

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 1 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06
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Report DAF-05-1: Test of 1-minute sampling of water level

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Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level		Page 2 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

CONTENTS:

1	ABSTRACT	3
2	INTRODUCTION.....	4
3	COLLECTING TEST DATA.....	4
4	VERTICAL REFERENCE LEVEL	7
5	ANALYSIS OF TEST DATA	10
5.1	Analysis of data set 1	10
5.1.1	Gaps in the data series and interpolation.....	10
5.1.2	Frequency content	14
5.2	Analysis of data set 2.....	15
5.2.1	Gaps in the data series and interpolation.....	15
5.2.2	Frequency content	17
6	FILTERING AND DECIMATING.....	18
6.1	Design of low pass filter	18
6.2	Filtering and decimating data set 1	25
6.2.1	LP-filtering	25
6.2.2	Decimating to 10-minute values	27
6.3	Filtering and decimating data set 2.....	29
6.3.1	LP-filtering	29
6.3.2	Decimating to 10 minute values	30
7	COMPARING TEST DATA SERIES USING TWO DIFFERENT FILTERS	31
7.1	General comments.....	31
7.2	Data set 1.....	32
7.3	Data set 2.....	36
8	COMPARING TEST DATA SERIES WITH MDS	40
8.1	General comments	40
8.2	Data set 1.....	41
8.2.1	Comparing with original MDS	41
8.2.2	Comparing with smooth MDS	45
8.3	Data set 2.....	48
8.3.1	Comparing with original MDS	48
8.3.2	Comparing with smooth MDS	51
9	COMPARING THE TWO SENSORS BOTH USING 3-MIN MEAN FILTER.....	54
9.1	General comments	54
9.2	Data set 1.....	54
9.3	Data set 2.....	56
10	CONCLUSIONS.....	57
	REFERENCES.....	60

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	3 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

1 Abstract

A low pass Butterworth filter of order 4 has been designed to filter the 1-min water level data before decimating to 10-min values. The filter is used in a post-processing mode, and the 1-min data series is filtered both forward and backward in time.

The water level data, data set 1 and data set 2, are from two different test periods. They are measured by a pressure gauge inside a stilling well with a sampling rate of 1 minute. The two data sets are filtered and decimated.

Following comparisons are carried out:

- The data set is compared to it self, using two different LP-filters (Butterworth order 4 and 3-minute mean) before decimating (see section 7).
- The data set (filtered with Butterworth order 4 before decimating) is compared to MDS (original and smoothed) (see section 8).
- The data set (filtered with 3-minute mean before decimating) is compared to MDS (normal and smoothed) (see section 9).

The most important result for data set 1 and 2 are summarised in the table below:

Data set	Difference due to filtering	Difference due to filtering when smoothing is used	Difference due to measurement techniques
1	+/- 0.9 cm (95%)	+/- 0.3 cm (95%)	[-0.5 cm, +0.3 cm] (95%)
2	+/- 0.6 cm (95%)	+/- 0.2 cm (95%)	+/- 0.3 cm (95%)

The observed difference is generally small, but we can see from the different time plots (see section 7 - section 9) that the difference vary over time. The difference is smaller for data set 2 than data set 1.

The “Difference due to filtering” (without smoothing) will have 2 causes:

- Aliasing in the time series filtered with the 3-minute mean filter.
- Real high frequency components in the time series filtered with the 3-minute mean filter.

These two components (in the time series filtered with the 3-minute mean filter) are mixed. It is not possible to separate them when only the 10-min series is available. These corrupted frequencies should be removed. This can be done with the smoothing filter. The “Difference due to filtering” (with smoothing) will have the same two causes, but both are reduced.

The best is to filter satisfactory before decimating but in the case of data set 1 and 2 the difference is small +/- 0.3 cm and +/- 0.2 cm.

The “Difference due to filtering” will be lager if there are more signal power in the frequency band from 0.000833... Hz (period 20 minutes) and up to ca. 0.004 Hz (period ca. 4 minutes). This can vary from site to site and with time. For the two data sets from Stavanger the PSD (Power Spectral Density) in this frequency band was low compared with the PSD at the tidal frequencies.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 4 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

2 Introduction

MDS is permanent stations for sea level measuring by Norwegian Hydrographic Service (NHS). The MDS tide gauge is based on a float in a stilling well. The Norwegian Tide Gauge Network consists of 23 stations at different locations. This network was modernised in the period 2000-2002.

In [9] it is shown that the filtering and sampling scheme in the stations after the modernisation is not ideal. Specifically, the arithmetic mean over 3 minutes (181 data measurements, one measurement every second) every 10-minute does not remove all energy above the Nyquist frequency before decimating to 10-minute values. This means that the collected 10-minute values contain aliasing noise, although it is unknown how much this affects the data.

It is waves with frequencies from 0.000833... Hz (period 20 minutes) and up to ca. 0.004 Hz (period ca. 4 minutes), which are not attenuated enough, and will appear as noise in lower frequencies after decimating to 10-minute values.

Since the datalogger used in the MDS only supports ordinary arithmetic mean, we can only choose the average period (length of mean interval, which is 3 minute today) and sampling period (which is 10 minute today).

In [9] the following sampling and filtering scheme was purposed as a future sampling scheme:

Sample interval in encoder	1 second
Filtering in data logger	1 minute mean
Sample interval in data logger	1 minute
Filtering at office	LP-filter (to be designed)
Decimating at office	10 minute interval

Since then we have collected two test series with 1-minute data. This report documents the analysis of these test series, and purposes a filter to be used before decimating to 10-minute values.

Note that [9] also concludes that the 1 Hz data measured in the stilling well in Stavanger which miss the narrowing at the orifice (stilling well and orifice has same dimensions), most likely will contain aliasing noise. This is because this stilling well is not a low-pass filter in this case. This problem will not be addressed here.

3 Collecting test data

Test data were collected in two periods 05.09-10.11.03 (data set 1) and 24.05-01.07.04 (data set 2) in Stavanger. In these periods a pressure gauge was placed inside a stilling well measuring the water level with a sampling frequency of 1 Hz. The datalogger made an arithmetic mean every minute (an arithmetic mean of 60 1-second values), and stored the 1-minute values. The two test data series are shown in Figure 3-1 and Figure 3-2.

It is a drawback that the test data were collected at the site in Stavanger, since it is the only site missing the narrowing at the orifice. The characteristic of the data may not be representative for the data collected at the other sites. But it was the most practical site to use, since it is close to the office of Norwegian Hydrographic Service (NHS).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	5 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

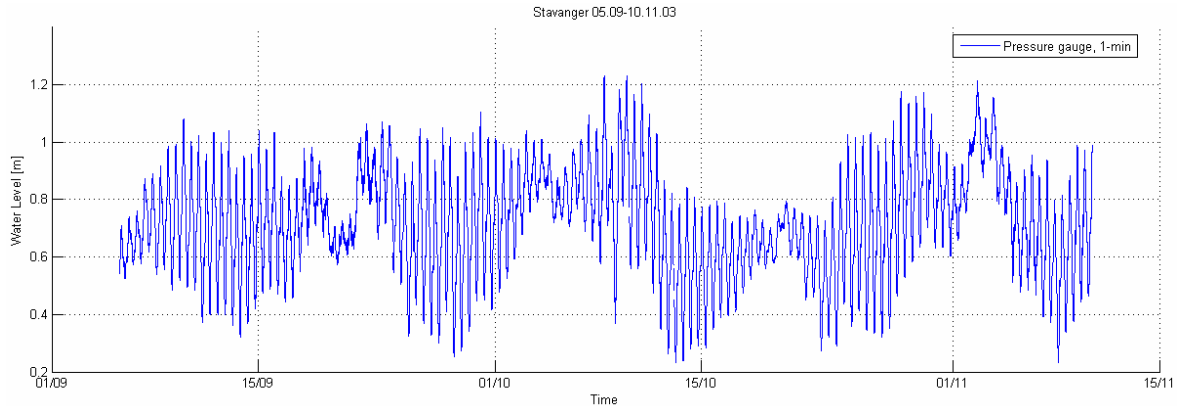


Figure 3-1 measured water level, pressure gauge inside stilling well (data set 1).

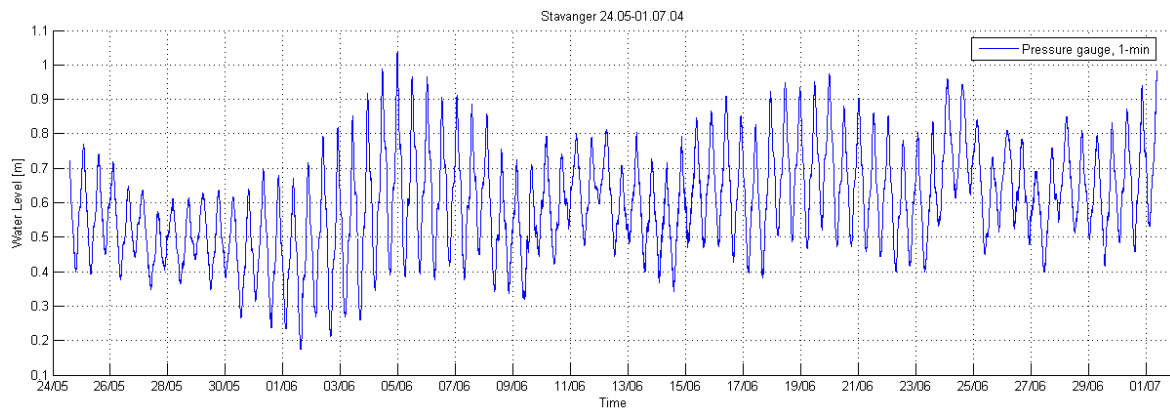


Figure 3-2 measured water level, pressure gauge inside stilling well (data set 2).

Parallel with the 1-minute logging of the pressure gauge, the MDS measured 10-minute values in the same stilling well (as normal). The MDS data series is shown in Figure 3-3 and Figure 3-4 together with predicted tide for the same periods.

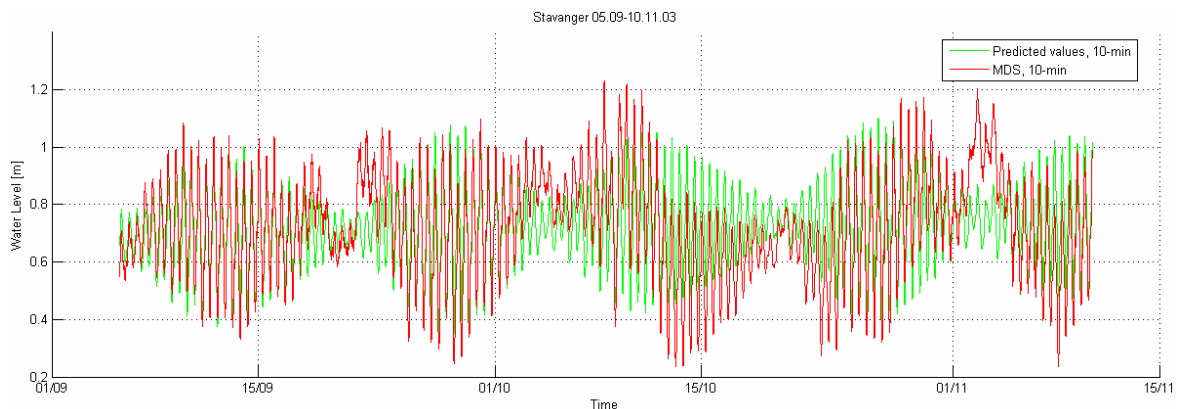


Figure 3-3 predicted tide and measured water level (ordinary MDS) (data set 1).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	6 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

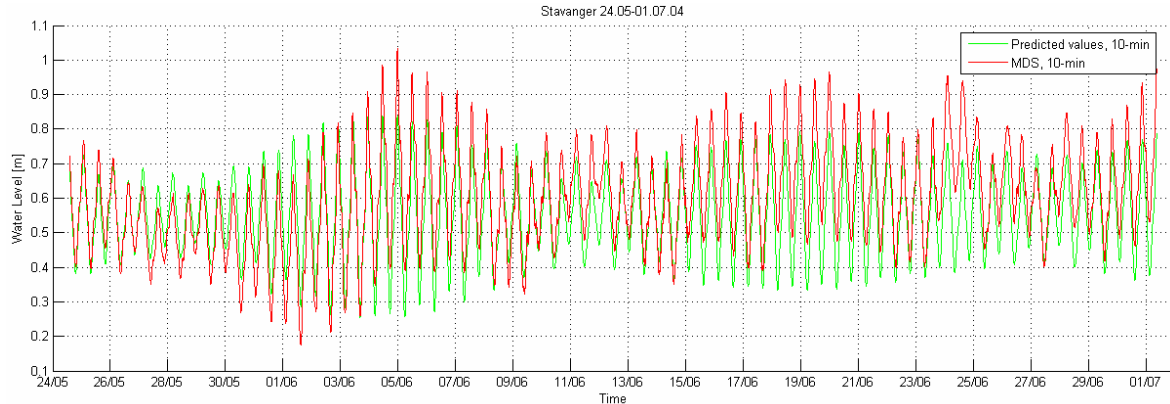


Figure 3-4 predicted tide and measured water level (ordinary MDS) (data set 2).

One week of the MDS data and the data from the pressure gauge (data set 1) are plotted together in Figure 3-5, and 24 hours in Figure 3-6. On the whole, it is a good agreement between the pressure gauge and the MDS, but the details differ because of the different filtering and sampling scheme and two different sensor types are used (see Figure 3-6).

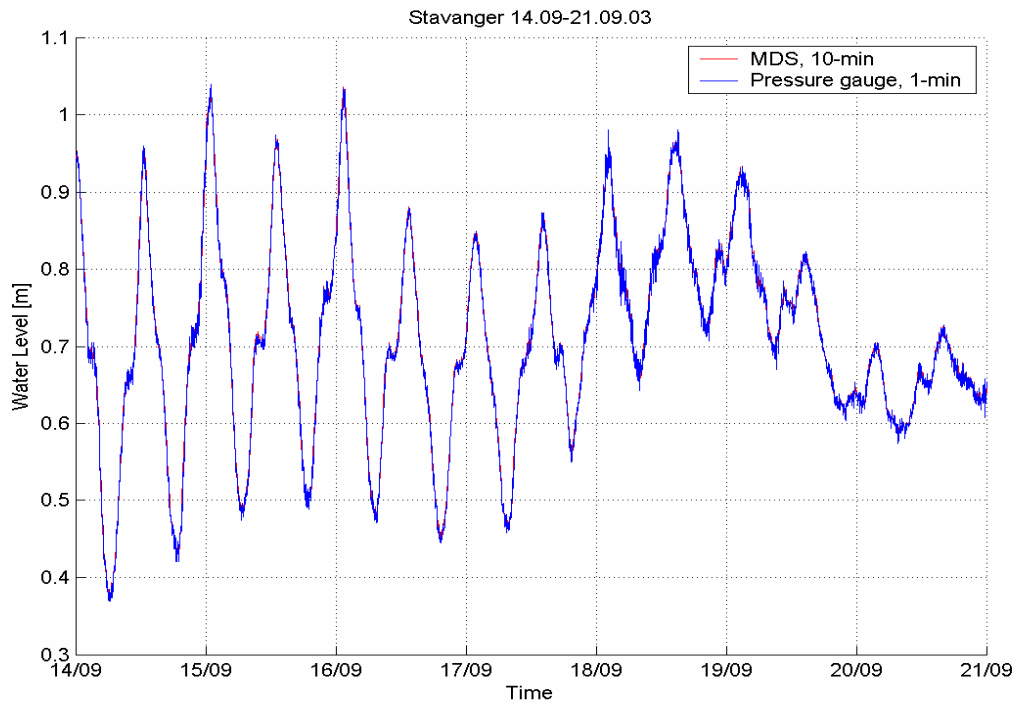


Figure 3-5 Pressure gauge and float, both in the same stilling well (one week).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	7 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

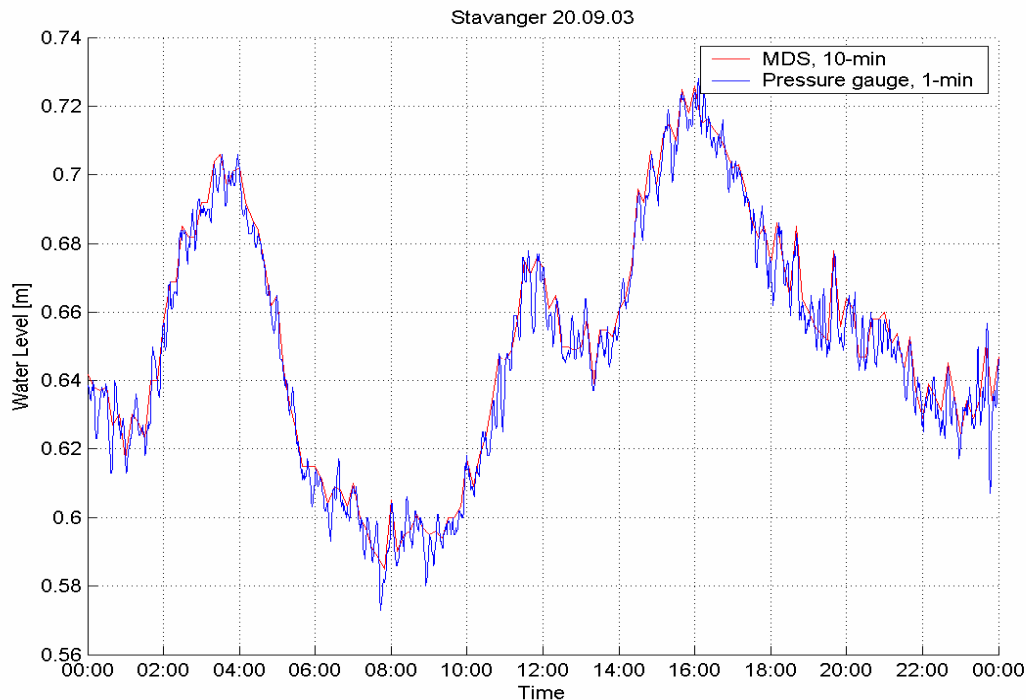


Figure 3-6 Pressure gauge and float, both in the same stilling well (24.hour period).

4 Vertical reference level

The MDS measurements are referred to chart datum.

There were not established a reference level for the pressure gauge in neither of the two measurement periods. Because of lack of reference level, the values measured by the pressure gauge are adjusted (shifted up or down by a constant) so that the mean of these series are the same as the mean of the MDS-series for the same time period. The two data sets are shifted individually.

The water level from the pressure gauge (shifted) and the MDS as well as the difference between them (MDS - Pressure gauge), are shown together in Figure 4-1 (data set 1) and Figure 4-2 (data set 2)

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Page	8 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

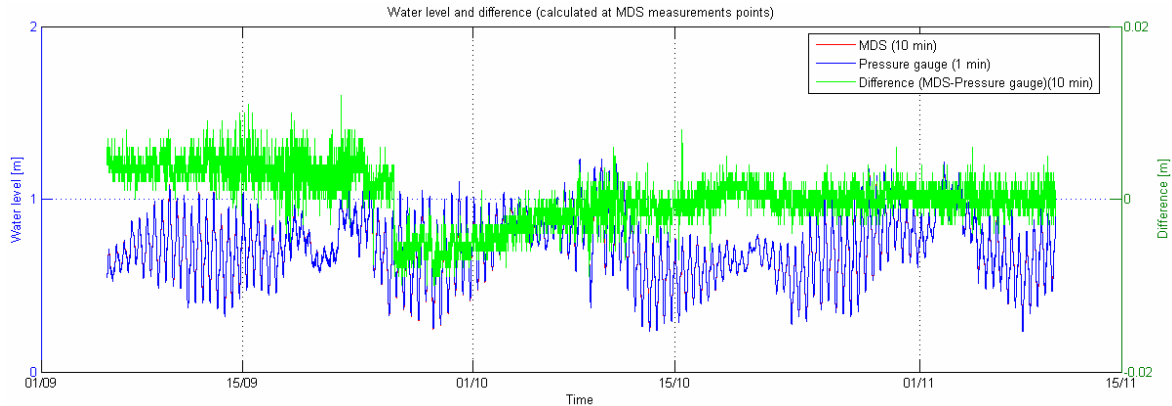


Figure 4-1 Measured water level, MDS, pressure gauge and the difference (data set 1).

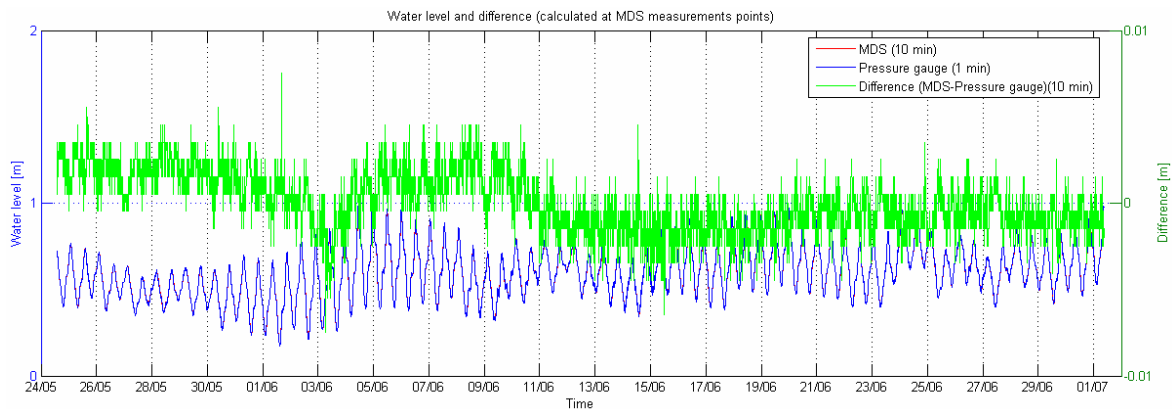


Figure 4-2 Measured water level, MDS, pressure gauge and the difference (data set 2).

In Figure 4-1 we can see a sudden step (down) in the difference between the two gauges. This step is located to 25.09.2004 12:07. In Figure 4-3 and Figure 4-4 we focus on this period. We can see that at 12:07 the water level measured by the pressure gauge suddenly drops (only one value) before it is re-established at a level slightly higher than the original level. The reason for this is that the gauge was inspected at this time. The pressure gauge was lifted up from the well (the low value), and put down again (not exactly at the same vertical position). At the same time it was observed that the anchoring had loosen. In the further analysis this outlier is removed.

After the removal of the one outlier the periods before and after the outlier are shifted independently. Which means that the first part of data set 1 (before the outlier) is shifted so that the mean of this first part of data set 1 are the same as the mean of the MDS-series for the same time period. The same is done for the last part of data set 1, and then the two parts are combined again. The resulting water lever series (data set 1) is shown in Figure 4-5 and Figure 4-6. This adjusted data series will be used in the further analysis in this document.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Page	9 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

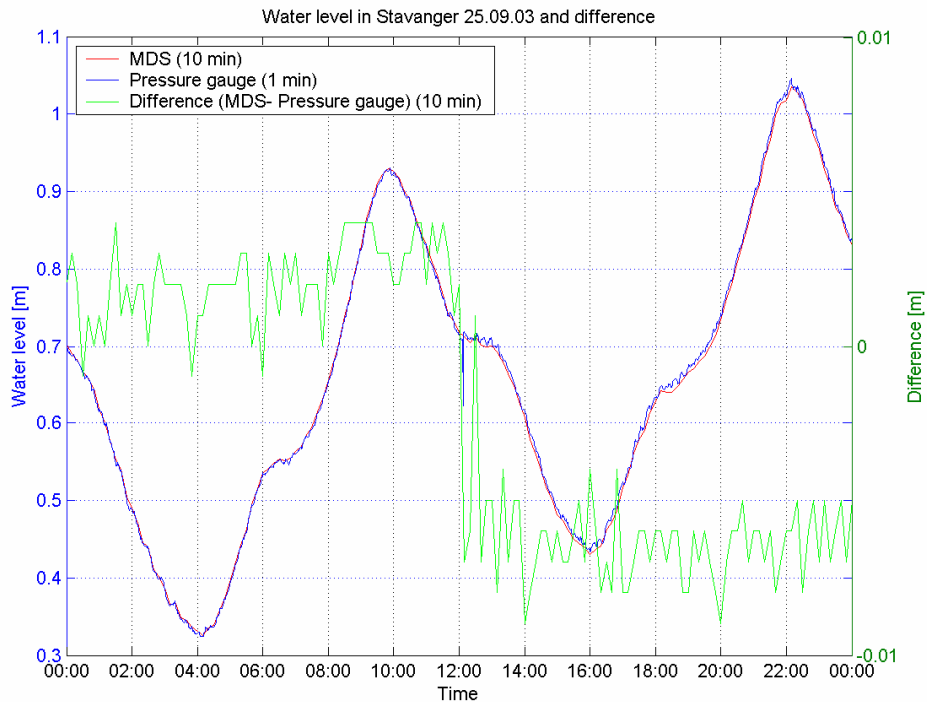


Figure 4-3 MDS, Pressure gauge and the difference (24 hours of data set 1).

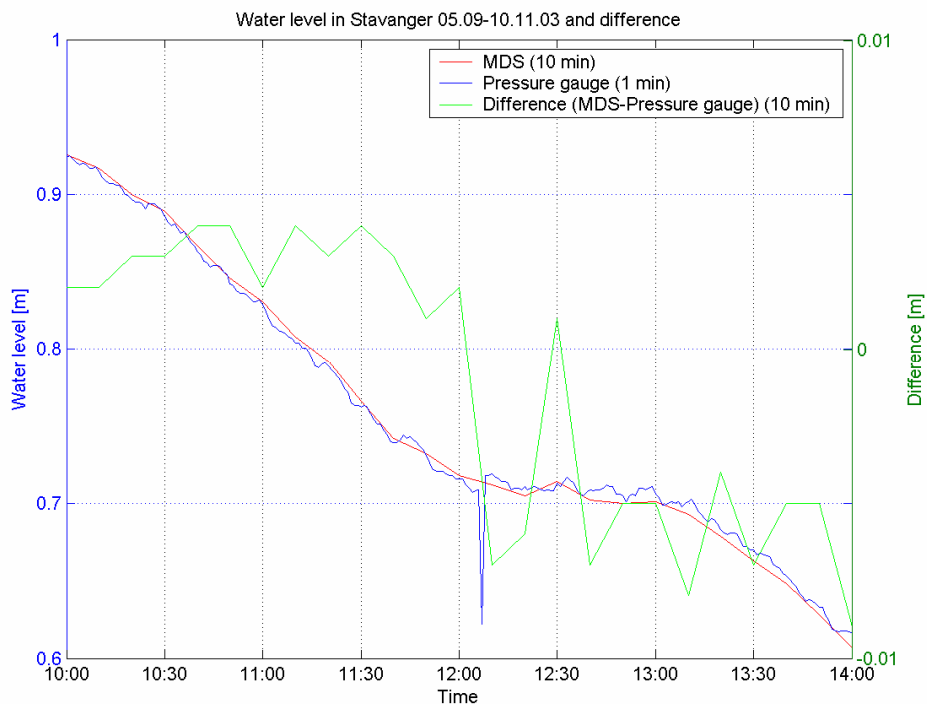


Figure 4-4 MDS, Pressure gauge and the difference (4 hours of data set 1), with outlier in the pressure measurements 25.09.04 12:07.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	10 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

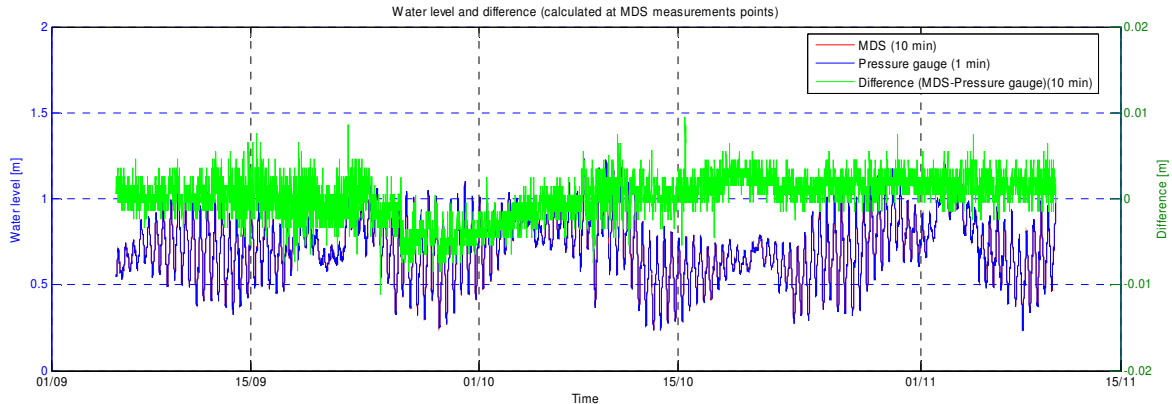


Figure 4-5. Measured water level, MDS, pressure gauge and the difference (data set 1).

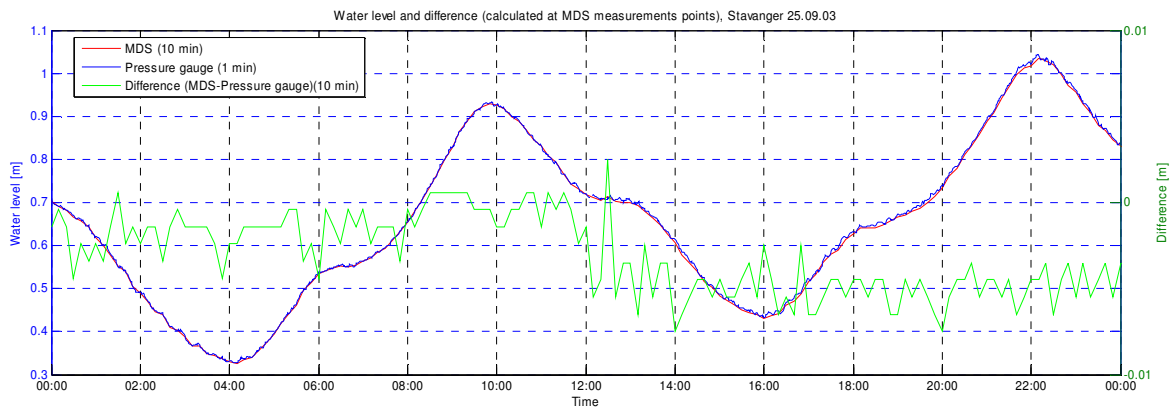


Figure 4-6. Measured water level, MDS, pressure gauge and the difference (24 hours of data set 1).

5 Analysis of test data

5.1 Analysis of data set 1

5.1.1 Gaps in the data series and interpolation

There are 9 gaps in the measured test data series 1 (plus one outlier that has been removed see section 4). In all the gaps 14 data values are missing. An overview of the gaps is shown in the table below, and Figure 5-1 and Figure 5-2 illustrates a few of the gaps. The reason for the gaps is unknown.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 11 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

Gap number	Time for last data before gap	Time for first data after gap	Length of gap in minutes (number of missing values)
1	15.09.2003 10:00	15.09.2003 10:15	15 min (14 values)
2	24.09.2003 02:02	24.09.2003 02:17	15 min (14 values)
3	10.10.2003 02:28	10.10.2003 02:43	15 min (14 values)
4	13.10.2003 02:16	13.10.2003 02:31	15 min (14 values)
5	13.10.2003 03:26	13.10.2003 03:41	15 min (14 values)
6	17.10.2003 06:54	17.10.2003 07:09	15 min (14 values)
7	17.10.2003 07:27	17.10.2003 07:42	15 min (14 values)
8	17.10.2003 10:01	17.10.2003 10:16	15 min (14 values)
9	20.10.2003 06:42	20.10.2003 06:57	15 min (14 values)

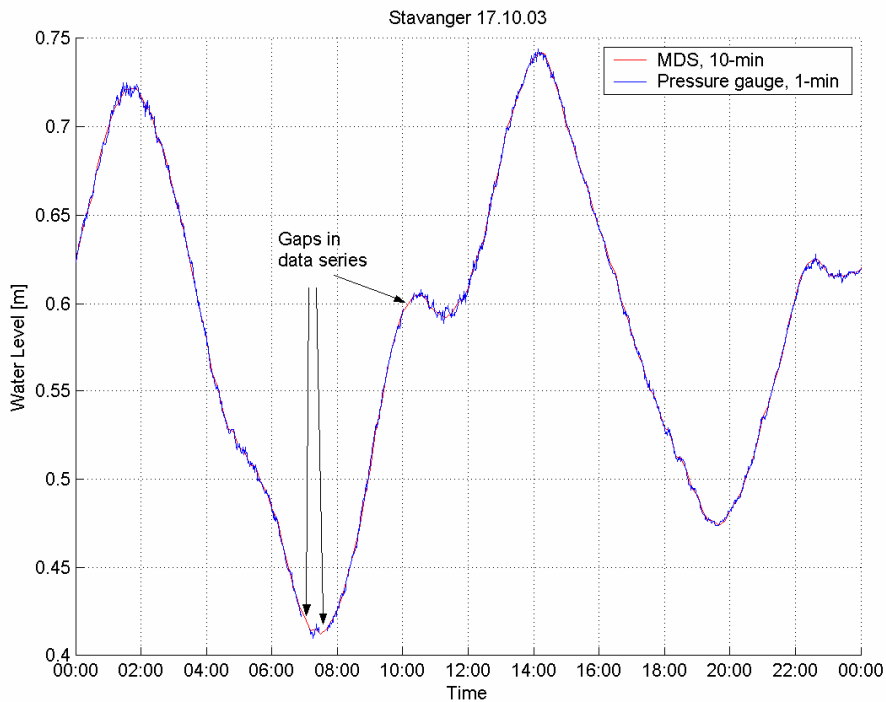


Figure 5-1 Gaps in the data series (gap number 6, 7 and 8).

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 12 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

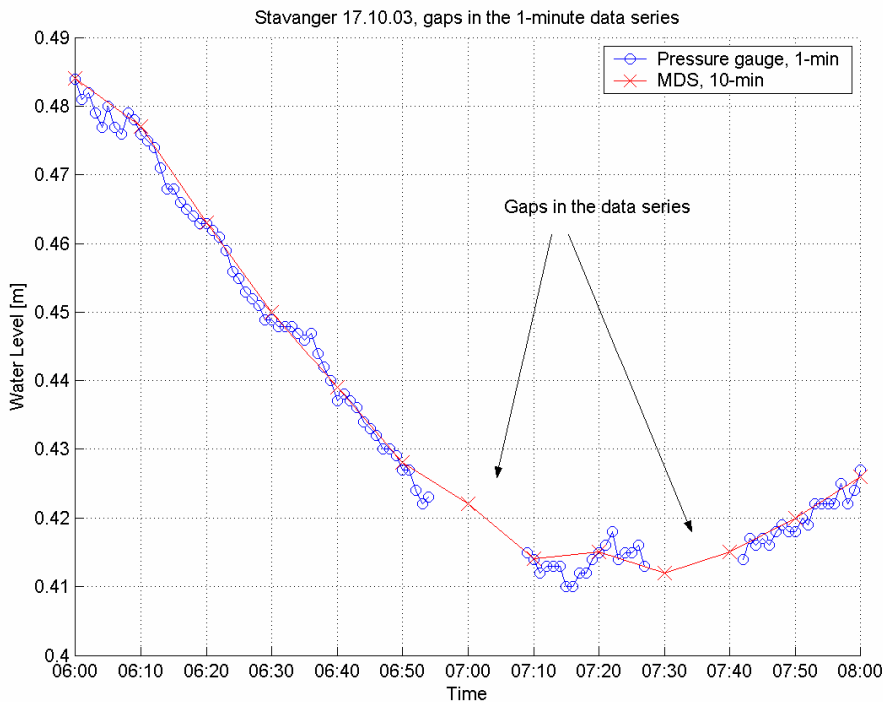


Figure 5-2 Gaps in the data series (gap number 6 and 7).

We have chosen to interpolate the time series over these gaps. Two different interpolation methods are shown in Figure 5-3 (linear interpolation) and Figure 5-4 (cubic spline interpolation). We can see that the cubic spline method (in Matlab), does not act very well, especially for gap number 7. Linear interpolation is chosen for this analysis, since this method work satisfactory for gaps of this size. If the gaps are longer, adjusted predictions (with interpolation between the predictions) can be used to fill the gaps, or we will have to accept the gaps. Gaps in the time series will have consequences when we want to filter the data, and when we want to estimate the power spectral density.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	13 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

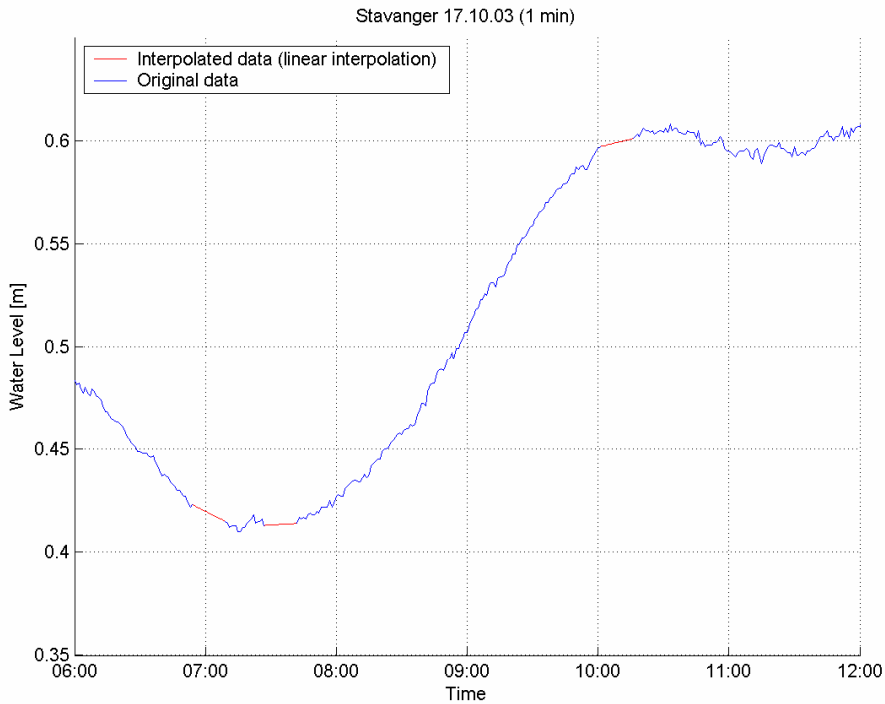


Figure 5-3 Linear interpolation over gaps in the data series (gap number 6, 7 and 8).

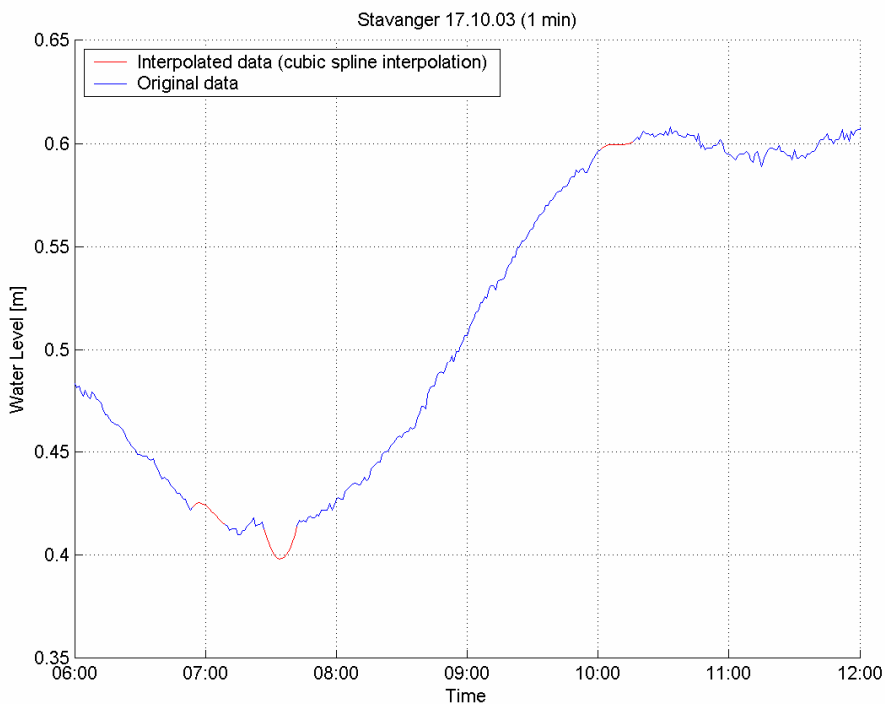


Figure 5-4 Cubic spline interpolation over gaps in the data series (gap number 6, 7 and 8).

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 14 of 60
Document no.:	DAF-05 - 1	Date:	1.0 15.09.06
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		

5.1.2 Frequency content

The power spectral density (PSD) of the test data series 1 is estimated and shown in Figure 5-5 (whole PSD) and Figure 5-6 (segment of the PSD). Welch's method is used in computing the PSD, this method makes a compromise between resolution and the variance of the estimate. With a longer time series we can get higher resolution and/or lower variance of the estimate.

We can see that the PSD has peaks at the tidal frequencies (which are marked with vertical coloured lines). The powers at the higher frequencies (above the tidal frequency) will be mainly wind driven (see [1] for a discussion of wave forming sources).

Note that the measured water level is not a stationary time series. The frequency content is weather dependent, and therefore time dependent (since weather changes with time). The estimated PSD in Figure 5-5 and Figure 5-6 shows the overall PSD for the whole period of data set 1.

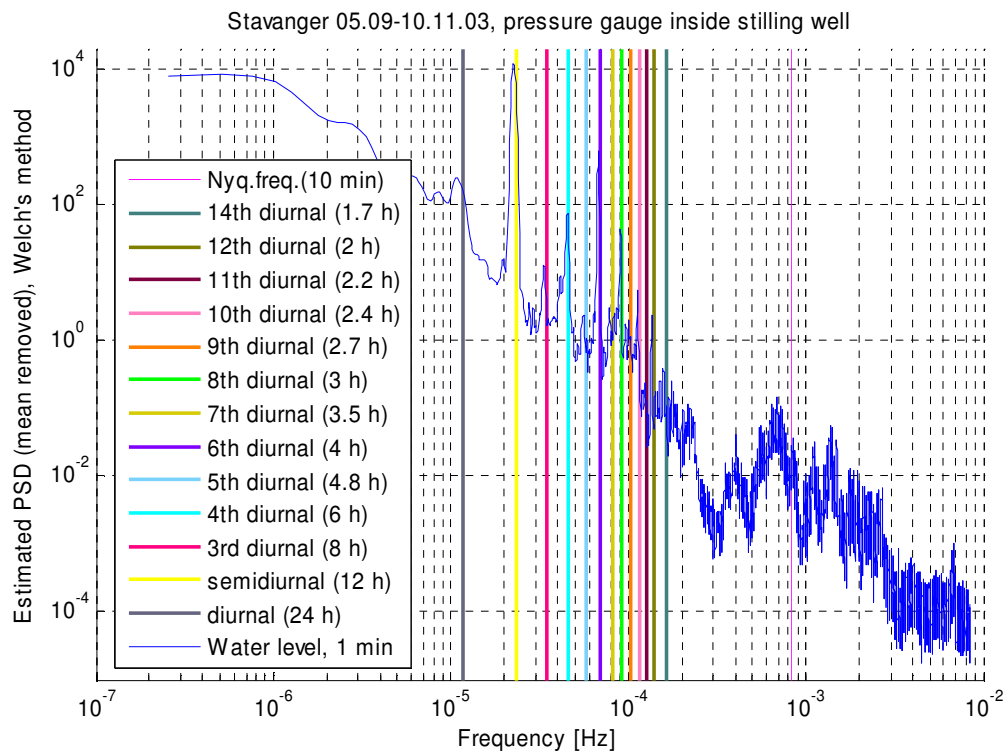


Figure 5-5 Estimated PSD of 1-minute water level data and tidal frequencies.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 15 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

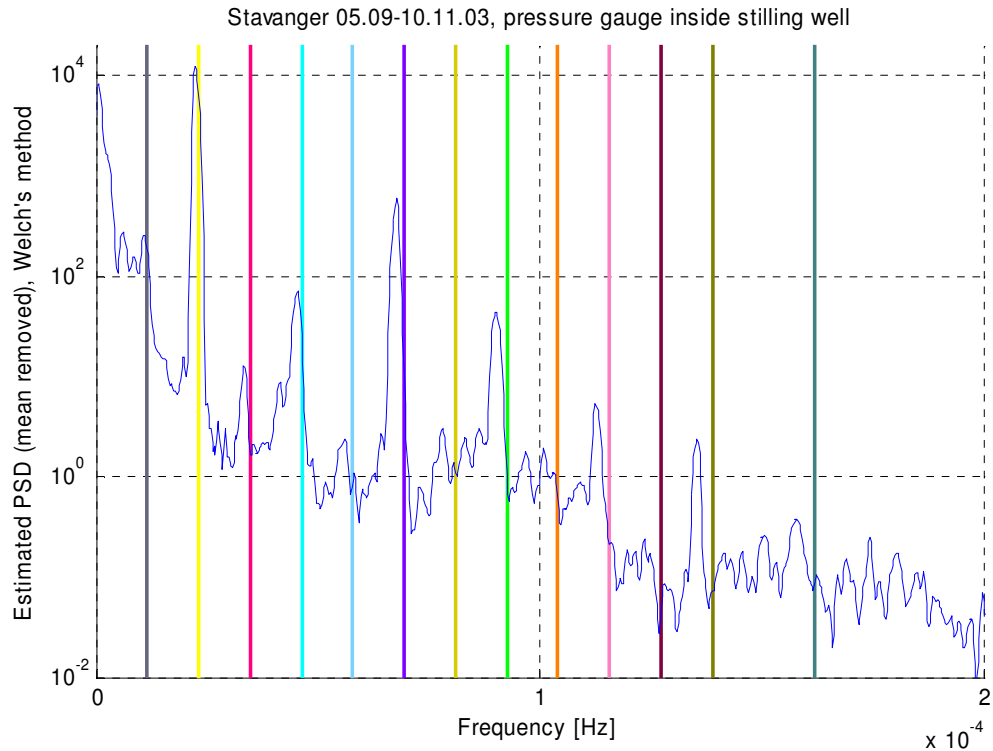


Figure 5-6. Same as Figure 5-5, but here it is focused on the tidal frequency band.

5.2 Analysis of data set 2

5.2.1 Gaps in the data series and interpolation

There are 3 gaps in data series 2. An overview of the gaps is shown in the table below. The reason for the gaps is unknown. Linear interpolation is used to fill these gaps. See linear interpolation over gap 1 and 3 in Figure 5-7 and Figure 5-8.

Gap number	Time for last data before gap	Time for first data after gap	Length of gap in minutes (number of missing values)
1	25.05.2004 13:54	25.05.2004 13:57	3 min (2 values)
2	03.06.2004 14:00	03.06.2004 14:02	2 min (1 value)
3	29.06.2004 12:17	29.06.2004 12:32	15 min (14 values)

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 16 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

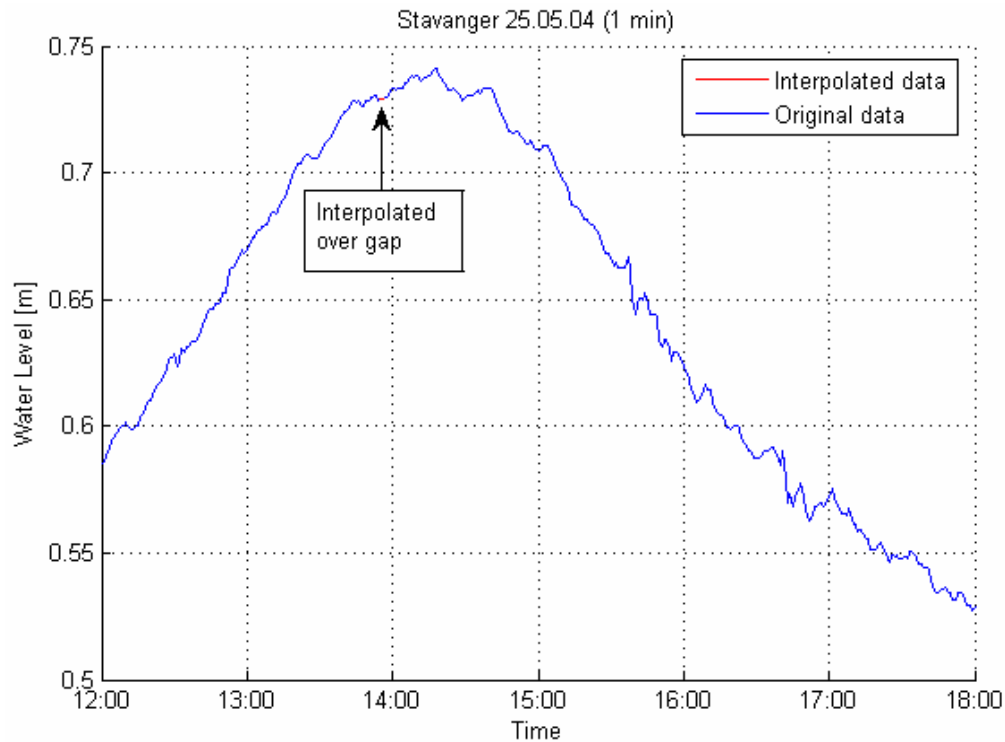


Figure 5-7 Linear interpolation over gap 1 in the data series 2

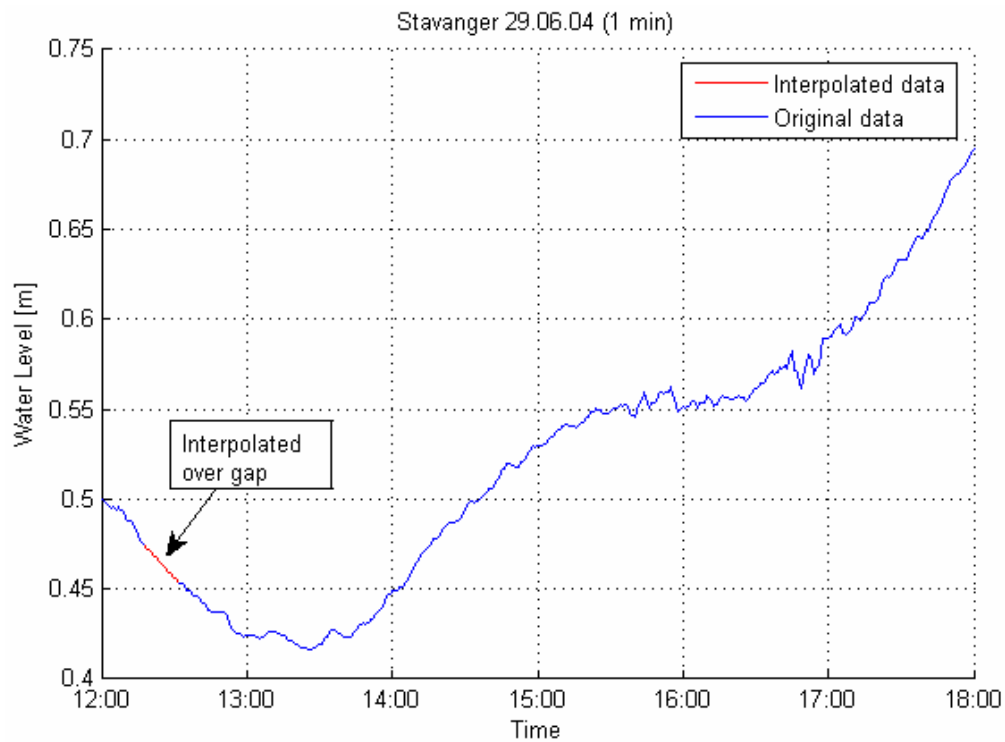


Figure 5-8 Linear interpolation over gap 3 in the data series 2

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 17 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

5.2.2 Frequency content

The power spectral density of the test data series 2 is estimated and shown in Figure 5-9 (whole PSD) and Figure 5-10 (segment of PSD).

We can see that the PSD has peaks at the tidal frequencies (which are marked with vertical coloured lines). The powers at the higher frequencies (above the tidal frequency) will be mainly wind driven (see [1] for a discussion of wave forming sources).

Note that the measured water level is not a stationary time series. The frequency content is weather dependent, and therefore time dependent (since weather changes with time). The estimated PSD in Figure 5-9 and Figure 5-10 shows the overall PSD for the whole period of data set 2.

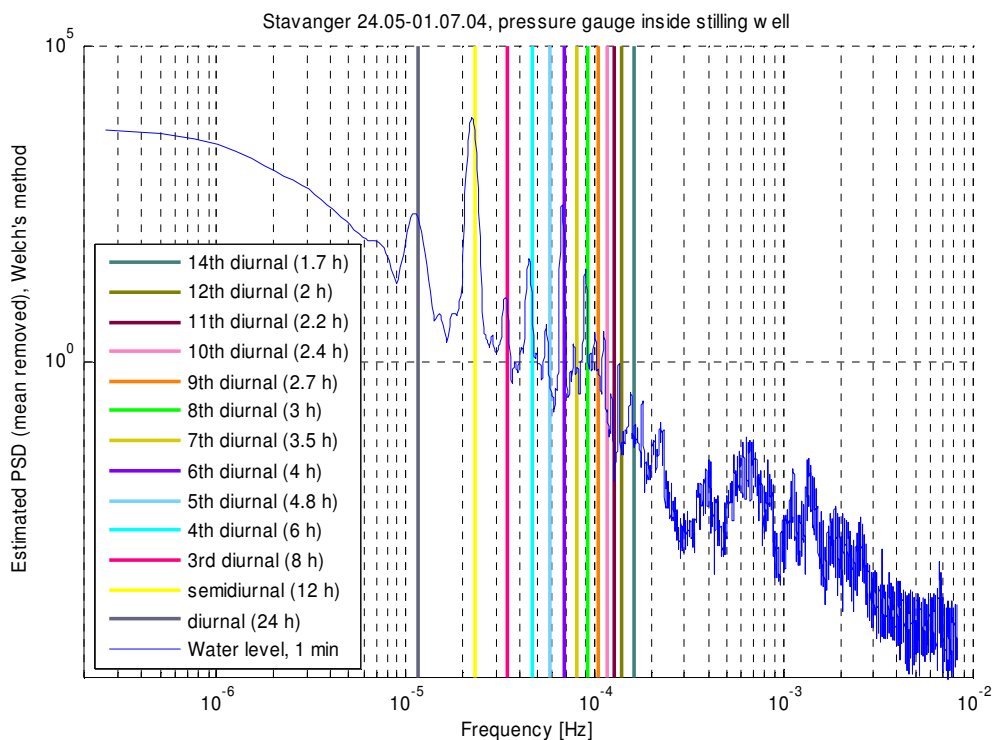


Figure 5-9 Estimated PSD of 1-minute water level data and tidal frequencies.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 18 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

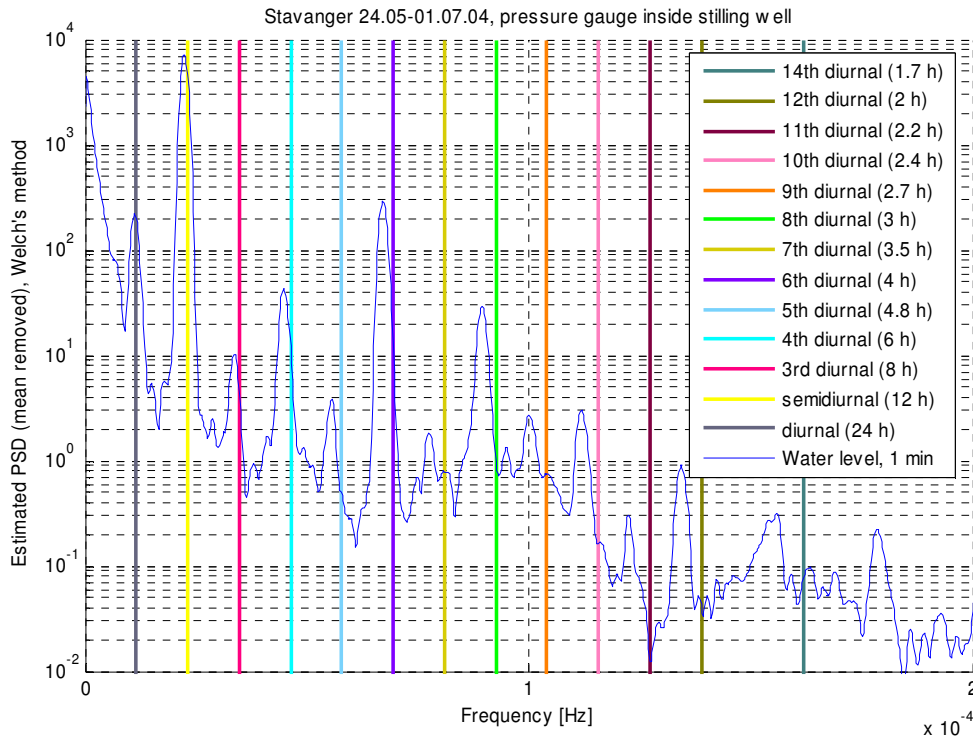


Figure 5-10. Same as Figure 5-9, but here it is focused on the tidal frequency band.

6 Filtering and decimating

6.1 Design of low pass filter

Normally we are not interested in the waves with the highest frequencies. For example when the data shall be used for a whole area, and not just at the point where the gauge is placed. The high frequency components will be very local. Another example is when the data is used for harmonic analysis, then we are only interested in the tidal frequencies and their over-harmonics. For this reasons the water level database are based on 10-minute values (harmonic analysis is based on 1-hour values). Before decimating to 10-minute values the 1-minute series has to be filtered with an anti-aliasing filter (low pass filter) to remove frequencies above the Nyquist frequency for 10-minute values. See more about anti-aliasing filter and Nyquist frequency in [9].

When we will decimate from 1-minute values to 10-minute values (decimate from 0.0166... Hz to $f_{s_dec} = 0.00166...$ Hz), all frequencies above f_{max} should be removed.

$$f_{max} \leq \frac{f_{s_dec}}{2} = \frac{1}{2 \cdot 10 \cdot 60s} = 0,0008333... \text{ Hz}$$

At the same time the tidal frequencies and their over-harmonics should be as undisturbed as possible. This sets the requirements for the filter:

- The pass-band start at 0 Hz and should end at about $1/(1 \text{ hour}) = 0.0002777... \text{ Hz}$
- The stop-band should start at $1/(20 \text{ minutes}) = 0.0008333... \text{ Hz}$ and ends at $f_s/2 = 1/(60 \text{ sec} \cdot 2) = 0.008333... \text{ Hz}$ (Nyquist frequency for 1 minute sampling)

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Page	19 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

The end of the pass-band is chosen so that the tidal frequencies and their over-harmonics are not disturbed (attenuated). The 14th diurnal component has a period of 1.7 hour (see Figure 5-6), which means that the frequency is 0.0001634 Hz and will be in the pass-band. Higher tidal over-harmonics frequencies are anticipated to be of little importance.

Since this filter may be used at the office in a post-processing mode, we can filter both forward and backward in time to get a zero phase filter response. This means that an IIR-filter can be used. A Butterworth-filter will be a good choice since it has a magnitude response that is maximally flat in the pass-band and monotonic overall.

If the 10-min water level data shall be published in near real time (NRT), another filter may be used. The NRT filter should be a relatively short (depending on the delay requirements of the NRT application) FIR filter. This filter will not be designed and studied in this report.

Figure 6-1 shows a design of a Butterworth-filter using Matlab. In this case the amplitude response of the pass-band is specified to be between 0 dB and -1 dB ($A_{pass} = 1$), which means that the attenuation is -1 dB at 0.0002777... Hz (where the pass-band ends). The amplitude response in the stop-band is specified to be -80 dB or lower ($A_{stop} = 80$), which means that the attenuation is -80 dB at 0.0008333... Hz (where the stop-band starts).

The chosen requirement lead to a Butterworth filter of order 9. If we reduce the filter requirements, for example by setting the stop-band attenuation to be minimum -40 dB (instead of -80 dB), a filter with order 5 will be designed (see Figure 6-2). It is also possible to specify the order and cut-off frequency of the filter as done in Figure 6-3. Then Matlab will design a filter with the specified order.

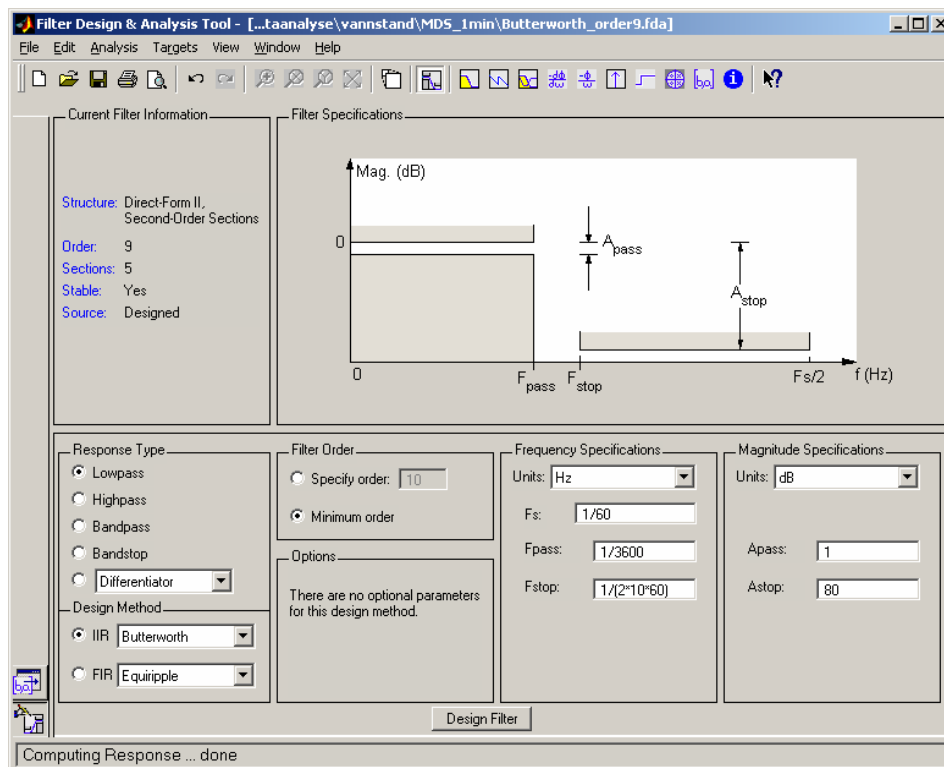


Figure 6-1 Design of low pass Butterworth filter (order 9) in Matlab

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	20 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

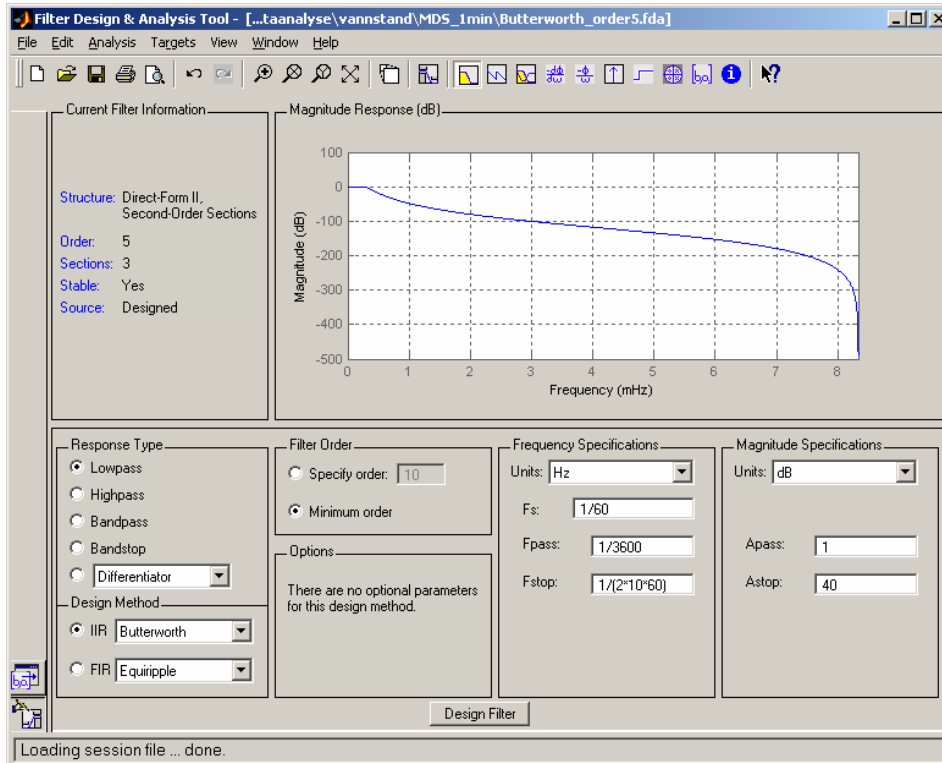


Figure 6-2 Design of low pass Butterworth filter (order 5) in Matlab

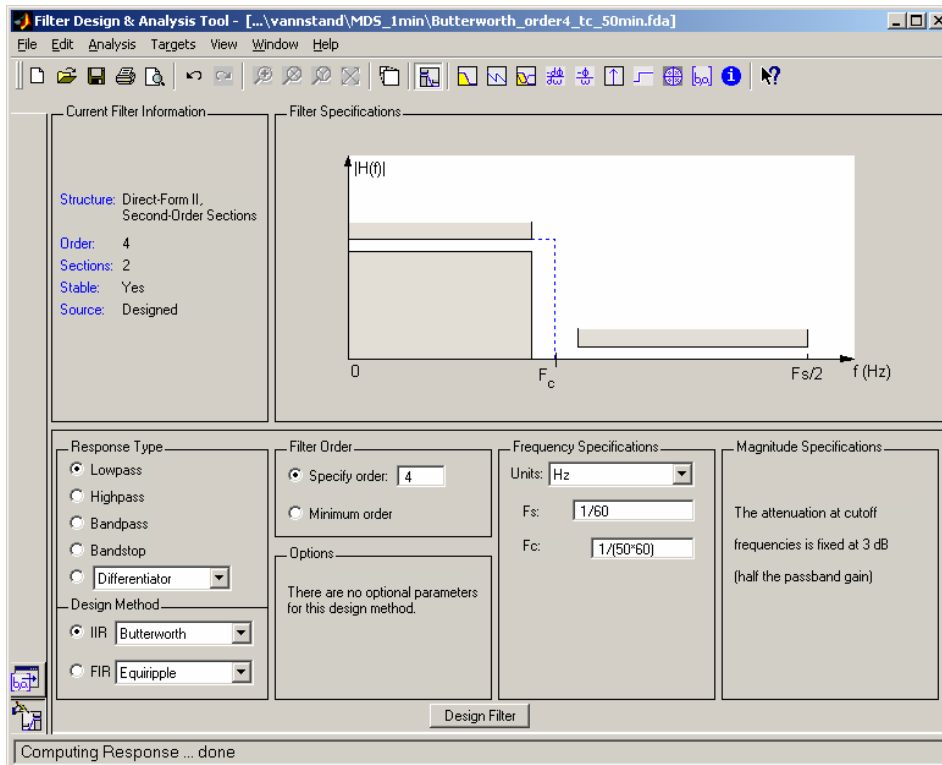


Figure 6-3 Design of low pass Butterworth filter (order 4) in Matlab.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	21 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

The amplitude responses of the 3 filters are shown in Figure 6-4. Since the filter will be run “forward and backward”, the over all response will be the squared response which is shown in Figure 6-5. All the 3 filters have an acceptable filter characteristic, and we choose the filter with the lowest order (order 4)

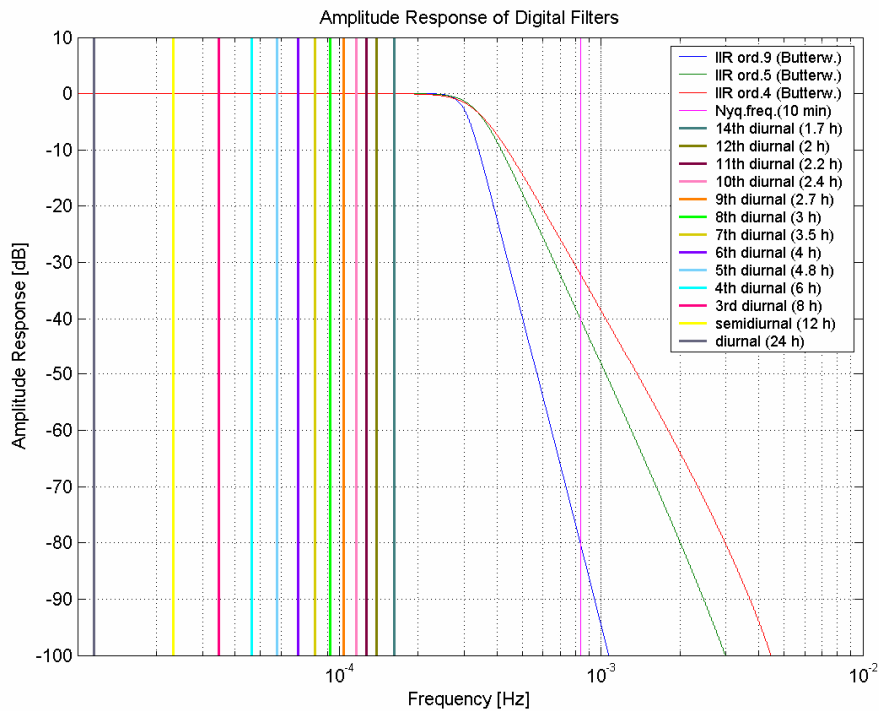


Figure 6-4 Amplitude response of three different Butterworth filters.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	22 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

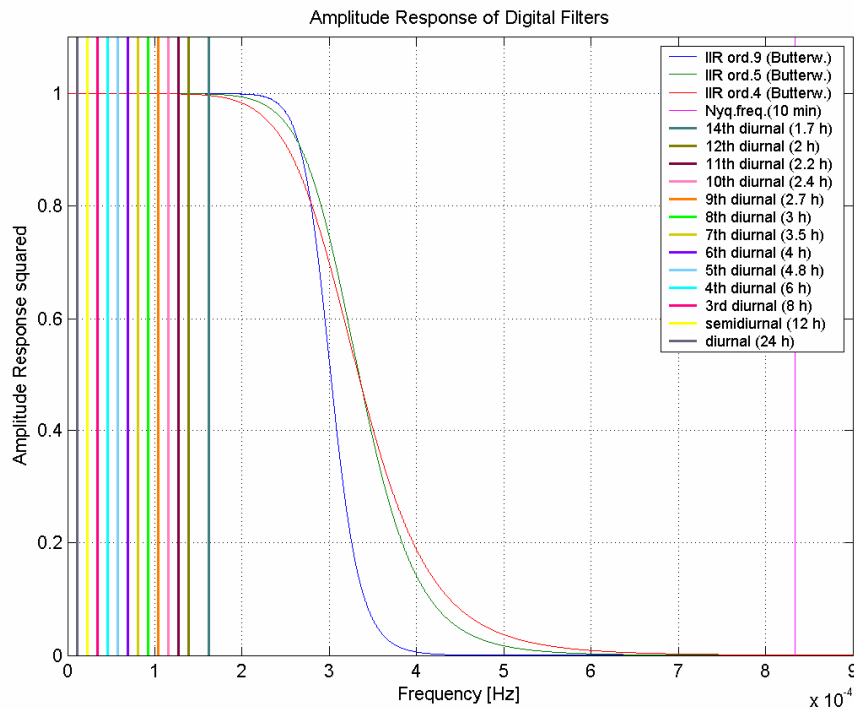


Figure 6-5 Amplitude response (squared) of three different Butterworth filters.

The chosen order-4 Butterworth filter is compared with the filter that is used in the MDS today and the filter used in the MDS before the renewal of the MDS. (The renewal took place in the period 2000-2002). The amplitude responses of the 3 filters are shown in Figure 6-6. The Butterworth filter which is an IIR-filter, is run forward and backward (possible because it is used in a post processing mode). The two other filters (FIR-filters) are run in real time, and only one way (forward). It is therefore misleading to compare the amplitude responses directly. The squared amplitude response of the Butterworth filter (that is run forward and backward) must be compared with the amplitude responses (not squared) of the two FIR-filters. This is done in Figure 6-7. Here we can see that the Butterworth filter and the FIR filter in the old MDS both have satisfactory damping above the Nyquist frequency. This is not the case for the FIR-filter in the new MDS (this was pointed out in [9]). We can also see that the Butterworth filter and the FIR-filter in the new MDS do not damp the tidal frequencies (advantage), but the FIR-filter in the old MDS has a weak attenuation of the higher tidal frequencies.

In Figure 6-8 and Figure 6-9 the proposed Butterworth filter is compared to a Butterworth filter used in the new MDS to smooth the 10-min values. This smoothing filter was introduced because the FIR-filter in the new MDS (before decimating to 10-min values) was too weak (all the frequencies above the Nyquist frequencies was not damped enough as discussed above). This smoothing filter is described in [10]. The two amplitude responses are quite similar (the smoothing filter has the lowest cut off frequency). The smoothing filter operates on 10-min values and is not defined for frequencies above the Nyquist frequency for 10-min values.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 23 of 60
Document no.:	DAF-05 - 1	Date:	1.0 15.09.06
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		

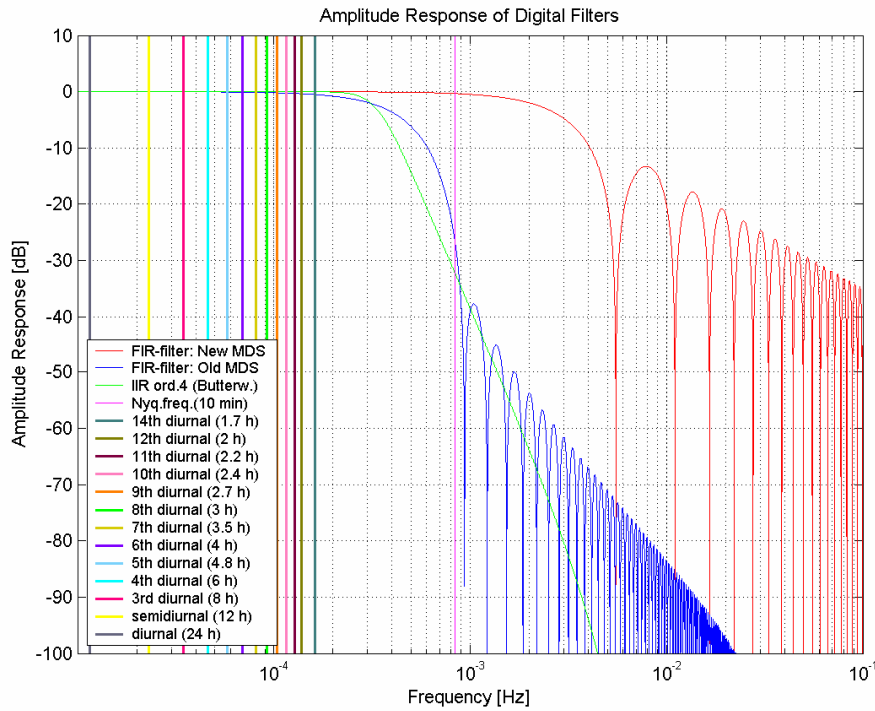


Figure 6-6 Amplitude responses of filters used in new MDS (today), old MDS (before year 2000) and proposed Butterworth filter.

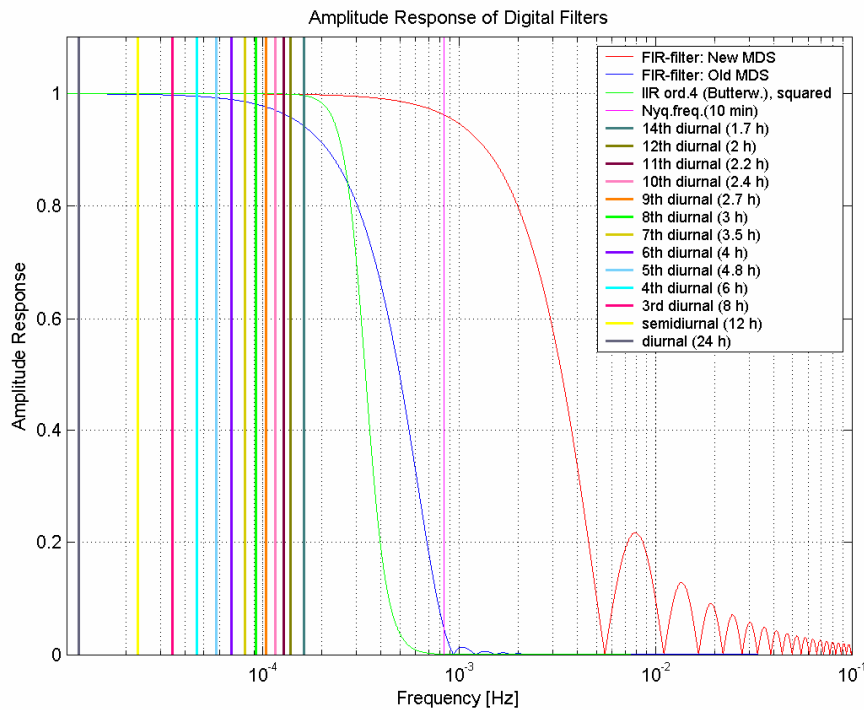


Figure 6-7 Amplitude responses of filters used in new MDS, old MDS and proposed filter.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 24 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

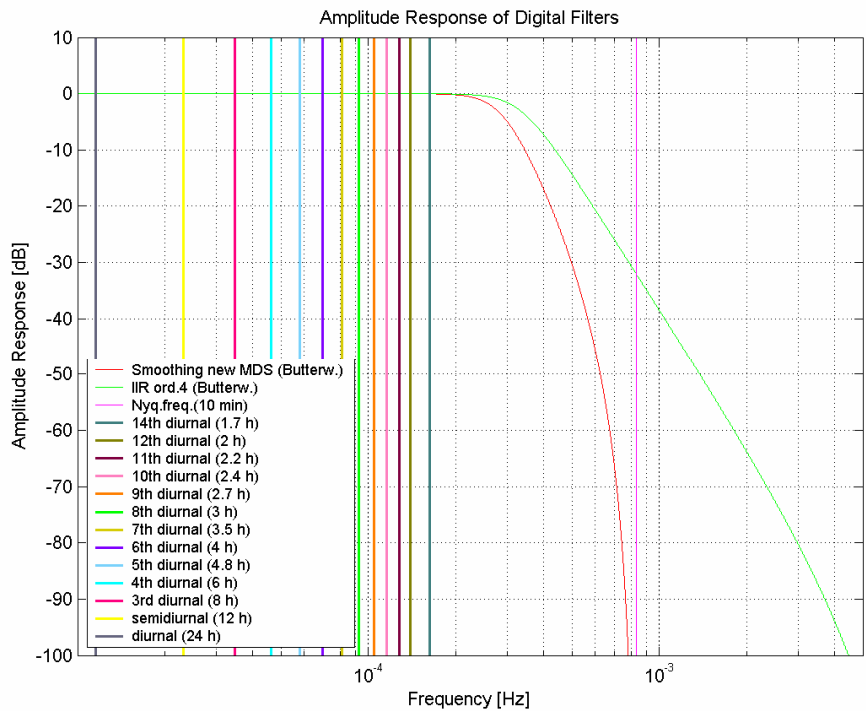


Figure 6-8 Amplitude response of filter used to smooth new MDS data (Butterworth order 4) and proposed Butterworth filter.

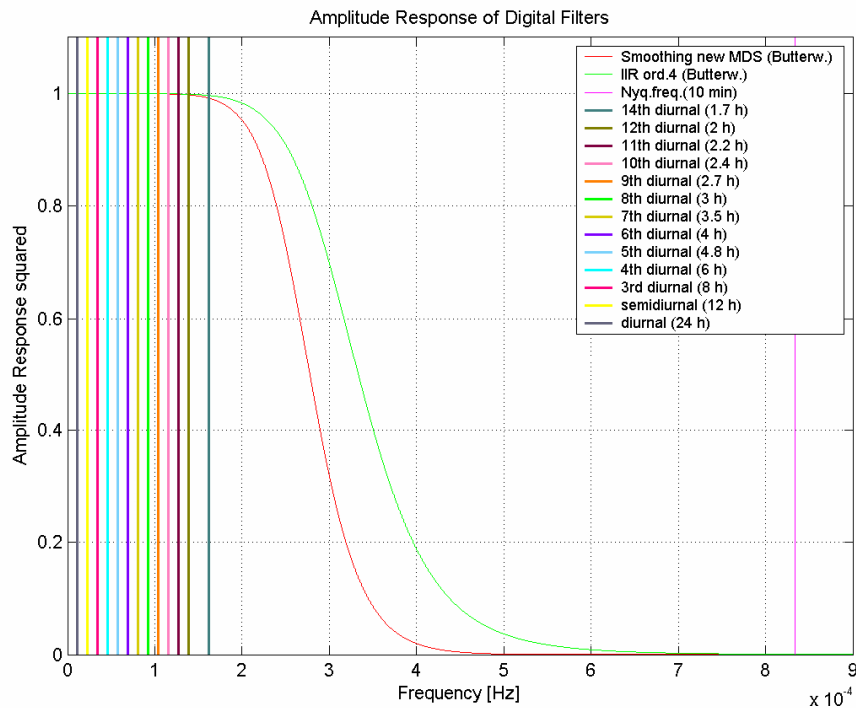


Figure 6-9 Amplitude response of filter used to smooth new MDS data and proposed filter.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 25 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

6.2 Filtering and decimating data set 1

6.2.1 LP-filtering

The original and filtered data is shown together in Figure 6-10 (whole series), Figure 6-11 (24 hours) and Figure 6-12 (6 hours). We can observe that the filtered signal is smoother.

The frequency content of the same two series are shown in Figure 6-13, and we can observe that the frequencies above the Nyquist frequency for 10-min. sampling is filtered away.

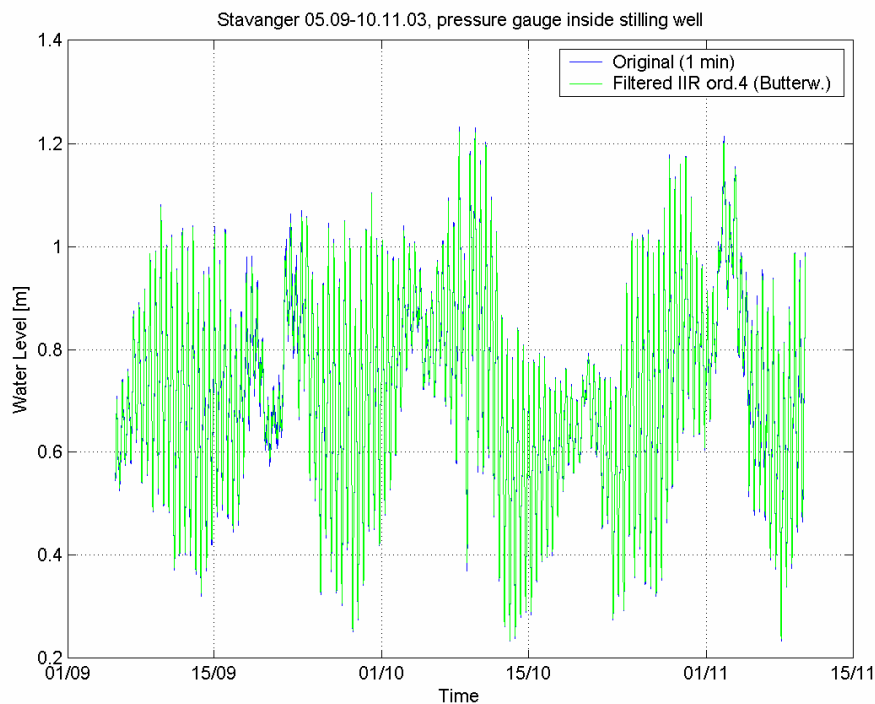


Figure 6-10 Water level (1-min. data) original and filtered (whole series).

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 26 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

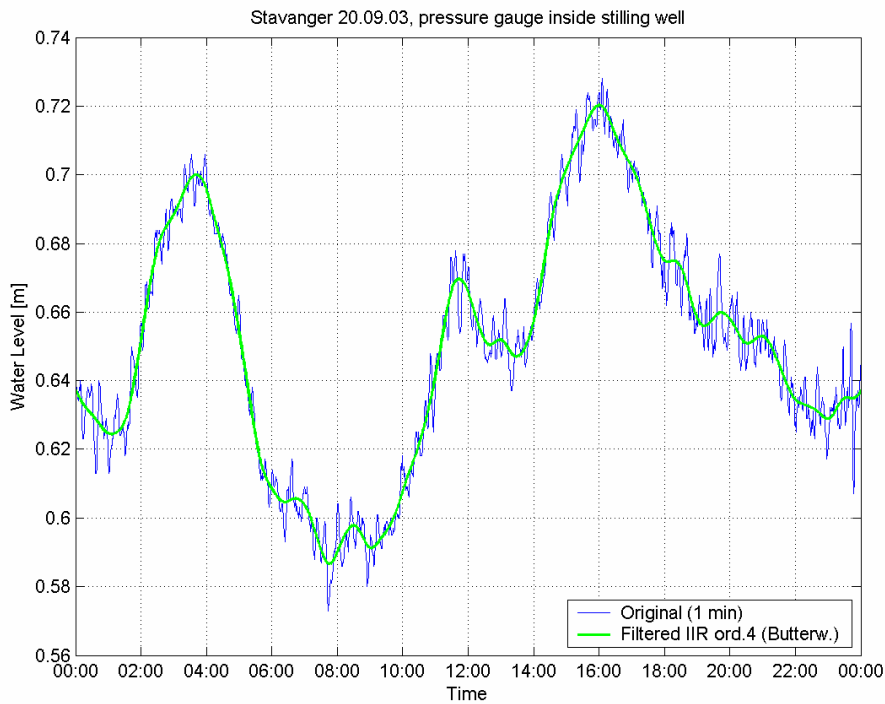


Figure 6-11 Water level (1-min. data) original and filtered (24 hours).

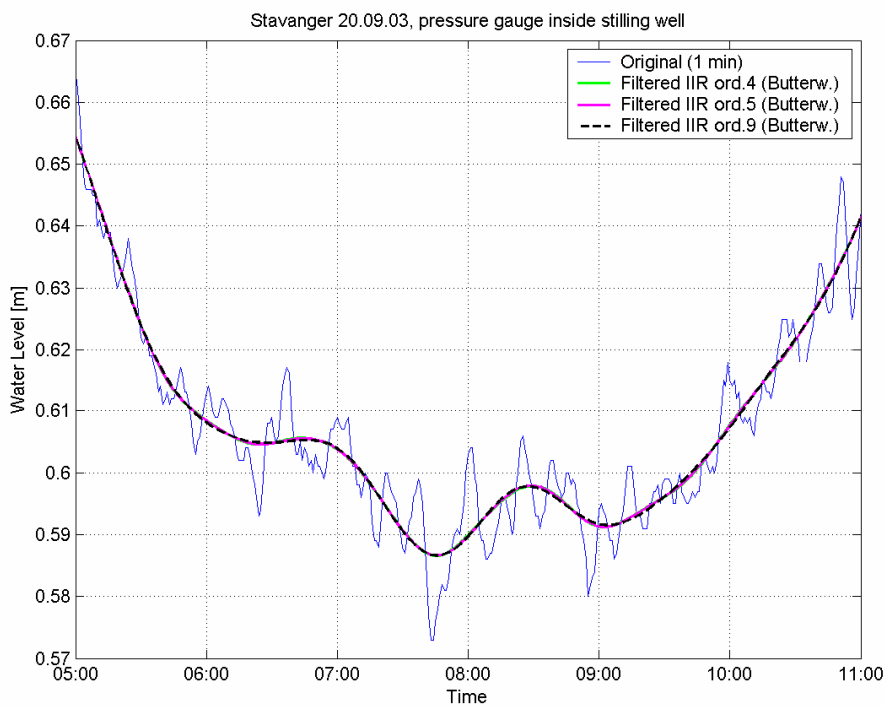


Figure 6-12 Water level (1-min. data) original and filtered with 3 different filters (6 hours).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 27 of 60
Document no.:	DAF-05 - 1	Date:	1.0 15.09.06
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		

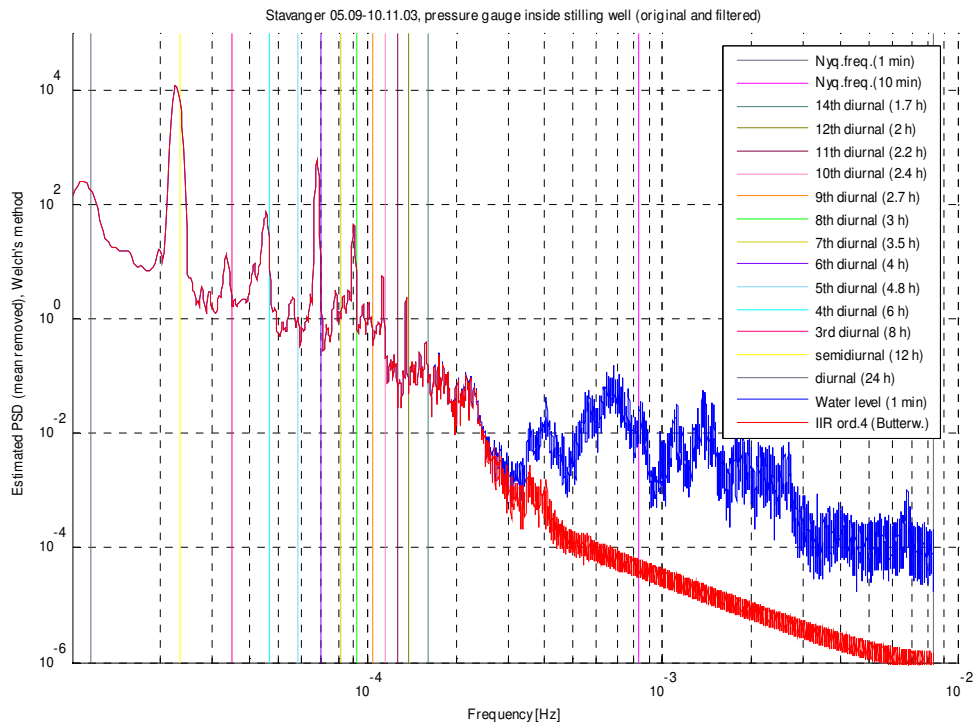


Figure 6-13 Estimated PSD of 1-minute water level data (original and filtered), tidal frequencies and Nyquist frequencies.

6.2.2 Decimating to 10-minute values

After the data has been filtered it can be decimated to 10-minute values as shown in Figure 6-14. A segment of the decimated time series is shown in Figure 6-15, and the estimated power spectral density is shown in Figure 6-16.

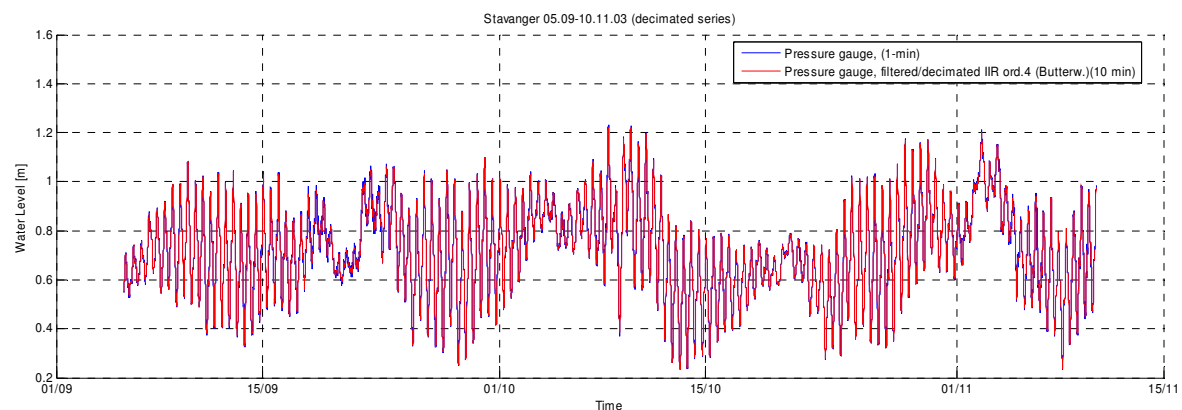


Figure 6-14 Water level data (pressure gauge inside a stilling well) original - and filtered/decimated data (whole data set 1).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 28 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

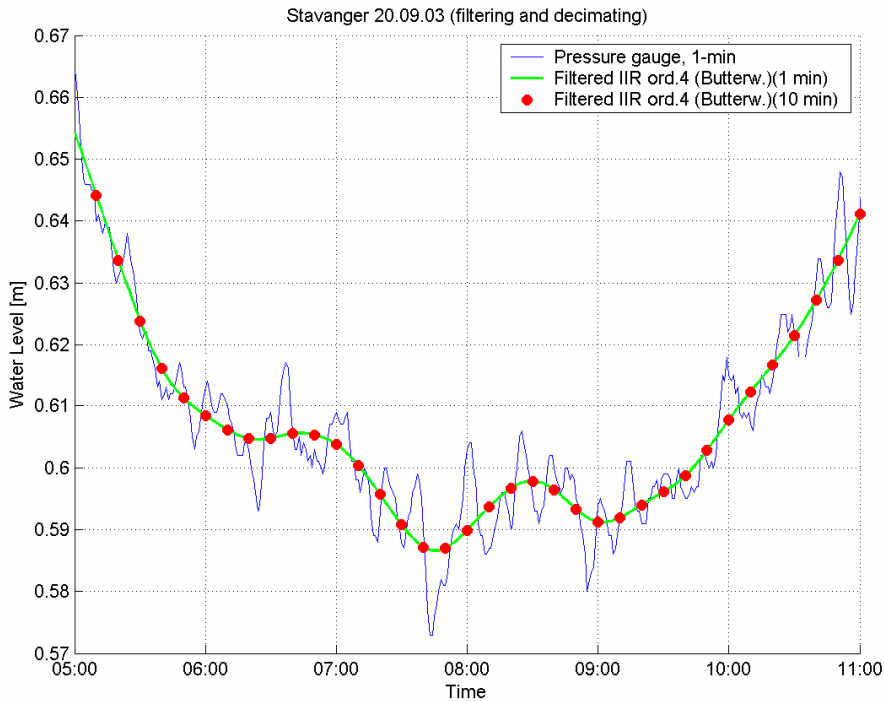


Figure 6-15 Water level (6 hour segment): Original, filtered and filtered/decimated.

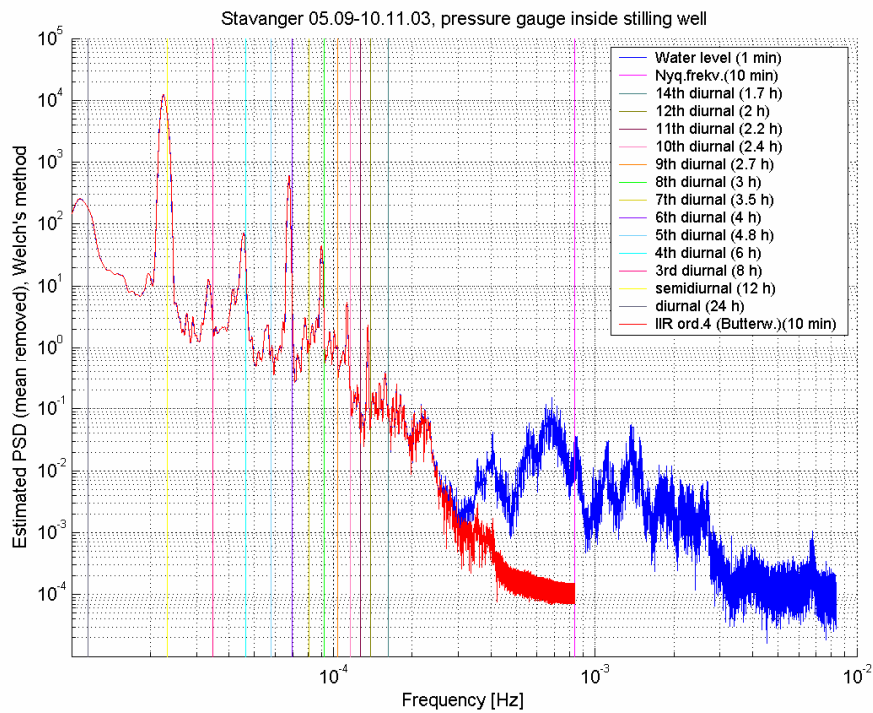


Figure 6-16 Estimated PSD of water level data (original and filtered/decimated data).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	29 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

6.3 Filtering and decimating data set 2

6.3.1 LP-filtering

The original and filtered 1-min. data are shown together in Figure 6-17 (whole series) and Figure 6-18 (24 hours), and their PSDs are shown in Figure 6-19.

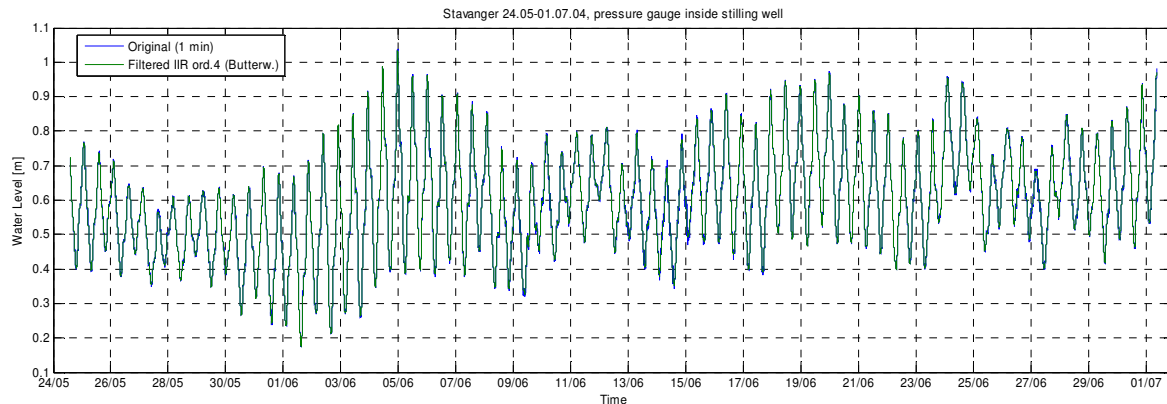


Figure 6-17 Water level (1-min. data) original and filtered (whole series).

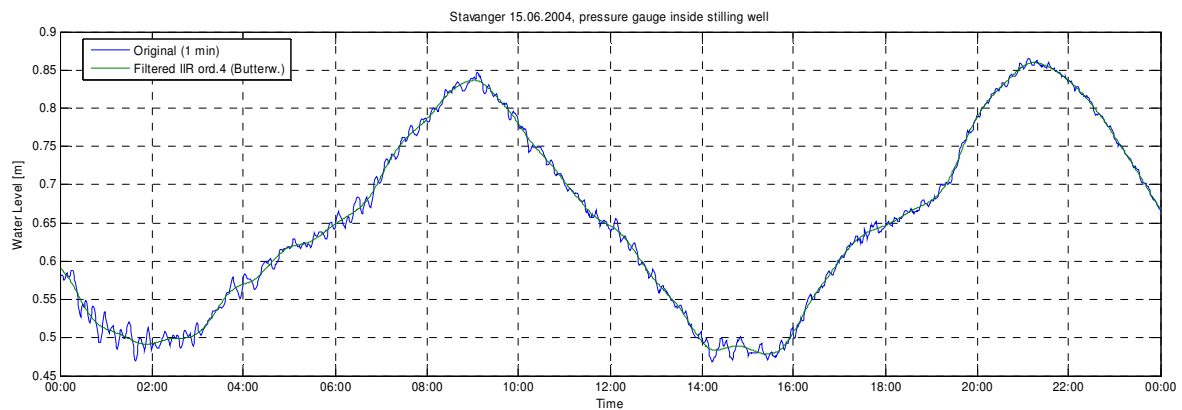


Figure 6-18 Water level (1-min. data) original and filtered (24 hours)

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Page	30 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

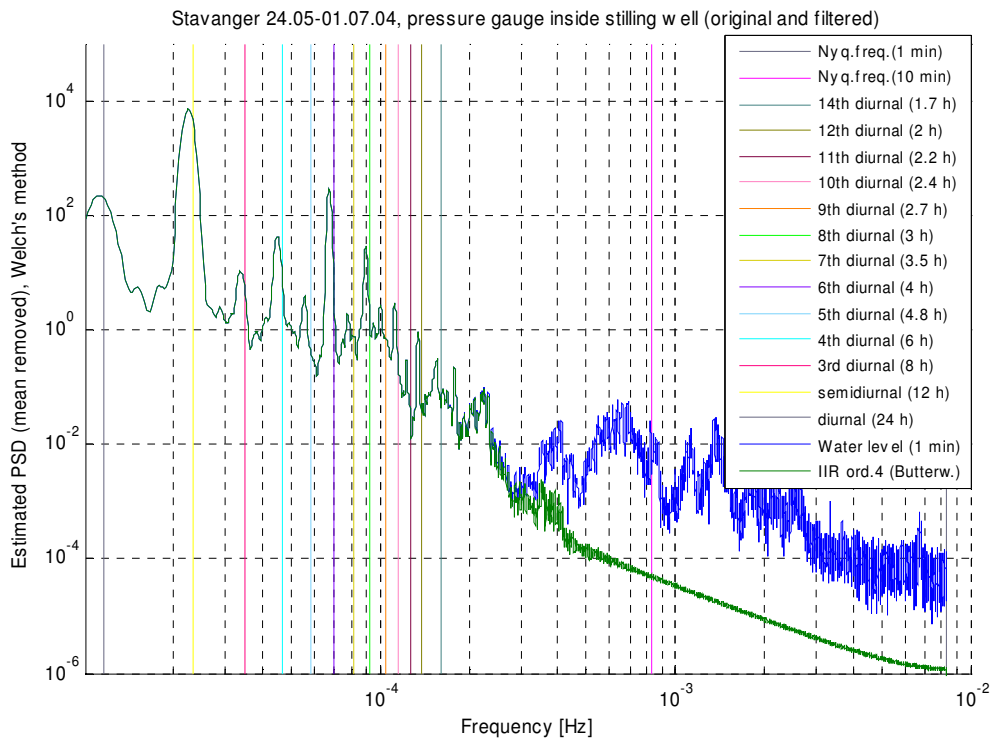


Figure 6-19 Estimated power spectral density of 1-minute water level data (original and filtered), tidal frequencies and Nyquist frequencies.

6.3.2 Decimating to 10 minute values

After the data has been filtered it can be decimated to 10-minute values. The decimated time series is shown in Figure 6-20 (whole series) and Figure 6-21 (24 hour period) together with the original 1-min. series. The estimated power spectral densities of the same two series are shown in Figure 6-22.

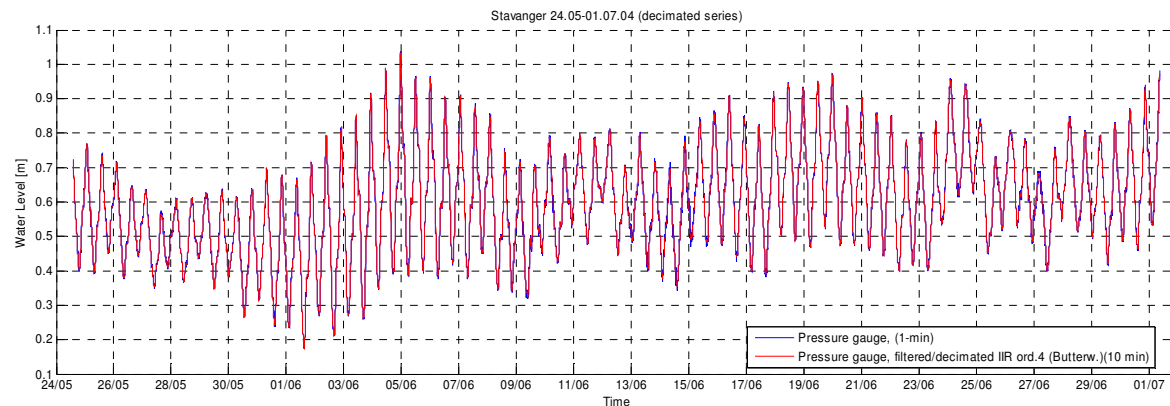


Figure 6-20 Water level data (pressure gauge inside a stilling well) original - and filtered/decimated data (whole data set 2).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	31 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

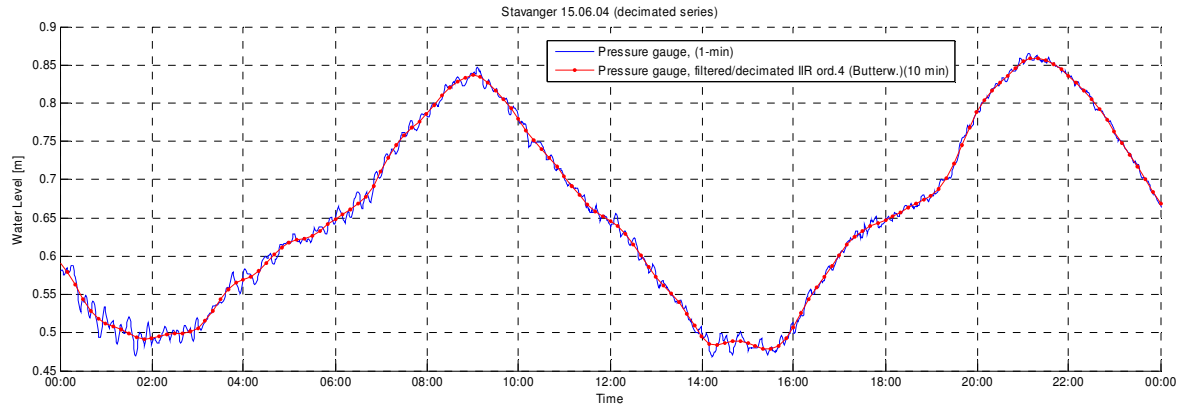


Figure 6-21 Water level data (pressure gauge inside a stilling well) original - and filtered/decimated data (24 hour period of data set 2).

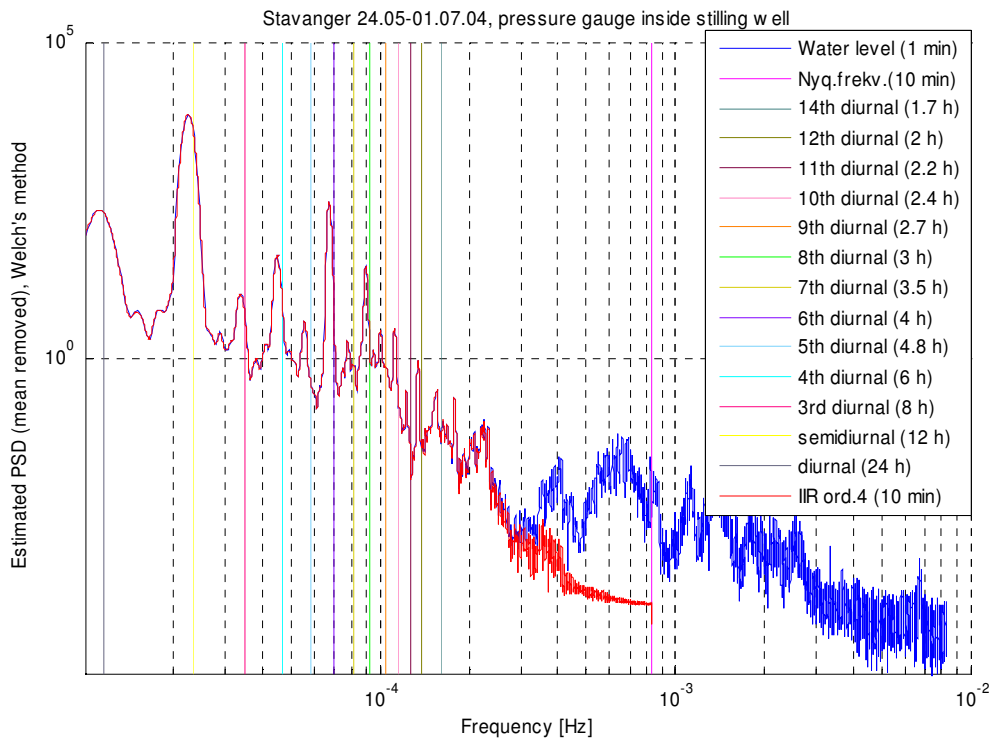


Figure 6-22 Estimated power spectral density of water level data (pressure gauge inside a stilling well, original and filtered/decimated data) and tidal frequencies.

7 Comparing test data series using two different filters

7.1 General comments

In this section we compare the pressure gauge test data series filtered and decimated as described in section 6.2 (using Butterworth filter of order 4) with the same test data series filtered with a 3-minute mean filter (which is principally the same as what is done in MDS today). This series is called "FIR ord.2 (mean)" in the figures. The reason for this comparison is to see the effect of the two different filtering and sampling schemes. Although the data series filtered with the 3-

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	32 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

minute mean will contain aliasing noise after decimating, the observed difference is not only caused by aliasing noise, but also from real signals (waves) in the higher frequencies (which are filtered away with the Butterworth filter).

We have also done the same comparison with the “FIR ord.2 (mean)”-series filtered one more time with the smoothing filter used on 10-min. values in MDS. This series is called “FIR ord.2 (mean) smooth”. Amplitude response of the smoothing filter is shown in Figure 6-8 and Figure 6-9.

The pressure gauge test data series (using Butterworth filter of order 4) is also compared with the MDS in section 8 and section 9. In section 8 the observed difference can be caused by the fact that two different sensors are used, as well as that different sampling and filtering schemes are used. In section 9 the same sampling and filtering scheme is used (3-min mean) and the difference is due to different sensors.

7.2 Data set 1

In Figure 7-1 (whole series), Figure 7-2 (24-hours) and Figure 7-3 (24-hours) the two time series are plotted together with the difference between them. We can see that the variance of the difference varies along the series. The overall statistics for the whole series are given in the table below. Note that the statistics can be different if another time segment of the series was used for the calculation. See Figure 7-3, which represent a day (18.09.2003) with relatively large difference. Here the standard deviation is 0.0097 m, while it for the whole series is 0.0042 m.

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
Mean filtered – Butterw.filtered	-0.0254 m	0.040 m	0.0042 m	-0.0090 m	0.0087 m	0.0042 m	0.0088 m

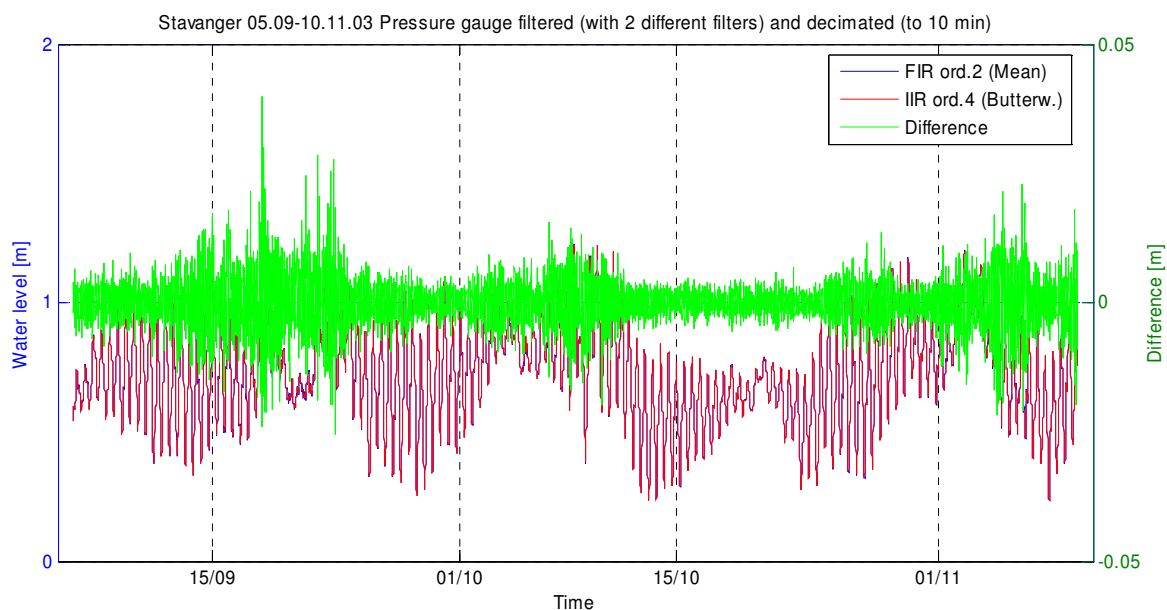


Figure 7-1 Pressure gauge (filtered with two different filters and decimated) and the difference (whole series).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	33 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

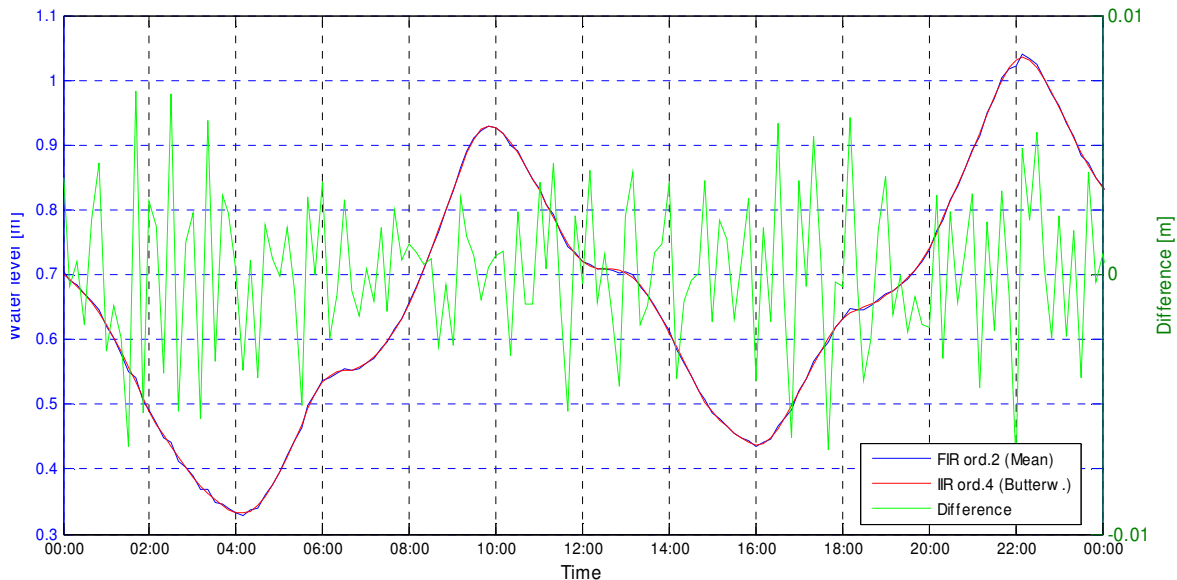


Figure 7-2 Pressure gauge (filtered with two different filters and decimated) and the difference (25.09.2003, 24 hours).

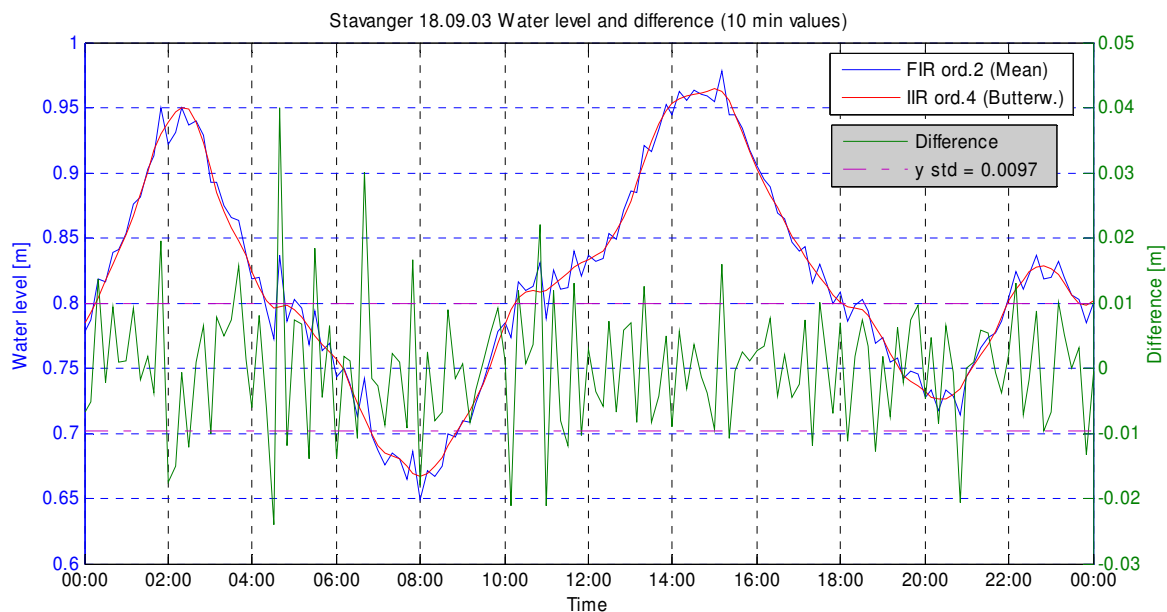


Figure 7-3 Pressure gauge (filtered with two different filters and decimated) and the difference (24 hours).

In Figure 7-4 we can see the estimated PSD for the water level data filtered with two different filters and the difference. The largest difference is found for the highest frequencies.

In Figure 7-5 two of the PSD from Figure 7-4 (but here with different colours) are plotted together with the PSD of the original 1-min data. The difference between the green and blue curve in Figure 7-5 is a result of aliasing. The red curve has filtered away these frequencies before decimating.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 34 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

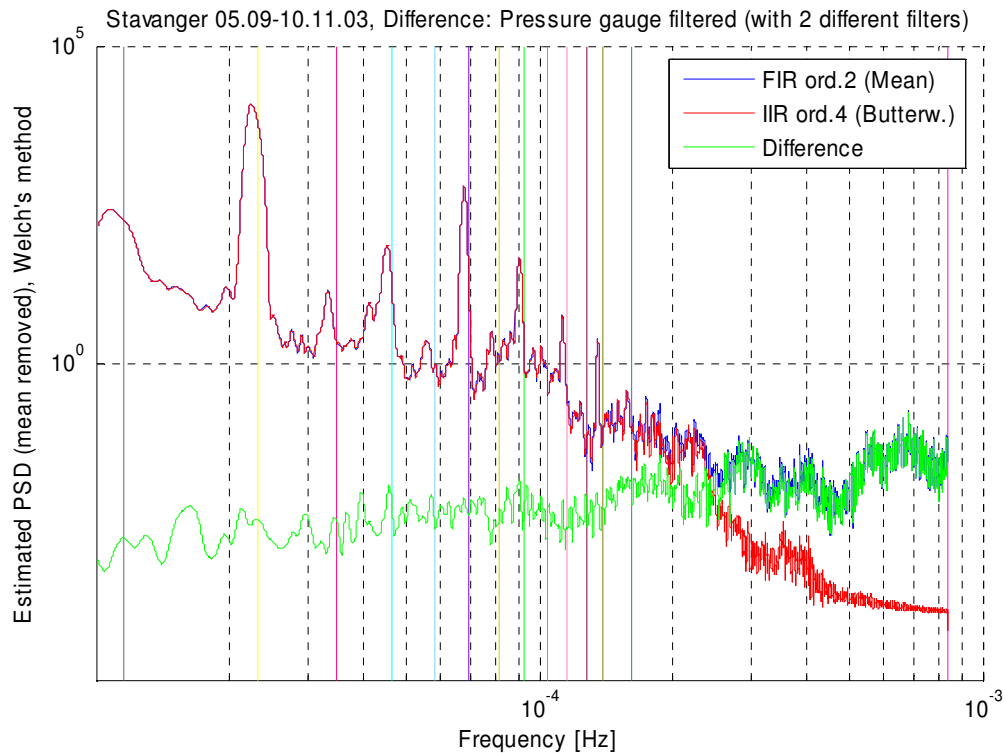


Figure 7-4 Estimated PSD of water level data (10 min) and difference.

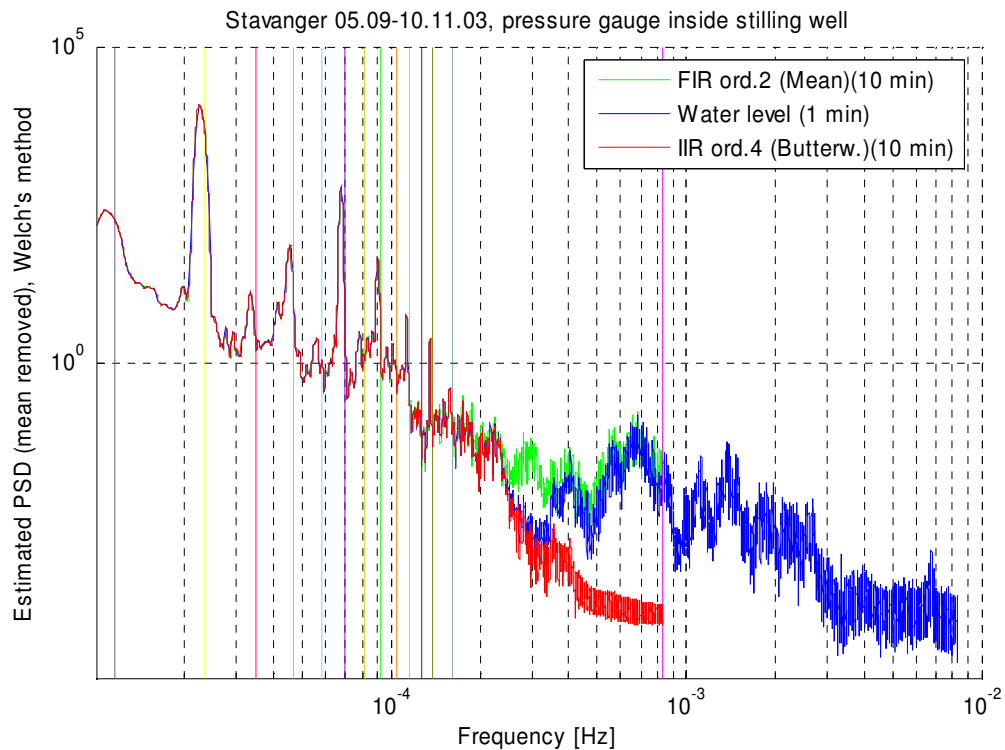


Figure 7-5 Estimated PSD of water level data. The 1-min data represents the “true” spectrum. The two other spectres result from filtering and decimating the 1-min data. The difference between the green and blue curve is a result of aliasing.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 35 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

The “FIR ord.2 (mean)”-series is filtered one more time with the smoothing filter used on 10-min. values in MDS. This series is called “FIR ord.2 (mean) smooth”, and is compared with the Butterworth filtered series in Figure 7-6. The overall statistics for the whole series are given in the table below. Note that the statistics can be different if another time segment of the series was used for the calculation. The difference is less than above (without smoothing).

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
Mean filtered and smoothed – Butterw.filtered	-0.0101 m	0.0089 m	0.0014 m	-0.0028 m	0.0031 m	0.0014 m	0.0030 m

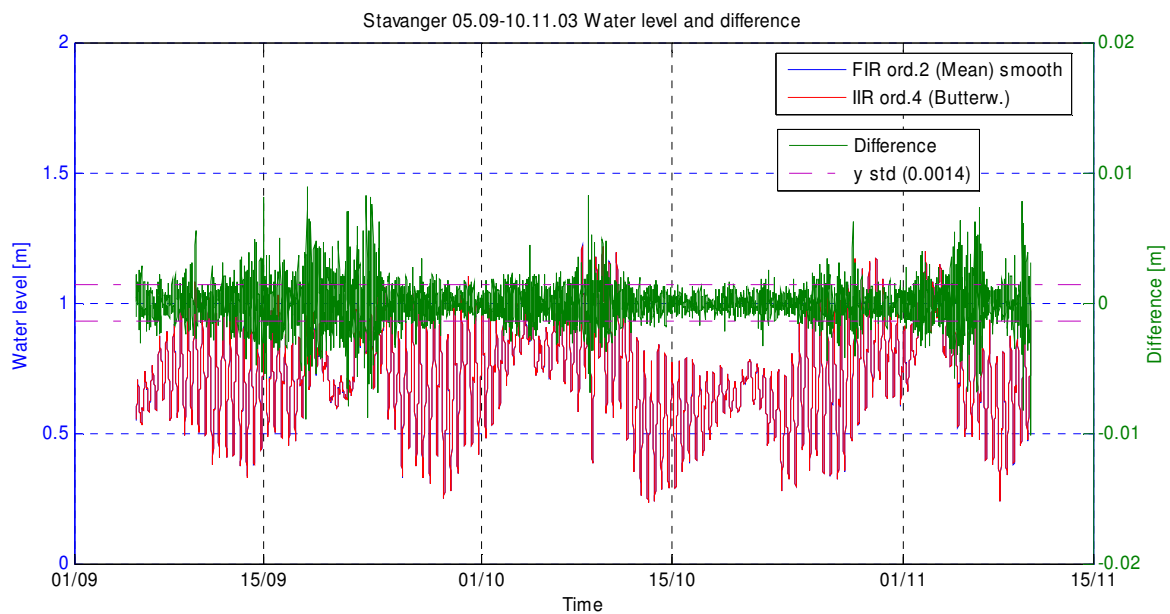


Figure 7-6 Pressure gauge (filtered with two different filters and decimated). The blue series is after decimating filtered again with the 4th order Butterworth filter used to smooth MDS-data. The difference between the two series are plotted as well (whole series).

In Figure 7-7 we can see the estimated PSD for the water level data filtered with two different filters before decimating (and one smoothed as well after decimating) and the difference.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	36 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

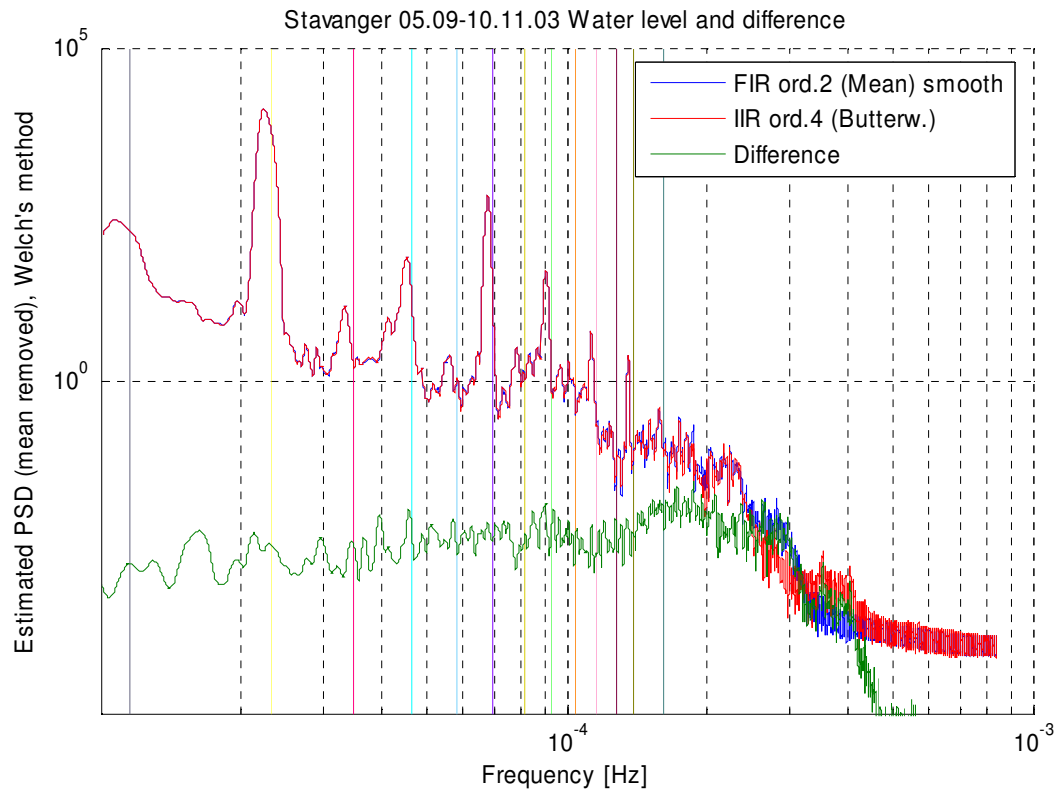


Figure 7-7 Estimated PSD of water level data (10 min) and difference.

7.3 Data set 2

In Figure 7-8 (whole series) and Figure 7-9 (24-hours) the two time series are plotted together with the difference between them. We can see that the variance of the difference varies along the series. The overall statistics for the whole series are given in the table below. Note that the statistics can be different if another time segment of the series was used for the calculation.

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
Mean filtered – Butterw.filtered	-0.0272 m	0.0219 m	0.0029 m	-0.0057 m	0.0056 m	0.0029 m	0.0056 m

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Page	37 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

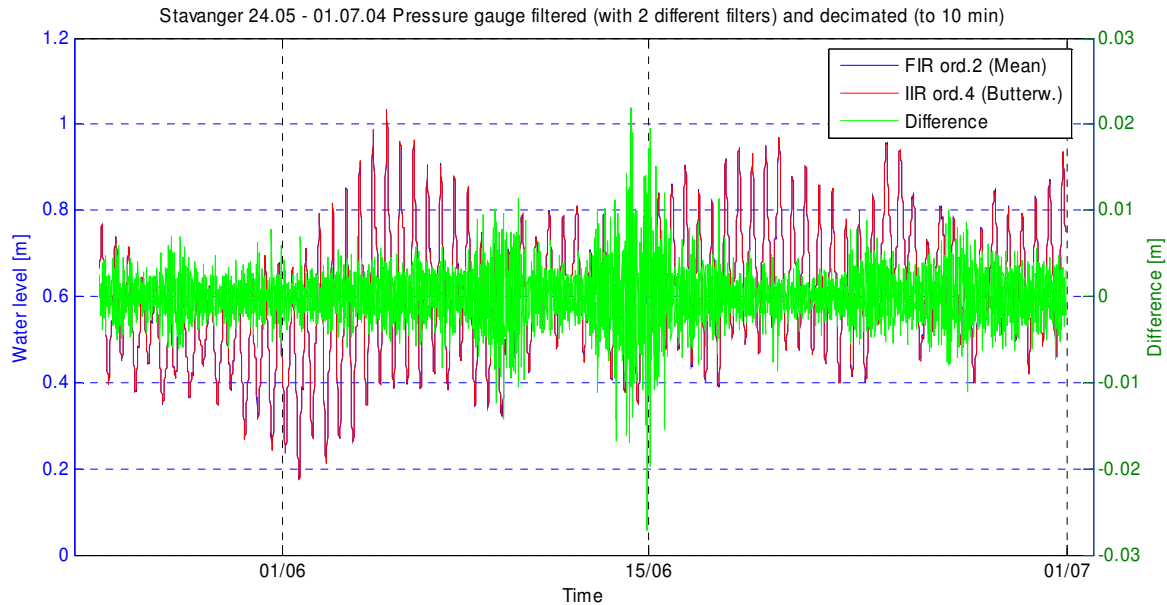


Figure 7-8 Pressure gauge (filtered with two different filters and decimated) and the difference (whole series).

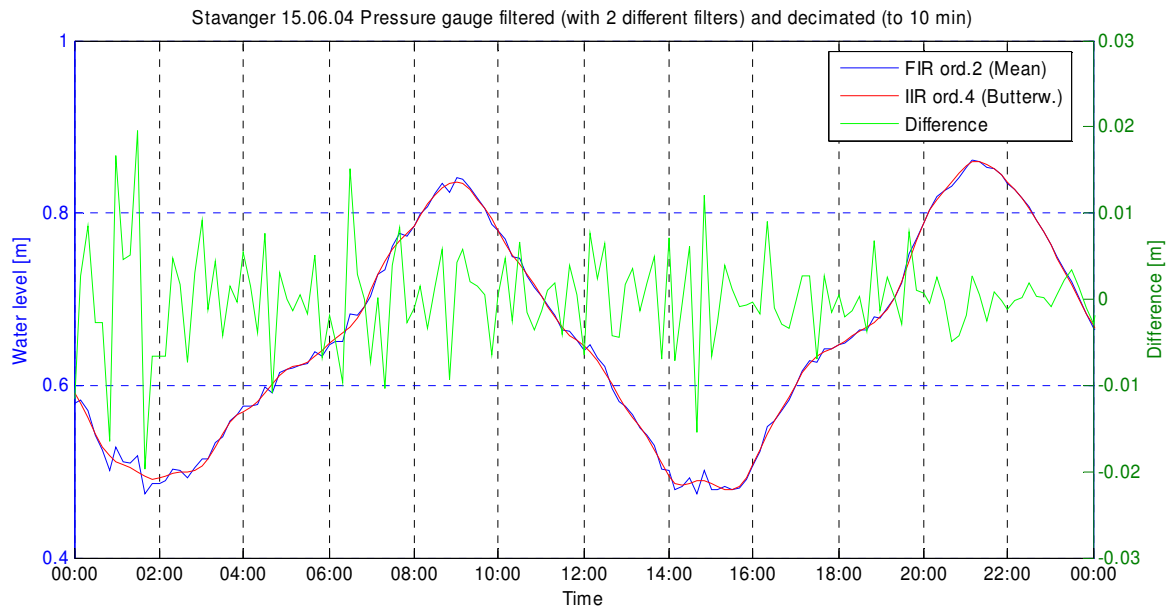


Figure 7-9 Pressure gauge (filtered with two different filters and decimated) and the difference (24 hours).

In Figure 7-10 we can see the estimated PSD for the water level data filtered with two different filters and the difference. The largest difference is found for the highest frequencies.

In Figure 7-11 two of the PSD from Figure 7-10 (but here with different colours) are plotted together with the PSD of the original 1-min data. The difference between the green and blue curve in Figure 7-11 is a result of aliasing. The red curve has filtered away these frequencies before decimating.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 38 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

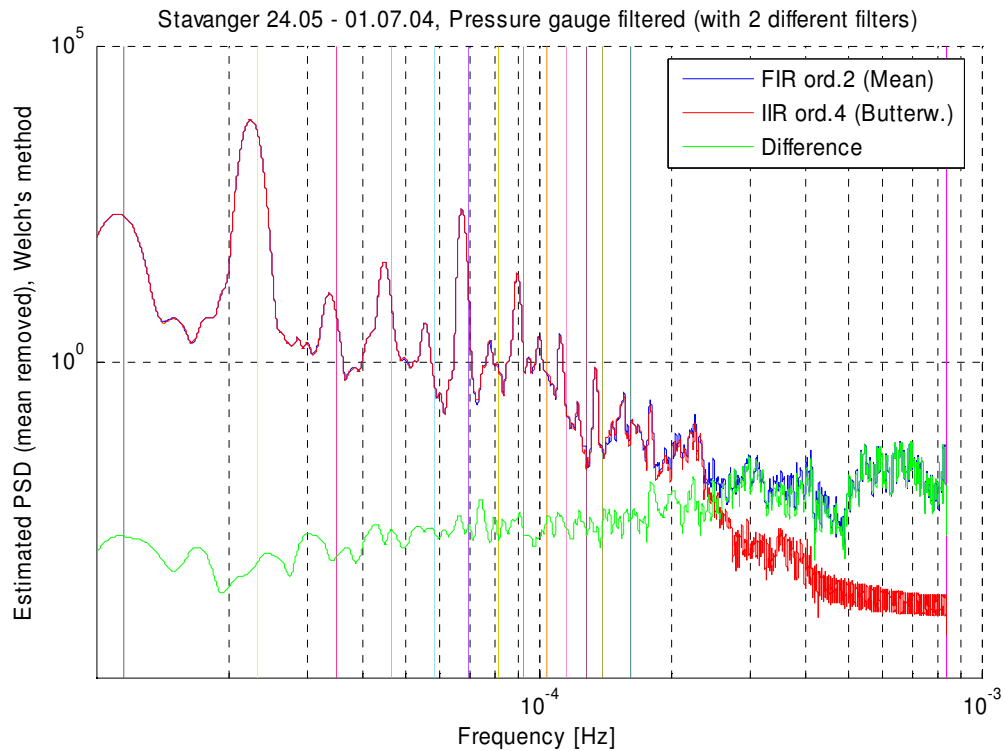


Figure 7-10 Estimated PSD of water level data (10 min) and difference.

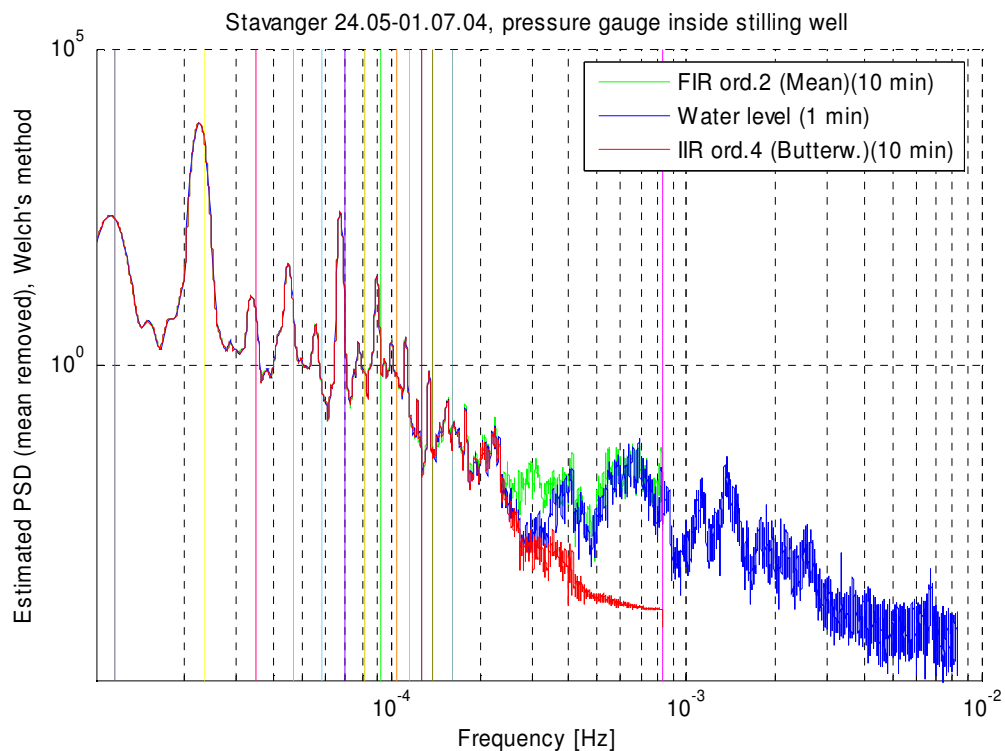


Figure 7-11 Estimated PSD of water level data. The 1-min data represents the “true” spectrum. The two other spectres result from filtering and decimating the 1-min data. The difference between the green and blue curve is a result of aliasing.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Page	39 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

The “FIR ord.2 (mean)”-series is filtered one more time with the smoothing filter used on 10-min. values in MDS. This series is called “FIR ord.2 (mean) smooth”, and is compared with the Butterworth filtered series in Figure 7-12. The overall statistics for the whole series are given in the table below. Note that the statistics can be different if another time segment of the series was used for the calculation. The difference is less than above (without smoothing).

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
Mean filtered and smoothed – Butterw.filtered	-0.0079 m	0.0079 m	0.0010 m	-0.0020 m	0.0019 m	0.0010 m	0.0020 m

In Figure 7-13 we can see the estimated PSD for the water level data filtered with two different filters before decimating (and one smoothed as well after decimating) and the difference.

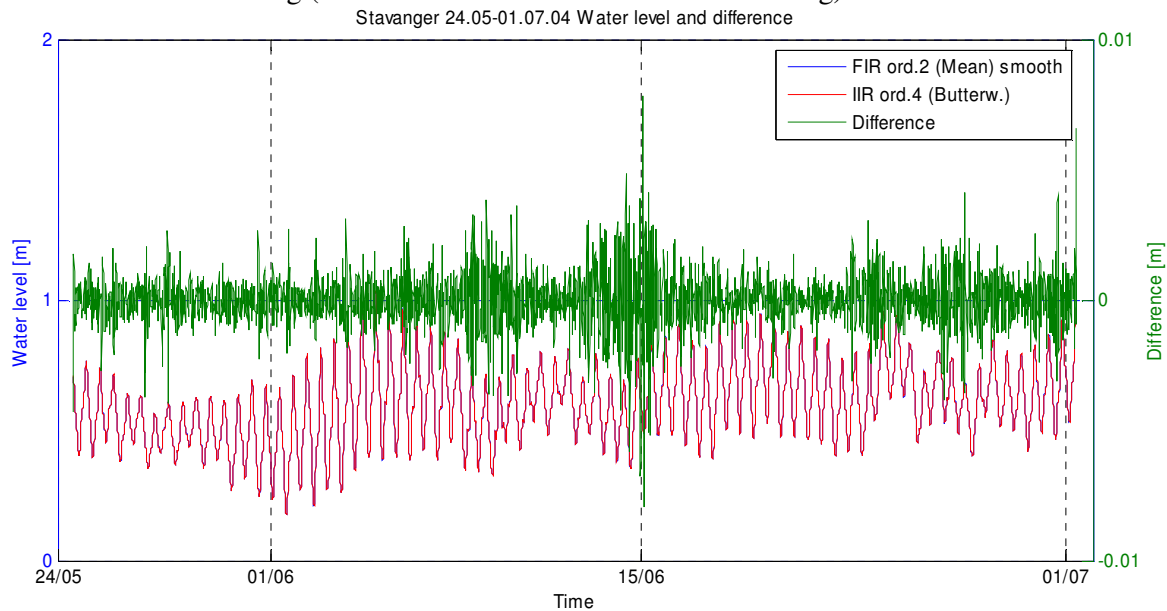


Figure 7-12 Pressure gauge (filtered with two different filters and decimated). The blue series is after decimating filtered again with the 4th order Butterworth filter used to smooth MDS-data. The difference between the two series are plotted as well (whole series).

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Page	40 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

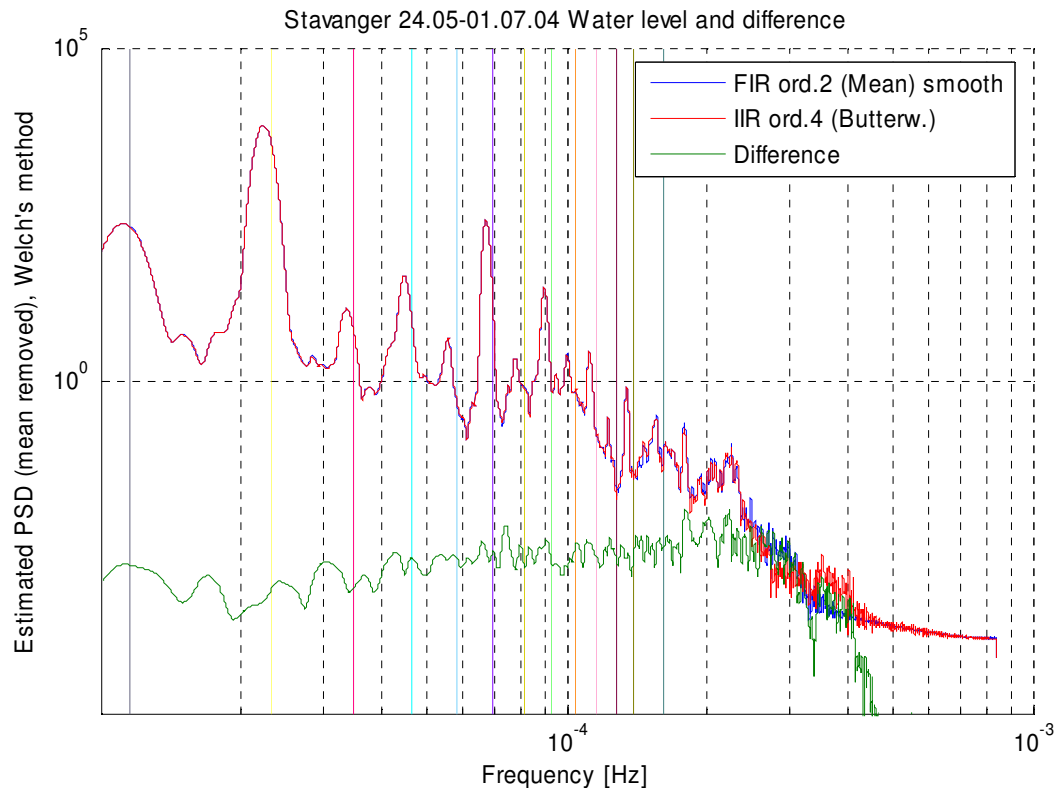


Figure 7-13 Estimated PSD of water level data (10 min) and difference.

8 Comparing test data series with MDS

8.1 General comments

When data from the pressure gauge (inside the stilling well) is compared with the MDS, the observed difference can be caused by the fact that two different sensors are used, as well as that different sampling and filtering schemes are used (for instance will MDS contain aliasing see [9]). We will only see the total difference between the two data sets. But in section 7 we can see the difference due to the different sampling and filtering scheme alone (same sensor), and in section 9 we can see the difference due to the sensors only (same sampling and filtering scheme).

The aliasing in MDS is most evident in the highest frequencies of the MDS data. The highest frequencies of the 10-min data are not always interesting (for instance when the data is used not exactly by the gauge, but in an area a bit away from the gauge, which often is the case in seabed measuring). Because of these two reasons a Butterworth filter (low pass) is sometimes used to smooth the MDS data before they are used (see [10] for details). This data is called smooth MDS.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 41 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

8.2 Data set 1

8.2.1 Comparing with original MDS

The filtered (Butterworth order 4) and decimated data series from section 6 is compared with MDS in Figure 8-1 (whole series), Figure 8-2 (24 hours) and Figure 8-3 (24 hours). Here the two time series are plotted together with the difference between them (MDS - Pressure gauge). We can see that the difference is quite small. The total range is from - 0.0285 m to 0.0369 m. 95% of the differences lies in the interval [-0.0091m, 0.0094m] (see table below). We can see that the variance of the difference as well as the level of the difference varies along the series.

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
MDS – Data set 1	-0.0285 m	0.0369 m	0.0046 m	-0.0091 m	0.0094 m	0.0046 m	0.0092 m

The power spectral density of the two series (pressure gauge filtered and decimated and MDS) is shown in Figure 8-4 (whole spectrum) and Figure 8-5 (focused on the tidal frequencies). There is a visible difference only for the highest frequencies, and for the main tidal frequencies it is no visible difference in spectral density. If we however estimate the PSD of the difference (MDS - Pressure gauge), which is shown in Figure 8-6, we can see frequency components at the diurnal, semidiurnal and 6th diurnal frequencies (grey-, yellow- and purple vertical line).

As pointed out in [9], it is waves with frequencies between the Nyquist frequency for 10-min. sampling (period 20 min.) and up to about 0.004Hz (period about 4 min), which can cause aliasing in MDS (because they are not filtered enough). This frequency band is indicated in Figure 8-7. Here we also can see the PSD of MDS and PSD of 1-min data. The visible difference just below the Nyquist frequency will mainly be caused by the aliasing.

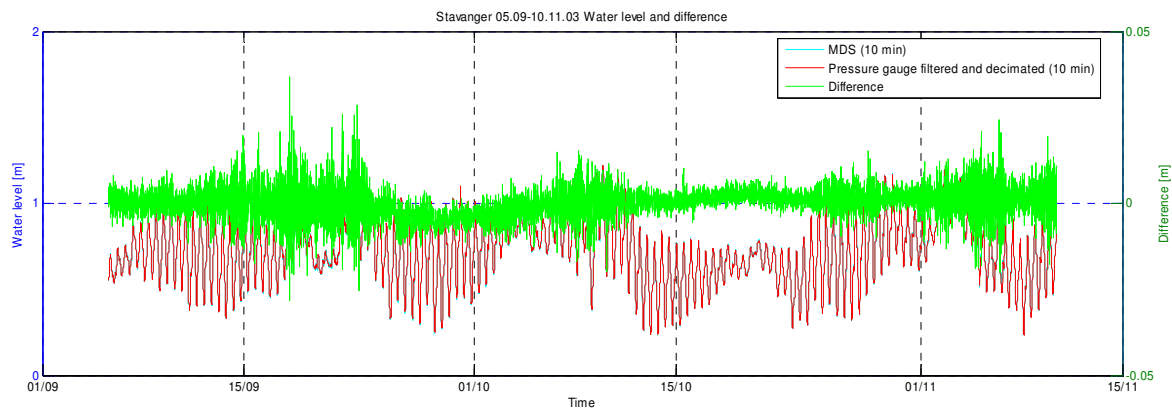


Figure 8-1 MDS, pressure gauge (filtered and decimated) and the difference (whole series).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	42 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

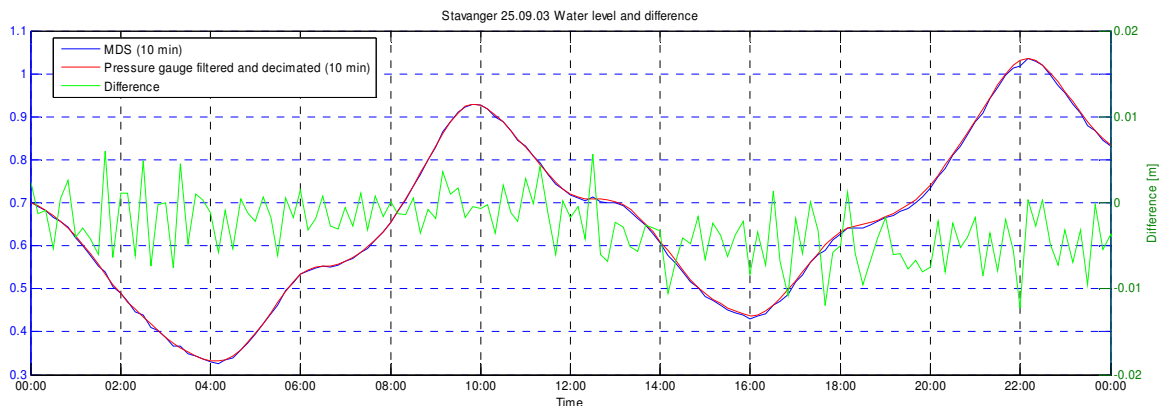


Figure 8-2 MDS, pressure gauge (filtered and decimated) and the difference (24-hours).

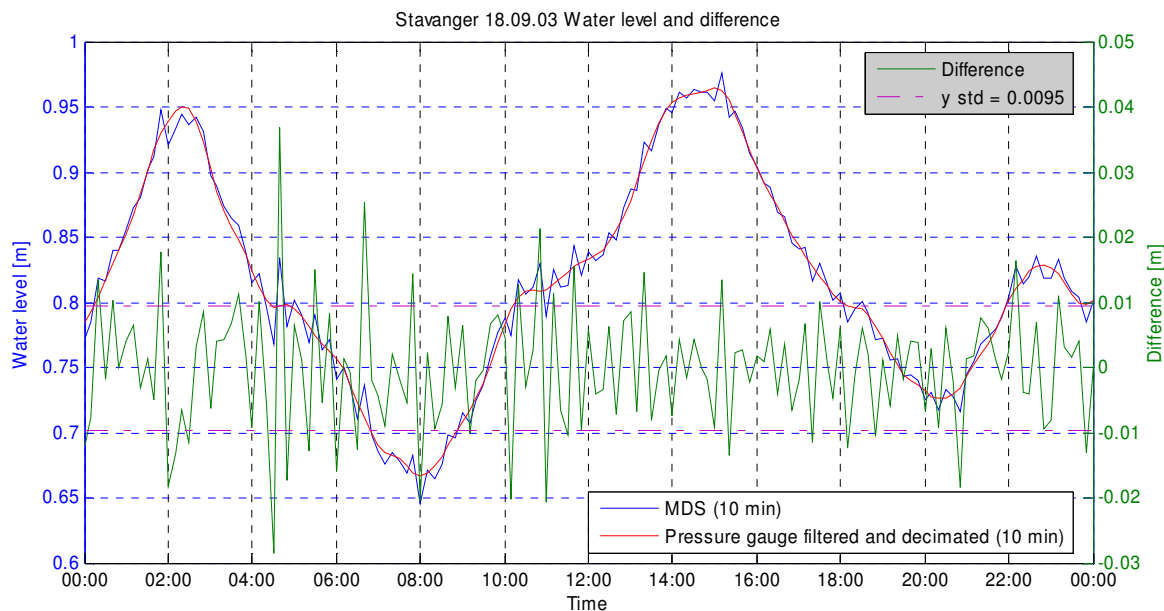


Figure 8-3 MDS, pressure gauge (filtered and decimated) and the difference (24-hours). The standard deviation for 18.09.2003 (0.0095 m) is higher than the standard deviation for the whole period of data set 1 (0.0046 m).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	43 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

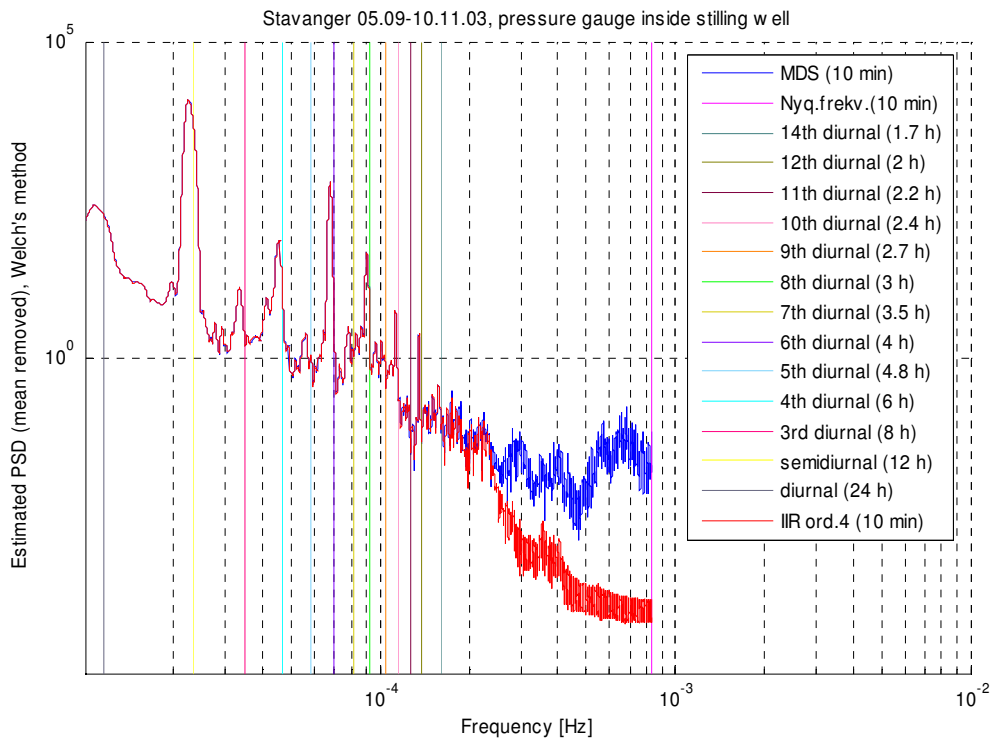


Figure 8-4 Estimated PSD of water level data (pressure gauge inside a stilling well filtered and decimated and MDS).

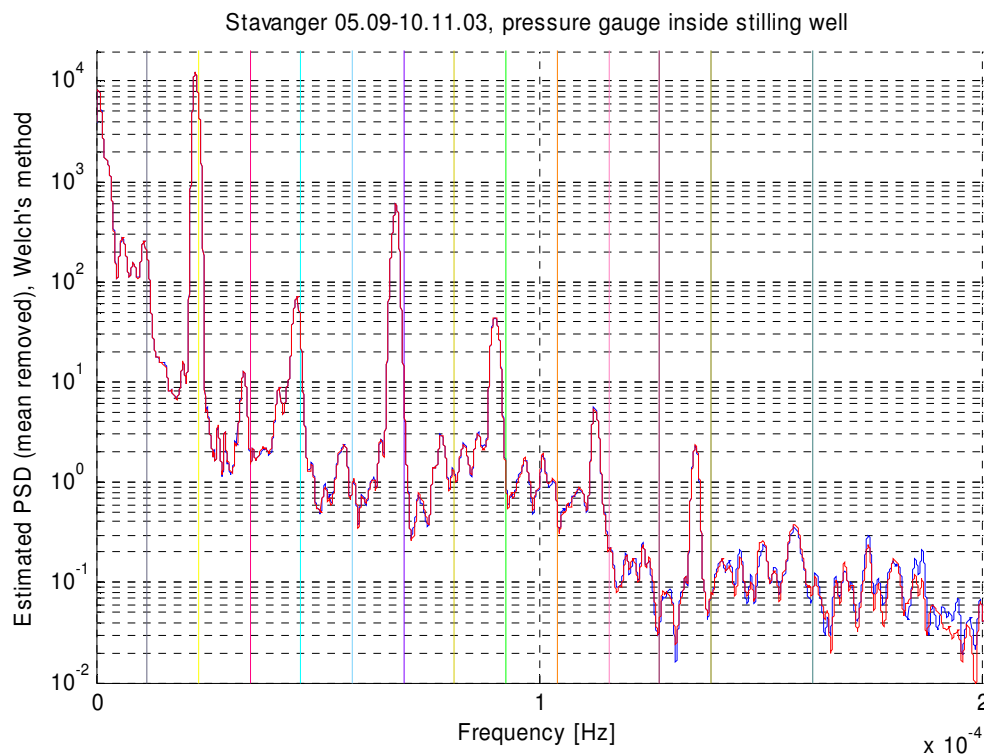


Figure 8-5. Same as Figure 8-4, but here it is focused on the tidal frequencies.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 44 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

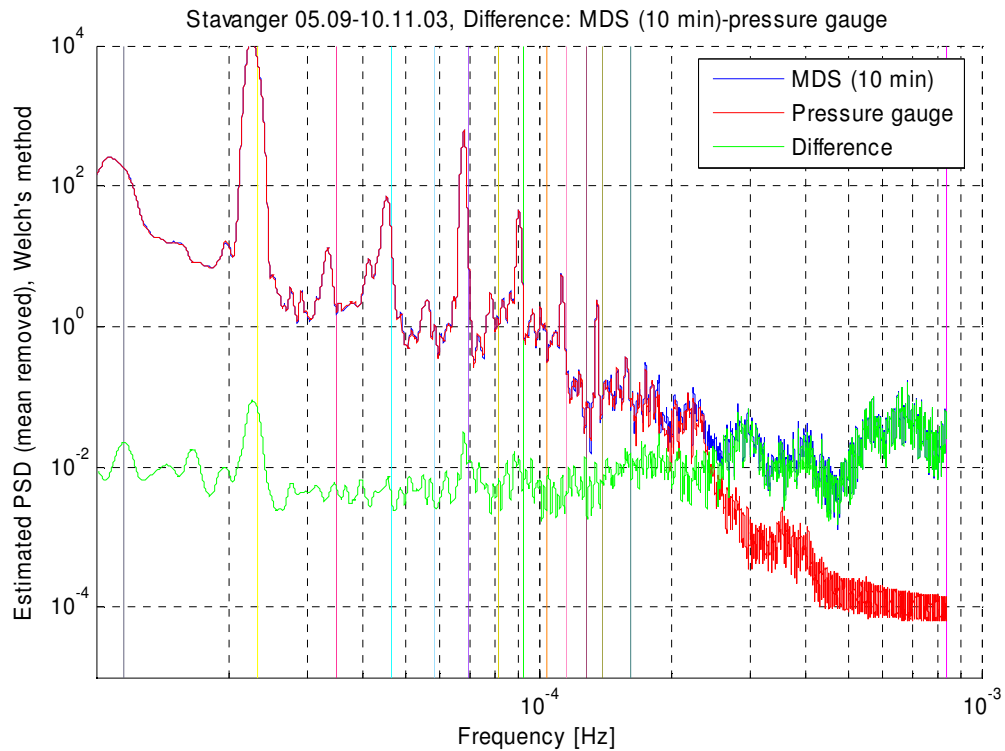


Figure 8-6 Estimated PSD of water level data and difference.

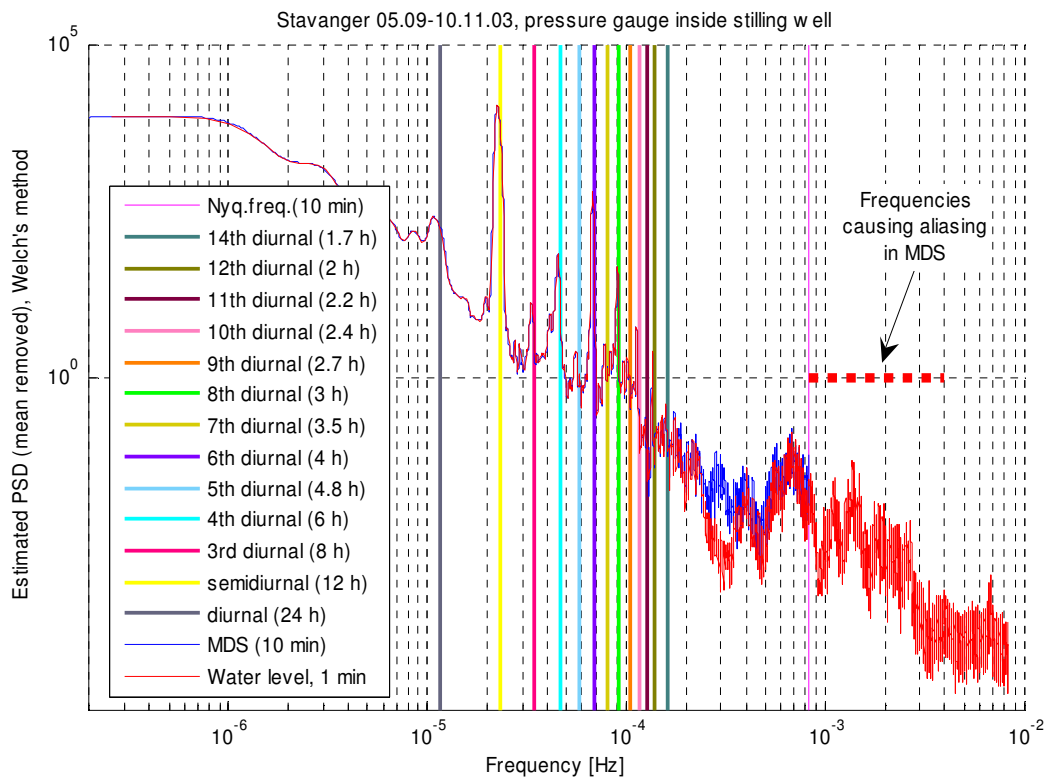


Figure 8-7 Estimated PSD of water level data: Pressure gauge inside a stilling well (1-min) and MDS.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 45 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

8.2.2 Comparing with smooth MDS

Here the filtered (Butterworth order 4) and decimated data series from section 6 is compared with the *smoothed* version of the MDS in Figure 8-8 (whole series) and Figure 8-9 (24 hours). Here the two time series are plotted together with the difference between them (MDS - Pressure gauge). We can see that the difference is smaller than it was when the decimated series was compared to the MDS (not smoothed) in section 8.2.1. The total range is from -0.0104 m to 0.0106 m. 95% of the difference lies in the interval [-0.0052 m, 0.0041 m] (see table below). We can see that the variance of the difference as well as the level of the difference varies along the series.

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
MDS smooth – Data set 1	-0.0104 m	0.0106 m	0.0024 m	-0.0052 m	0.0041 m	0.0024 m	0.0048 m

The power spectral density of the two series (pressure gauge filtered and decimated and MDS) is shown in Figure 8-10 (whole spectrum) and Figure 8-11 (focused on the tidal frequencies). There is a visible difference in PSD for the highest frequencies, but these PSD-values are so small (are in fact filtered away), and it is therefore uninteresting if they differ. For the main tidal frequencies it is no visible difference in spectral density. If we however estimate the PSD of the difference (MDS - Pressure gauge), which is shown in Figure 8-12, we can see frequency components at the semidiurnal and 6th-diurnal frequencies (yellow- and purple vertical line).

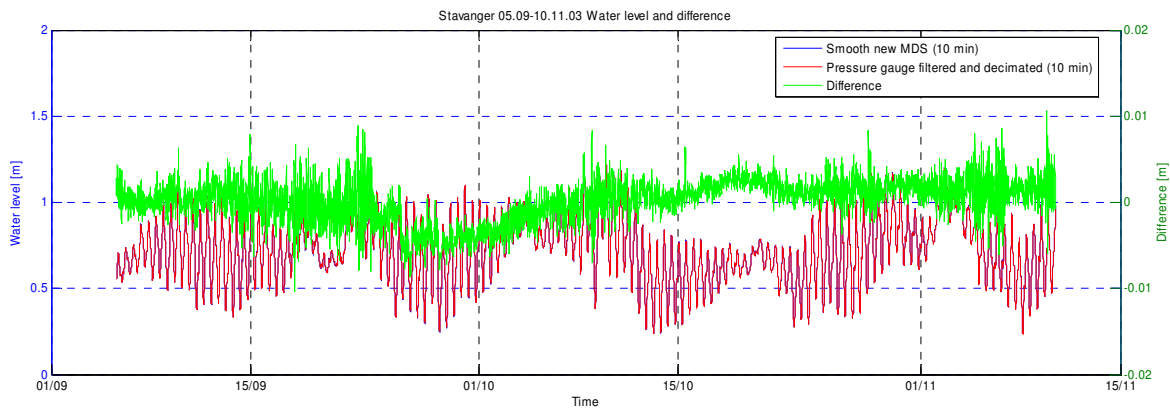


Figure 8-8 MDS (smoothed), pressure gauge (filtered and decimated) and the difference (whole series).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 46 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

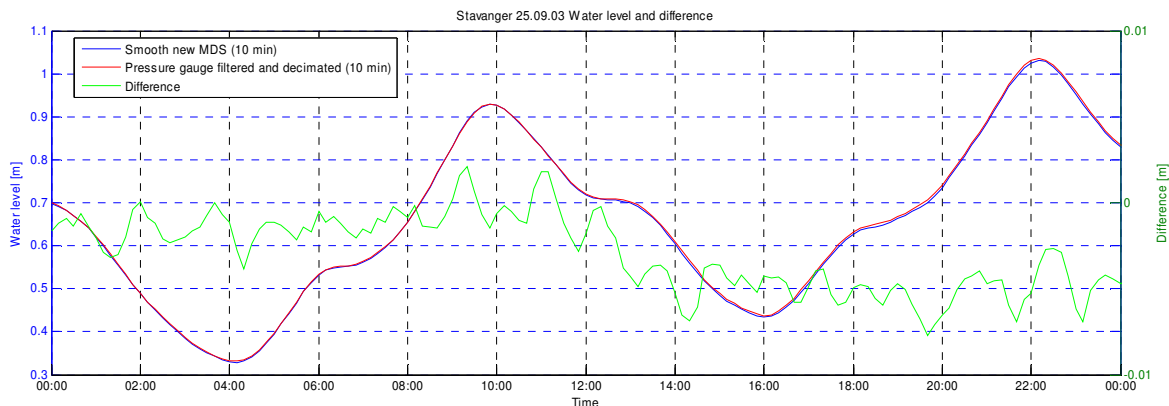


Figure 8-9 MDS (smoothed), pressure gauge (filtered and decimated) and the difference (24-hours).

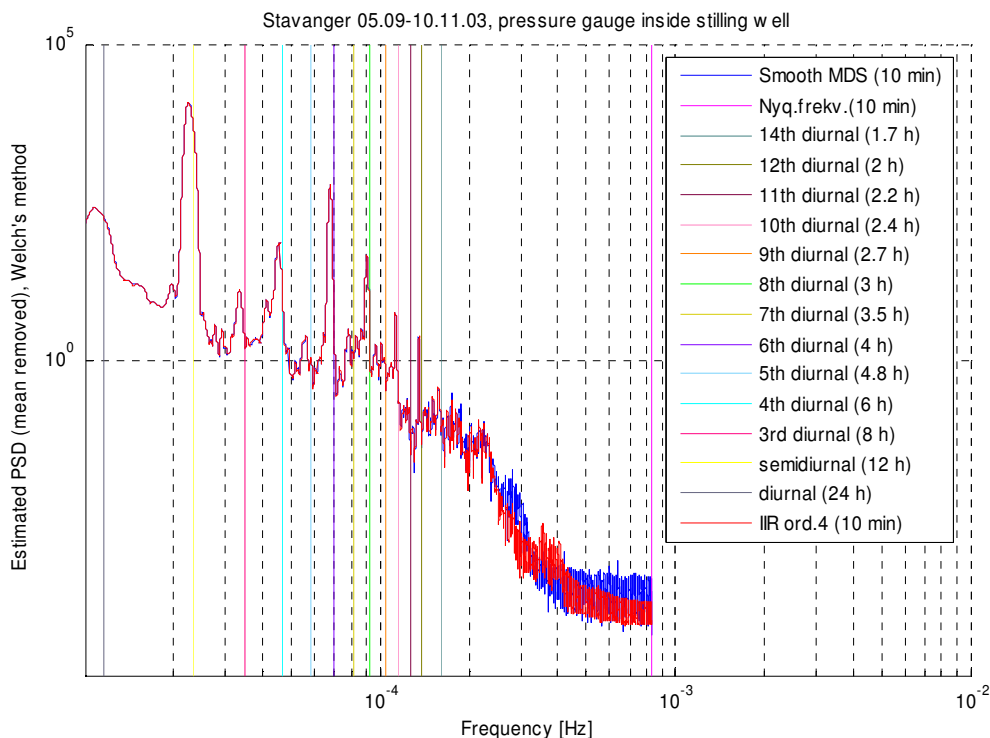


Figure 8-10 Estimated PSD of water level data (pressure gauge inside a stilling well filtered and decimated, and MDS smoothed) and tidal frequencies.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Page	47 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

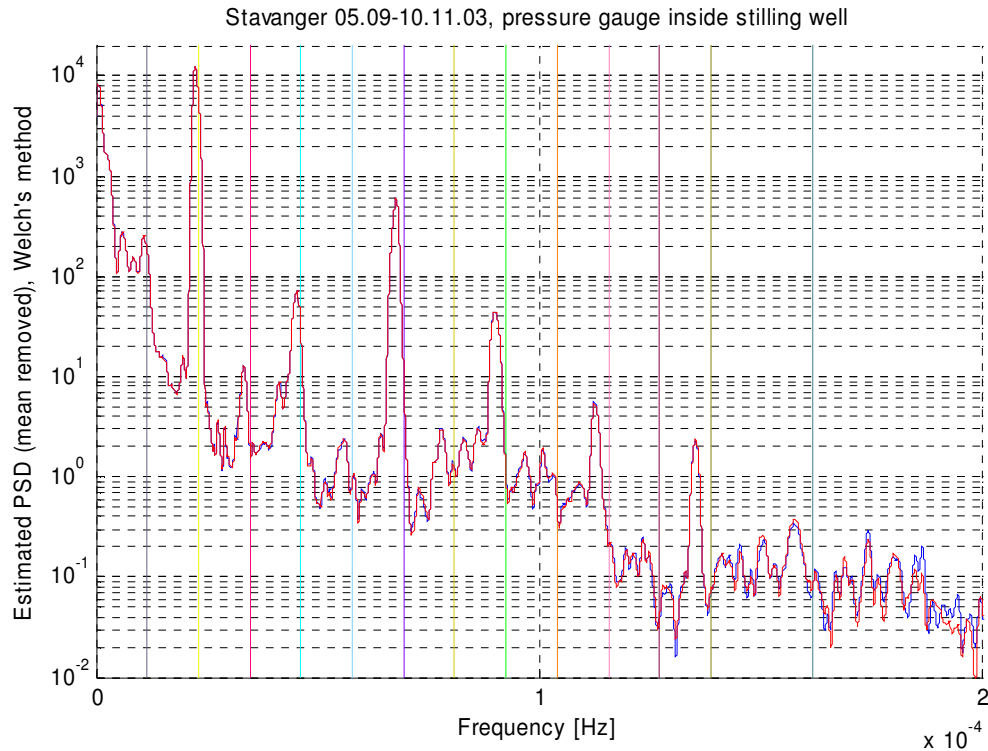


Figure 8-11. Same as Figure 8-10, but here it is focused on the tidal frequency band.

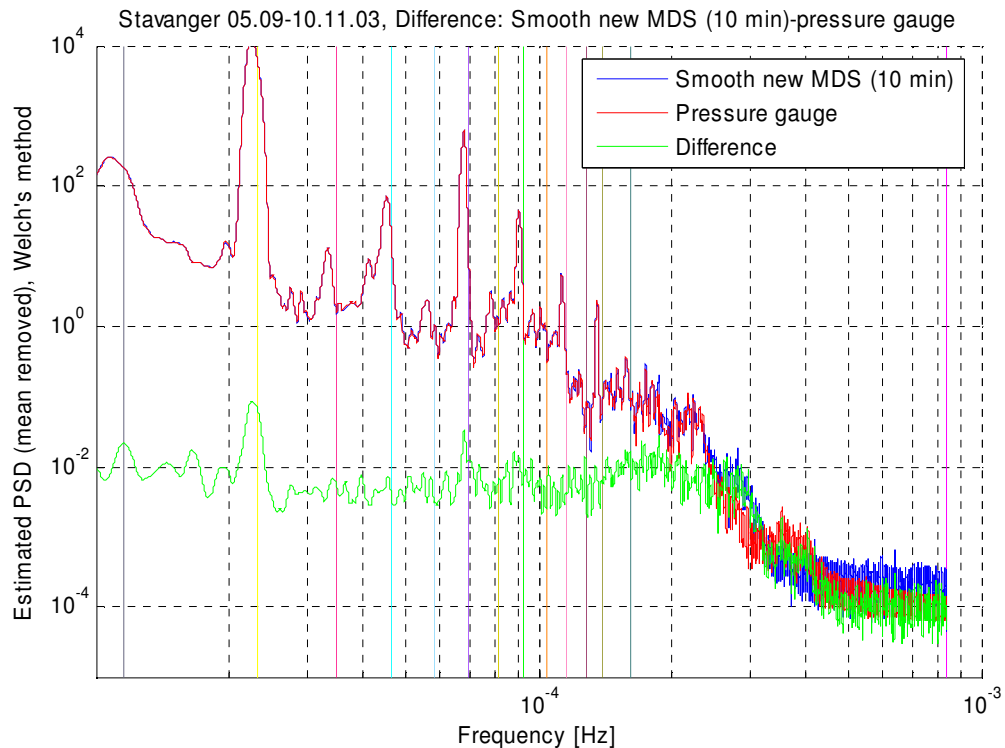


Figure 8-12 Estimated PSD of water level data: Smooth MDS, Pressure gauge inside a stilling well (1-min) and the difference.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	48 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

8.3 Data set 2

8.3.1 Comparing with original MDS

The filtered (Butterworth order 4) and decimated data series from section 6 is compared with MDS in Figure 8-13 (whole series) and Figure 8-14 (24 hours). Here the two time series are plotted together with the difference between them (MDS - Pressure gauge). We can see that the difference is quite small. The total range is from -0.0290 m to 0.0208 m. 95% of the differences lies in the interval [-0.0064m, 0.0061m] (see table below). We can see that the variance of the difference as well as the level of the difference varies along the series.

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
MDS – Data set 2	-0.0290 m	0.0208 m	0.0032 m	-0.0064 m	0.0061 m	0.0032 m	0.0062 m

The power spectral density of the two series (pressure gauge filtered and decimated and MDS) is shown in Figure 8-15 (whole spectrum) and Figure 8-16 (focused on the tidal frequencies). There is a visible difference only for the highest frequencies, and for the main tidal frequencies it is no visible difference in spectral density. If we however estimate the PSD of the difference (MDS - Pressure gauge), which is shown in Figure 8-17, we can see frequency components at the diurnal and semidiurnal frequencies.

As pointed out in [9], it is waves with frequencies between the Nyquist frequency for 10-min. sampling (period 20 min.) and up to about 0.004Hz (period about 4 min), which can cause aliasing in MDS (because they are not filtered enough). This frequency band is indicated in Figure 8-18. Here we also can see the PSD of MDS and PSD of 1-min data. The visible difference just below the Nyquist frequency will mainly be caused by the aliasing.

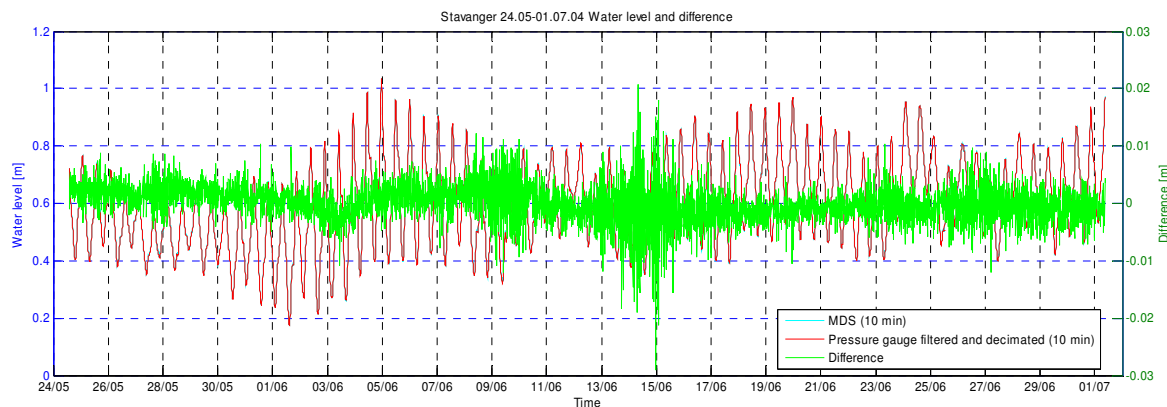


Figure 8-13 Pressure gauge (filtered and decimated), MDS and the difference (whole series).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	49 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

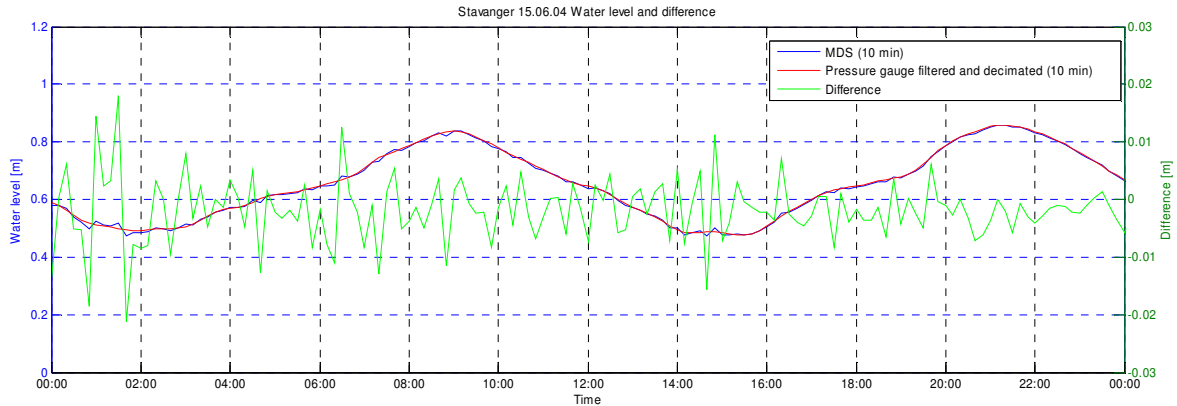


Figure 8-14 Pressure gauge (filtered and decimated), MDS and the difference (24 hours).



Figure 8-15 Estimated PSD of water level data (pressure gauge inside a stilling well filtered and decimated and MDS).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 50 of 60
Document no.:	DAF-05 - 1	Date:	1.0 15.09.06
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		

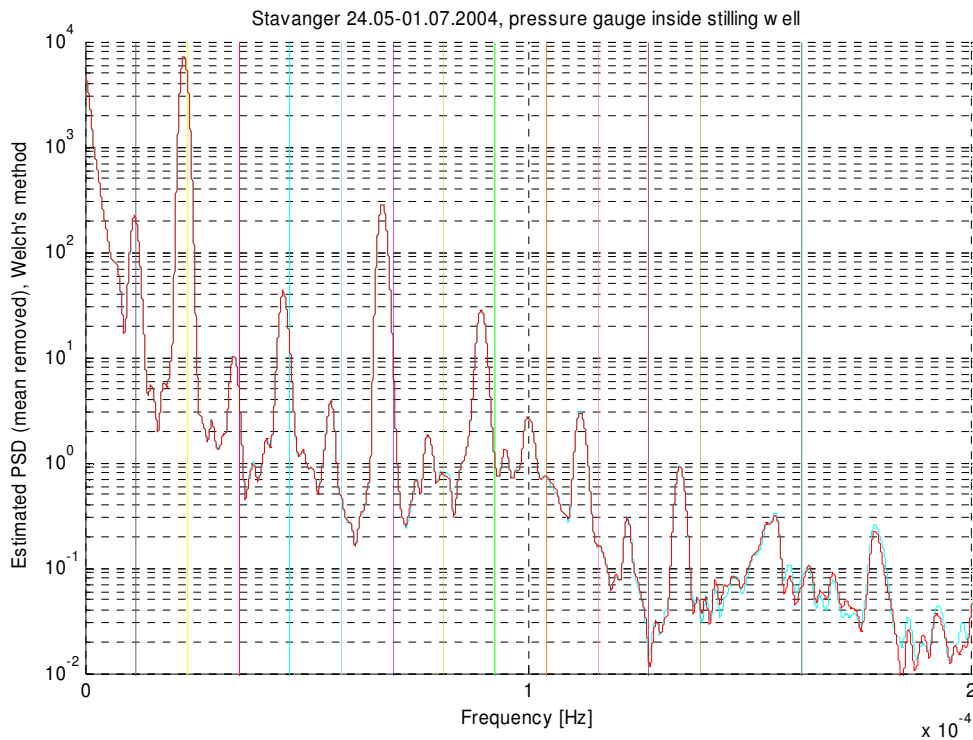


Figure 8-16 Same as Figure 8-15, but here it is focused on the tidal frequencies.

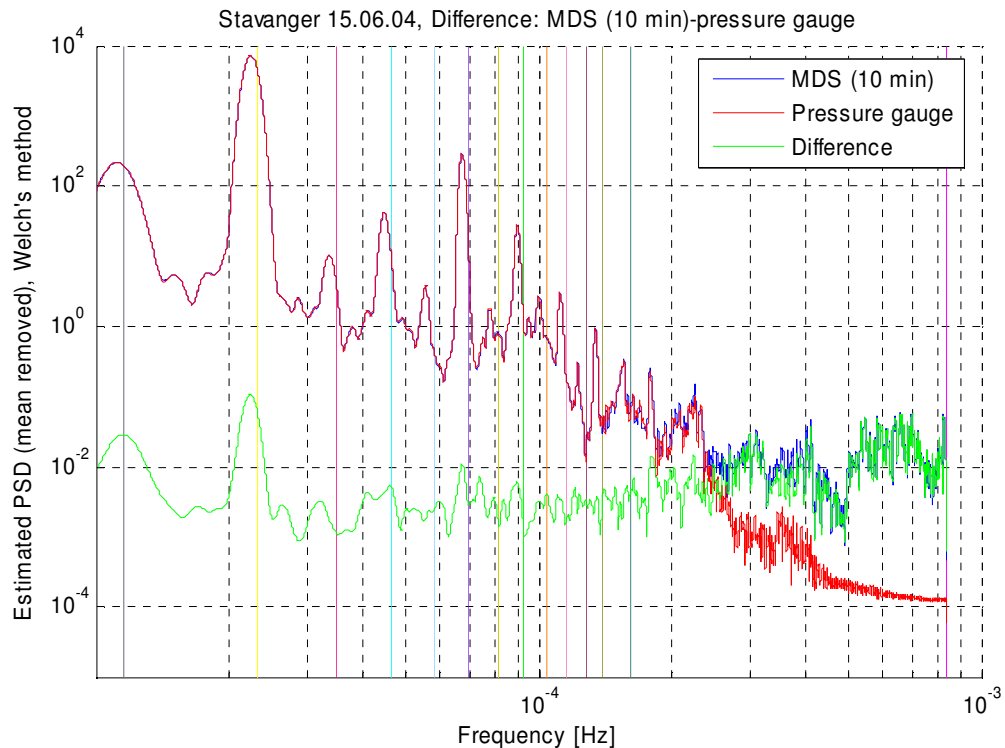


Figure 8-17 Estimated PSD of water level data (pressure gauge inside a stilling well, filtered and decimated, MDS and the difference between them).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 51 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

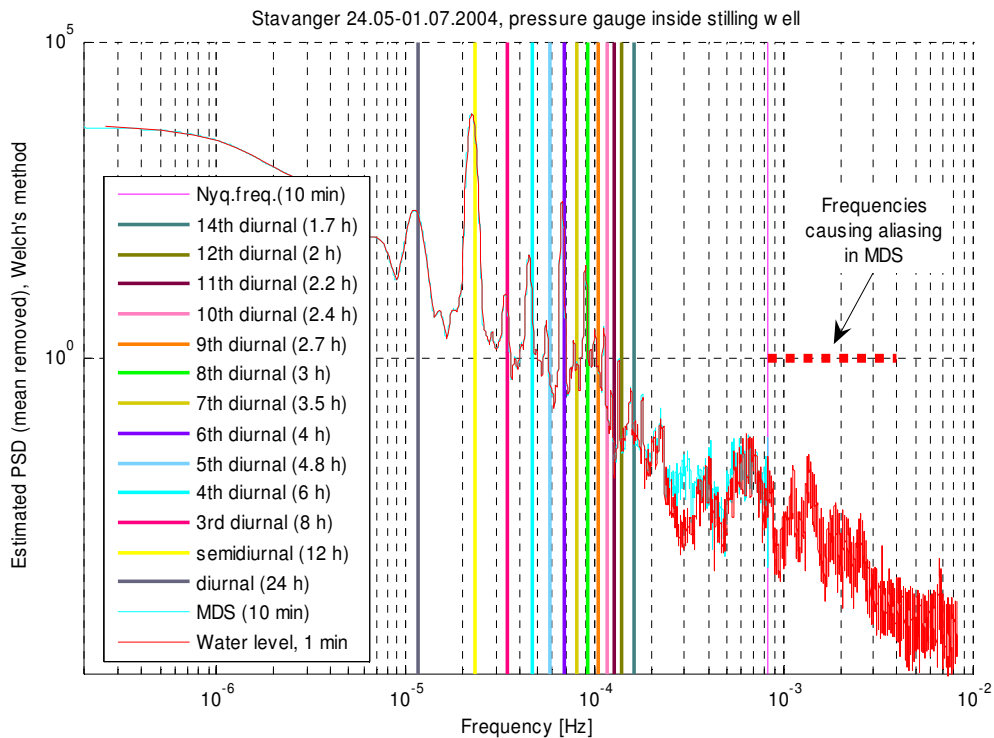


Figure 8-18 Estimated PSD of water level data: Pressure gauge inside a stilling well (1-min) and MDS.

8.3.2 Comparing with smooth MDS

Here the filtered (Butterworth order 4) and decimated data series from section 6 is compared with the *smoothed* version of the MDS in Figure 8-19 (whole series) and Figure 8-20 (24 hours). Here the two time series are plotted together with the difference between them (MDS - Pressure gauge). We can see that the difference is smaller than it was when the decimated series was compared to the MDS (not smoothed) in section 8.3.1. The total range is from -0.0094 m to 0.0063 m. But 95% of the differences lies in the interval [-0.0034m, 0.0033m] (see table below).

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
MDS smooth – data set 2	-0.0094 m	0.0063 m	0.0018 m	-0.0034 m	0.0033 m	0.0018 m	0.0033 m

The source of the difference can be the different sampling schemes and the fact that two different sensors are used.). We can see that the variance of the difference as well as the level of the difference varies along the series.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	52 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

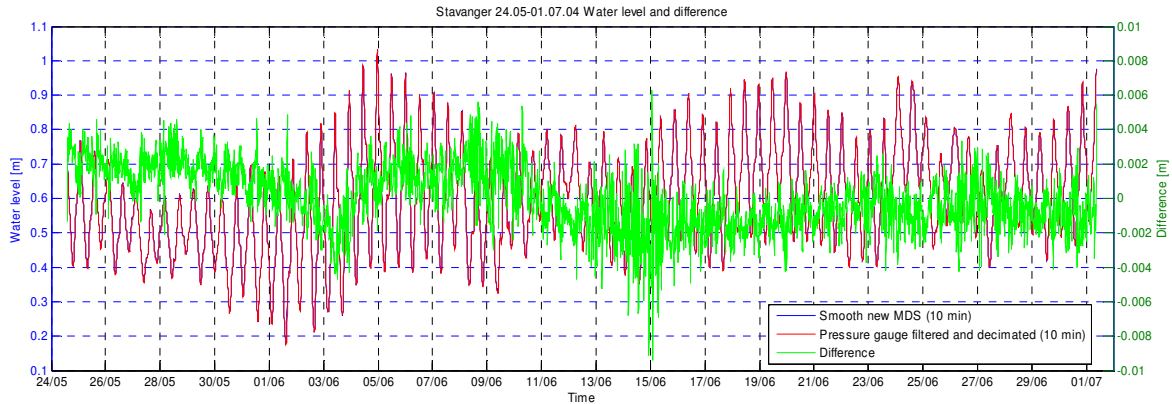


Figure 8-19 MDS (smoothed), pressure gauge (filtered and decimated) and difference (whole series).

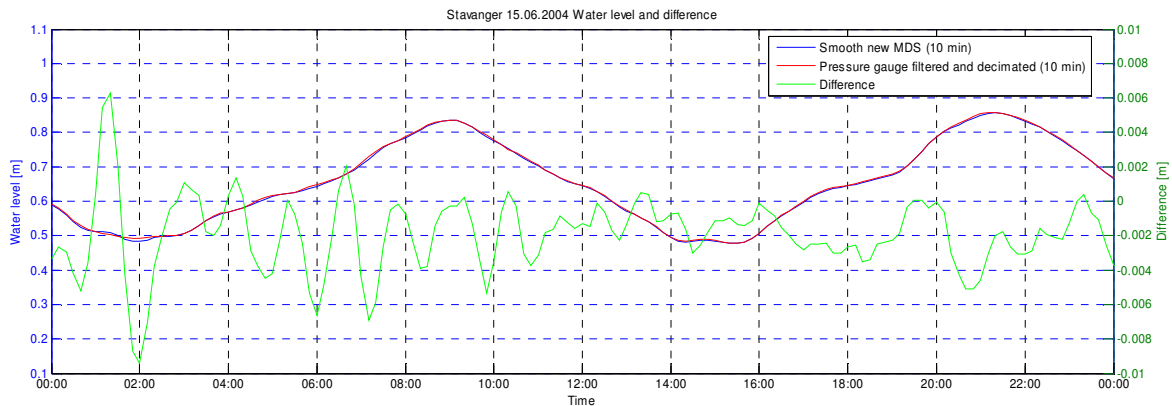


Figure 8-20 MDS (smoothed), pressure gauge (filt. and dec.), and difference (24 hours).

The power spectral density of the two series (pressure gauge filtered and decimated and MDS smoothed) is shown in Figure 8-21, Figure 8-22 and Figure 8-23. In Figure 8-23 the PSD of the difference is plotted as well, and we can see that the difference has frequency components at the diurnal and semidiurnal frequencies.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Version:	Page 53 of 60
Document no.:	DAF-05 - 1	Date:	1.0 15.09.06
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		

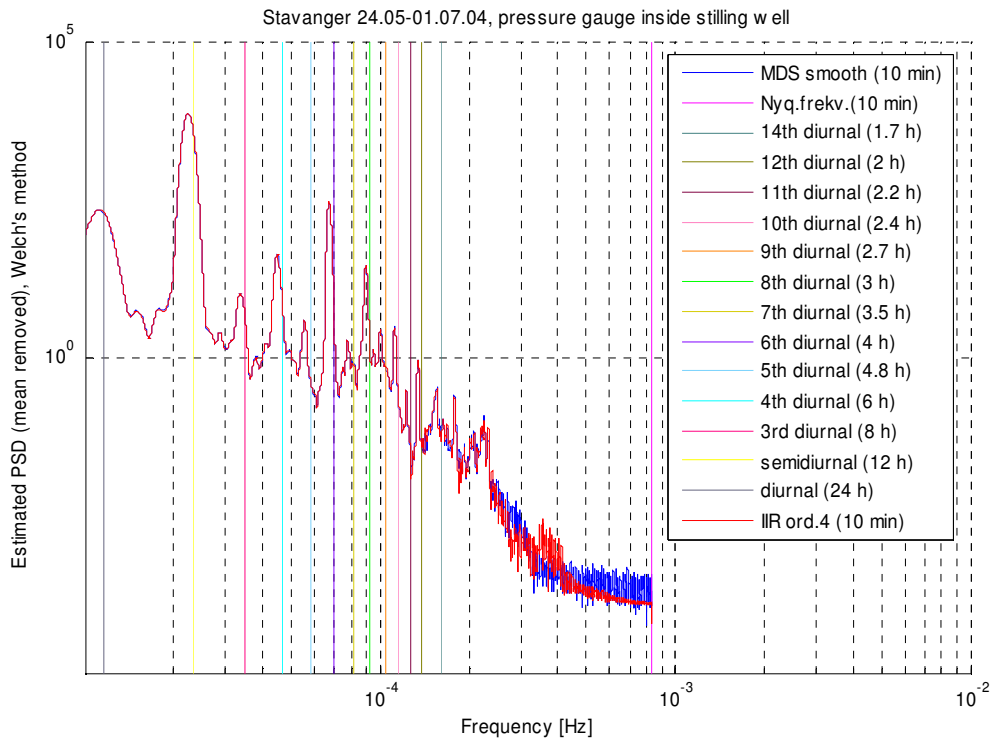


Figure 8-21 Estimated PSD of water level data (pressure gauge inside a stilling well filtered and decimated, and MDS smoothed) and tidal frequencies.

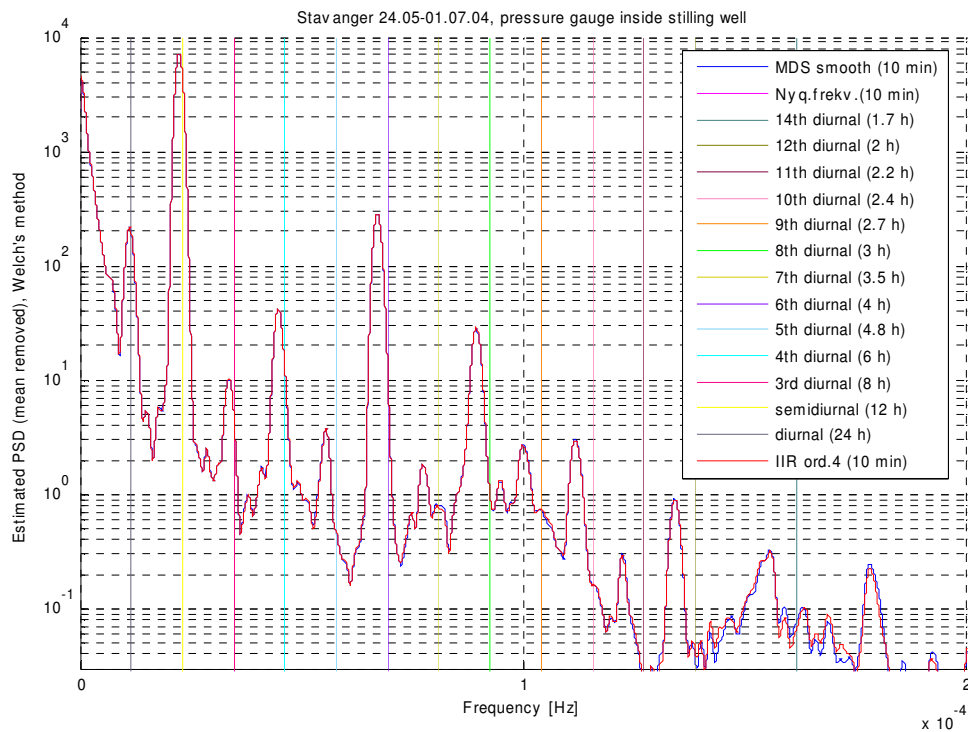


Figure 8-22 Same as Figure 8-21, but here it is focused on the tidal frequency band.

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	54 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

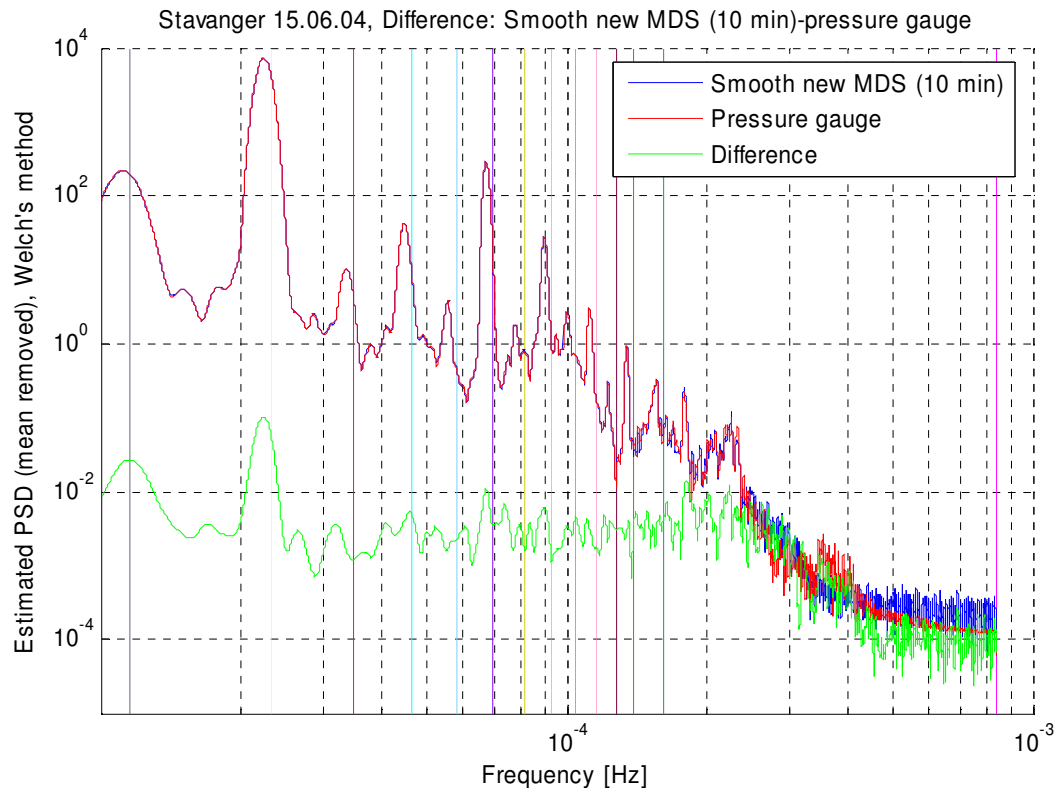


Figure 8-23 Estimated PSD of water level data: Smooth MDS, Pressure gauge inside a stilling well (1-min) and the difference.

9 Comparing the two sensors both using 3-min mean filter

9.1 General comments

In this section we compare the test data sets (data set 1 and 2) filtered with a 3-min mean filter before decimating with the MDS (which is also filtered with a 3-min mean filter before decimating). Here we want to look at the difference due to the different measurement technology (sensors) used, and not the difference due to different sampling and filtering scheme.

9.2 Data set 1

The water level and the difference are shown in Figure 9-1 (whole series) and Figure 9-2 (24 hours).

The overall statistics for the whole series are given in the table below. Note that the statistics can be different if another time segment of the series was used for the calculation. The difference due to the sensors is less than the difference due to the sampling and filtering scheme (see section 7.2).

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
MDS - Mean filtered dataset 1	-0.0111	0.0102	0.0022	-0.0052	0.0032	0.0022	0.0045

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level	Page	55 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

In Figure 9-3 we can see the estimated PSD for the water level data measured with two different sensors and the difference. We can see frequency components at the diurnal, semidiurnal and 6th diurnal frequencies (grey-, yellow- and purple vertical line).

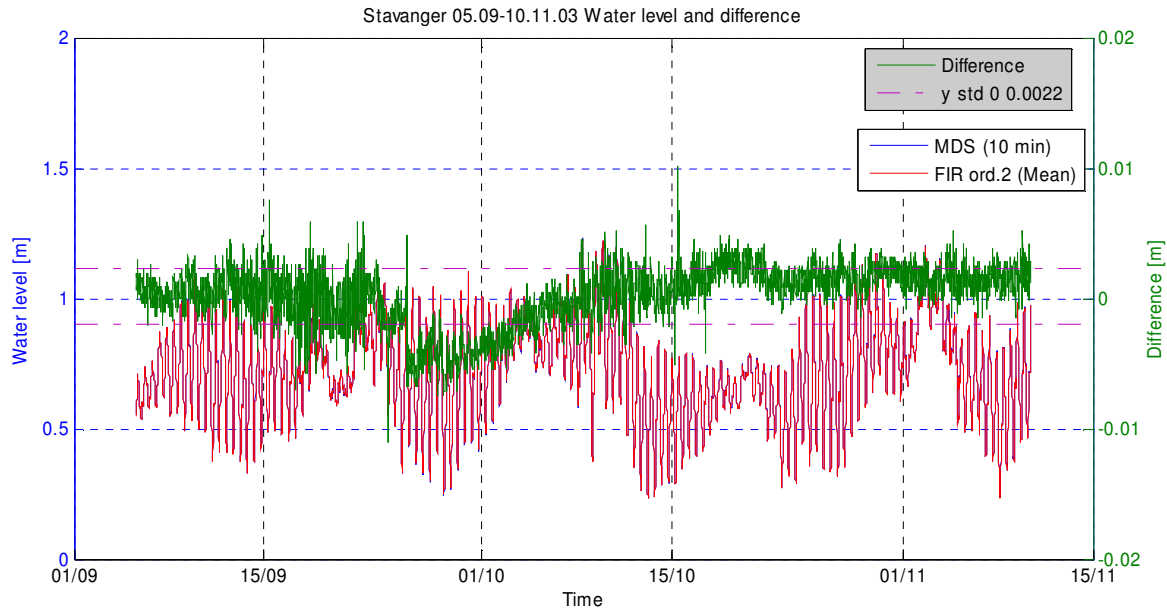


Figure 9-1 MDS and pressure gauge (filtered with 3-min mean filter and decimated) and the difference (whole data set 1).

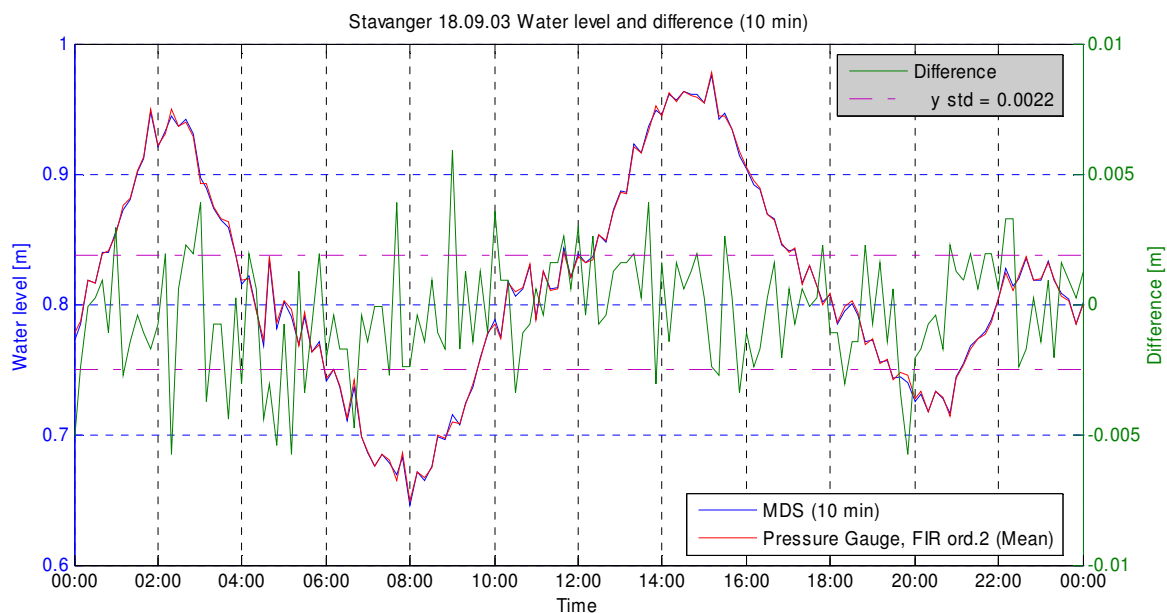


Figure 9-2 MDS and Pressure gauge, both filtered with 3 min mean filters and decimated to 10-min values (24 hours).

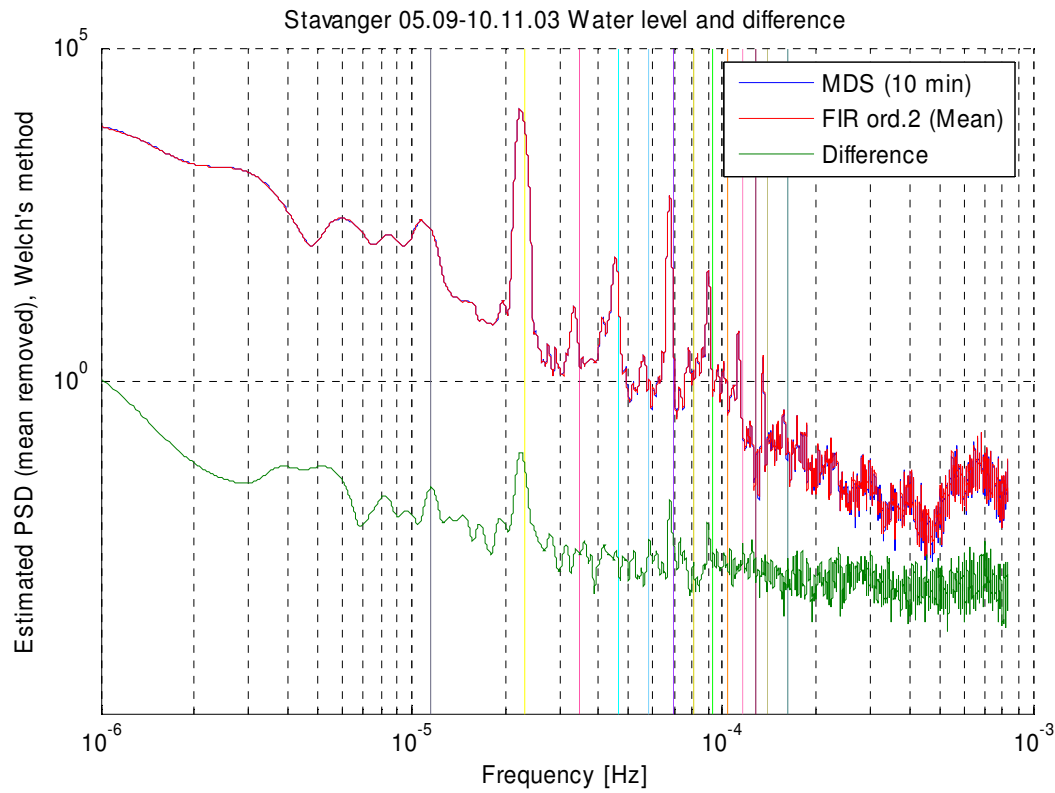


Figure 9-3 Estimated PSD of water level data (10 min) and difference.

9.3 Data set 2

The water level and the difference are shown in Figure 9-4.

The overall statistics for the whole series are given in the table below. Note that the statistics can be different if another time segment of the series was used for the calculation. The difference due to the sensors is less than the difference due to the sampling and filtering scheme (see section 7.3).

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
MDS - Mean filtered dataset 2	-0.0051 m	0.0045 m	0.0016 m	-0.0028 m	0.0029 m	0.0016 m	0.0029 m

In Figure 9-5 we can see the estimated PSD for the water level data measured with two different sensors and the difference. We can see frequency components at the diurnal, semidiurnal 4th diurnal and 6th diurnal frequencies (grey-, yellow-, blue- and purple vertical line).

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 57 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

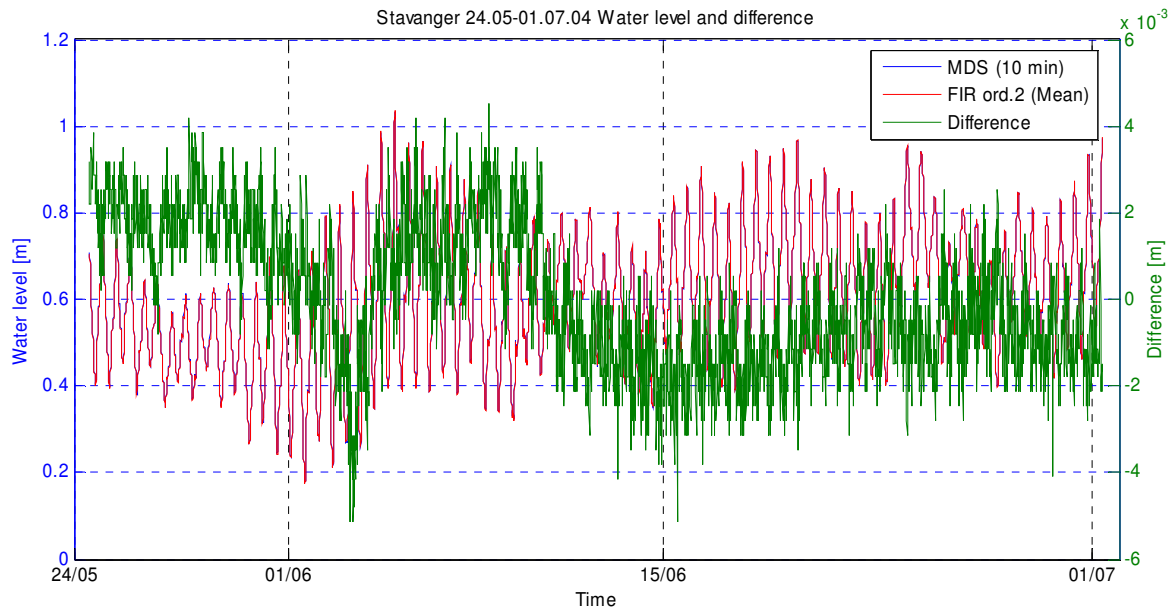


Figure 9-4 MDS and pressure gauge (filtered with 3-min mean filter and decimated) and the difference (whole data set 2).

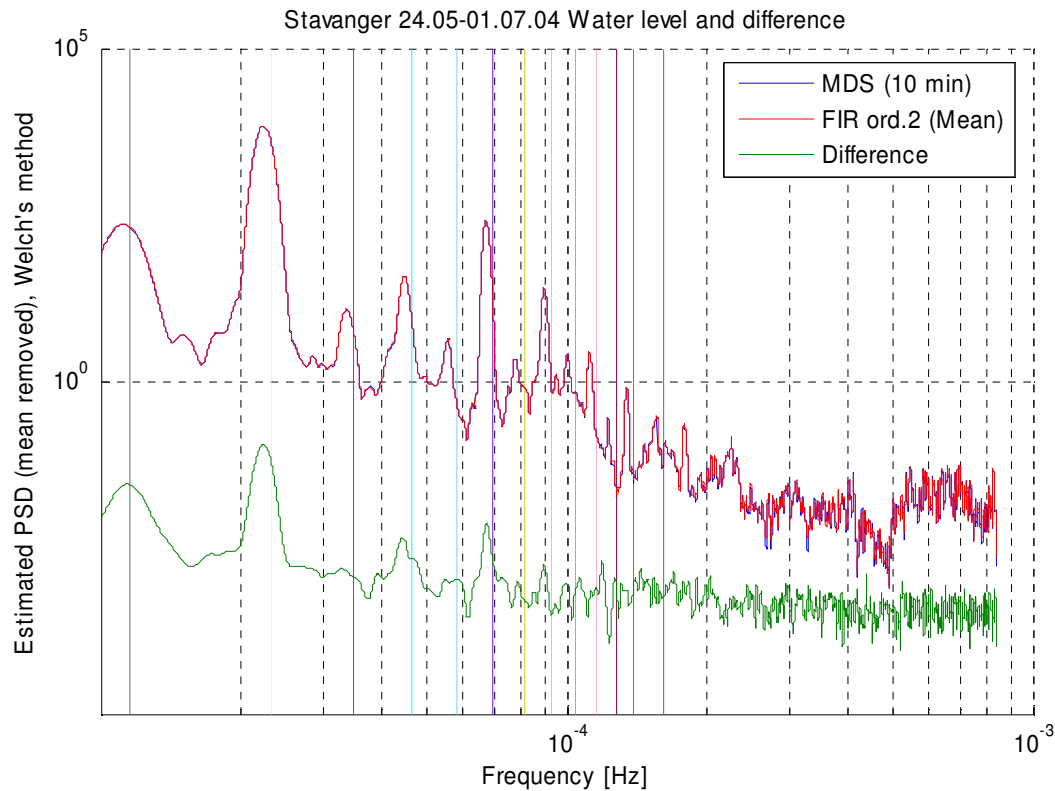


Figure 9-5 Estimated PSD of water level data (10 min) and difference.

10 Conclusions

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Version:	Page 58 of 60
Document no.:	DAF-05 - 1	Date:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc		15.09.06

A low pass Butterworth filter of order 4 has been designed to filter the 1-min water level data before decimating to 10-min values. The filter is used in a post-processing mode, and the 1-min data series is filtered both forward and backward in time.

If the 10-min water level data is to be produced in near real time (NRT), another filter may be used. The NRT filter should be a relatively short (depending on the delay requirements of the NRT application) FIR filter for forward filtering only. Such a filter has not been designed and studied in this report.

The water level data, data set 1 and data set 2, are from two different test periods. They are measured by a pressure gauge inside a stilling well with a sampling rate of 1 minute. The two data sets are filtered and decimated.

Following comparisons are carried out:

- The data set is compared to it self, using two different LP-filters (Butterworth order 4 and 3-min mean) before decimating (see section 7).
- The data set (filtered with Butterworth order 4 before decimating) is compared to MDS (original and smoothed) (see section 8).
- The data set (filtered with 3-min mean before decimating) is compared to MDS (normal and smoothed) (see section 9).

The result for data set 1 is given in the table below:

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
Mean filt 1 – Butterw.filt. 1	-0.0254 m	0.040 m	0.0042 m	-0.0090 m	0.0087 m	0.0042 m	0.0088 m
Mean filt. and smoothed 1 – Butterw.filt.1	-0.0101 m	0.0089 m	0.0014 m	-0.0028 m	0.0031 m	0.0014 m	0.0030 m
MDS – Butterw.filt 1	-0.0285 m	0.0369 m	0.0046 m	-0.0091 m	0.0094 m	0.0046 m	0.0092 m
MDS smooth – Butterw.filt 1	-0.0104 m	0.0106 m	0.0024 m	-0.0052 m	0.0041 m	0.0024 m	0.0048 m
MDS - Mean filtered dataset 1	-0.0111	0.0102	0.0022	-0.0052	0.0032	0.0022	0.0045

The same result for data set 2 is given in the table below:

Difference series	Minimum	Maximum	Standard deviation	2.5% percentile	97.5% percentile	RMS (root mean square)	95% percentile of root square
Mean filt 2 – Butterw.filt. 2	-0.0272 m	0.0219 m	0.0029 m	-0.0057 m	0.0056 m	0.0029 m	0.0056 m
Mean filt. and smoothed 2 – Butterw.filt.2	-0.0079 m	0.0079 m	0.0010 m	-0.0020 m	0.0019 m	0.0010 m	0.0020 m
MDS – Butterw.filt 2	-0.0290 m	0.0208 m	0.0032 m	-0.0064 m	0.0061 m	0.0032 m	0.0062 m
MDS smooth – Butterw.filt 2	-0.0094 m	0.0063 m	0.0018 m	-0.0034 m	0.0033 m	0.0018 m	0.0033 m
MDS - Mean filtered dataset 2	-0.0051 m	0.0045 m	0.0016 m	-0.0028 m	0.0029 m	0.0016 m	0.0029 m

Norwegian Hydrographic Service (NHS)		Data Acquisition Section	
Document title:	Test of 1-minute sampling of water level	Page	59 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

The observed difference is generally small, but we can see from the different time plots (see section 7 - section 9) that the difference vary over time. The difference is smaller for data set 2 than data set 1. The following is observed for whole data set 2 (overall results):

- The difference due to the filtering scheme is **+/- 0.6 cm (95 %)**
- The difference due to the filtering scheme is reduced to **+/- 0.2 cm (95%)** by smoothing the 10-min values (with a smoothing Butterworth filter)
- The difference due to the two different measurement techniques is **+/- 0.3 cm (95%)**

The most important result for data set 1 and 2 are summarised in the table below:

Data set	Difference due to filtering	Difference due to filtering when smoothing is used	Difference due to measurement techniques
1	+/- 0.9 cm (95%)	+/- 0.3 cm (95%)	[-0.5 cm, +0.3 cm] (95%)
2	+/- 0.6 cm (95%)	+/- 0.2 cm (95%)	+/- 0.3 cm (95%)

The different results appearing from the analysis of the two data sets can have the following reasons:

- Different result for “Difference due to filtering” (with or without smoothing) can be a result of different weather conditions in the two periods.
- Different result for “Difference due to measurement techniques” can be a result of varying sea temperature and/or salinity (used by the pressure gauge to calculate depth) over the measurement period, and/or the fact that the pressure gauge was badly anchored while measuring data set 1.

The “Difference due to filtering” (without smoothing) will have 2 causes:

- Aliasing in the time series filtered with the 3-minute mean filter.
- Real high frequency components in the time series filtered with the 3-minute mean filter.

These two components (in the time series filtered with the 3-minute mean filter) are mixed. It is not possible to separate them when only the 10-min series is available. These corrupted frequencies should be removed. This can be done with the smoothing filter. The “Difference due to filtering” (with smoothing) will have the same two causes, but both are reduced.

The best of course is to filter satisfactory before decimating but in the case of data set 1 and 2 the difference is small +/- 0.3 and +/- 0.2 cm (95%).

The “Difference due to filtering” will be lager if there are more signal power in the frequency band from 0.000833... Hz (period 20 minutes) and up to ca. 0.004 Hz (period ca. 4 minutes). This can vary from site to site and with time. For the two data sets from Stavanger the PSD in this frequency band was low compared with the PSD at the tidal frequencies.

<i>Norwegian Hydrographic Service (NHS)</i>		<i>Data Acquisition Section</i>	
Document title:	Test of 1-minute sampling of water level		Page 60 of 60
Document no.:	DAF-05 - 1	Version:	1.0
File identification:	S:\Grupper\Rapporter\2005\DAF-05-1 Test of 1-minute sampling of water level.doc	Date:	15.09.06

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