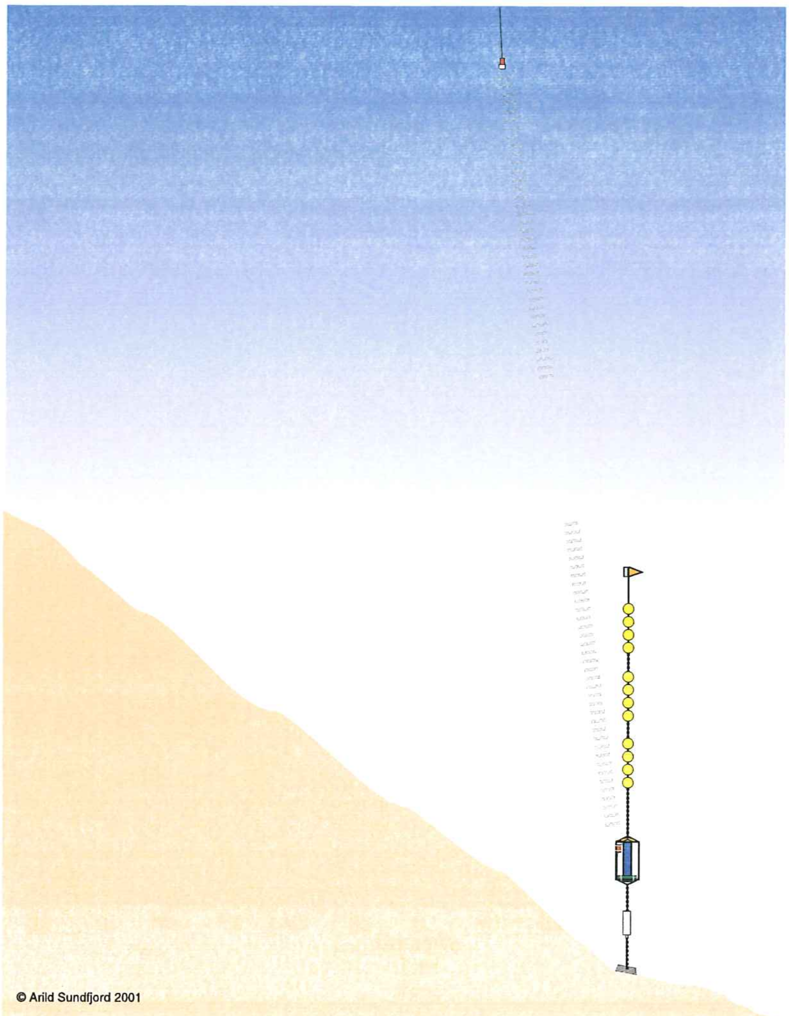
REPORT SNO 4375-2001

The international project on Ocean CO_2 sequestration

Measuring Ocean currents using ADCP and Acoustic Modem, Keahole Point, Hawaii, 27 - 31 October, 2000



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REPORT

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Abstract

The report presents data and analysis from current measurements made near Keahole Point, Big Island, Hawaii, in October 2000. The measurements were made with an RDI ADCP recording 3D current profiles in 5 m depth cells from 785 to 290 m depth. Recording interval for the instrument was 10 minutes. Average current velocities ranges from ~ 9.2 cm/s at 300 m depth to ~ 4.9 cm/s at 750 m depth. Net water transport was to the northwest in most of the water column, but the current direction changed frequently. An intermediate layer at around 500 - 600 m dept showed particularly unstable currents. The current structure was generally very similar to that observed in measurements made in the same area in 1999, but with some discrepancies in the deepest layer.

4 keywords, Norwegian	4 keywords, English
1. Havlagring av CO_2	1. CO_2 ocean sequestration
2. CO_2 eksperiment	2. CO_2 experiment
3. ADCP strømmåling	3. ADCP current measurements
4. Hawaii	4. Hawaii

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The international project on Ocean CO_2 sequestration

Measuring Ocean currents using ADCP and Acoustic Modem, Keahole Point, Hawaii, 27 - 31 October, 2000

Preface

The report presents current measurements made near Keahole Point, Big Island, Hawaii, in the fall of 2000. We are grateful for the good support from and co-operation with crew and scientists on board the R/V 'Kaimikai-O-Kanaloa' (KOK), and on-shore support from PICHTR (Pacific International Center for High Technology Research) and the University of Hawaii.

We also thank the Norwegian Institute for Marine Research for lending us the LinkQuest Acoustic modem used for ADCP communication.

Bergen, May 2001

Arild Sundfjord

Contents

Summary

As part of the International Project on Ocean CO_2 Sequestration, current measurements were carried out at a location near Keahole Point, Hawaii, 27-31 October 2000. The measurements were made using an upward looking RDI ADCP moored at ~800 m depth. The instrument profiled 3D current in 5 m vertical cells, in total covering the range from 785 to 290 m depth (100 cells). The recording interval was set to 10 minutes.

At different intervals, a LinkQuest Acoustic Modem was used to communicate with the bottom mounted ADCP using the R/V KOK as a platform. Current data were transfered to the surface for near real-time analysis. In addition, various instrument settings can be altered after deployment using the modem communication protocol. The testing of these capabilities was successful, and the general impression was that the ambient conditions in the area, in terms of acoustics, are advantageous for this type of devices.

Data analysis reveals a horizontal current structure with distinct layers. In the upper part of the measurement domain (approximately 290 to 500 m depth) northwesterly currents dominate. Average current velocities in this layer decrease from around 9.2 cm/s to 5.8 cm/s. An intermediate layer from around 500-600 m shows less directional stability and a very small net current, although the average instantaneous current velocities are around 5.5 cm/s also at these depths. Below this intermediate layer, the current again becomes more directionally stable. The main transport is towards the northwest, but current direction changes frequently. Average current velocities are around 5.0-5.5 cm/s. In the very deepest few cells the current increases to an average of around 7.0 cm/s, with little directional stability.

Comparison with similar measurements made in the same area in August-September 1999 show significant agreement between the two data sets. Average and maximum current velocities are very similar. The layer structure was also seen in the first measurement series. In the upper layer NW currents dominated both times. In the near-bottom layer the 1999 data showed a net transport towards the SE - this was torwards the NW in the 2000 measurements. It should be noted that the 1999 series covered a five week period compared with the four days in the fall of 2000. During certain parts of the 1999 measurements, NW currents did dominate also in the deepest layer.

Some attention has been given to quantification of the duration of current "events" such as length of periods with particularly weak currents, directional stability etc. This should be helpful when planning monitoring activities in connection with the planned 2001 CO_2 release experiment. Spectral analysis of current energy is performed to identify any periodical phenomena. In addition to the main tidal components, oscillations with periods of 2.8 and 1.2 hours were found. Again, this is similar to what was seen in the 1999 measurements.

1. Introduction

The International Project on Ocean CO_2 Sequestration is preparing for an experimental release of liquid CO_2 off Keahole Point, on the west side of the Big Island of Hawaii (**Figure 1**). The purpose of the experiment is to evaluate the feasability of future large scale sequestration of CO_2 in the ocean. Background studies of local ocean dynamics, chemistry and biology have been carried out to allow modelling of dissolution and spreading of the injected CO_2, and provide a baseline for evaluation of potential environmental impacts from the experiment. As part of these studies, ocean currents were measured with various instruments during a five week period in the summer of 1999 (Maeda et al. 2000, Sundfjord and Golmen 2000). Current data were also collected with a RDI Long Ranger ADCP during a shorter research cruise in October 2000. This report presents and discusses these latter measurements, and a brief comparison with the data from 1999 is given.

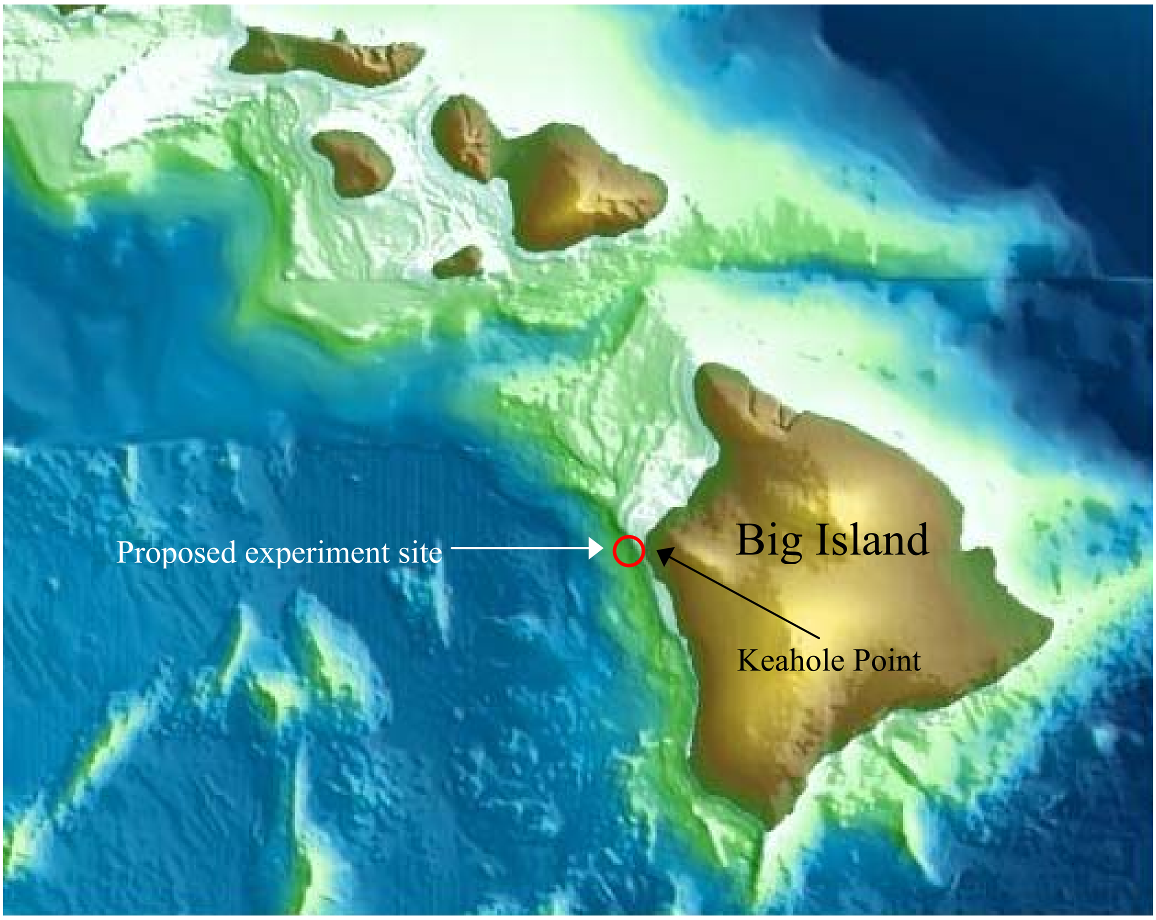


Figure 1. Location of the proposed experiment site near Keahole Point. The ADCP was moored at approximately 800 m depth. The exact position of the mooring is given in **Table 1**.

2. Deployment information

The current meter mooring was deployed near Keahole Point, Big Island, Hawaii. The current measurements were made with an upward-looking, bottom-mounted RDI Long Ranger 75 kHz ADCP. Gordon (1996) describes the working principle of ADCP instruments. The Acoustic Doppler Current Profiler measures motion in vertical "cells", with user selected thickness and range. Some specific information on the Oct. 2000 deployment and ADCP settings is given in Table 1, along with corresponding data on the 1999 measurements.

Table 1. Information on the ADP measurements near Keahole Point, Oct. 2000 and Aug - Sept. 1999

Measurement time	**2000**	**1999**
Instrument	RDI Long Ranger ADCP	RDI Long Ranger ADCP
Instrument number	SN 0923	SN 0923
Instrument depth	~ 797 m	~ 777 m
Measurement depth	290 - 785 m	259 - 763 m
Number of cells	100	85
Cell thickness	5.0 m	6.0 m
Position, North	19º43.243 N	19º43.064 N
Position, West	156º04.759 W	156º04.605 W
Deployment time (first valid measurement) *	07:43 October 27, 2000	20:30 August 5, 1999
Mooring recovery (last valid measurement) *	18:05 October 31, 2000	23:30 Sept. 12, 1999
Logging interval	10 minutes	40 minutes

* Time given in UTC

The 2000 location was somewhat deeper (20 m) and to the NW (250 m) of the 1999 site. Furthermore, the number and thickness of the ADCP cells were different, and the logging interval significantly shorter in the last series.

3. Acoustic Modem operations

During the survey, a LinkQuest Acoustic Modem was used for communication between the research vessel and the ADCP. This device can be used to retrieve data from the ADCP when it is moored at the sea bottom, and send new instructions to change instrument settings if desired.

The modem system consists of a surface transponder which is connected to a PC and lowered into the water, and a bottom transponder with separate battery pack fixed to the mooring frame and connected to the ADCP via cable. Operating frequency for the modem pair is in the 27 KHz – 45 KHz range (center Frequency: 35.7 KHz). The payload data transfer rate is 6600 bits/second under normal oceanic acoustic conditions.

During this survey, data were collected and retrieved in three separate series. Elapsed time between the end of one set and the beginning of the next is between 45 and 55 minutes. The three time series have been merged and are treated as one continuous data set in most of the following presentation and analysis.

A typical communication sequence with the RDI ADCP using the LinkQuest Acoustic Modem can be summarized as follows;

- check of ambient noise level (in water) using surface modem
- establish and optimize communication between surface and bottom modem using synchronization command (this becomes quicker each time it is performed in same environment)
- use RDI software to wake up ADCP (this implies that the instrument stops logging) - wait for receipt
- send command to retrieve data recorder information → get chronological list of data sets
- use modem data transfer protocol to upload selected (usually last) measurement series - the longer they are, the greater the risk of data transfer being interrupted
- go back into RDI software, send new wake-up command, wait for receipt
- Send script file to start new data collection series (this is also where one would usually change instrument settings if desired)

Experiences made in Hawaii Fall 2000:

- very good environmental conditions for acoustic data transfer; few particles in the water give little interference (compared with previous experiments in the Norwegian Sea).
- it is important to maintain position as directly above the ADCP as possible.
- uploading data is time consuming - in Oct. 2000 we have between 45 and 55 minute "holes" between the measurement series. These gaps can be divided into:
    a) actual communication time with the modem/ADCP (this was generally longer than strictly necessary because we wanted to take the opportunity to do a few extra tests when possible)
    b) the last ensemble of the previous file being cut before it was finished (up to 10 minutes lost)
    c) the first ensemble of the next series is averaged and recorded 10 minutes after start.
- care must be taken when selecting recording intervals (shorter ensembles means less cut-off, but also more data to transfer) and number/thickness of cells (the more cells the more data to upload).

There is an option of continuous uploading of data in real-time; this is however not considered a realistic option given the planned depth of the mooring and relatively strong surface/upper-layer currents.

4. Data presentation

Current velocities in all three spatial dimensions are the main parameters collected with the ADCP. In addition to increasing the general understanding of the sub-surface current regime in the area, these data are valuable for numerical modelling of both initial dilution and subsequent advection of injected CO_2, as well as for planning the monitoring activities for the experimental release. Measurements of the intensity of returning acoustic signals yields additional information on the presence of back-scattering surfaces such as particles and zooplankton and possibly also surfaces between fluids of different density (e.g. water-CO_2-interface).

The horizontal current velocities from the three different sub-sets of measurements made during the October 2000 deployment are shown in **Figure 2 - Figure 4** (corresponding to the three sub-series as described before - note that the time scales differ). In general, the data show good agreement with those from August-September 1999. Two regimes are present, as can be seen more clearly from the average current velocities shown in **Figure 5**. A predominantly northwesterly current, decreases (more or less uniformly) from an average of ~9.2 cm/s at 300 m depth to ~5.8 cm/s at around 500 m depth. An intermediate layer from 500 to 600 meters exhibits a more fluctuating current field, with much less directional stability (although the NW and SE currents are the more common as can be expected from local topography). Below this, average currents are more uniform, ranging from around 5.7 at 600 m to 4.9 cm/s at 750 m. The net current direction is towards the northwest.

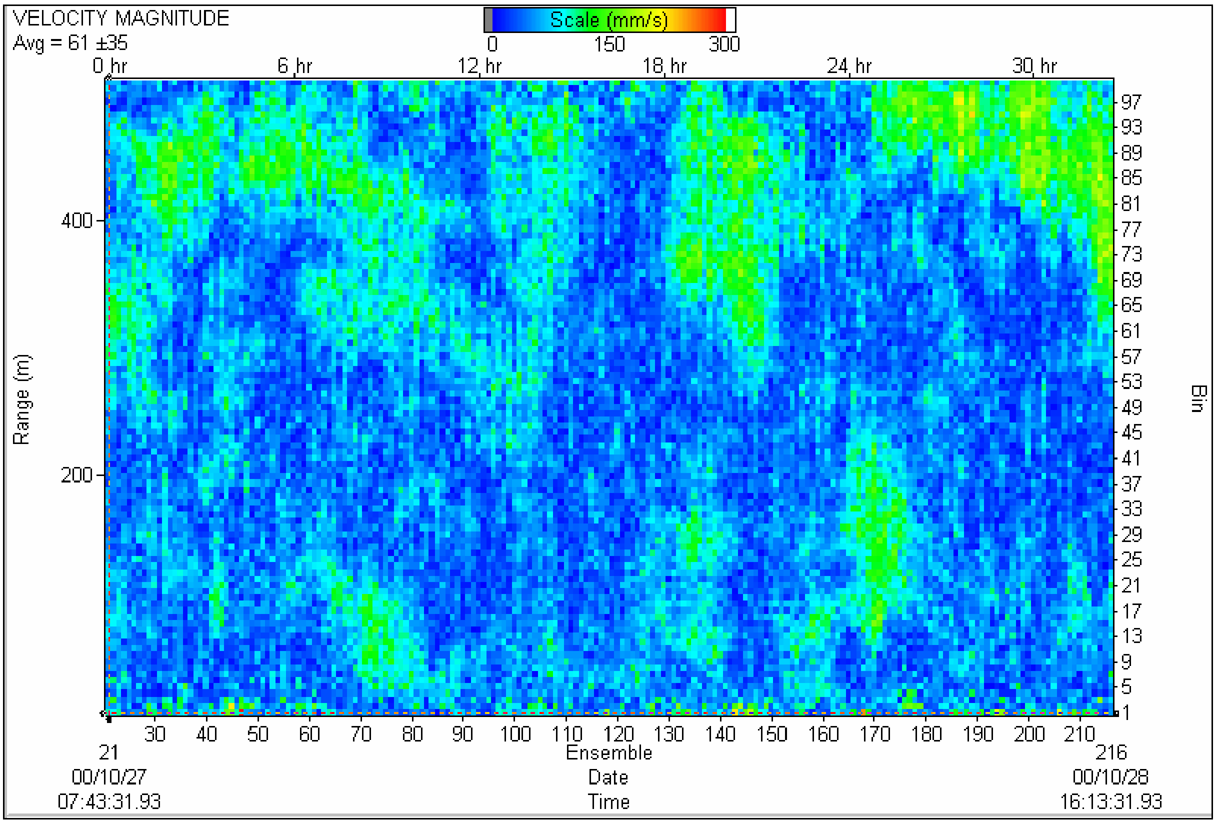


Figure 2. Current velocity [mm/s] for October 27-28 2000. Distance from ADCP [m] on left axis, measurement number and time on horizontal axis.

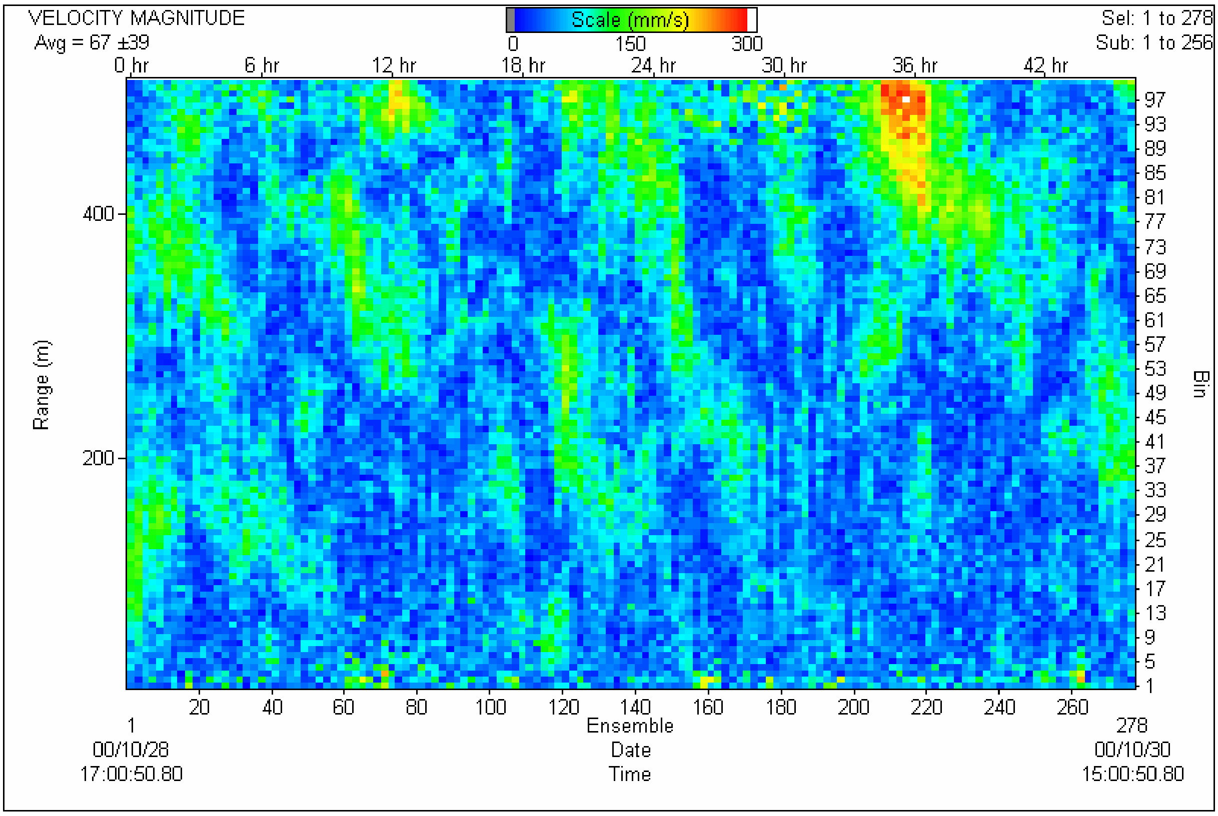


Figure 3. Current velocity [mm/s] for October 28-30 2000. Distance from ADCP [m] on left axis, measurement number and time on horizontal axis.

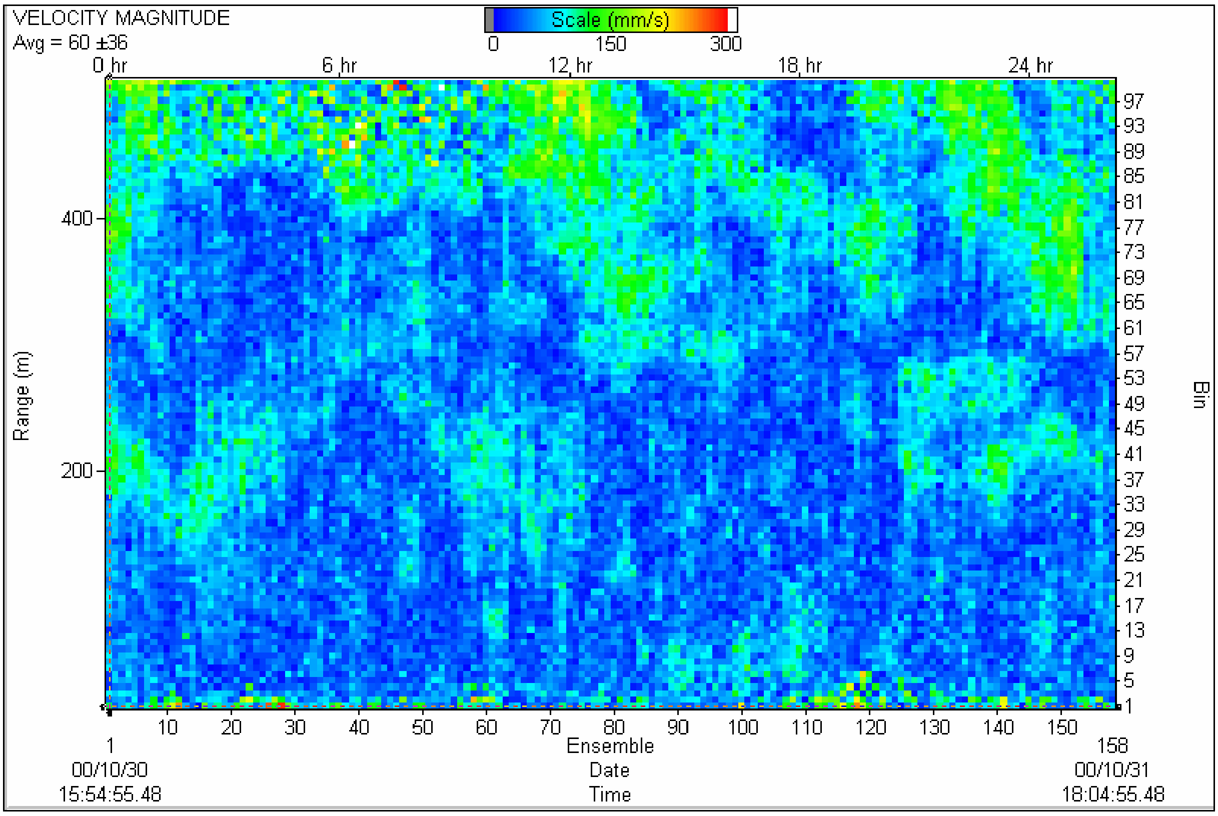


Figure 4. Current velocity [mm/s] for October 30-31 2000. Distance from ADCP [m] on left axis, measurement number and time on horizontal axis.

The deepest 3-4 cells show a marked increase in current velocity and greater directional variation towards the bottom (see **Figure 5**). This tendency was also observed in the 1999 measurements, but whether this is induced by topography or reflects interference on the current from the mooring buoys, or an artefact caused by acoustic backscatter from the rig/steep slope is not clear. It should also be noted that the signal strength normally will decrease with distance from the ADCP, and the accuracy of the measurements in the upper cells can therefore be expected to be lower than for the deeper ones as the signal to noise ratio dwindles.

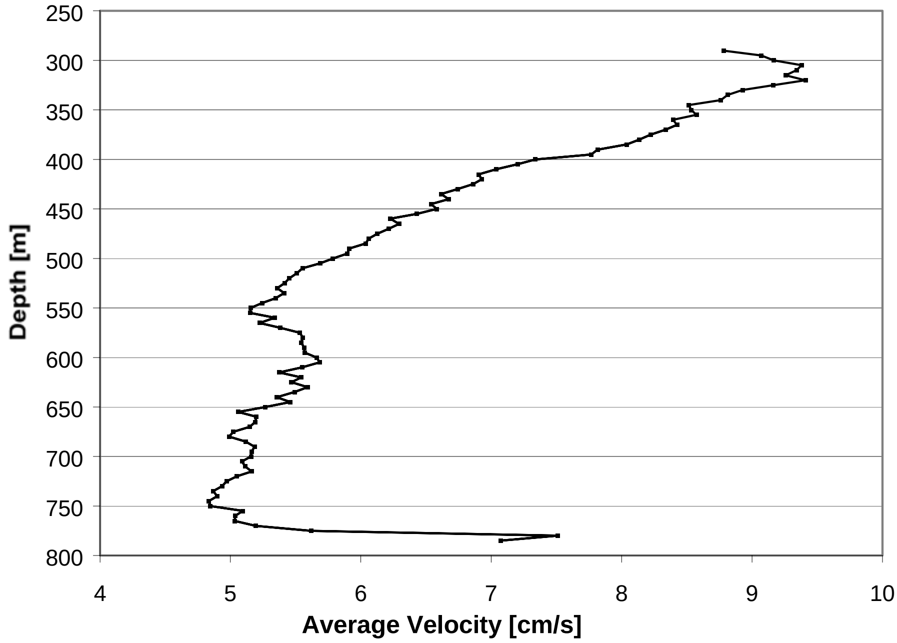


Figure 5. Average ADCP Current Velocity for the whole measurement period, for all depth cells.

Maximum current velocities (**Figure 6**) show more or less the same features as the average velocities, with values ranging from over 30.0 cm/s at 300 m to about 16.0 cm/s at 500 m, and between 14.0 and 16.0 cm/s below 600 m (again, the deeper few cells show increasing values).

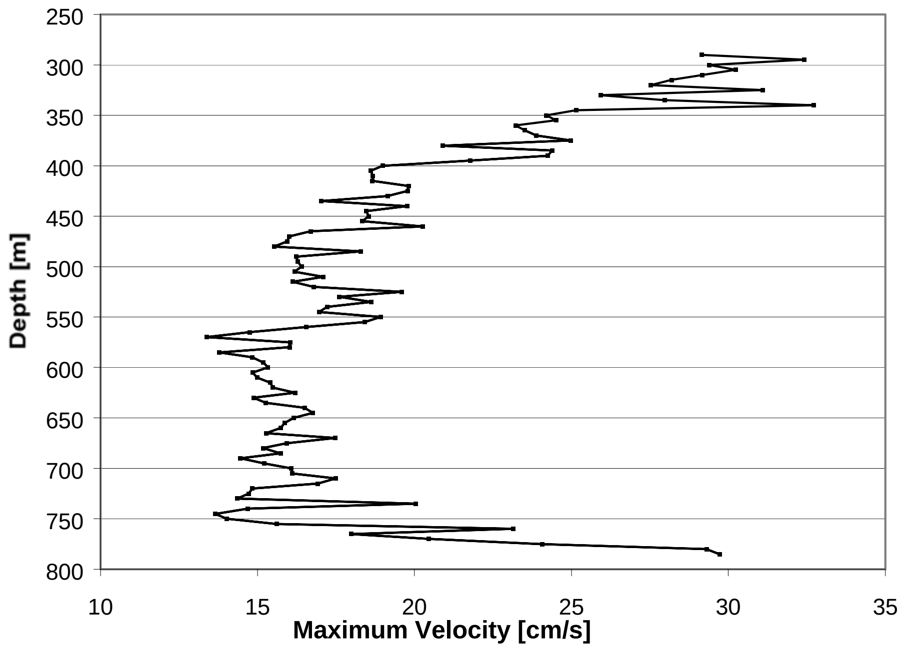


Figure 6. Maximum ADCP Current Velocity for the whole period, all depth cells.

Some relevant statistics for every 50 m (plus the first and last cell) are shown in **Table 2**. Along with average and maximum currents, the residual current velocity and direction are given for each depth. Residual current represents the vector sum of single measurements, and can be seen as representing a net, uni-directional current for the whole measurement period (**Figure 7**). The Stability Factor is found by dividing the residual current velocity by the average (absolute) current velocity, giving a measure of how directionally uniform the current is over time.

Table 2. Selected current statistics at 50 m intervals (plus first and last cell) based on the whole measurement period. Current velocities are given in cm/s, direction in degrees. The stability factor is a non-dimensional unit.

Depth [m]	Cell #	Average Current Velocity	Maximum Current Velocity	Residual Current Velocity	Residual Current Direction	Stability Factor
290	100	8.78	29.15	5.11	323.2	0.58
300	98	9.17	29.38	6.33	324.9	0.69
350	88	8.53	24.20	6.87	321.2	0.80
400	78	7.34	18.98	5.20	322.1	0.71
450	68	6.58	18.54	4.17	321.6	0.63
500	58	5.78	16.40	2.13	326.3	0.37
550	48	5.16	18.92	0.23	261.2	0.04
600	38	5.66	15.33	0.47	181.0	0.08
650	28	5.27	16.16	1.15	315.6	0.22
700	18	5.16	16.07	1.25	327.3	0.24
750	8	4.85	14.02	2.19	321.6	0.45
785	1	7.08	29.72	0.48	236.7	0.07

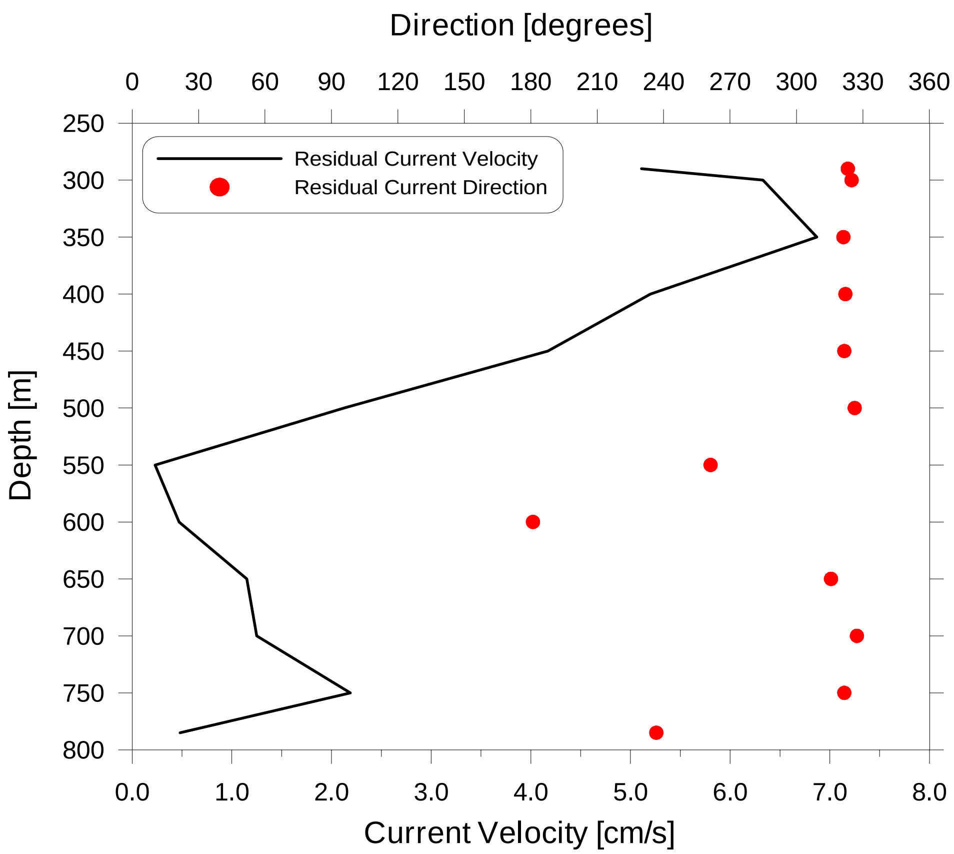


Figure 7. Residual Current Velocity and Direction for every 50 meters plus first and last cell.

In Appendix B, the following graphic plots are shown for every 50 m from 300 to 750 m depth, plus cell # 1 at 785 m:

- Current Velocity and Direction vs. Time
- Mean Current Velocities in different directions
- Relative Flux in different directions
- Progressive Vector Diagram ("net transport" from Eulerian measurements)
- Signal Strength vs. Time

As an example, the same plots are shown for cell 8 at 750 m depth in **Figure 8 - Figure 12** below. Note that time is given in UTC (Universal Time Coordinate), which is 10 hours ahead of local time on Hawaii.

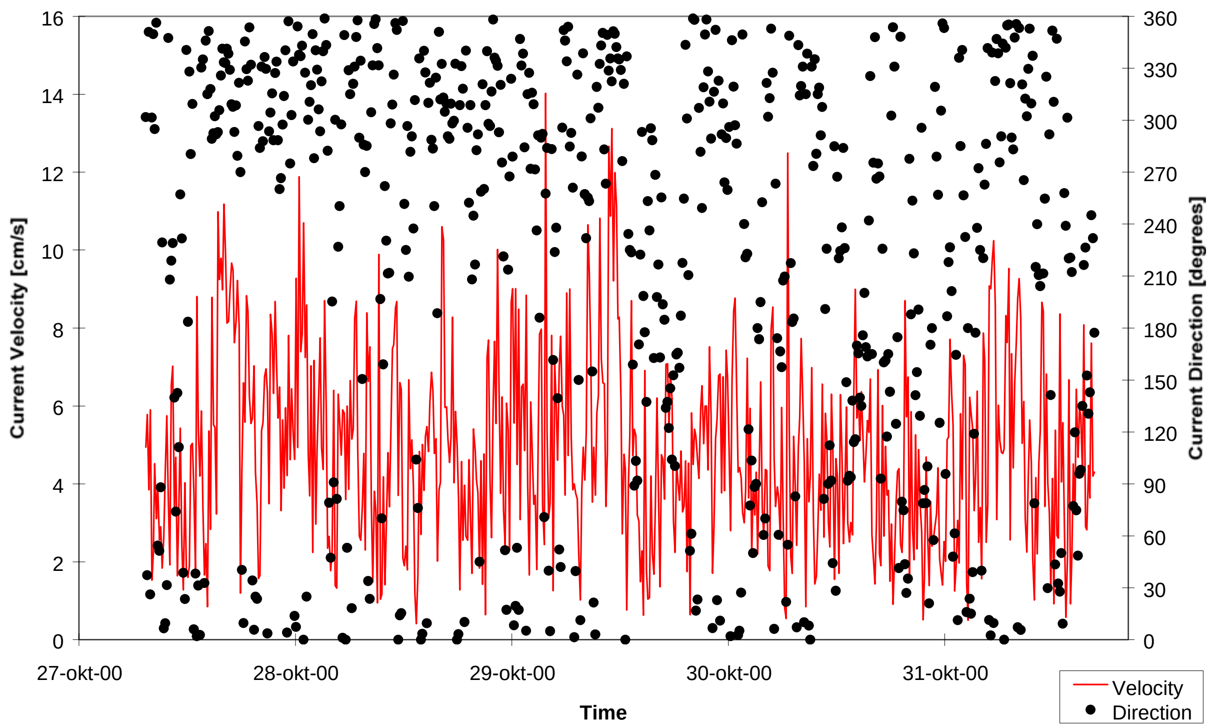


Figure 8. Current velocity (line) and direction (dots) vs. time for cell 8, 750 m.

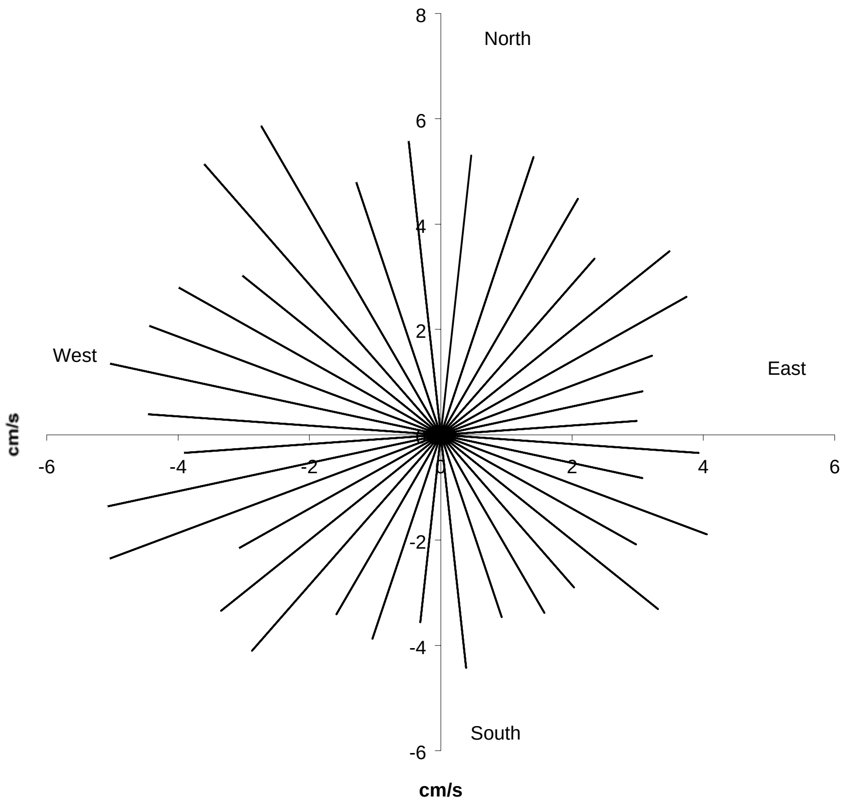


Figure 9. Mean current velocities in different directions for cell 8, 750 m.

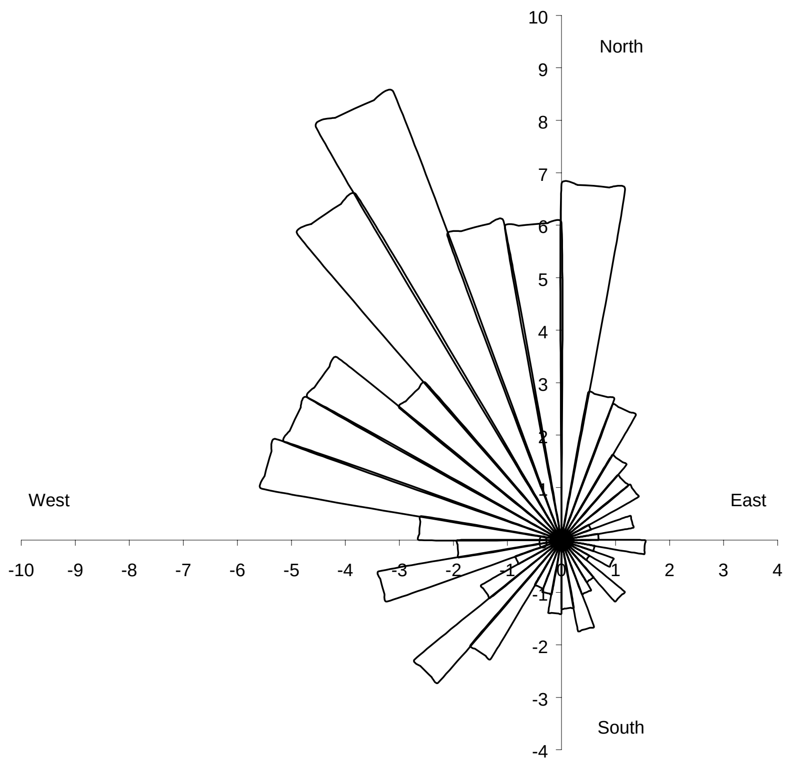


Figure 10. Relative flux (percent) in different directions for cell 8, 750 m.

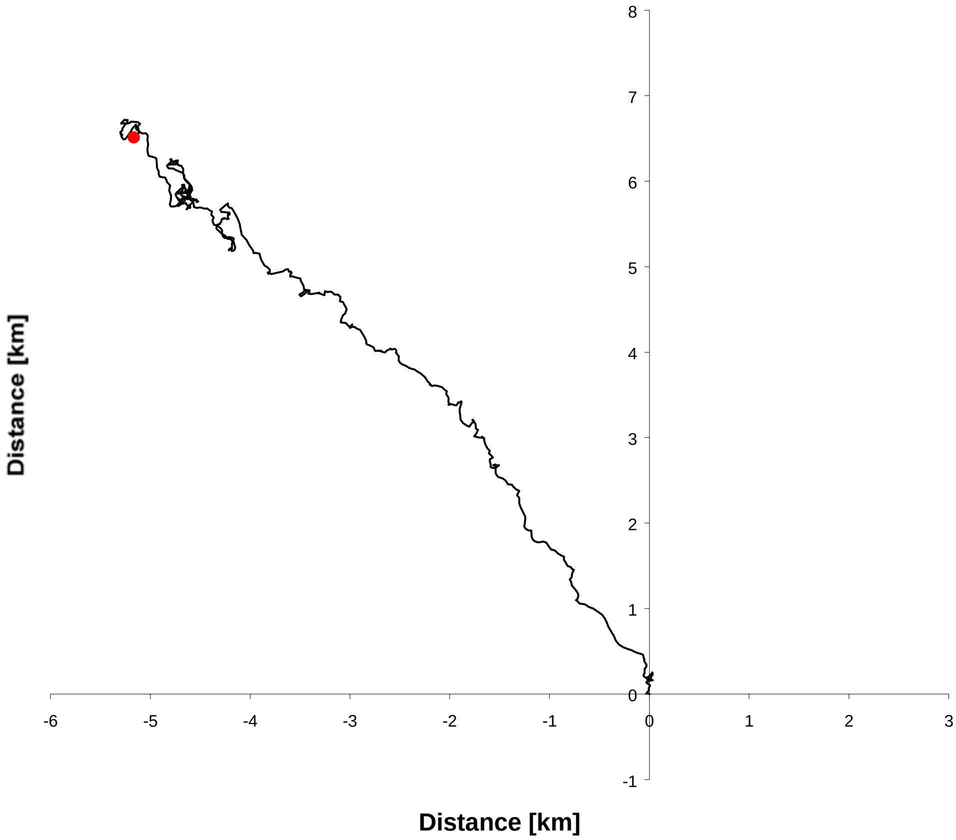


Figure 11. Progressive vector diagram for cell 8, 750 m.

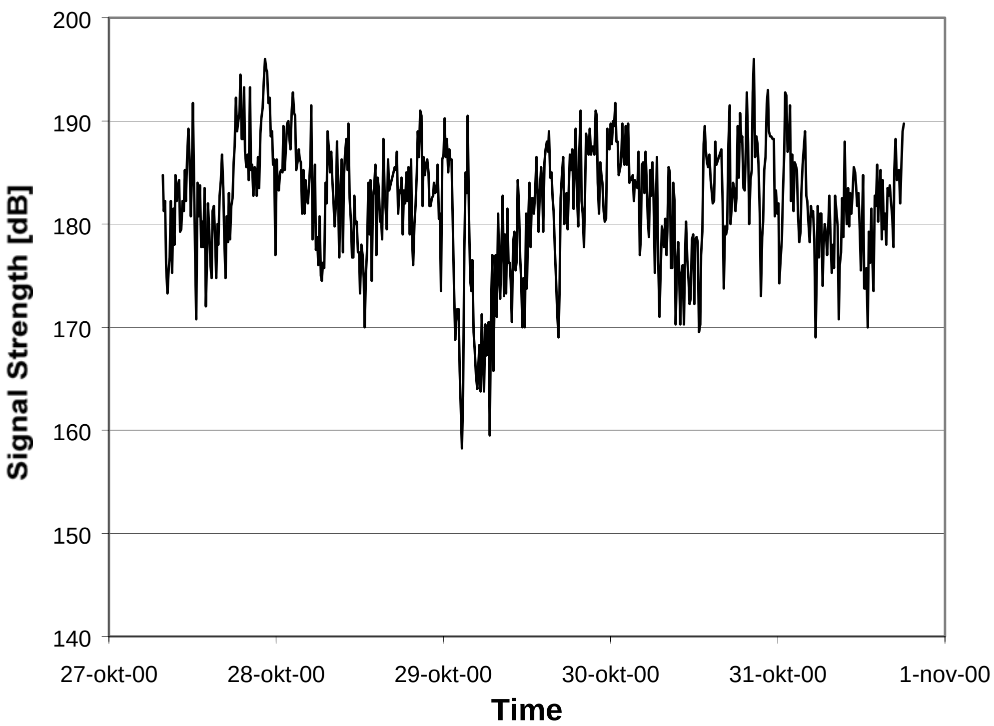


Figure 12. Signal strength vs. time for cell 8, 750 m.

5. Data Analysis

For the planning of monitoring activities, the frequency of change of current direction and strength is of particular interest. Current in cell 8 (750 m depth) was chosen to illustrate depths near the CO_2 injection point, and has been analysed to some extent. Stick plots for the first ~ 10 hours of measurements in cell 8 (750 m depth) (**Figure 13**) visualize how the current velocity and direction typically changes. In general, the current direction and speed changes frequently at this depth. Some periods with higher velocities, typically towards the NW, can be found (e.g. the last 8-10 measurements in **Figure 13**). Such periods often start with a slower, more westerly current, which increases in velocity as the direction turns towards the north. As the tidal maximum passes the northerly current velocity component decreases. Stick plots for the rest of the measurements from cell 8 are shown in Appendix C.

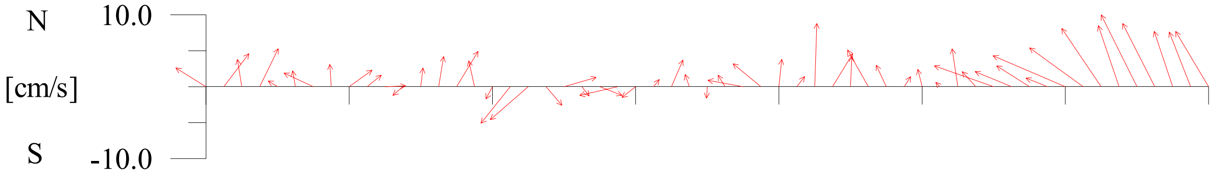


Figure 13. Stick plots of individual current measurements (10 minute intervals) for the first ~ 10 hours in cell 8. The length of each arrow represents current velocity (scale on left), direction is given as north upwards and east to the right.

5.1 Current velocity - distribution and duration

The actual duration of various current "events" such as periods with a particularly weak or strong current, and length of periods with direction within a given sector has been statistically analysed to some extent. The fall 2000 measurement series is relatively short, and a comprehensive study has therefore not been undertaken.

Average current velocity for cell 8 was 4.85 cm/s, and the majority (72.5 %) of the recorded velocities were in the range from 2.0 to 7.5 cm/s (see **Figure 14**). About 12.3 % of the registrations were below 2.0 cm/s, and about 15.2 % above 7.5 cm/s.

There were no long periods with low current velocities. The longest period with current under 2.0 cm/s was 30 minutes, and the average sub-2.0 cm/s period was 13 minutes. Average period under 4.0 cm/s was 20 minutes, with the longest continuous period being 1.2 hours. For the stronger currents, the picture is similar; periods with current over 7.5 cm/s lasted for 18 minutes on the average, with a maximum period of 2.5 hours. The longest period with current stronger than 10.0 cm/s was 30 minutes.

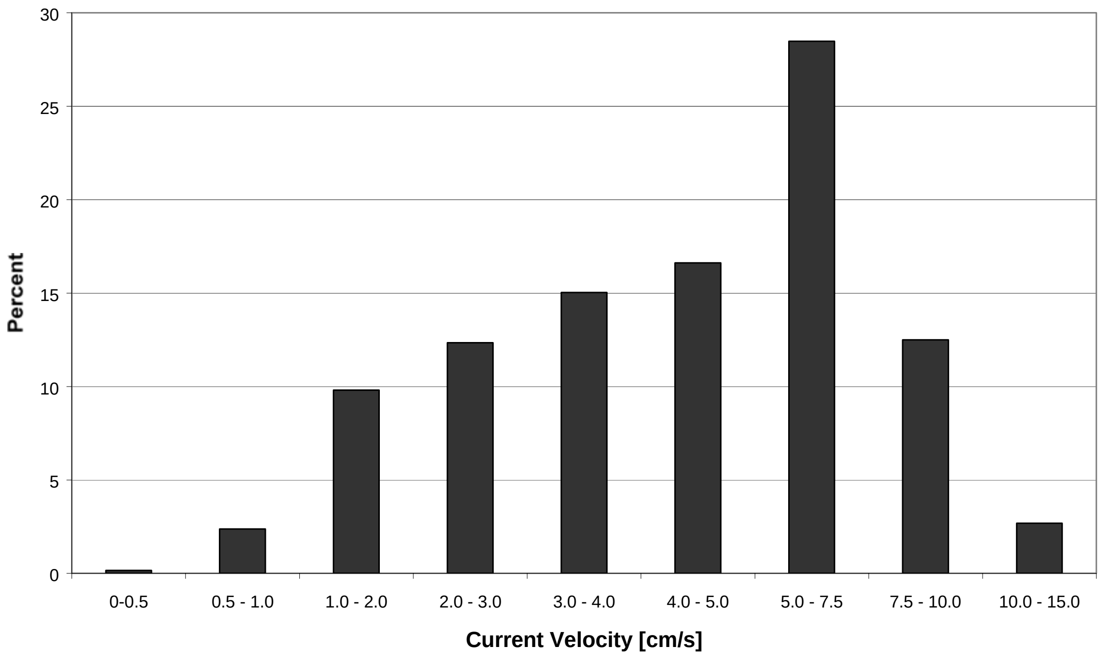


Figure 14. Distribution of current velocities for cell 8 (750 m).

5.2 Current direction - distribution and duration

Figure 15 shows the relative distribution of currents in 45-degree sectors. As was seen in **Figure 10** above, currents towards NW dominate. This 45-degree sector alone comprises about 25% of all recordings, and the two other main sectors are centered at 270 and 360 degrees. There are, however, frequent changes in direction. The mean period that the current direction stays within a given 45-degree sector is around 15 minutes for all sectors, and only slightly longer for the W/NW/N sectors.

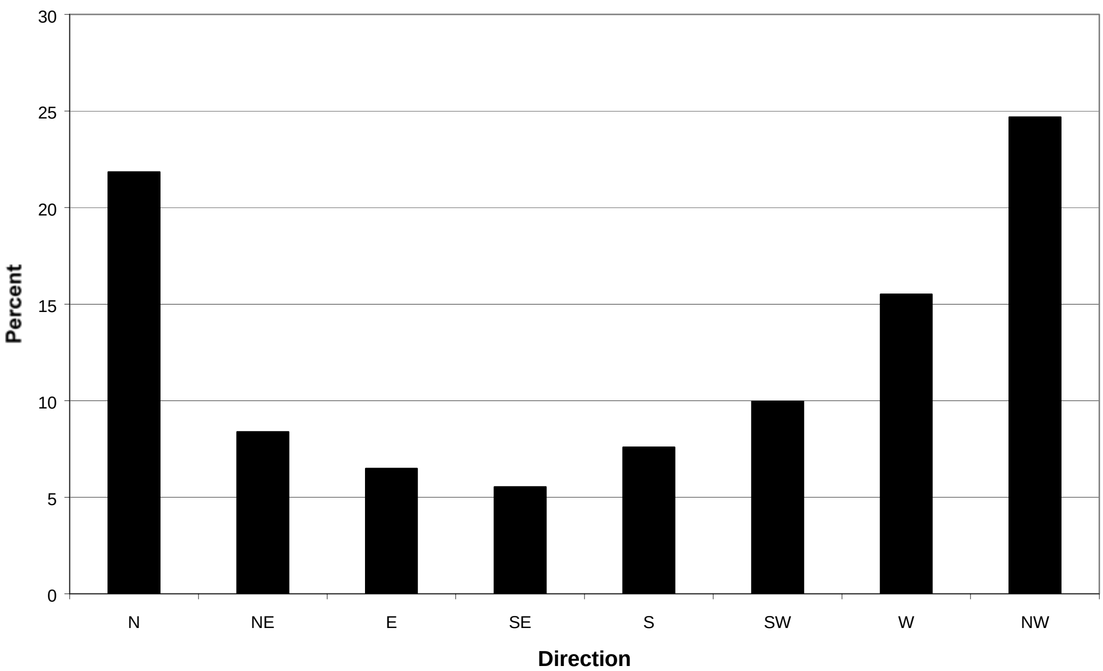


Figure 15. Direction distribution in 45 degree sectors for cell 8, 750 m depth. Letters denote centers of 45-degree sectors, i.e. "E" means the sector from 67.5 to 112.5 degrees.

Looking at the length of time the current is outside each sector, the difference between the predominant sectors and the rest becomes clearer. Mean period outside each of these three sectors is approximately one hour, whereas for the less frequent directions the period outside can be three to four hours. Longest periods outside the predominant sectors are 4.0 (W), 5.2 (NW) and 7.0 hours (N). For the others, the longest period outside the sector is 12.5 (NE) to 21.5 (SE) hours.

Grouping currents within 90-degree sectors underscores the previous points; the sector from 270 to 360 degrees accounts for 47.2 % of all measurements. Mean period with current inside this range is 31 minutes, and the longest continuous period measured here is 4.0 hours. On the average, the current is only directed outside of the sector for 35 minutes, and the longest recorded period outside is 3.5 hours.

5.3 Spectral analysis

The current velocity in cell 8 (750 m) has been analyzed for high-energy frequencies, using Fourier analysis in the STATISTICA™ Time Series module. The higher the Spectral Density, the higher the velocity for the oscillating phenomena. Some of the most prominent frequencies are shown in **Table 3**, along with their corresponding periods (computed for 10 minute sampling interval). Peak values are the actual periodogram values, density values are smoothed peak values that show the relative contribution to the cyclical phenomena from each frequency "region".

Table 3. Major frequency peaks with corresponding periods for cell 8 (750 m depth).

Frequency	Period [hrs]	Periodogram peak value	Spectral Density
0.0063	26.6	122.9	88.6
0.0157	10.6	108.9	54.6
0.0188	8.9	112.7	61.7
0.0266	6.3	85.8	55.3
0.0345	4.8	76.8	39.8
0.0596	2.8	86.5	57.6
0.0862	1.9	55.6	37.3
0.1144	1.5	39.1	29.6
0.1364	1.2	42.9	26.0

The lower frequency part of the spectrum is shown in **Figure 16**. Distinct peaks are clearly seen; the diurnal tidal component is the most energetic, with frequency 0.0063 (26.6 hours). Another, more prolonged peak is found for periods 8.9-10.6 hours, and again at 6.3 and 4.8 hours.

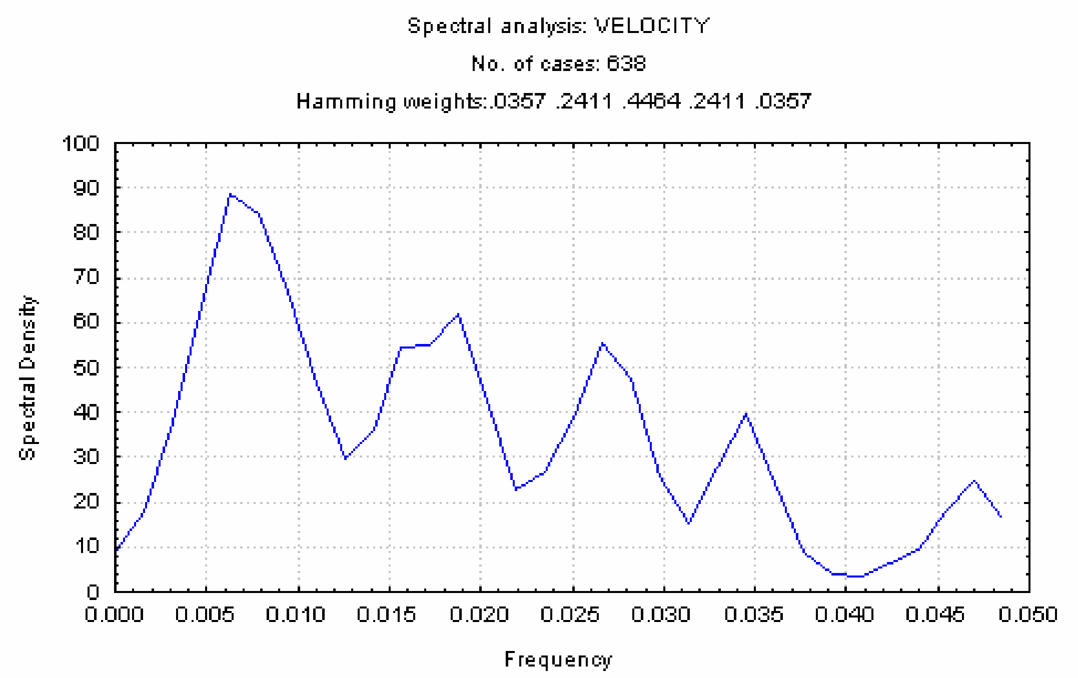


Figure 16. Energy spectrum for cell 8 (750 m depth). The upper limit of 0.50 cycles corresponds to a period of 3.33 hrs.

For comparison, the same plot is shown for cell 78 (400 m) in **Figure 17**. The same major components are seen, but with somewhat lower frequencies (longer periods). The first peak extends from 35.4 to 26.6 hrs, next is the semi-diurnal tide from around 10.6 to 13.3 (peak at 11.4) hrs, and smaller peaks at around 7.4 and 5.6 hrs.

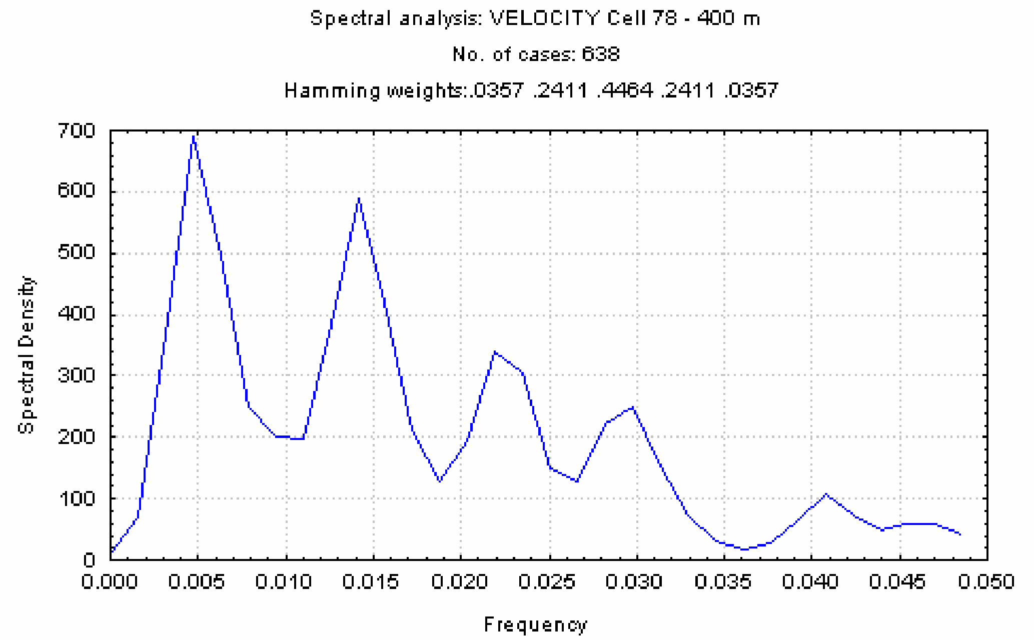


Figure 17. Energy spectrum for cell 78 (400 m depth). Note that the spectral density scale is different from that in the previous figure.

The higher frequency end of the spectrum for cell 8 is shown in **Figure 18**. Several energy peaks are evident, with corresponding periods of ~ 2.8 hrs, 1.9 hrs, 1.5 hrs and 1.2 hrs. When similar analysis was performed on the 1999 data (Sundfjord & Golmen 2000) periods of ~ 2.6 and 1.1 hours were found. We therefore believe that this can be a more or less consistent phenomenon such as a topographically induced internal wave, driven and modified by fluctuations in the barotropic current field.

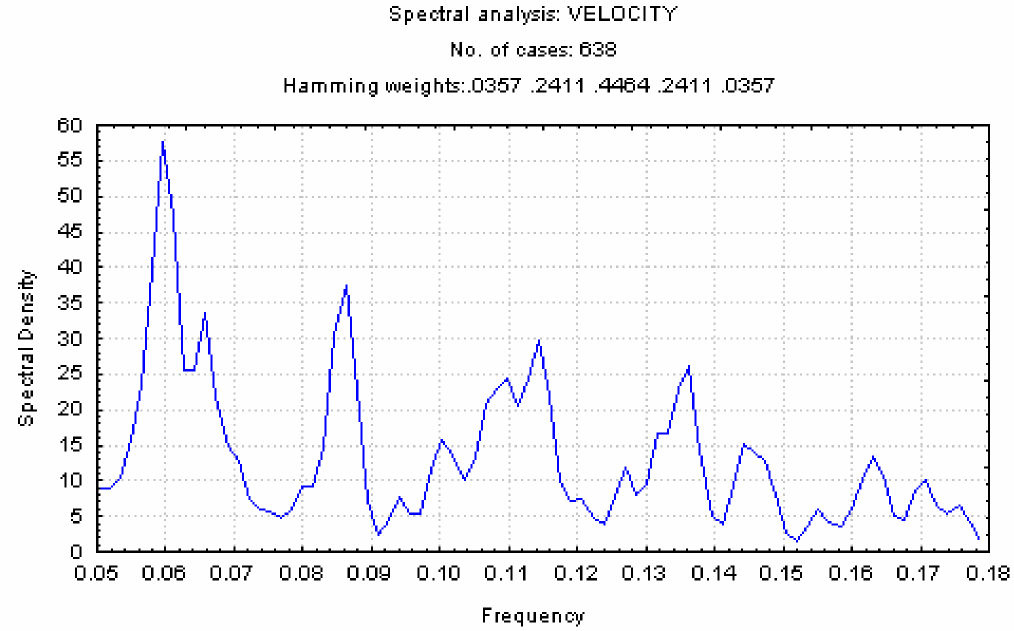


Figure 18. High-end energy spectrum for cell 8 (750 m depth). The spectral density scale is different from the previous figures.

The ADCP data were originally recorded in three separate series. For this analysis, missing data between the different sets (3-4 data points) have been filled in by interpolation from adjacent points.

5.4 Comparison between 1999 and 2000 measurements

The measurements from summer 1999 and fall 2000 have several similarities, despite the different seasons. Most striking is the conformity of the average current velocities, as seen in **Figure 19**.

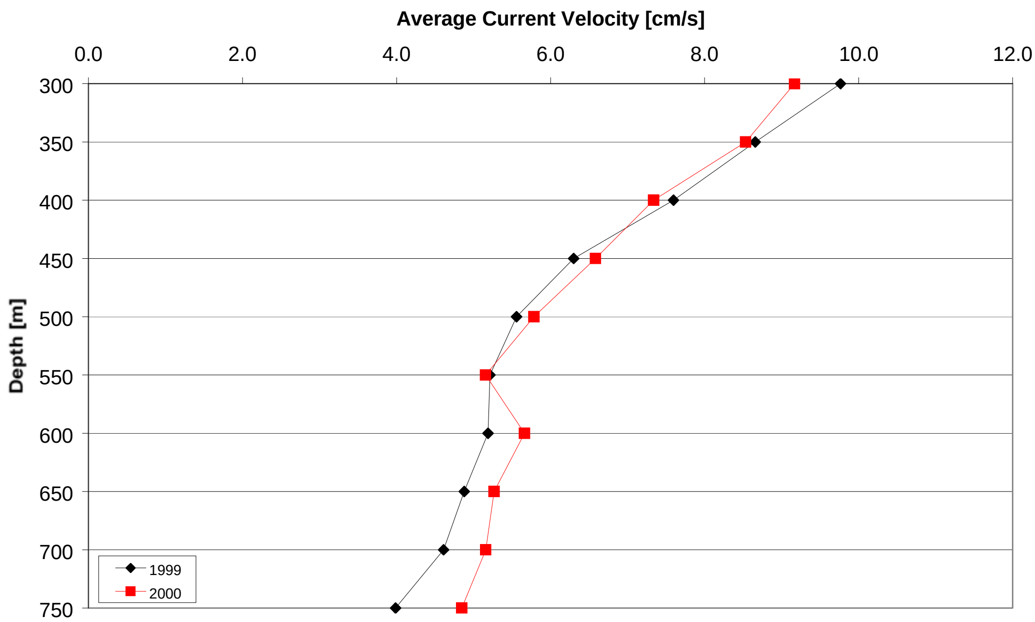


Figure 19. Average current velocities for 1999 (◆) and 2000 (■) measurements.

Residual current magnitude (**Figure 20**) also show very similar features; the currents decrease with depth until they reach local minima at 500 m (1999) and 550 m (2000), where the net transport is close to zero. Below this they increase again, particularly in the 1999 series.

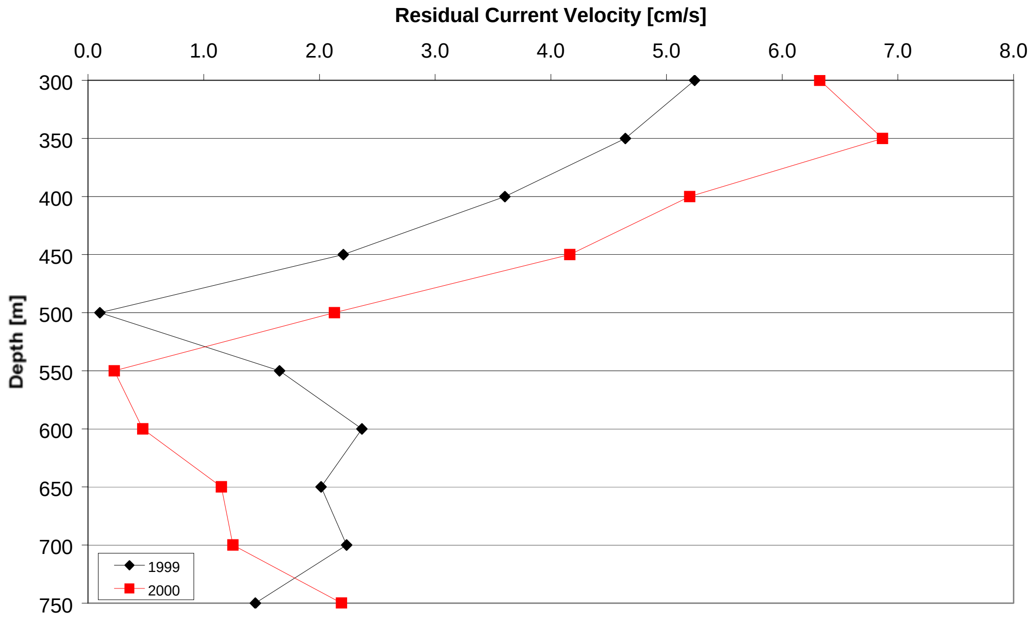


Figure 20. Residual current magnitude for 1999 (◆) and 2000 (■) measurements.

Residual current direction (**Figure 21**) for the two data sets reveal an extreme degree of correlation between 300 and 450 meters. There is more difference in the transitional zone at around 5-600 m depth (the net current is very small at these depths, and the residual current direction is not a very useful entity here). In the deepest part of the measurement domain the two series are quite different; in 1999 the net current is towards SE, in 2000 to the NW (as in the upper part of the water column).

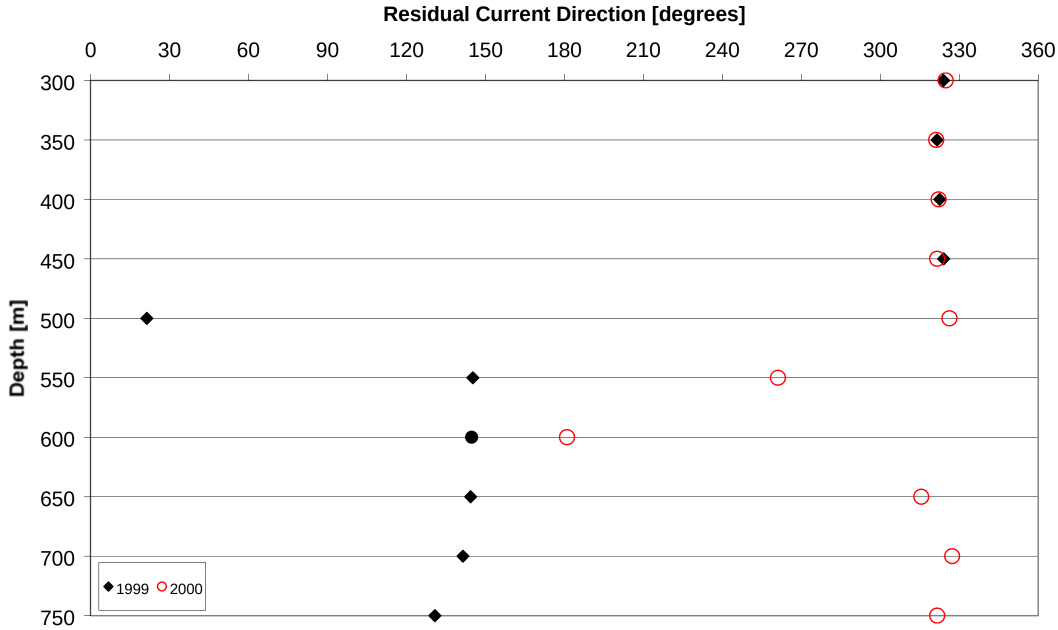


Figure 21. Residual current direction for 1999 (◆) and 2000 (○) measurements.

The stability factors (explained above) can be seen as representing how directionally uniform the horizontal current is at each particular depth. **Figure 22** shows that the directional stability was larger at shallower depths in the fall 2000 than summer 1999. The transitional layer, with distinct minima, is somewhat deeper in the 2000 measurements. In the deeper cells, the current was more uniform in direction in 1999 than in 2000 (the net direction was also reversed as seen in **Figure 21**).

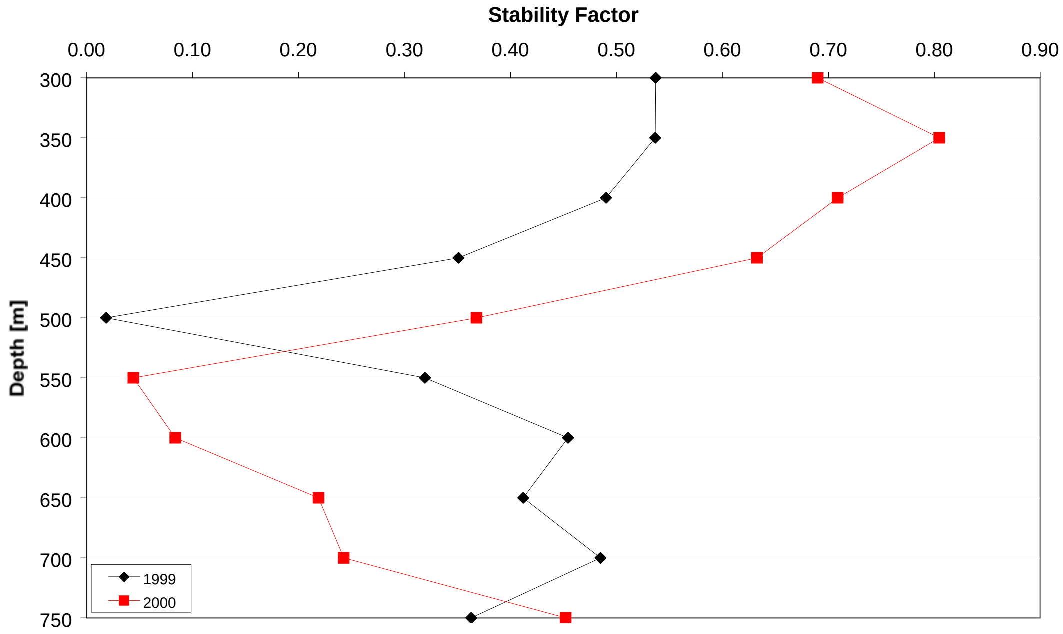


Figure 22. Stability factors for 1999 (◆) and 2000 (■) measurements.

The main findings of the October 2000 current measurements can be summarized as follows;

- Current velocities below the transitional layer at around 500-550 m depth are mostly in the range from 2.0 to 7.5 cm/s (average 5.0 - 5.5 cm/s).

- Current direction varies frequently. Predominant directions are to the NW and SE, following topography. Net transport at depths 550-750 meters was to the SE in the 1999 measurements, and to the NW in 2000.

6. References

Gordon, R. L. 1996: Acoustic Doppler Current Profiler - Principles of operation: a practical primer. RD Instruments, San Diego, California, 54 pages.

Maeda, Y., Y. Koike, K. Shitashima, N. Nakashiki and T. Ohsumi 2000: Direct measurements of Currents in West Coast of Hawaii Island (1.2 miles offshore of Keahole Pt.). Technical note, CRIEPI, Japan, 15 pages.

Sundfjord, A. and L. G. Golmen 2000: Ocean current measurements off Keahole Point, Hawaii, 5 August – 12 September, 1999. NIVA Report SNO 4198-2000, Oslo, 104 pages.

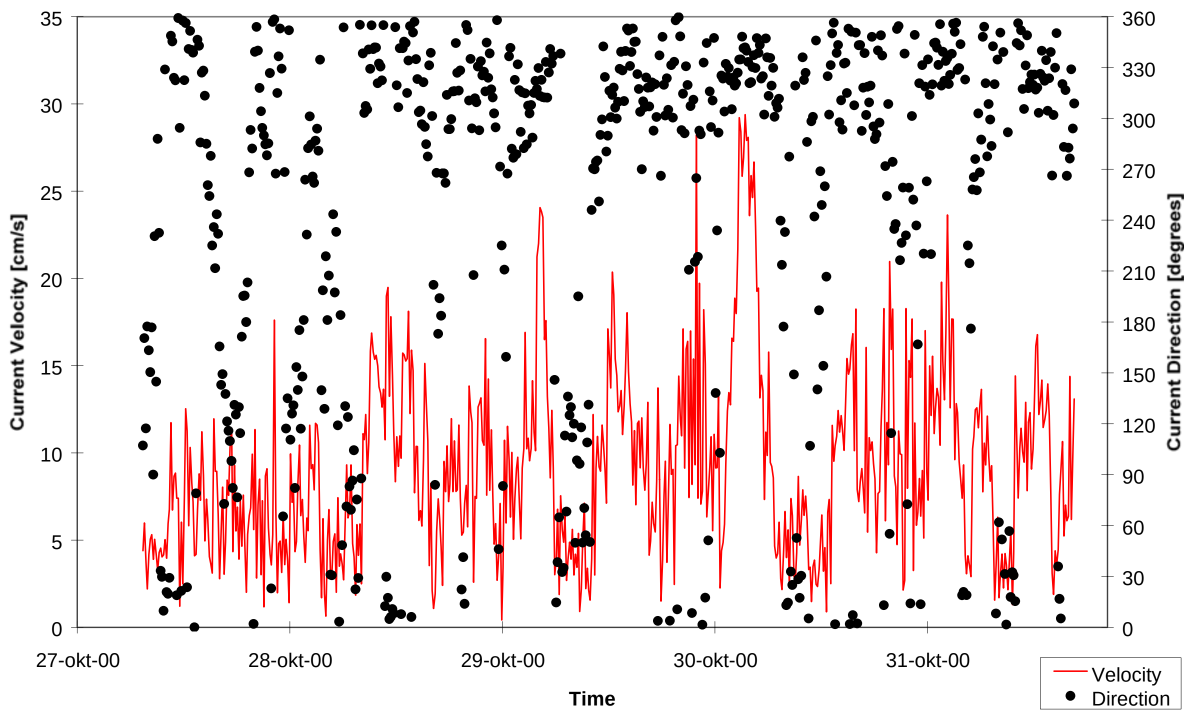
Appendix A. ADCP data

The following plots are shown for every 50 m from 300 to 750 m depth, plus cell # 1 at 785 m:

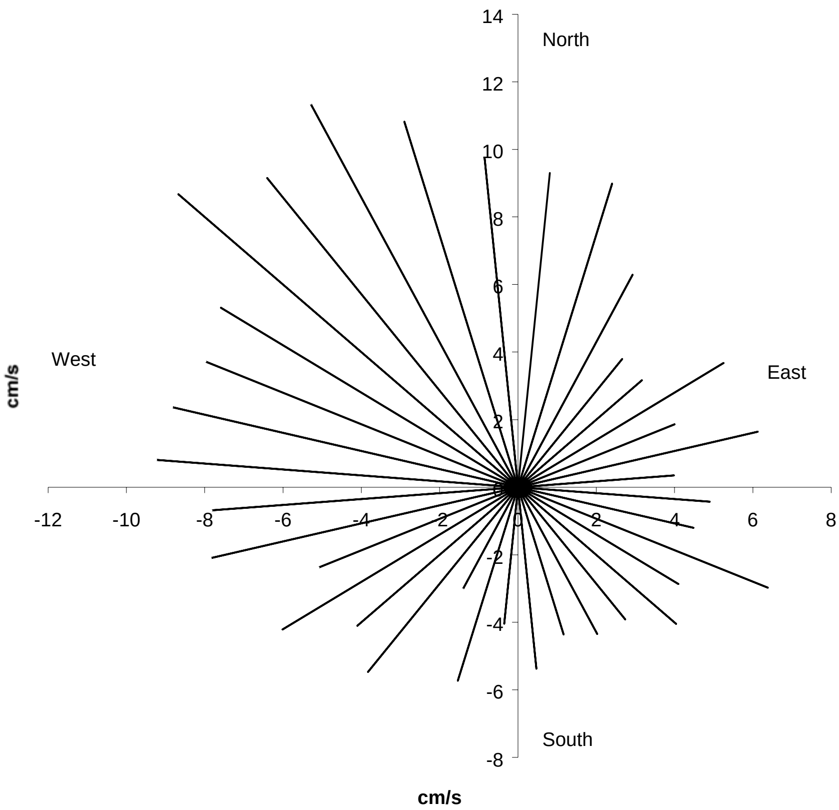
Current velocity and direction vs. time - A
Mean current velocities in different directions - B
Relative flux in different directions - C
Progressive vector diagram ("net transport" from Eulerian measurements) - D
Signal strength vs. time - E

Please note that all times are given as UTC (Universal Time Coordinates).

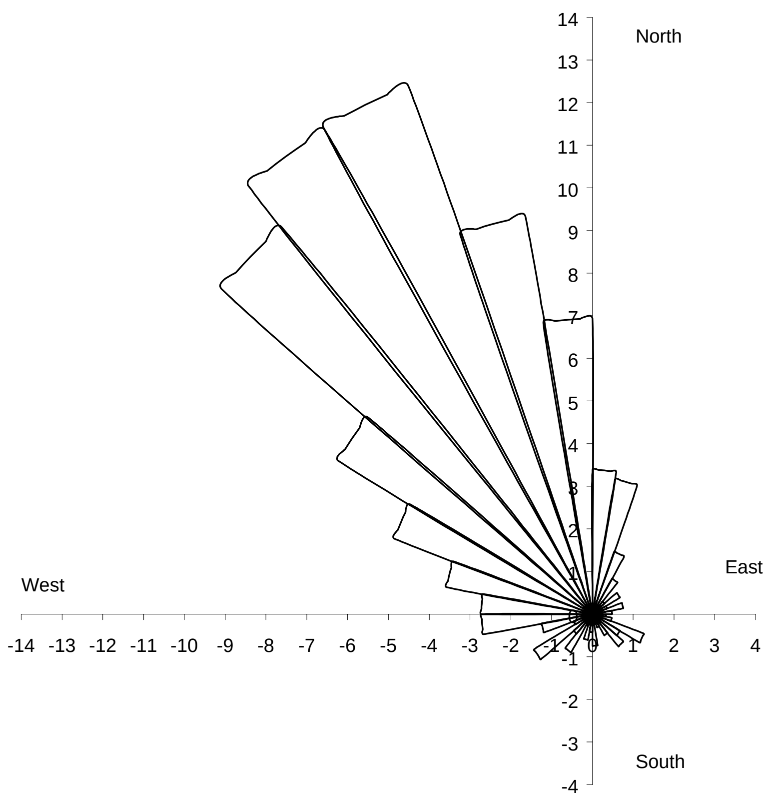
300 m - Cell 98



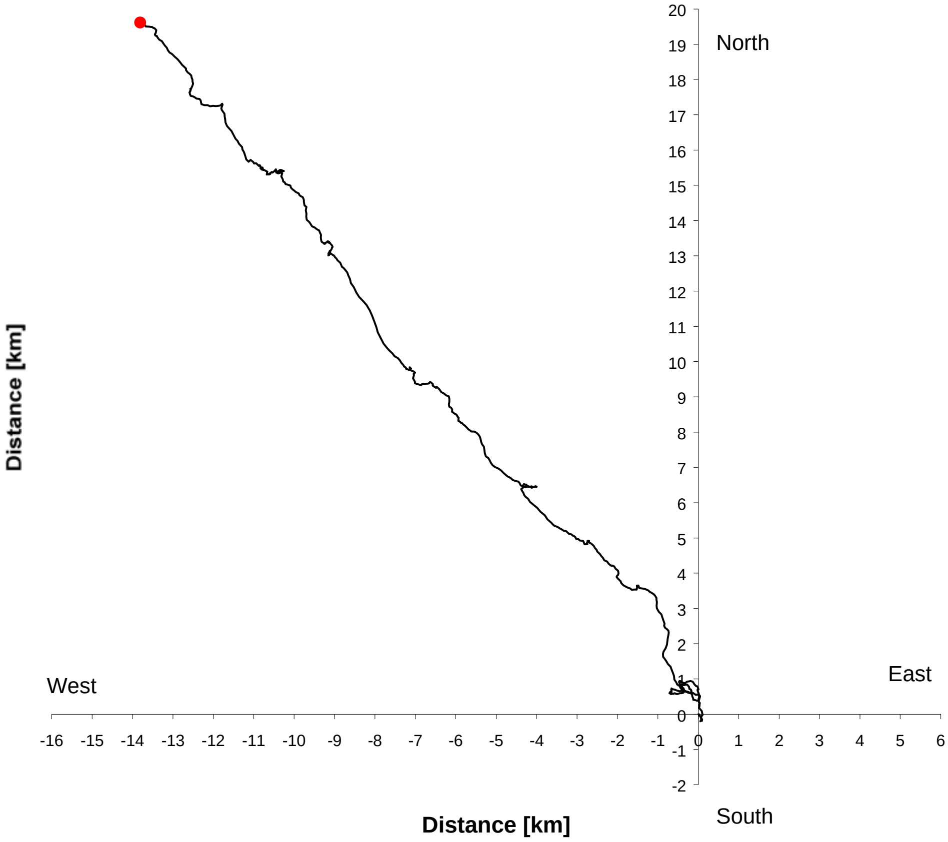
A


14
North
12
10
8
6
4
West
East
cm/s
2
0
-12
-10
-8
-6
-4
-2
0
2
4
6
8
-2
-4
-6
South
-8
cm/s

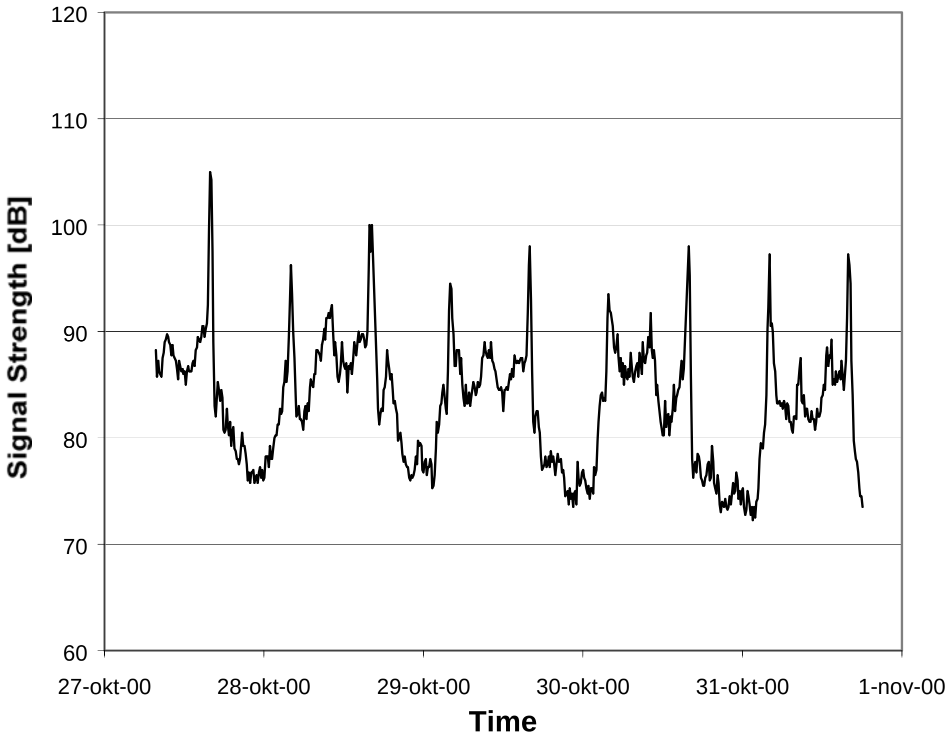
B


14
North
13
12
11
10
9
8
7
6
5
4
3
2
1
East
West
0
-14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4
-1
-2
-3
South
-4

C

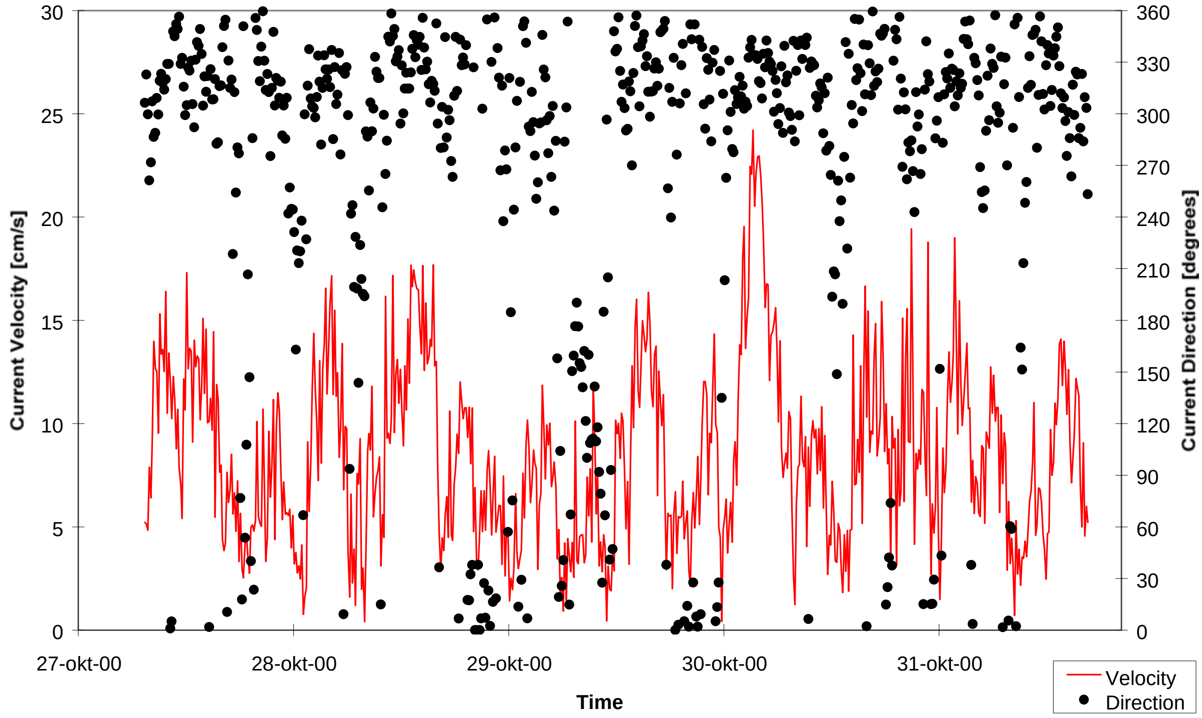

North
South
West
East
Distance [km]
Distance [km]

D

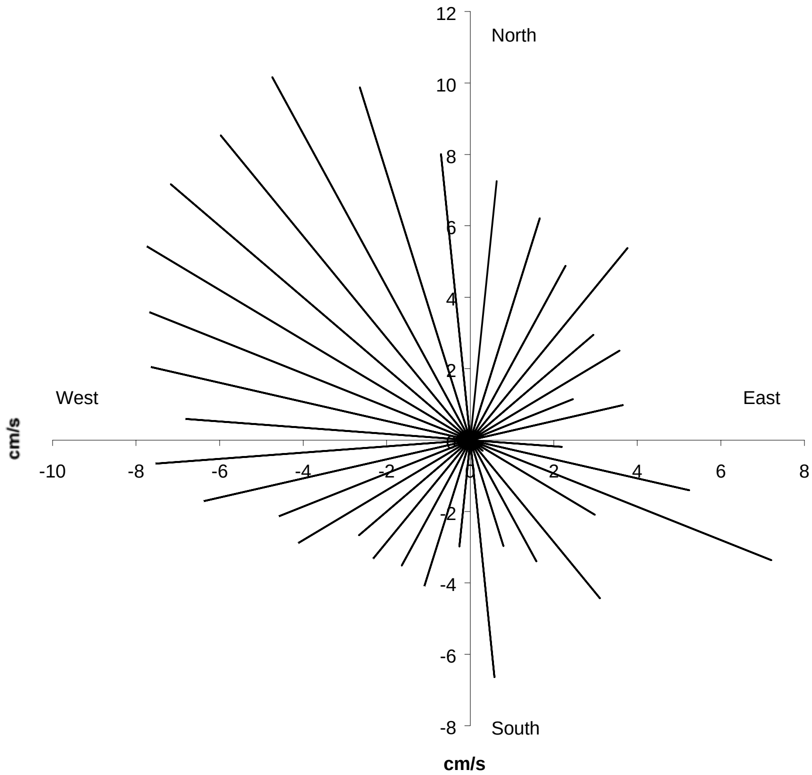

Signal Strength [dB]
Time
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
1-nov-00

E

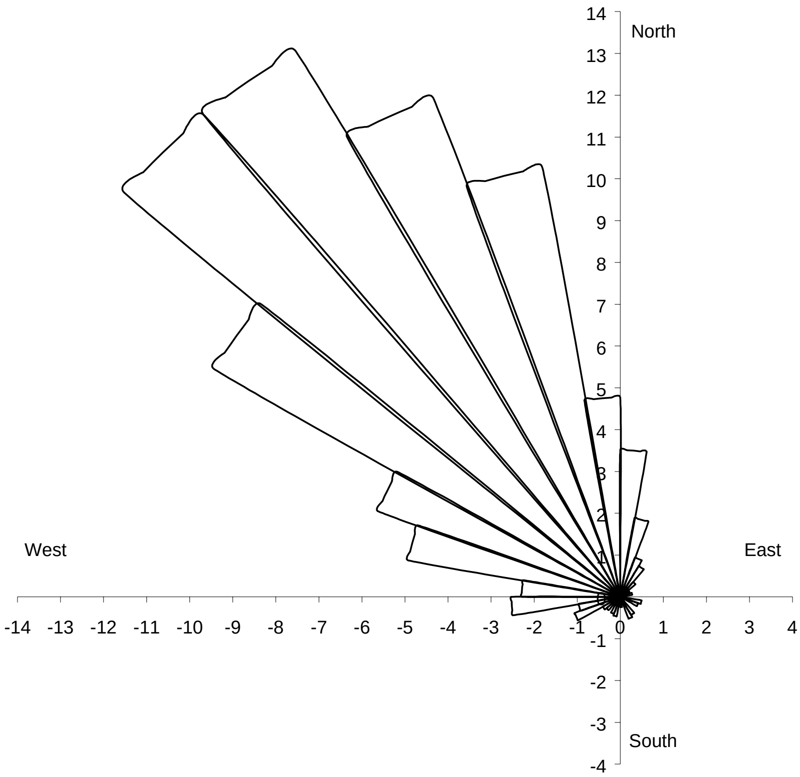
350 m - Cell 88



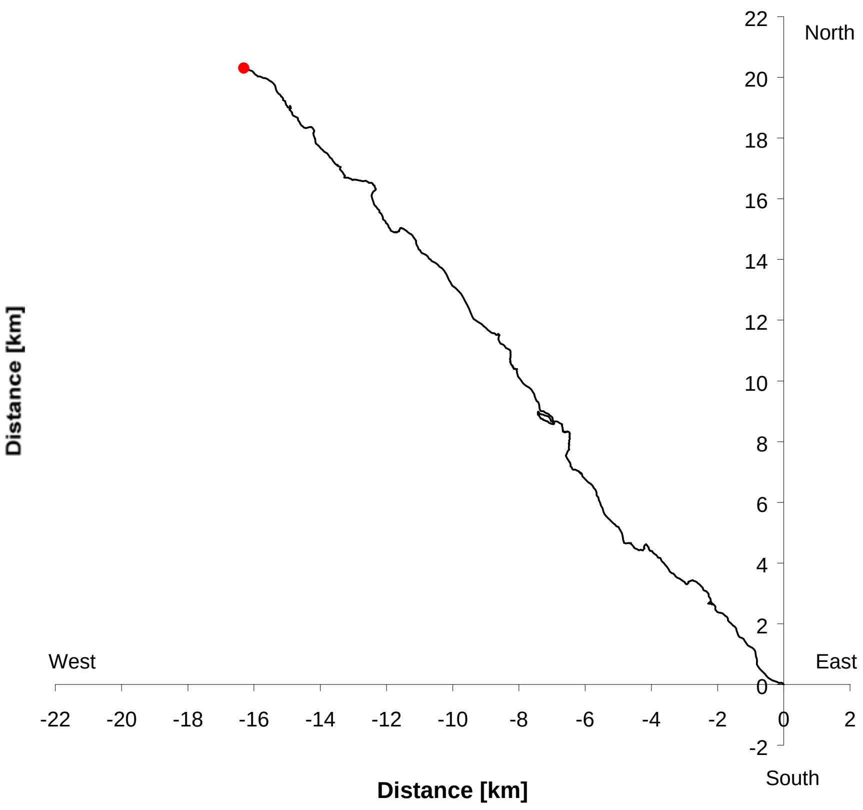
A



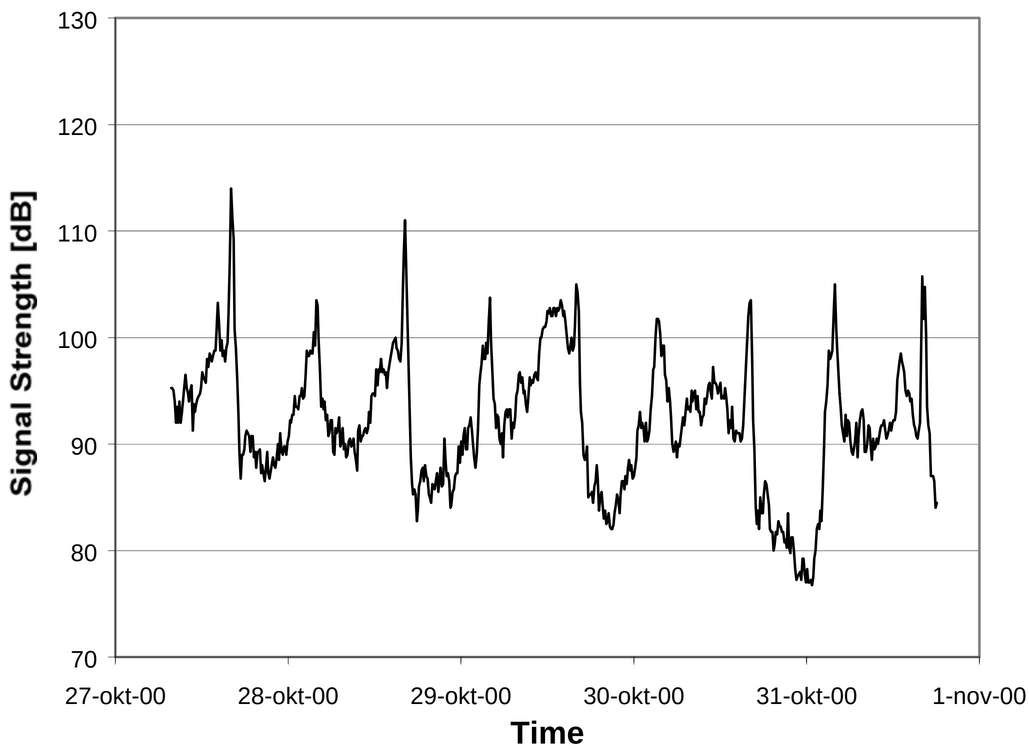
B


North
West
East
South
14
13
12
11
10
9
8
7
6
5
4
3
2
1
-1
-2
-3
-4
-14 -13 -12 -11 -10 -9 -8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4

C

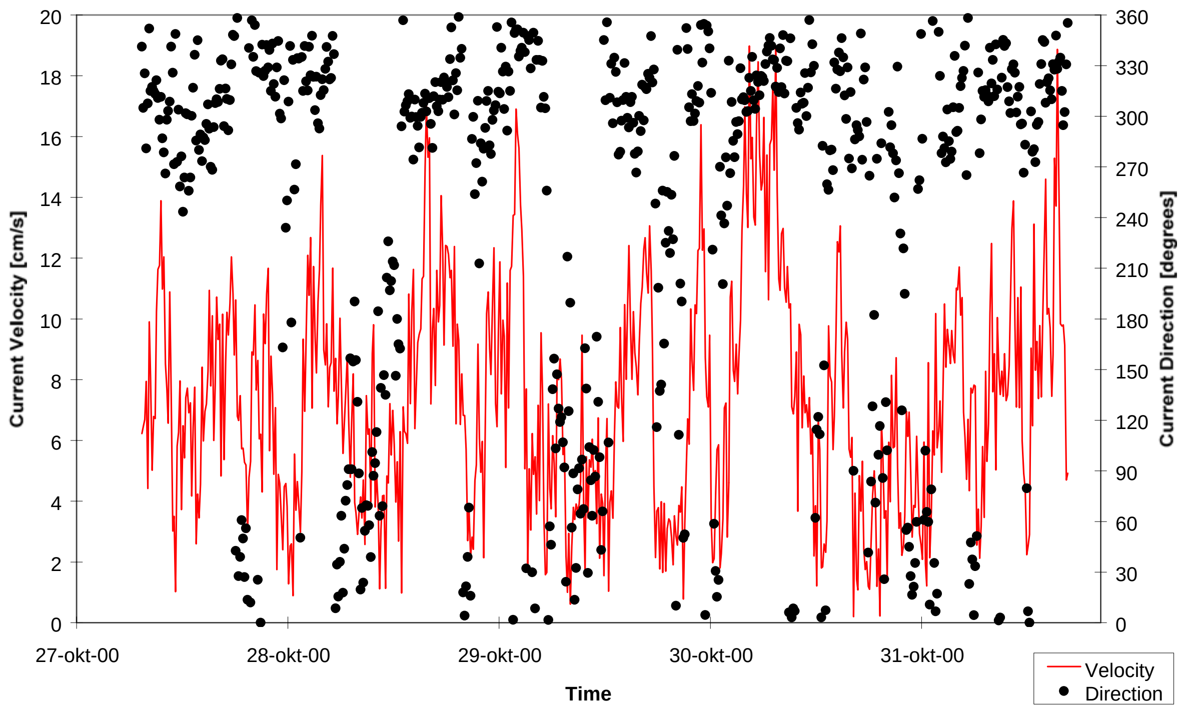

North
West
East
South
Distance [km]
Distance [km]
22
20
18
16
14
12
10
8
6
4
2
0
-2
-22 -20 -18 -16 -14 -12 -10 -8 -6 -4 -2 0 2

D

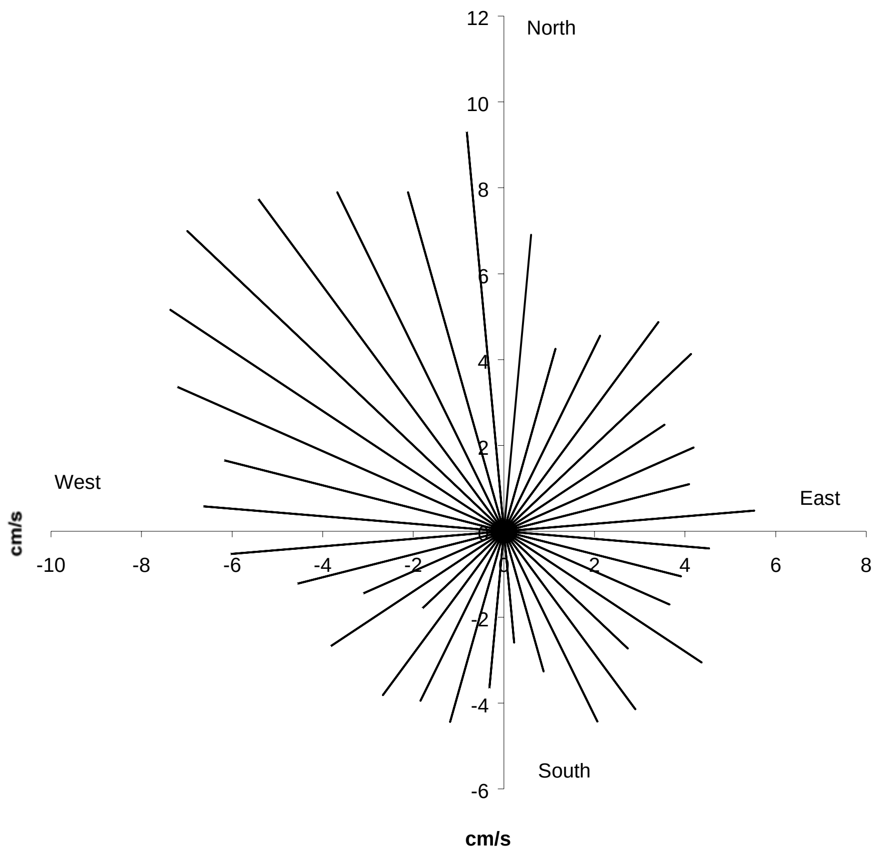


E

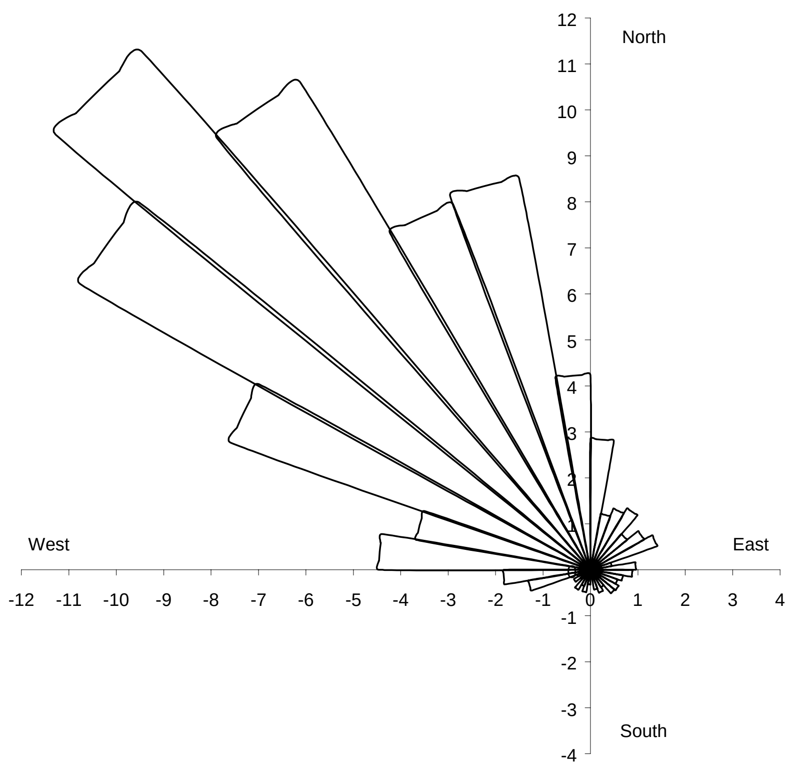
400 m - Cell 78



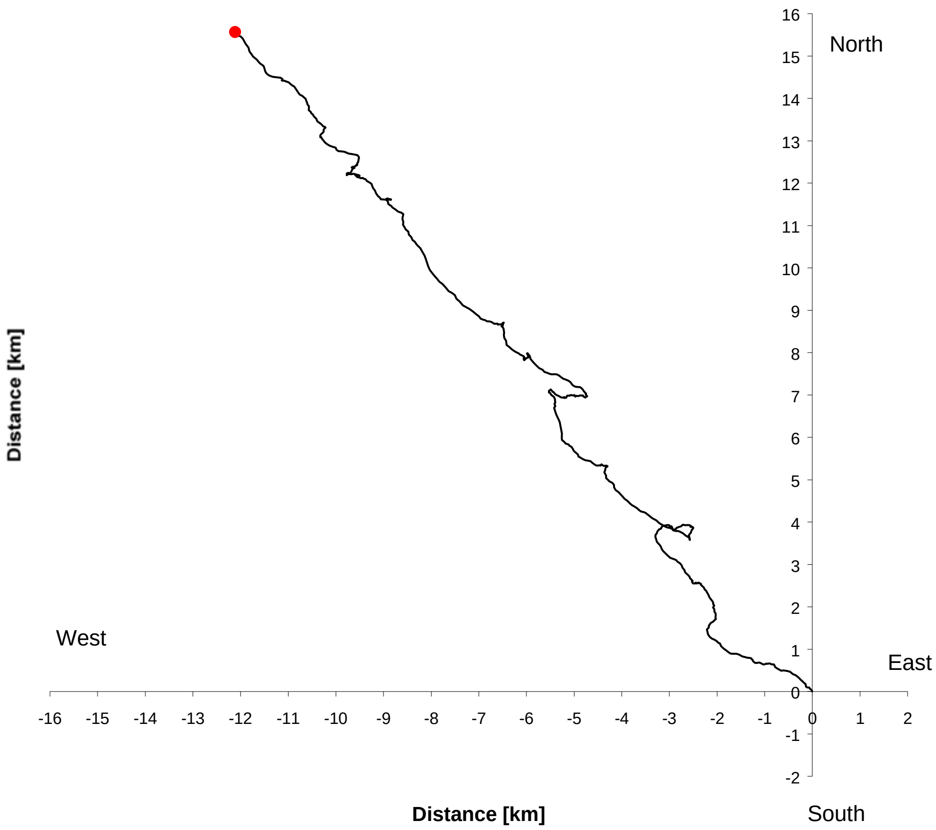
A


North
West
East
South
cm/s
cm/s
12
10
8
6
4
2
0
-2
-4
-6
-10
-8
-6
-4
-2
0
2
4
6
8

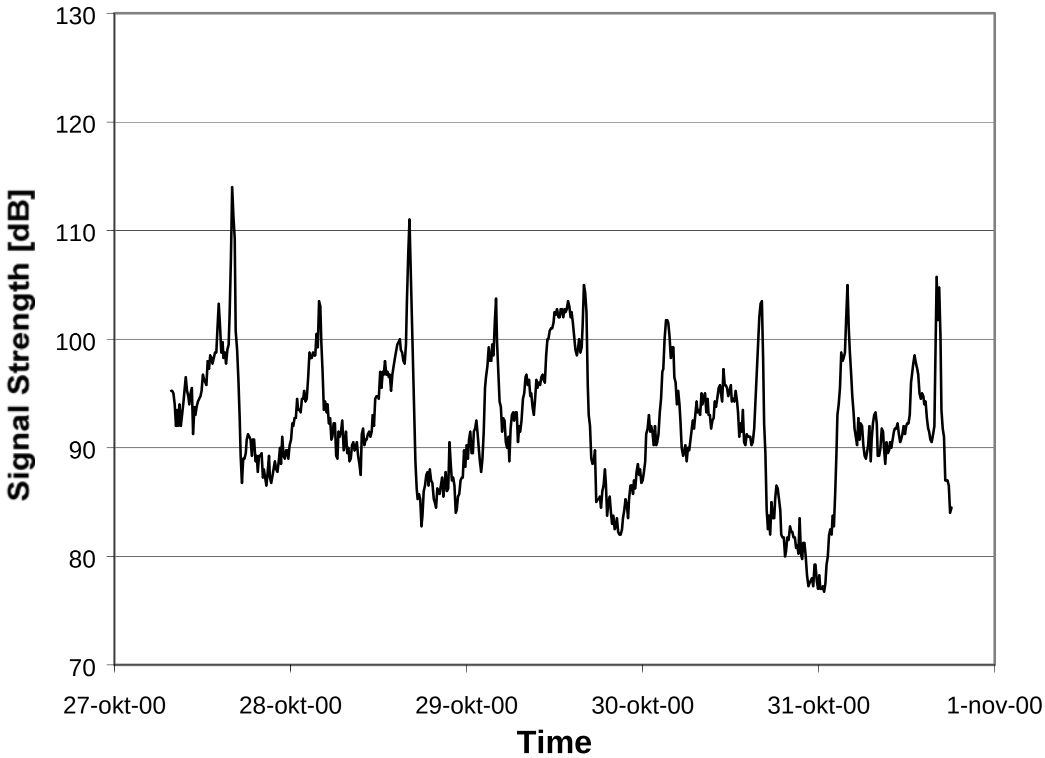
B


North
West
East
South
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4

C

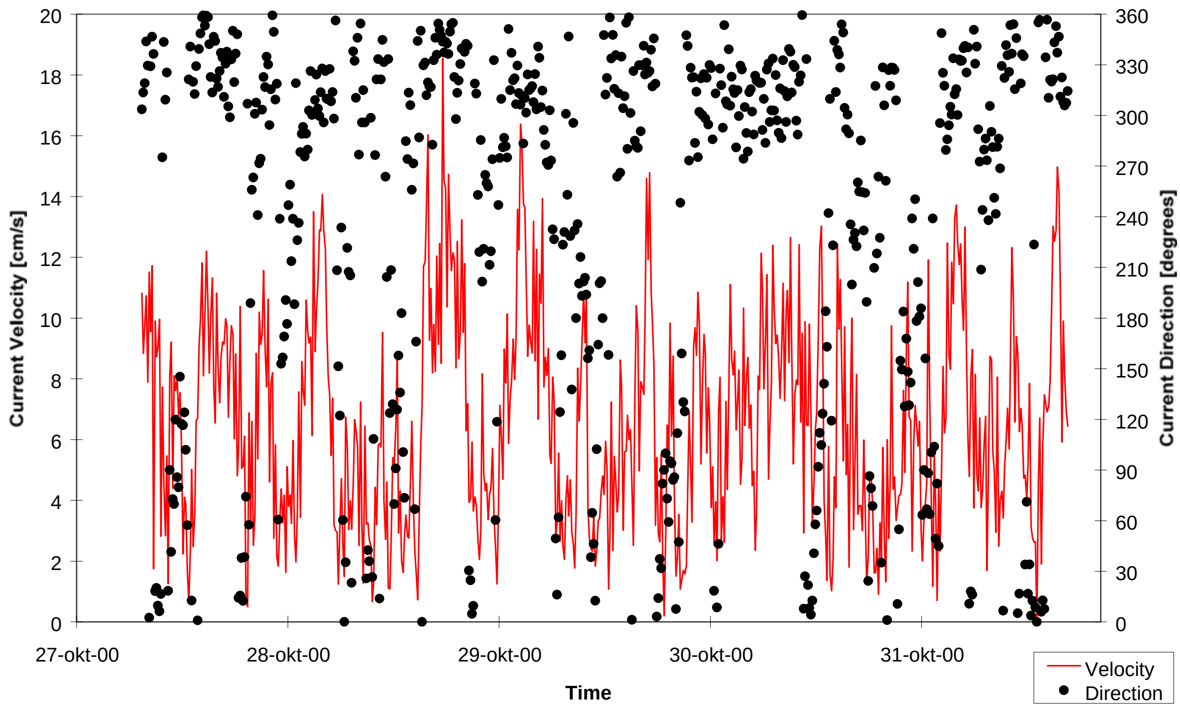

North
West
East
South
Distance [km]
Distance [km]
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-16
-15
-14
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2

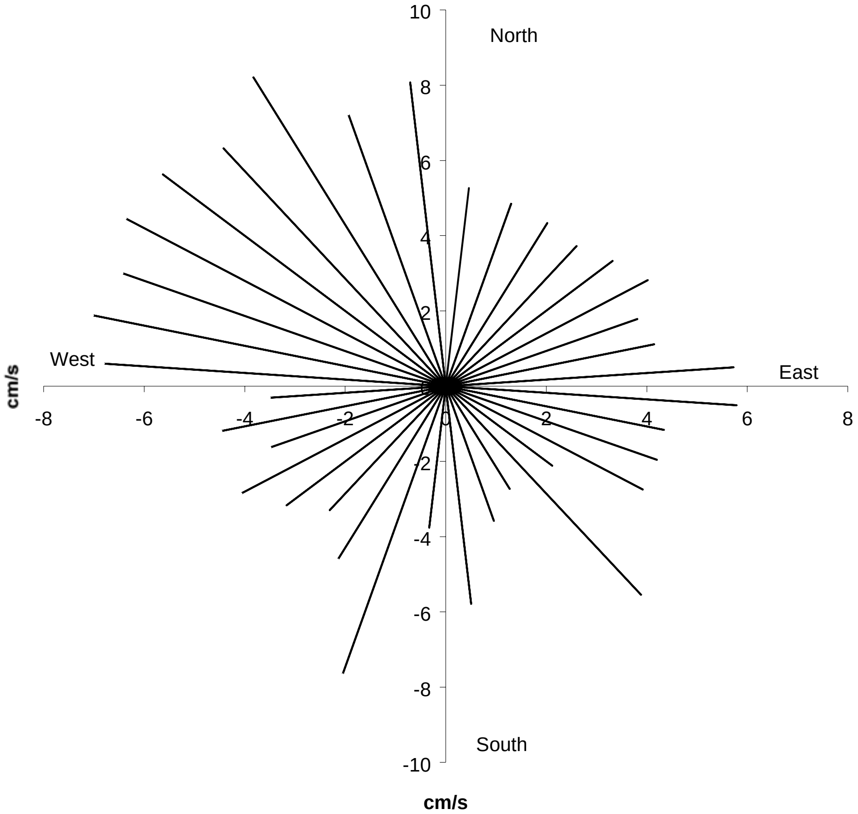
D

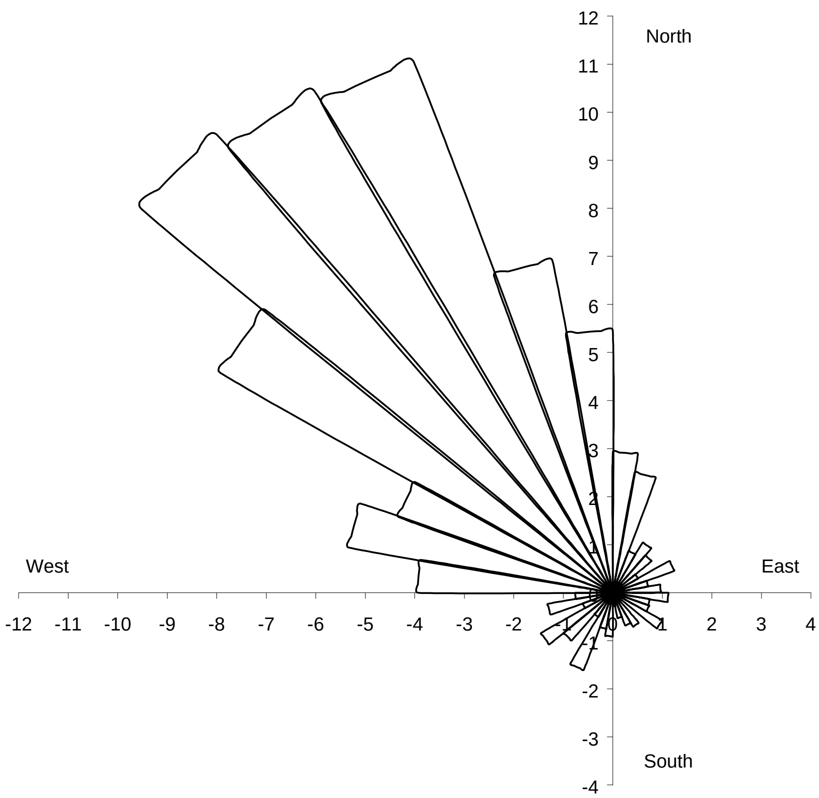

Signal Strength [dB]
130
120
110
100
90
80
70
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
1-nov-00
Time

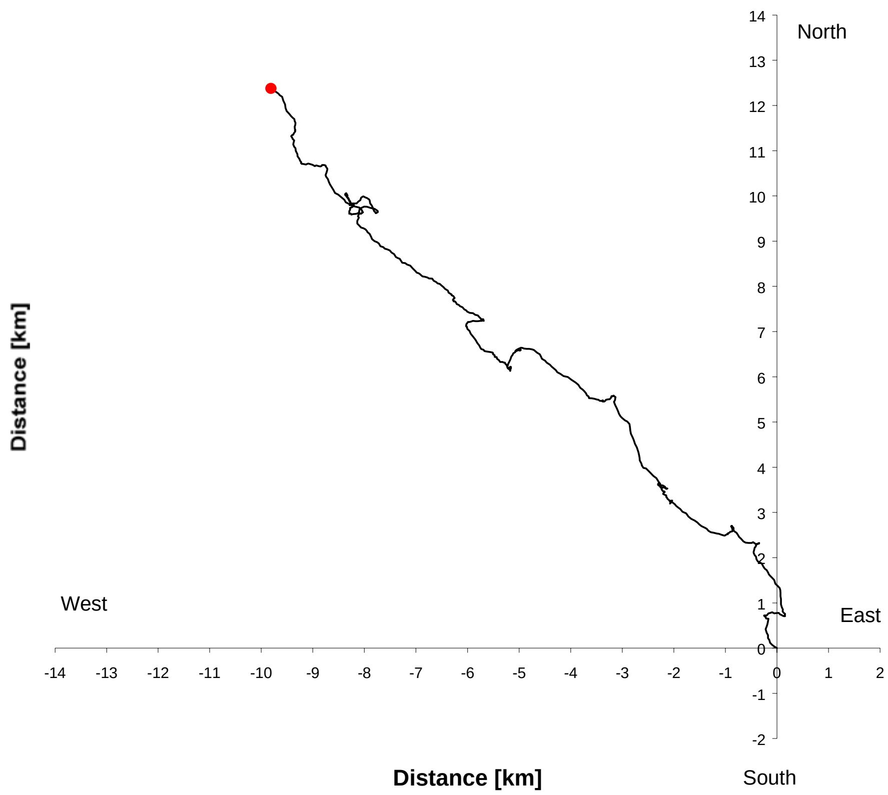
E

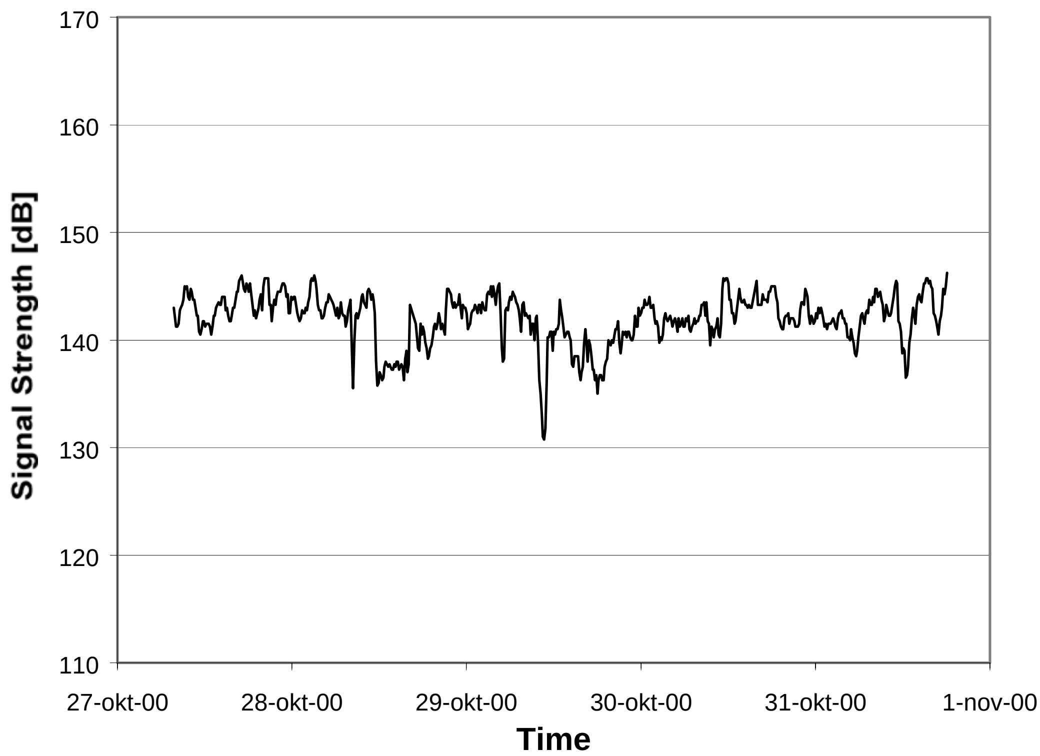
450 m - Cell 68


Current Velocity [cm/s]
0
2
4
6
8
10
12
14
16
18
20
Current Direction [degrees]
0
30
60
90
120
150
180
210
240
270
300
330
360
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
Time
Velocity
Direction

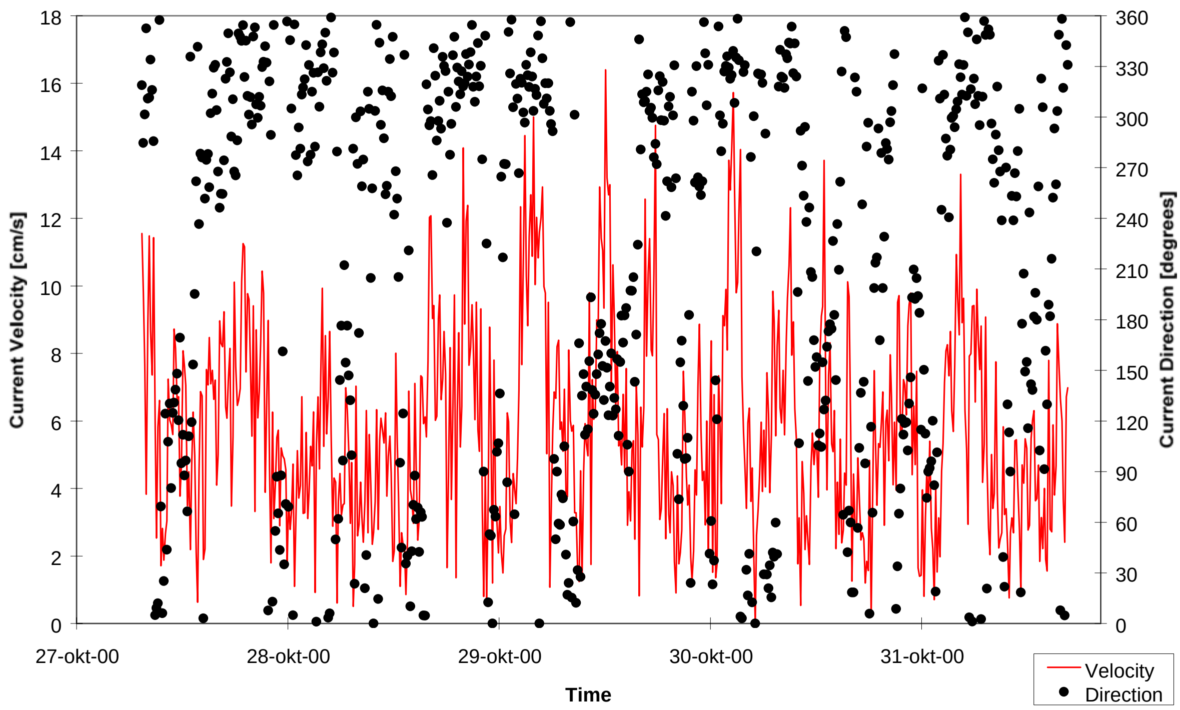

North
West
East
South
cm/s
cm/s
10
8
6
4
2
-2
-4
-6
-8
-10
-8
-6
-4
-2
0
2
4
6
8


North
West
East
South
12
11
10
9
8
7
6
5
4
3
2
1
-1
-2
-3
-4
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4

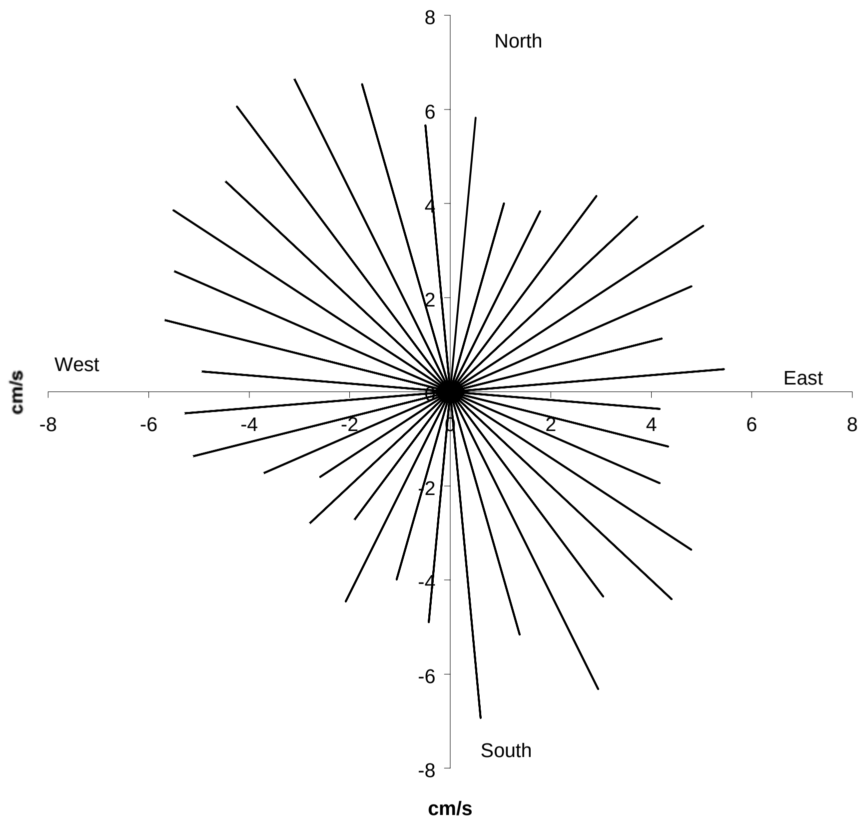

North
West
East
South
Distance [km]
Distance [km]
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-14
-13
-12
-11
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2


Signal Strength [dB]
170
160
150
140
130
120
110
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
1-nov-00
Time

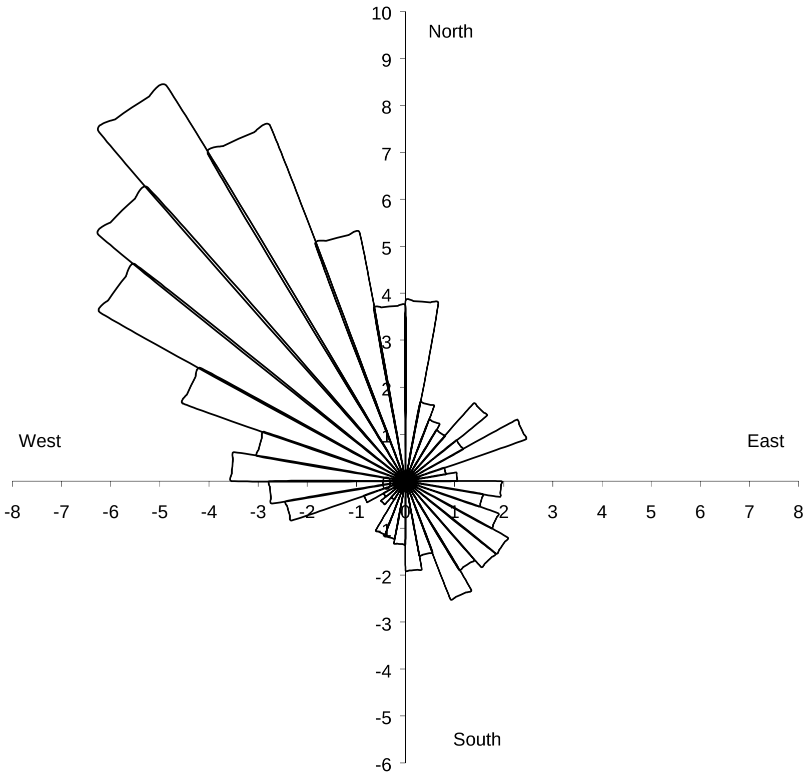
500 m - Cell 58

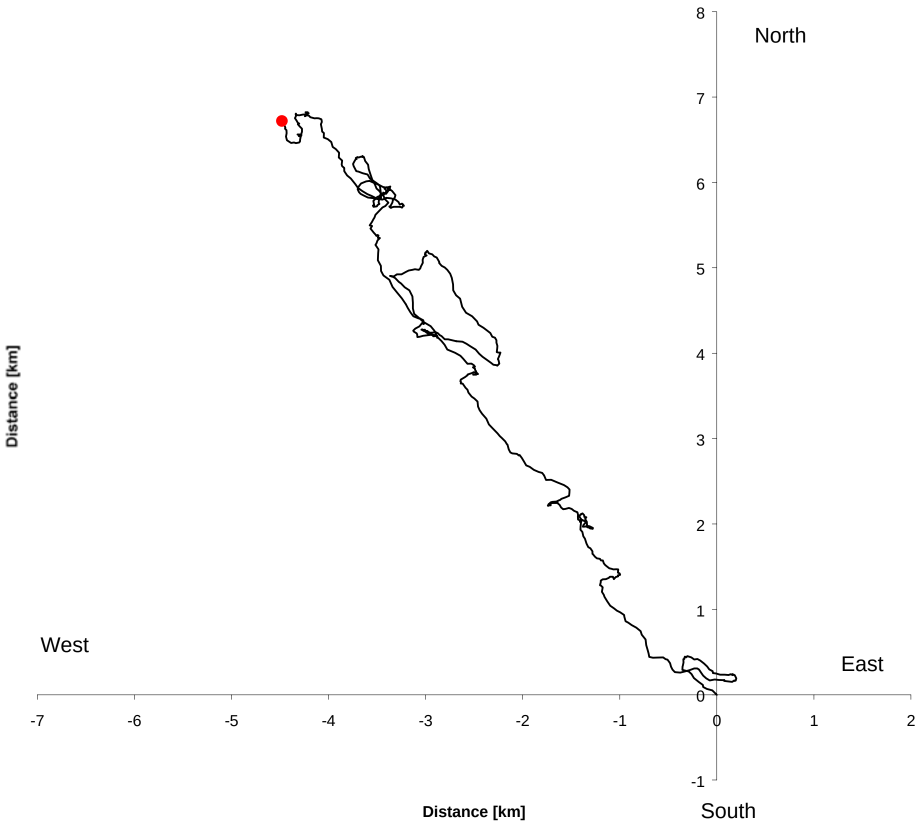


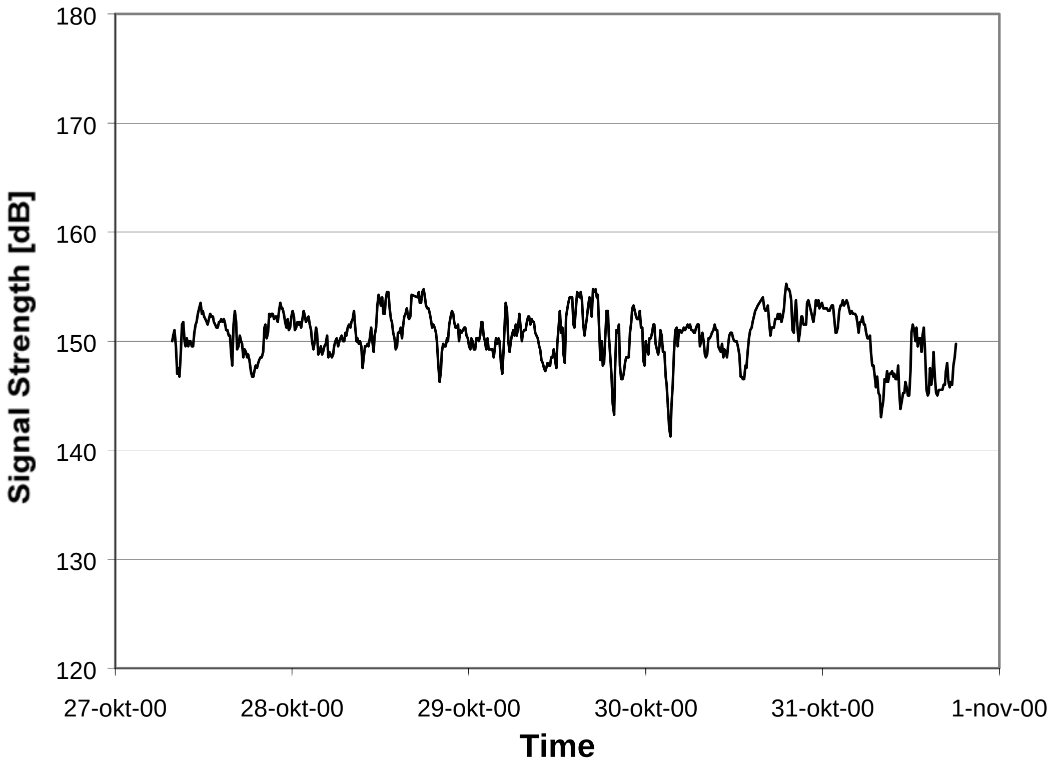
Current Velocity [cm/s]
18
16
14
12
10
8
6
4
2
0
Current Direction [degrees]
360
330
300
270
240
210
180
150
120
90
60
30
0
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
Time
Velocity
Direction



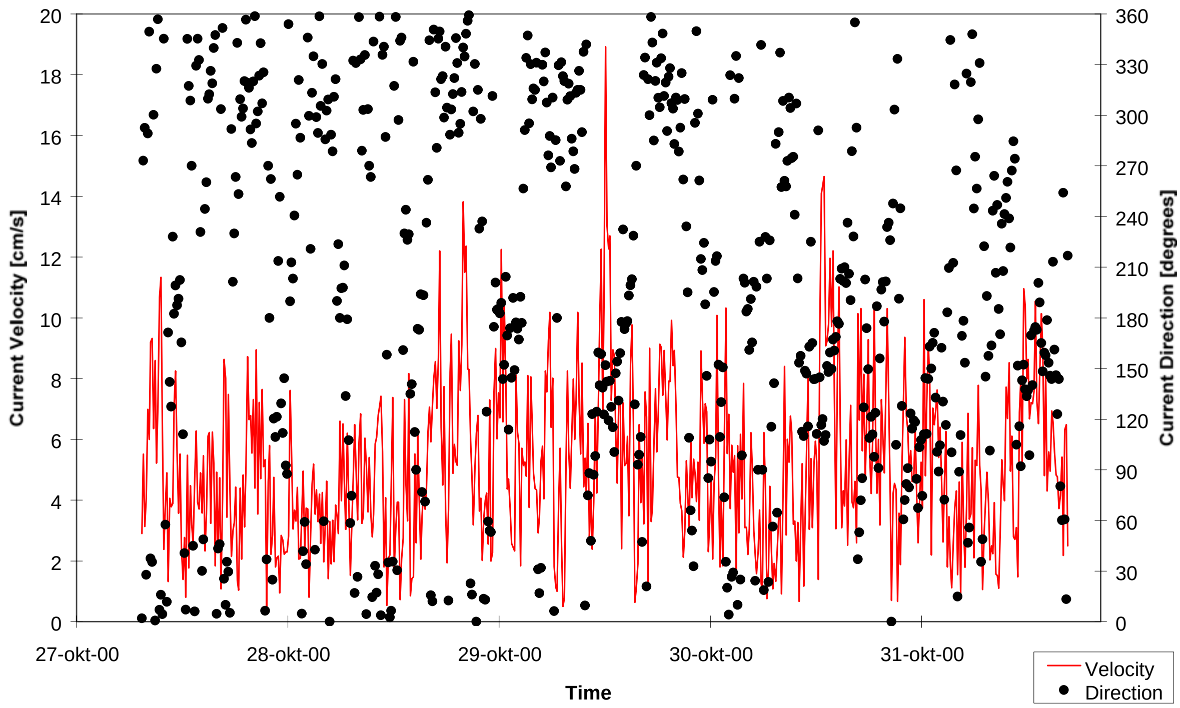
North
West
East
South
cm/s
cm/s
8
6
4
2
0
-2
-4
-6
-8

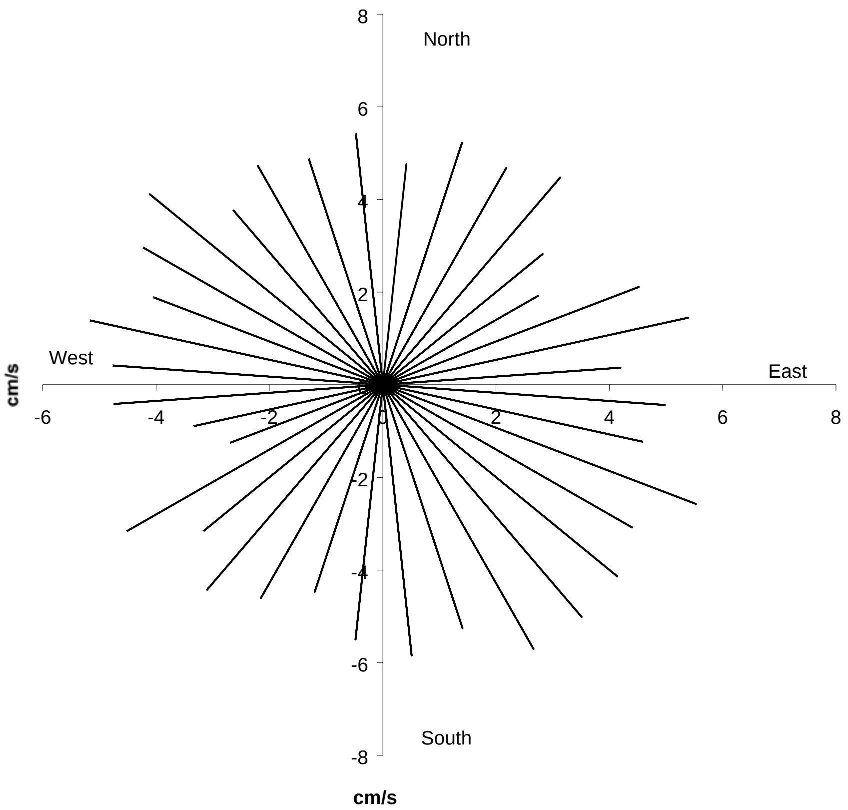

North
West
East
South
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8

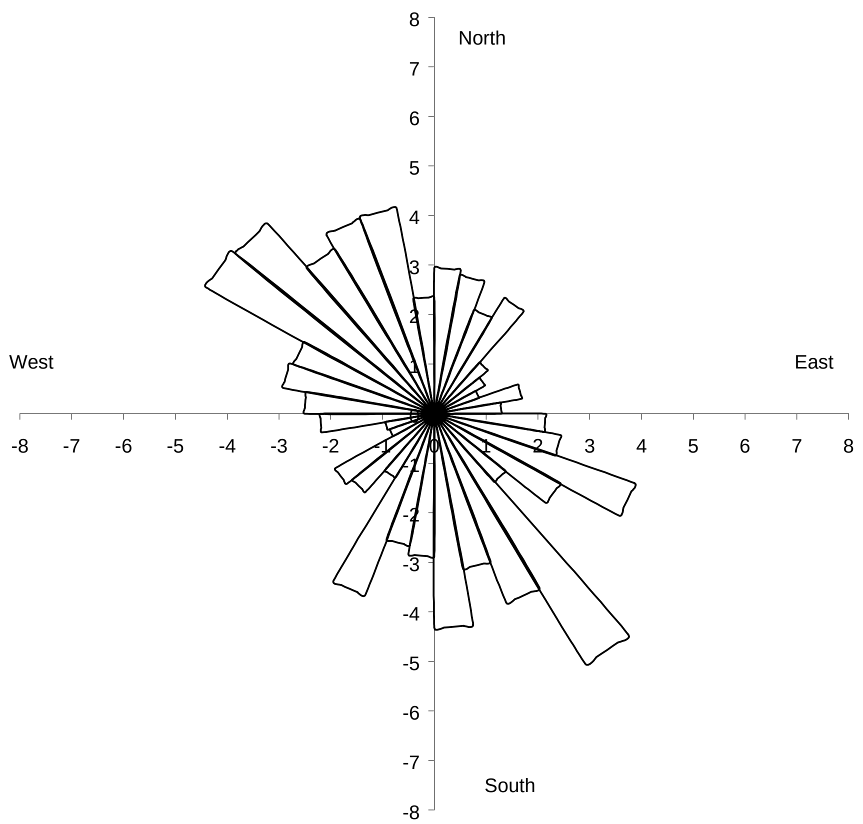

North
West
East
South
Distance [km]
Distance [km]
8
7
6
5
4
3
2
1
0
-1
-7
-6
-5
-4
-3
-2
-1
0
1
2

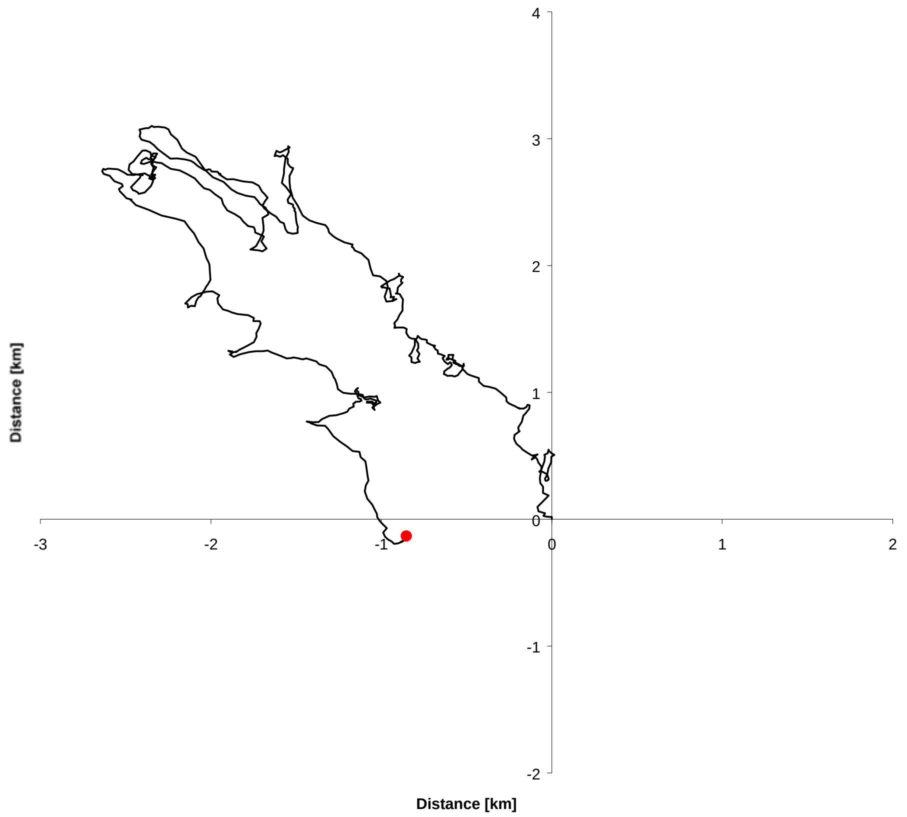

Signal Strength [dB]
180
170
160
150
140
130
120
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
1-nov-00
Time

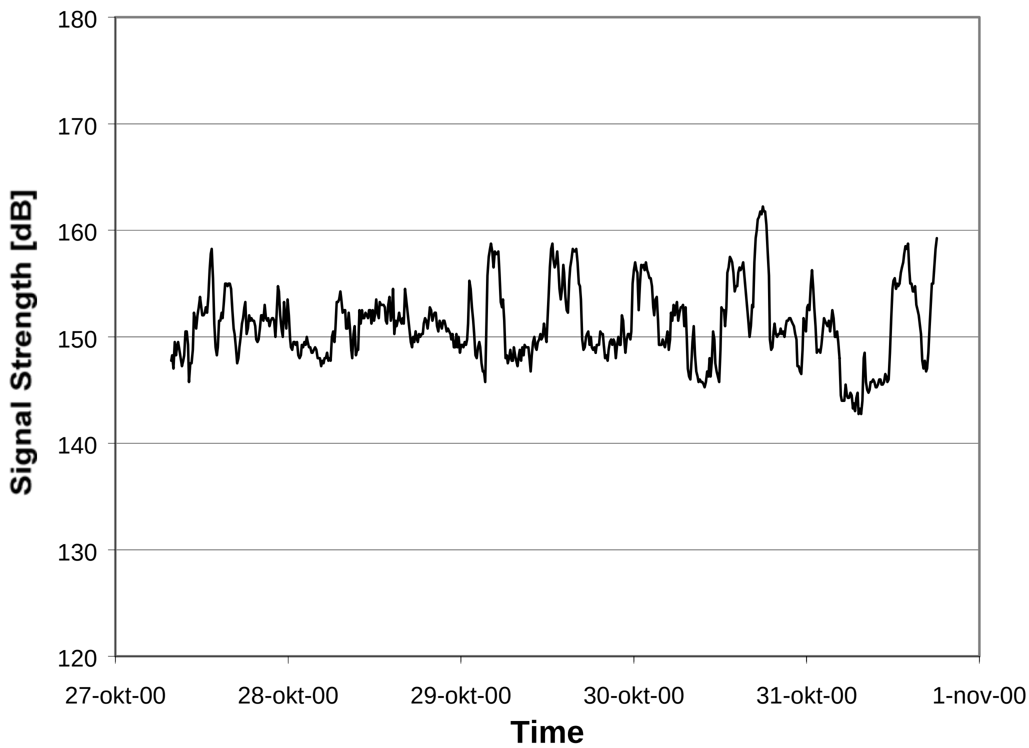
550 m - Cell 48


Current Velocity [cm/s]
20
18
16
14
12
10
8
6
4
2
0
Current Direction [degrees]
360
330
300
270
240
210
180
150
120
90
60
30
0
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
Time
Velocity
Direction

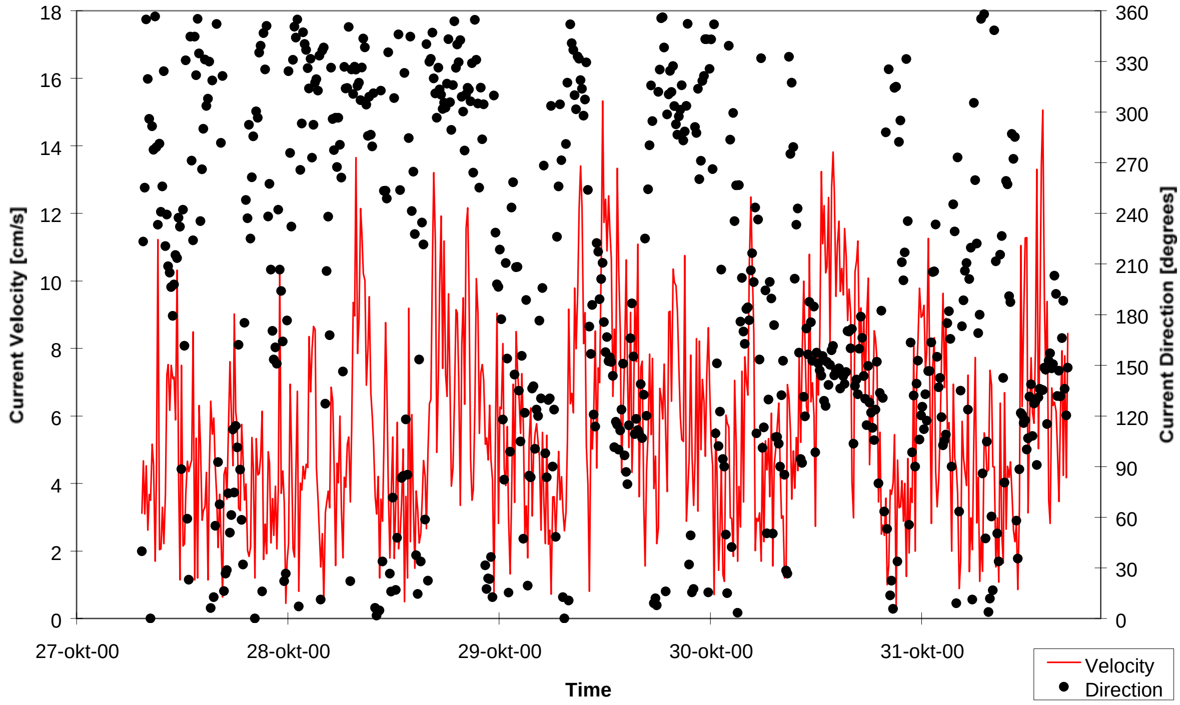

North
West
East
South
cm/s
cm/s

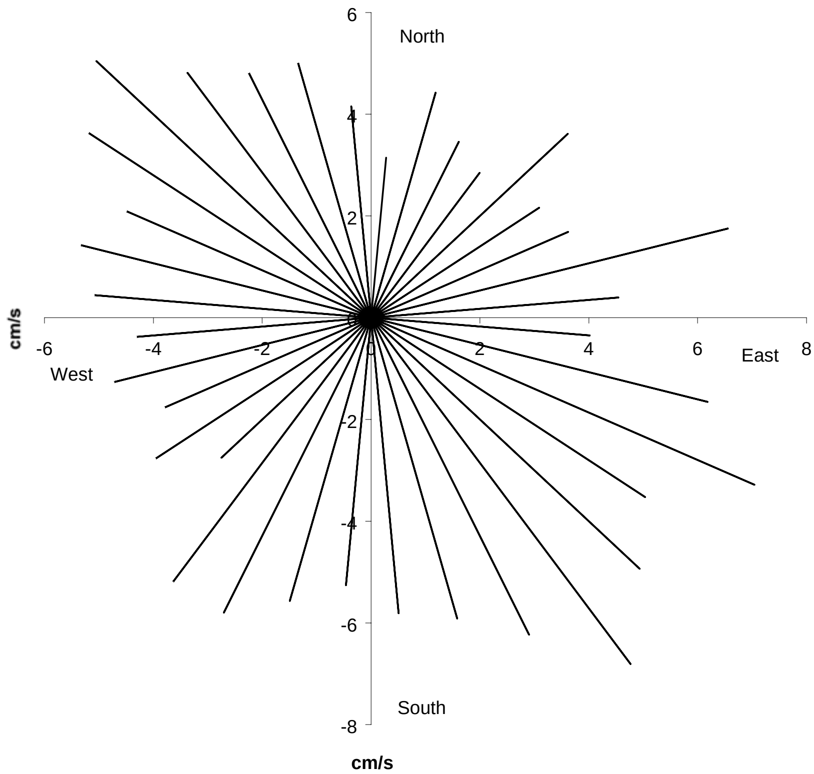

North
West
East
South

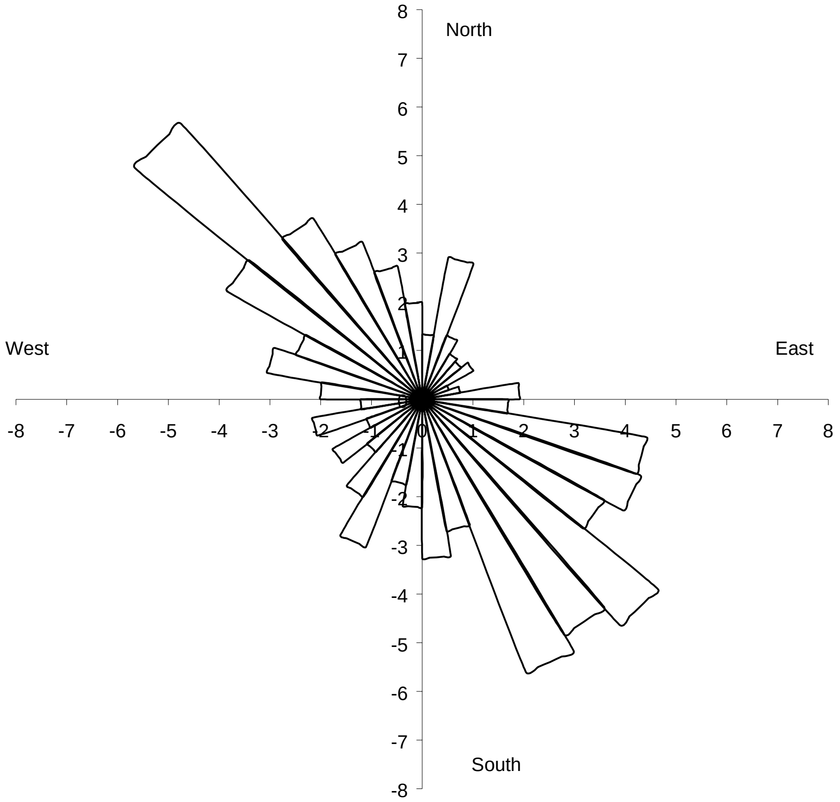

4
3
2
1
0
-1
-2
-3
-2
-1
0
1
2
Distance [km]
Distance [km]

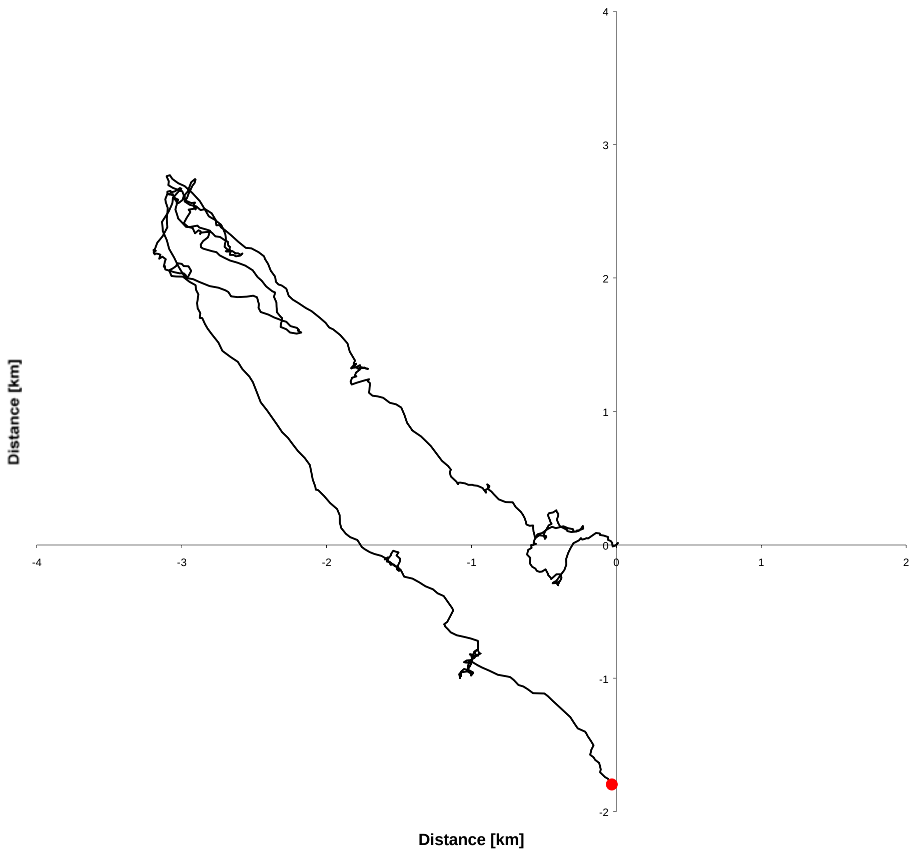

180
170
160
150
140
130
120
Signal Strength [dB]
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
1-nov-00
Time

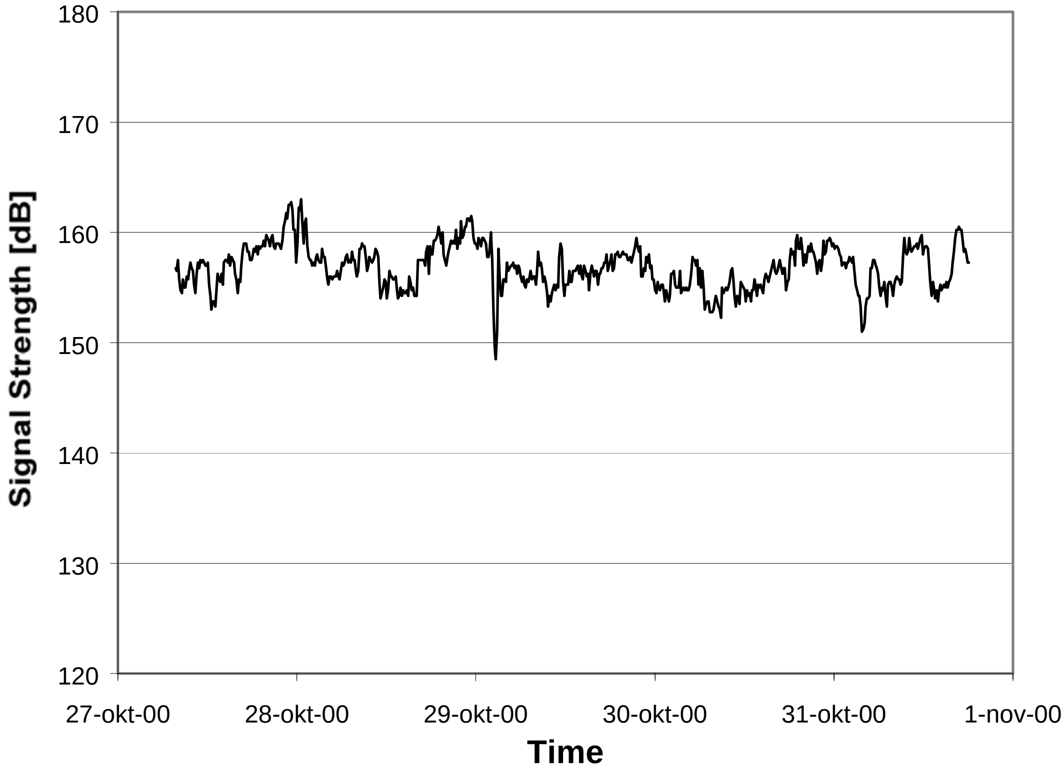
600 m - Cell 38


Current Velocity [cm/s]
Current Direction [degrees]
18
16
14
12
10
8
6
4
2
0
360
330
300
270
240
210
180
150
120
90
60
30
0
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
Time
Velocity
Direction

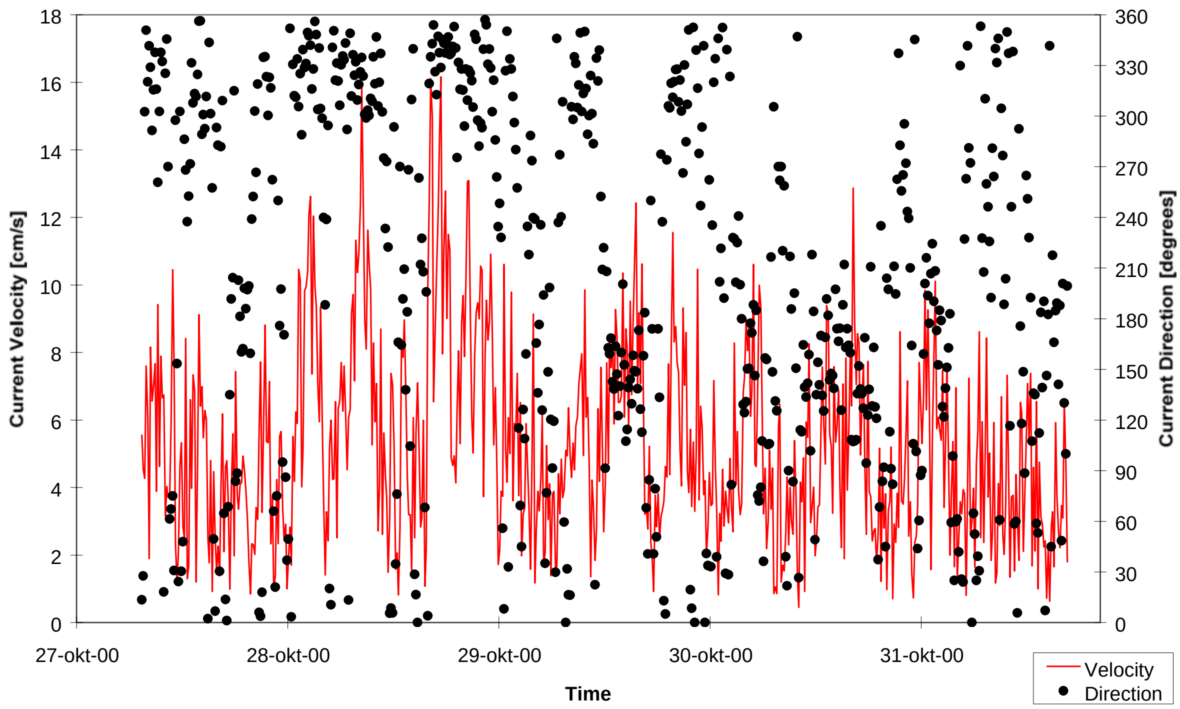

North
South
East
West
cm/s
cm/s
6
4
2
0
-2
-4
-6
-8
-6
-4
-2
0
2
4
6
8

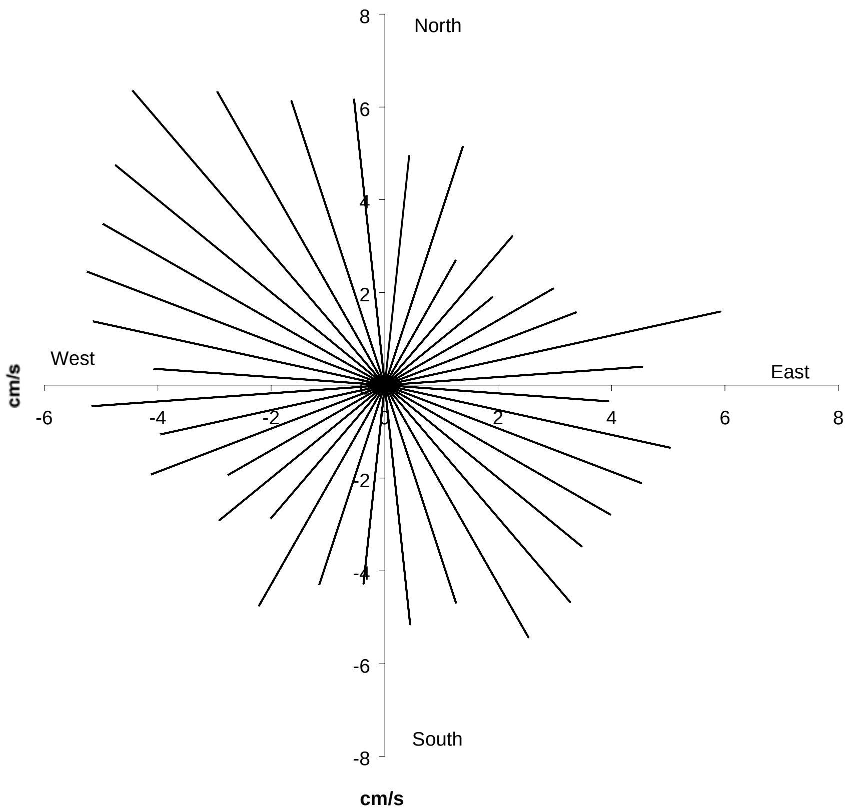

North
West
East
South
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-5
-6
-7
-8
-8 -7 -6 -5 -4 -3 -2 -1 0 1 2 3 4 5 6 7 8

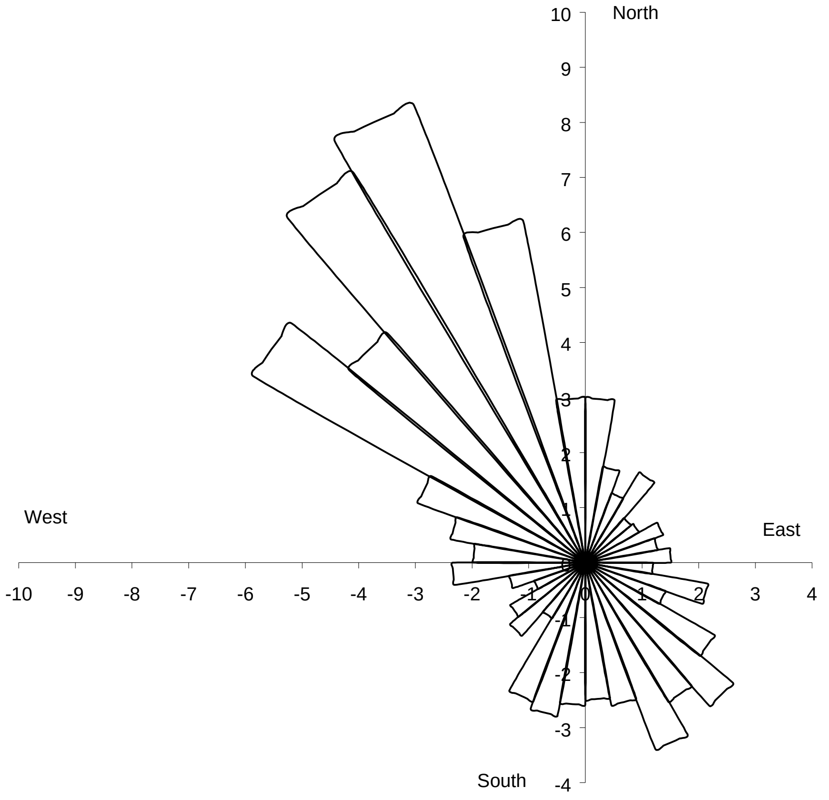

4
3
2
1
0
-1
-2
-4
-3
-2
-1
0
1
2
Distance [km]
Distance [km]

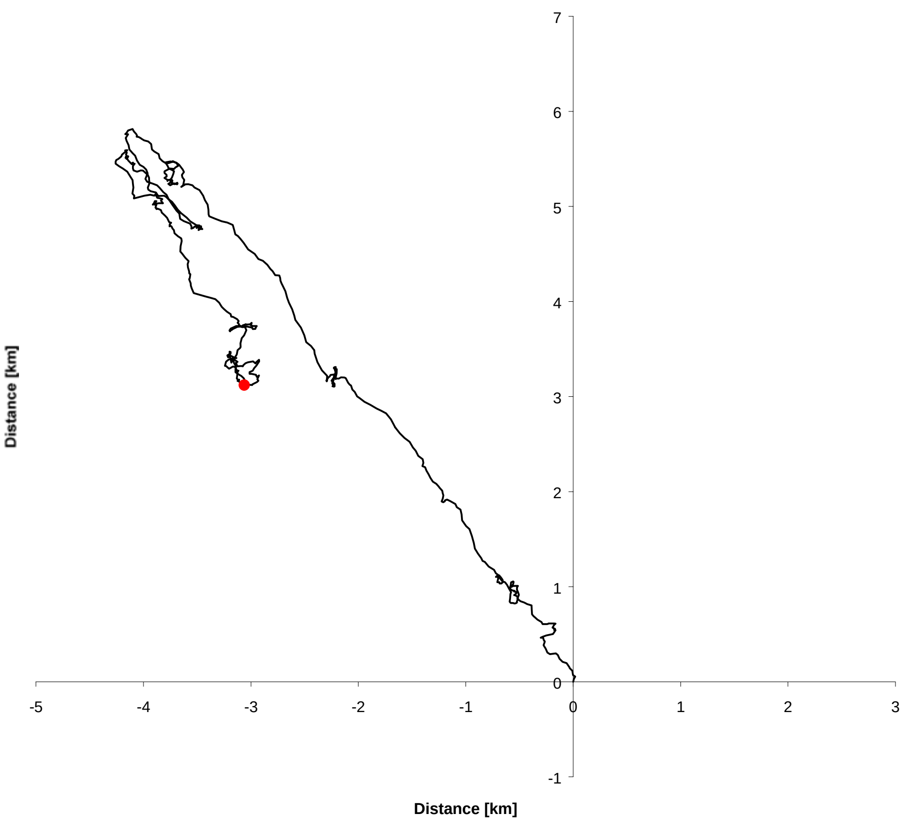

180
170
160
150
140
130
120
Signal Strength [dB]
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
1-nov-00
Time

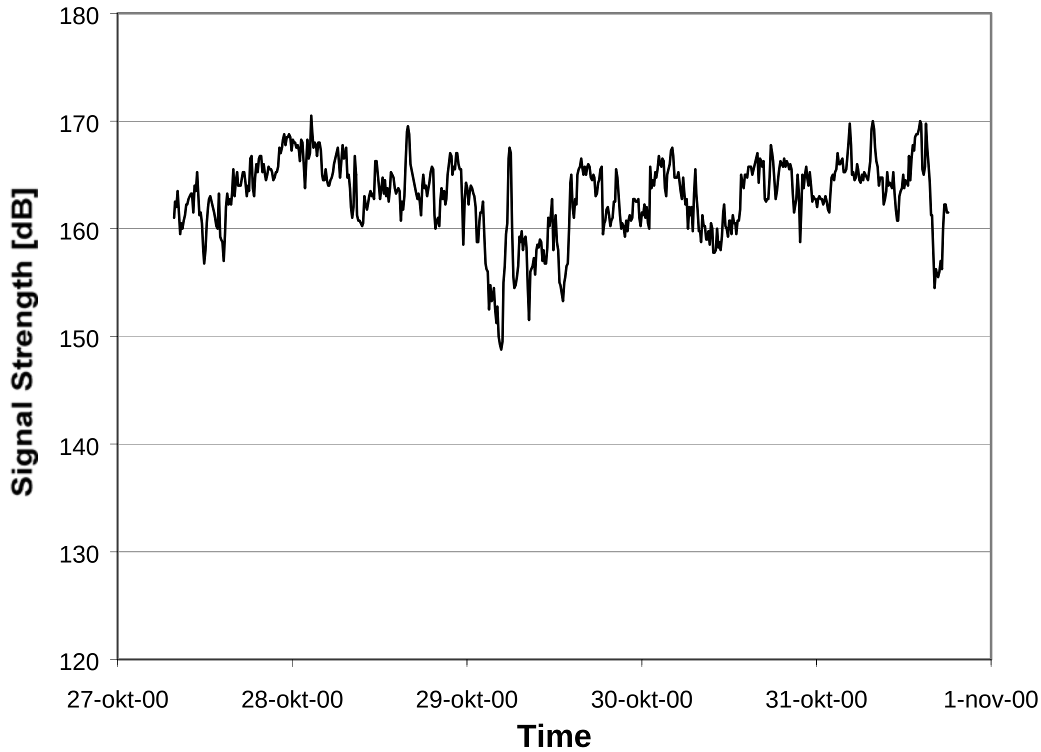
650 m - Cell 28


18
16
14
12
10
8
6
4
2
0
Current Velocity [cm/s]
360
330
300
270
240
210
180
150
120
90
60
30
0
Current Direction [degrees]
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
Time
Velocity
Direction

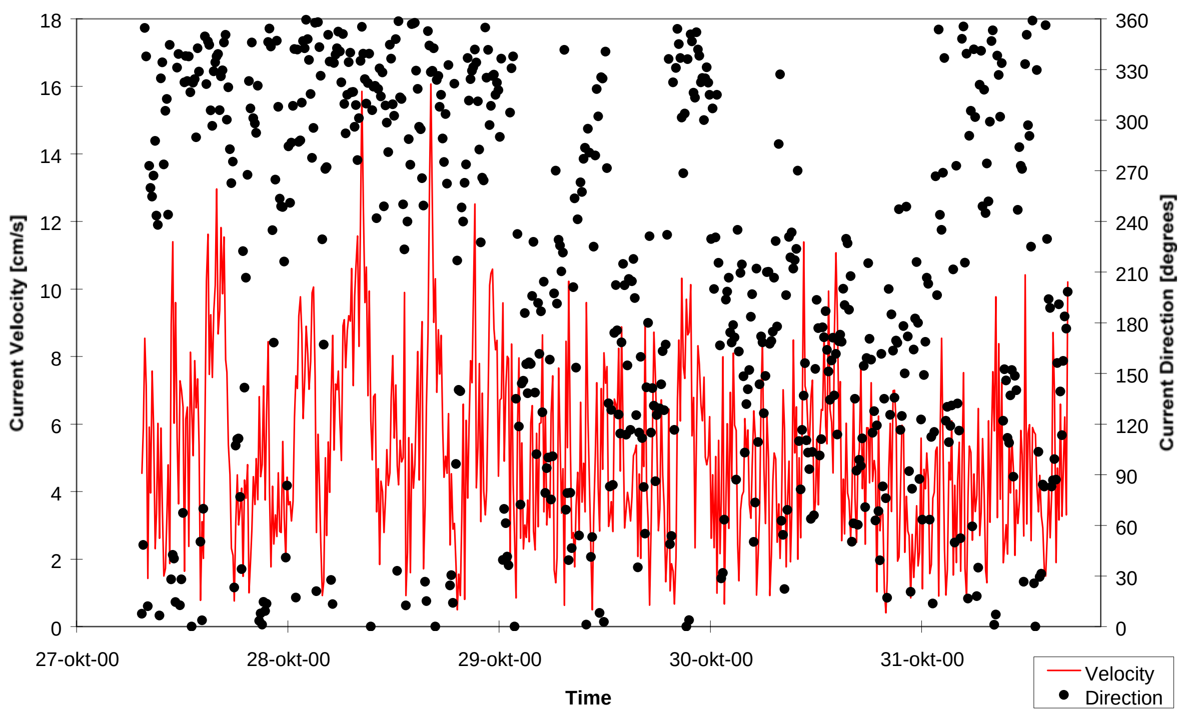

North
West
East
South
cm/s
cm/s
8
6
4
2
-2
-4
-6
-8
-6
-4
-2
0
2
4
6
8

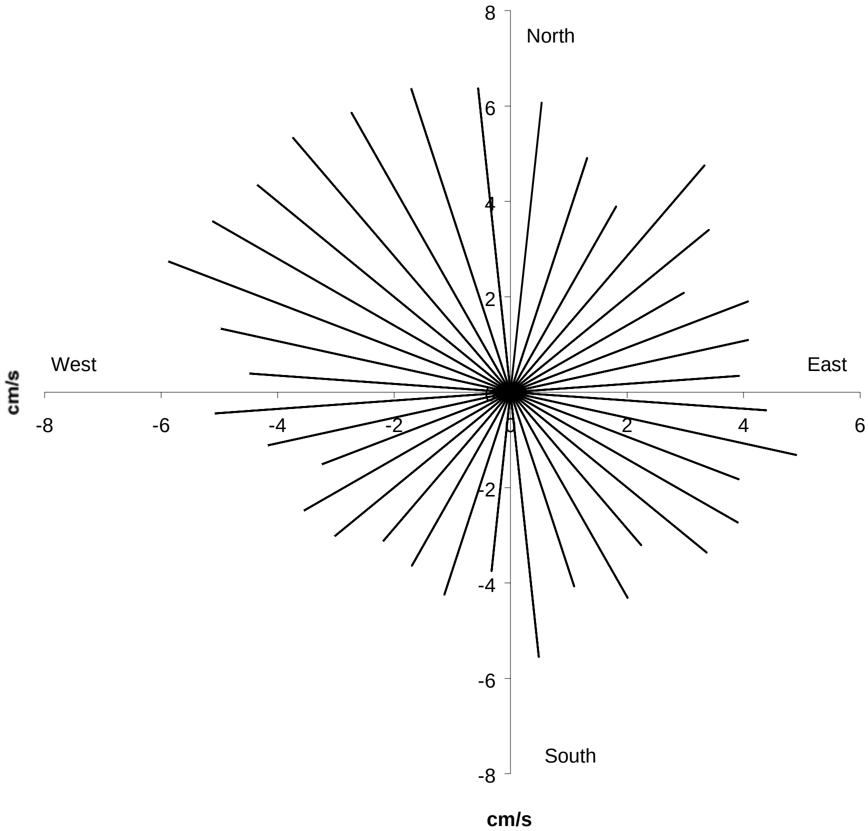

North
West
East
South
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4

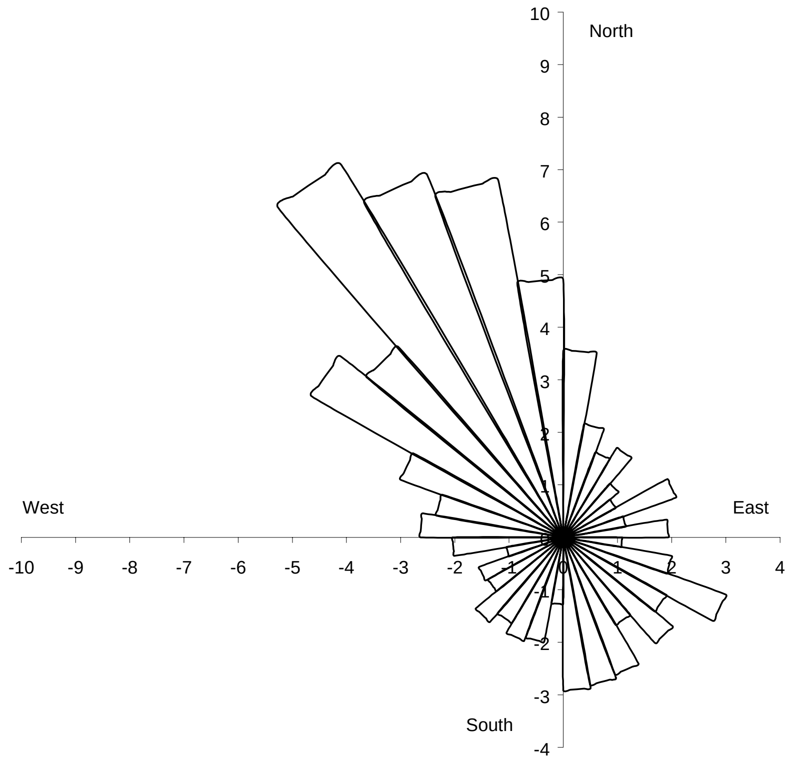

Distance [km]
Distance [km]
7
6
5
4
3
2
1
0
-1
-5
-4
-3
-2
-1
0
1
2
3

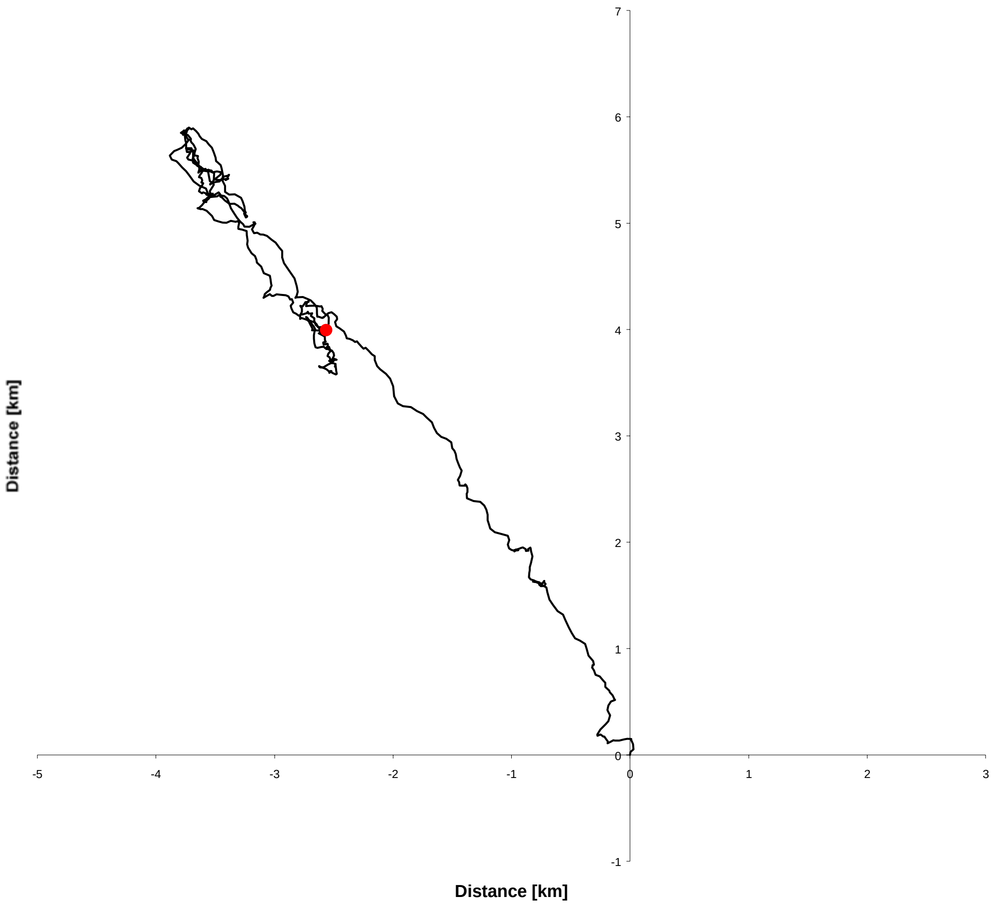

Signal Strength [dB]
180
170
160
150
140
130
120
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
1-nov-00
Time

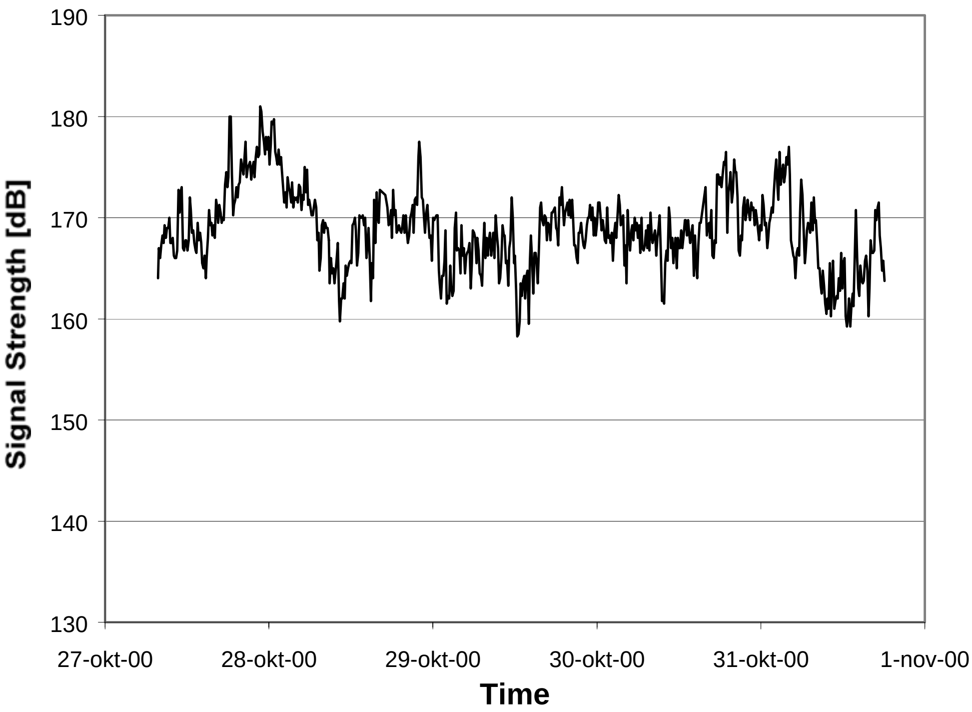
700 m - Cell 18


Current Velocity [cm/s]
18
16
14
12
10
8
6
4
2
0
Current Direction [degrees]
360
330
300
270
240
210
180
150
120
90
60
30
0
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
Time
Velocity
Direction

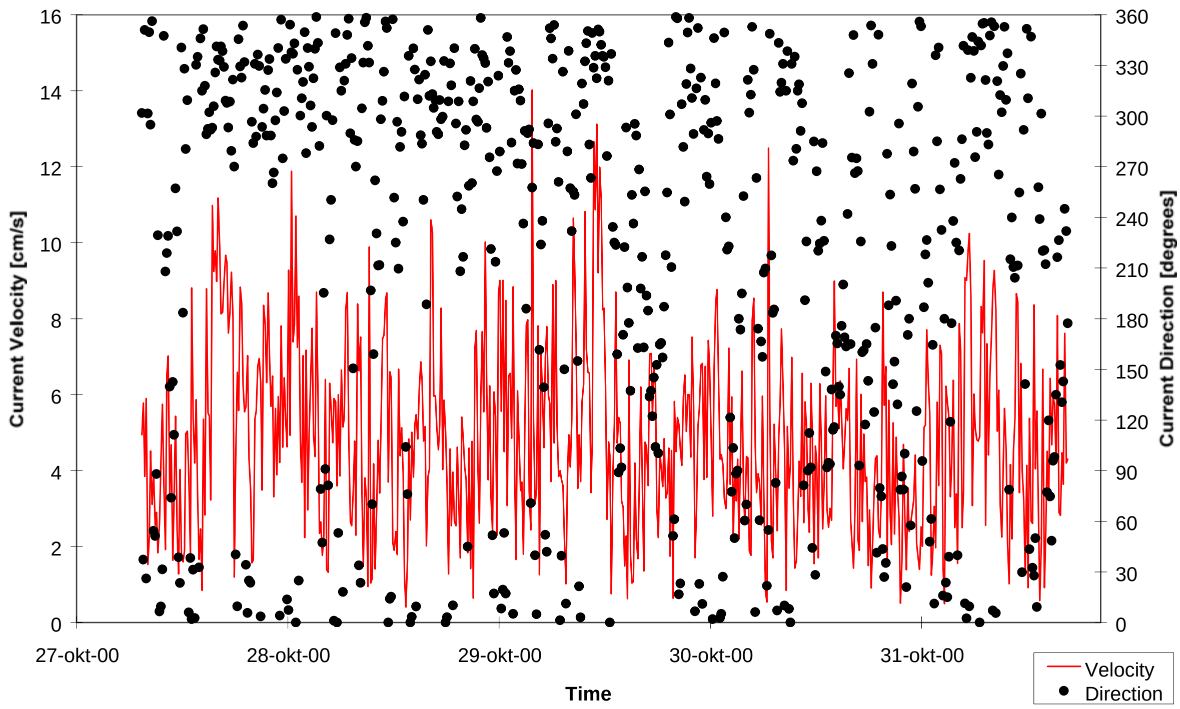

North
West
East
South
cm/s
cm/s
8
6
4
2
-2
-4
-6
-8
-8
-6
-4
-2
0
2
4
6


North
West
East
South
10
9
8
7
6
5
4
3
2
1
0
-1
-2
-3
-4
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4

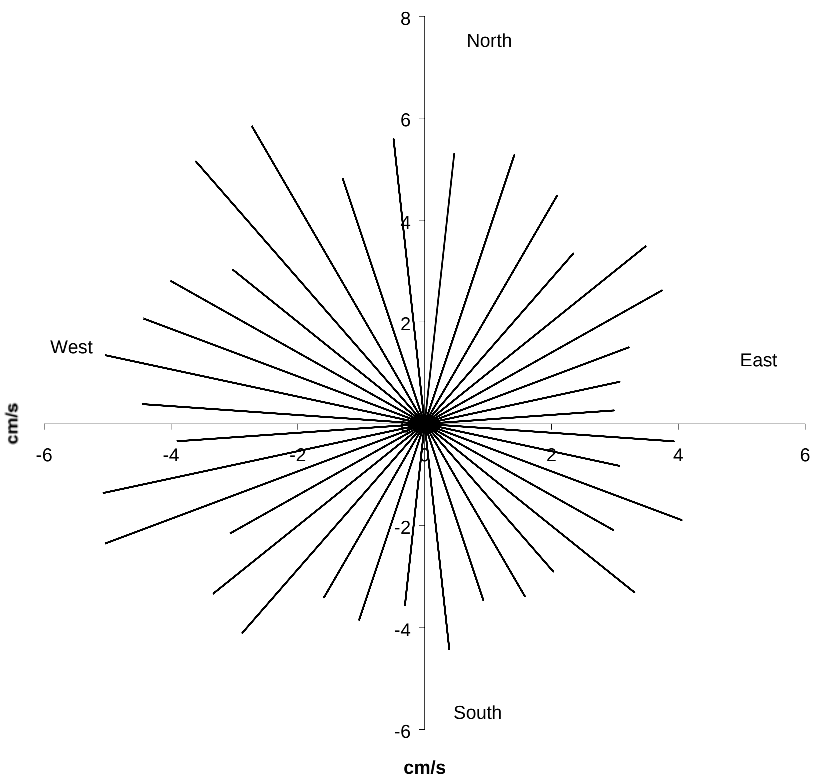

Distance [km]
Distance [km]
7
6
5
4
3
2
1
0
-1
-5
-4
-3
-2
-1
0
1
2
3


Signal Strength [dB]
190
180
170
160
150
140
130
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
1-nov-00
Time

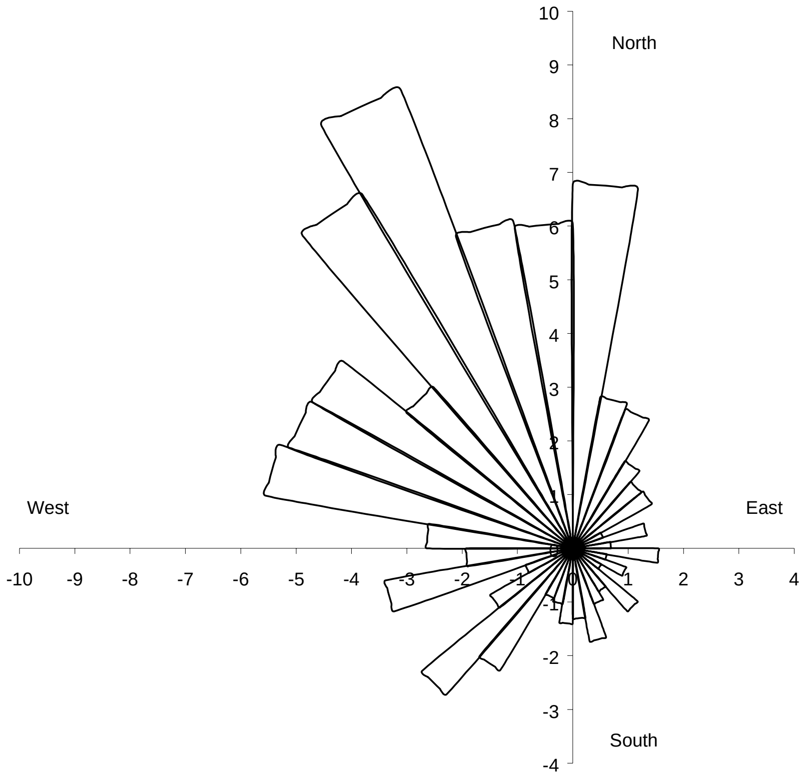
750 m - Cell 8

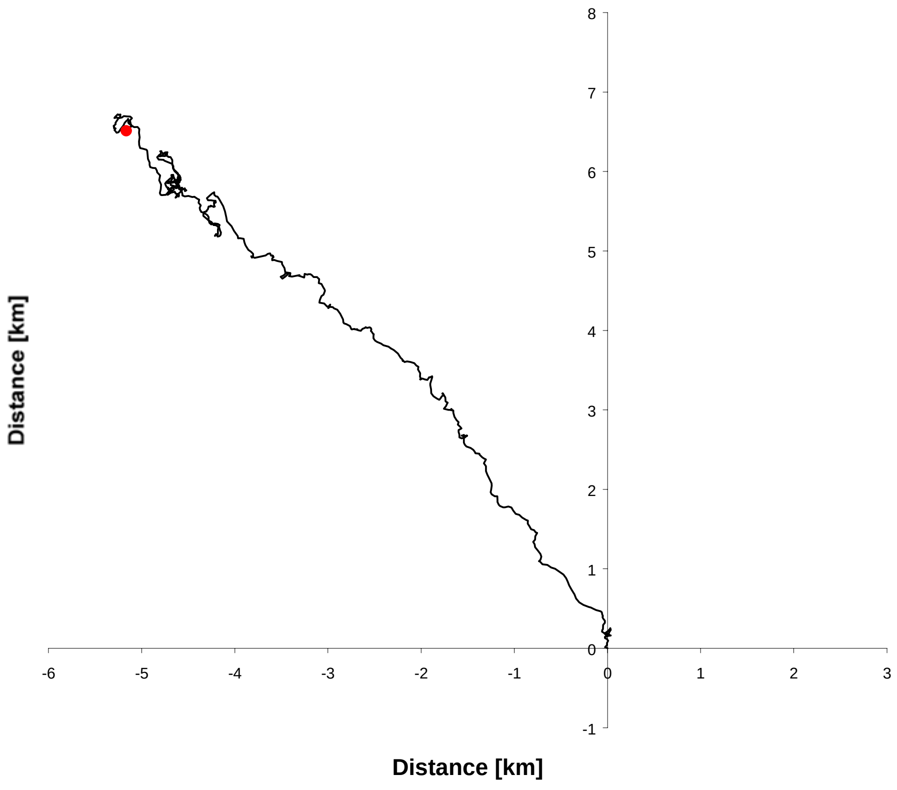


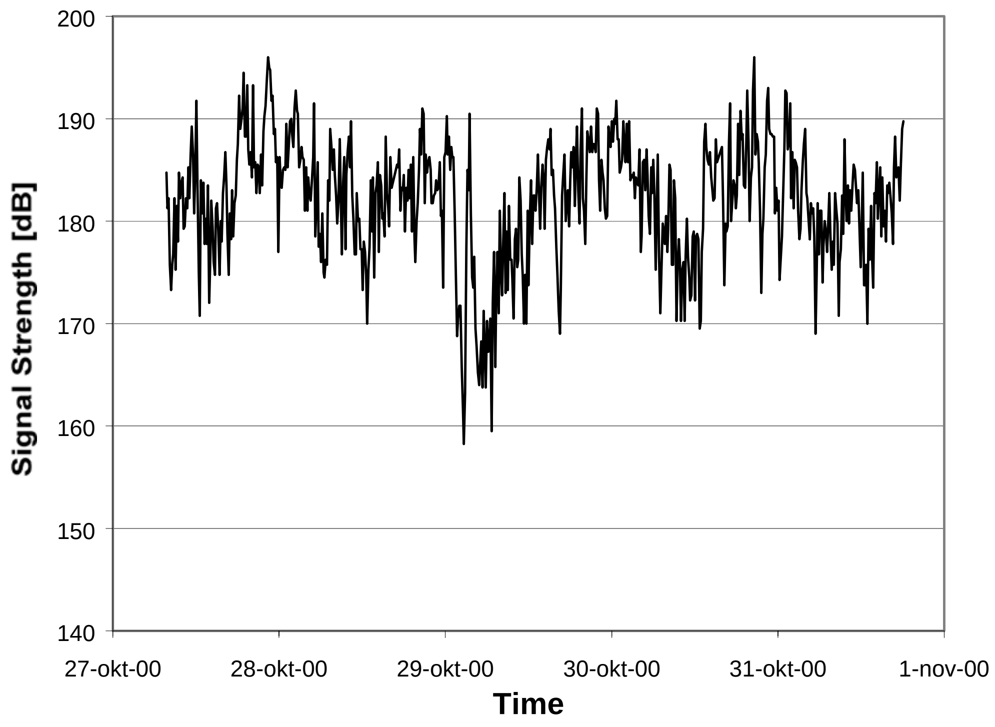
Current Velocity [cm/s]
16
14
12
10
8
6
4
2
0
360
330
300
270
240
210
180
150
120
90
60
30
0
Current Direction [degrees]
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
Time
Velocity
Direction



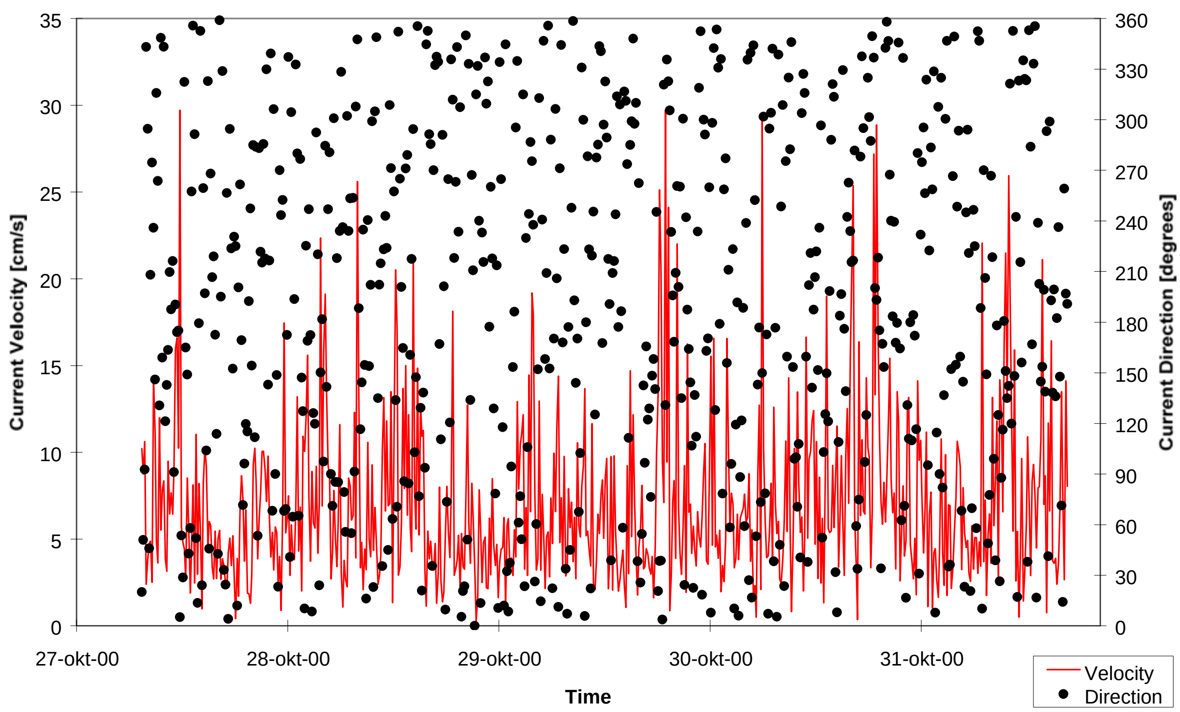
8
6
4
2
-2
-4
-6
North
West
East
South
cm/s
-6
-4
-2
0
2
4
6
cm/s

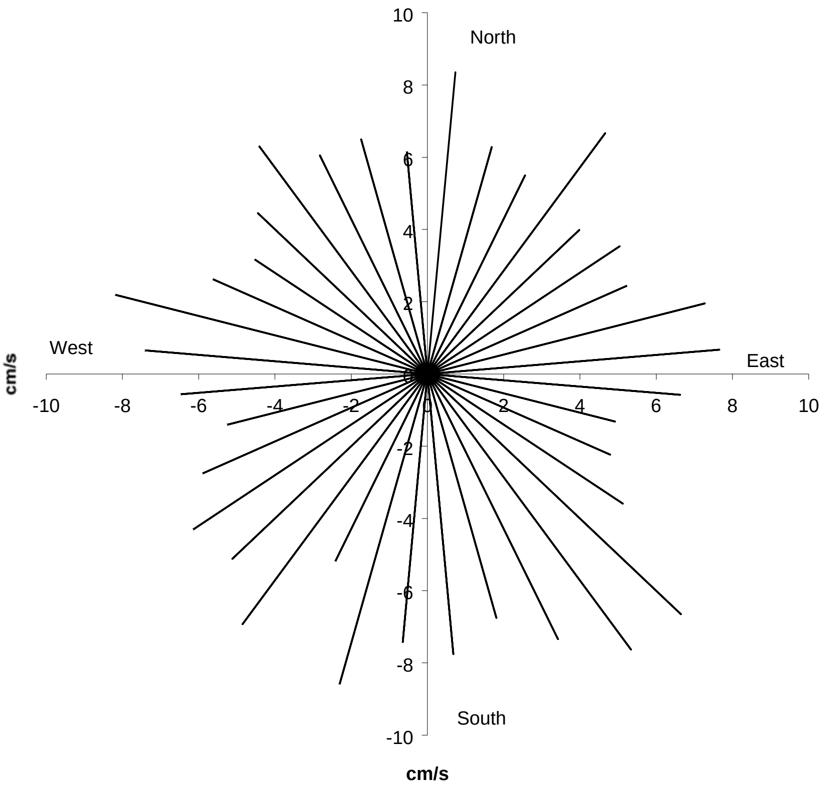

North
South
West
East
10
9
8
7
6
5
4
3
2
1
-1
-2
-3
-4
-10
-9
-8
-7
-6
-5
-4
-3
-2
-1
0
1
2
3
4

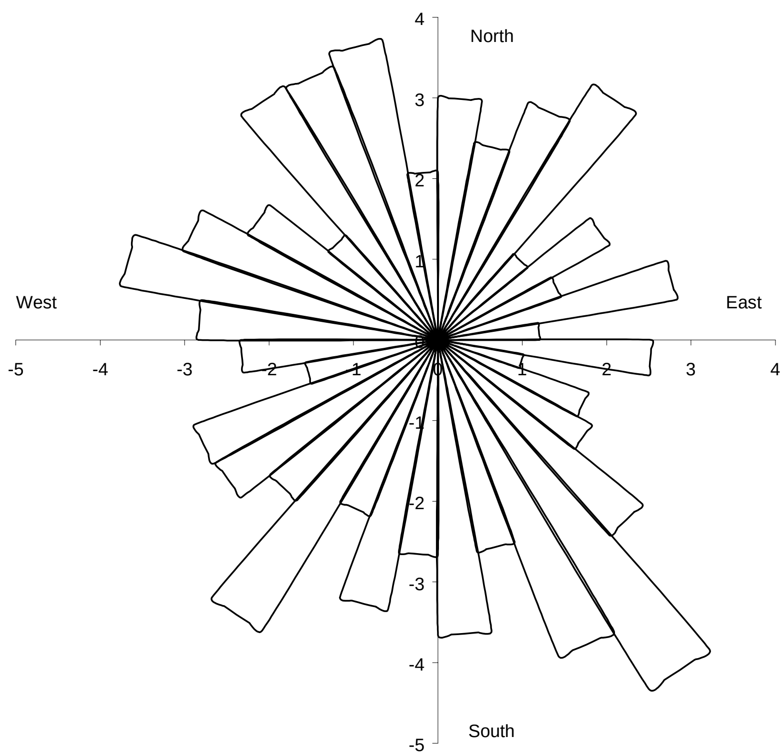

Distance [km]
Distance [km]
8
7
6
5
4
3
2
1
0
-1
-6
-5
-4
-3
-2
-1
0
1
2
3

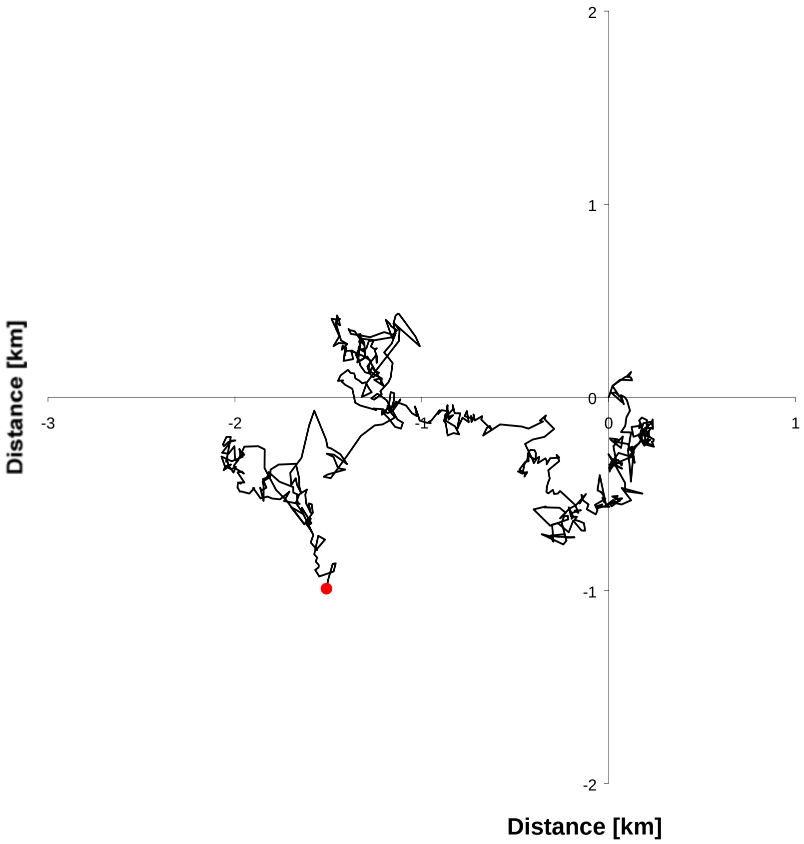

Signal Strength [dB]
200
190
180
170
160
150
140
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
1-nov-00
Time

785 m - Cell 1

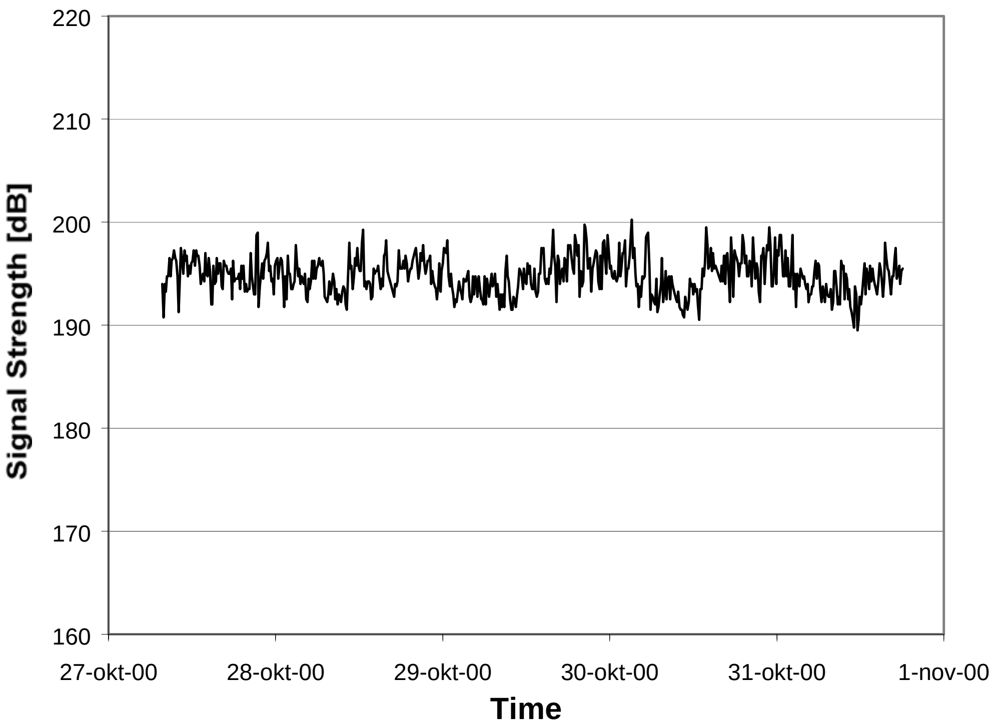

Current Velocity [cm/s]
35
30
25
20
15
10
5
0
Current Direction [degrees]
360
330
300
270
240
210
180
150
120
90
60
30
0
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
Time
Velocity
Direction


North
West
East
South
cm/s
cm/s


North
West
East
South



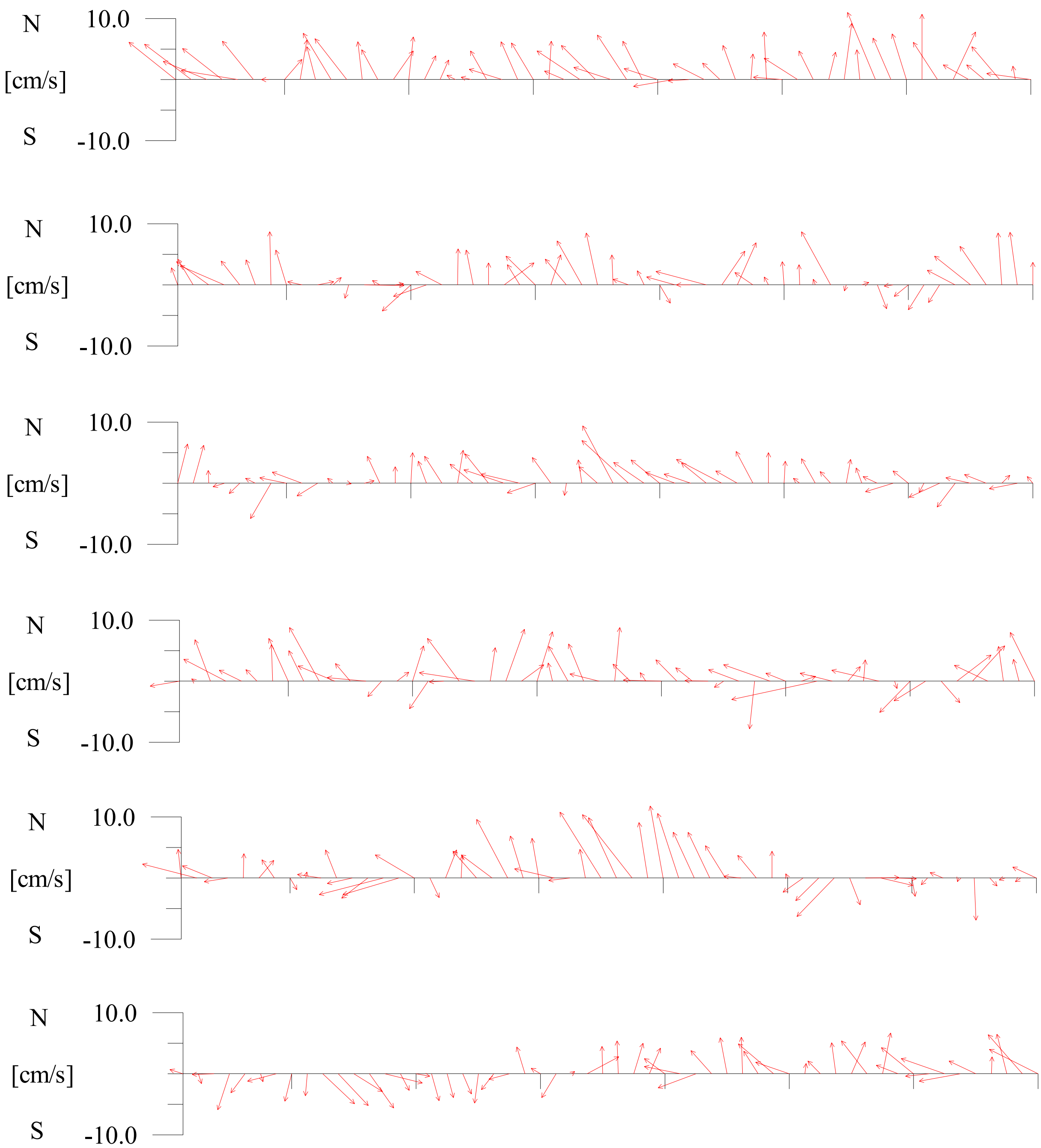
Distance [km]
Distance [km]
2
1
0
-1
-2
-3
-2
-1
0
1

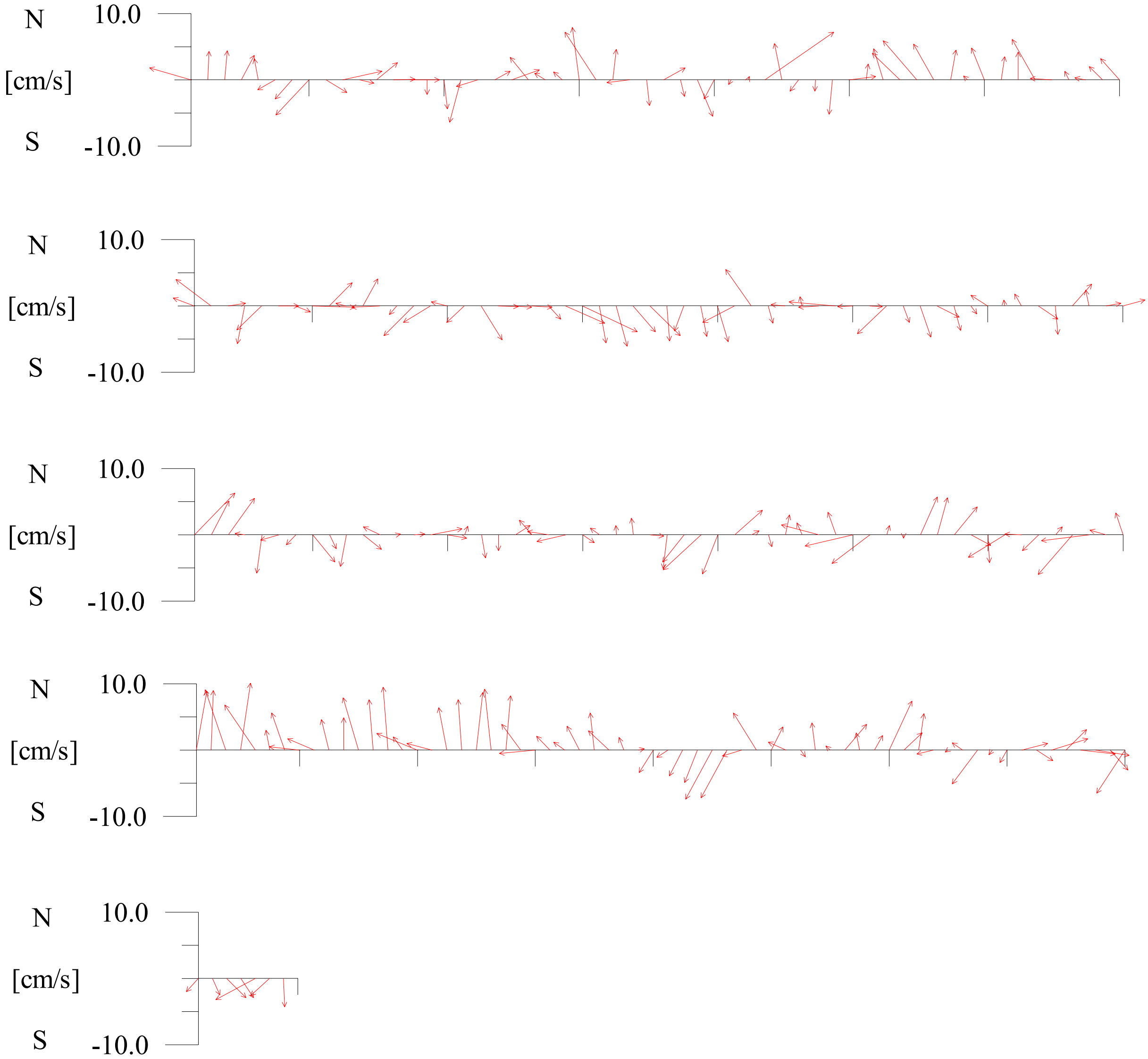


Signal Strength [dB]
220
210
200
190
180
170
160
27-okt-00
28-okt-00
29-okt-00
30-okt-00
31-okt-00
1-nov-00
Time

Appendix B. Vector stick plots for 750 m depth

Vector stick plots for current in cell 8 (750 m depth). Time between each measurement is 10 minutes.




N
10.0
[cm/s]
S
-10.0
N
10.0
[cm/s]
S
-10.0
N
10.0
[cm/s]
S
-10.0
N
10.0
[cm/s]
S
-10.0
N
10.0
[cm/s]
S
-10.0