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	IN ENGLISH:		**IN NORWEGIAN:**
a)	geo-magnetic noise	a)	geo-magnetisk støy
b)	noise cancellation	b)	støyfjerning
c)	spatial noise coherence	c)	romlig støykoherens
d)	linear prediction	d)	lineær prediksjon
e)	scalar magnetometer	e)	skalarmagnetometer

THESAURUS REFERENCE: **clue**

8) **ABSTRACT**

In this report we investigate data from three scalar Overhauser magnetometers w.r.t noise suppression. We use remote reference methods with and without filters, and obtain suppressions in the order of respectively 17-38dB and 20-27dB. Employing a linear prediction method resulted in a signal-to-noise ratio improvement of 16-22dB. In addition the method has the advantage of not requiring inter magnetometer communications. A non-causal filter gives the least residual noise energy for the most cases.

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CONTENTS

Geomagnetic noise supression in Overhauser magnetometer data – a comparative study

1 EXECUTIVE SUMMARY

The objective of the work is to contribute to the basic knowledge needed for discussing the feasibility of using scalar versus tri-axial magnetometers as one of the major sensor components in an autonomous sensor concept. Geo-magnetic data from three scalar Overhauser magnetometers arranged in a triangular geometry has been analysed. Noise suppression on one of the magnetometers has been assessed employing data from one of the other magnetometers as a remote reference (RR). Processing methods without and with filters and causal and non-causal schemes were employed. A linear prediction (LP) noise suppression algorithm on single sensor data has been evaluated and is reported. The methods are described in references (1) and (2).

The available data set from a sea trial set up at Herdla in September 2004 was divided into 21 cases of intervals containing geomagnetic background noise only, free of target signals, some of which are overlapping with earlier studies of three-axial magnetometer recordings at Herdla.

In this study we found that utilizing the remote reference filtered approach (non-causal version) gave the most suppression of the background noise. In the frequency interval <0.001,0.01>Hz we experienced 17-38dB suppression. The unfiltered RR method suppressed the background noise 20-27dB. The signal suppression depends on the relative sensor separation.

The lowest residual noise level after RR filtering is approximately $-22dBnT/\sqrt{Hz}$ ($80\,pT/\sqrt{Hz}$) within the <0.001, 0.3>Hz interval of the analysis.

The LP method obtained only 16-22dB improvement in the SNR, but has the advantage over the RR of requiring no inter magnetometer data exchange. The signal suppression depends on the radial velocity of a target.

These results compare with suppression figures of approximately 20dB for RR, and 10dB for LP reported in reference (2).

2 INTRODUCTION

This work is done within project 886 NIMSES (Network Integrated Maritime Sensor and Effector Systems). The project investigates the use of underwater sensor systems detecting passing vessels, and in these explorations magnetic recordings are carried out. In September 2004 recordings on three Overhauser magnetometers were made, deployed close to the measurement range Herdla, outside of Bergen on the west coast of Norway. The magnetometers are of type Sentinel from Marine Magnetics, and were provided by SPAWAR (SPAce and naval WARfare systems command) (USA).

In the following we use methods based on remote reference (RR) with causal and non-causal filtering as well as direct subtraction to suppress noise. We found using an adaptive filter with a recursive least squares (RLS) scheme to be the most adequate. In addition we also applied linear prediction (LP). The methods are presented in references (1) and (2) for three-axial measurements, but are here applied to the simpler case of scalar Overhauser measurement data. The analysis presented here is a continuation of the work described in references (3) and (4), and the work on magnetic data in reference (5).

The results can be compared to noise suppression obtained for data from the permanently installed magnetometers at Herdla in the same time period, reference (2) and (5). It is believed that such a comparison could give important inputs for choosing between scalar or tri-axial magnetometers for the autonomous sensor concept under consideration.

3 MAGNETOMETER RECORDINGS

The Overhauser magnetometers were placed in a triangular geometry with about 150-300 meter spacing, see Figure 3.1.

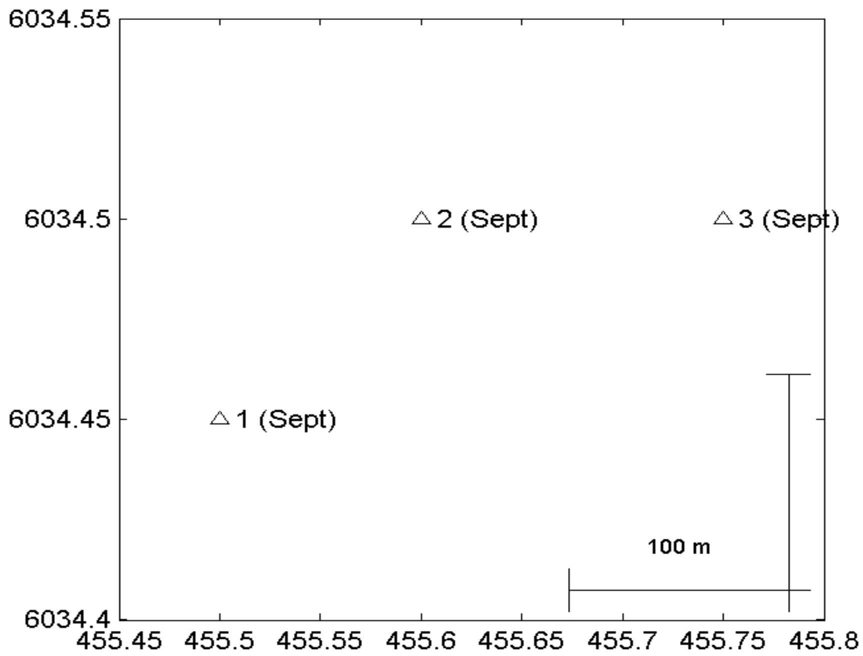


Figure 3.1 Positioning of the Overhauser magnetometers in September 2004. Magnetometers 1, 2, and 3 from left to right

We have analysed noise data (no passing vessels) recorded with the Overhauser magnetometers, including an overlapping time interval where recordings also were made at the stationary Herdla magnetometers, investigated in (2). The data employed in the analysis originates from the files shown in Table 3.1, where the times for start and stop recording of the three magnetometer data files are given.

File	Start recording (date time)		Stop recording (date time)	
Magnetometer1	22.09.04	12:15:37	24.09.04	08:43:57
Magnetometer2	22.09.04	12:31:18	25.09.04	04:34:02
Magnetometer3	22.09.04	12:40:24	25.09.04	09:40:35

Table 3.1 The start and stop recording times for the three magnetometers

All time references are given in UTC.

4 DATA ANALYSIS

Selection of target time series of data containing noise only, relevant for this study, rendered the 21 cases summarized in Table 4.1. The last case, Case 21, include data coinciding with tri-axial data acquired at the Herdla range, analysed and reported in ref (2) and (5).

All of the 21 cases were analysed and used for producing the statistical results presented in section 5. However, the analysis of some of the records is treated in more detail, appearing in appendix A.2. The selection is based on cases (cases 7 and 20) that produced unexpected results, hence where one of the simpler methods did best. We also included one case (case 2) where the more complex method did best.

The time interval between 9:15AM on the 23rd of September 2004 and 5:45AM on the 24th contains data from several passages of a trial target vessel. When we investigate the noise characteristics we make sure there are no passages of vessels by searching and visually inspecting the time series. The intervals between passages are rather short, but this does not influence the results using the chosen method for analysis.

In Table 4.1 a schematic overview of the case study time intervals is given.

Case	Start (date time)		Stop (date time)		Duration
1	22.09.04	12:40:24	22.09.04	15:06:00	2h 25m 36s
2	22.09.04	15:09:00	22.09.04	17:24:00	2h 15m
3	22.09.04	18:00:00	22.09.04	22:40:00	4h 40m
4	22.09.04	22:56:00	23.09.04	10:26:00	11h 30m
5	23.09.04	10:28:00	23.09.04	12:07:00	1h 39m
6	23.09.04	12:10:00	23.09.04	12:32:00	0h 22m
7	23.09.04	12:34:00	23.09.04	13:23:00	0h 49m
8	23.09.04	13:26:00	23.09.04	13:50:00	0h 24m
9	23.09.04	13:53:00	23.09.04	14:42:00	0h 49m
10	23.09.04	14:45:00	23.09.04	18:10:00	3h 25m
11	23.09.04	18:12:00	23.09.04	19:42:00	1h 30m
12	23.09.04	19:45:00	23.09.04	22:21:00	2h 36m
13	23.09.04	22:25:00	23.09.04	23:12:00	0h 47m
14	23.09.04	23:19:00	23.09.04	23:36:00	0h 17m
15	23.09.04	23:41:00	24.09.04	00:33:00	0h 52m
16	24.09.04	00:37:00	24.09.04	01:52:00	1h 15m
17	24.09.04	01:59:00	24.09.04	02:10:00	0h 11m
18	24.09.04	02:20:00	24.09.04	04:47:00	2h 27m
19	24.09.04	04:50:00	24.09.04	05:12:00	0h 22m
20	24.09.04	05:15:00	24.09.04	05:44:00	0h 29m
21	24.09.04	05:47:00	24.09.04	08:43:57	2h 56m 57s

Table 4.1 The start and stop times (UTC) for the case intervals, and duration given in hours (h), minutes (m), and seconds (s)

We ran the raw data through a pre-processing step of band pass (bp) filtering using a 8th order Butterworth filter, passing frequencies in the band 1-300 mHz.

The following noise suppression methods were used:

- direct data subtraction between the magnetometers
- subtraction augmented by a causal least square recursive filter
- subtraction augmented by a non-causal least square recursive filter
- linear prediction noise suppression. However, as was pointed out in (2) these results can not be directly compared to the results of the subtraction methods.

The data analysis comprised a FFT (Fast Fourier Transform) length of 512 samples, a forgetting factor for the adaptive filter of 0.95, and a filter order of 27, <0, 26> for the causal and <-13, 13> for the non-causal version. The order for the linear prediction (LP) filter was 17. The sampling rate was 1Hz.

Results from the noise suppression are summarized in section 5, while a collection of some plots are shown in A.2.

5 RESULTS

We have used two measures to assess the noise suppression results. We looked at the relative suppression and at the minimum energy defining the noise floor. In addition we evaluated the signal to noise ratio for the linear prediction (LP) method. For comparison we mention that the results from reference (2) for the tri-axial magnetometers were about 20dB suppression for the RR methods, and about 10dB for LP.

The relative suppression figures are assessed by computing the reduction (in dB) obtained by subtracting the residual power spectrum levels (after processing) from power spectrum levels of the input signal. The reduction figures are obtained for the RR cases with and without filtering. Using no filter is only direct subtraction of a reference magnetometer; one of the two neighbours, from the magnetometer in question. The filter versions use either a causal or a non-causal scheme with one of the neighbouring magnetometers as reference. The results are shown in Figure 5.1 and Table 5.1, and give an overview of the methods producing the maximum noise suppression.

The residual noise level after RR filtering is at least approximately $-22\mathrm{dBnT}/\sqrt{\mathrm{Hz}}$ within the low frequency interval of the analysis.

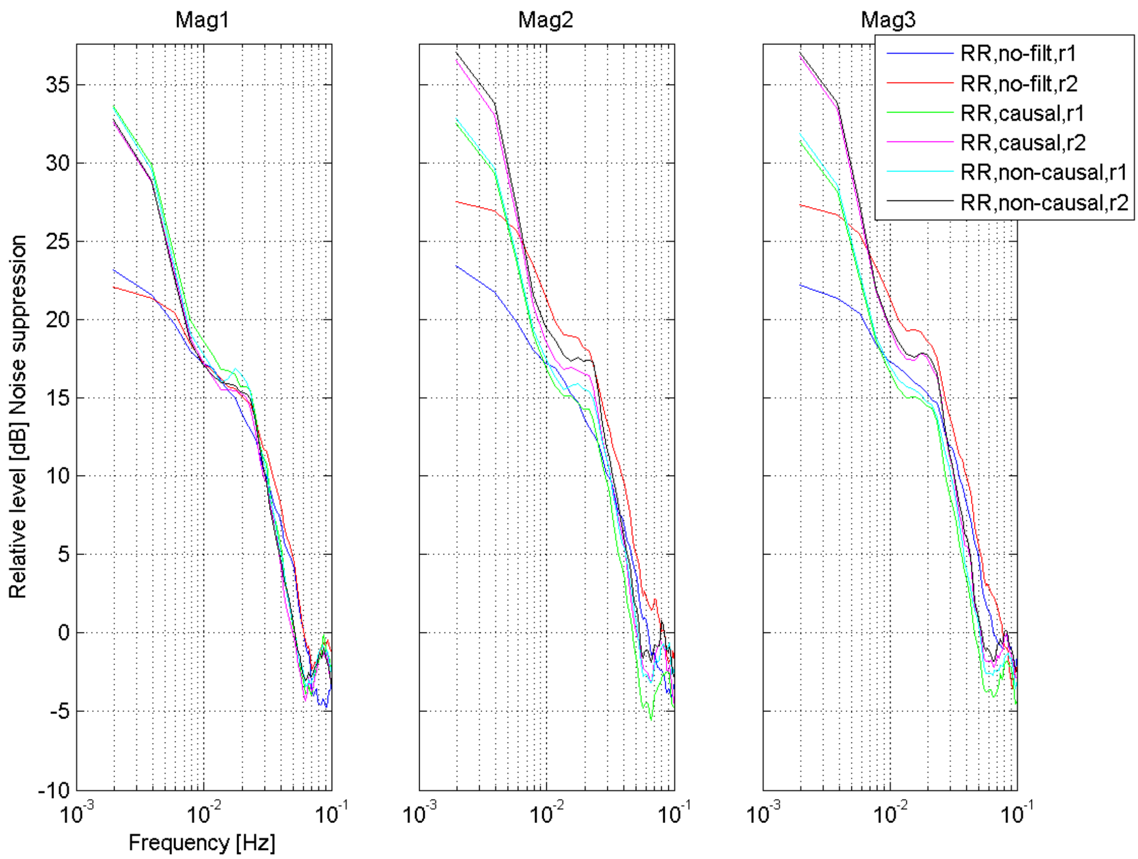


Figure 5.1 *Results from the noise suppression of the magnetometer data. Relative level between the input signals power spectrum level and the noise suppressed levels. In the left plot magnetometer 2 (r1) and magnetometer 3 (r2) were used as reference magnetometers for noise suppression in magnetometer 1. In the middle plot magnetometer 1 (r1) and magnetometer 3 (r2) were used as reference magnetometers. In the right plot magnetometer 1 (r1) and magnetometer 2 (r2) were used as reference magnetometers*

Method	Number of times
RR, no filter	8
RR, causal filter	25
RR, non-causal filter	30

Table 5.1 *Number of times the different methods caused maximum suppression among the three methods in the frequency interval <0.001, 0.3>Hz*

Another measure for finding the best method is evaluating the energy content in the output signals after processing. For frequencies higher than 0.1Hz we seldom experience any suppression. In these cases we are noise limited and as expected the processing makes the situation worse.

For frequencies below 0.3Hz we define the energy level as the mean value over the frequency interval. The method producing the lowest energy level is considered the one giving the best suppression. The results are summarized in Table 5.2.

Method	Number of times
RR, no filter	0
RR, causal filter	11
RR, non-causal filter	52

Table 5.2 Number of cases the different methods produced the best results within the frequency range <0.001, 0.3>Hz

To evaluate the performance of the LP method we compute the signal and noise suppression and look at the relative suppression (increase in signal to noise ratio, SNR). Since the data contains no passing vessels the magnetic influence of a modelled target is used as signal. For each case and each magnetometer we compute an autoregressive (AR) filter of length 17 taps, over the frequency interval <0.001, 0.3>Hz. This output is compared to the unfiltered delayed signal in order to compute the suppression of the signal at certain frequencies. The theoretical signal and its spectrum are included in A.1. The relative velocity of the target used here is v/r=0.02 s^{-1}.

The values for the SNR improvement for the three chosen frequencies are computed for each case. The average results are shown in Table 5.3. The frequency band is <0.001, 0.3>Hz.

At frequency	SNR improvement [dB]
3.9mHz	21.6
5.9mHz	18.3
7.8mHz	15.8

Table 5.3 Signal to noise improvement using the LP method. Computations made at three different frequencies

Contrary to the remote methods the LP does not require a reference magnetometer. Hence no communication between the magnetometers is needed, see reference (2).

5.1 Signal energy suppression

The signal experiences the same filtering as the noise. In this section we investigate the total energy suppression, in the same manner as in ref (2). First we take a look at the LP case. The suppression is computed as a function of relative velocity, and shown in Figure 5.2.

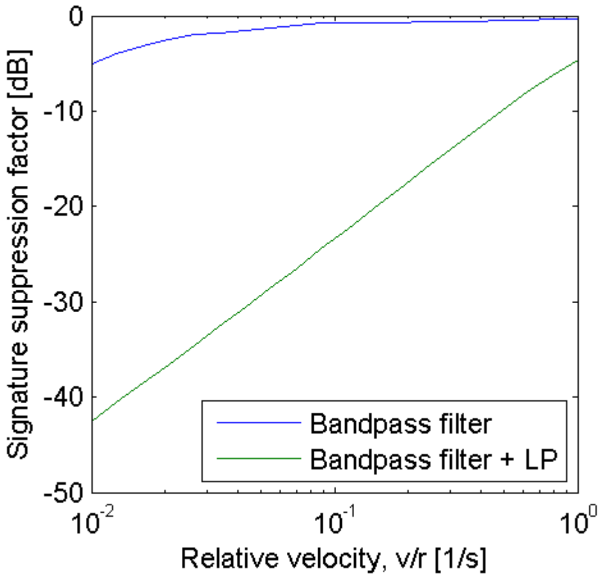


Figure 5.2 Signal energy suppression factor using the LP filter for case 10.

We see that the relative velocity has a significant impact on the energy suppression. The above graphs are computed using case 10 from magnetometer 3. The results were similar for other cases. The numbers should be compared to noise suppression seen in the power spectrum figures in Appendix A.2. Note that in Table 5.3, the signal suppression as well as the noise suppression has been taken into account, at selected frequencies.

Signal energy suppression using the RR-method depends on the heading of the vessel relative to the sensor pair. The suppression can be viewed in Figure 5.3. In one graph the line between the sensors is normal to track of vessel, and in the other parallel to track. Both graphs are functions of relative sensor separation (d is distance to reference sensor, and r is distance to vessel).

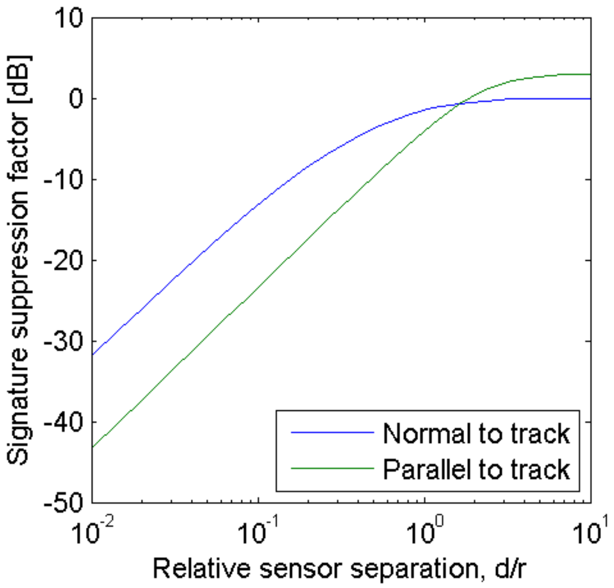


Figure 5.3 Signal energy suppression factor using RR filter

For both geometries the signal energy suppression decreases with increased relative sensor separation.

6 CONCLUSIONS

Our intent in this study was to analyse the performance of the Overhauser magnetometers after using noise suppression algorithms. The results can be compared to results obtained using data recorded at the stationary magnetometers at Herdla.

What we experienced was that the remote reference method, including filters for noise suppression, performed best. From the analysis we are not able to conclusively point out which of the causal or non-causal scheme performed best, or which magnetometer combinations is the best. The magnetometers are not positioned that far away from each other that one of the combinations should perform far better than the others. However using the measures we have computed indicates the non-causal scheme to be the best, obtaining 17-38dB suppression of background noise in the 0.01-0.001Hz region.

The disadvantage using the remote reference filtering method is that it needs communication between the magnetometers. The direct subtraction method also calls for communication between the magnetometers, but is a more simple computational method. Using this method we obtained performances somewhat lower, about 20-27dB background noise suppression in the 0.01-0.001 Hz interval.

We also looked at the minimum energy measure. In the interval of <0.001, 0.3>Hz the non-causal scheme produced the least residual noise energy for most of the cases.

The residual noise level after RR filtering is approximately $-22\mathrm{dBnT}/\sqrt{\mathrm{Hz}}$ at the lowest, within the interval of the analysis.

The signal energy suppression for the RR-methods depends on the relative sensor separation.

The LP results gave from 16 to 22dB signal-to-noise-ratio improvement for the chosen frequencies in the analysis, see Table 5.3. The method did not obtain as high improvement as the other methods, but does not require a remote reference magnetometer for computation. The signal energy suppression depends on the relative velocity.

Note that the SNR improvements reported for the LP method here is significantly higher than what is predicted for a scalar magnetometer according to (6), Sec. 4.5. The latter report is based on recordings during more disturbed geomagnetic conditions.

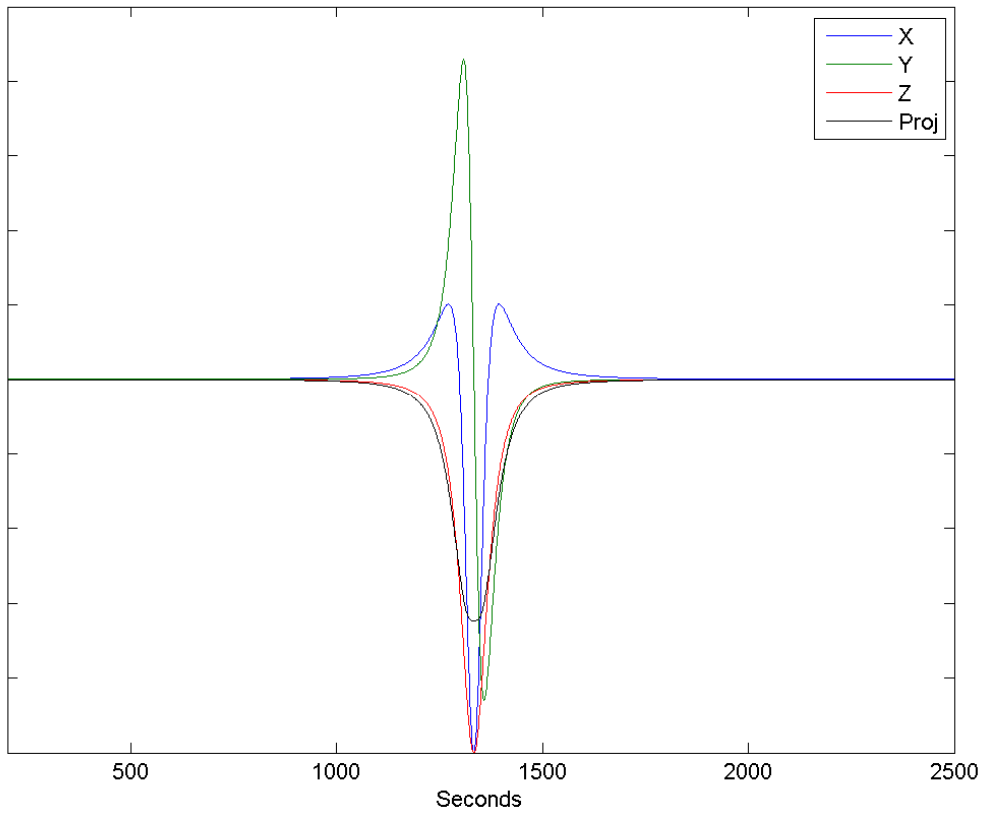
7 ACKNOWLEDGEMENTS

This work was made possible by the Next Generation Autonomous Sensors (NGAS) Joint Research Project (JRP), a collaboration between NATO Undersea Research Centre (URC), DRDC Atlantic (Canada), FFI (Norway), and the Office of Naval Research (U.S.). We would also acknowledge SPAWAR for providing the magnetometers.

APPENDIX

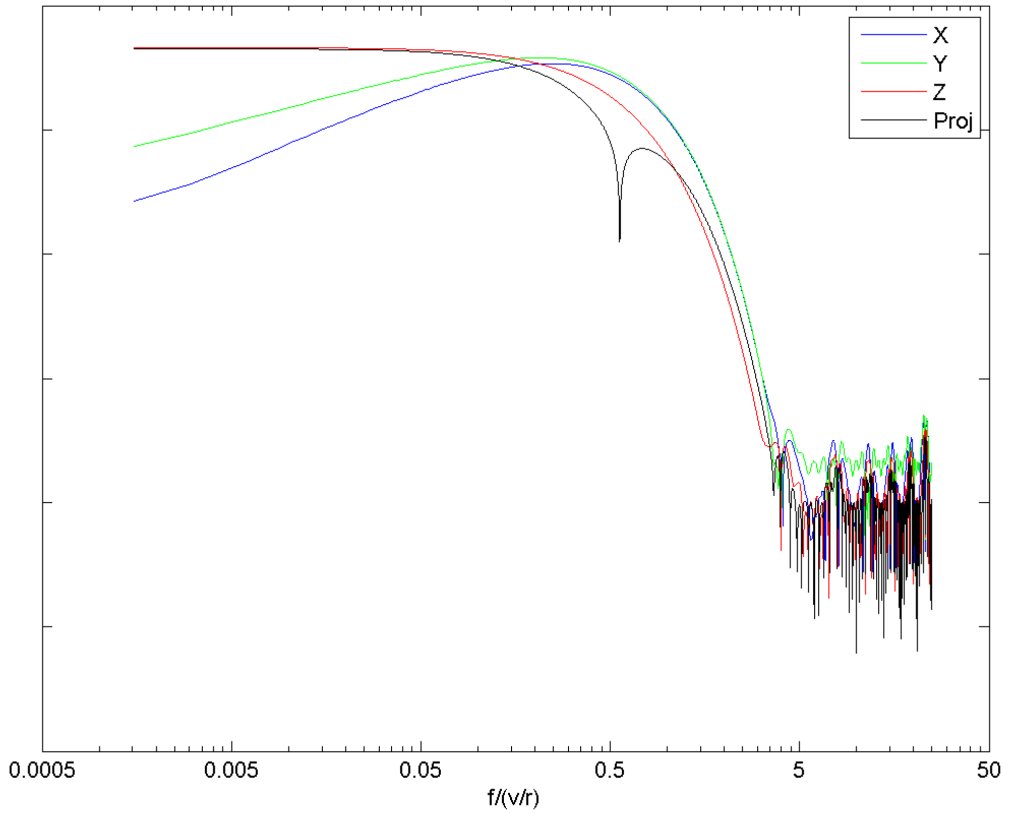
A.1 Vessel signal

In order to identify the signal frequencies we look at the vessel signal in time and frequency. The signal is theoretically represented via three functions in time, one for each axial direction, but we only have scalar measurements. In the computations of the LP signal suppression we make use of a projection signal, made up by the three components.



Figur App 1 The theoretical signal shape in the three axial directions, and the projected (proj) version. In this figure, v/r=0.02 s^{-1}

In Figur App 2, a representation in the frequency domain is shown. The x-axis is dimensionless. The relation v/r is the relation between the vessel velocity and the CPA (closest point of approach) vessel-magnetometer. This relation scales the time axis, which causes a shift in the frequency domain and a change in amplitude.



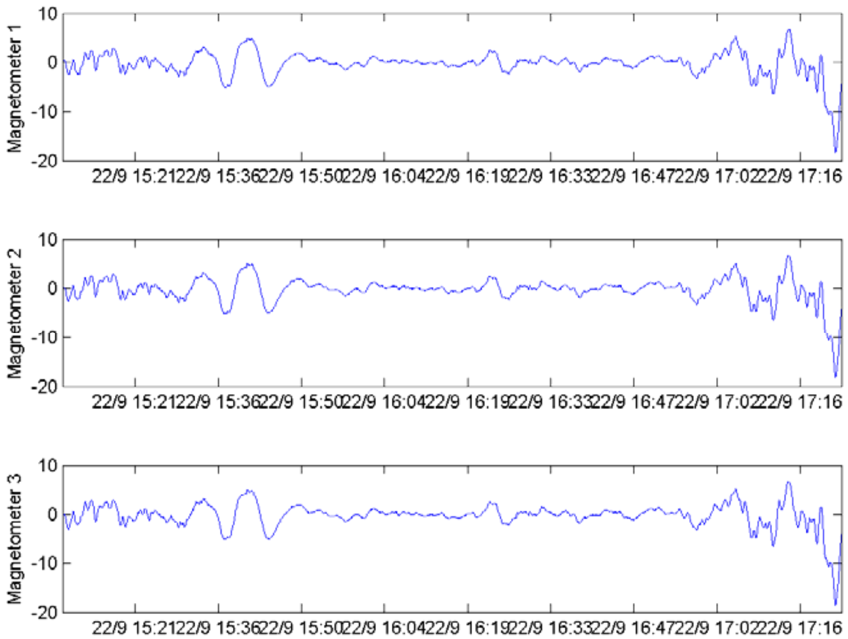
Figur App 2 The frequency content of the theoretical signal, three axis and projection

A.2 Noise suppression

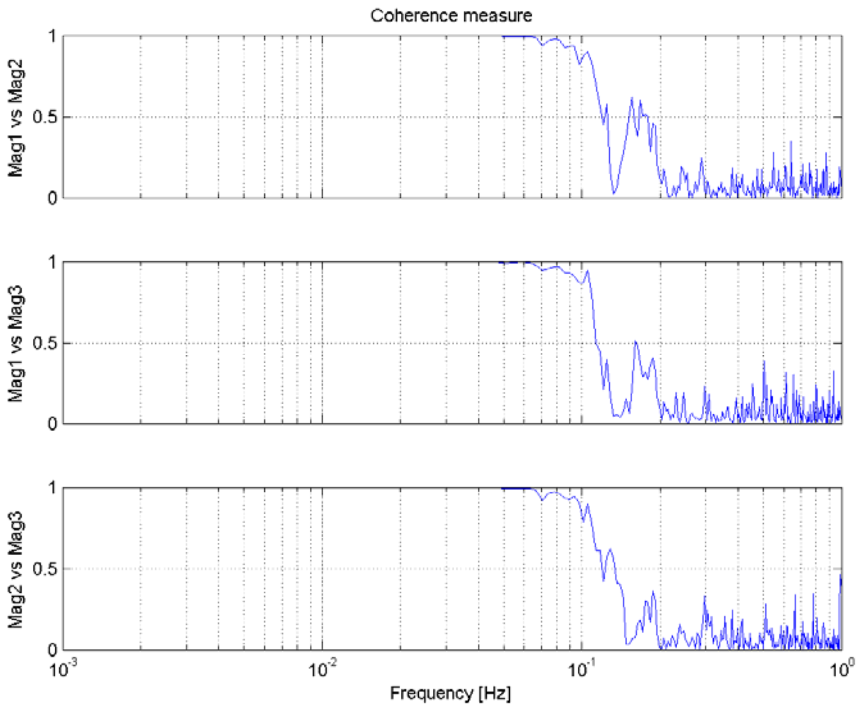
We have included a coherence measure computed through the frequency domain. This tells us which magnetometers are most similar, and hence are best suited for noise suppression.

A.2.1 Case study 2

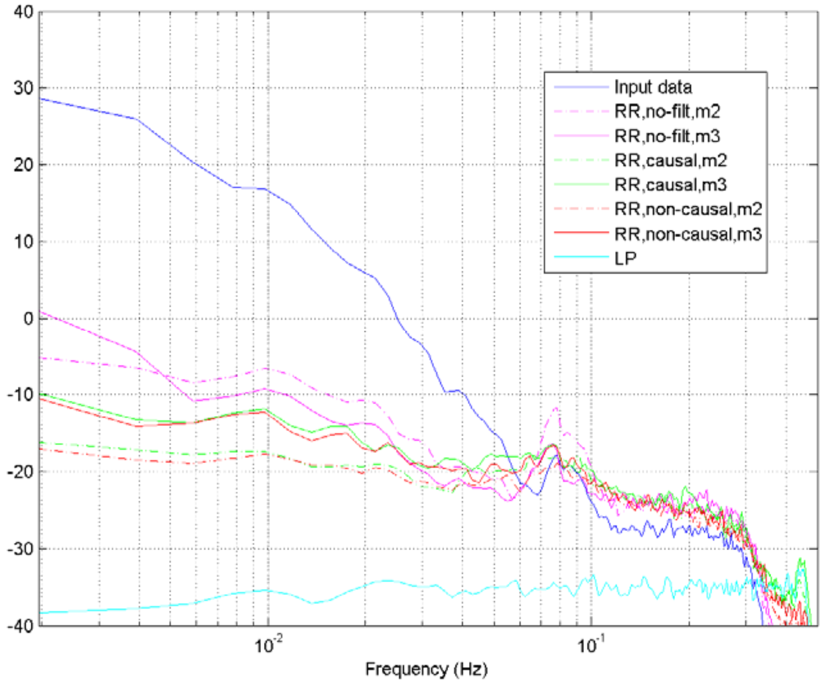
Data from 22nd of September 2004, from 15:09:00 to 17:24:00.



Figur App 3   Time series, band pass filtered



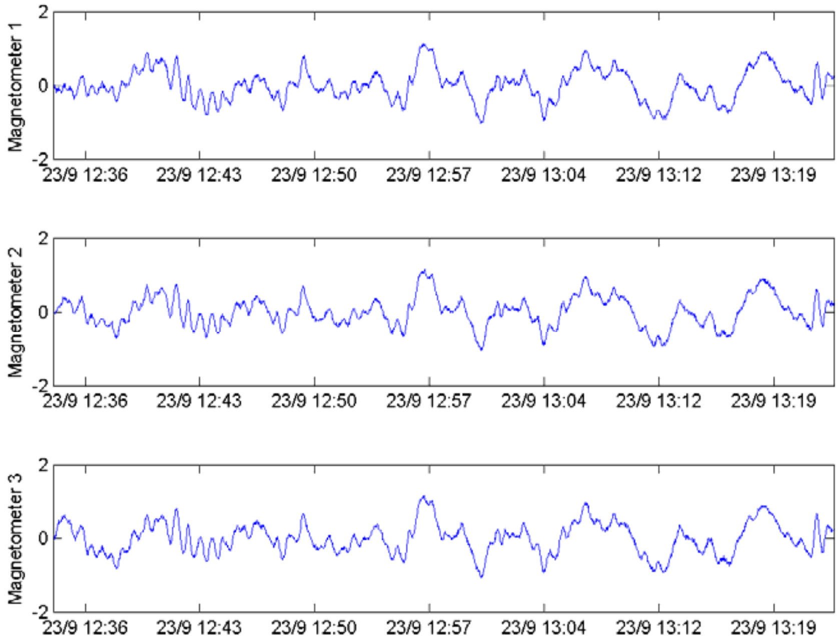
Figur App 4   Coherence measure via frequency domain



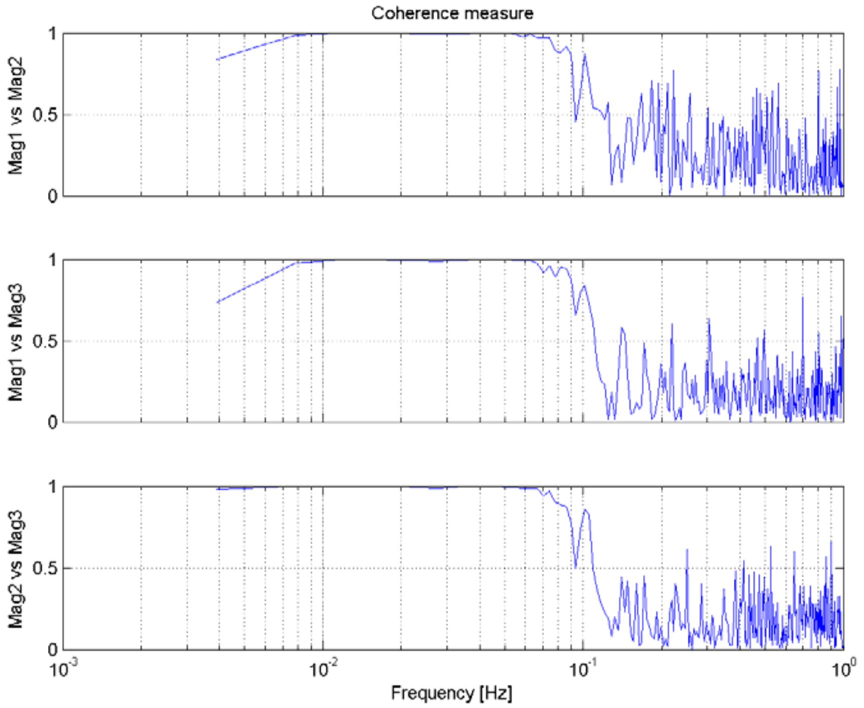
Figur App 5 Background noise measured by magnetometer 1. Different noise reduction methods using magnetometer 2 and 3 as references

A.2.2 Case study 7

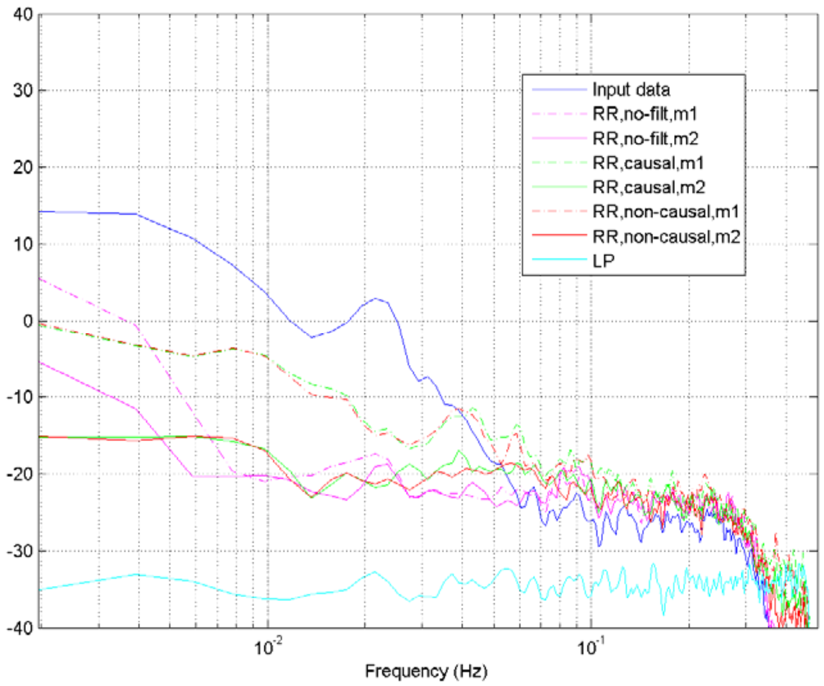
Data from 23rd of September 2004, from 12:34:00 to 13:23:00.



Figur App 6 Time series, band pass filtered



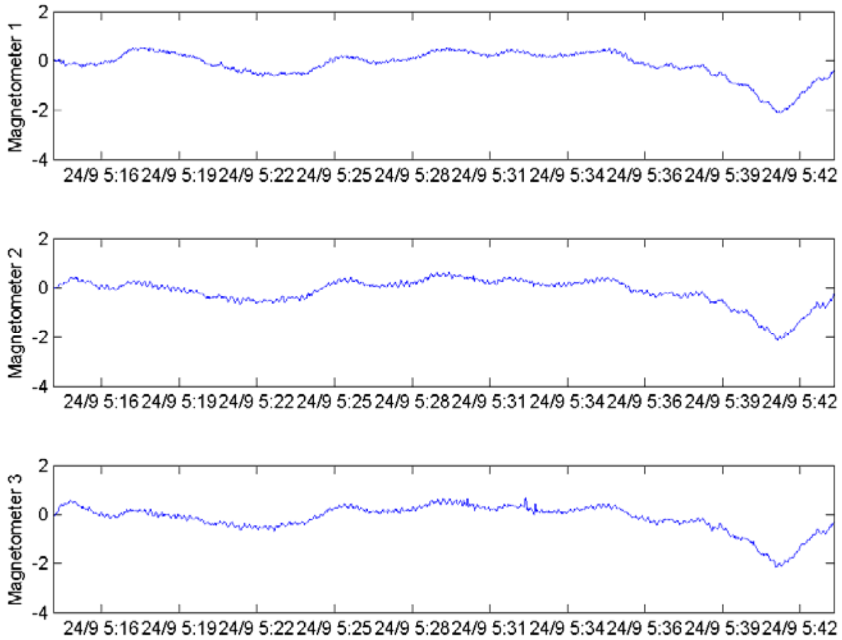
Figur App 7 Coherence measure via frequency domain



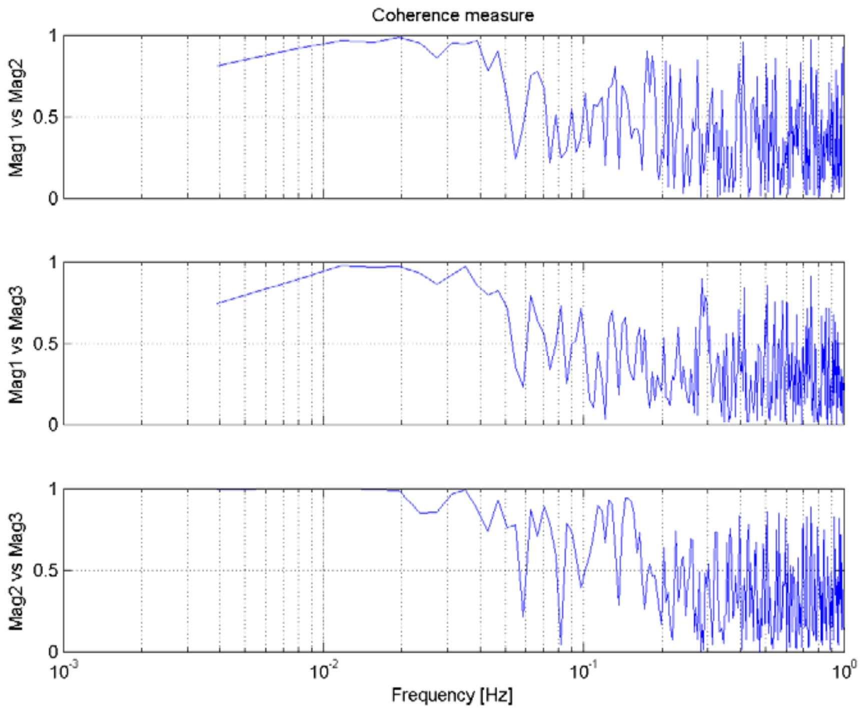
Figur App 8 Background noise measured by magnetometer 3. Different noise reduction methods using magnetometer 1 and 2 as references

A.2.3 Case study 20

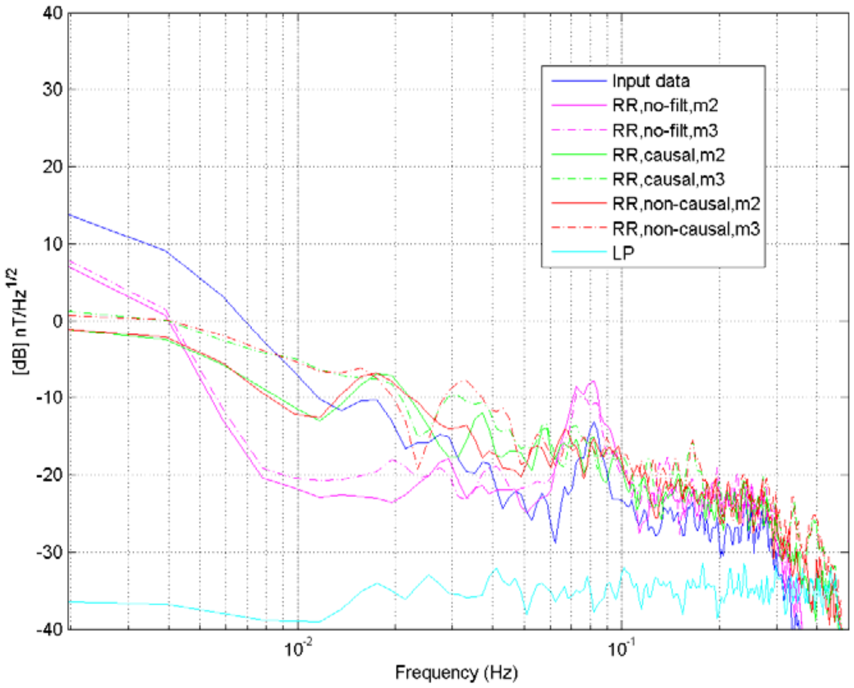
Data from 24th of September 2004, from 05:15:00 to 05:44:00.



Figur App 9 Time series, band pass filtered



Figur App 10 Coherence measure via frequency domain



Figur App 11 Background noise measured by magnetometer 1. Different noise reduction methods using magnetometer 2 and 3 as references

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