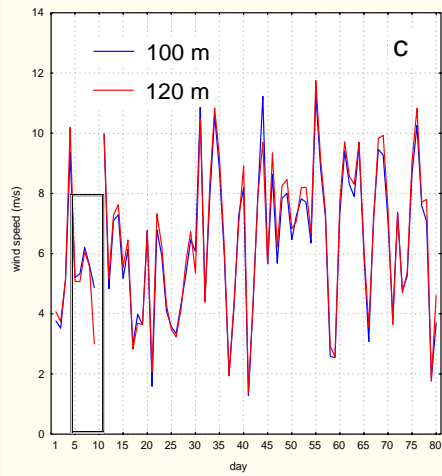
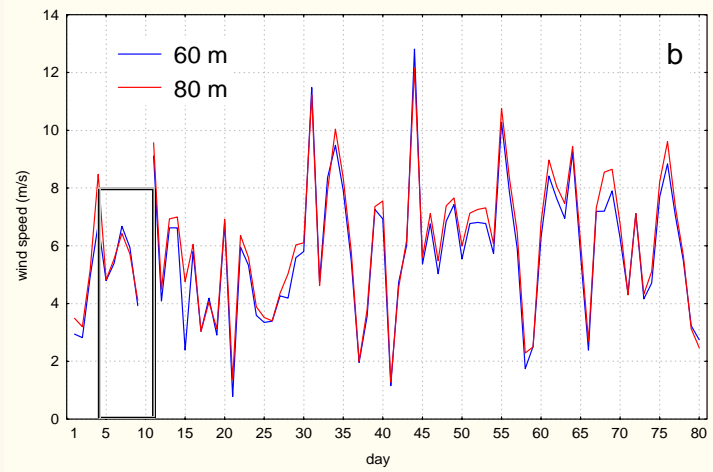
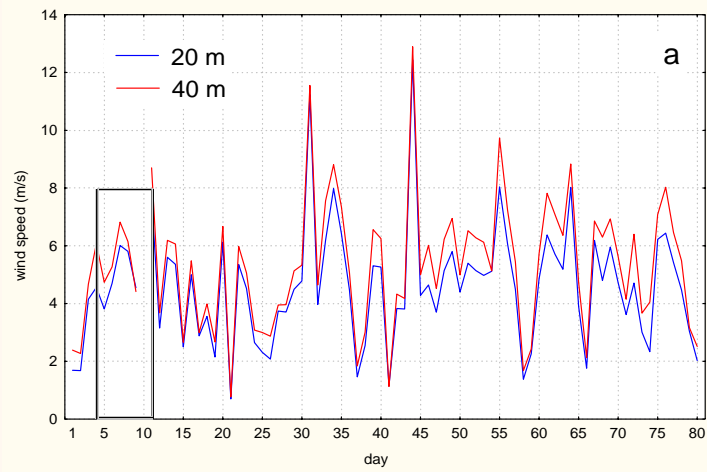


Figure 6-42 Daily mean wind speed (dashed rectangle encloses suspect data)

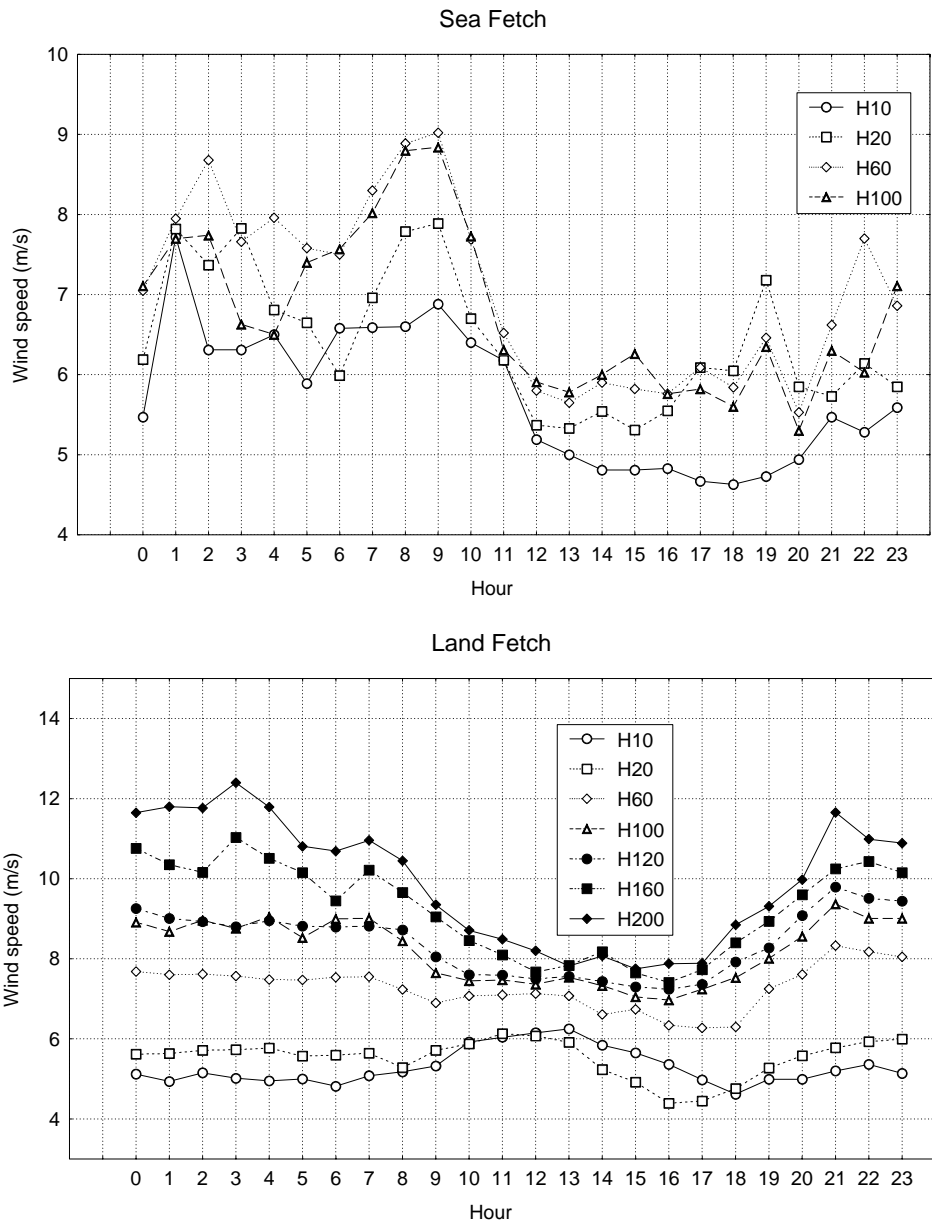


Figure 6-43 Diurnal cycles of sea-fetch and land-fetch wind speeds

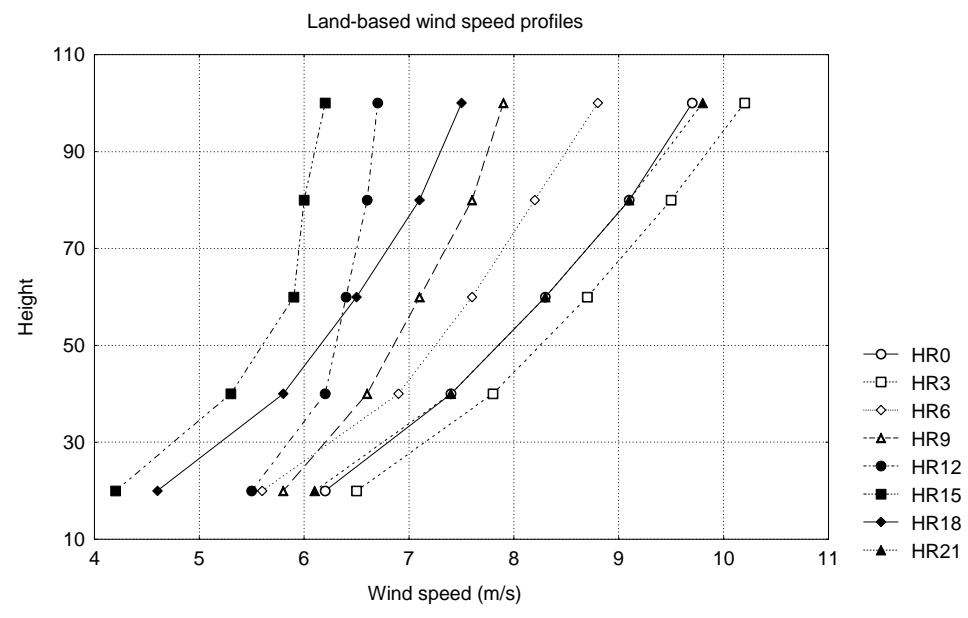
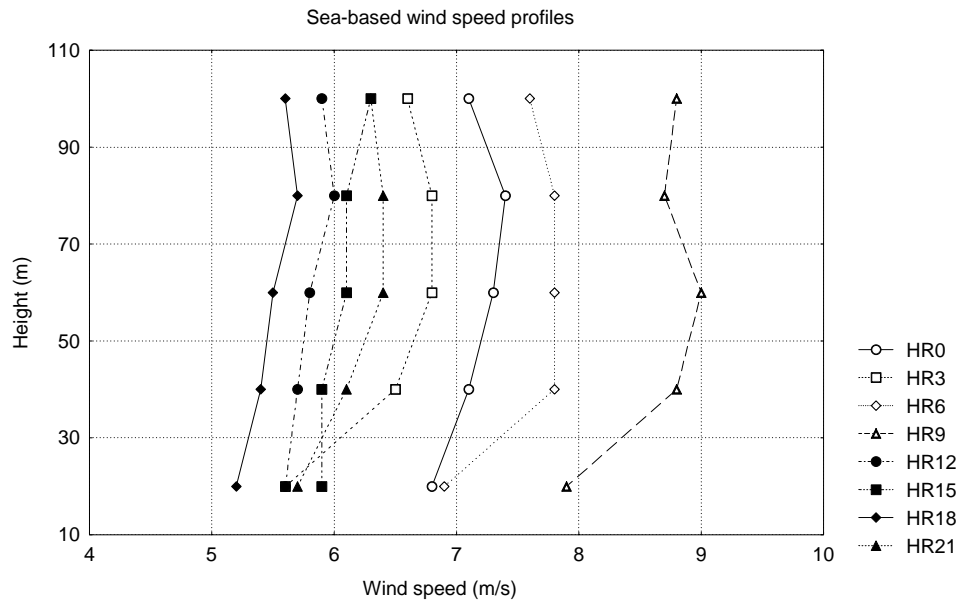


Figure 6-44 Vertical profiles of sea-fetch and land-fetch wind speeds

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