Gabriella Stenberg
Swedish Institute of Space Physics
Uppsala Division
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The Updated Cluster EFW Filter Calibration Report

...featuring an additional chapter with conclusions...

Version 2.0

Contents

1 Introduction

The electric field and wave experiment (EFW) on the Cluster spacecraft is designed to measure the electric field and the plasma density. The sensors consist of 16 spherical probes, four at each of the four spacecraft. The logical structure of the EFW instrument is shown in Figure 1. There are five different filters available, low

Figure 1: Block diagram of the Cluster EFW instrument. To the left of the multiplexors (MUX1 and MUX2) the names of the different signals are shown.

pass filters at 10 Hz, 180 Hz, 4 kHz and 32 kHz and a bandpass filter at 50 Hz-8 kHz. The different signals from the EFW instrument considered in this report can be grouped as follows:

1. Lowest-frequency band, single-probe signals: V1L, V2L, V3L, V4L (10 Hz low pass filters)
2. Medium-frequency band signals: (180 Hz low pass filters)
   (a) single-probe signals: V1M, V2M, V3M, V4M
   (b) double-probe signals: V12M, V34M
3. Higher-frequency band signals
   (a) single-probe signals: V1H, V2H, V3H, V4H (4 kHz low pass filters)
   (b) double-probe signals: V12H, V34H (50 Hz-8 kHz bandpass filters)
4. Highest-frequency band, single-probe signals: V1U, V2U, V3U, V4U (32 kHz low pass filters)

This report considers only the analog side of the instrument and its purpose is, firstly, to verify the analog filter calibrations, and secondly, to analyze the resulting transfer functions. Of special interest is whether or not calibrations in the frequency domain is needed. The report also contains comparisons between the transfer functions from different probes and different satellites in order to determine how identical the signals are within the different groups listed above. One of the sections is devoted to a comparison between the 10 Hz and 180 Hz filters. In the last section the results are summarized and the transfer functions that describe the different filter responses are presented.

2 Verification of the analog calibrations

2.1 Introduction

To validate the analog calibrations, we compare the results from two different test setups, providing two independent observations of the transfer functions. Results from two different test setups are available for both the 10 Hz (L) and the 180 Hz (M) filters. Apart from the validation of the calibrations, the results also provide an estimation of the accuracy of the obtained transfer functions.

2.2 Results

An example of the calibration results for the L-filters is shown in Figure 2 (Cluster 1: V1L). The amplitude and phase responses are plotted as functions of frequency using both a logarithmic frequency scale (left) and linear scale (right). The two curves in these panels, corresponding to the two different tests, lie almost on top of each other indicating high reliability of the calibrations.

At low frequencies we observe a slight difference between the results. This feature can be explained by the fact that one of the test setups is designed for coverage of high frequencies. Hence, quantifying the differences, by computing the mean and maximum difference between the two curves, we exclude the low-frequency part. For the L-filters the two calibration curves are compared in the frequency range 5-10 Hz. The mean and maximum differences between the two tests, both for the amplitude and the phase responses, are indicated in Figure 2.

An estimation of the group delay, $-d\phi/2\pi df$, where ϕ is the phase and f the frequency, is computed and shown in the bottom panels of Figure 2. A clear peak in the group delay can be observed at the filter cut-off frequency (10 Hz). The group delay is almost constant for lower frequencies but cannot be regarded constant over the entire frequency range of interest.

Table 1 shows the mean and maximum differences between the two calibration setups for all L-filter signals on all satellites. The differences presented are the ones obtained in the frequency range 5-10 Hz. The results are similar to the ones presented in Figure 2, with one exception: V3L on Cluster 3 shows very large differences between the two independent observations. The calibration results for this signal are presented in detail in Figure 3. The systematic difference between the two measurements is obvious and larger for larger frequencies. For reasons presented later in this report (cf. section 3.2.1) we believe that the calibration made with the setup for coverage of low frequencies are the correct one (blue curves in Figure 3).

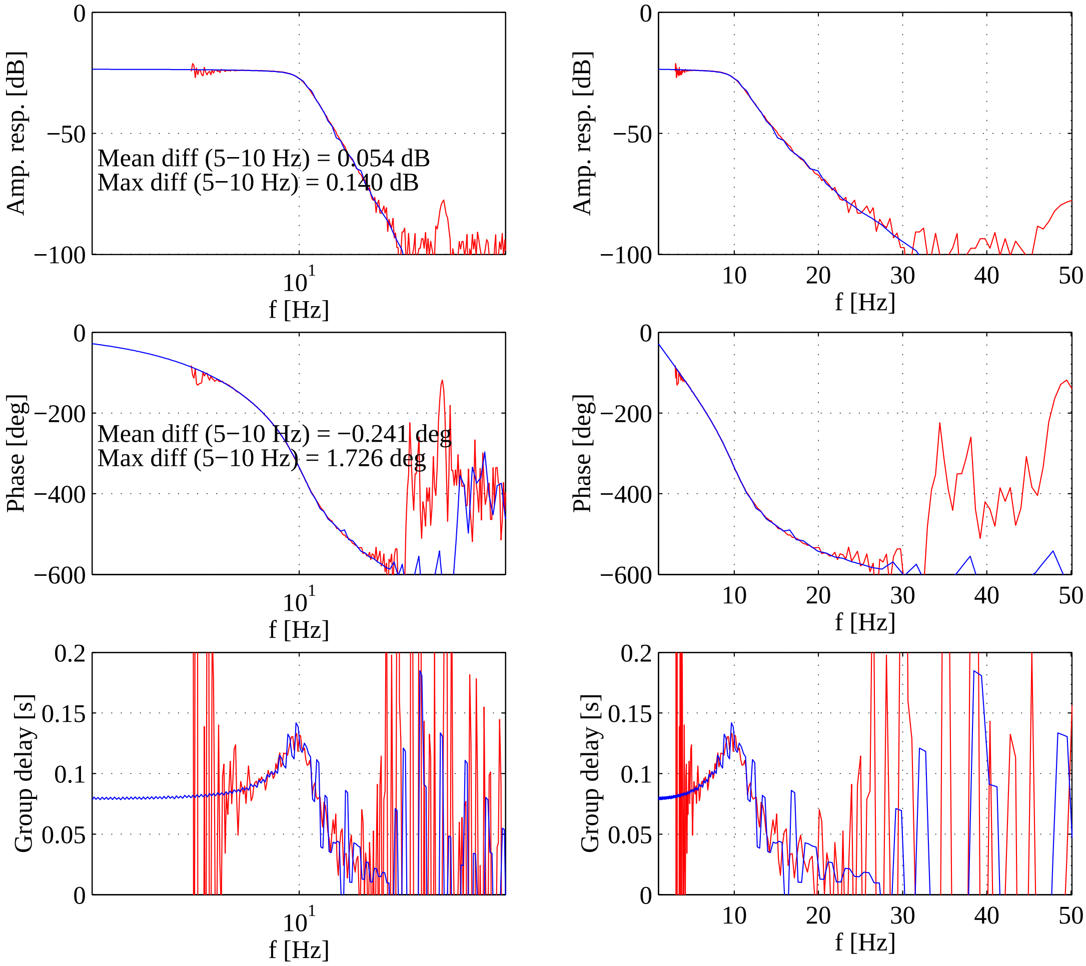

Figure 2: Typical calibration results for the L-filters (C1:V1L). The panels show amplitude and phase responses versus frequency. The two different curves in each panel correspond to the two different calibration setups. The group delay is computed from the phase response and is plotted versus frequency in the bottom panels. The results are shown both using a logarithmic frequency scale (left) and a linear one (right). Observe that the frequency ranges are different. The mean and maximum difference between the two curves in the frequency range 5-10 Hz are also presented.

From Table 1 we can also observe a tendency for larger differences both in amplitude and phase on Cluster 4 and for larger differences in phase on Cluster 3.

Figure 4 and Table 2 shows the corresponding results for the M-filter calibrations. In Figure 4 similar features as for the L-filters can be observed. The curves from the two independent tests are almost identical, except at frequencies well above the cut-off frequency of the filter, and at low frequencies, where we know that one of the setups is not reliable. The computed group delay peaks at the cut-off frequency.

Table 2 show the mean and maximum differences between the results from the two calibration setups, in the range 10-180 Hz, for all available medium-frequency signals on all satellites. The differences between the results from the two test setups are small, but show a clear systematic pattern. Mean differences in amplitude and phase have a positive sign for all signals on all spacecraft, with small standard

Quantity		Cluster 1	Cluster 2	Cluster 3	Cluster 4
V1L	Mean diff amp: (dB)	0.054± 0.055	0.092±0.053	0.008±0.067	0.217±0.0.086
	Mean diff phase: (deg)	-0.241± 0.579	-0.105±0.513	-0.120±0.752	-0.363±0.774
	Max diff amp: (dB)	0.140	0.166	0.127	0.349
	Max diff phase: (deg)	1.726	1.624	2.033	2.760
V2L	Mean diff amp:	0.040±0.074	0.091±0.031	0.040±0.064	0.154±0.063
	Mean diff phase:	-0.197±0.577	0.053±0.345	-0.335±0.640	-0.559±0.649
	Max diff amp:	0.154	0.156	0.159	0.270
	Max diff phase:	1.567	1.326	2.002	2.273
V3L	Mean diff amp:	0.035±0.075	0.105±0.049	**-0.663±0.215**	0.174±0.065
	Mean diff phase:	-0.127±0.731	0.121±0.507	**-20.951±4.279**	-0.578±0.692
	Max diff amp:	0.155	0.177	**1.246**	0.275
	Max diff phase:	1.908	1.640	**27.898**	2.509
V4L	Mean diff amp:	0.022±0.076	0.109±0.046	0.036±0.0.063	0.140±0.063
	Mean diff phase:	0.081±0.552	-0.114±0.484	-0.348±0.722	-0.488±0.680
	Max diff amp:	0.149	0.199	0.126	0.225
	Max diff phase:	1.352	1.584	2.382	2.446

Table 1: Differences between the results from the two setups for all probes and all spacecraft. Mean and maximum differences between the observed amplitude (dB) and phase (deg) responses are shown. Comparisons are made in the frequency range 5-10 Hz. The results from the different satellites and the different probes are similar with exception to the results from V3L on Cluster 3.The differences between the two calibration results for this particular signal are very large and are marked with boldface in the table.

deviations. It is also clear that the results for the different signals on the same satellite are more similar than when we compare all results. These systematic relationships between results from the two calibration setups are not as evident for the L-filter responses (cp. Table 1), but can be observed there as well. However, for the L-filters the mean phase difference is negative in most cases.

The only available observation on Cluster 4 (V1M) shows larger maximum differences and larger standard deviations than the other signals.

As a summary, typical mean and maximum differences in amplitude and phase for the different filters are shown below in Table 3. The values presented are the mean values of the results shown in Table 1 and 2, with the result from V3L on Cluster 3 excluded.

2.3 Conclusions

We believe that the calibration results accurately describe the amplitude and phase responses of the filters. We find that results from the calibration setup for coverage of low frequencies are the most reliable over the whole frequency range both for the L- and the M-filters. The summary results presented in Table 3 are a measure of the accuracy of the calibrations.

Large differences between results from the two different setups are found only in one case (C3: V3L, cp. Table 1 and Figure 3). This is probably due to a slight measurement failure. We believe that the calibration made with the setup suited for low frequencies is correct. There is also a slight tendency that the differences between the two calibration setups are larger for Cluster 4.

Quantity		Cluster 1	Cluster 2	Cluster 3	Cluster 4
V1M	Mean diff amp: (dB)	0.064± 0.020	0.147±0.016	0.009±0.012	**0.142±0.035**
	Mean diff phase: (deg)	0.351±0.050	0.234±0.067	0.164±0.047	**0.859±0.304**
	Max diff amp: (dB)	0.126	0.179	0.052	**0.219**
	Max diff phase: (deg)	0.469	0.347	0.308	**1.344**
V2M	Mean diff amp:	0.064±0.020	0.148±0.013	0.019±0.012	n/a
	Mean diff phase:	0.374±0.065	0.242±0.098	0.139±0.045	n/a
	Max diff amp:	0.119	0.178	0.066	n/a
	Max diff phase:	0.523	0.568	0.266	n/a
V3M	Mean diff amp:	0.066±0.019	0.138±0.016	0.0.017±0.012	n/a
	Mean diff phase:	0.359±0.059	0.224±0.068	0.154±0.051	n/a
	Max diff amp:	0.128	0.171	0.065	n/a
	Max diff phase:	0.479	0.344	0.318	n/a
V4M	Mean diff amp:	0.064±0.019	0.140±0.016	0.016±0.013	n/a
	Mean diff phase:	0.334±0.059	0.222±0.068	0.163±0.049	n/a
	Max diff amp:	0.123	0.169	0.067	n/a
	Max diff phase:	0.501	0.335	0.313	n/a
V12M (signal to probe 1)	Mean diff amp:	0.065±0.019	n/a	0.015±0.012	n/a
	Mean diff phase:	0.337±0.064	n/a	0.157±0.052	n/a
	Max diff amp:	0.125	n/a	0.058	n/a
	Max diff phase:	0.510	n/a	0.320	n/a
V12M (signal to probe 2)	Mean diff amp:	0.066±0.018	n/a	0.013±0.012	n/a
	Mean diff phase:	0.328±0.077	n/a	0.183±0.046	n/a
	Max diff amp:	0.124	n/a	0.058	n/a
	Max diff phase:	0.513	n/a	0.306	n/a
V34M (signal to probe 3)	Mean diff amp:	0.070±0.019	n/a	n/a	n/a
	Mean diff phase:	0.333±0.065	n/a	n/a	n/a
	Max diff amp:	0.127	n/a	n/a	n/a
	Max diff phase:	0.504	n/a	n/a	n/a
V34M (signal to probe 4)	Mean diff amp:	0.067±0.018	n/a	n/a	n/a
	Mean diff phase:	0.331±0.063	n/a	n/a	n/a
	Max diff amp:	0.122	n/a	n/a	n/a
	Max diff phase:	0.472	n/a	n/a	n/a

Table 2: Comparison between the two different measurements of the amplitude and phase responses for all M-filter signals. Mean and maximum differences between the two curves are computed in the frequency range 10-180 Hz. The amplitude differences are given in dB and the phase differences in deg. V1M on Cluster 4 show somewhat larger differences (marked with boldface).

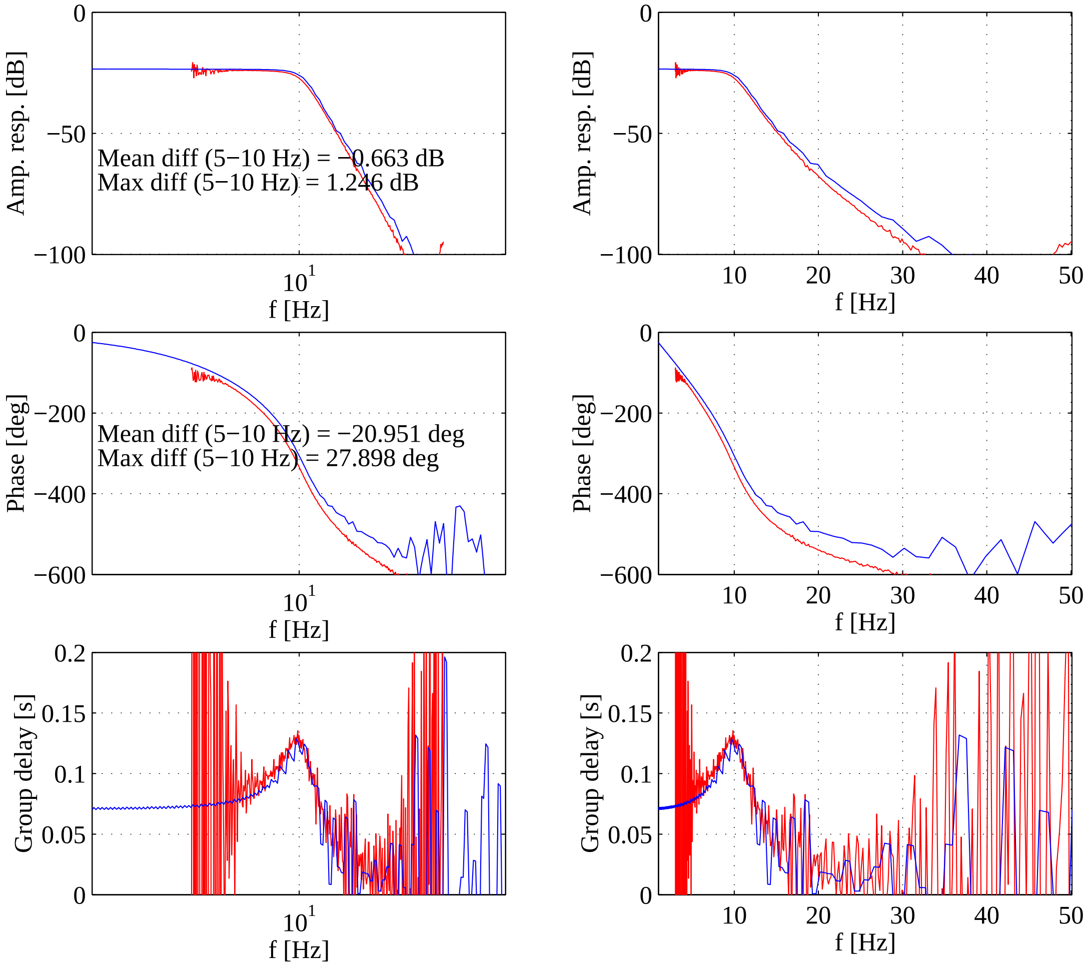

Figure 3: Calibration results for V3L on Cluster 3. The panels show amplitude and phase responses versus frequency. The two different curves in each panel correspond to the two different calibration setups. The group delay is computed from the phase response and is plotted versus frequency in the bottom panel. The results are shown both using a logarithmic frequency scale (left) and a linear one (right). The systematic difference between the two curves is obvious.

Summary		
10 Hz filter (5-10 Hz)	Mean difference in amplitude:	0.088 dB
	Mean difference in phase:	-0.221 deg
	Maximum difference in amplitude:	188 dB
	Maximum difference in phase:	1.942 deg
180 Hz filter (10-180 Hz)	Mean difference in amplitude:	0.070 dB
	Mean difference in phase:	0.289 deg
	Maximum difference in amplitude:	0.119 dB
	Maximum difference in phase:	0.460 deg

Table 3: Typical values from the comparisons between the different test setups. The presented numbers are obtained taking the mean values of the results in Table 1 and Table 2.

The variations in the group delay with a peak at the cut-off frequency of the filters clearly suggest that a frequency dependent calibration should be applied to the EFW data, rather then a simple time shift of the timeseries. To see this,

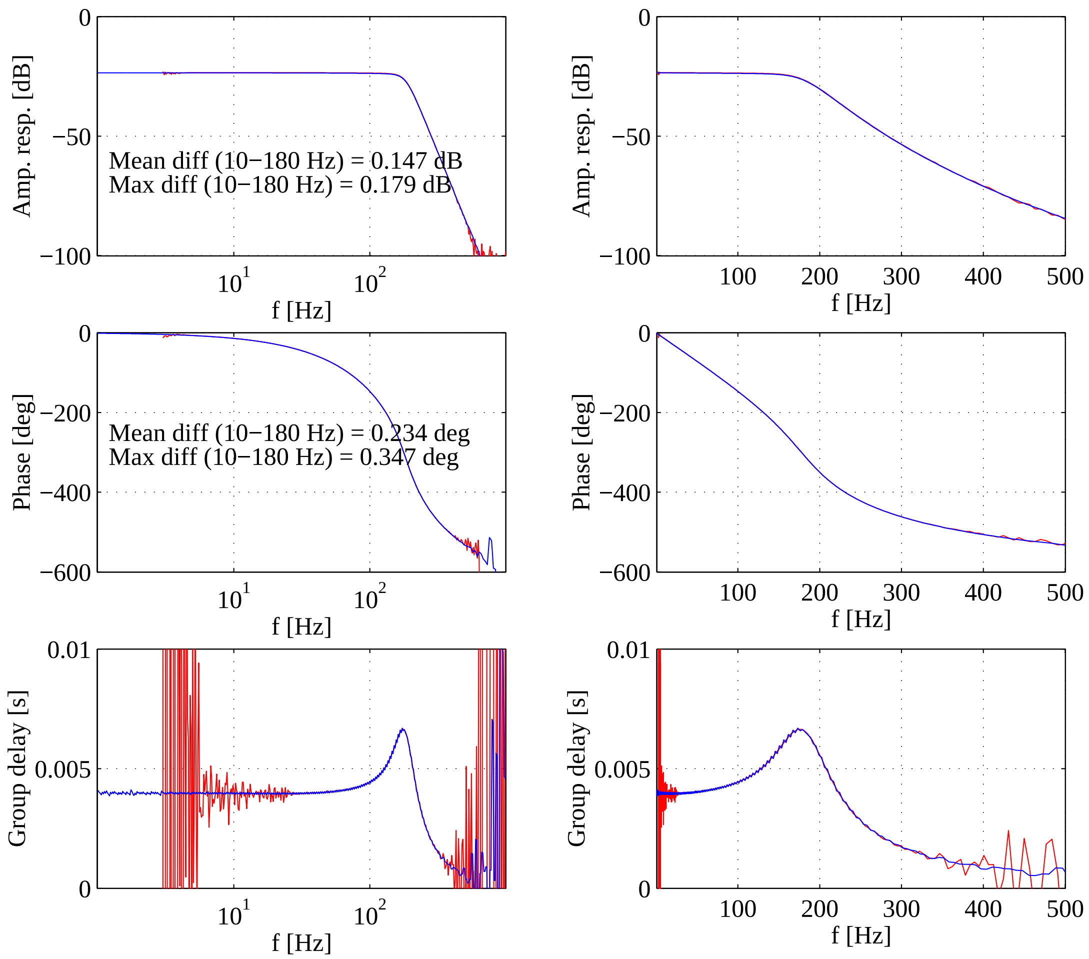

Figure 4: Typical calibration results for the M-filters. The panels show amplitude and phase responses versus frequency. The two different curves in each panel correspond to the results from the two different calibration setups. The group delay is computed from the phase response and is plotted versus frequency in the bottom panel. The results are shown both using a logarithmic frequency scale (left) and a linear one (right).

consider a 150 Hz signal. Assume that we use a time shift of 4 ms, suggested by the phase response at low frequencies. However, the correct time shift for the 150 Hz signal should be 6 ms. Hence, the error made in this case is $> 100°$, which of course is unacceptable.

3 Transfer functions

3.1 Introduction

The next step is to investigate if we can apply filter-specific transfer functions to the EFW data. That is, can we use, for example, one transfer function for all L-filter signals. Hence, we compare the calibrations from all probes and all spacecraft for each filter type.

3.2 Results

3.2.1 L-filters

We compare the L-filter results obtained using the results from the calibration setup suitable for coverage of low frequencies. Figure 5 show all the available 16

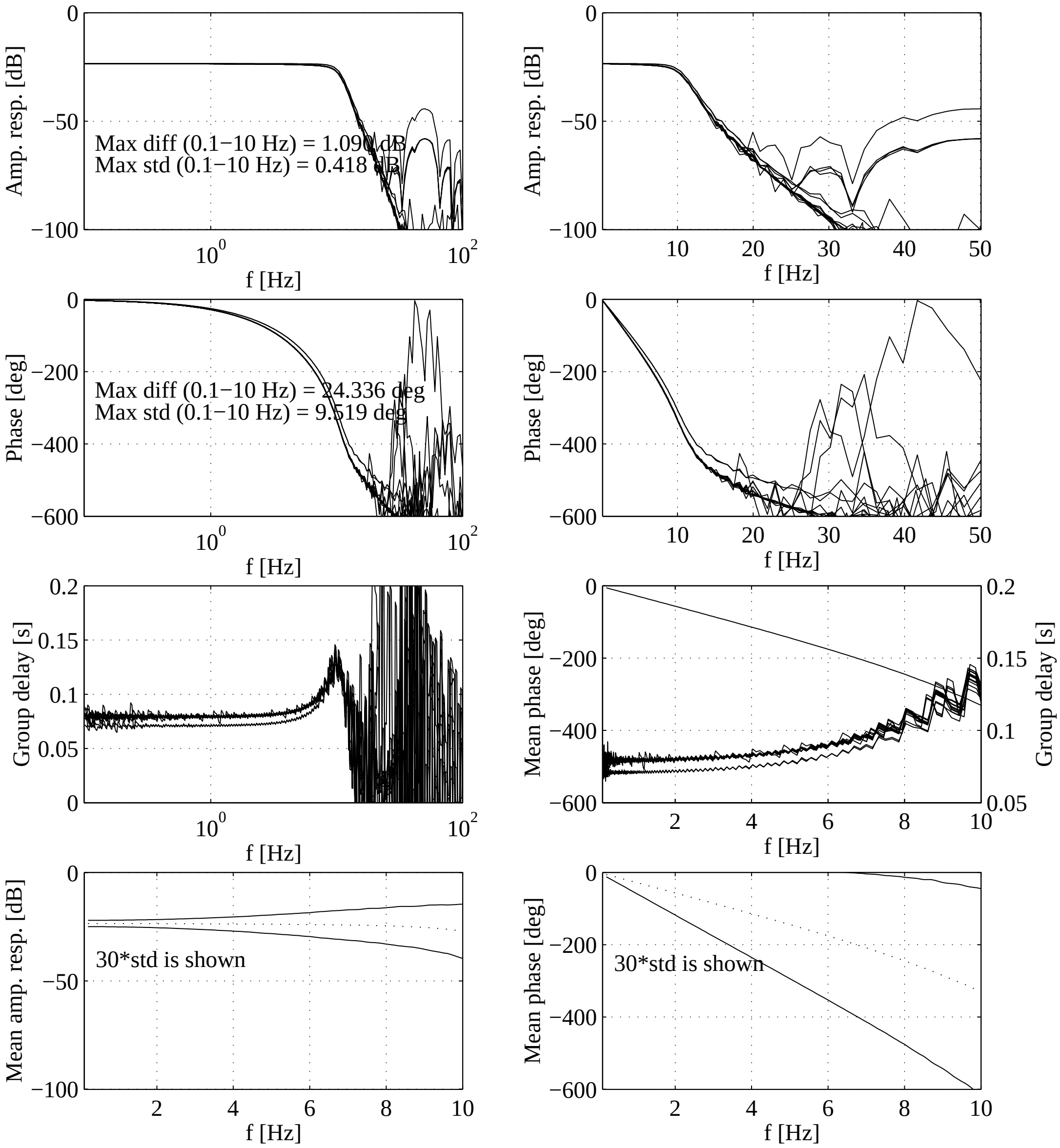

Figure 5: All L-filter calibration results. The panels show amplitude and phase responses as well as group delay versus frequency. The different curves in each panel correspond to the different signals. The results are shown both using a logarithmic frequency scale (left) and a linear one (right). The bottom panels show the mean transfer function (amplitude and phase) computed from the different signals. The standard deviation (multiplied with 30) is also shown.

calibrations. There are obviously two "branches" of curves, giving rise to large deviations from mean. The bottom panels show the mean function computed from the different signals and the standard deviation (multiplied by 30). It is clear that the differences are larger at larger frequencies. A closer analysis reveals that two signals are responsible for one of the branches. Excluding V1L and V3L from Cluster 3, the curves are almost on top of each other. V3L can be included if we instead use the second calibration made (with the setup suited for higher frequencies). Remember the large differences between the two observations in this particular case (cf. Figure 3). However, we still think the calibration made with the setup suited for low frequencies is the correct one. Some filters were actually changed during the construction phase of EFW, and as the filters come in pairs it is more probable that two filters are different from the other than just one. This assumption should, however, be further investigated.

The results from comparing the L-filters (excluding C3:V1L,V3L) are summarized in Table 4, together with the results from the other filters. Since the standard deviation is frequency dependent (as can be seen from Figure 5) we present the mean and maximum standard deviation in the frequency range 0.1-10 Hz.

3.2.2 M-filters

When comparing the different M-filters we also use the results from the setup suited for low frequencies. Figure 6 show the result of the comparison. All calibration results are plotted on top of each other and they look very similar except for frequencies well above the cut-off frequency, 180 Hz. Note that both the single-probe and the double-probe signals calibrated with the same setup are included, totally 21 different signals. Note also that some signals are only calibrated with the second test setup.

As in the L-filter case we compute a mean function, this time for frequencies between 10-180 Hz, with a resolution of 0.5 Hz. The standard deviation is computed at each of these points. The mean and maximum standard deviation in the specified frequency range, together with the maximum differences from the mean function are given in Table 4.

3.2.3 H-filters

For the H-filters only one calibration setup is available. The single-probe signals use the low-pass filter at 4 kHz. All 16 signals are compared in Figure 7. The difference between the transfer functions must be regarded small. The group delay does not show the same clear peak at the cut-off frequency as for the previous filter types, but varies slightly over the frequency range of interest.

The double-probe signals use the 8 kHz bandpass filter which give different amplitude and phase responses as can be seen from Figure 8. The different filters seem similar and the mean function is computed in the frequency range 50-8 000 Hz. It is obvious that the calibrations in the frequency domain is needed, as both the amplitude response and the group delay vary in the relevant frequency range.

The H-filter comparison results are summarized in Table 4.

3.2.4 U-filters

For the highest-frequency band we have only one calibration setup. The results from comparing all signals are shown in Figure 9. Comparisons are made from 100 Hz to 32 kHz. These tests show larger deviations. Primarily, C3:V1U, C3:V4U and C2:V4U are responsible for these deviations, but even with these removed, some differences between the calibrations remain as can be seen from Table 4.

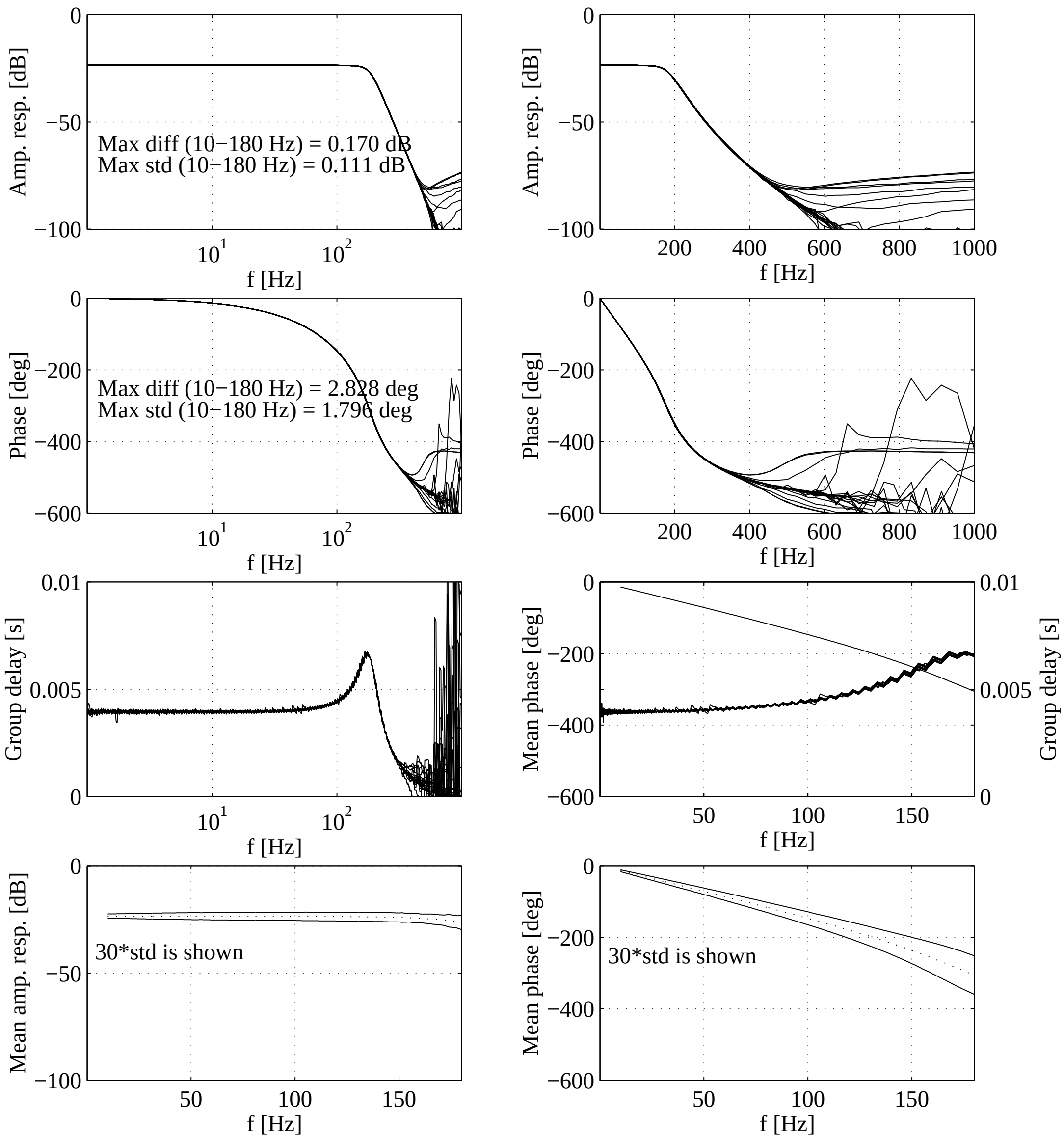

Figure 6: All M-filter calibration results. The panels show amplitude and phase responses as well as group delay versus frequency. The different curves in each panel correspond to the different signals. The results are shown both using a logarithmic frequency scale (left) and a linear one (right). The bottom panels show the mean transfer function (amplitude and phase) computed from the different signals. The standard deviation (multiplied with 30) is also shown. Note that both single-probe and double-probe calibrations are included.

A summary for all the different filter types is provided in Table 4, where the maximum deviations from the mean function are presented, together with the mean and maximum standard deviation in the specified frequency range. All the dubious signals are removed when computing these numbers.

The results presented in Table 4 can be compared with the ones in Table 5, where only the signals on the same satellite are compared. We observe that the deviations from mean are slightly smaller as expected.

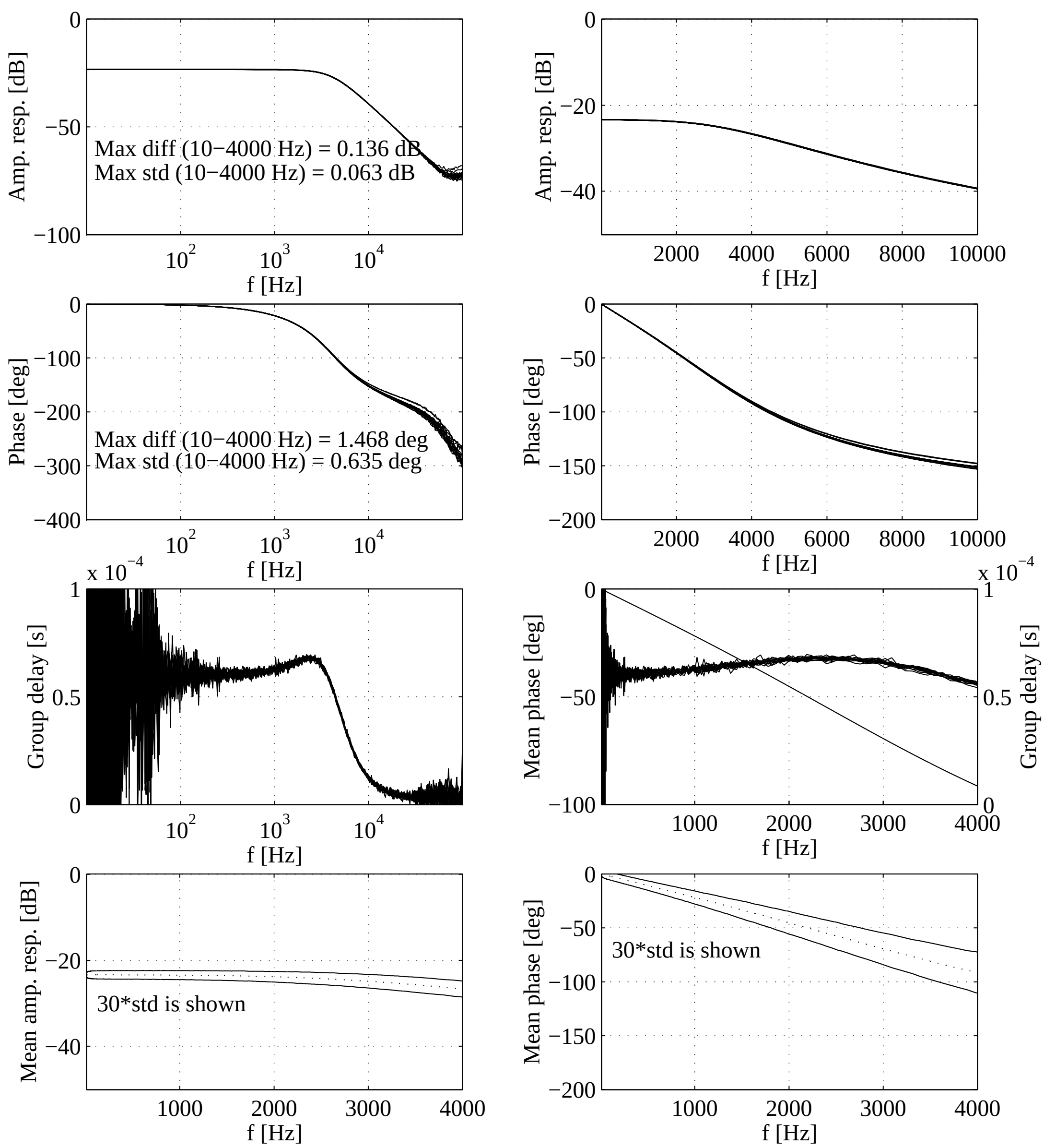

Figure 7: All H-filter single-probe results. The panels show amplitude and phase responses as well as group delay versus frequency. The different curves in each panel correspond to the different signals. The results are shown both using a logarithmic frequency scale (left) and a linear one (right). The bottom panels show the mean transfer function (amplitude and phase) computed from the different signals. The standard deviation (multiplied with 30) is also shown.

3.3 Conclusions

With a few exceptions the filter responses seem very similar. The exceptions are the L-filter signals V1L and V3L on Cluster 3 and the U-filters signals V1U and V4U on Cluster 3 as well as V4U on Cluster 2.

The 8 kHz bandpass filters are as expected very different from the low pass filters. To scientifically use EFW data from these filters a frequency domain calibration must be used regardless of the science of interest. Both the amplitude and group delay vary considerable.

We can probably use a mean transfer function for all the signals from a specific

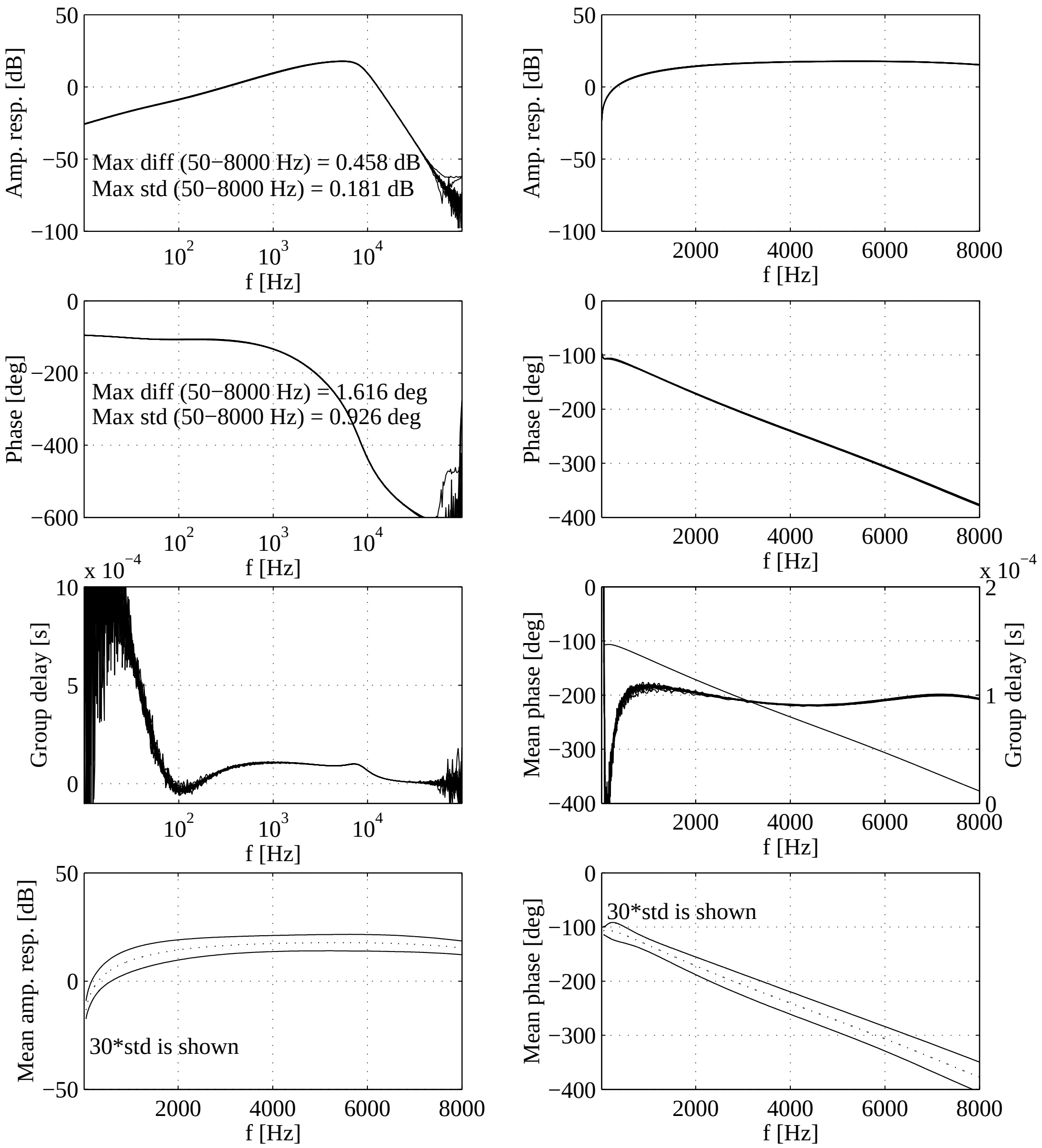

Figure 8: All H-filter double-probe results. The panels show amplitude and phase responses as well as group delay versus frequency. The different curves in each panel correspond to the different signals. The results are shown both using a logarithmic frequency scale (left) and a linear one (right). The bottom panels show the mean transfer function (amplitude and phase) computed from the different signals. The standard deviation (multiplied with 30) is also shown.

filter type. However, a different transfer function for the two different L-filters might be useful. The filters on respective satellite are more similar than when we compare all filters. If necessary, we can increase the accuracy of the calibration by using different transfer functions for different spacecraft.

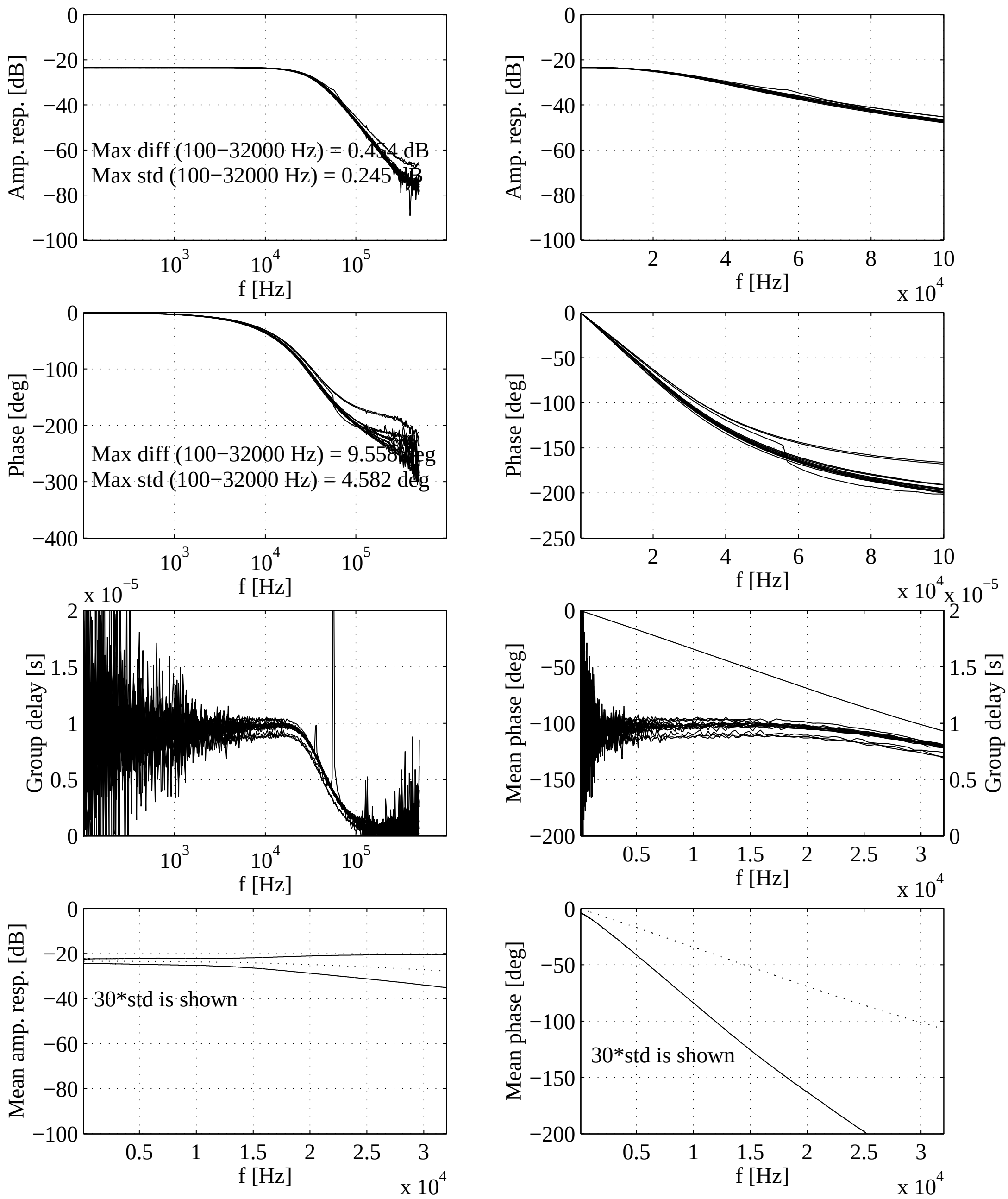

Figure 9: All U-filter calibration results. The panels show amplitude and phase responses as well as group delay versus frequency. The different curves in each panel correspond to the different signals. The results are shown both using a logarithmic frequency scale (left) and a linear one (right). The bottom panels show the mean transfer function (amplitude and phase) computed from the different signals. The standard deviation (multiplied with 30) is also shown.

4 Comparison between filters

4.1 Introduction

It is also interesting to compare the L- and M-filters. The two filters have the same design but different cut-off frequencies and their transfer functions should show the same characteristics. To compare the filters we multiply the frequencies from the L-filter calibrations by a factor, ideally equal to 18, and plot these calibrations

Summary		
L-filters (0.1-10 Hz)	Maximum difference in amplitude:	0.157 dB
	Mean standard deviation amplitude:	0.076 dB
	Maximum standard deviation amplitude:	0.041 dB
	Maximum difference in phase:	1.912 deg
	Mean standard deviation phase:	0.374 deg
	Maximum standard deviation phase:	0.915 deg
M-filters (10-180 Hz)	Maximum difference in amplitude:	0.170 dB
	Mean standard deviation amplitude:	0.062 dB
	Maximum standard deviation amplitude:	0.111 dB
	Maximum difference in phase:	2.828 deg
	Mean standard deviation phase:	0.704 deg
	Maximum standard deviation phase:	1.796 deg
H-filters, 4 kHz (10-4000 Hz)	Maximum difference in amplitude:	0.136 dB
	Mean standard deviation amplitude:	0.044 dB
	Maximum standard deviation amplitude:	0.063 dB
	Maximum difference in phase:	1.468 deg
	Mean standard deviation phase:	0.350 deg
	Maximum standard deviation phase:	0.635 deg
H-filters, 8 kHz (50-8000 Hz)	Maximum difference in amplitude:	0.458 dB
	Mean standard deviation amplitude:	0.137 dB
	Maximum standard deviation amplitude:	0.181 dB
	Maximum difference in phase:	1.616 deg
	Mean standard deviation phase:	0.665 deg
	Maximum standard deviation phase:	0.926 deg
U-filters (100-32 000 Hz)	Maximum difference in amplitude:	0.383 dB
	Mean standard deviation amplitude:	0.103 dB
	Maximum standard deviation amplitude:	0.205 dB
	Maximum difference in phase:	4.366 deg
	Meam standard deviation phase:	1.239 deg
	Maximum standard deviation phase:	1.888 deg

Table 4: Maximum differences from mean as well as mean and maximum standard deviation in the specified frequency ranges for the different filters. In the comparisons all available probes on all spacecraft are used. However, all dubious signals are removed. Hence, for the L-filters, V1L and V3L on Cluster 3 are excluded, and for the U-filters V1U and V4U on Cluster 3 as well as V4U on Cluster 2 are excluded.

together with the M-filter calibrations.

4.2 Results

We are using results from the same calibration setups as in the previous sections. If the filters are ideal we could simply multiply the frequencies from the L-filter responses with 18 and they would look exactly like the M-filter responses. The result from such a comparison is shown in Figure 10. All available single-probe signals are used.

There are considerable differences, especially in the phase response. These differences are not due to the different C3:V1L and C3:V3L results. Rather the opposite; the difference between the M-filter signals and C3:V1L and C3:V3L is much smaller than the difference between the M-filters and the other L-filters signals. Figure 11 shows the comparison between only C3:V1L and C3:V3L, and the M-filter signals. The agreement is obviously very good.

L-filters on different spacecraft, 0.1-10 Hz						
Quantity		**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Comments**
VxL	Max diff amp: (dB)	0.082	0.095	**0.618**	0.101	Diffs due to
	Mean std amp: (dB)	0.015	0.012	**0.250**	0.024	C3:V1,V3
	Max std amp: (dB)	0.064	0.065	**0.640**	0.080	
	Max diff phase: (deg)	0.928	0.864	**13.954**	0.876	
	Mean std phase: (deg)	0.268	0.162	**7.956**	0.330	
	Max std phase: (deg)	0.638	0.596	**15.262**	0.682	

M-filters on different spacecraft, 10-180 Hz						
Quantity		**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Comments**
VxM,	Max diff amp:	0.046	0.010	0.035	n/a	C4: Results
VxyM	Mean std amp:	0.009	0.006	0.014	n/a	are not
	Max std amp:	0.043	0.009	0.031	n/a	available with
	Max diff phase:	0.892	0.120	0.746	n/a	the same setup.
	Mean std phase:	0.303	0.044	0.189	n/a	C2: Only VxM
	Max std phase:	0.828	0.104	0.605	n/a	signals.

H-filters (4 kHz) on different spacecraft, 10-4000 Hz						
Quantity		**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Comments**
VxH	Max diff amp:	0.069	0.050	0.040	0.061	
	Mean std amp:	0.026	0.019	0.012	0.022	
	Max std amp:	0.062	0.045	0.028	0.043	
	Max diff phase:	0.703	0.945	1.388	0.558	
	Mean std phase:	0.335	0.331	0.431	0.281	
	Max std phase:	0.493	0.688	0.947	0.463	

H-filters (8 kHz) on different spacecraft, 50-8000 Hz						
Quantity		**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Comments**
VxyH	Max diff amp:	0.175	0.254	0.069	0.098	
	Mean std amp:	0.070	0.133	0.034	0.036	
	Max std amp:	0.153	0.224	0.058	0.069	
	Max diff phase:	1.001	1.426	0.371	0.354	
	Mean std phase:	0.764	0.512	0.119	0.180	
	Max std phase:	1.113	1.089	0.258	0.375	

U-filters on different spacecraft, 100-32000 Hz						
Quantity		**Cluster 1**	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Comments**
VxU	Max diff amp:	0.272	0.486	0.159	0.281	Diffs due to
	Mean std amp:	0.084	0.141	0.051	0.080	C2:V4
	Max std amp:	0.192	0.382	0.126	0.226	C3:V1,V4
	Max diff phase:	2.240	**6.797**	**5.625**	3.776	
	Mean std phase:	1.107	**2.715**	**2.891**	1.630	
	Max std phase:	1.508	**4.679**	**5.650**	2.862	

Table 5: Comparison between calibration results from the different spacecraft for each filter. For comparisons between L- and M-filter signals we use the calibrations made with the setup suitable for low frequency coverage. The amplitude differences are given in dB and the phase differences in deg.

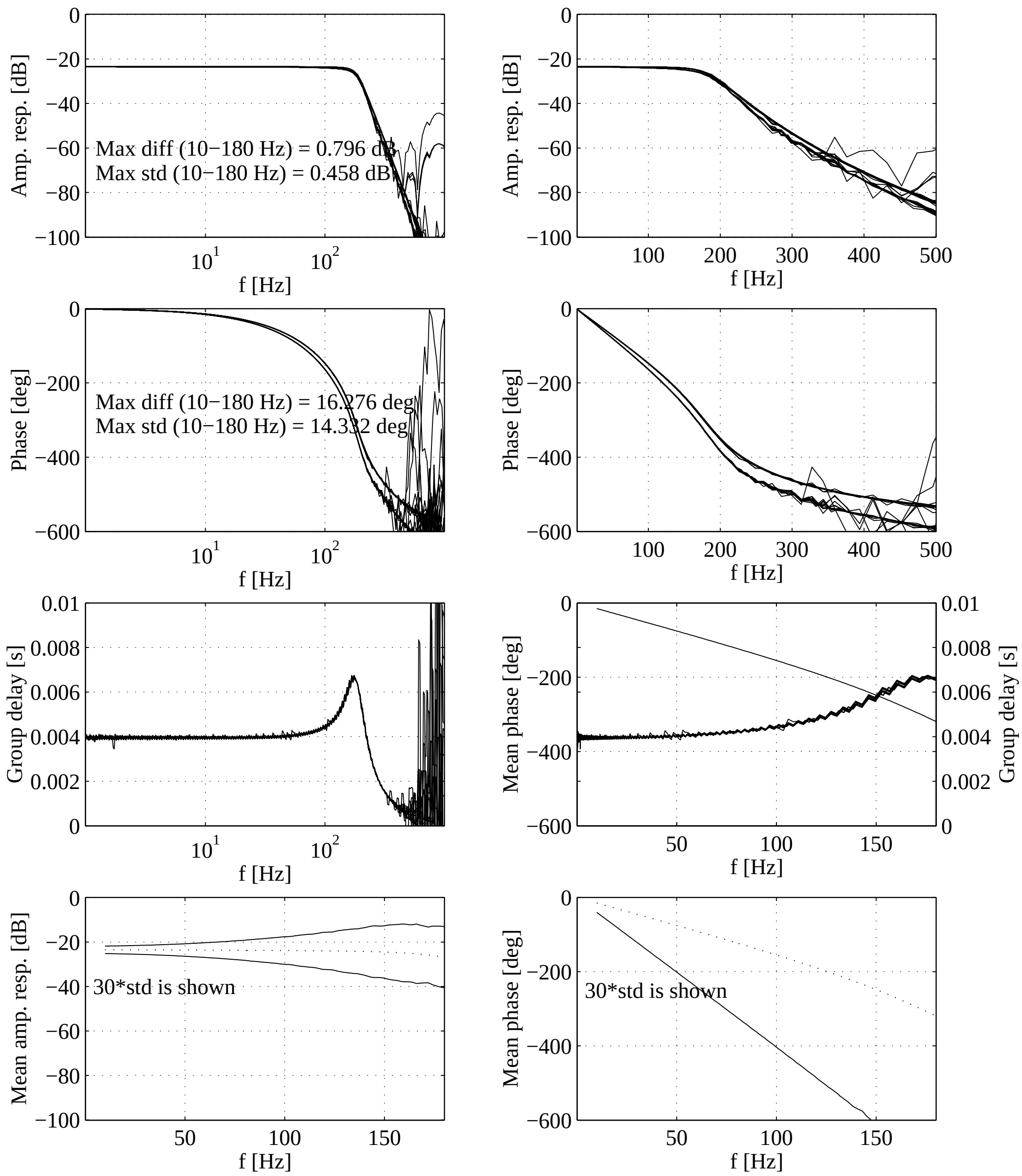

Figure 10: All calibrations of the single-probe L- and M-filter signals shown together. For the L-filter responses the frequencies are multiplied by 18. The different panels show amplitude, phase and group delay as functions of frequency, both using a logarithmic frequency axis (left) and a linear one (right). In the bottom panels the computed mean function is shown together with the standard deviation (multiplied by 30).

If we return to the other L-filter signals, what factor should they be multiplied with to minimize the difference between them and the M-filter signals? If we minimize the maximum difference in phase in the frequency range 10-180 Hz, we find that we should multiply with 19.2 instead of 18. Figure 12 shows this case. To achieve the closest fit for the amplitude response the factor to multiply with is somewhat smaller, but still considerably larger than 18. Note though that the shape of the curves are still different, which is especially obvious at larger frequencies. Compare with Figure 11, where the shapes of the curves are much

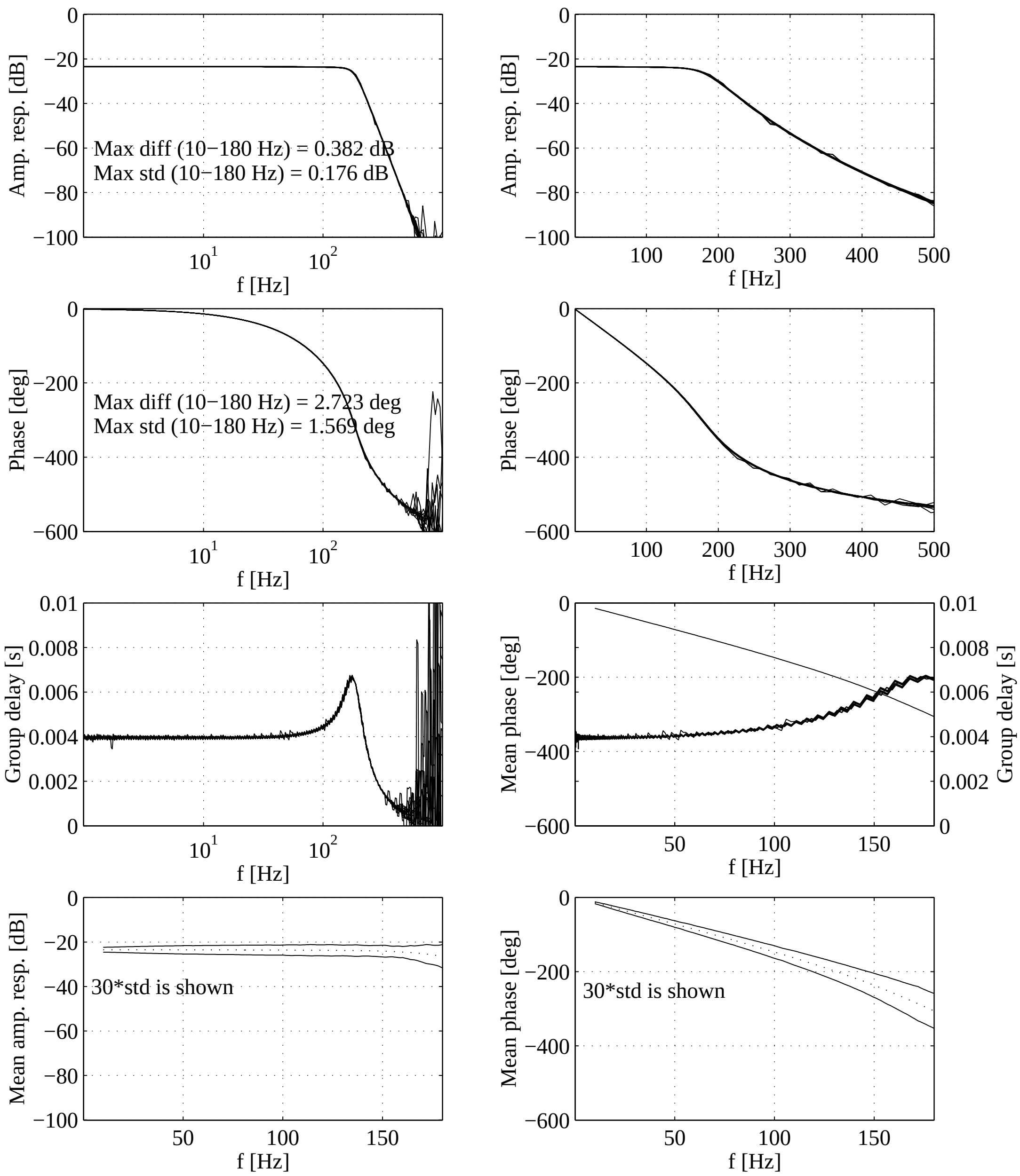

Figure 11: The C3:V1L and C3:V3L signals together with all single-probe M-filter signals. For the two L-filter signals the frequencies are multiplied with 18. Panels are the same as in Figure 10.

more similar.

4.3 Conclusions

The results show that the L- and M-filters are very similar. The two L-filters C3:V1L and C3:V3L are more similar to the M-filters then the other L-filters. The analysis indicates that nothing is wrong with the C3:V1L and C3:V3L filters; they are just different. That the factor is different from 18 for most of the L-filters is not surprising. This factor is determined by the specific values of the components within the filters.

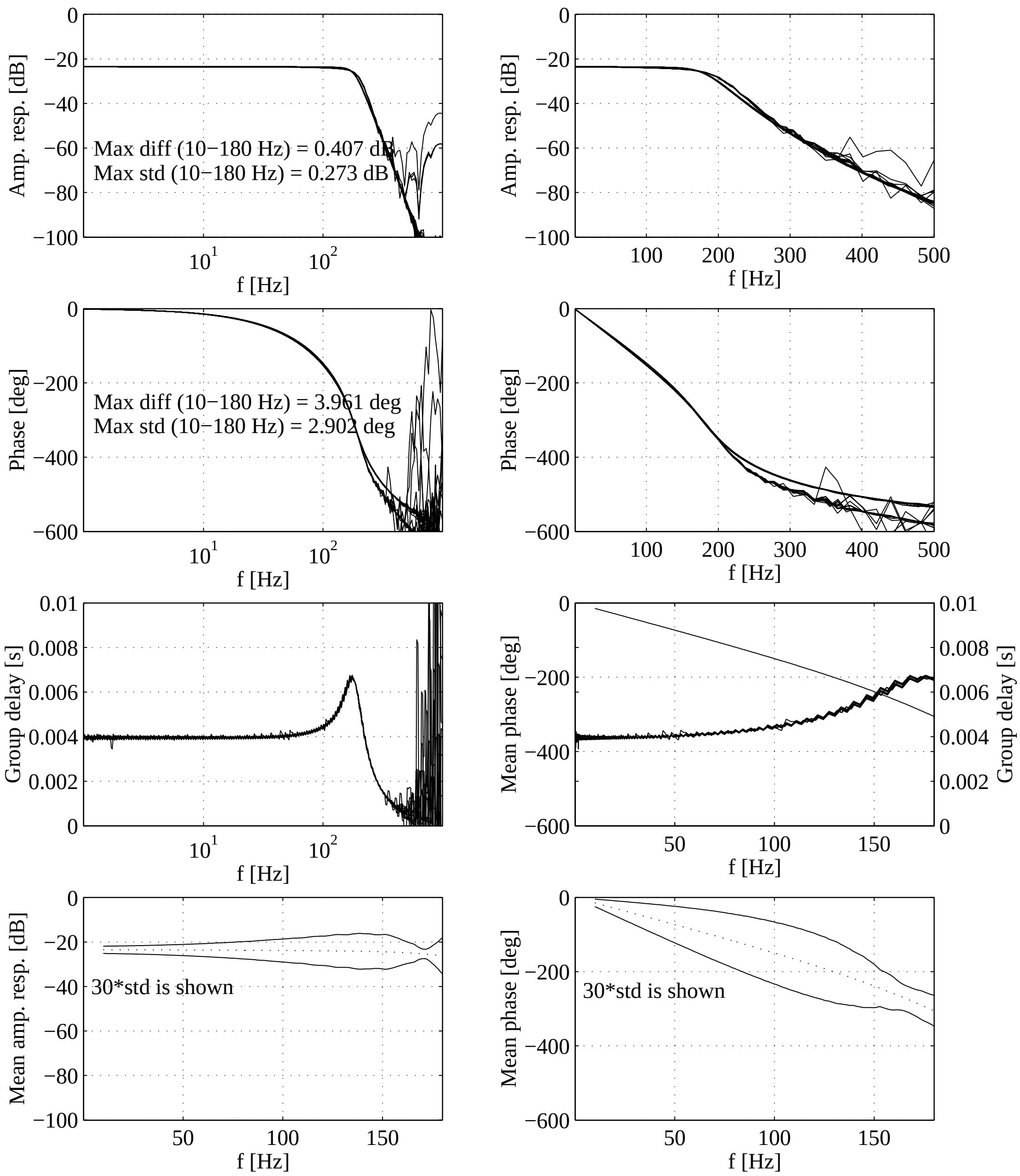

Figure 12: All L-filter signals but C3:V1L and C3:V3L together with the single-probe M-filter signals. The frequencies for the L-filter signals are multiplied with 19.2 in order to minimize the maximum difference in phase from the mean function. All panels are the same as in Figure 10.

5 Conclusions

First we can state that the calibrations are very accurate. Two independent observations give virtually the same results. From the observed transfer functions it is immediately clear that there is a need for calibrations in the frequency domain, at least if the phase response is important. The estimated group delay is generally not constant over the entire frequency range of interest and, hence, a time shift is not enough to compensate for the filters. However, depending on the application, a time shift might still be reasonable in some cases.

We conclude that all filters are behaving according to specifications and that all filters of a certain type is very similar. Hence, in most cases and for most applications it is accurate to describe all filters of the same type with the same transfer function. However, from the detailed analysis of the filter calibrations, we observe that two of the L-filters (C3:V1L and C3:V3L) seem to be different from the other L-filters (cp. Figure 5). Therefore, we suggest a separate transfer function to be used for these two signals.

The two different L-filter transfer functions are shown in Figure 13 (most of the L-filters) and Figure 14 (C3:V1L and C3:V3L). The presented transfer functions are obtained by resampling the calibrations to the frequencies used in the STAFF calibration files, using linear interpolation. At each frequency we then average over all available signals and finally we average over 5 points in the frequency domain to smooth the curves. Figure 13 and Figure 14 show the amplitude response (in dB, upper panel) and the phase response (in deg, middle panel) as well as the group delay computed from the phase response curve (in s, bottom panel). In the upper panel the horizontal dash-dot line indicates -3 dB from maximum value of the amplitude response, defining the cut-off frequency of the filter.

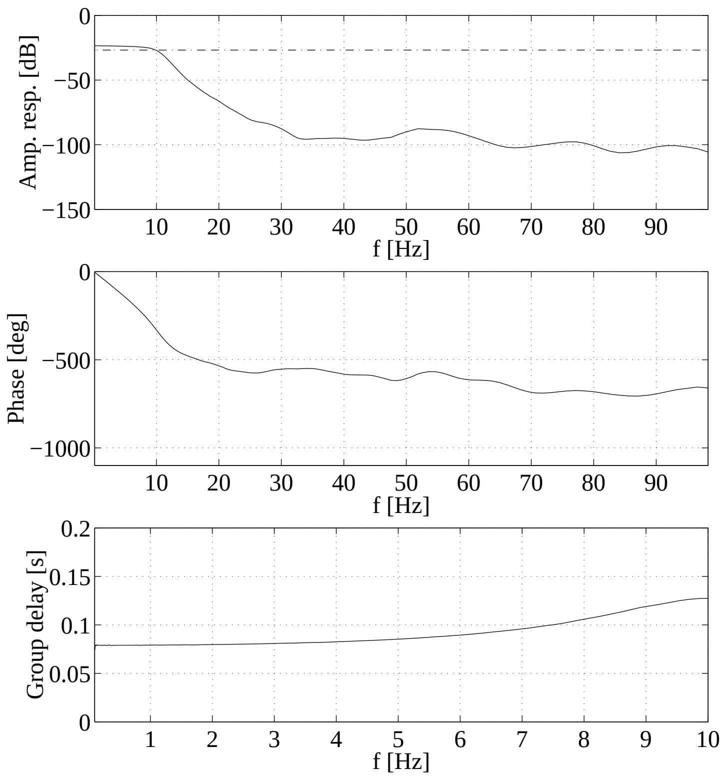

Figure 13: The transfer function describing the response of the L-filters on all probes and all spacecraft, with exception to the signals V1L and V3L on Cluster 3. The top panel show the amplitude response (in dB) versus frequency. The horizontal dash-dot line indicated the -3 dB level giving the cut-off frequency. The phase response in presented in the middle panel. Although the cut-off frequency is 10 Hz we present the transfer function for frequencies up to 100 Hz as is done in calibration files used by STAFF. The bottom panel show the group delay below the cut-off frequency computed from the phase response presented in the panel above.

All M-filters are very similar up to frequencies well above the cutoff-frequency. The same is true for the two different H-filters (low pass 4 kHz and bandpass 50 Hz-8 kHz). We suggest using one transfer function for each of these filter types.

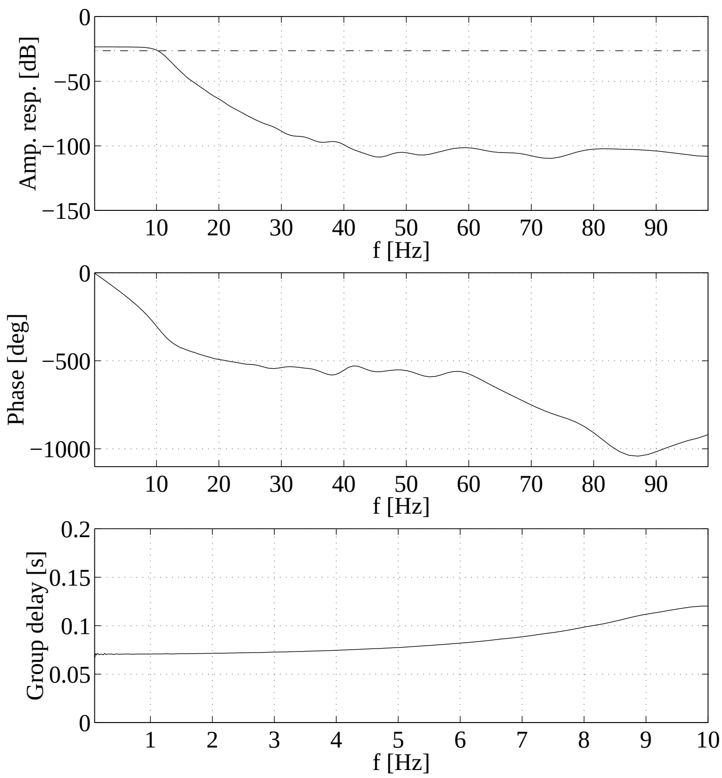

Figure 14: The transfer function describing the response of the L-filters for the signals V1L and V3L on Cluster 3, which are believed to be different from the other L-filters. Panels are the same as in Figure 13.Note that the frequency scale in the bottom panel is different from that in the two upper panels.

The differences between the probes and the spacecraft are small enough to be neglected. The transfer functions are computed in the same way as the L-filter transfer functions. For the M-filters we resample to STAFF frequencies, average over all available calibration at each frequency and finally average in frequency. For the H-filters we resample in order to get 400 frequencies between 10 and 4000, logarithmically spaced. The averaging procedure is the same as described for the L- and M-filters. The resulting transfer functions are displayed in Figure 15, Figure 16 and Figure 17. All panels are similar to those presented for the L-filters above.

For the U-filters the situation is somewhat different. The amplitude response is similar on all probes and spacecraft, but the phase response show some differences between different signals as can be seen from Figure 9. However, the maximum sampling rate used is 18 000 samples/s and thus, the response of the filter at frequencies above 10 kHz can be neglected. There are differences between the filters at lower frequencies as well and some caution must be taken, especially if the exact phase response is important. We choose, however, to compute one common transfer function for the U-filters as well. The result is shown in Figure 18.

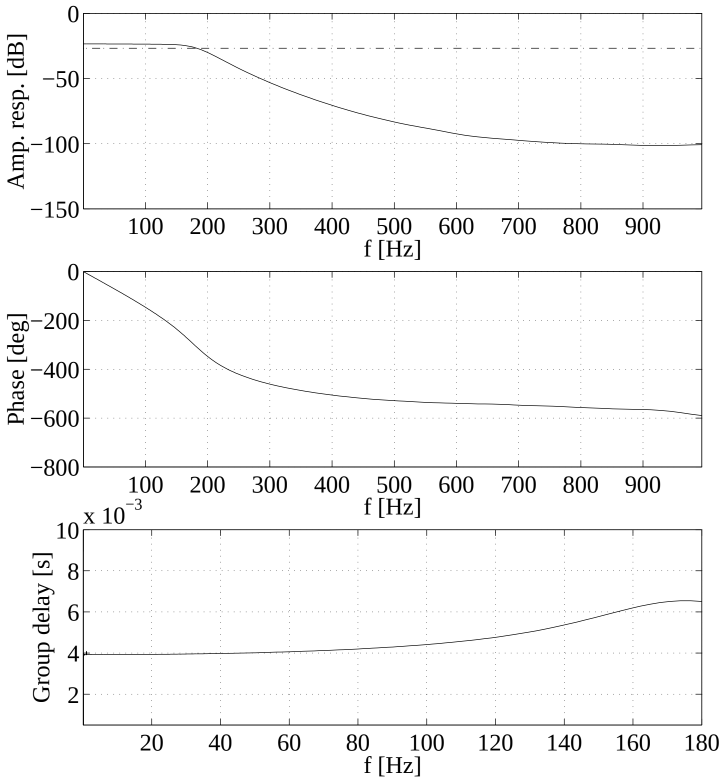

Figure 15: The transfer function describing the response of the M-filters on all probes and all spacecraft. All panels are the same as in Figure 13

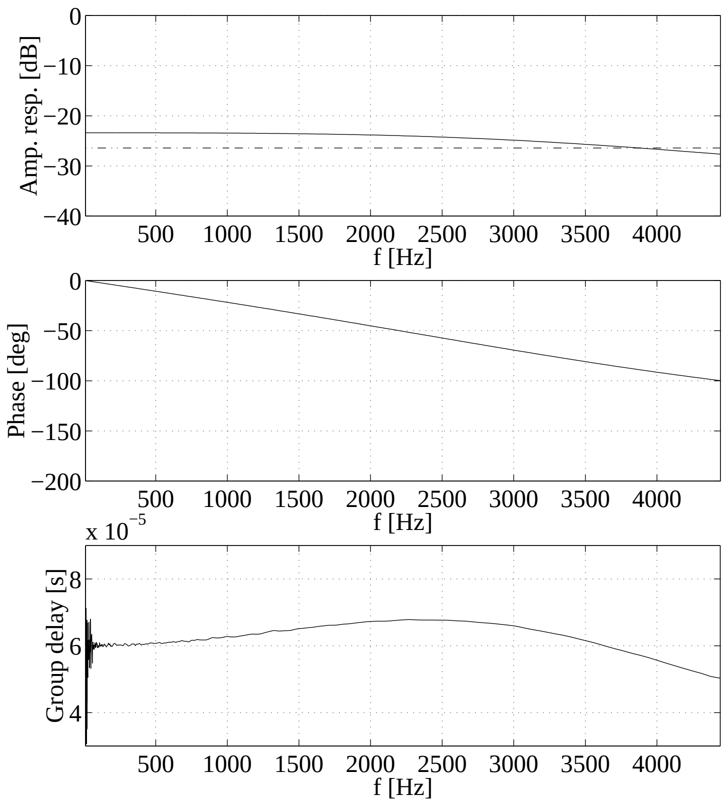

Figure 16: The transfer function describing the response of the H-filters used for single-probe signals (low pass 4 kHz) on all probes and all spacecraft. All panels are the same as in Figure 13

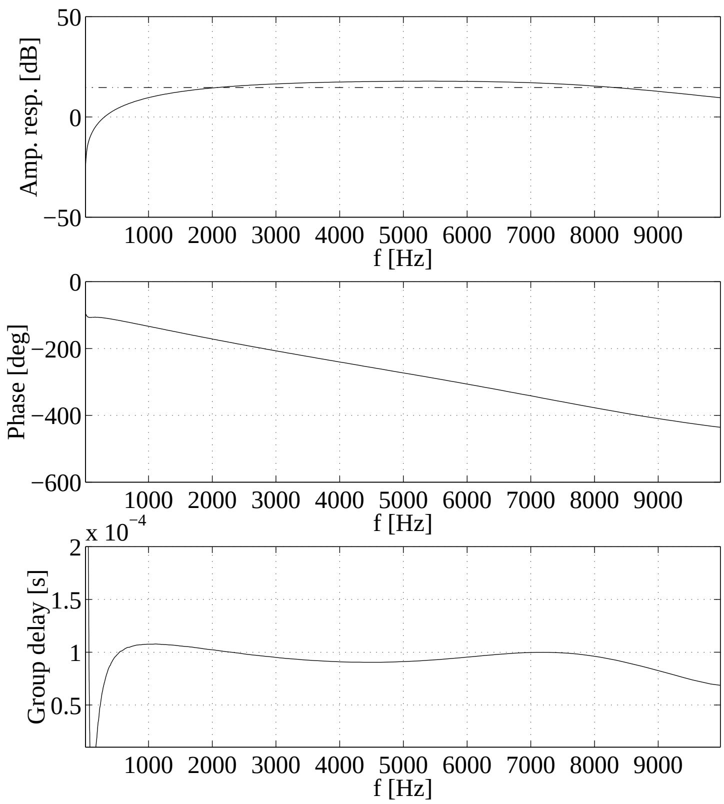

Figure 17: The transfer function describing the response of the H-filters used for double-probe signals (bandpass 50 Hz-8 kHz) on all probes and all spacecraft. All panels are the same as in Figure 13

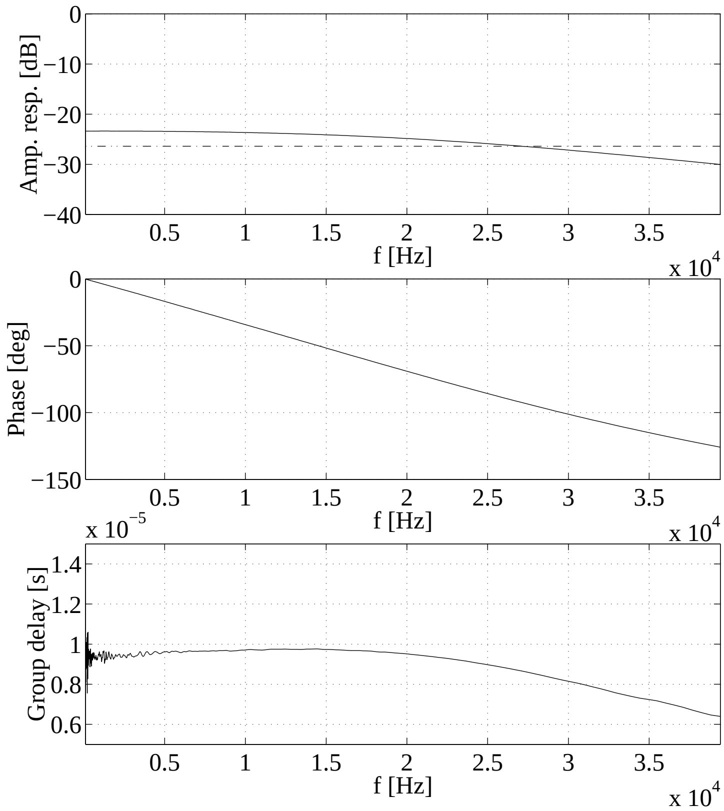

Figure 18: The transfer function describing the response of the U-filters used on all probes and all spacecraft. All panels are the same as in Figure 13.