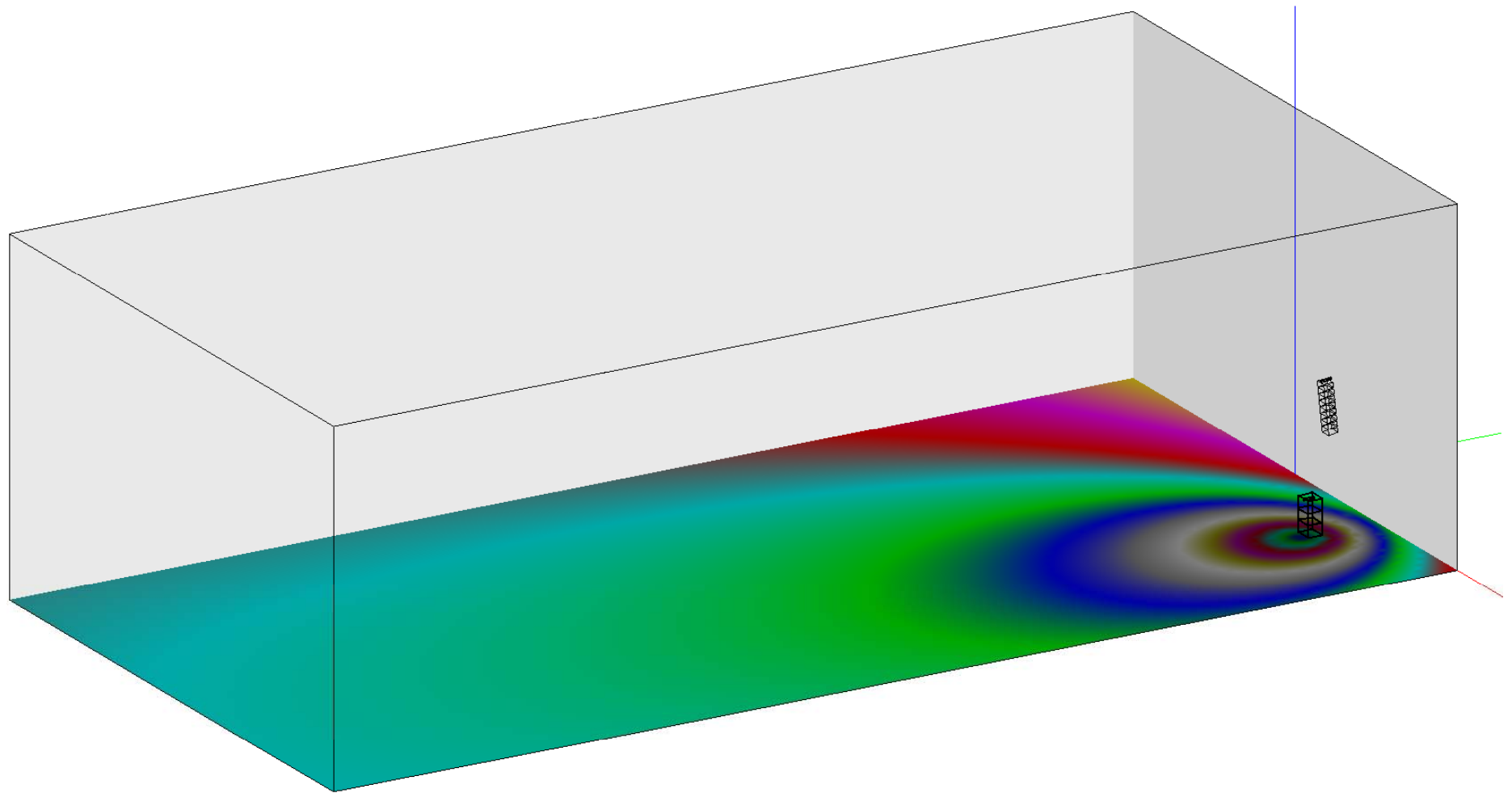# Subwoofer Alignment with a Full-Range System
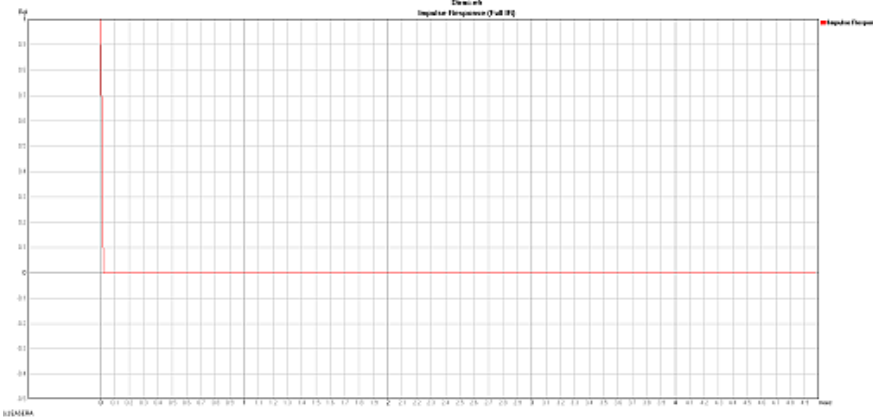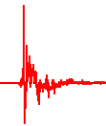
Initial Arrival Time

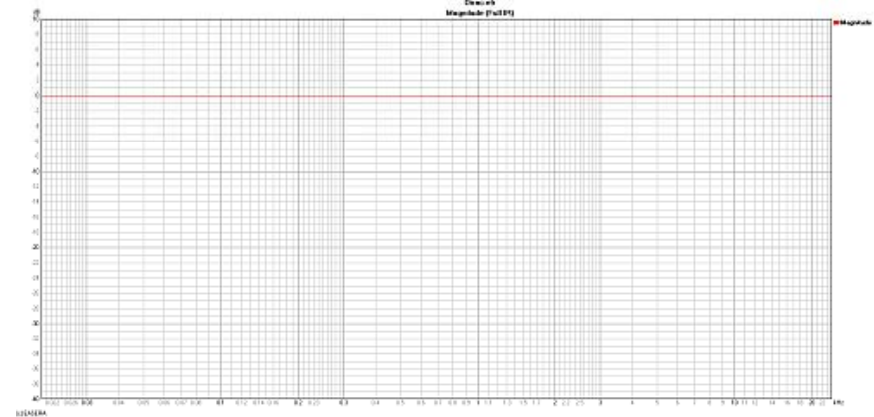All of these IRs have the same initial arrive time, 5 ms

Target Response

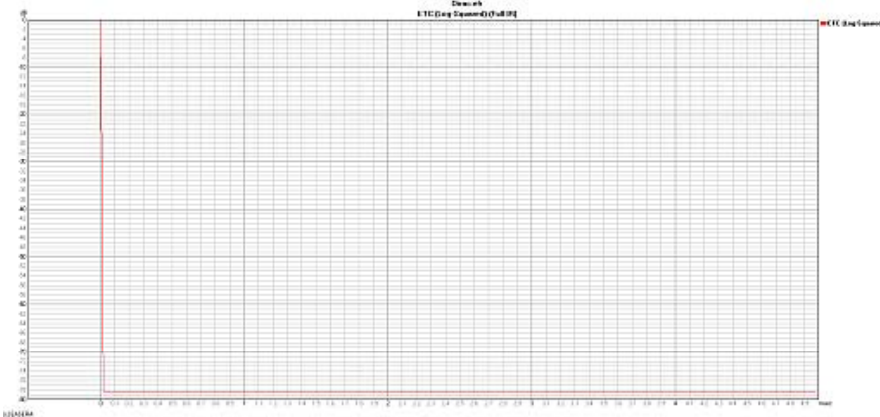Perfect impulse at time t=0

Impulse Response

Magnitude Response (Frequency)

ETC Response (Envelope Time Curve)
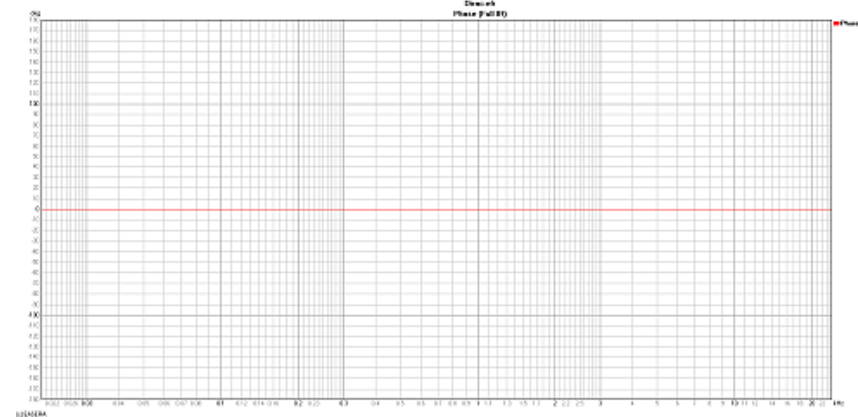
Phase Response

Target Response

Linkwitz-Riley LP & HP Filters – 4th Order, 1 kHz

Impulse Response

Magnitude Response (Frequency)
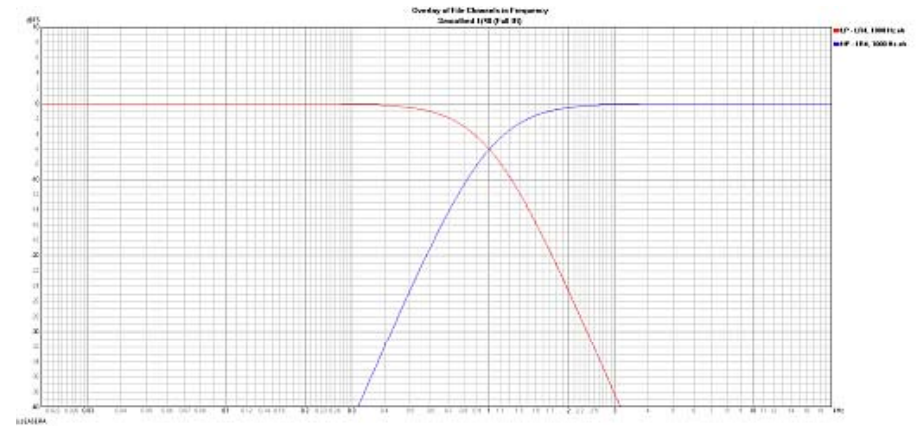
LP – Red;   HP – Blue

ETC Response (Envelope Time Curve)

Phase Response

Target Response

Linkwitz-Riley LP & HP Filters – 4th Order, 1 kHz

Impulse Response (zoomed in)

Initial energy arrivals aligned
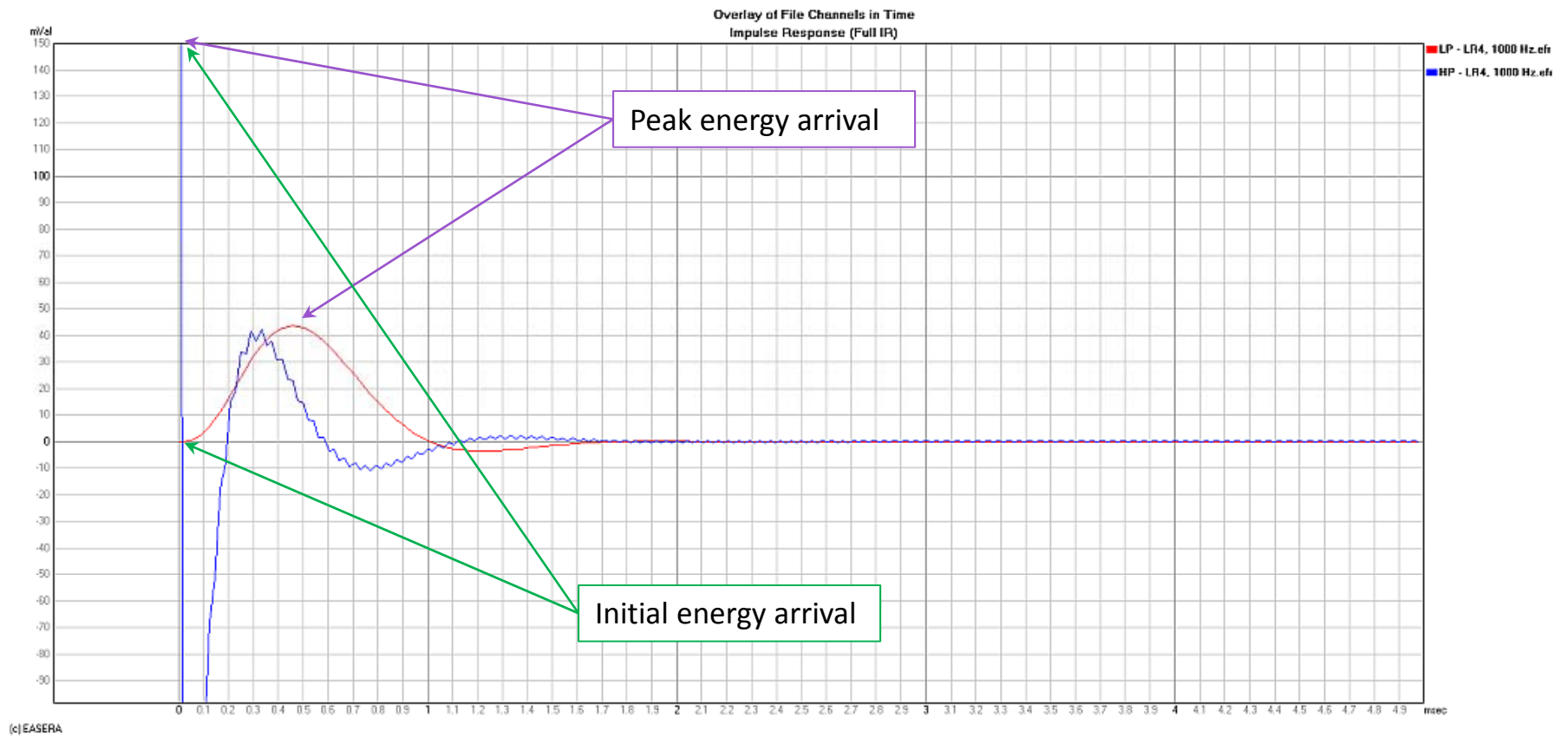
LP – Red;   HP – Blue
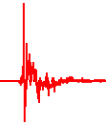
Target Response

Summation of Linkwitz-Riley LP & HP Filters – 4th Order, 1 kHz
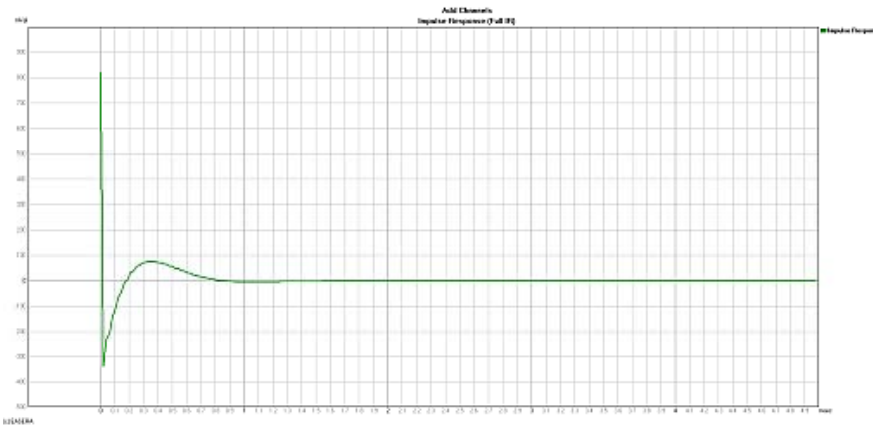
Impulse Response

Magnitude Response (Frequency)
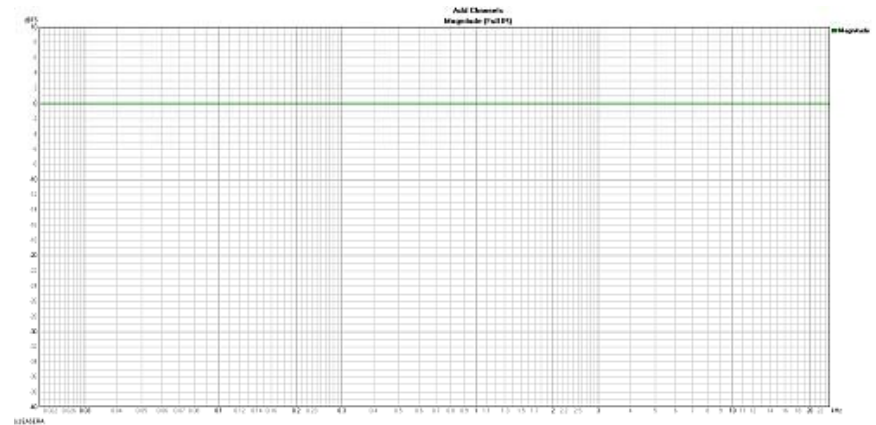
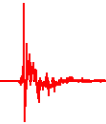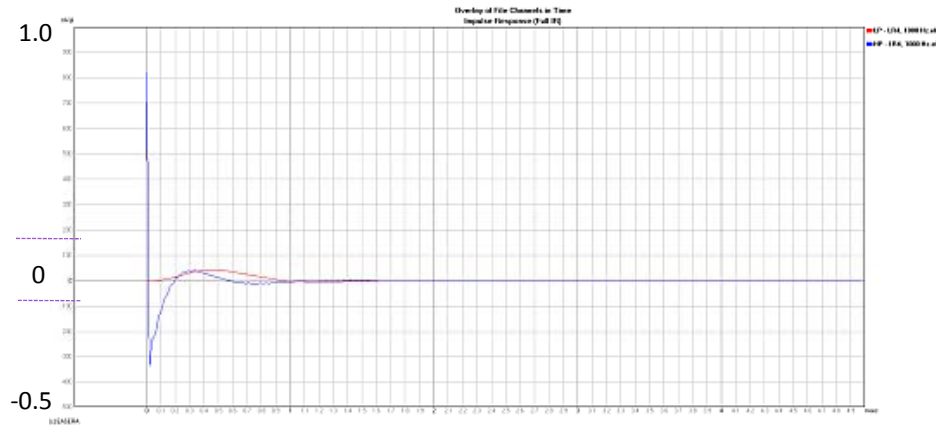Summation – Green

ETC Response (Envelope Time Curve)
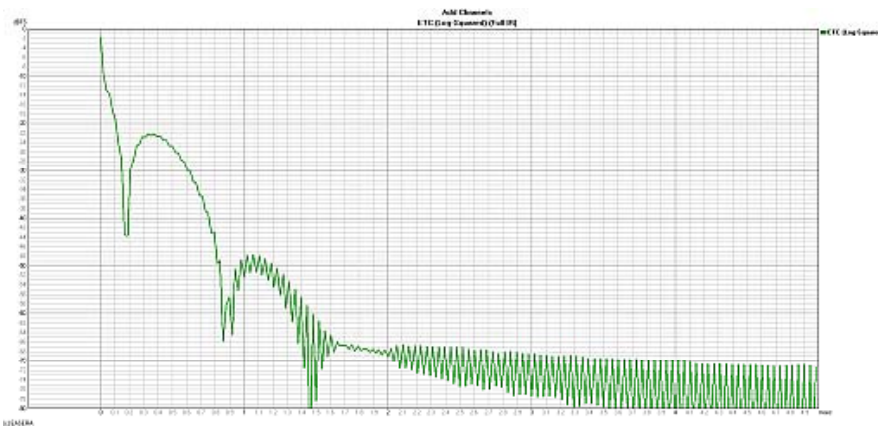
Phase Response

Target Response

Linkwitz-Riley LP & HP Filters – 4th Order, 1 kHz

HP signal delayed 0.46 ms
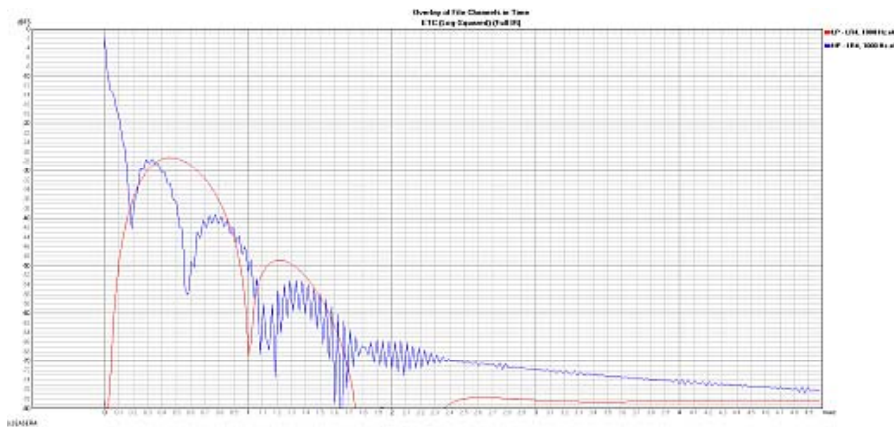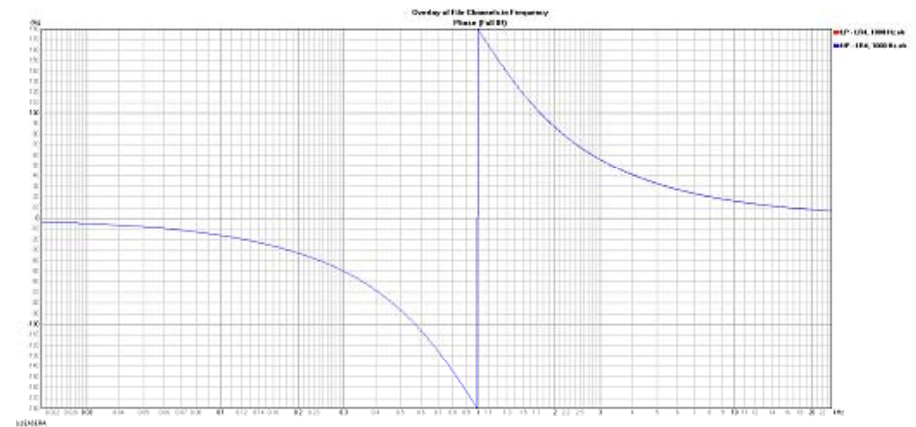
Peak energy arrivals aligned

Impulse Response

Initial energy arrival

Peak energy arrival

Overlay of File Channels in Time
Impulse Response (Full IR)
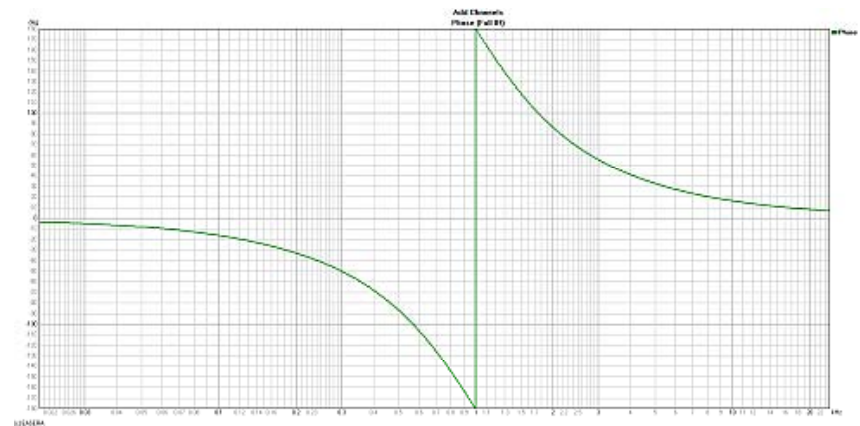
LP – Red;   HP – Blue

Target Response

Linkwitz-Riley LP & HP Filters – 4th Order, 1 kHz

HP signal delayed 0.46 ms

Impulse Response

Peak energy arrivals aligned
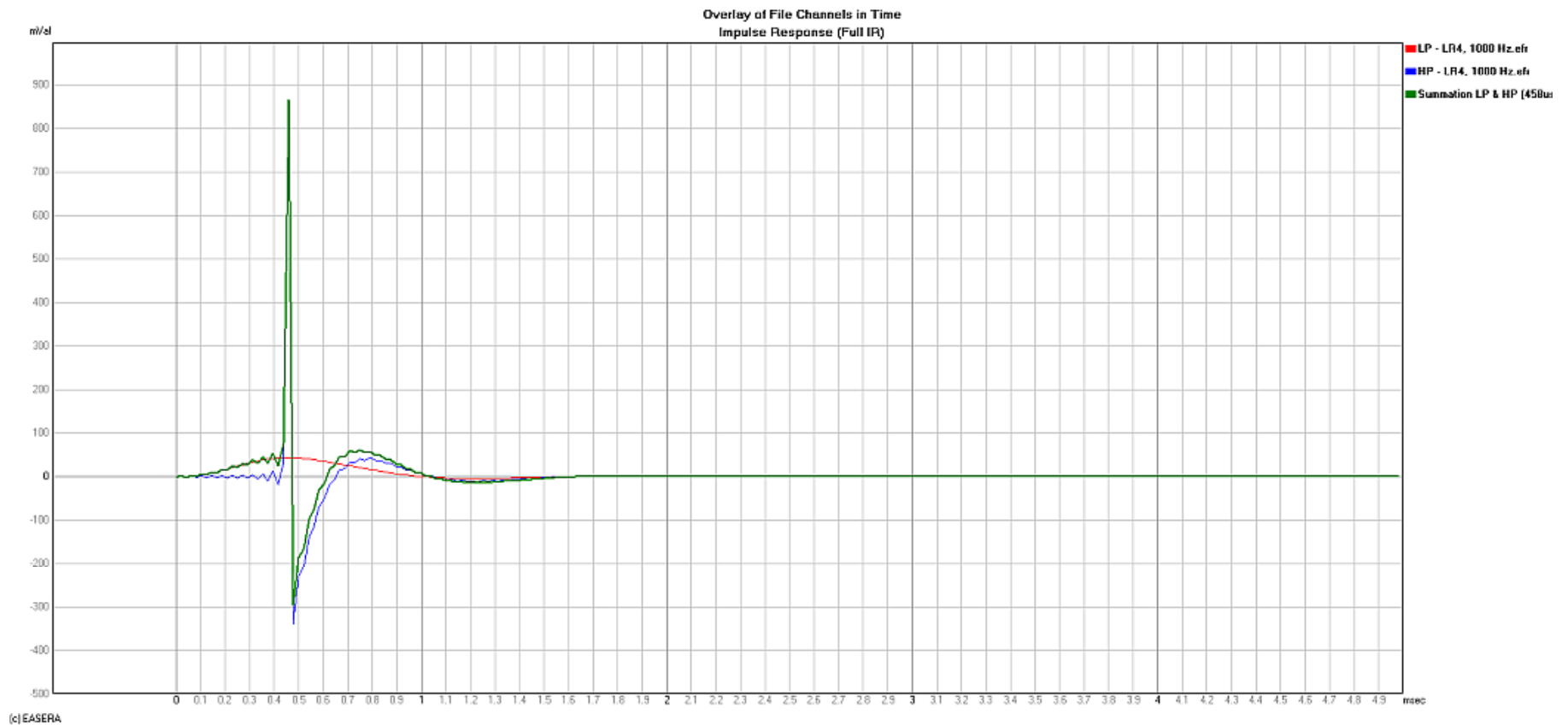
LP – Red;   HP – Blue;   Summation of LP+HP – Green

Target Response

Linkwitz-Riley LP & HP Filters – 4th Order, 1 kHz

HP signal delayed 0.46 ms

Peak energy arrivals aligned

Magnitude Response

Large cancellation due to time domain misalignment

LP – Red;   HP – Blue;   Summation of LP+HP – Green

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Target Response

Linkwitz-Riley LP & HP Filters – 4th Order, 100 Hz

LP – Red;   HP – Blue

Impulse Response
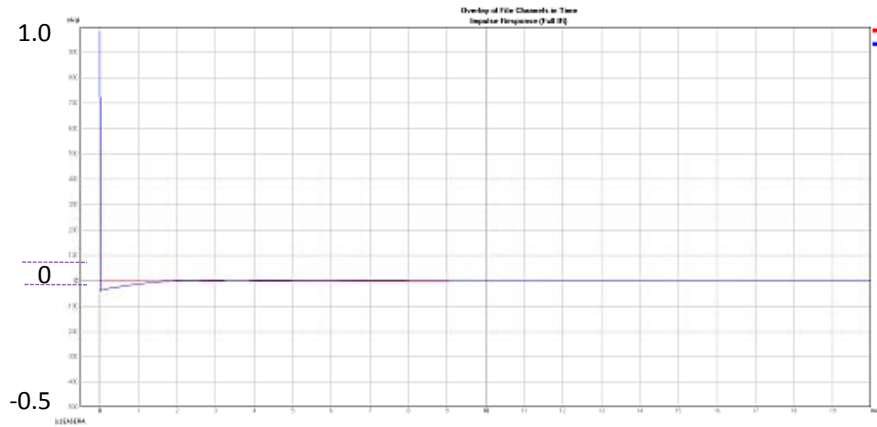
Magnitude Response (Frequency)
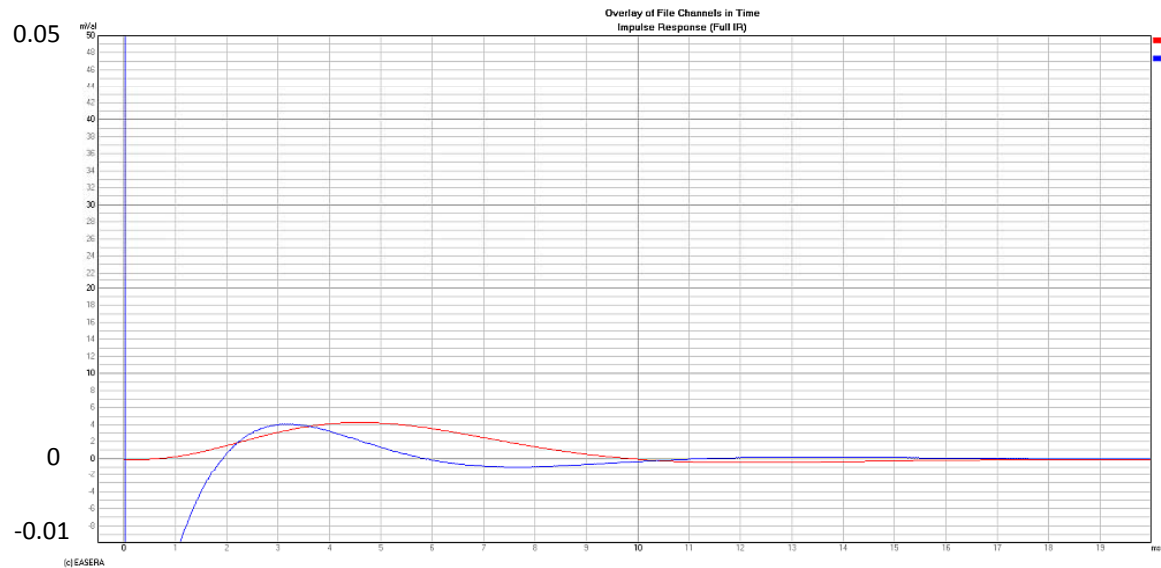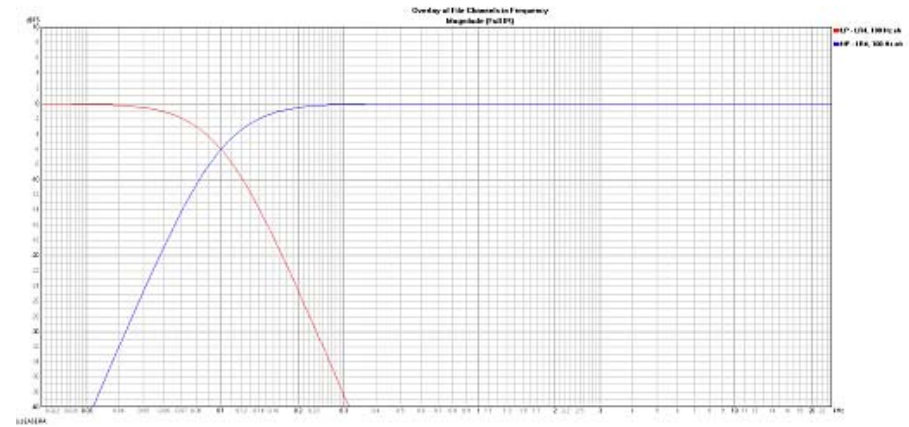
Impulse Response (zoomed)

Measurements and Determining Arrival Time

Allow as much HF energy output from the subwoofer as possible

Disengage LP filter or raise it to a very high frequency

More HF energy in the signal from a device increases our ability to resolve smaller time increments, $\Delta t = 1/\Delta f$

Period = 1/frequency

P_{20kHz} = 0.05 ms

P_{1kHz} = 1.0 ms

P_{100Hz} = 10 ms

20 kHz Sine Wave

100 Hz Sine Wave

1 kHz Sine Wave
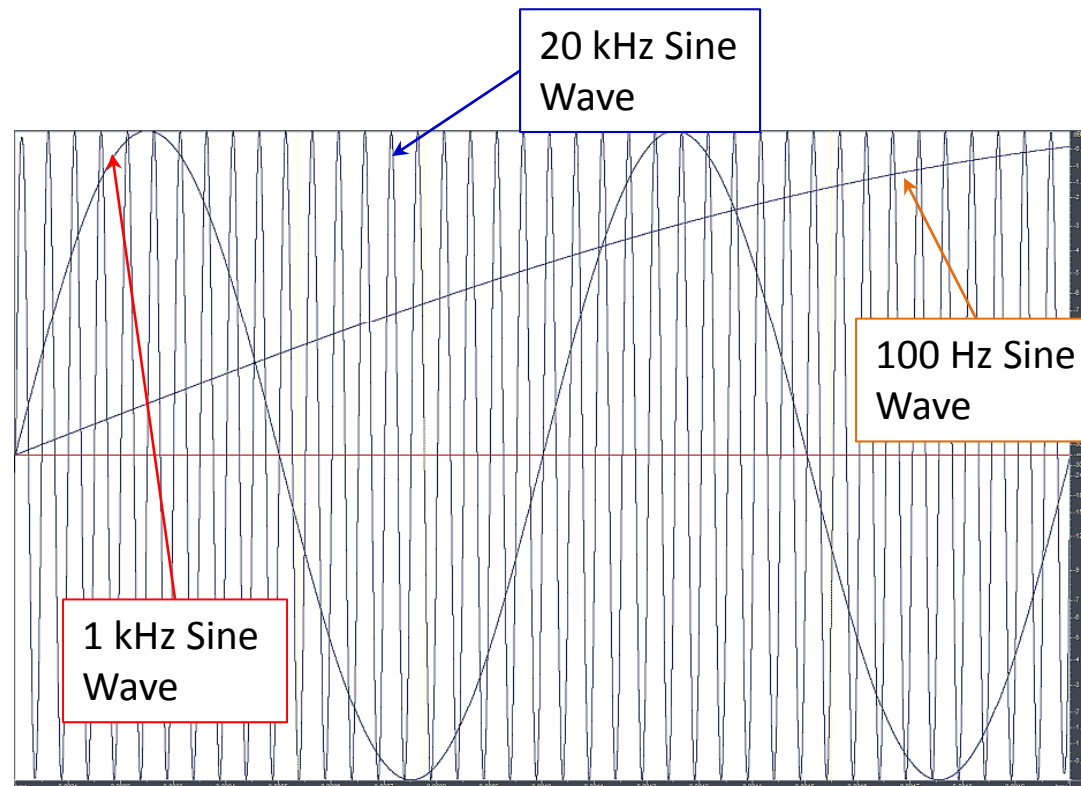
Measurements and Determining Arrival Time

Apparent time gap in the LP response is not due to a pure, broadband delay but rather a lack of high frequency energy content and the necessary phase shift of the low frequency energy content

Initial energy arrival
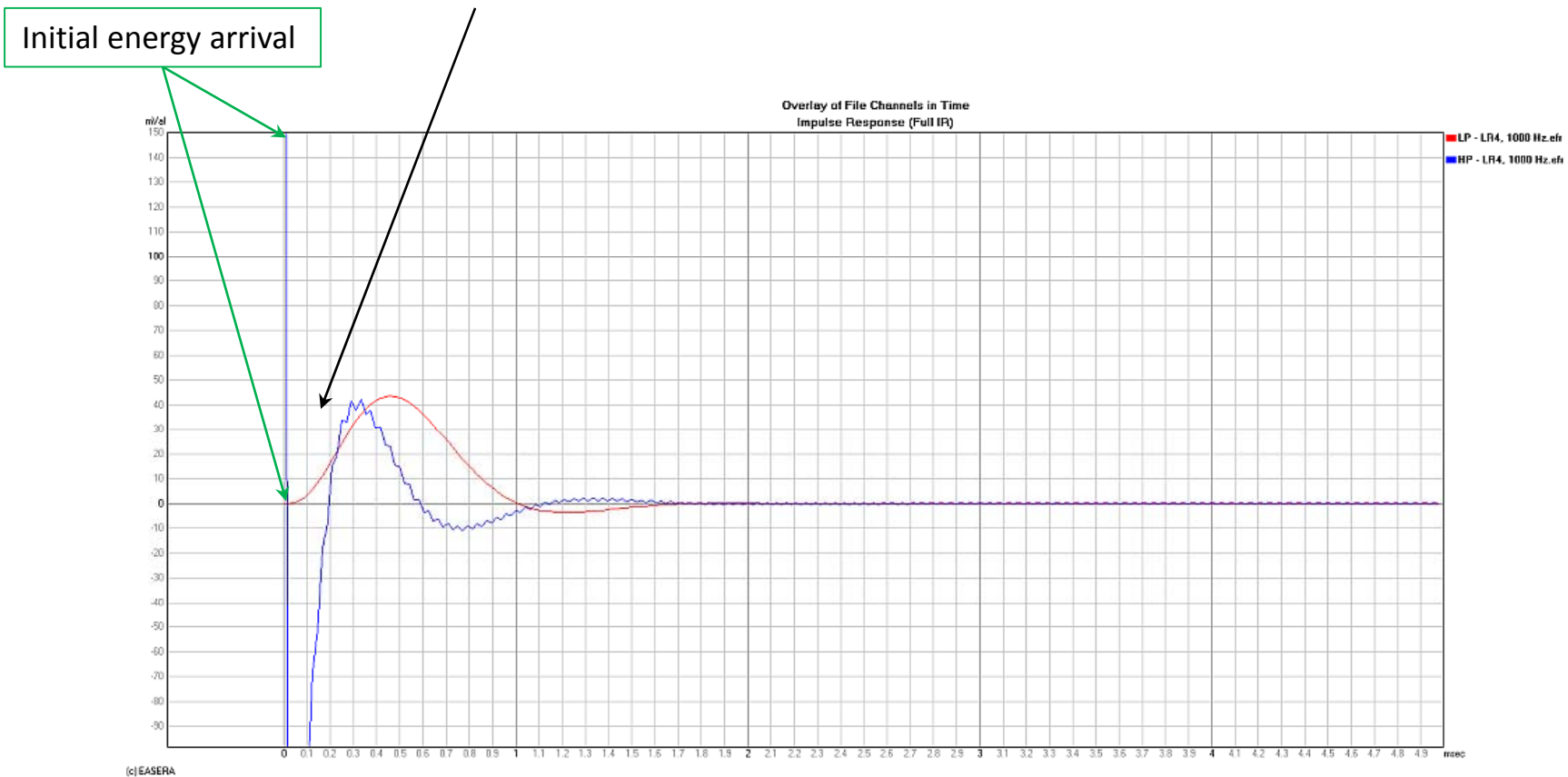
Linkwitz-Riley 4th order filters at 1 kHz: LP – Red;   HP – Blue;

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Arrival Time Goals

Energy from adjacent pass bands (Subs & Full-Range) need to arrive at the listener at the same time

Locate the Subs and the Full-Range units very close to each other to minimize arrival time differences

1) **All Ground Stacked**

    In many situations this is not desirable for audience coverage and other reasons

2) **All Flown**

    While possible, and can yield very good results, it may not always be practical due to size and weight constraints

→   3) **Flown Full-Range and Ground Stacked Subs**   ←

    Very commonly seen configuration
    Worse case for timing differences

Arrival Time Goals

Energy from adjacent pass bands (Subs & Full-Range) need to arrive at the listener at the same time

Physically separated Subs and Full-Range

Less than 1 dB variation
Adjacent pass bands must not be out-of-phase by more than 55°
At 100 Hz this is 1.53 ms

Less than 2 dB variation
Adjacent pass bands must not be out-of-phase by more than 75°
At 100 Hz this is 2.08 ms   *At 112 Hz this is 1.86 ms*

Less than 3 dB variation
Adjacent pass bands must not be out-of-phase by more than 90°
At 100 Hz this is 2.50 ms

Note: Above the crossover frequency the outputs from the filters are within 10 dB of each other and the wavelengths/periods are shorter. Arrival time constraints must be based on slightly higher frequency. For the Linkwitz-Riley 4th order response in our example this will be approximately 1/6 octave.

Frequency Domain Alignment

Overall Target Response

4th order Linkwitz-Riley system with a 100 Hz crossover frequency
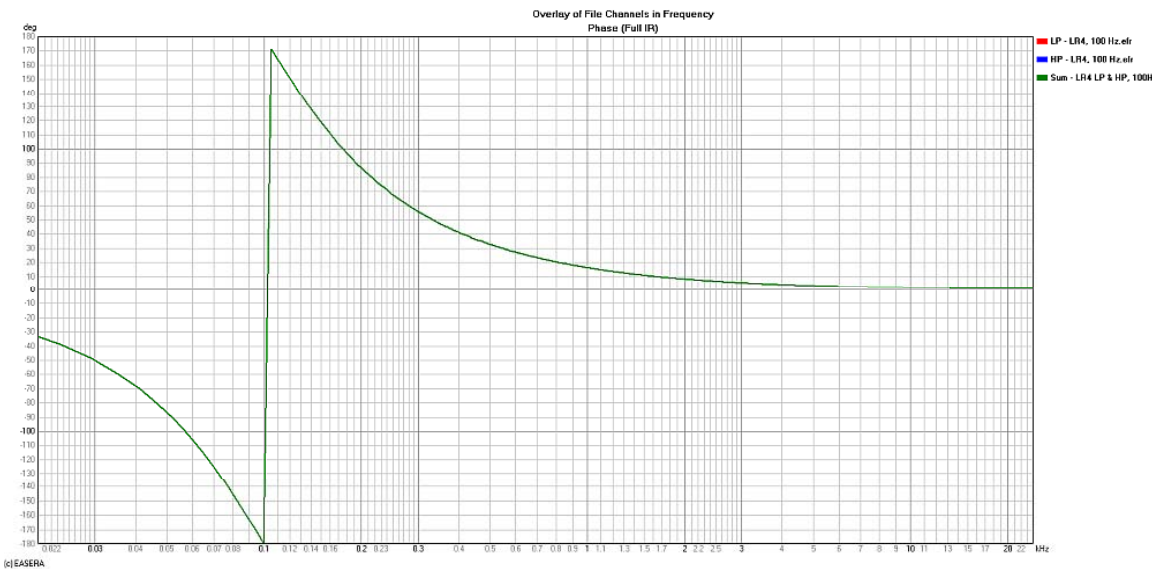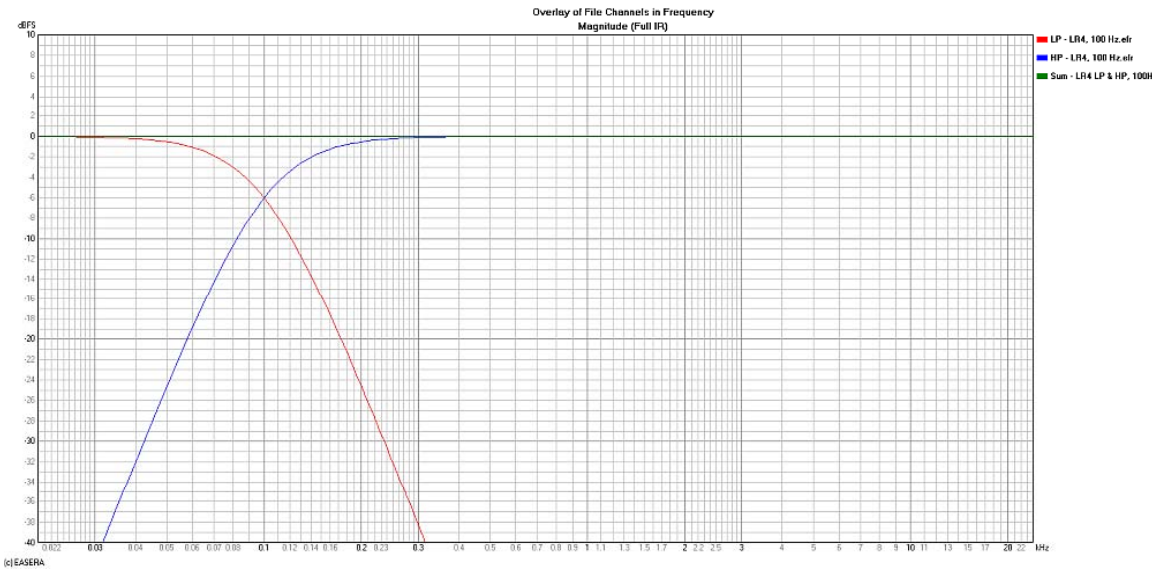
Note that the LP and HP response functions are in phase at all frequencies

LP – Red
HP – Blue
LP+HP – Green

Frequency Domain Alignment

FR - 01, Driver Response.efr
Magnitude (Full IR)

FR - 01, Driver Response.efr
Phase (Full IR)

Full-Range Loudspeakers

LF is a sealed box
12 dB/octave
(2nd order) roll-off
-3 dB at 60 Hz

Flat magnitude response
through HF region, but not flat
phase response

This All Pass response is due to
the crossover in the
loudspeaker (approx. 1 kHz)

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AES Atlanta Section – Atlanta, GA
February 19, 2011

Frequency Domain Alignment

Sub - 01, Driver Response.efr
Magnitude (Full IR)
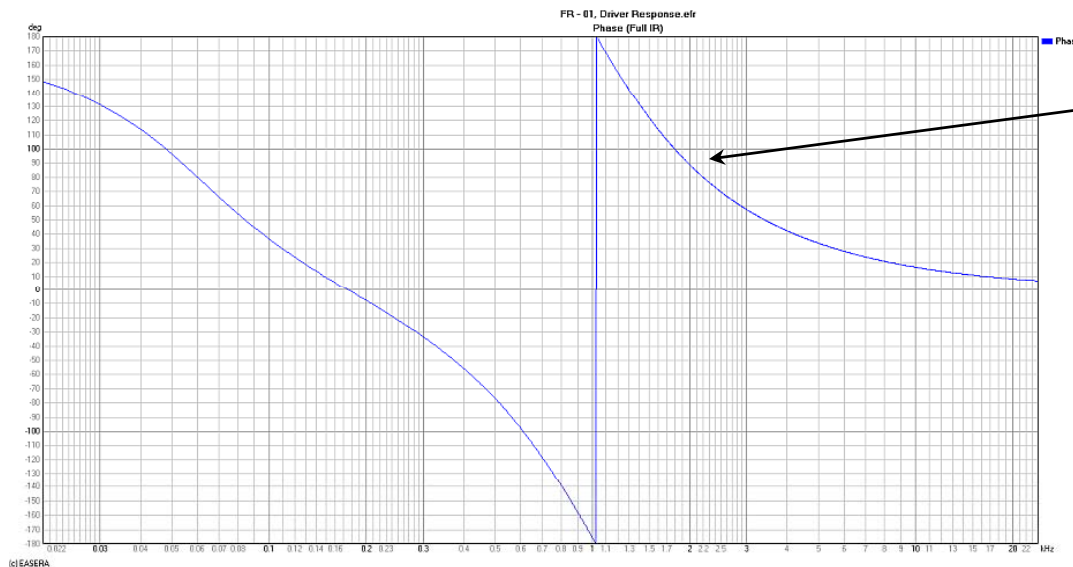
Sub - 01, Driver Response.efr
Phase (Full IR)

Subwoofer Loudspeakers

Vented box
24 dB/octave
(4th order) roll-off
-3 dB at 20 Hz

HF roll-off at approximately
12 dB/octave roll-off
-3 dB at 400 Hz
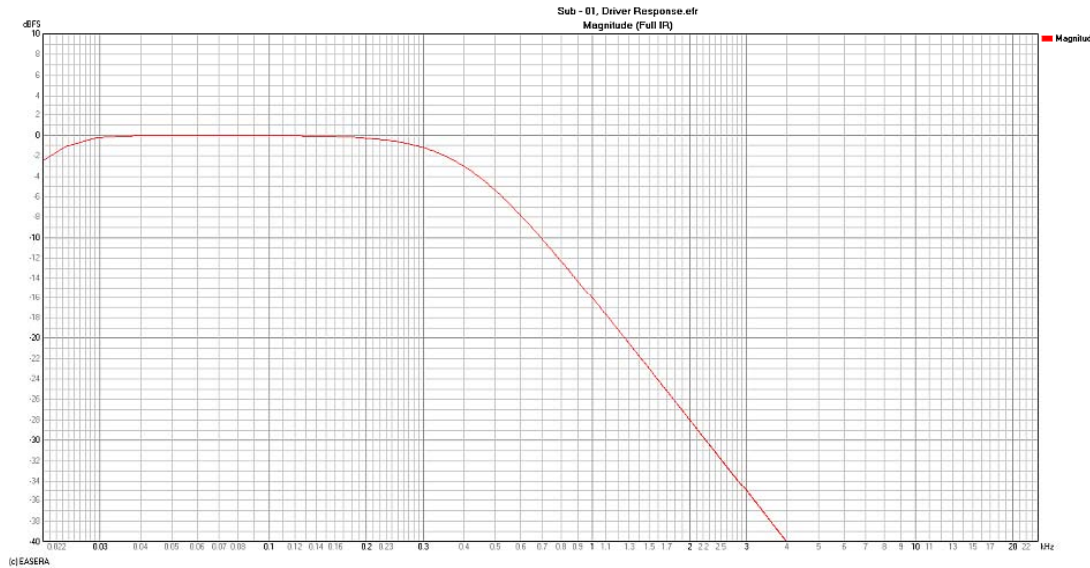
Frequency Domain Alignment

Overall Target Response

Applying 4th order Linkwitz-Riley filters to our loudspeakers results in summing errors

In this case the errors are small, approx. -0.6 dB (cancellation)
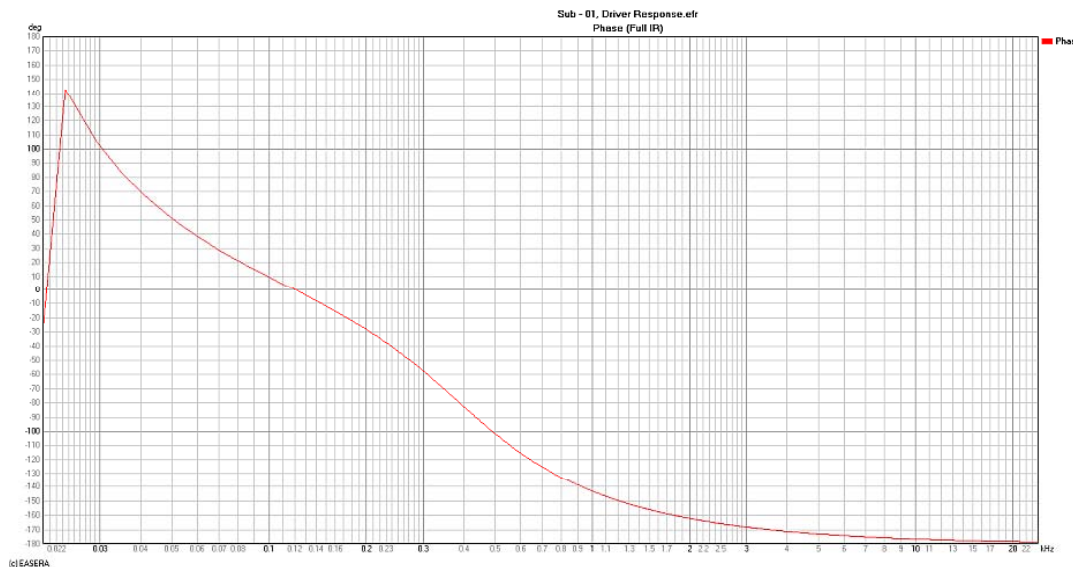
In general, can't simply apply 4th order Linkwitz-Riley filters to loudspeakers and achieve the target 4th order Linkwitz-Riley response

Subs – Red
Full-Range – Blue
Subs + Full-Range – Green

Frequency Domain Alignment

Subwoofer LP Filtering
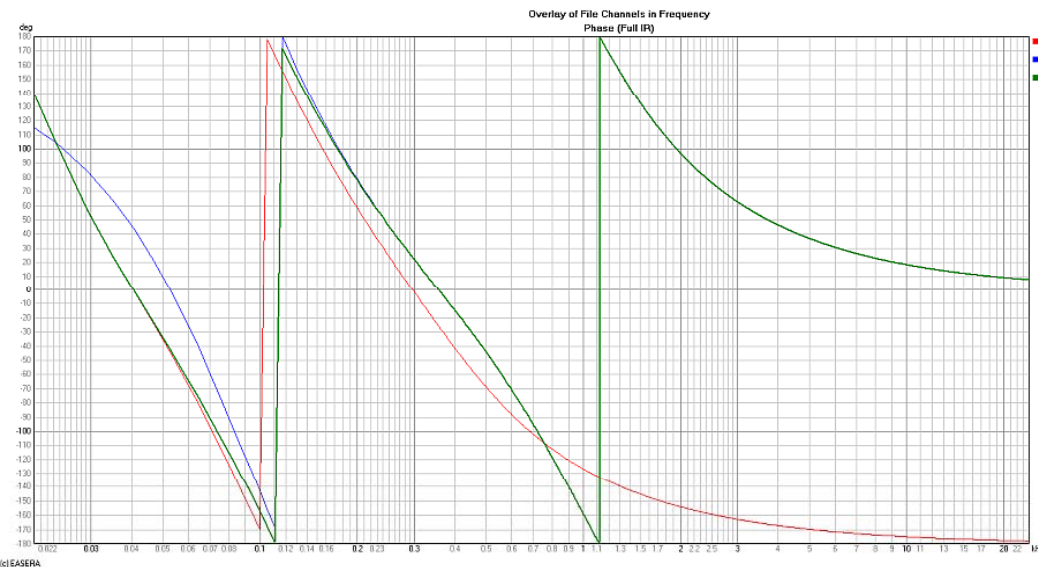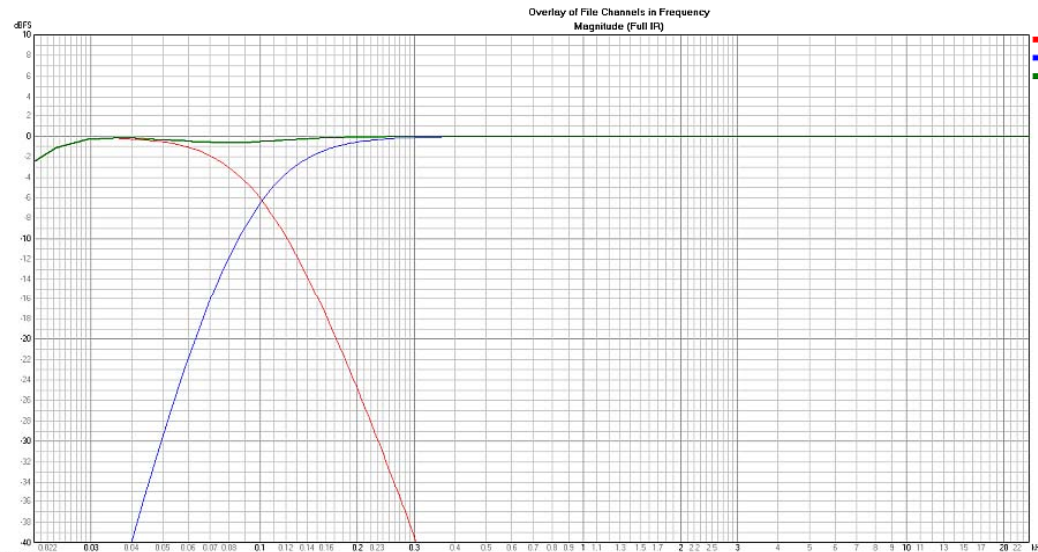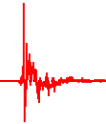
LP - 82 Hz, 3rd order Butterworth

Target LR4 LP Response – Red
Subwoofer Loudspeaker Response – Blue
Subwoofer + Filtering – Green

Frequency Domain Alignment

Full-Range HP Filtering

HP - 165 Hz, 2nd order Butterworth

PEQ - 105 Hz, +4.0 dB, Q=1.3

Target LR4 HP Response – Red

Full-Range Loudspeaker Response – Blue

Full-Range + Filtering – Green
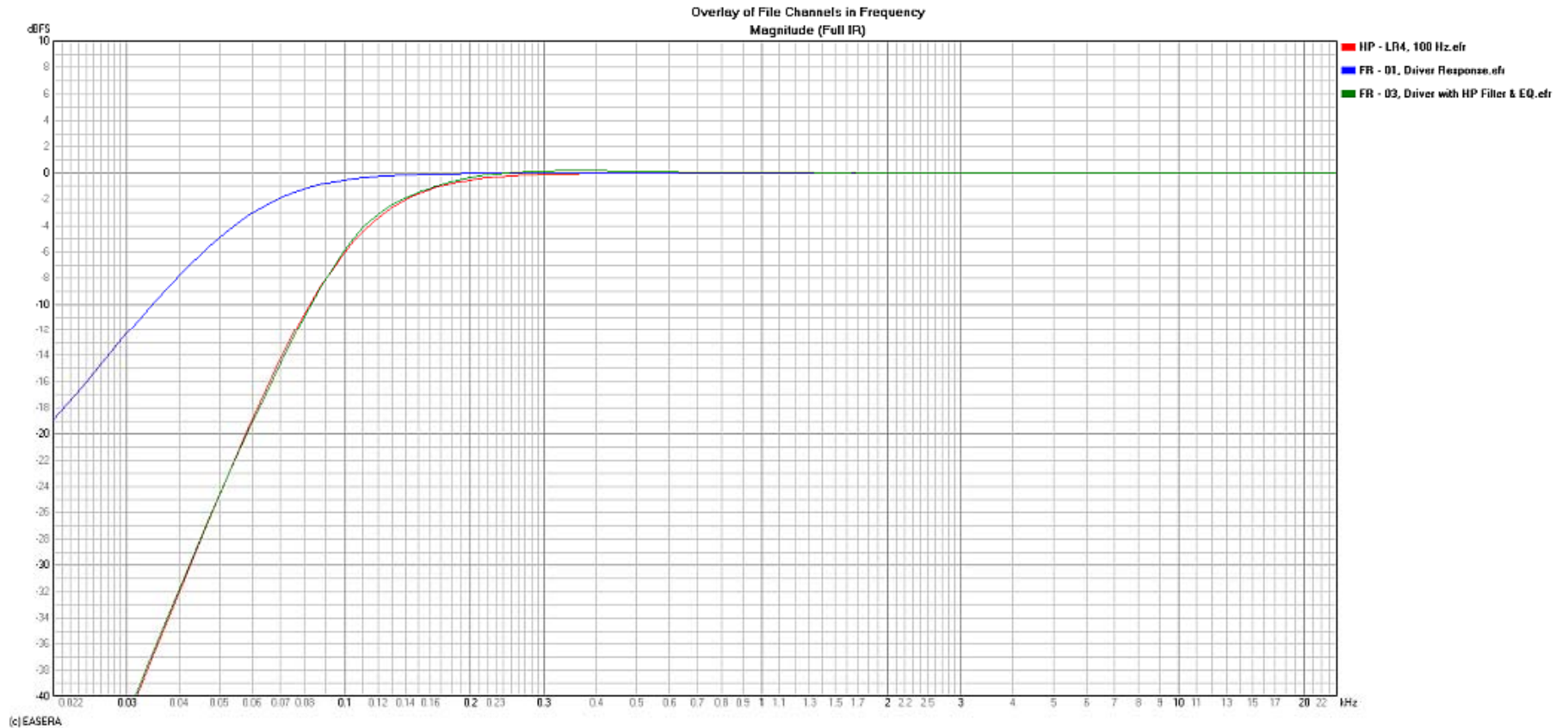
Frequency Domain Alignment

Sub & Full-Range with New Filtering

As previously seen the magnitude responses with the new filtering matches the target Linkwitz-Riley responses closely

However, the phase responses don't match (overlay) as they should

Certain aspects of the subs are not accounted for in the full-range and vice-versa

Subs with New Filters – Red
Full-Range with New Filters – Blue

Frequency Domain Alignment
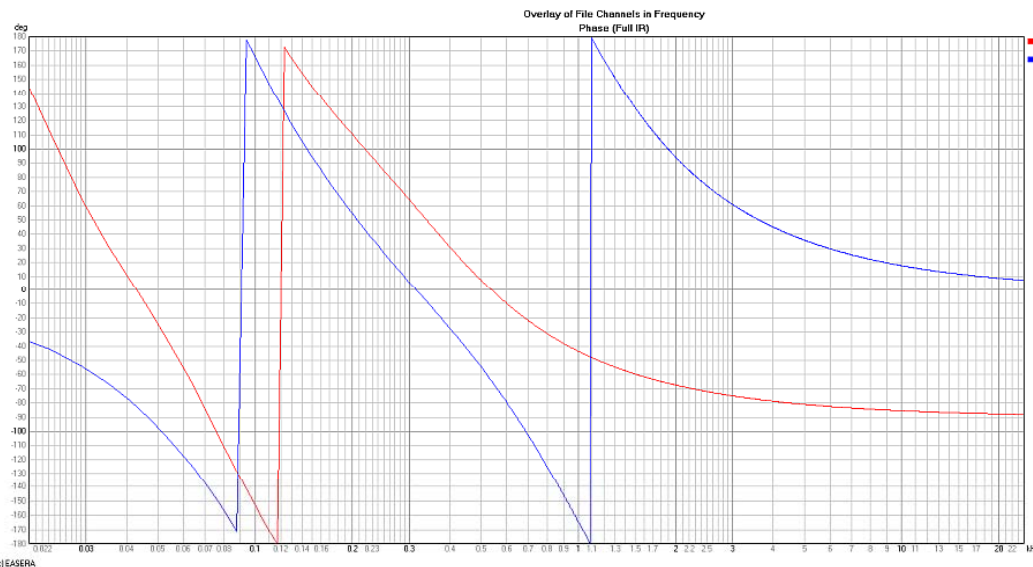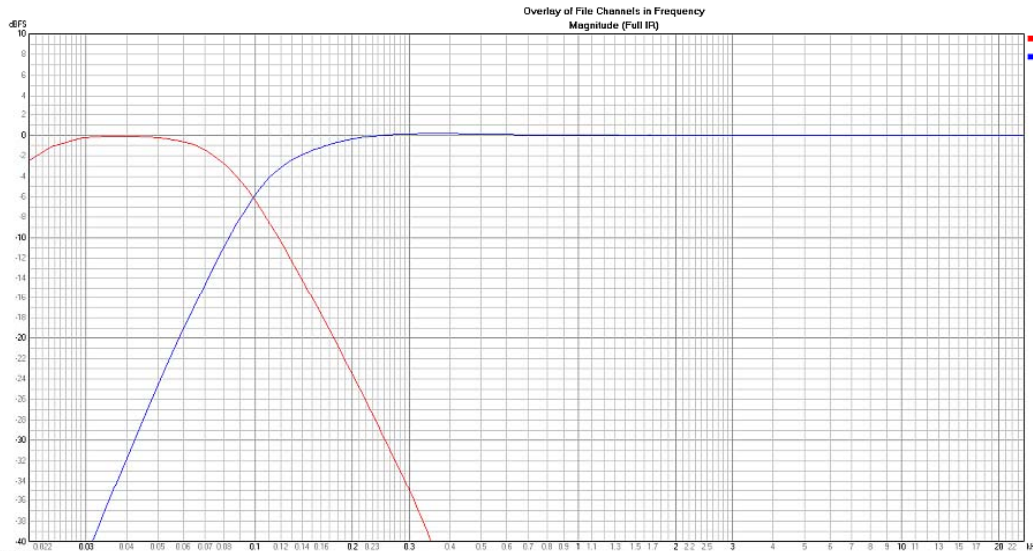

Sub & Full-Range with Added Filtering

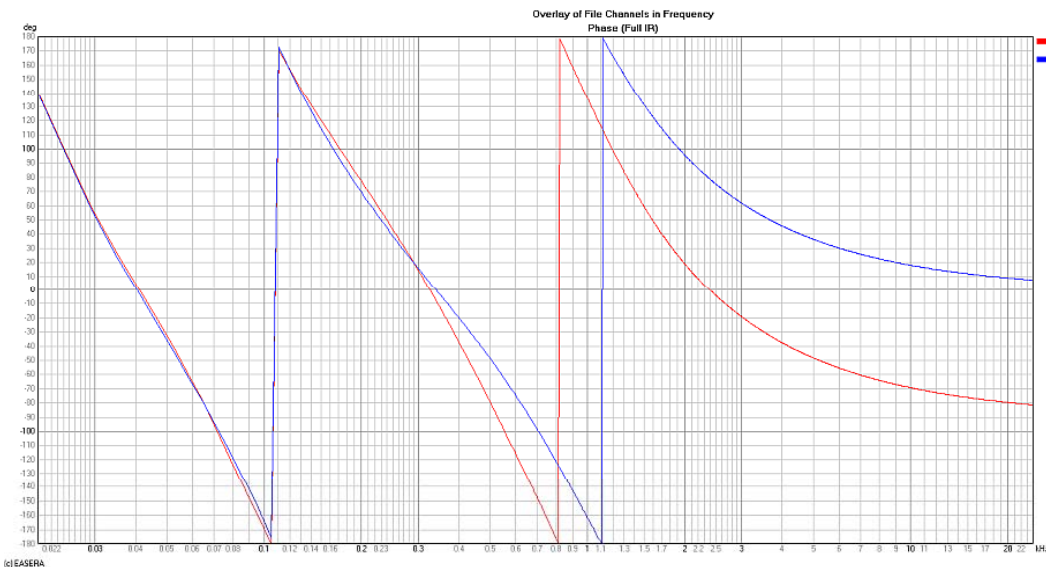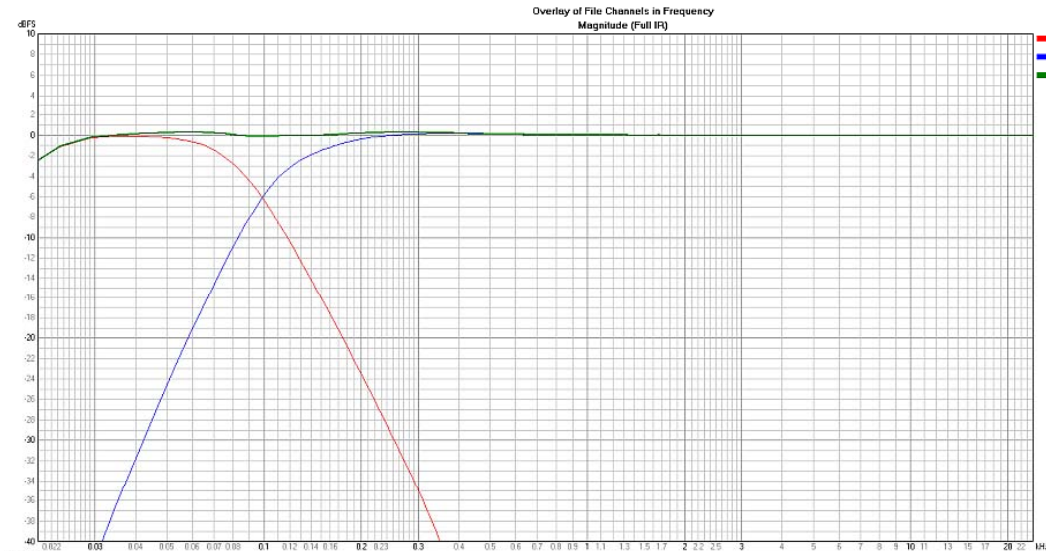Full-Range added:
HP - 20 Hz, 4th order Butterworth

Subwoofer added:
AP - 1 kHz, 2nd order Butterworth

No change in the magnitude response from before but now the phase response matches in the 100 Hz crossover region

Smaller summation error compared to using Linkwitz-Riley filters, approx. 0.3dB (increase)

Subs with Added Filters – Red
Full-Range with Added Filters – Blue
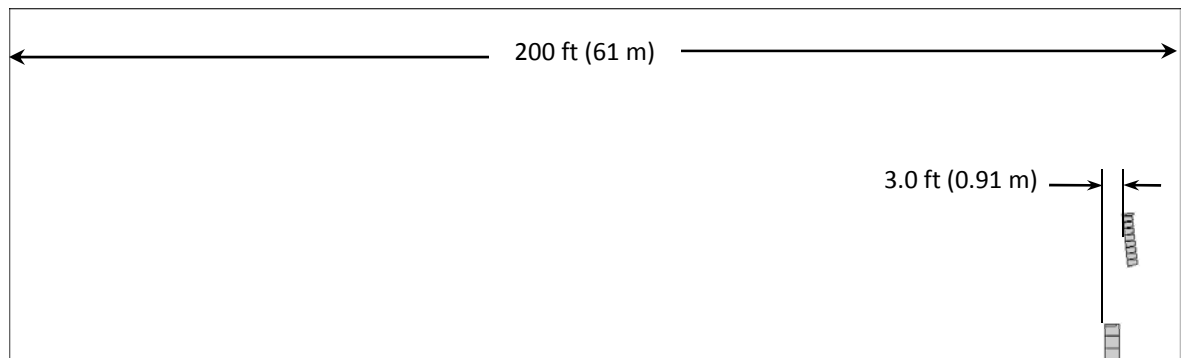Subs + Full-Range – Green

Recap & Putting It All Together

1) We know that to properly align devices we must align the initial energy arrivals, not the peak energy arrivals.

2) We know what to look for to determine the initial energy arrival time from full-range and low frequency band-limited loudspeakers.

3) We have criteria for maximum arrival time variation (time domain) from separated sources in order to keep the overall response variation (frequency domain) below a selected level.

4) We know how to apply filtering to the input of loudspeakers so that the output from the loudspeakers conforms to our desired target response.

Example System in a
Non-Reflective Room

8 Box Line Array

8.6 ft (2.67 m) total height

3 Subwoofers
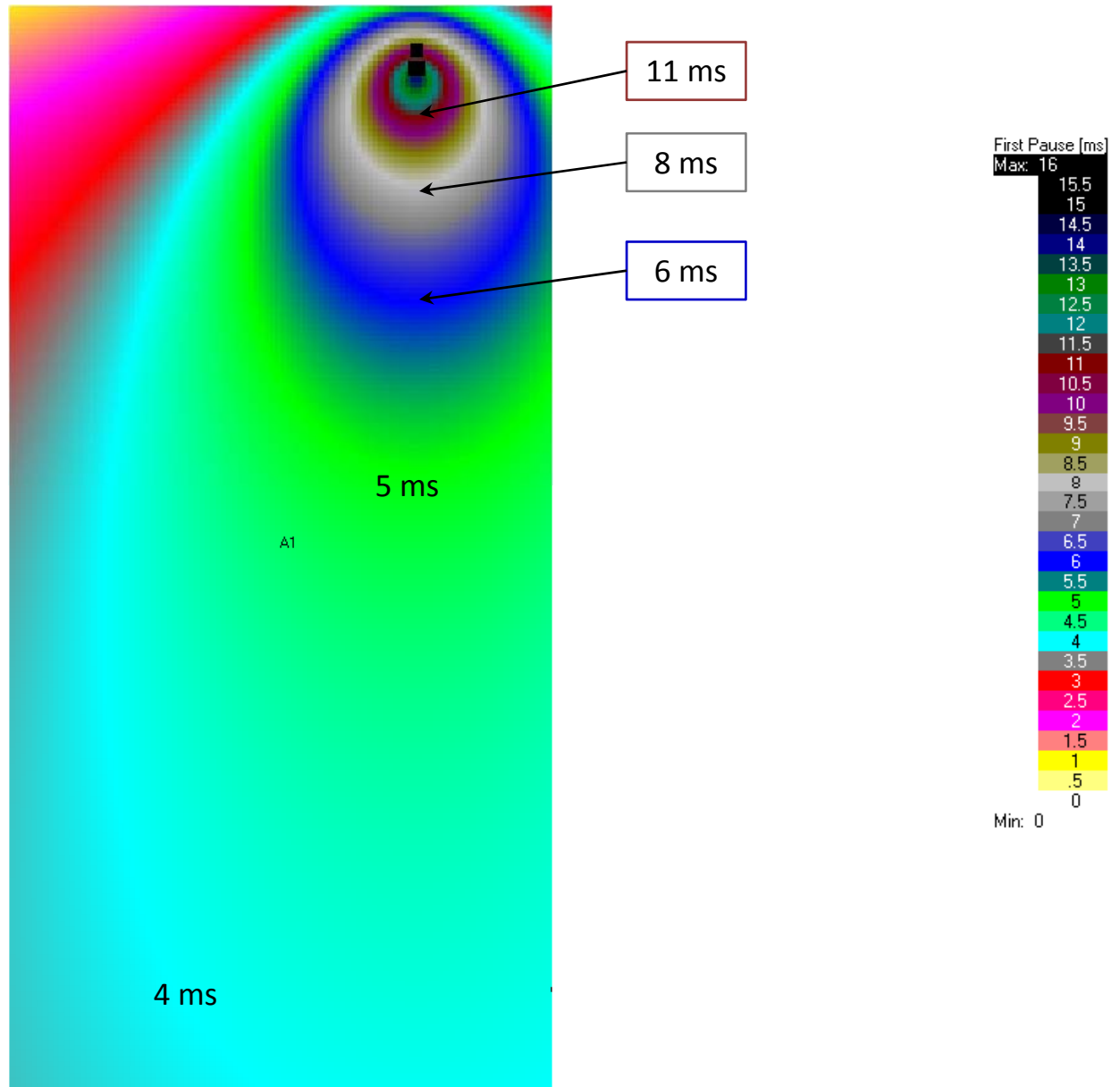
6.0 ft (1.83 m)
total height

100 ft (30.5 m)

200 ft (61 m)

25.0 ft (7.62 m)

3.0 ft (0.91 m)

16.5 ft (5.0 m)

16.5 ft (5.0 m)
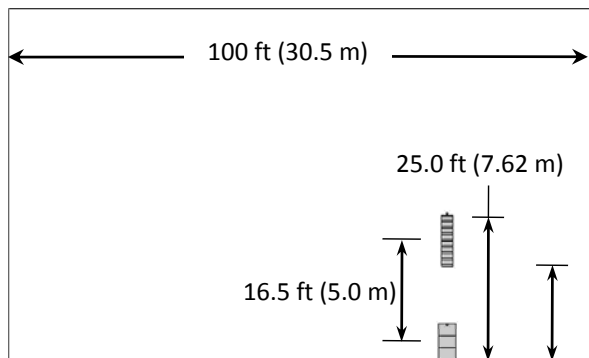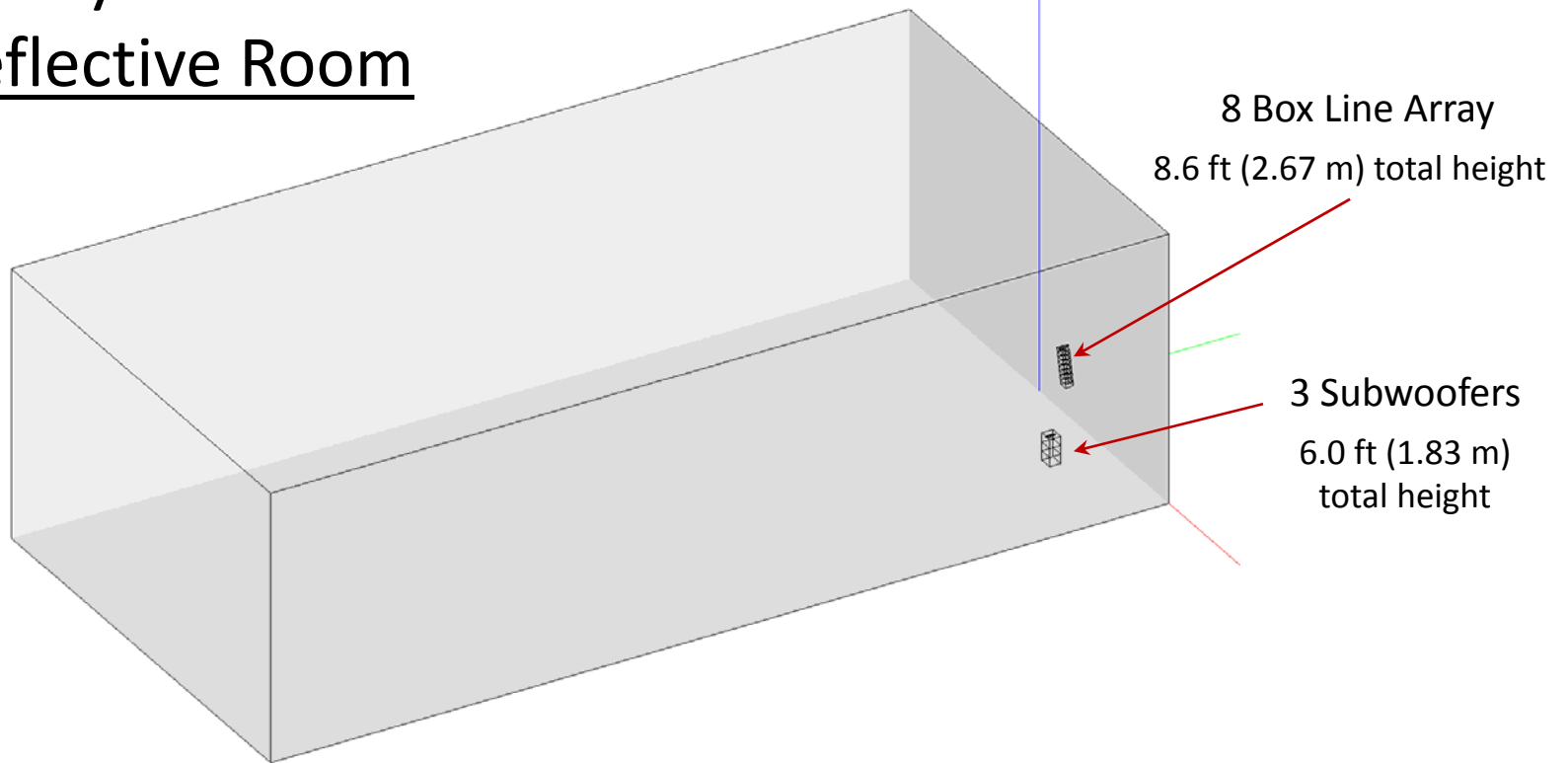
Arrival Time Difference Map

For the majority of the audience area the arrival time difference ranges from 4 – 10 ms (> 90% of house-right)

11 ms

8 ms

6 ms

5 ms

A1

4 ms

First Pause [ms]
Max: 16

15.5
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
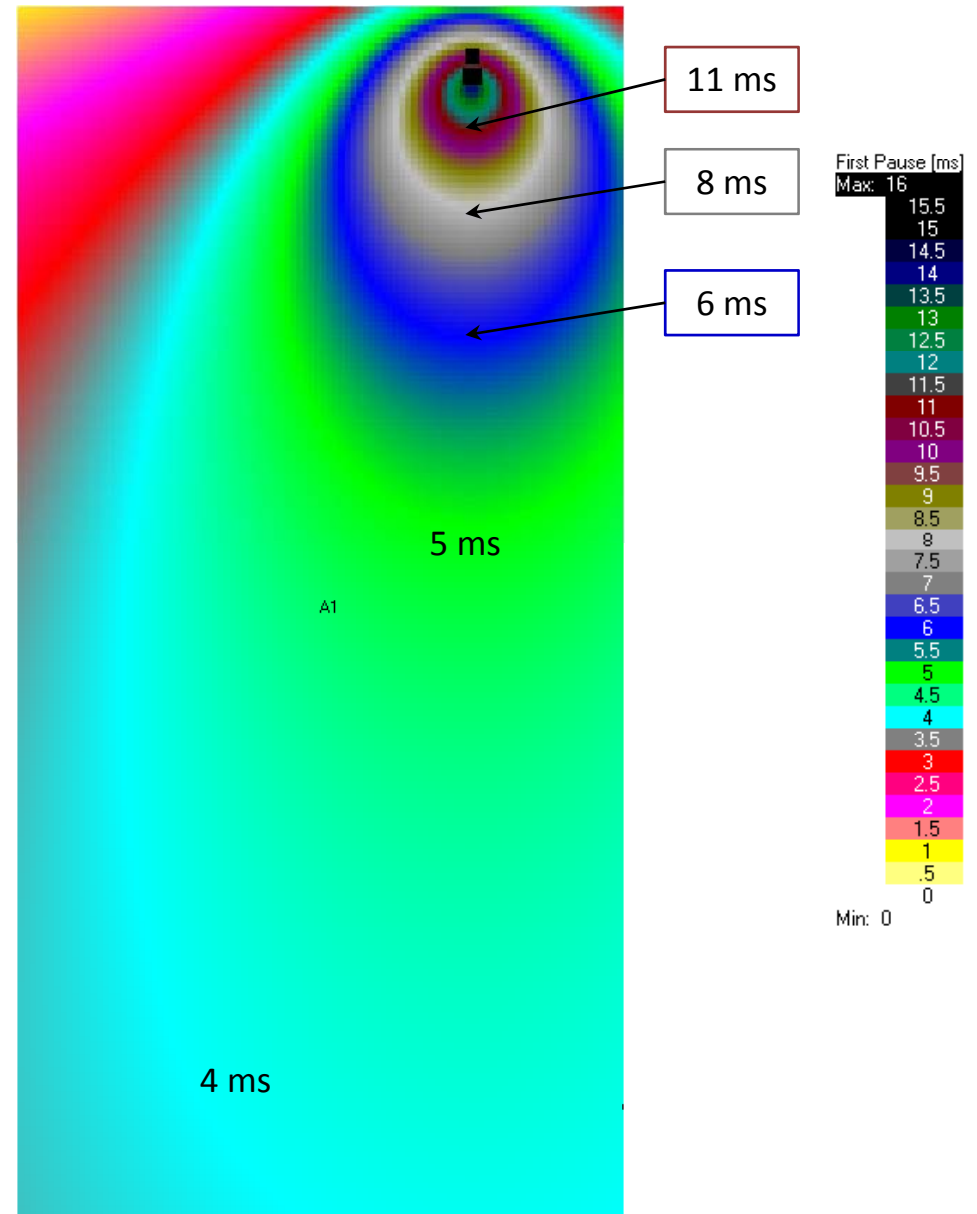8.5
8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
.5
0

Min: 0

For 2 dB Uniformity (+/-1 dB)

Method A

Start at the back and work forward

1) Look at the area(s) of smallest arrival time difference

2) Delay the first signal arrival by this time plus 1.9 ms (approx. 6 ms)

3) Examine new arrival time differences

11 ms

8 ms

6 ms

5 ms

A1

4 ms

First Pause [ms]
Max: 16
15.5
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
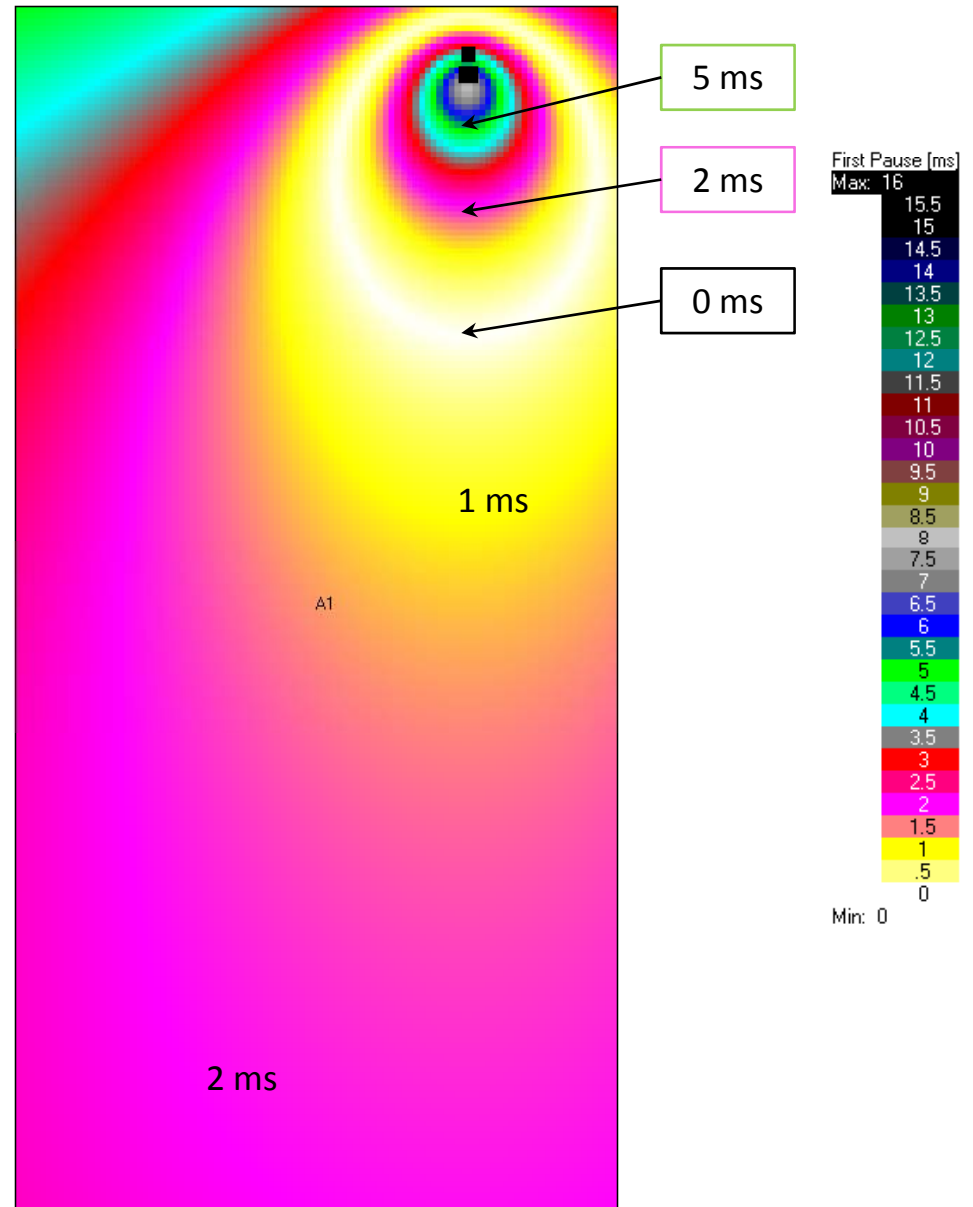8
7.5
7
6.5
6
5.5
5
4.5
4
3.5
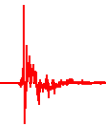3
2.5
2
1.5
1
.5
0
Min: 0

For 2 dB Uniformity (+/-1 dB)

Subs Delayed 6 ms

Method A

Start at the back and work forward

1) Look at the area(s) of smallest arrival time difference

2) Delay the first signal arrival by 6 ms

3) Examine new arrival time differences

    a) Areas greater than 1.9 ms (75°) will vary by more than 2 dB

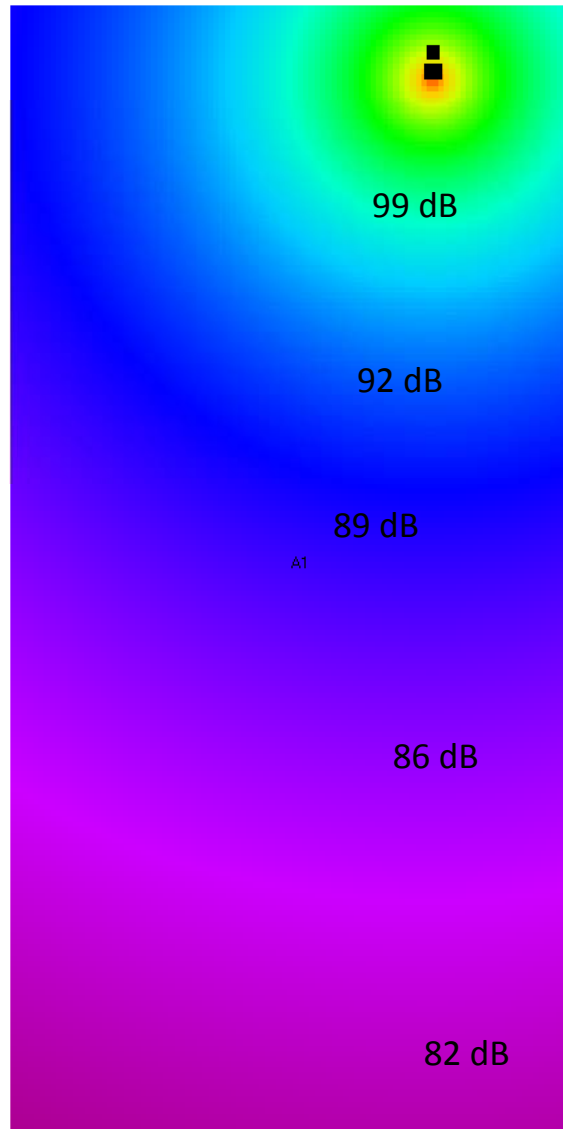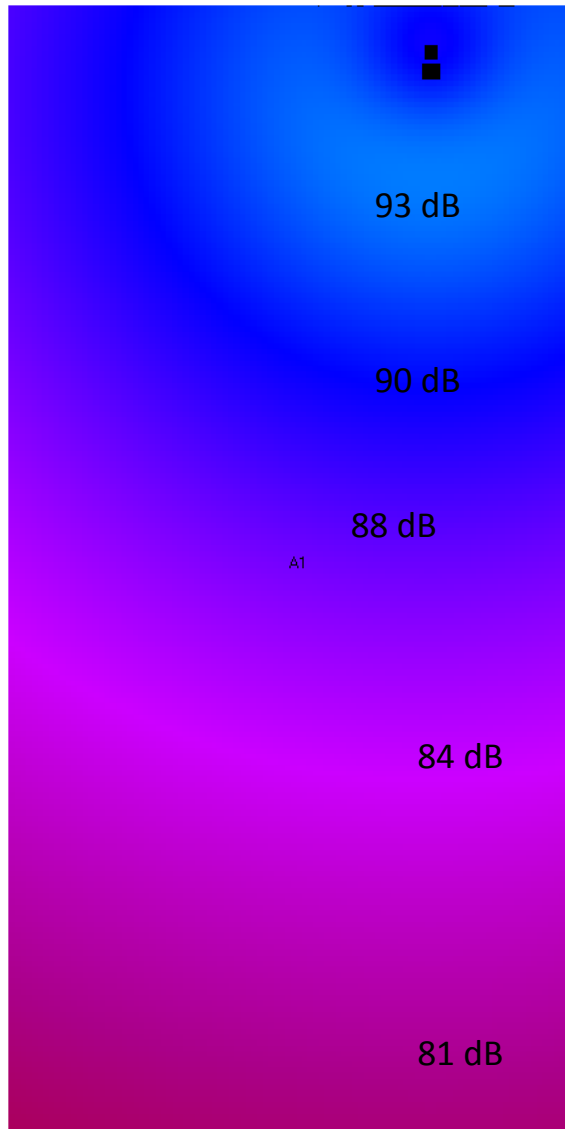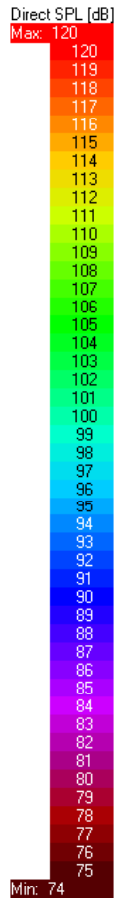   b) Areas greater than 2.3 ms (90°) will vary by more than 3 dB

5 ms

2 ms

0 ms

1 ms

A1

2 ms

First Pause [ms]
Max: 16

15.5
15
14.5
14
13.5
13
12.5
12
11.5
11
10.5
10
9.5
9
8.5
8
7.5
7
6.5
6
5.5
5
4.5
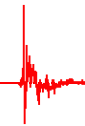4
3.5
3
2.5
2
1.5
1
.5
0

Min: 0

SPL Map – 100 Hz

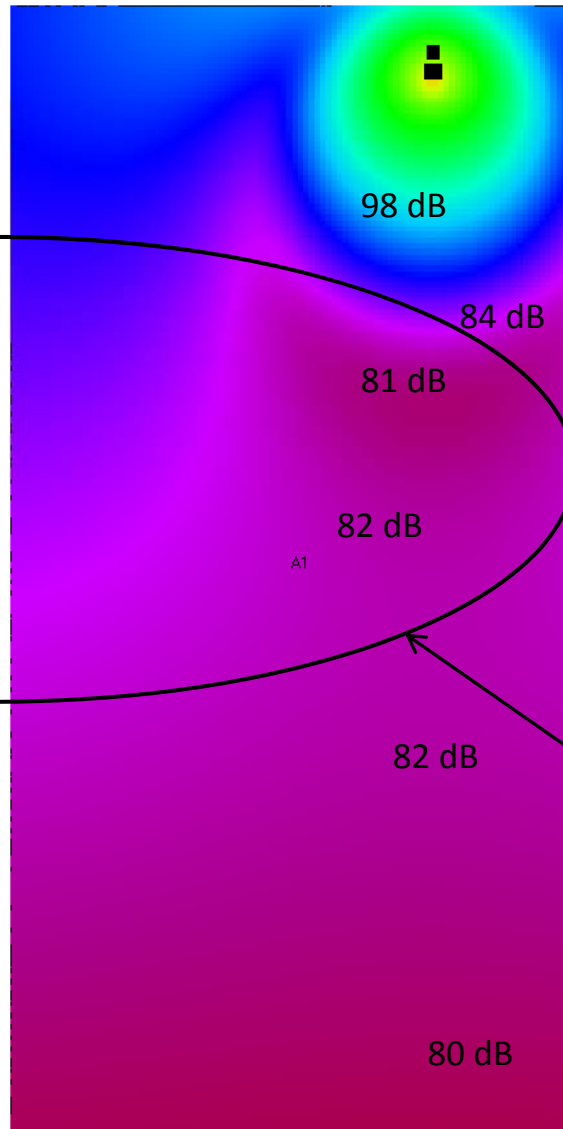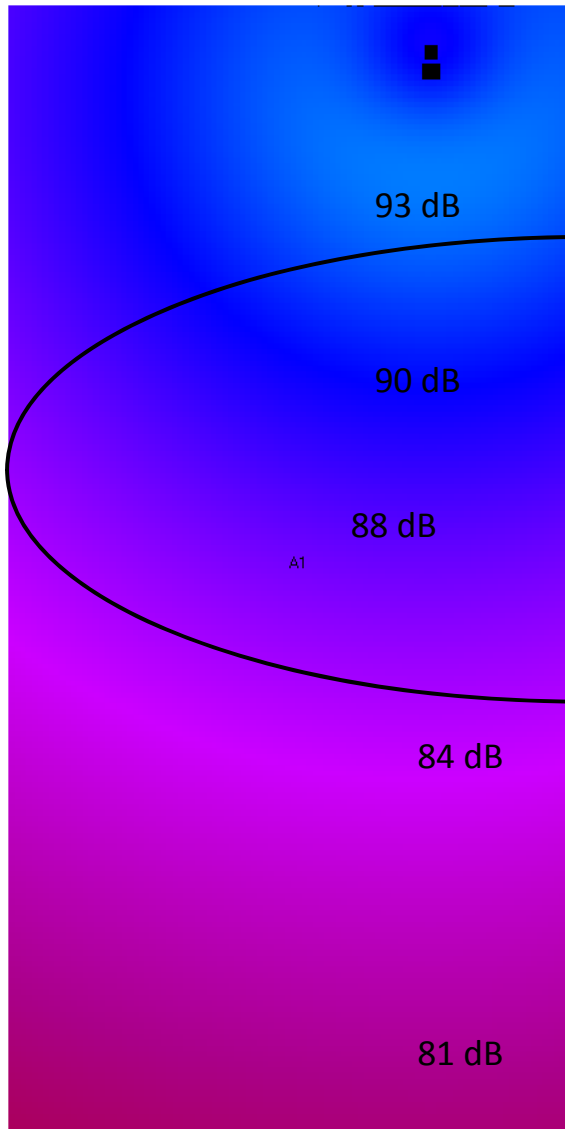### Array Only

Subs Only

No HP or LP filters applied

SPL Map – 100 Hz
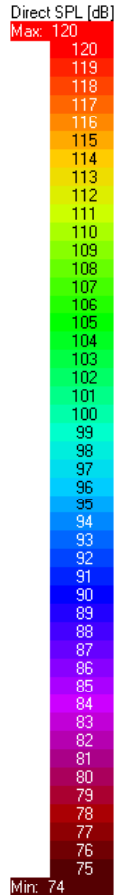

*Using 100 Hz Linkwitz-Riley filters, no delay on Subs

This would be very similar to aligning the peak arrivals of the loudspeakers and applying 4th order Linkwitz-Riley filters to them without taking their inherent response into account
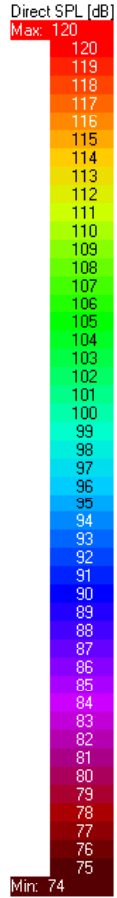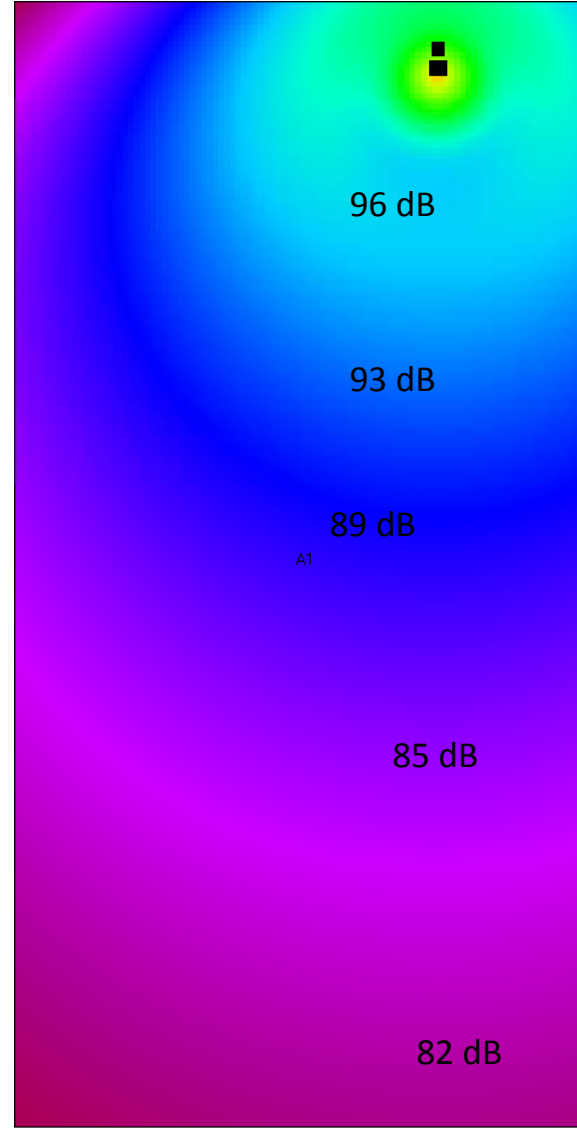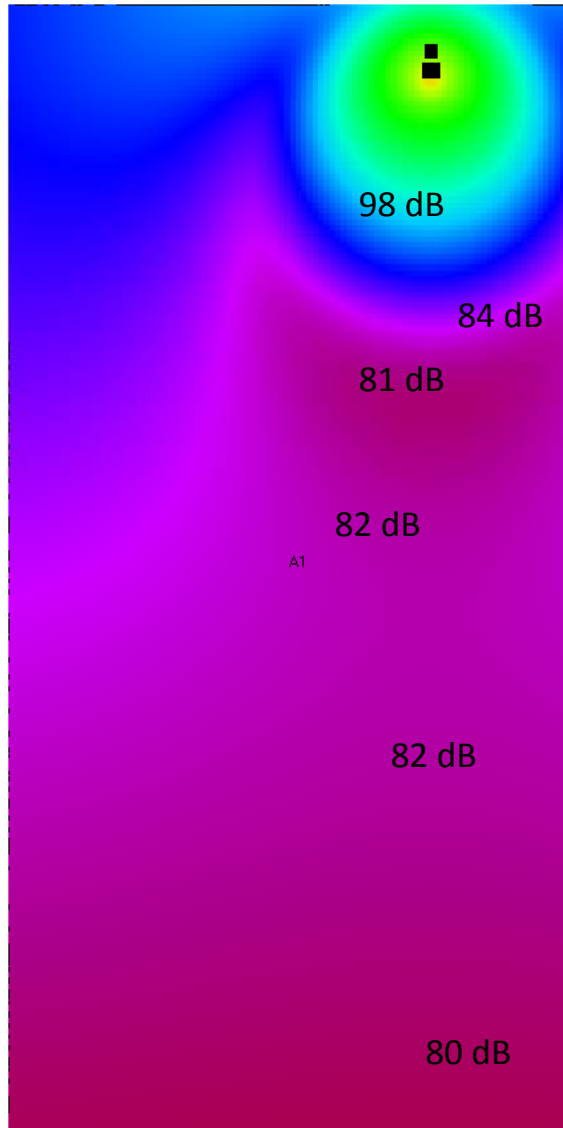
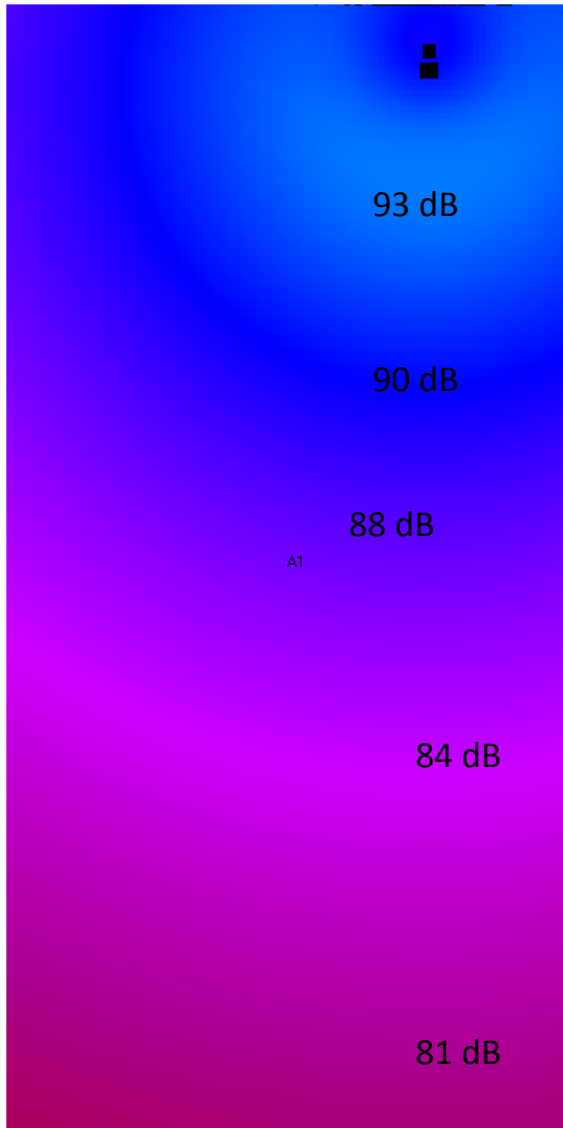Cancellations of 6 – 9 dB over a large area

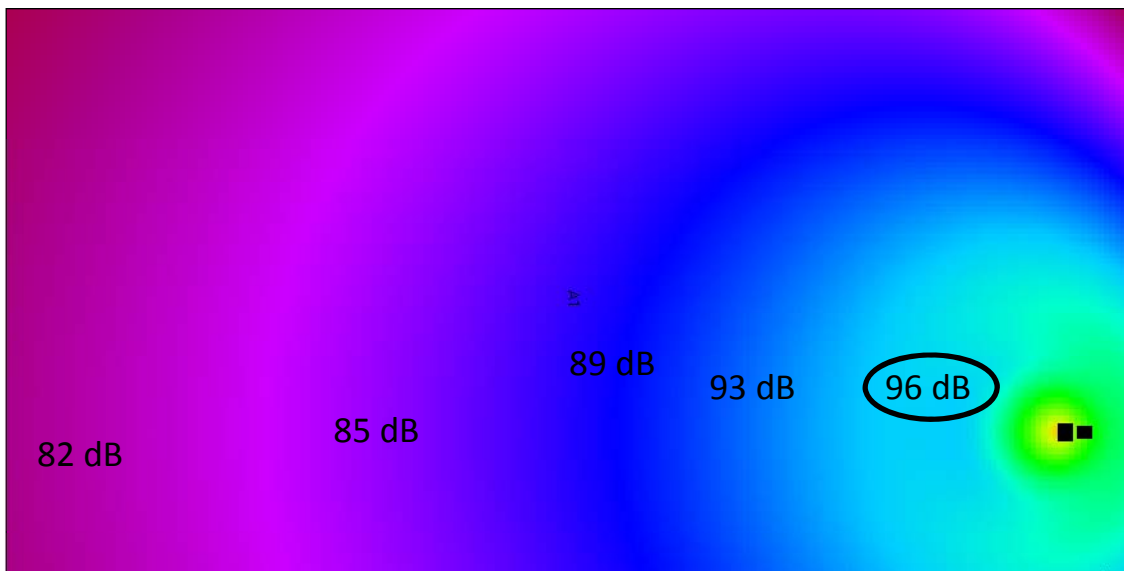**Excelsior Audio**

SPL Map – 100 Hz

Array Only

Subs (no delay) & Array*

Proposed Alignment Method
Subs (6 ms) & Array

SPL Map (100 Hz) & Frequency Response

Proposed Alignment Method
Subs (6 ms delay) & Array

Note increased SPL below 125 Hz due to being much closer to ground-stacked subs than flown array
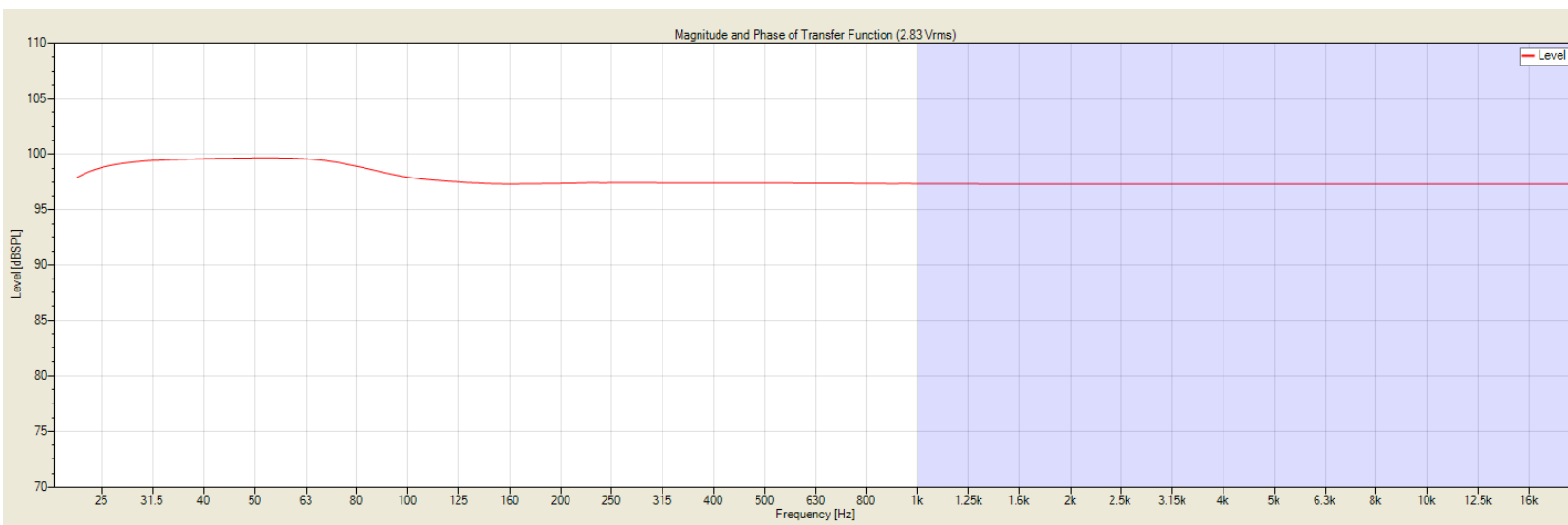
Frequency Response at Location 1

SPL Map (100 Hz) & Frequency Response

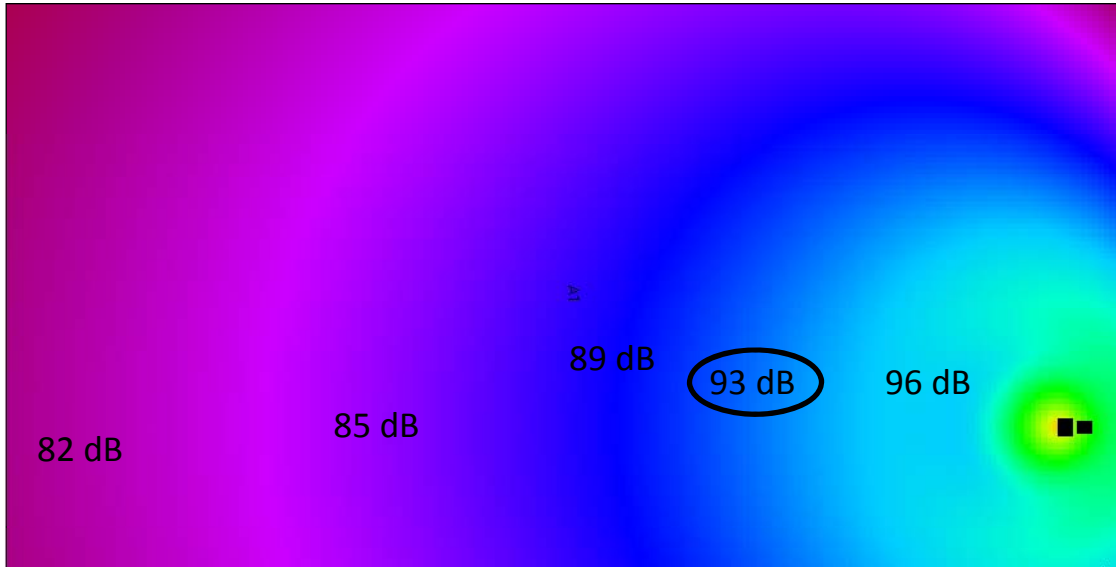**Proposed Alignment Method Subs (6 ms delay) & Array**

Slightly increased SPL below 100 Hz due to being closer to ground-stacked subs than flown array

Frequency Response at Location 2
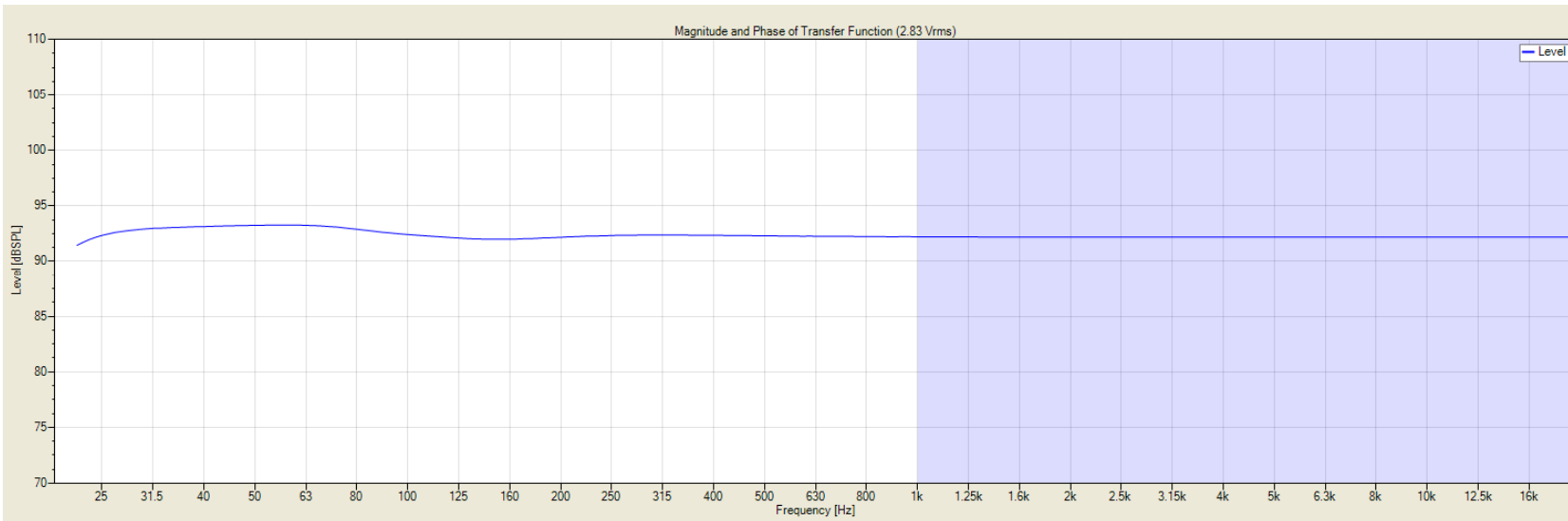
SPL Map (100 Hz) & Frequency Response

Proposed Alignment Method
Subs (6 ms delay) & Array

Frequency Response at
Location 3

SPL Map (100 Hz) & Frequency Response

Proposed Alignment Method
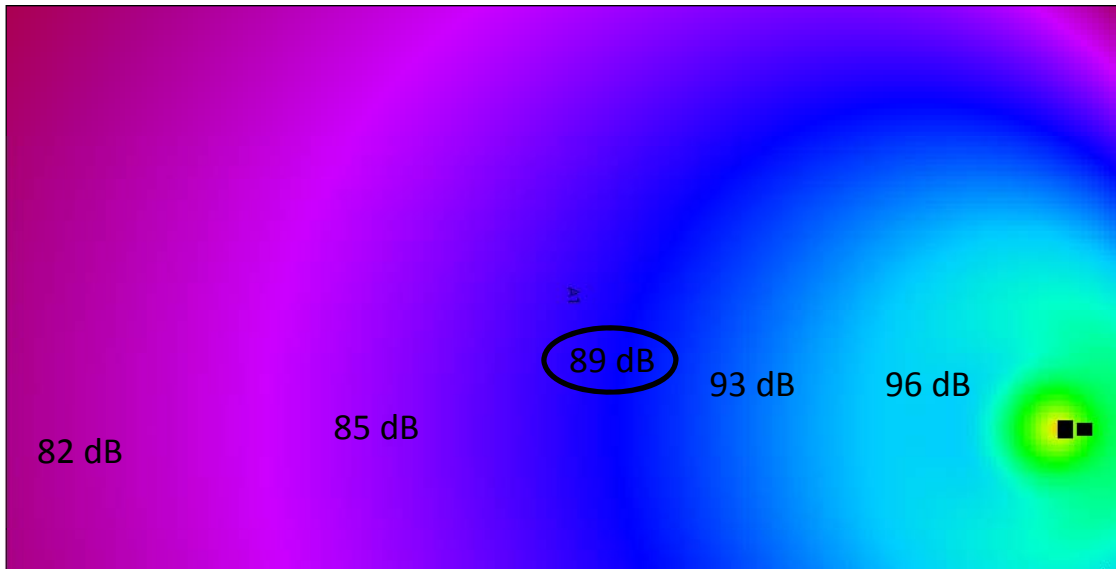Subs (6 ms delay) & Array
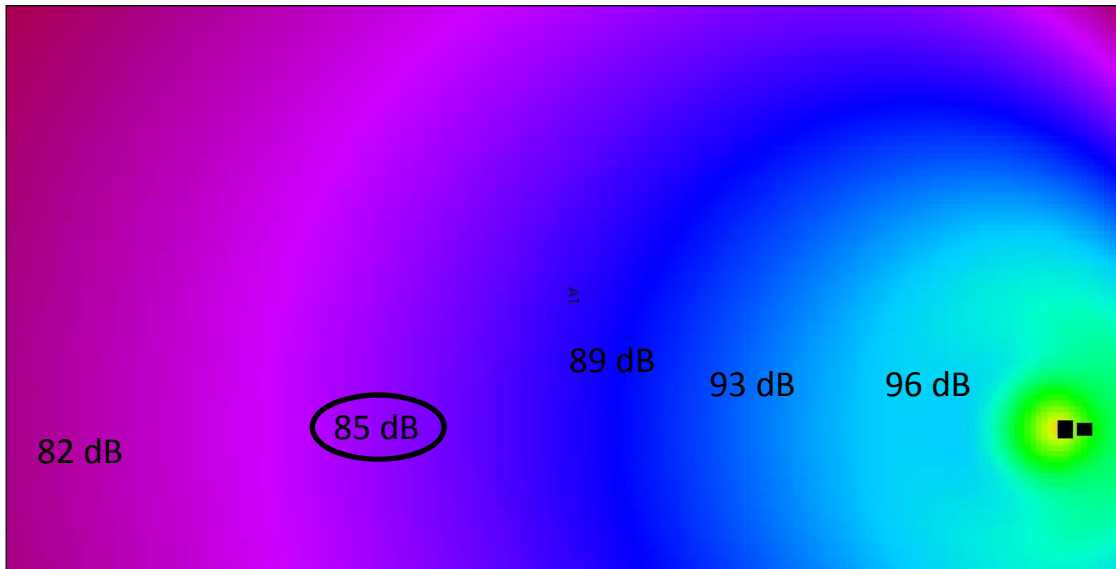
89 dB   93 dB   96 dB

85 dB

82 dB

Frequency Response at
Location 4

SPL Map (100 Hz) & Frequency Response

Proposed Alignment Method
Subs (6 ms delay) & Array

89 dB

93 dB

96 dB

85 dB

82 dB

Frequency Response at
Location 5
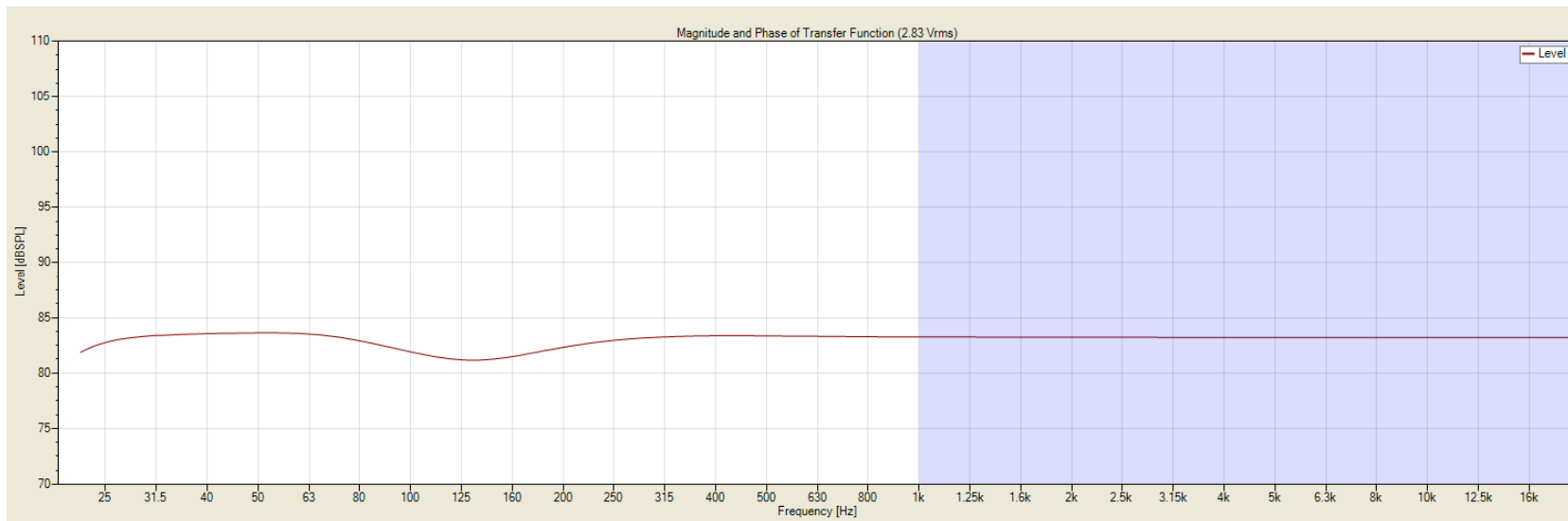
Frequency Response

Frequency Response at Locations 1 – 5

Proposed Alignment Method
Subs (6 ms delay) & Array
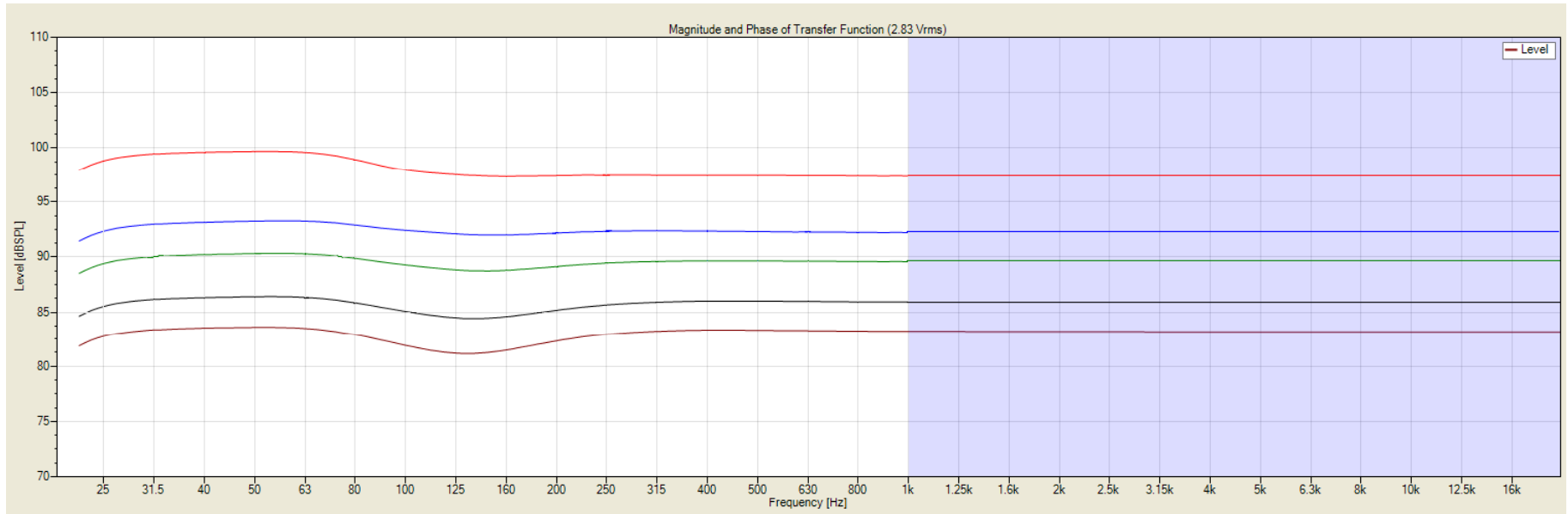
Very even coverage and response with no more than 2 dB deviation in the crossover region

Increased SPL below 125 Hz at Location 1 is due to being much closer to ground-stacked subs than flown array

For 2 dB Uniformity (+/-1 dB)

Method B

Choose area for exact alignment

1) Let's pick the area with a 5ms difference in arrival time

2) Delay the first signal arrival by this time

3) Examine new arrival time differences

For 2 dB Uniformity (+/-1 dB)

Subs Delayed 5 ms

Method B

Choose area for exact alignment

1) Let's pick the area with a 5ms difference in arrival time

2) Delay the first signal arrival by 5 ms

3) Examine new arrival time differences

   a) Areas greater than 1.9 ms (75°) will vary by more than 2 dB

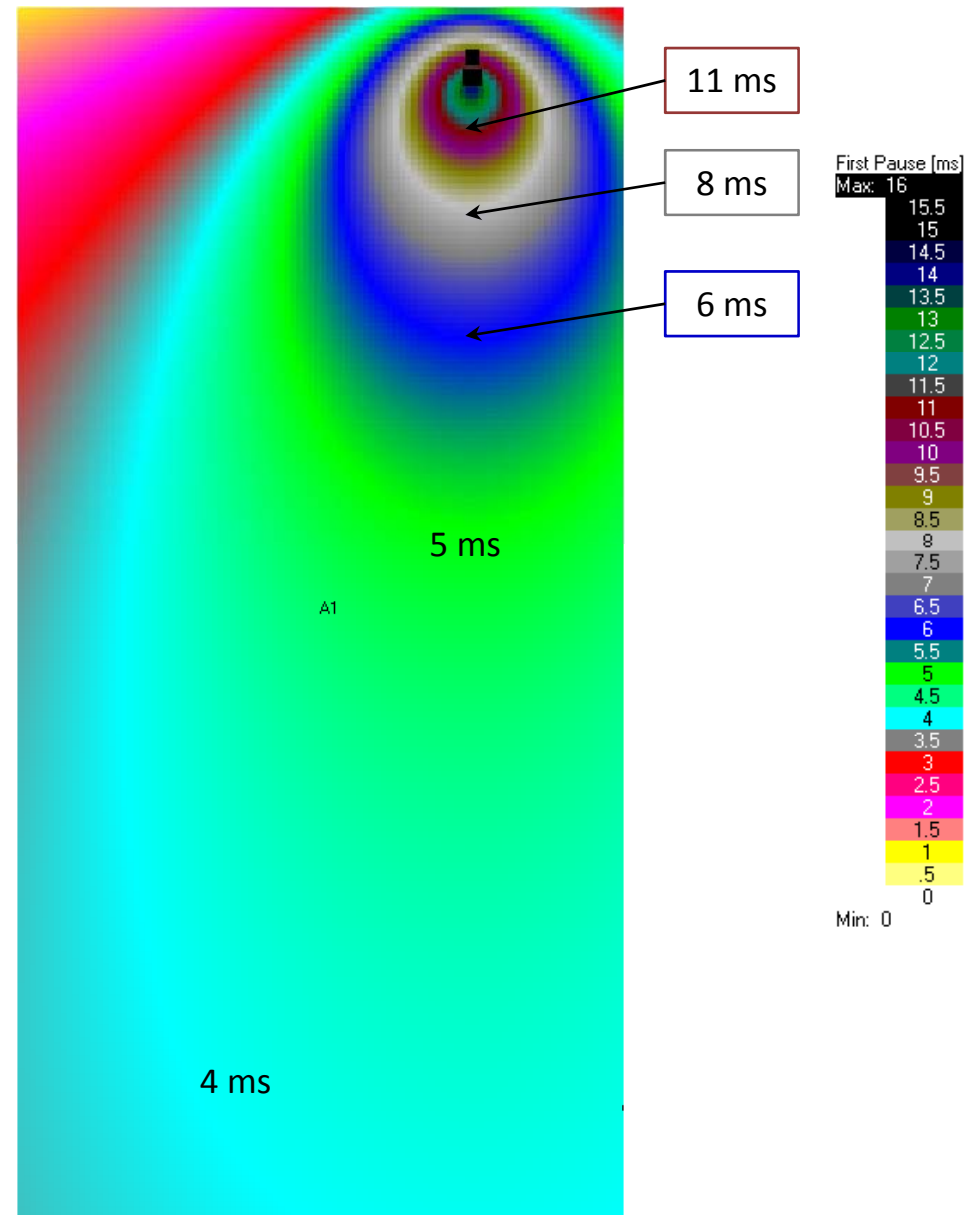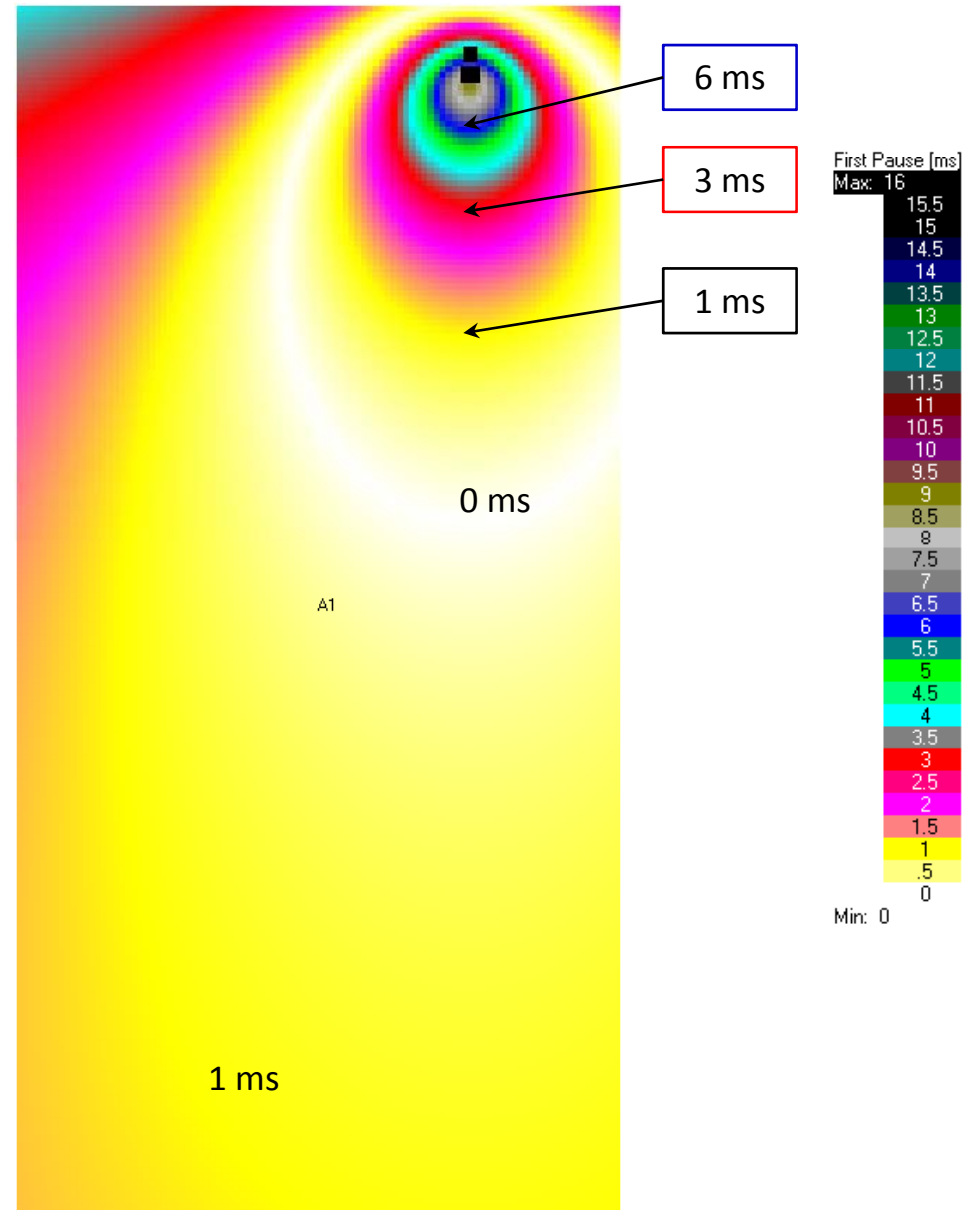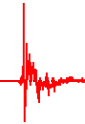   b) Areas greater than 2.3 ms (90°) will vary by more than 3 dB

SPL Map – 100 Hz

The summation is still very good throughout the area.

The 5 ms delay improves the middle and rear of the coverage area at the expense of the front.

Subs (5 ms) & Array

94 dB

93 dB

90 dB

A1

86 dB

83 dB

Previous Method A
Subs (6 ms) & Array

96 dB

93 dB

89 dB

A1

85 dB

82 dB

Direct SPL [dB]
Max: 120
120
119
118
117
116
115
114
113
112
111
110
109
108
107
106
105
104
103
102
101
100
99
98
97
96
95
94
93
92
91
90
89
88
87
86
85
84
83
82
81
80
79
78
77
76
75
Min: 74

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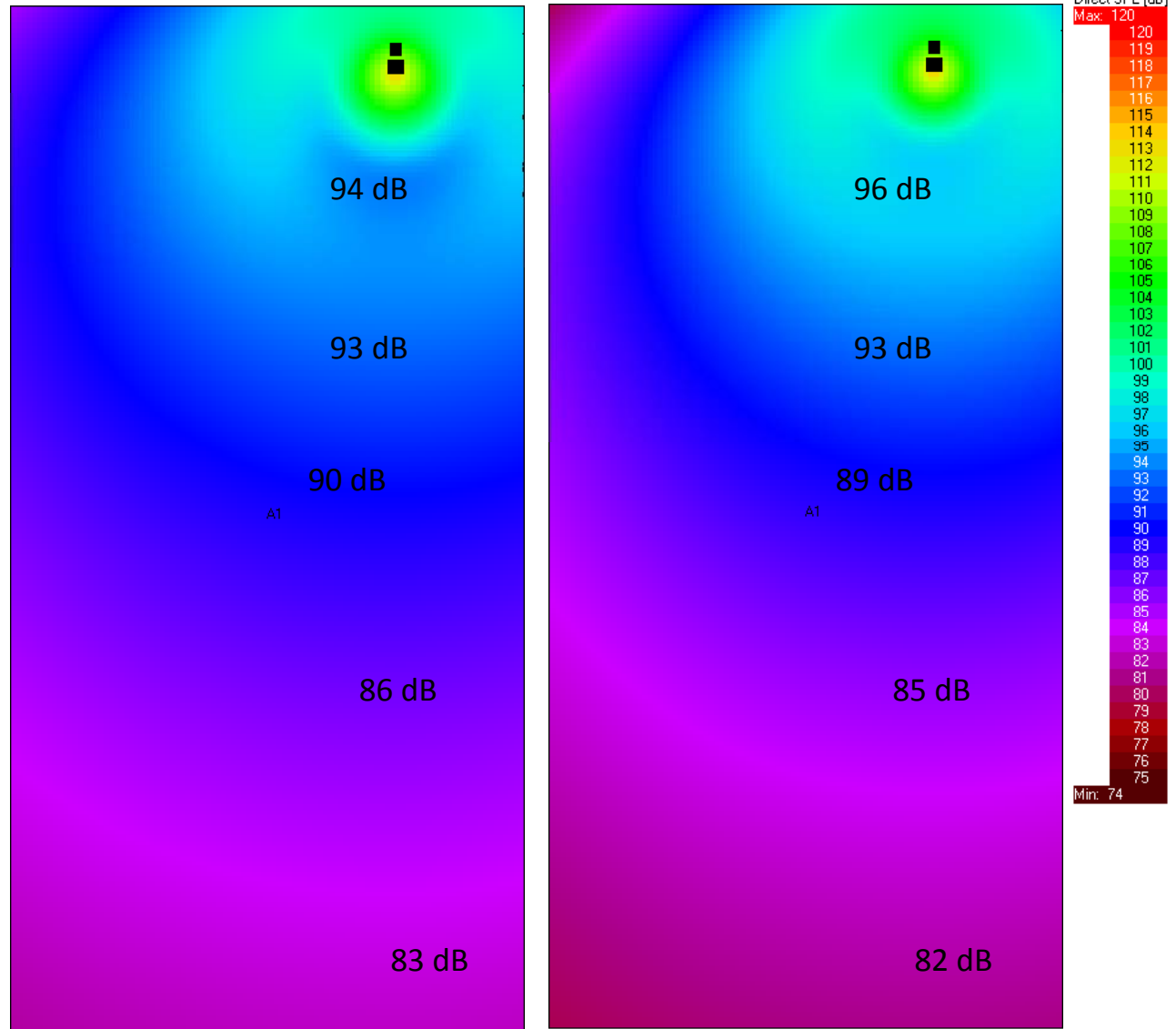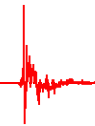
Frequency Response

Frequency Response at Locations 1 – 5

Proposed Alignment Method
Subs (5 ms delay) & Array

Very even coverage and response with no more than 2 dB deviation in the crossover region, except for Location 1.

This is due to it being out of alignment by more than 1.9 ms (approx. 2.5 – 3 ms).

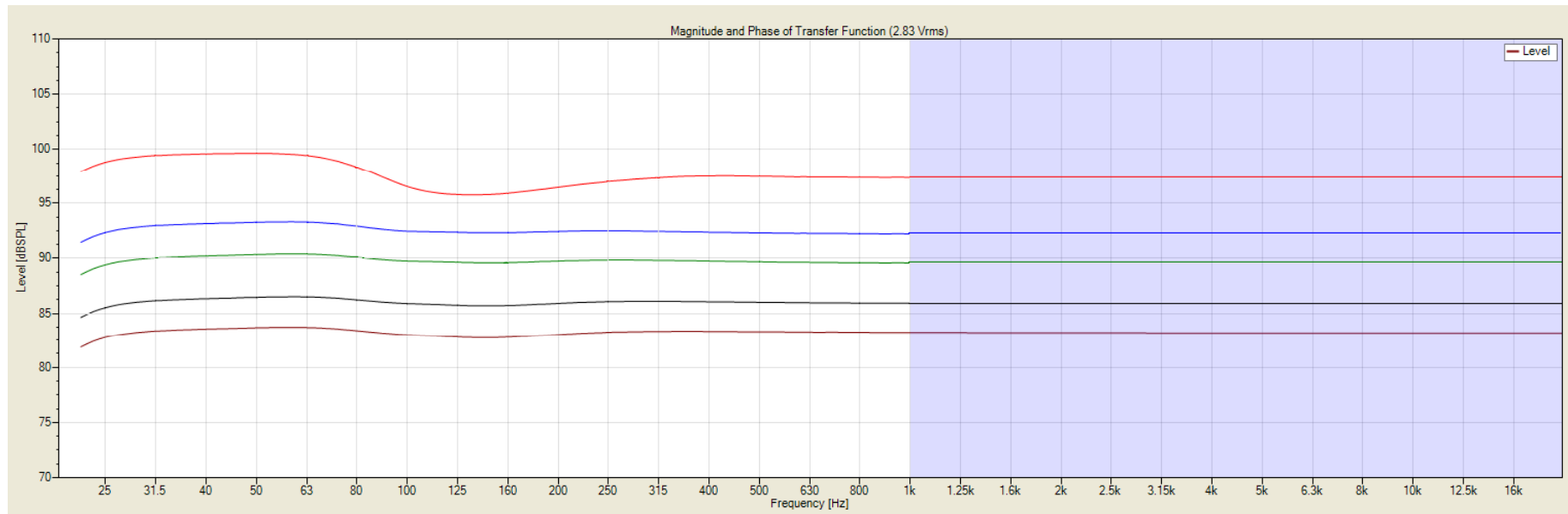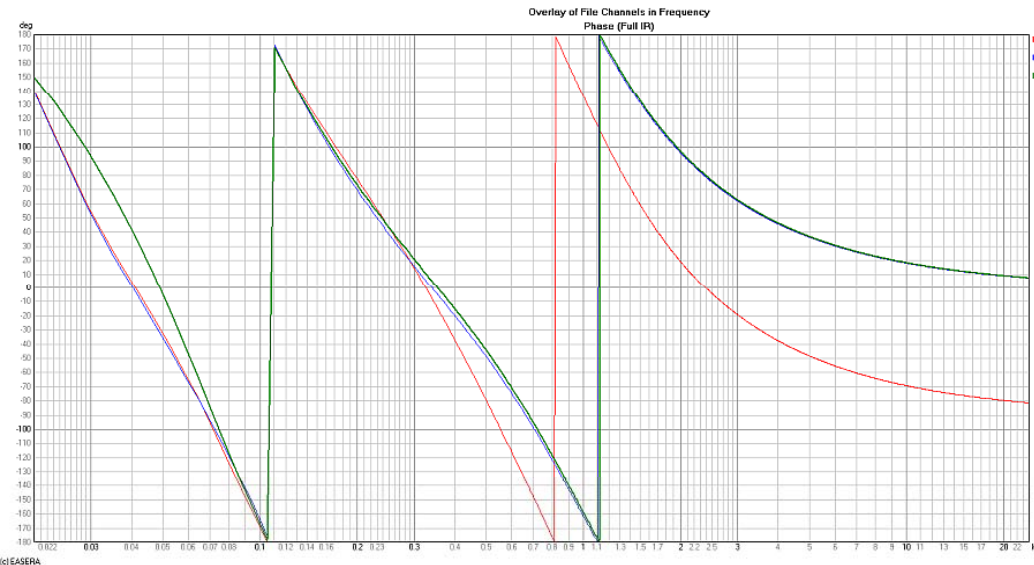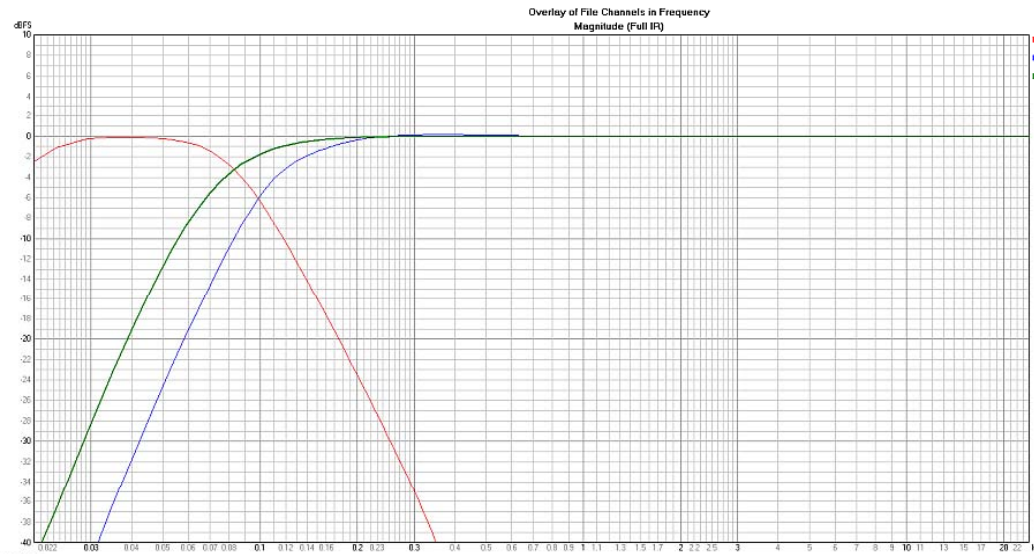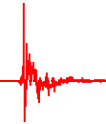# Full-Range Overlapping Subs

Extending LF output of full-range array to overlap the output from the subs

Full-Range new filtering:
HP - 75 Hz, 2nd order Butterworth
AP - 10 Hz, 1st order
AP - 80 Hz, 1st order

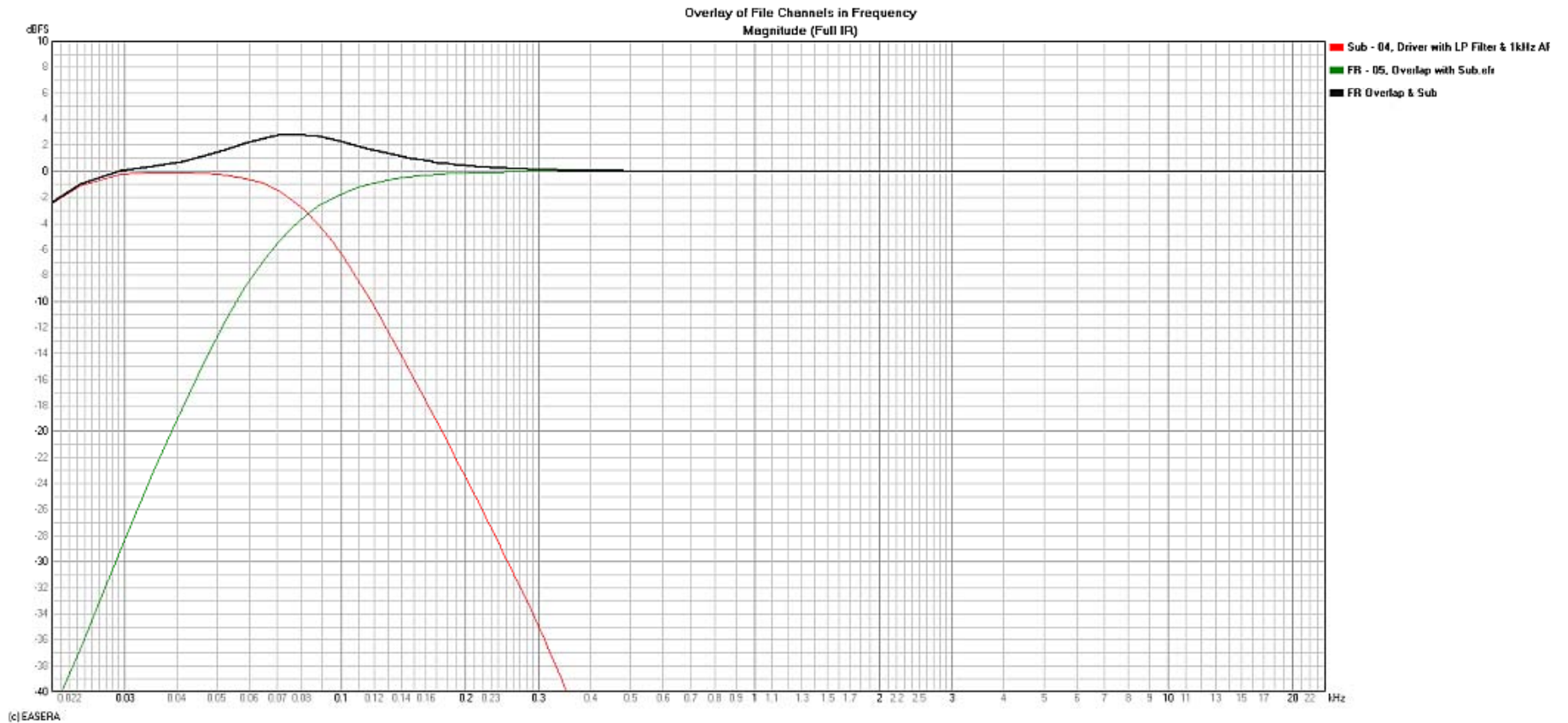We must still maintain matching phase response of the subs through the crossover region

Subs – Red
Full-Range original filtering– Blue
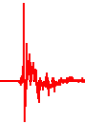Full-Range with new filtering– Green

Full-Range Overlapping Subs

The overlapping response of the full-range array with the subwoofers results in a +3 dB bump in the combined system response.

Subs – Red
Full-Range with new filtering– Green
Subs + Full-Range - Black
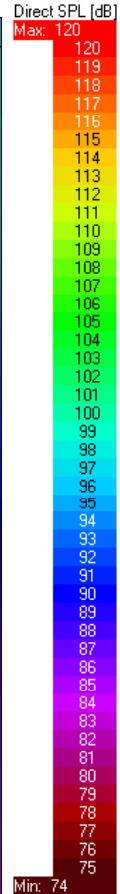
SPL Map – 100 Hz

Subs (6 ms) & Overlapping Array
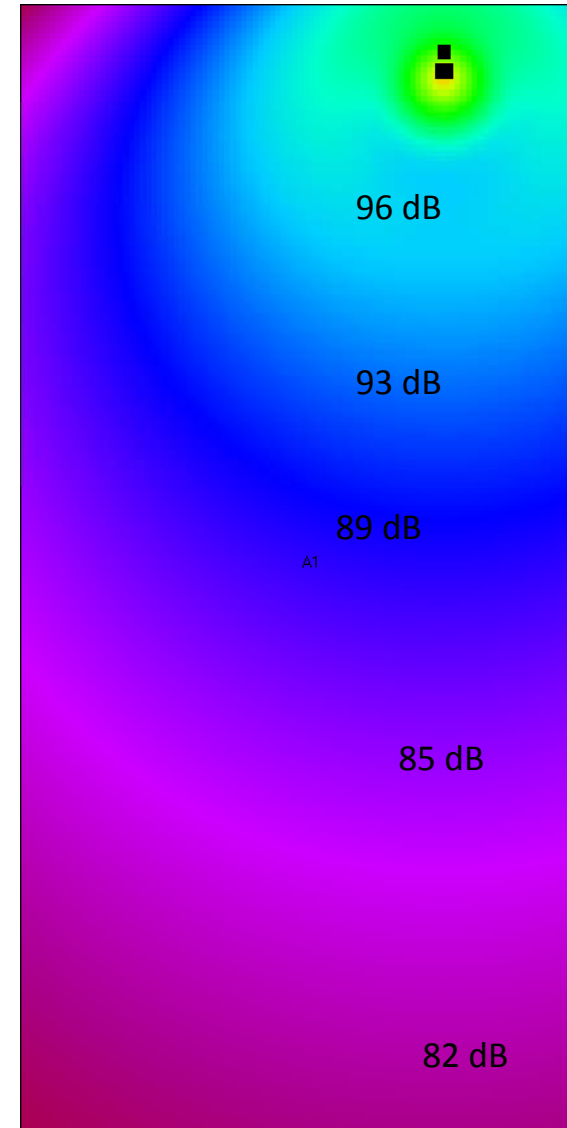
Proposed Alignment Method
Subs (6 ms) & Array

The summation is still very good throughout the area.

The overlapping neither significantly helps nor hurts the coverage.

It just increases the overall level a bit, but only in the crossover region.

This could have easily been achieved with system EQ.
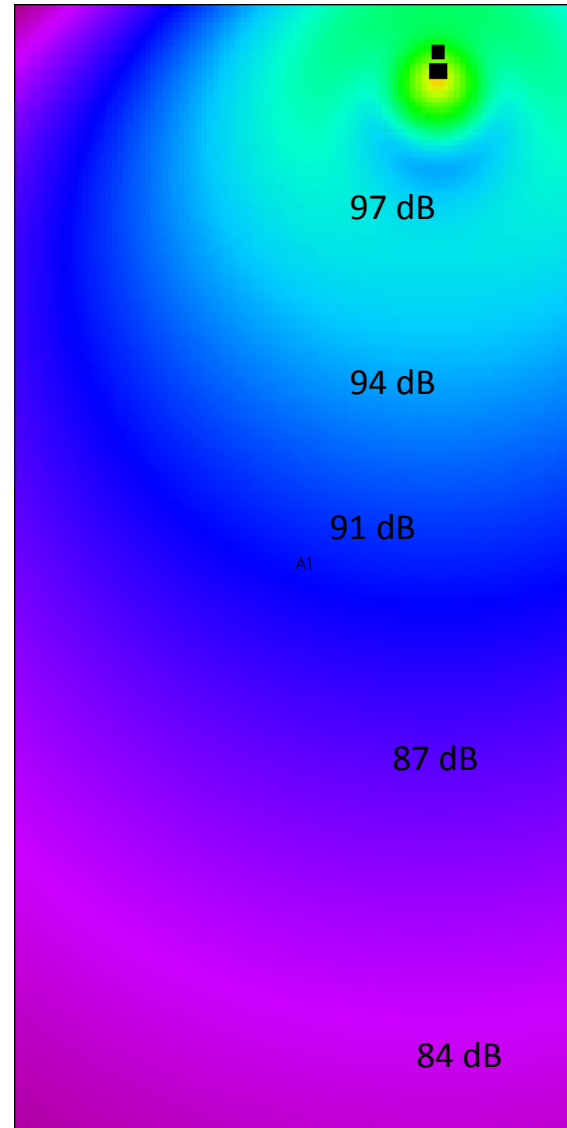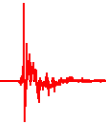
Left panel (Subs (6 ms) & Overlapping Array):
97 dB
94 dB
91 dB
A1
87 dB
84 dB

Right panel (Proposed Alignment Method – Subs (6 ms) & Array):
96 dB
93 dB
89 dB
A1
85 dB
82 dB

Direct SPL [dB]
Max: 120
120 119 118 117 116 115 114 113 112 111 110 109 108 107 106 105 104 103 102 101 100 99 98 97 96 95 94 93 92 91 90 89 88 87 86 85 84 83 82 81 80 79 78 77 76 75
Min: 74

Frequency Response

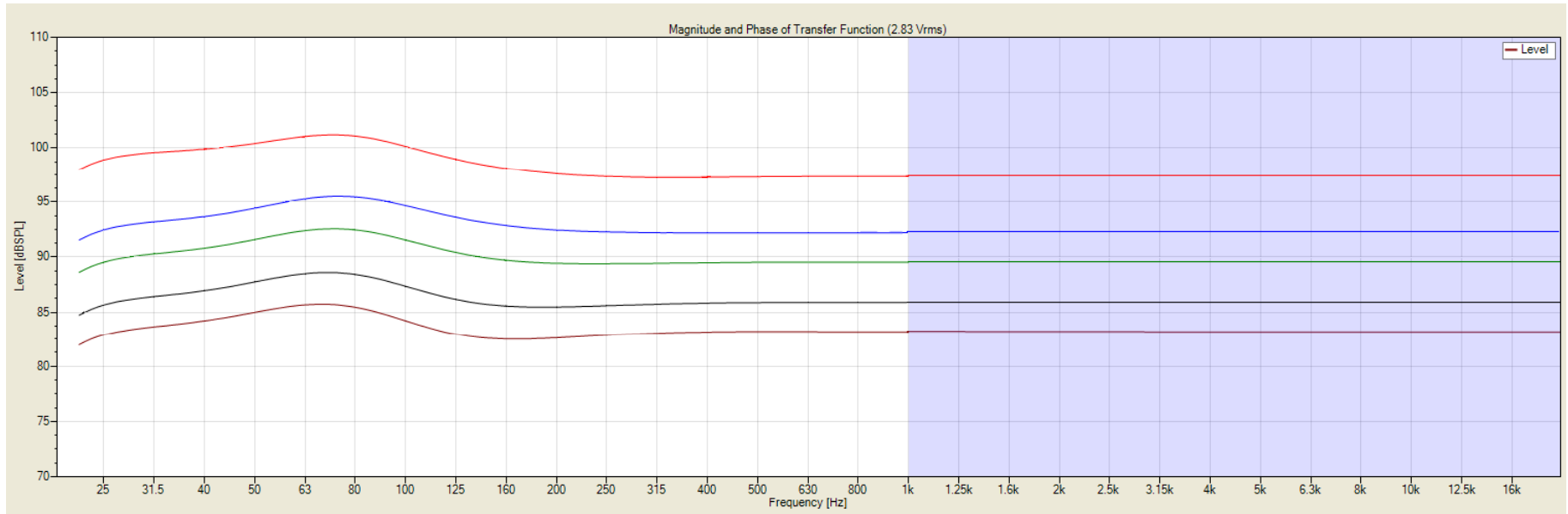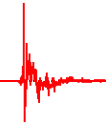Frequency Response at Locations 1 – 5

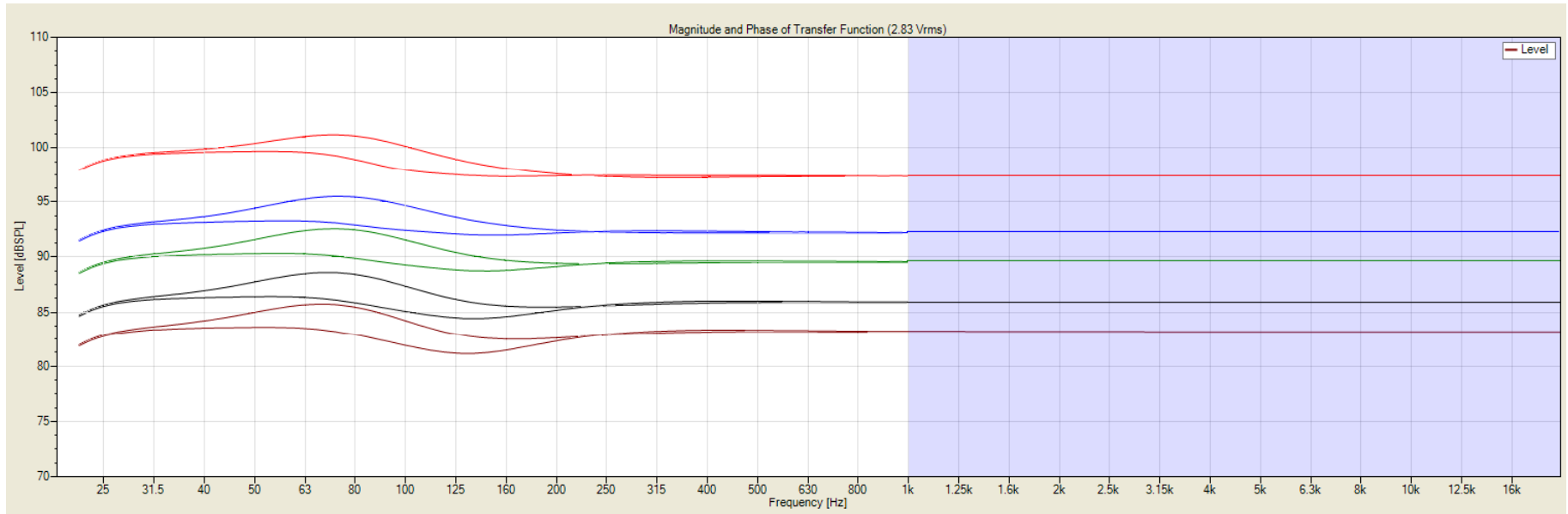Proposed Alignment Method
Subs (6 ms delay) & Overlapping Array

Similar response to original filtering but with increased SPL in the 50 – 150 Hz region.

Frequency Response

Frequency Response at Locations 1 – 5

Comparison of the loudspeakers at the same locations with the original filtering and with the full-range array overlapping the sub

Conclusions

For the most consistent response over a relatively large area:

1) Determine the differences in initial energy arrival times for the subwoofer and the full-range loudspeakers over the intended coverage (audience) area

2) Choose the target region of the coverage area in which the subwoofer and the full-range loudspeakers should be in near perfect alignment

3) Align the initial energy arrivals of the subwoofer and the full-range loudspeakers in the **time domain**

4) Choose a target alignment response function in the frequency domain for the outputs of the subwoofer and full-range loudspeakers **after** the crossover filtering has been applied, e.g. Linkwitz-Riley 4th order

5) Align the phase responses of the subwoofer and the full-range loudspeakers through the crossover region in the frequency domain