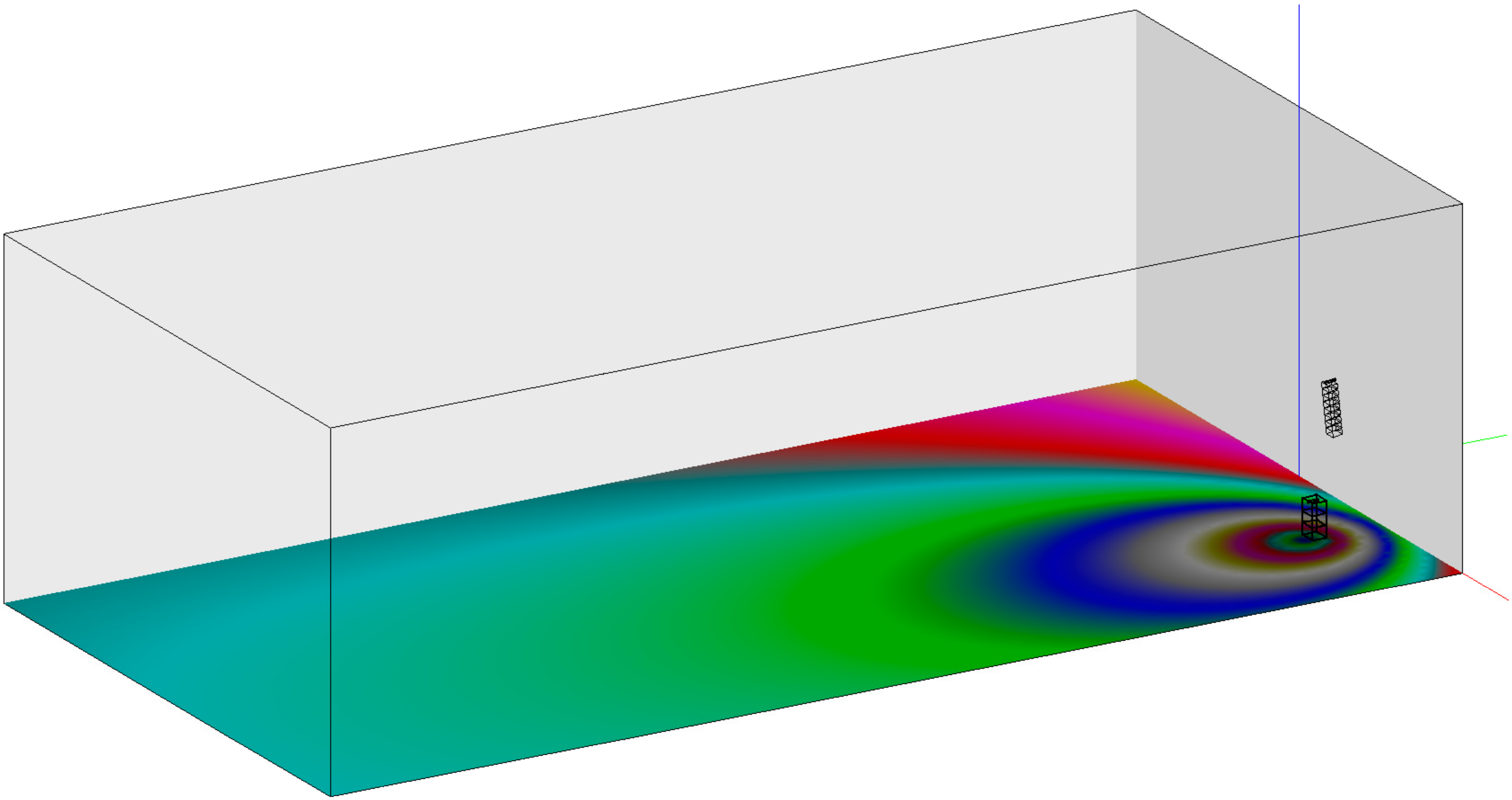
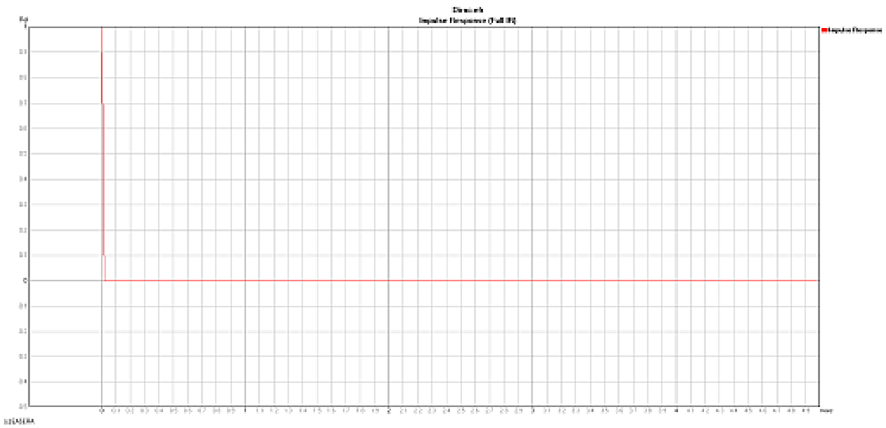
Subwoofer Alignment with a Full-Range System



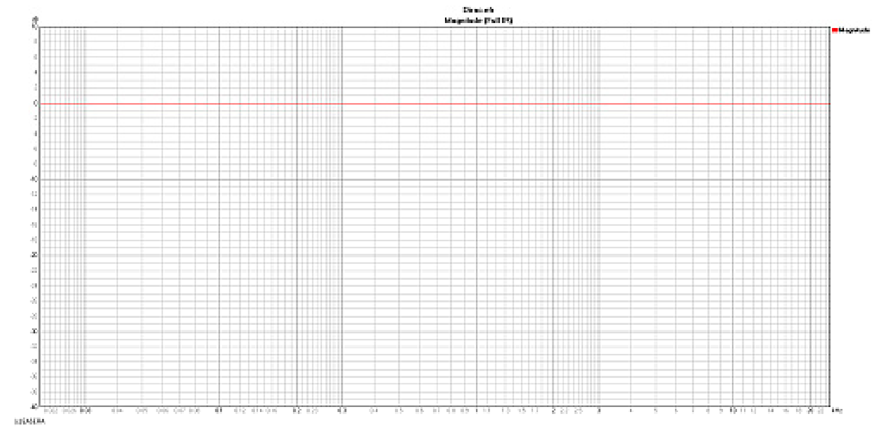
Target Response

Perfect impulse at time t=0

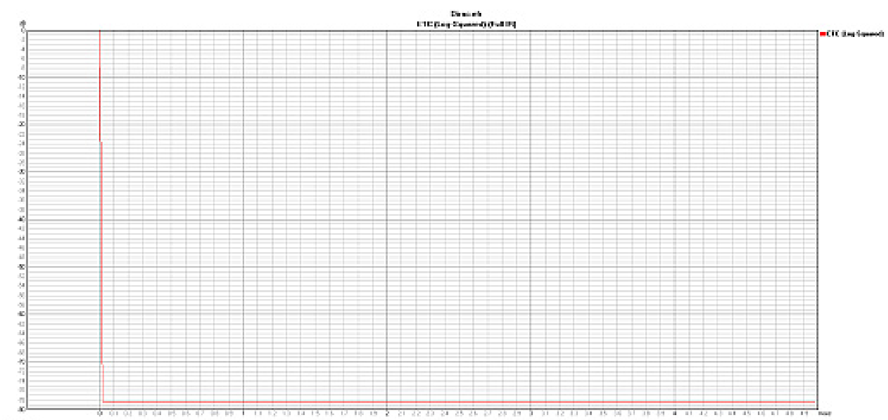
Impulse Response



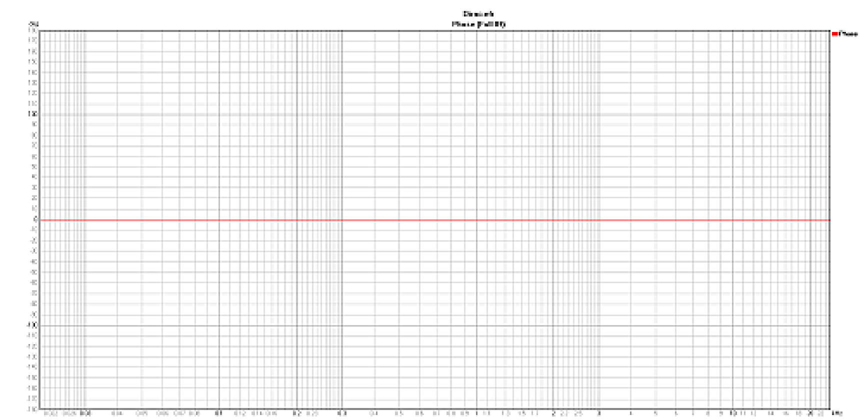
Magnitude Response (Frequency)



ETC Response (Envelope Time Curve)



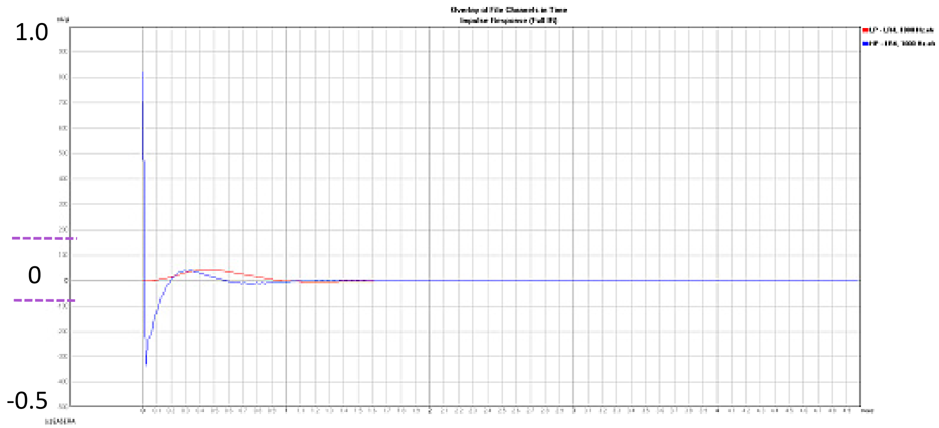
Phase Response



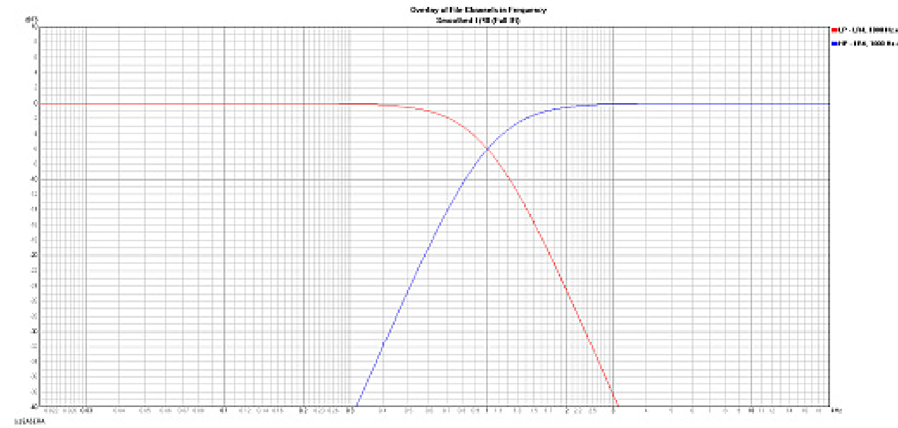
Target Response

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

Impulse Response

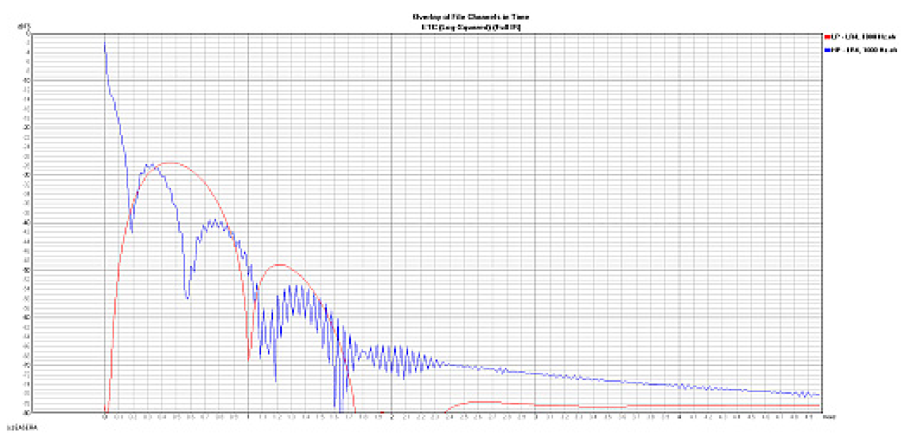


Magnitude Response (Frequency)

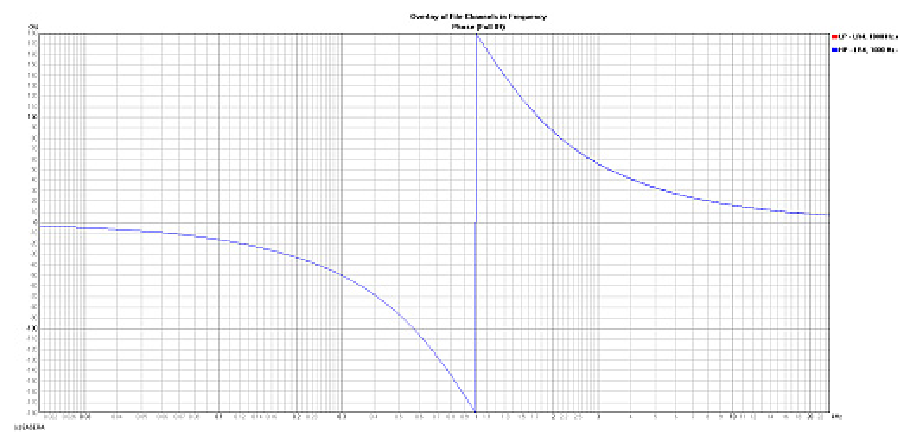


LP – Red; HP – Blue

ETC Response (Envelope Time Curve)



Phase Response

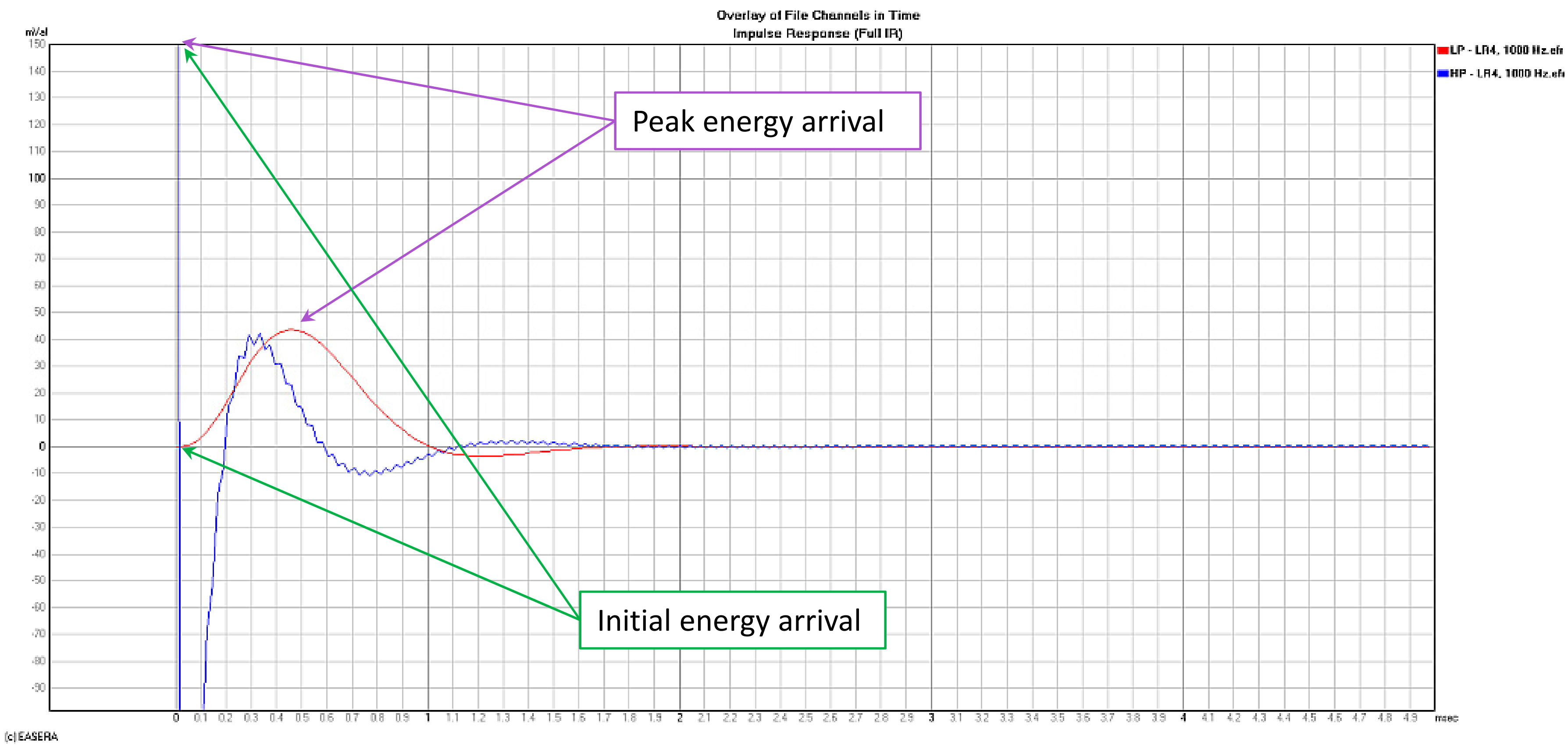


Target Response

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

Impulse Response (zoomed in)

Initial energy arrivals aligned

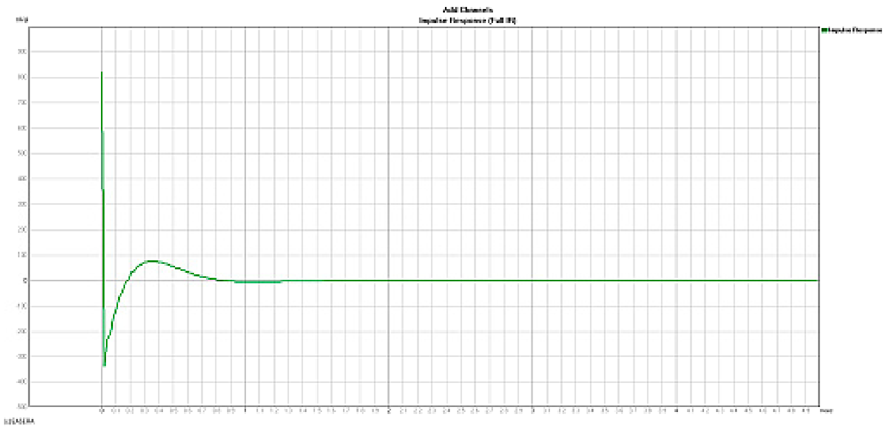


LP – Red; HP – Blue

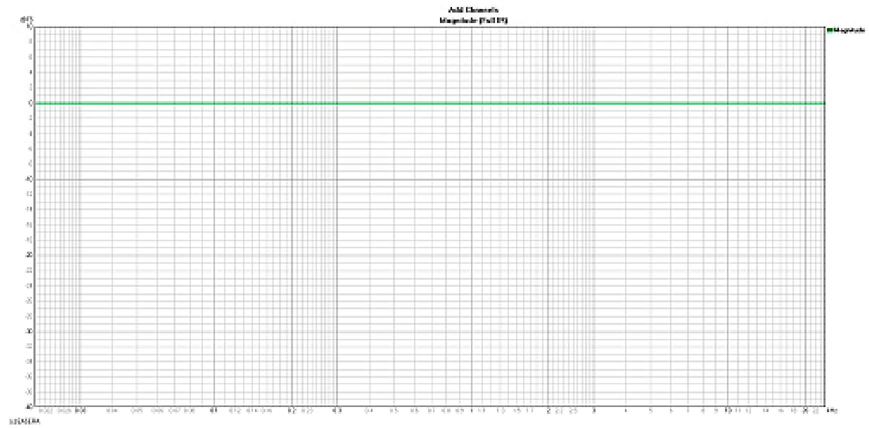
Target Response

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

Impulse Response

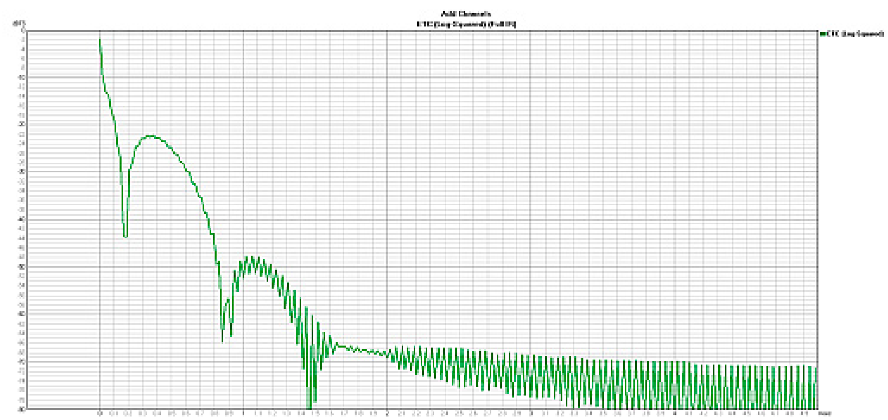


Magnitude Response (Frequency)

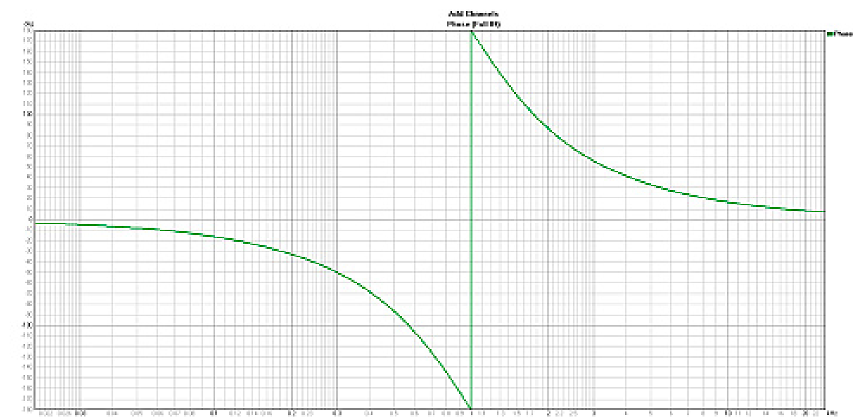


Summation – Green

ETC Response (Envelope Time Curve)



Phase Response



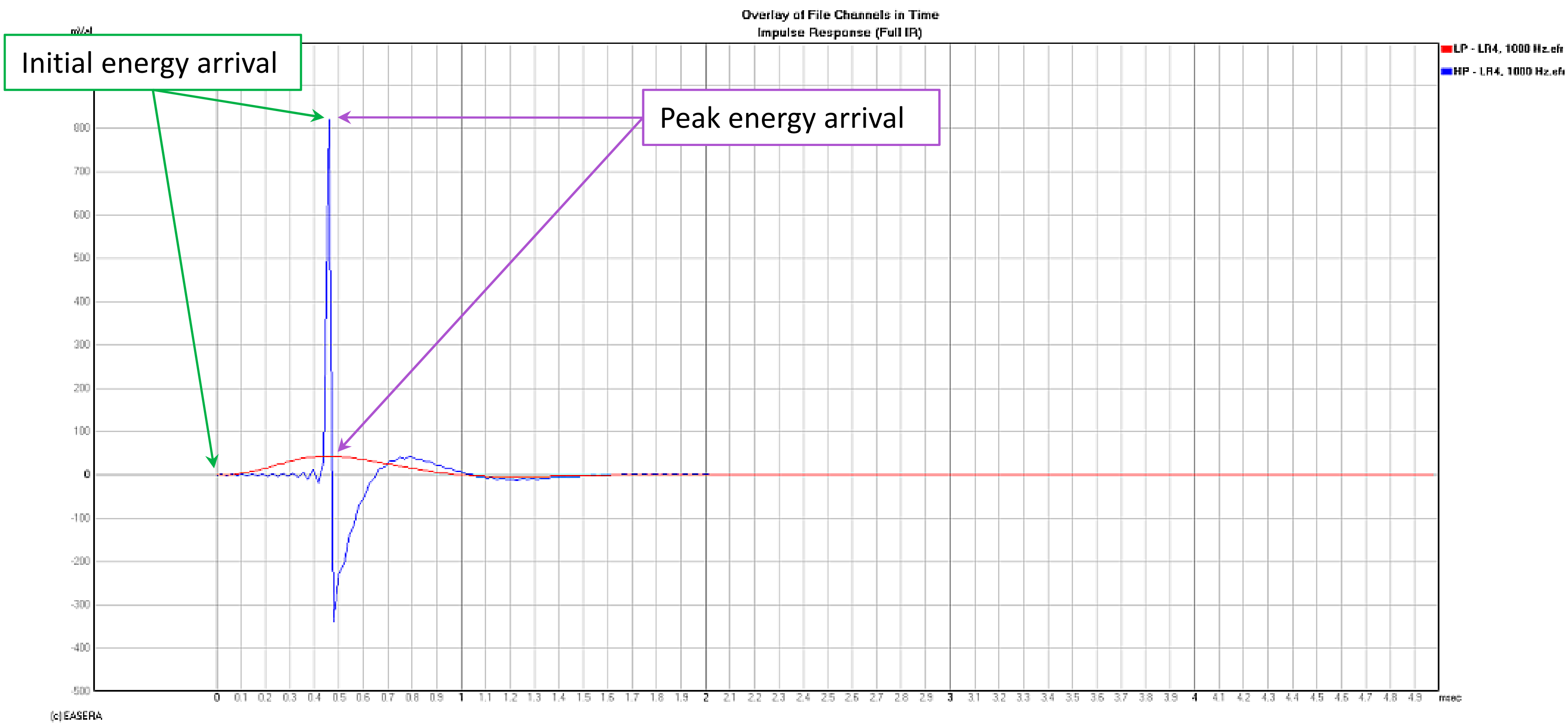
Target Response

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

Impulse Response

HP signal delayed 0.46 ms

Peak energy arrivals aligned



LP – Red; HP – Blue

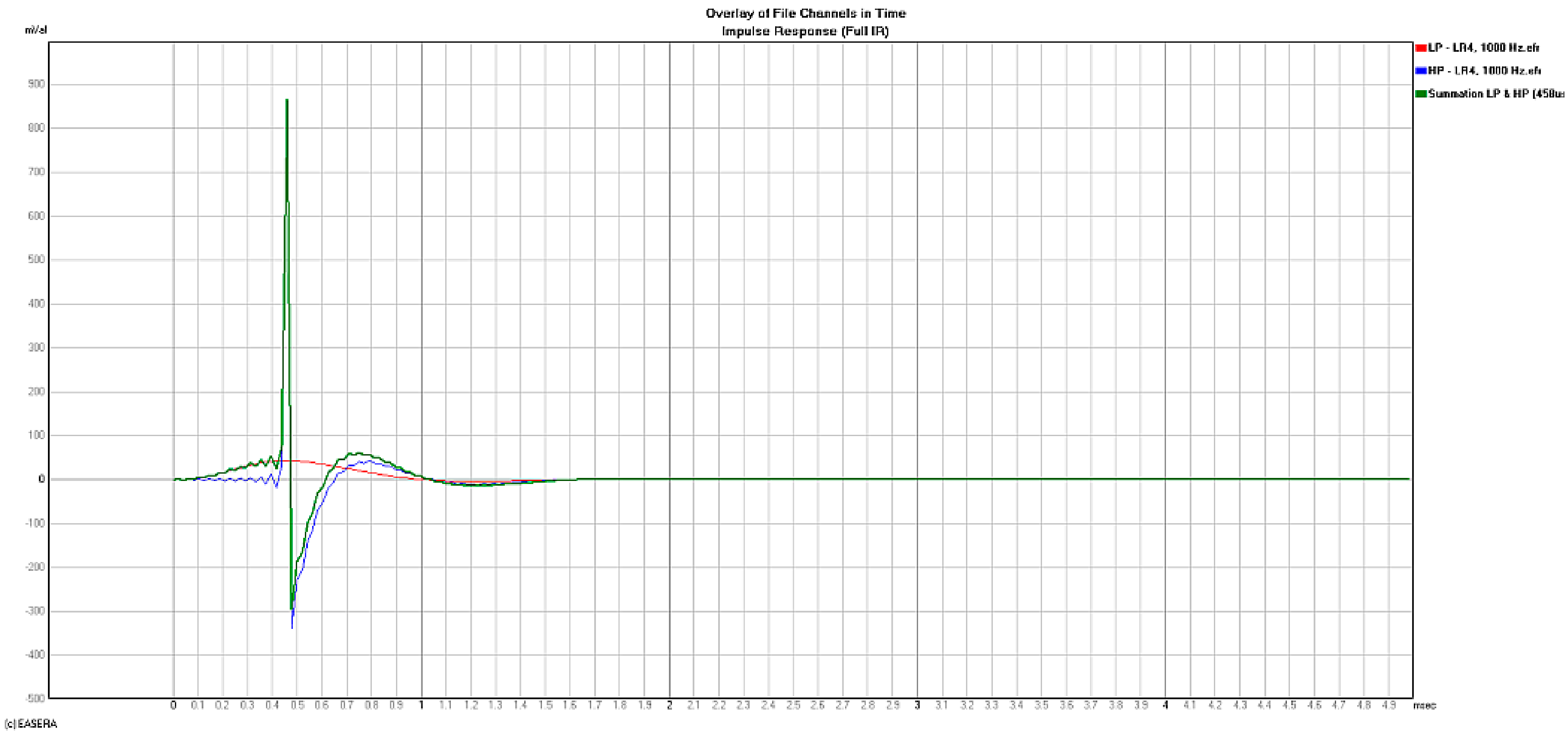
Target Response

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

Impulse Response

HP signal delayed 0.46 ms

Peak energy arrivals aligned



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

Target Response

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

Impulse Response

HP signal delayed 0.46 ms

Peak energy arrivals aligned

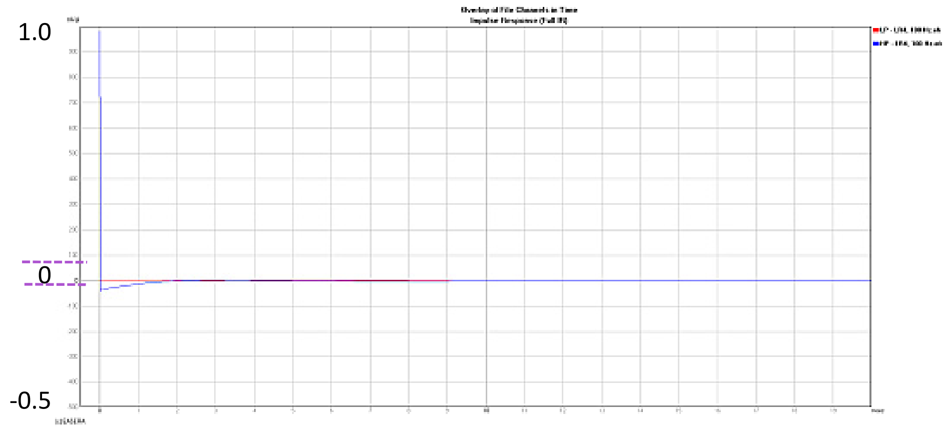
LP – Red; HP – Blue; Summation of LP+HP – Green

Target Response

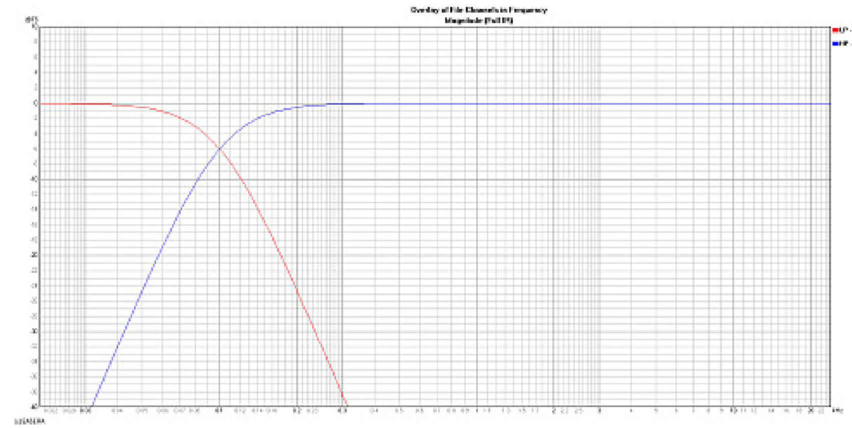
Linkwitz-Riley LP & HP Filters – 4th Order, 100 Hz

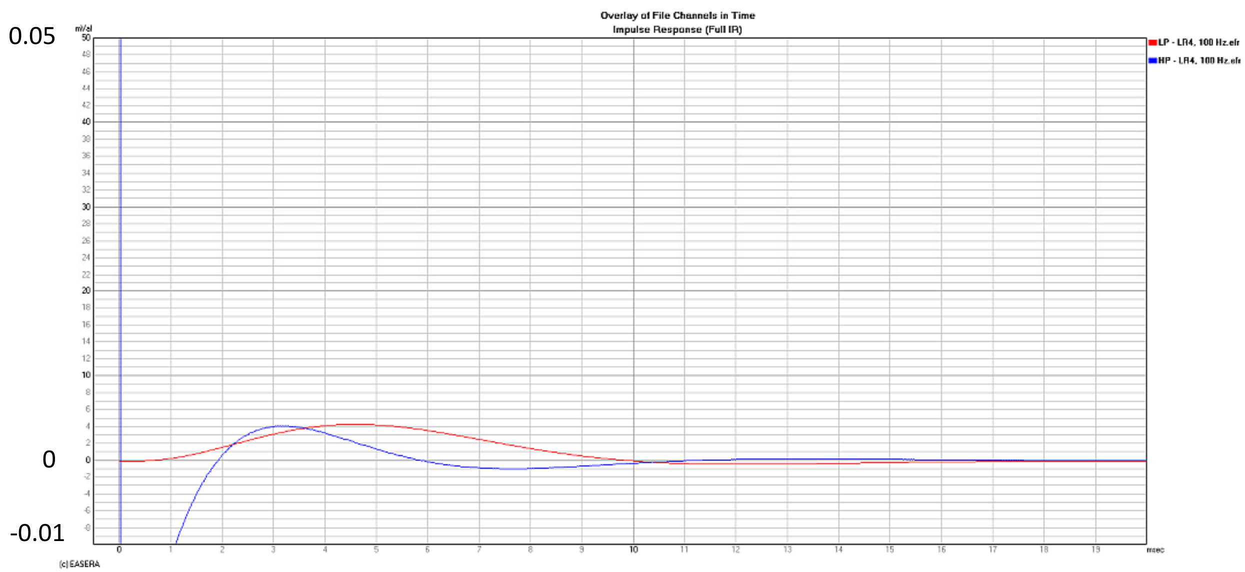
LP – Red; HP – Blue

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

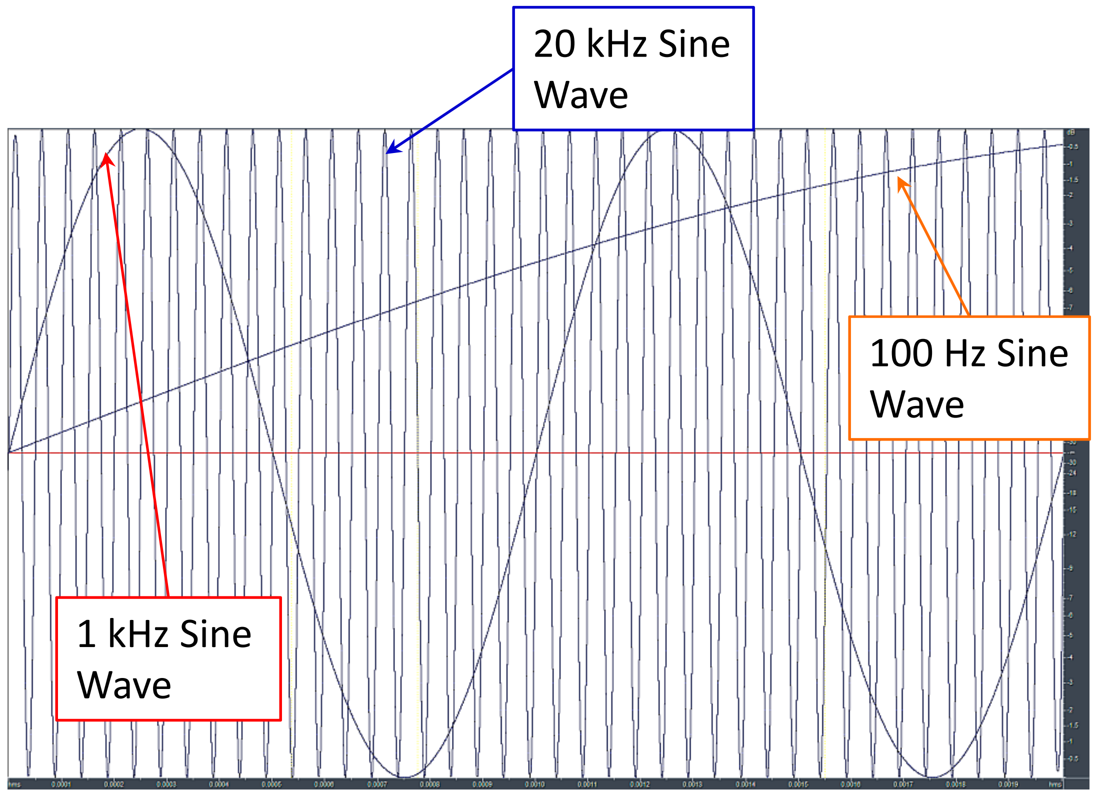
More HF energy in the signal from a device increases our ability to resolve smaller time increments, $\Delta t = 1/\Delta f$

Period = 1/frequency

$P_{20kHz} = 0.05$ ms

$P_{1kHz} = 1.0$ ms

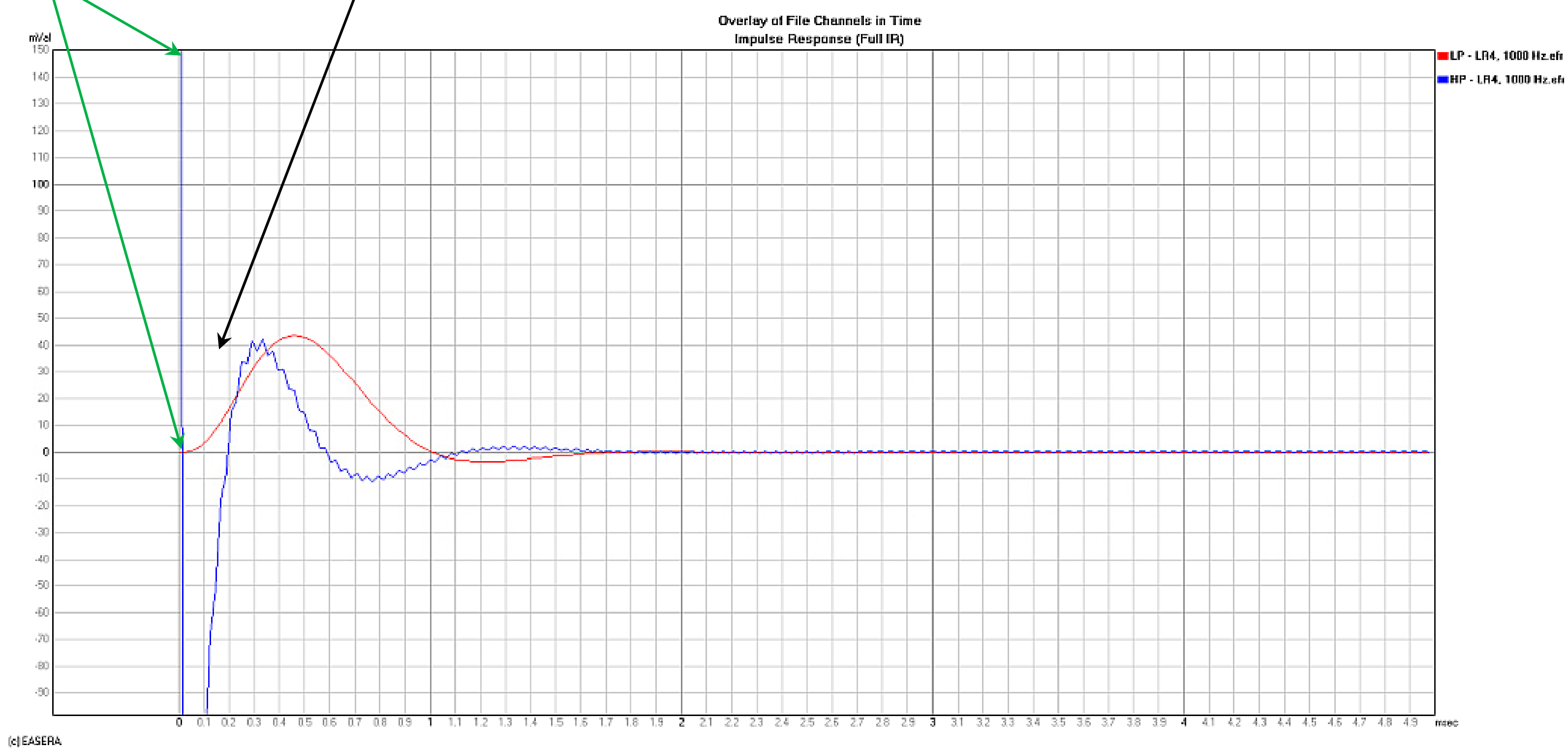
$P_{100Hz} = 10$ ms



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 4^{th} order filters at 1 kHz: LP – Red; HP – Blue;

Measurements and Determining Arrival Time

Group Delay is another way to help determine the true arrival time of a signal

$$\tau_g = -d\phi/d\omega$$

Negative rate of change (slope) of phase with respect to frequency

1) Must inspect frequency region far above the pass band of the device

    This is the region of the missing high frequency energy content (LP).

    Phase has reached a constant (almost constant) value in this region.

2) Requires exceptional signal-to-noise ratio

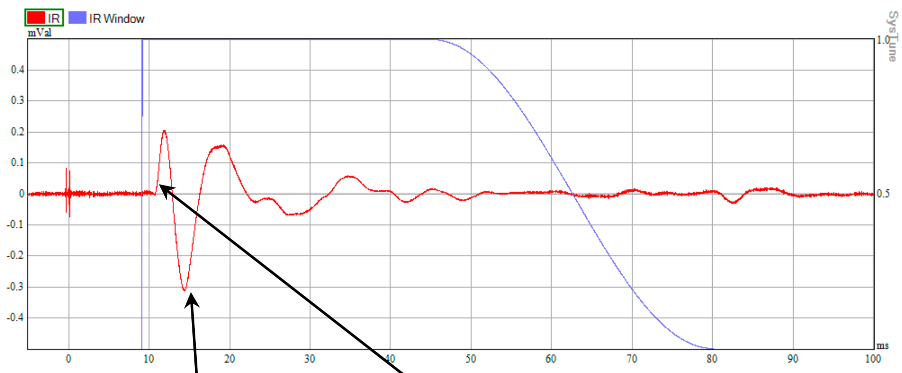
    Dual-channel FFT using sweeps and lots of averages

    Time Delay Spectrometry (TDS)

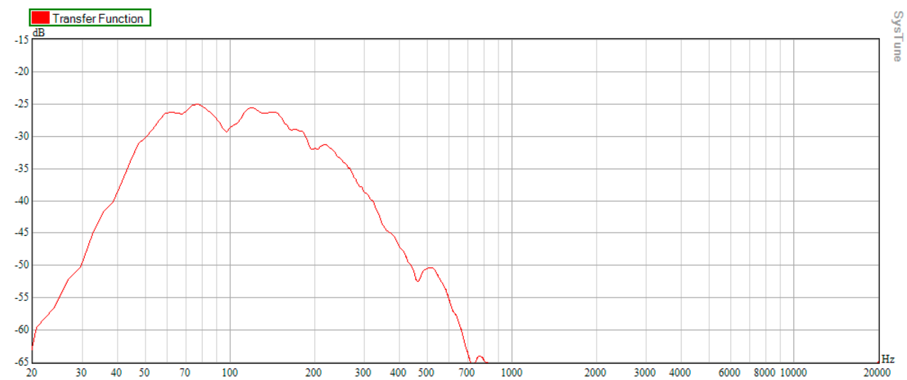
Measurements and Determining Arrival Time

Woofer with 200 Hz LP filter (Limited HF information)

Impulse Response



Magnitude Response (Frequency)

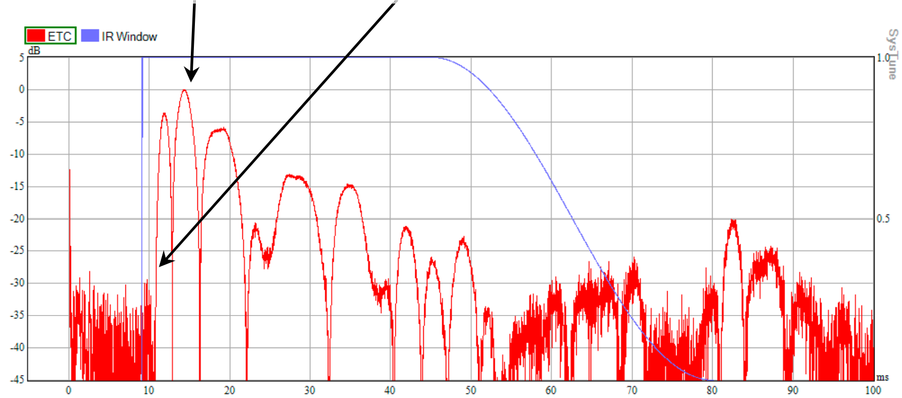


(Approx. 4 ms before energy peak)

Initial energy arrival approx. 10.8 ms

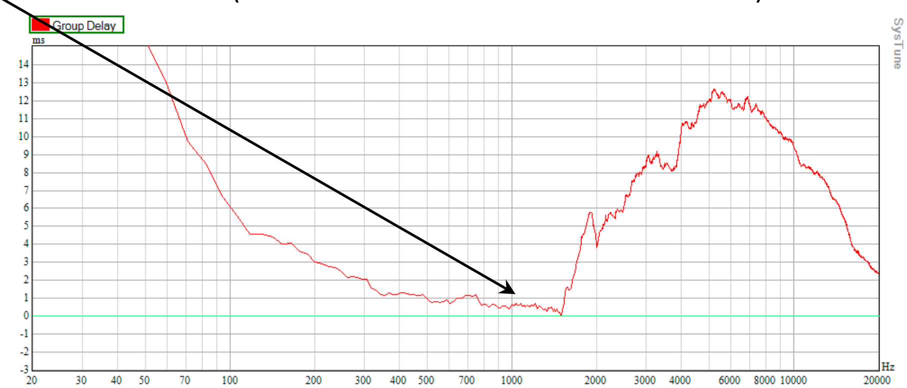
Within 0.2 ms – Less than 8° at 100 Hz!

ETC Response (Envelope Time Curve)



Group Delay

(t=0 referenced to IR window at t=10 ms)



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

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*

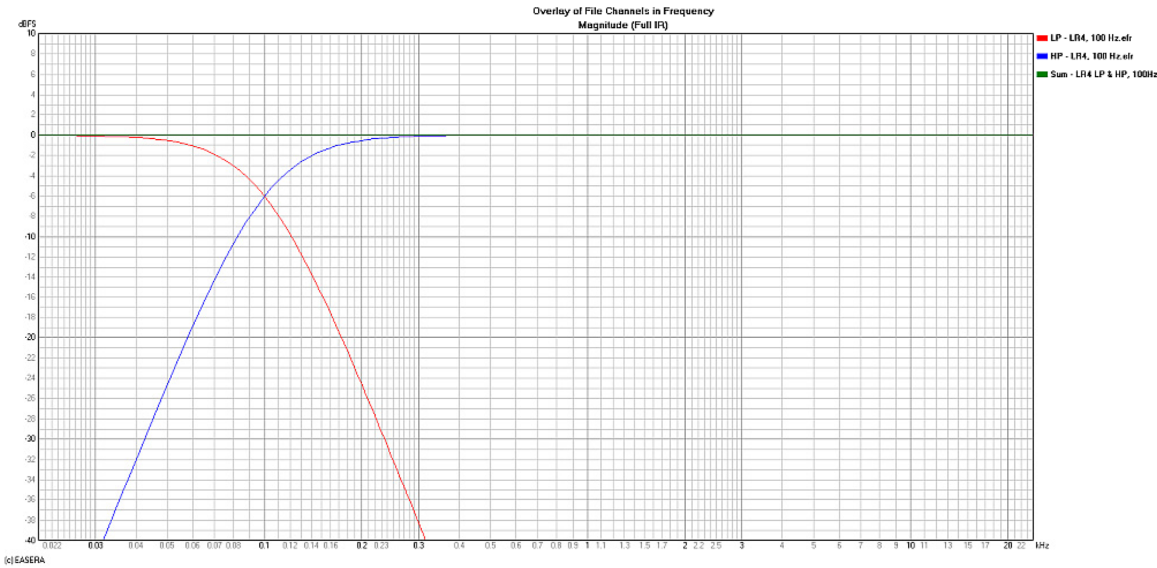
Less than 3 dB variation

Adjacent pass bands must not be out-of-phase by more than 90°

At 100 Hz this is 2.50 ms

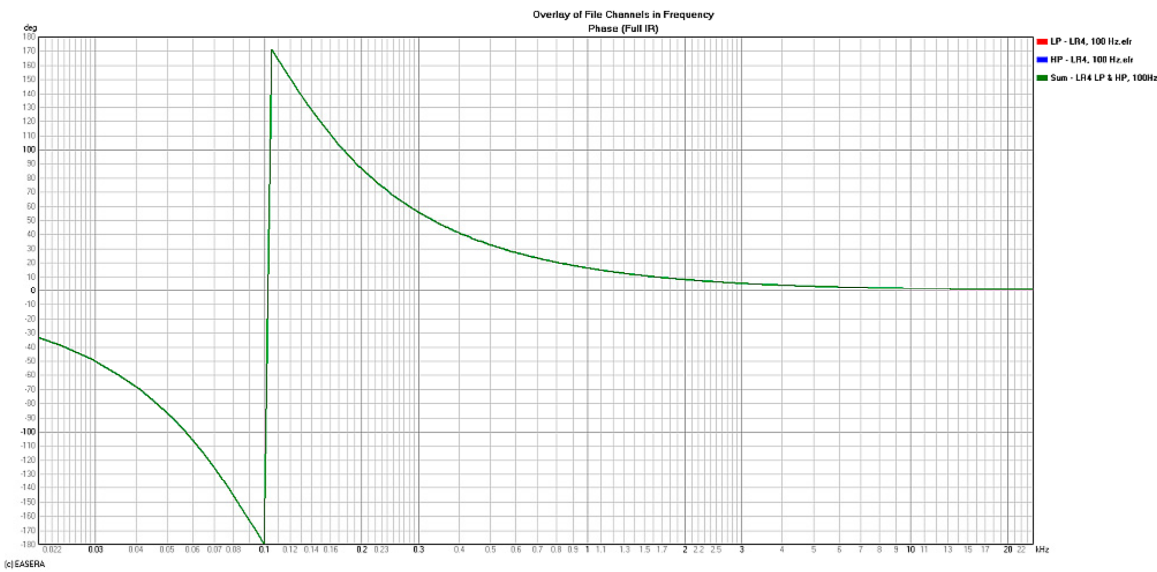
Note: Above the crossover frequency the outputs from the filters are within 10 dB of each other and the wavelengths/periods are shorter. Arrival time constraints must be based on slightly higher frequency. For the Linkwitz-Riley 4th order response in our example this will be approximately 1/6 octave.

Frequency Domain Alignment



Overall Target Response

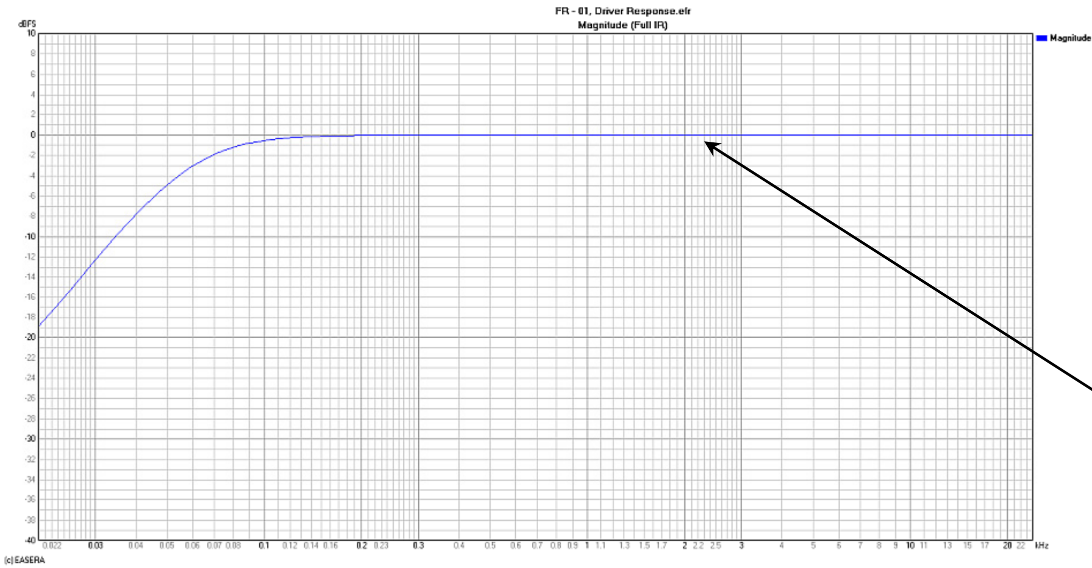
4th order Linkwitz-Riley system with a 100 Hz crossover frequency

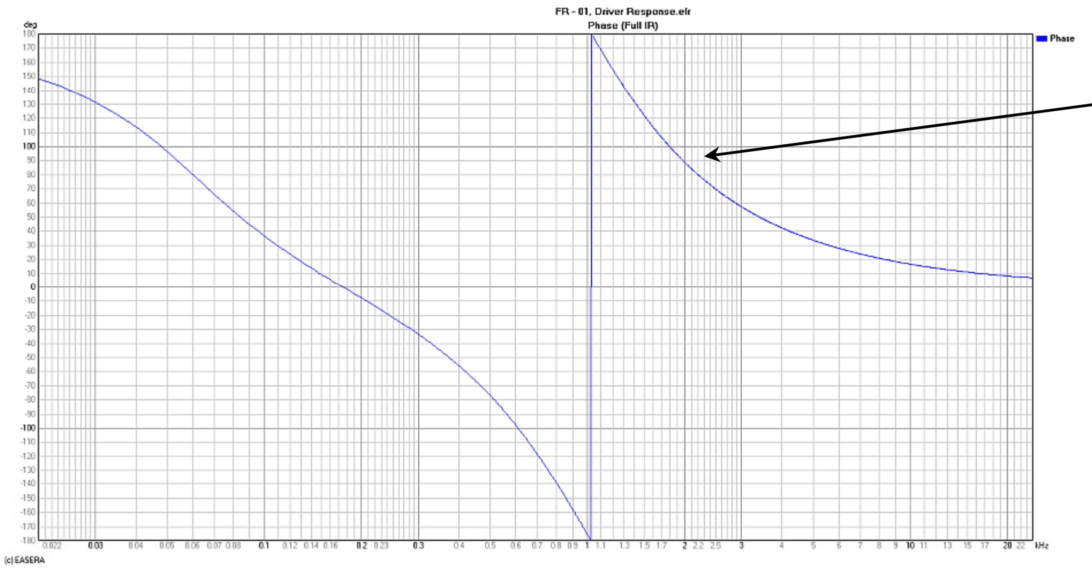


Note that the LP and HP response functions are in phase at all frequencies

LP – Red
HP – Blue
LP+HP – Green

Frequency Domain Alignment





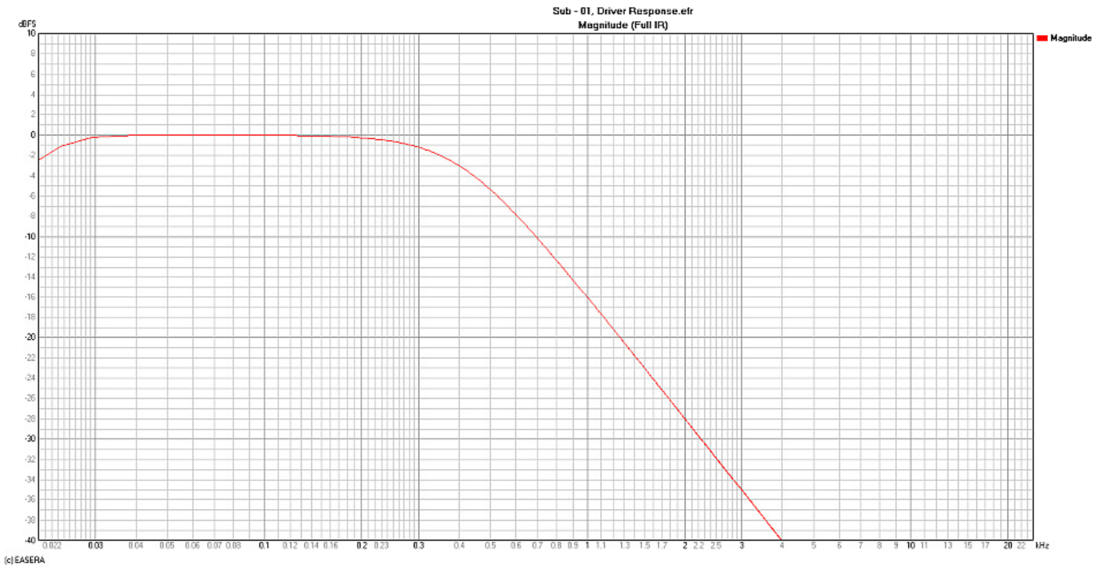
Full-Range Loudspeakers

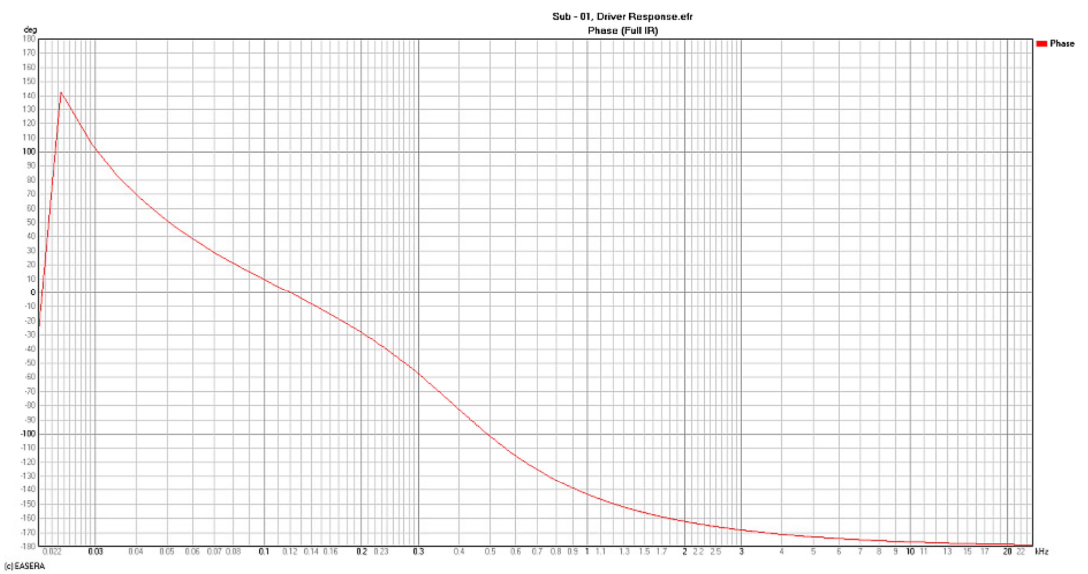
LF is a sealed box
12 dB/octave
(2nd order) roll-off
-3 dB at 60 Hz

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)

Frequency Domain Alignment



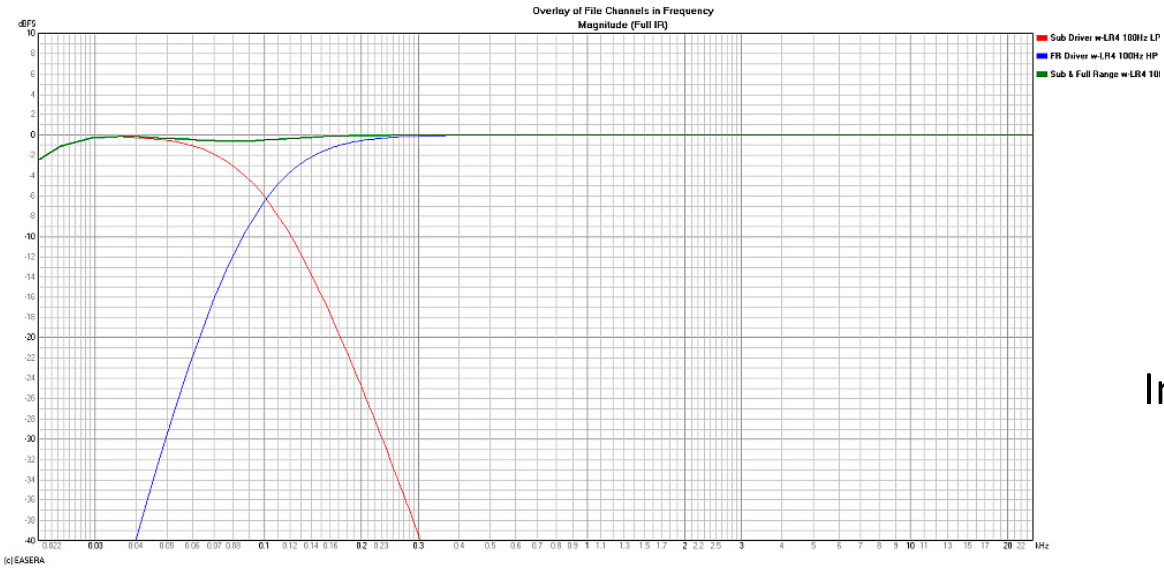


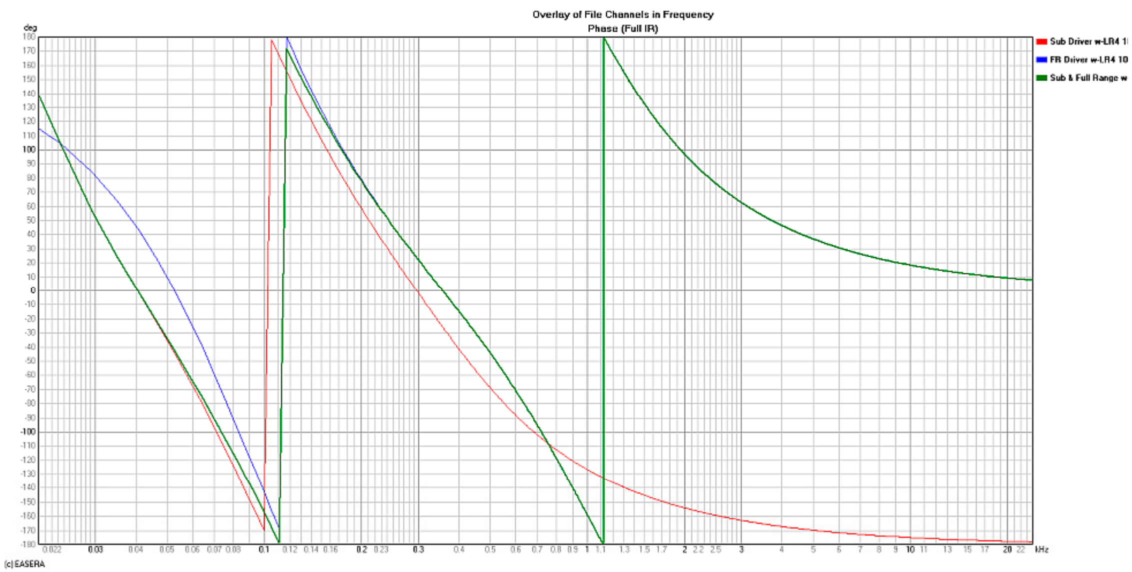
Subwoofer Loudspeakers

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

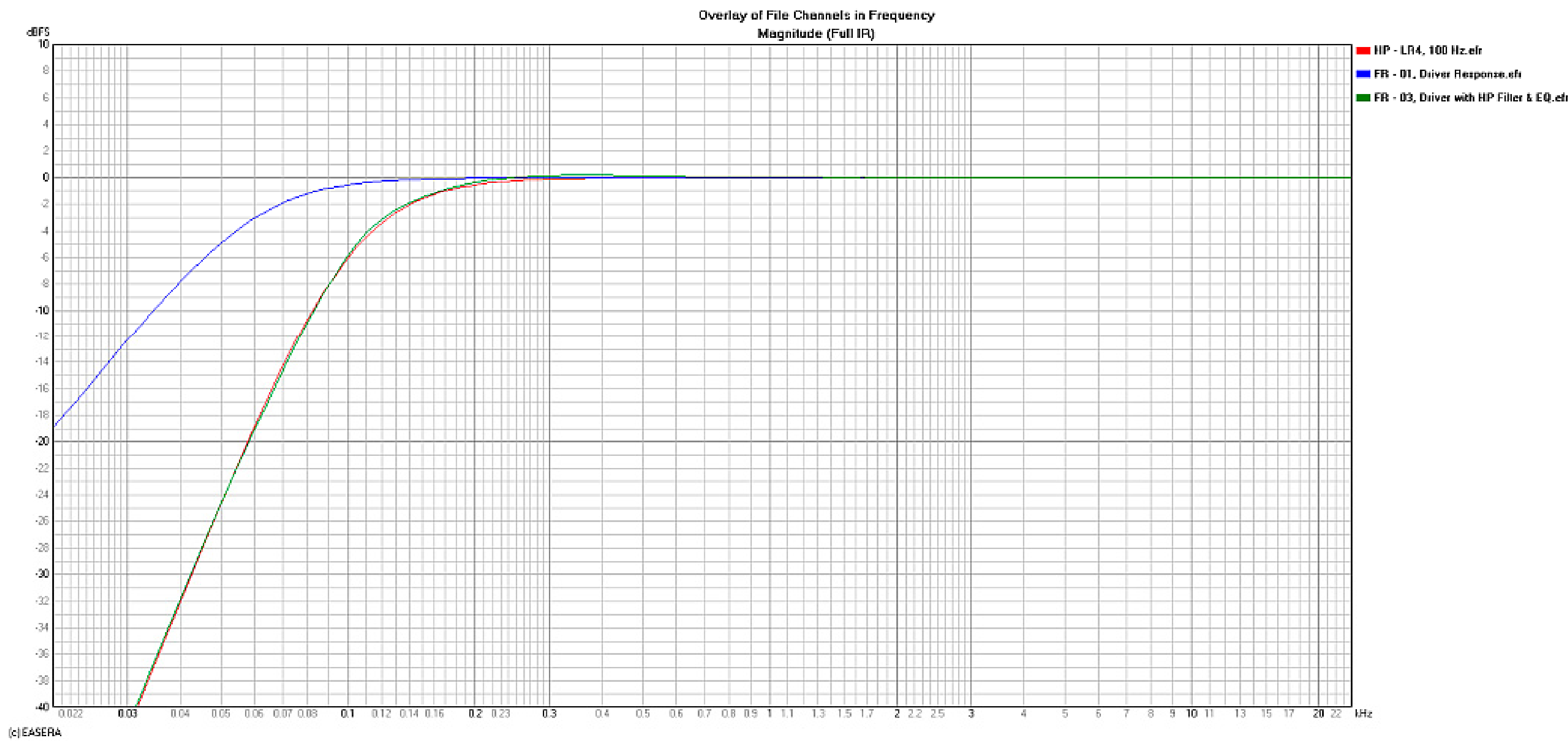
Target LR4 LP Response – Red
Subwoofer Loudspeaker Response – Blue
Subwoofer + Filtering – Green

Frequency Domain Alignment

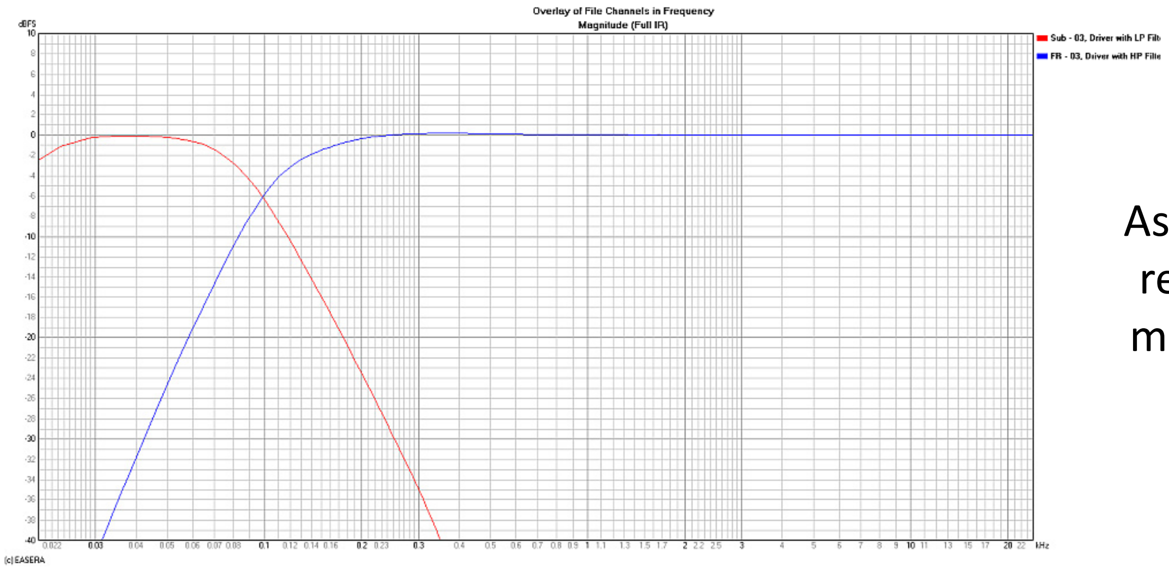
Target LR4 HP Response – Red
Full-Range Loudspeaker Response – Blue
Full-Range + Filtering – Green

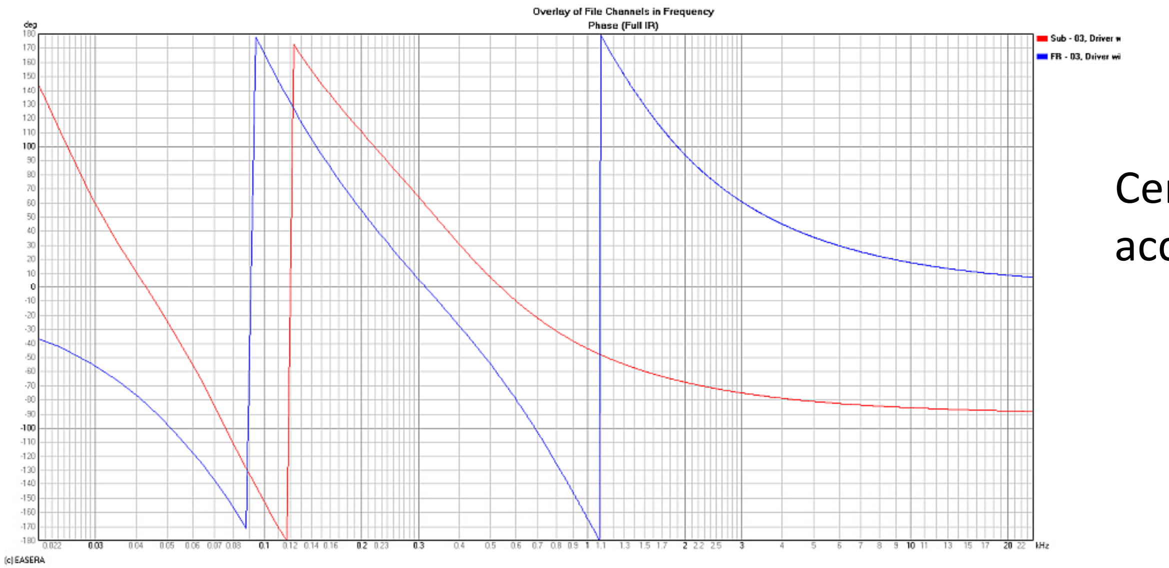
Full-Range HP Filtering

HP - 165 Hz, 2nd order Butterworth
PEQ - 105 Hz, +4.0 dB, Q=1.3



Frequency Domain Alignment





Sub & Full-Range with New Filtering

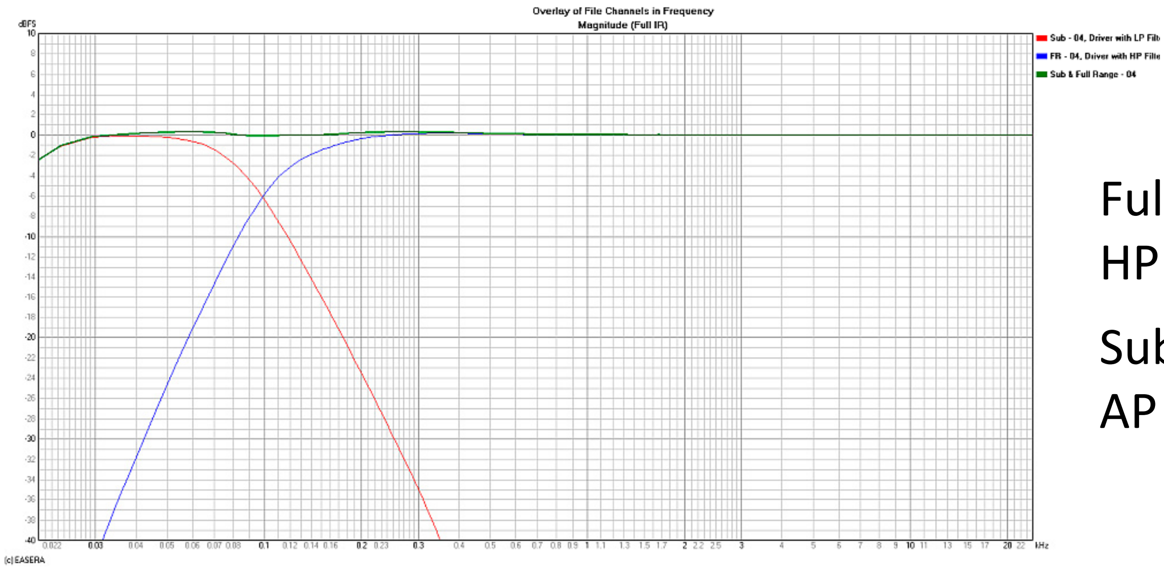
As previously seen the magnitude responses with the new filtering matches the target Linkwitz-Riley responses closely

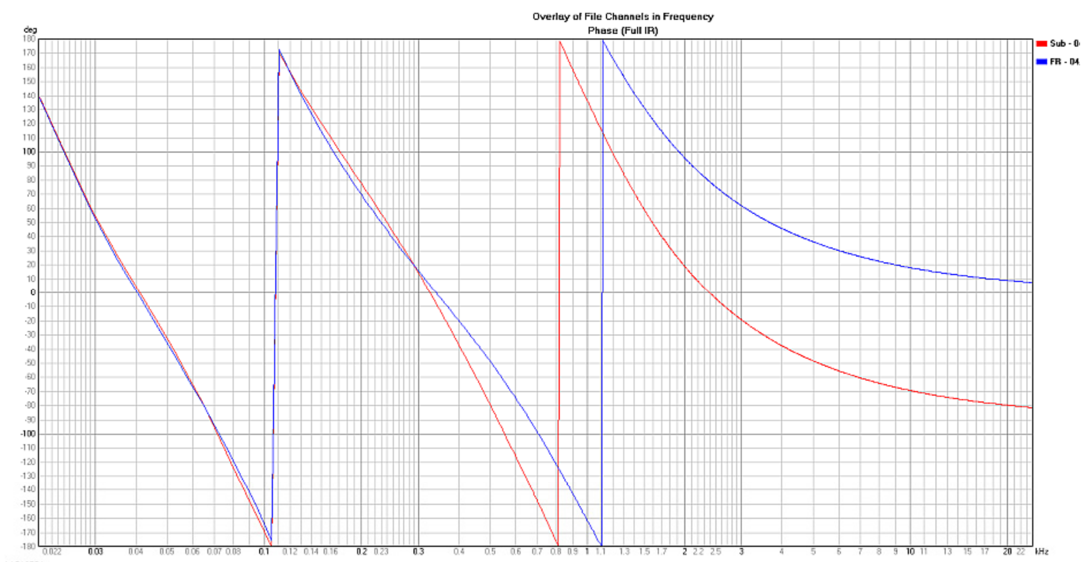
However, the phase responses don't match (overlay) as they should

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

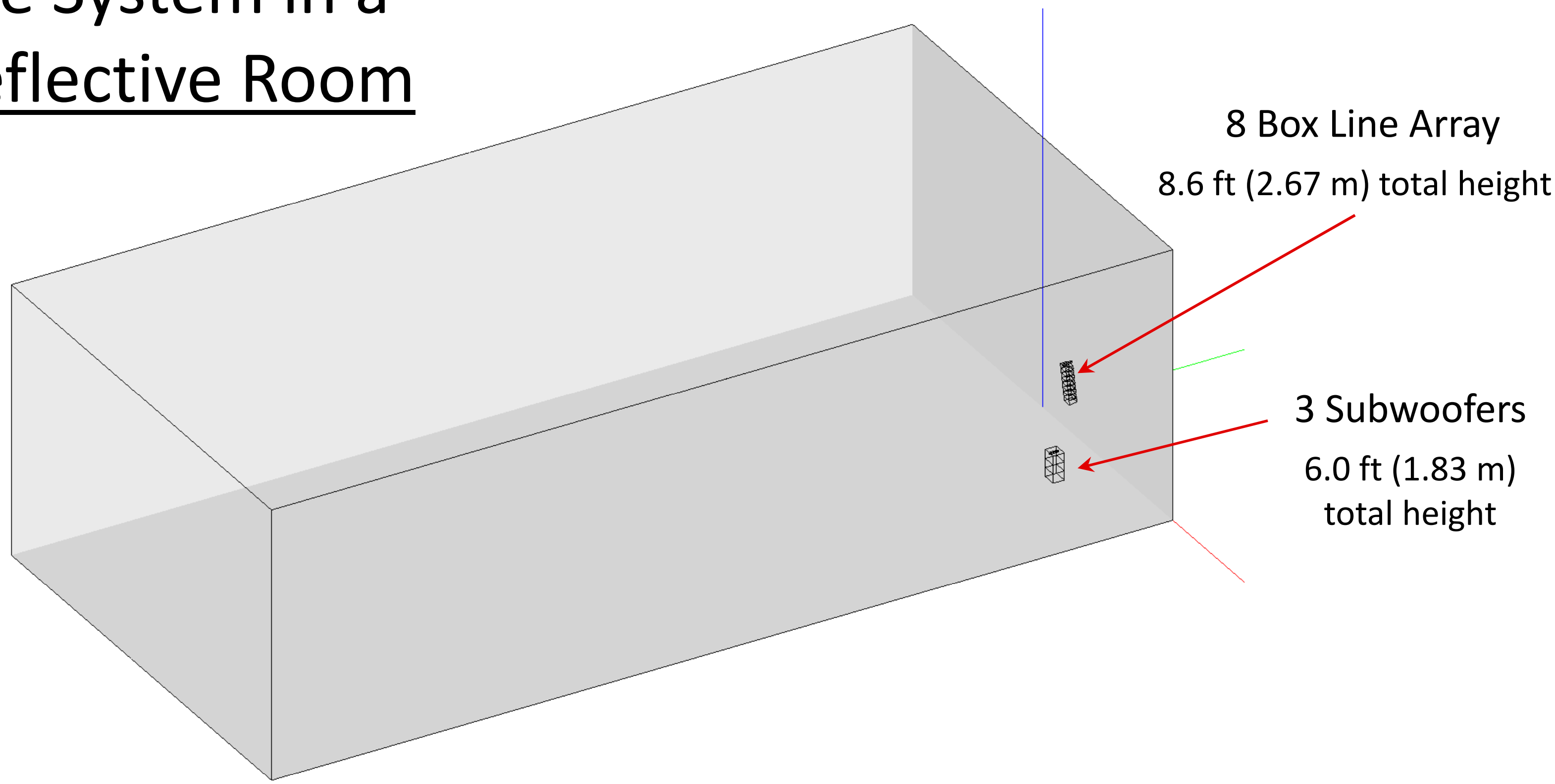
1) We know that to properly align devices we must align the initial energy arrivals, not the peak energy arrivals.

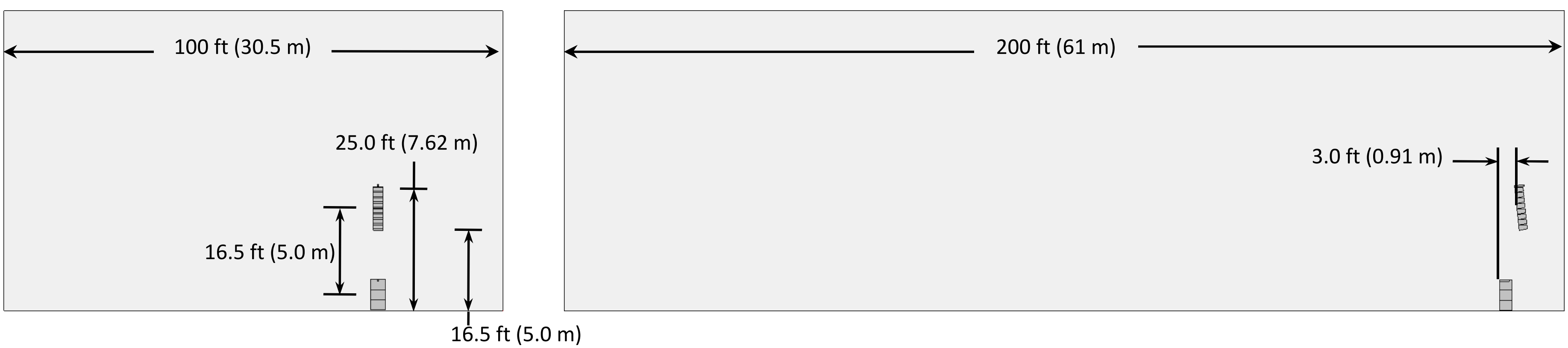
2) We know what to look for to determine the initial energy arrival time from full-range and low frequency band-limited loudspeakers.

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.

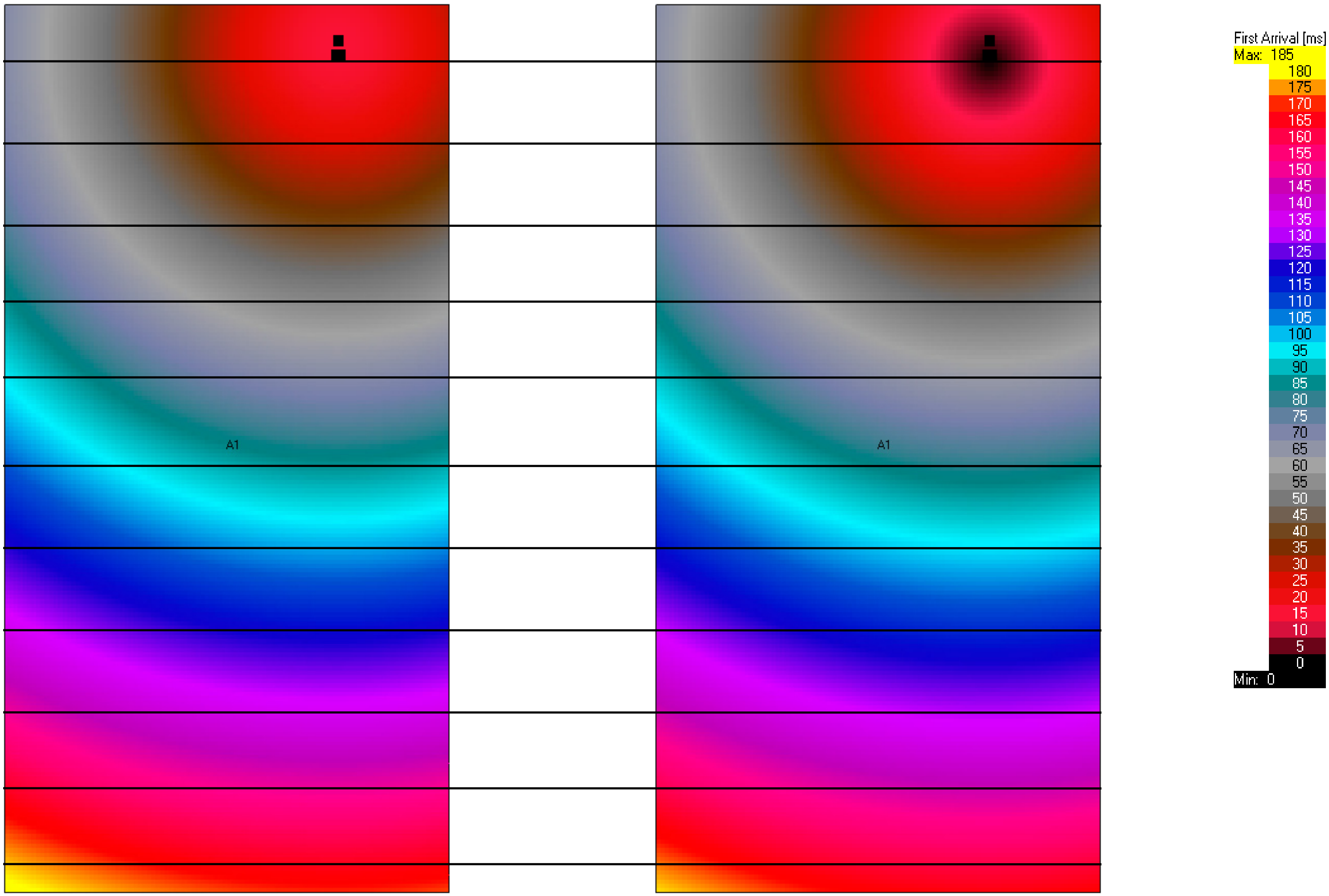
Example System in a Non-Reflective Room





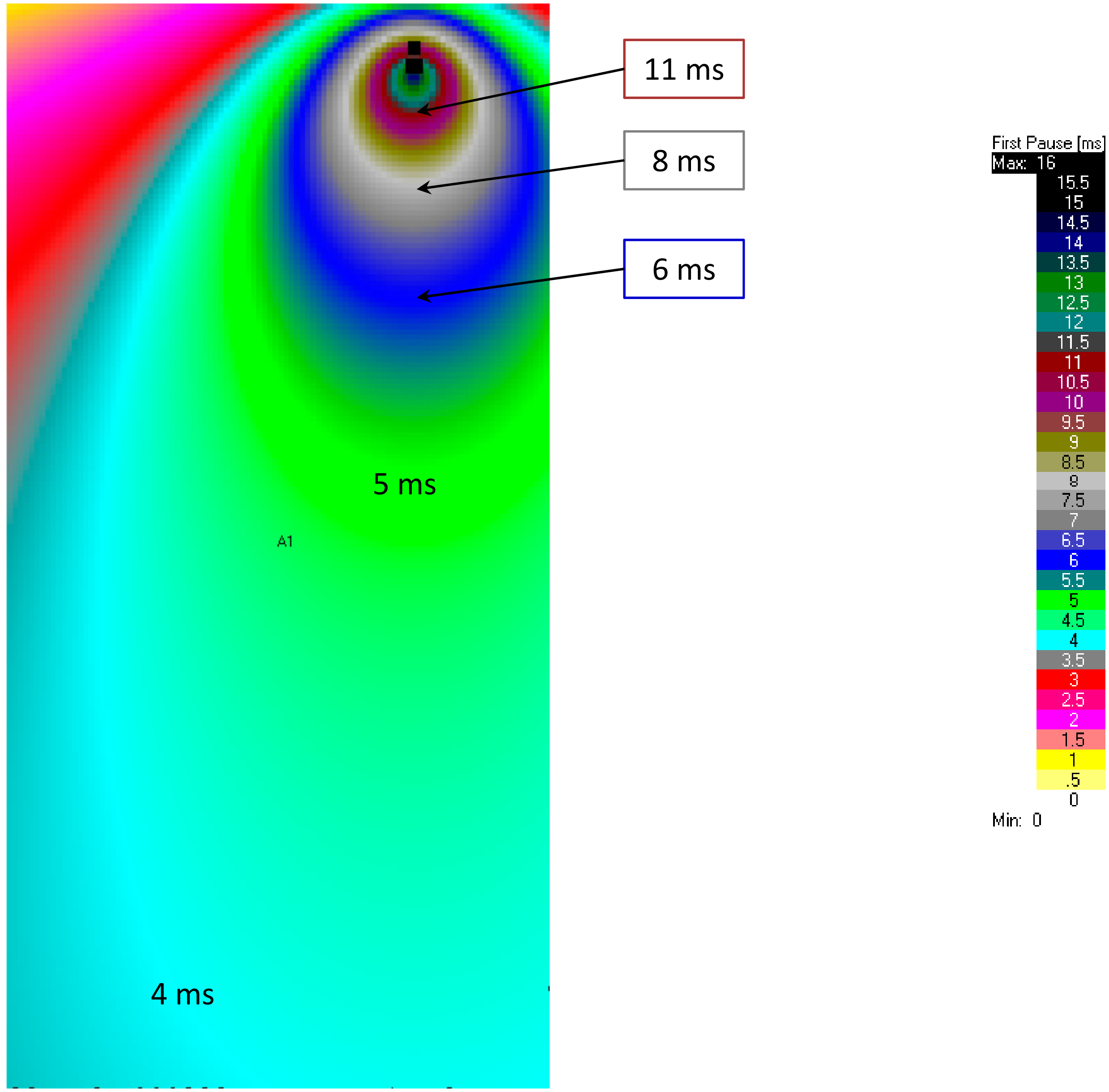
Arrival Time Map

Array Only | Subs Only



Arrival Time Difference Map

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



For 2 dB Uniformity (+/-1 dB)

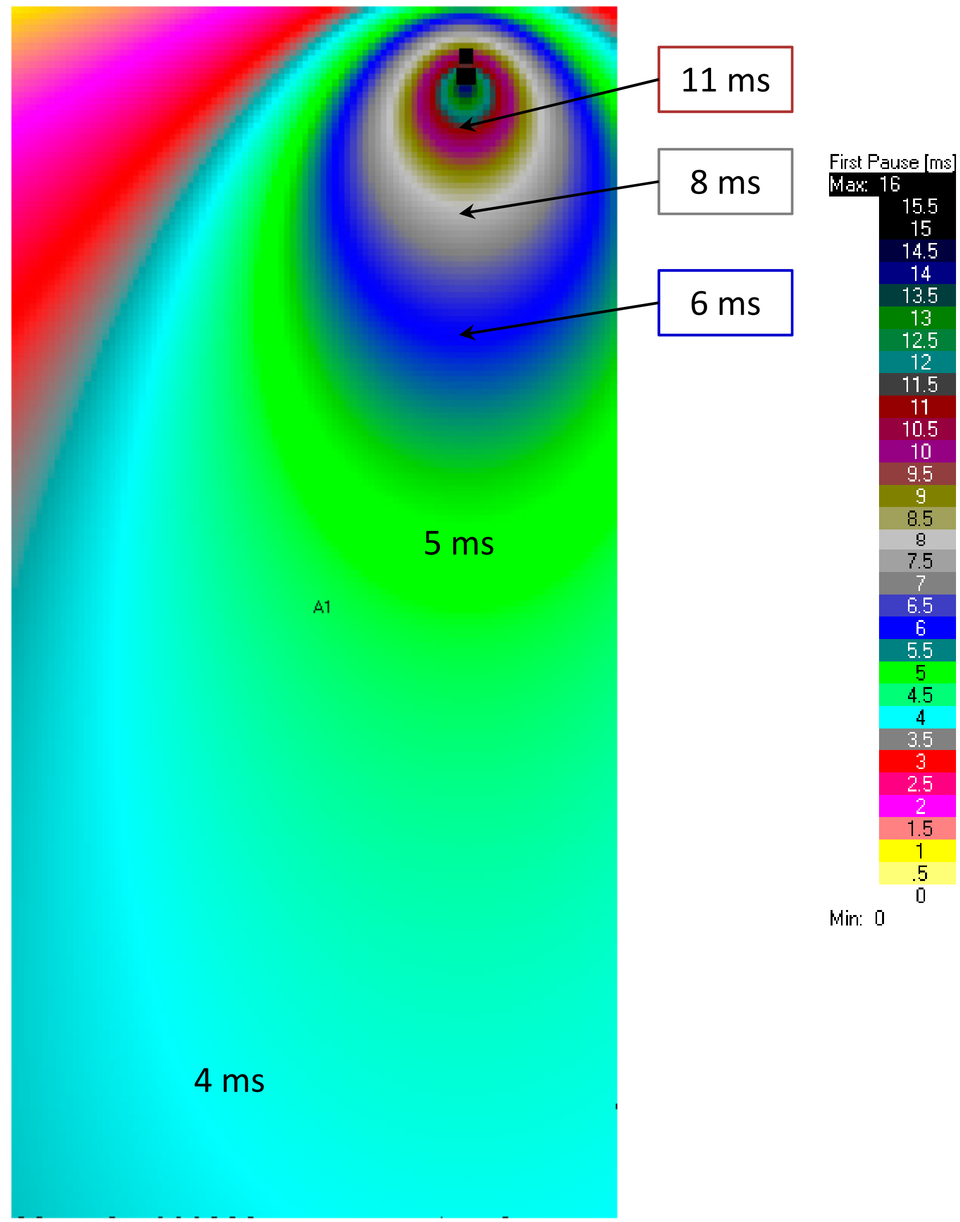
Method A

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

3) Examine new arrival time differences



For 2 dB Uniformity (+/-1 dB)

Subs Delayed 6 ms

Method A

Start at the back and work forward

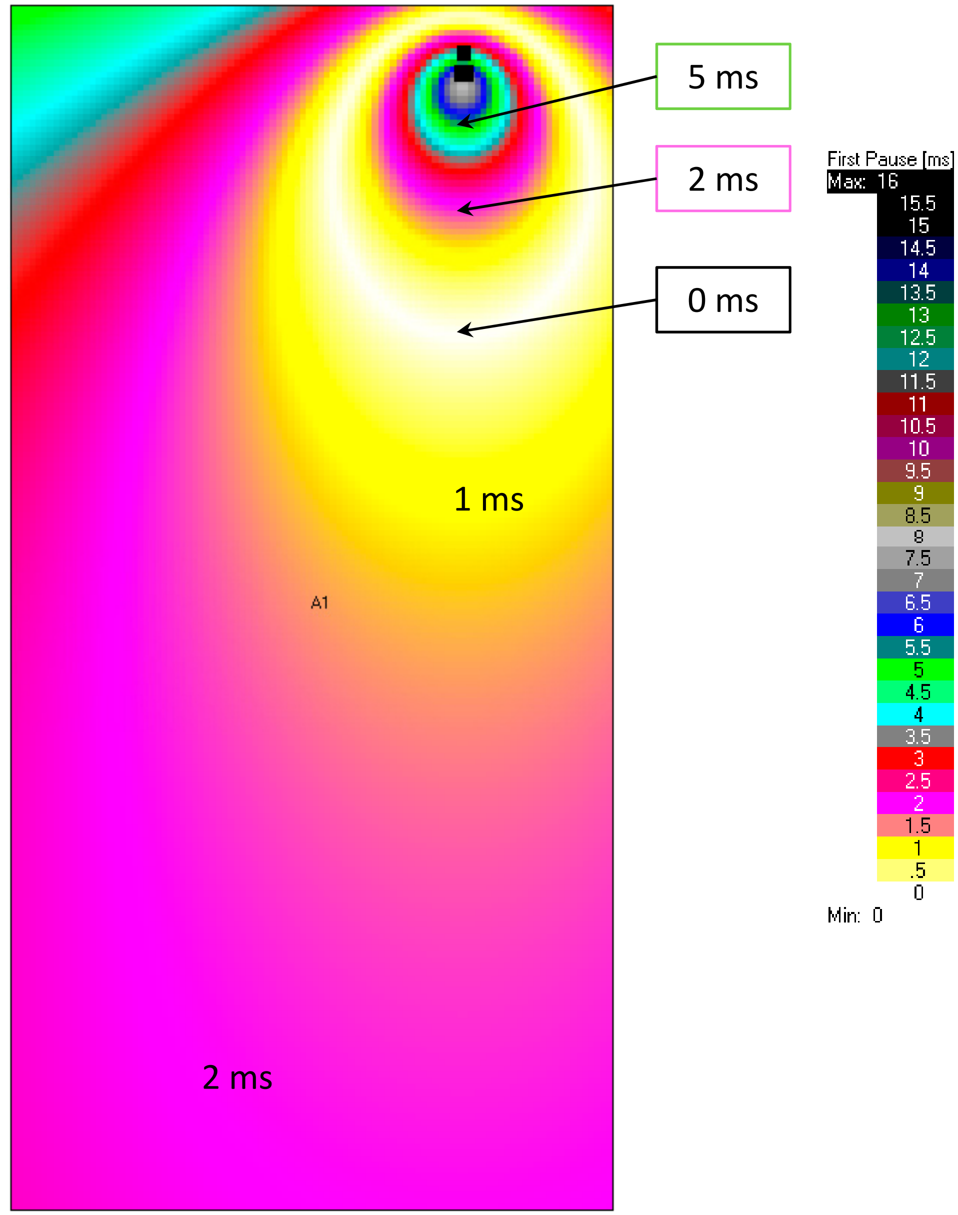
1) Look at the area(s) of smallest arrival time difference

2) Delay the first signal arrival by this time plus 1.9 ms

3) Examine new arrival time differences

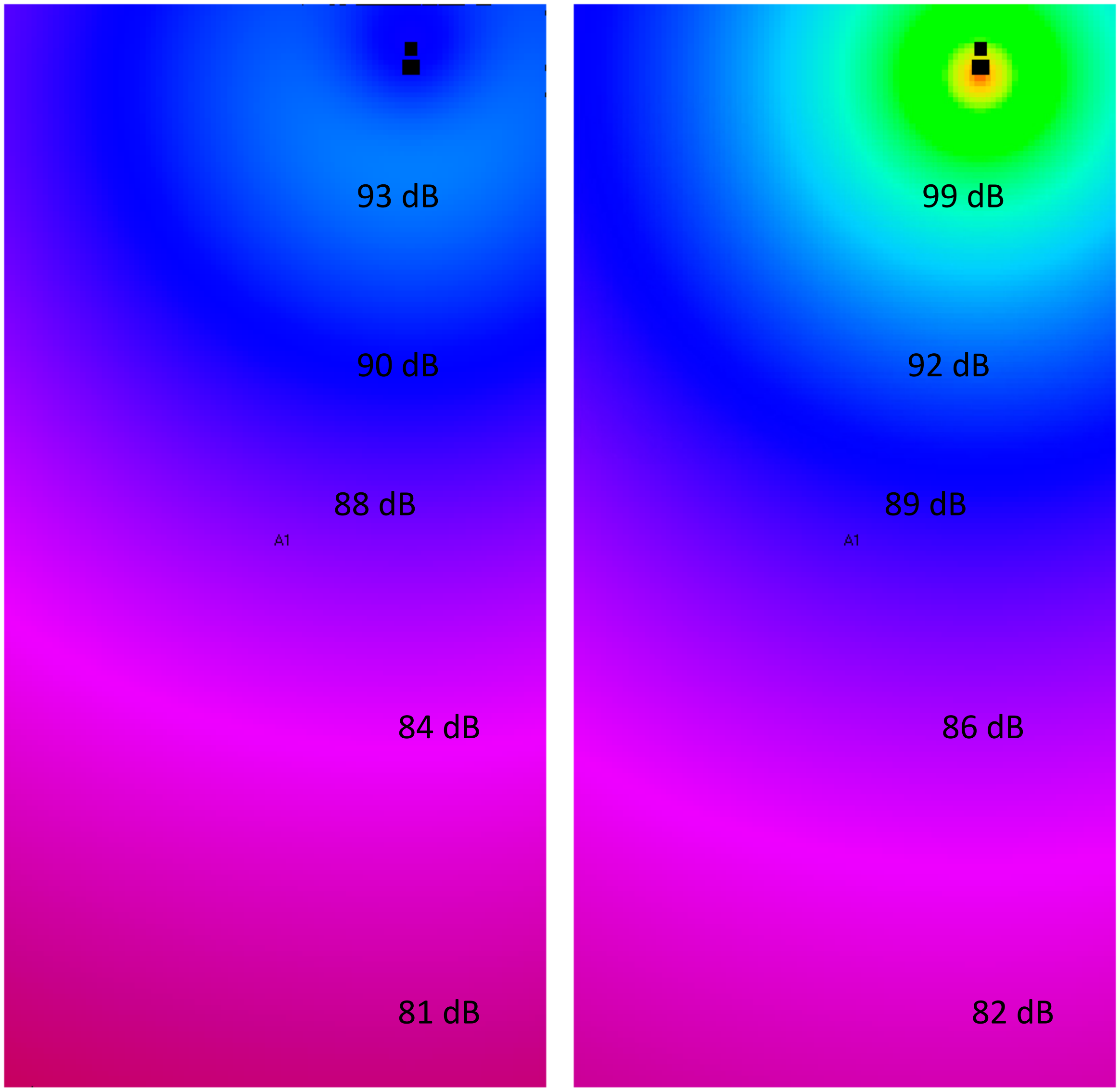
   a) Areas greater than 1.9 ms (75°) will vary by more than 2 dB

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

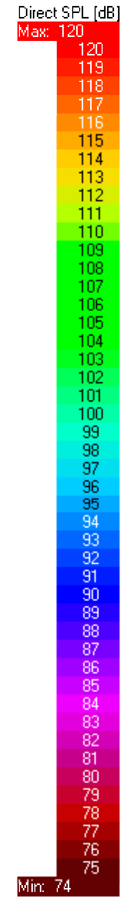


SPL Map – 100 Hz

Array Only | Subs Only

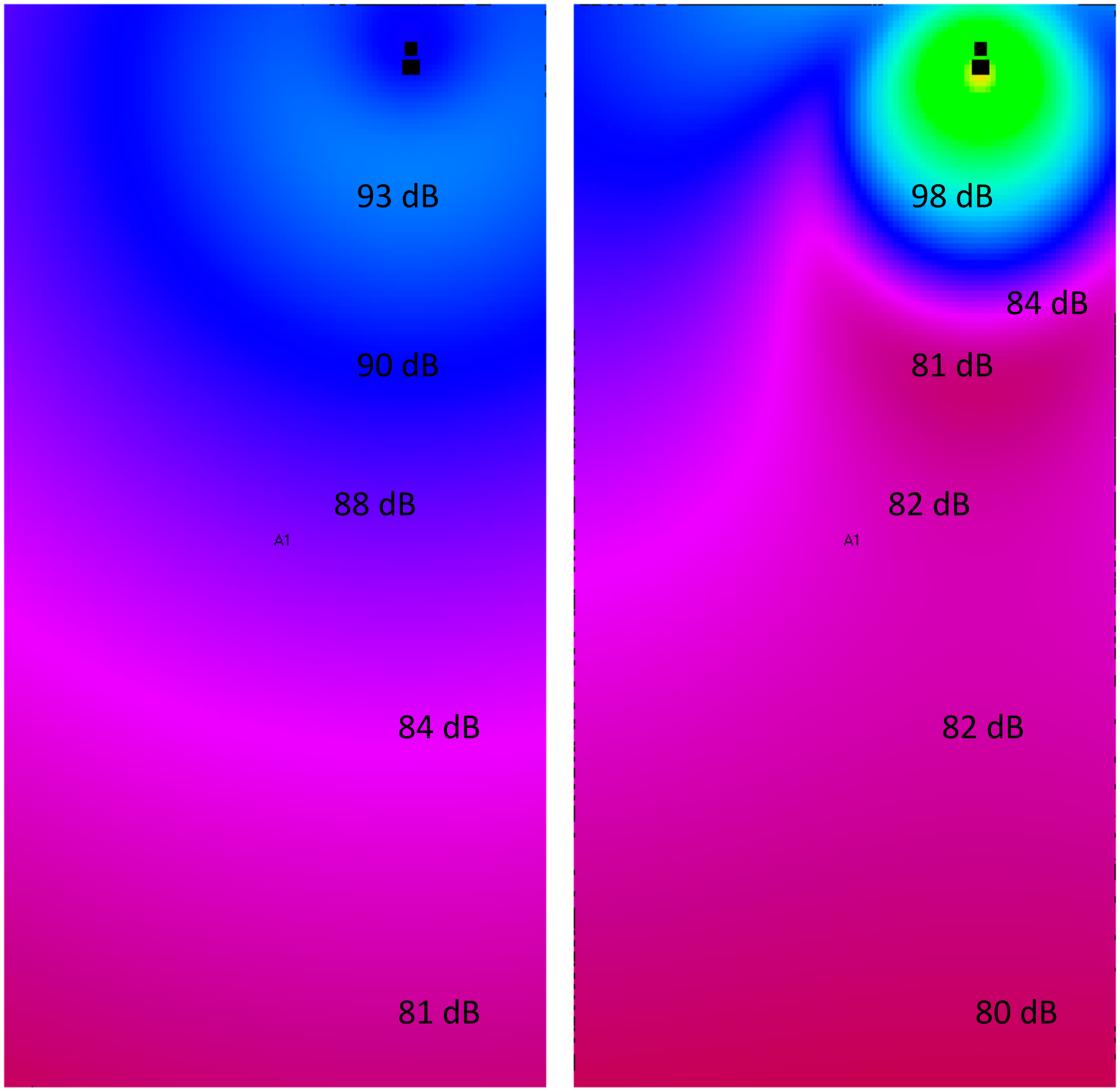


No HP or LP filters applied



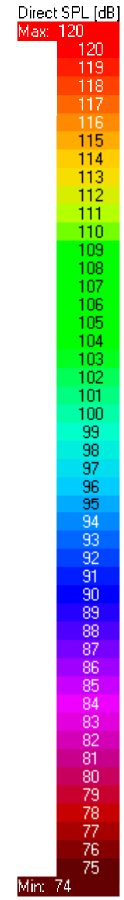
SPL Map – 100 Hz

Array Only | Subs (no delay) & Array*



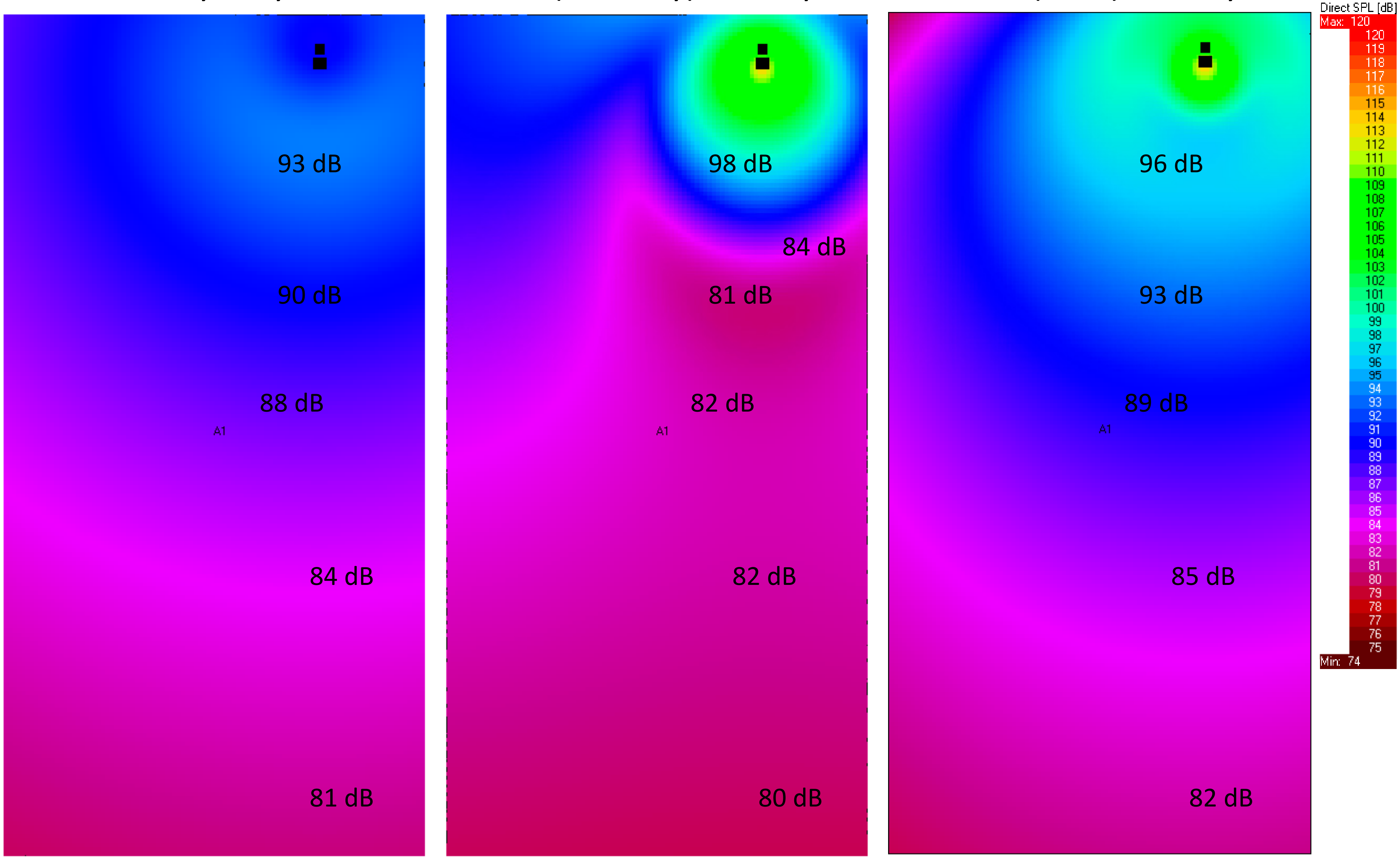
*Using 100 Hz Linkwitz-Riley filters, no delay on Subs

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

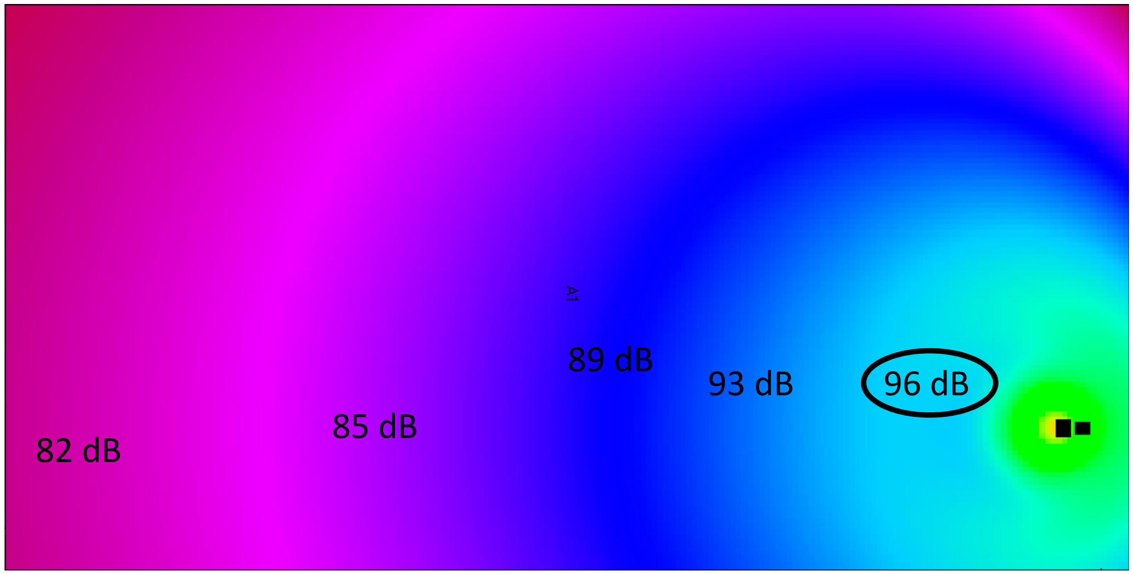


SPL Map – 100 Hz

Array Only | Subs (no delay) & Array* | Proposed Alignment Method Subs (6 ms) & Array



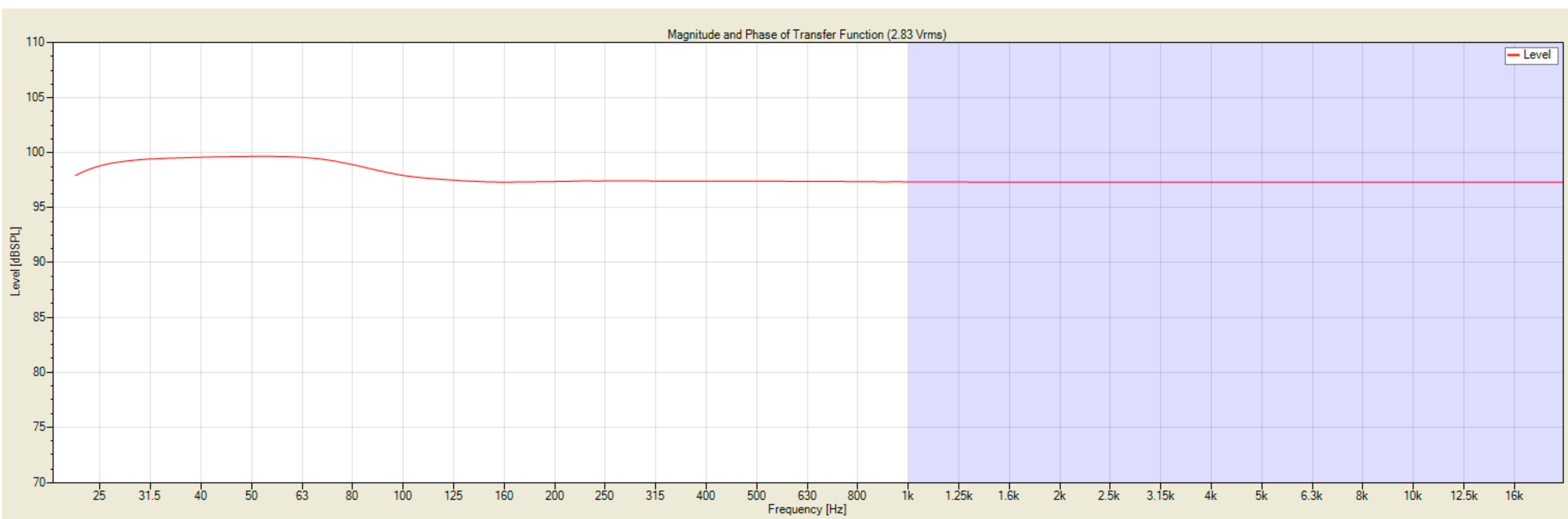
SPL Map (100 Hz) & Frequency Response



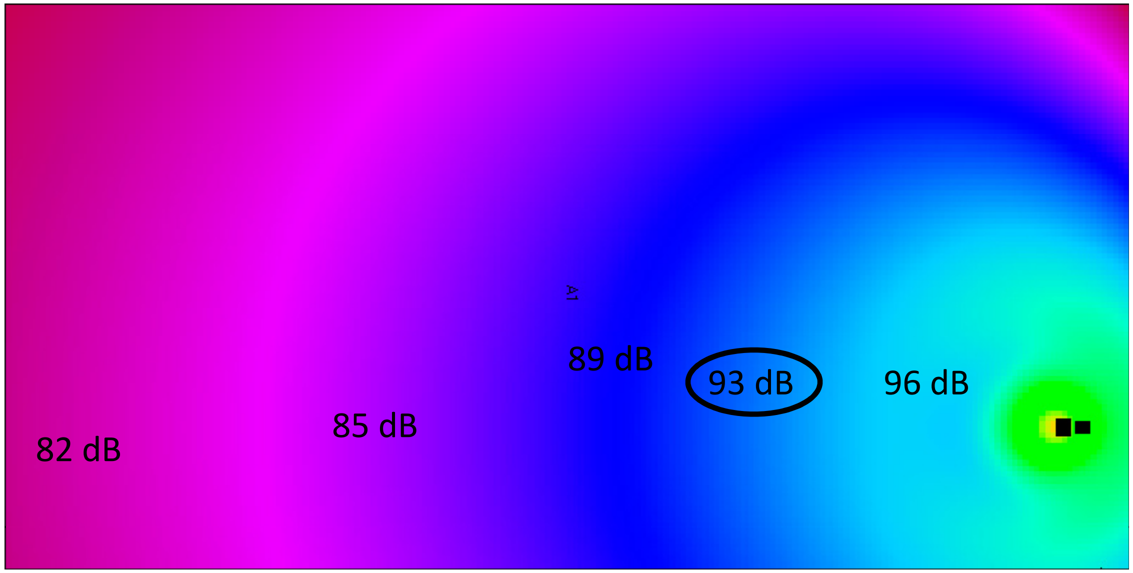
Proposed Alignment Method
Subs (6 ms delay) & Array

Note increased SPL below 125 Hz due to being much closer to ground-stacked subs than flown array

Frequency Response at Location 1



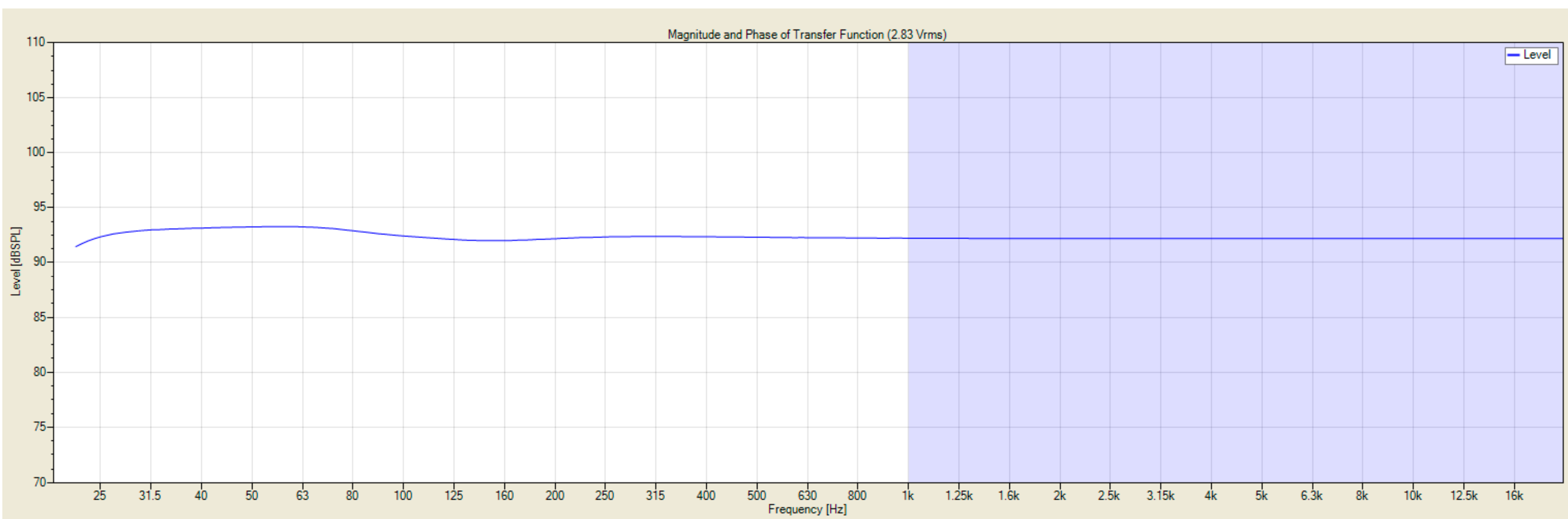
SPL Map (100 Hz) & Frequency Response



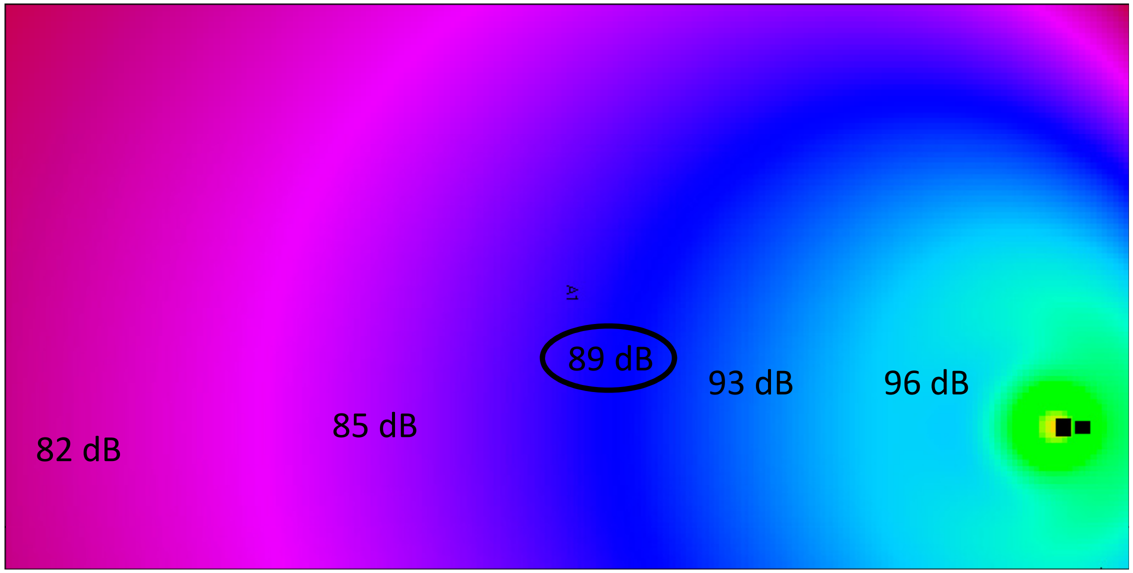
Proposed Alignment Method
Subs (6 ms delay) & Array

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

Frequency Response at Location 2

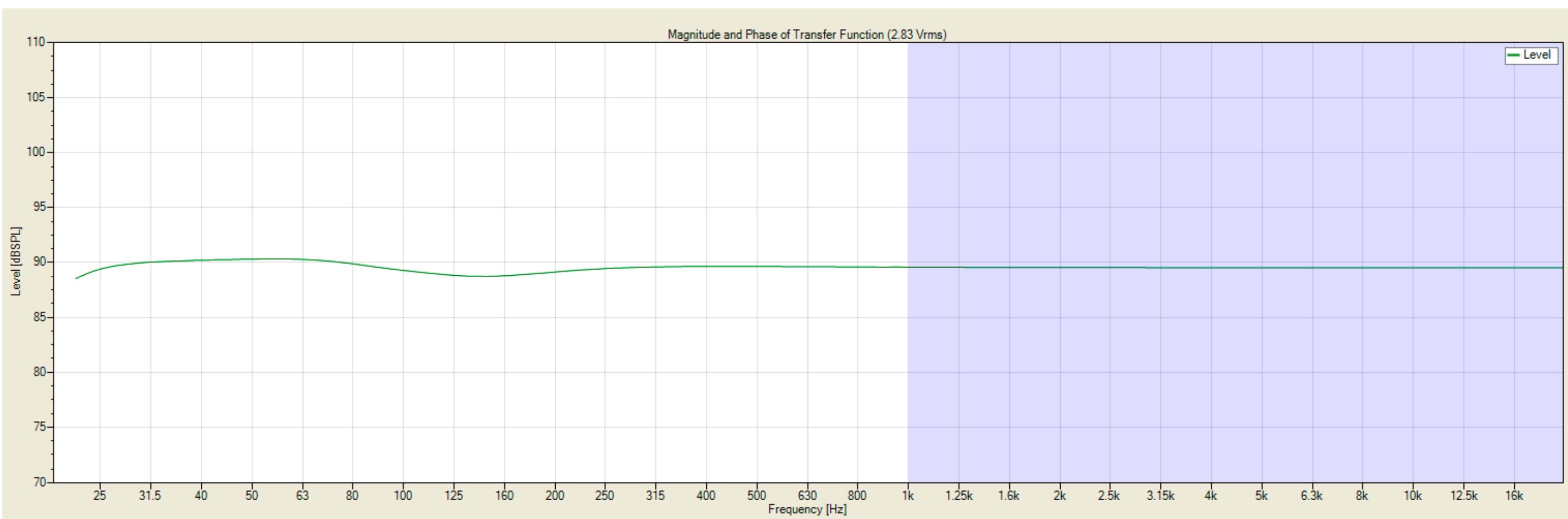


SPL Map (100 Hz) & Frequency Response

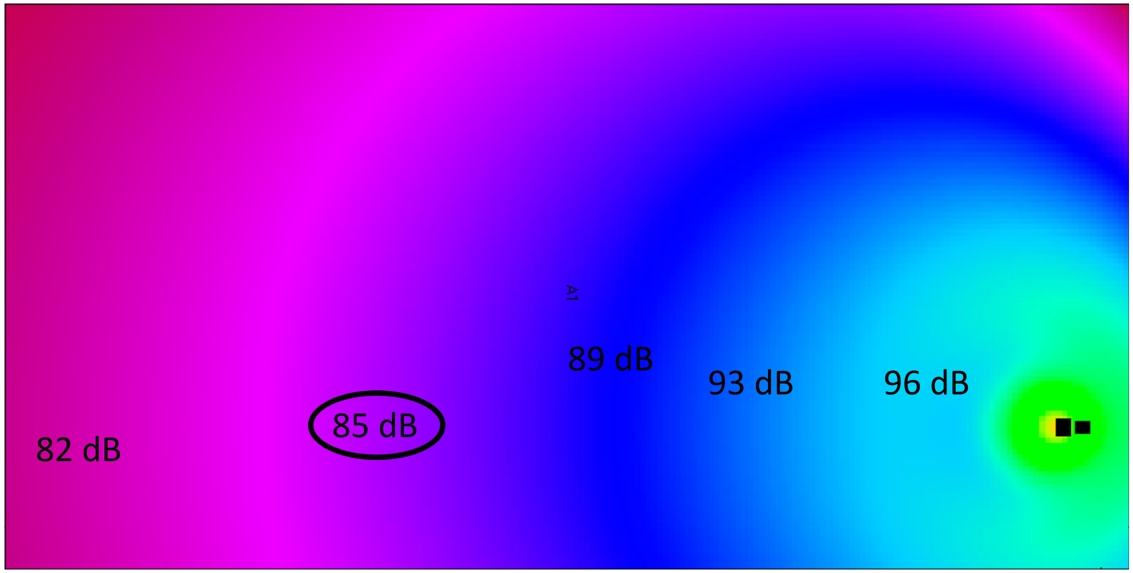


Proposed Alignment Method
Subs (6 ms delay) & Array

Frequency Response at
Location 3

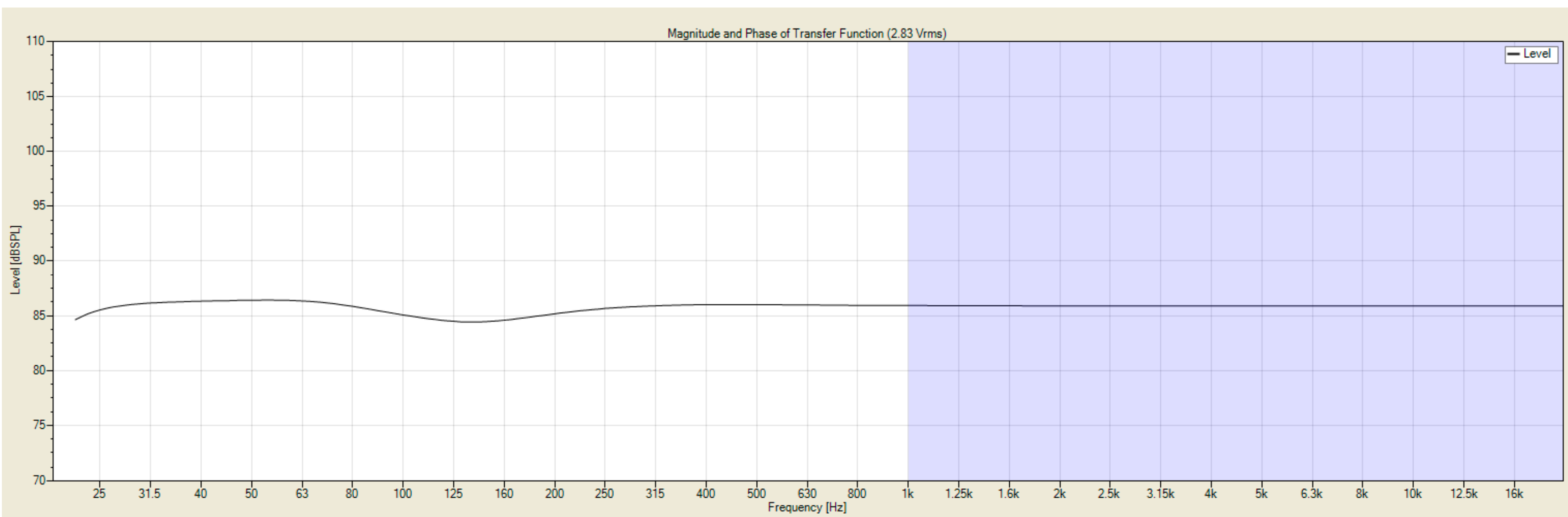


SPL Map (100 Hz) & Frequency Response

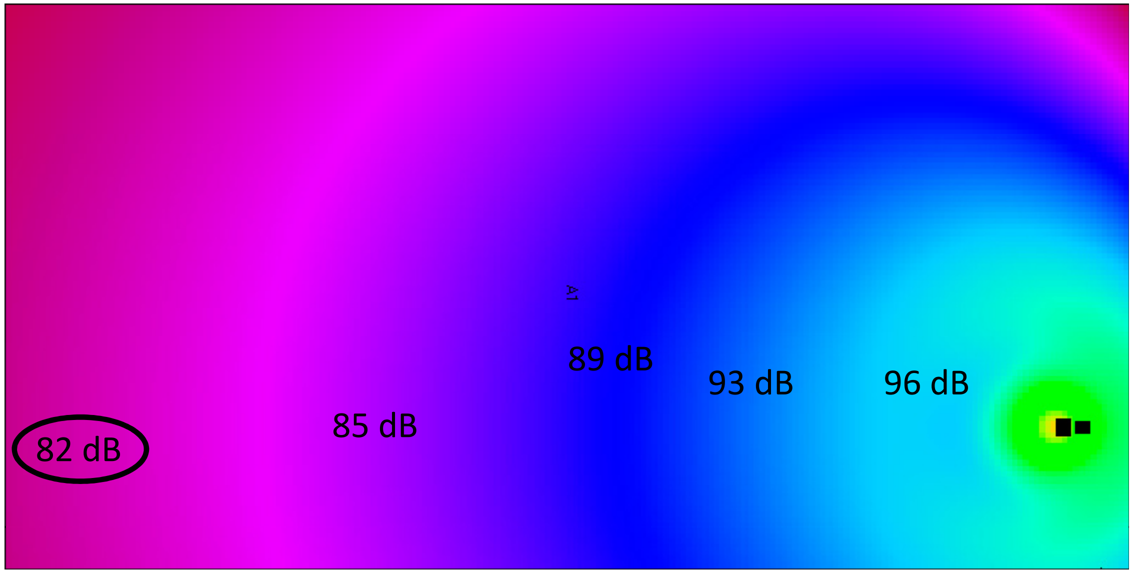


Proposed Alignment Method
Subs (6 ms delay) & Array

Frequency Response at
Location 4

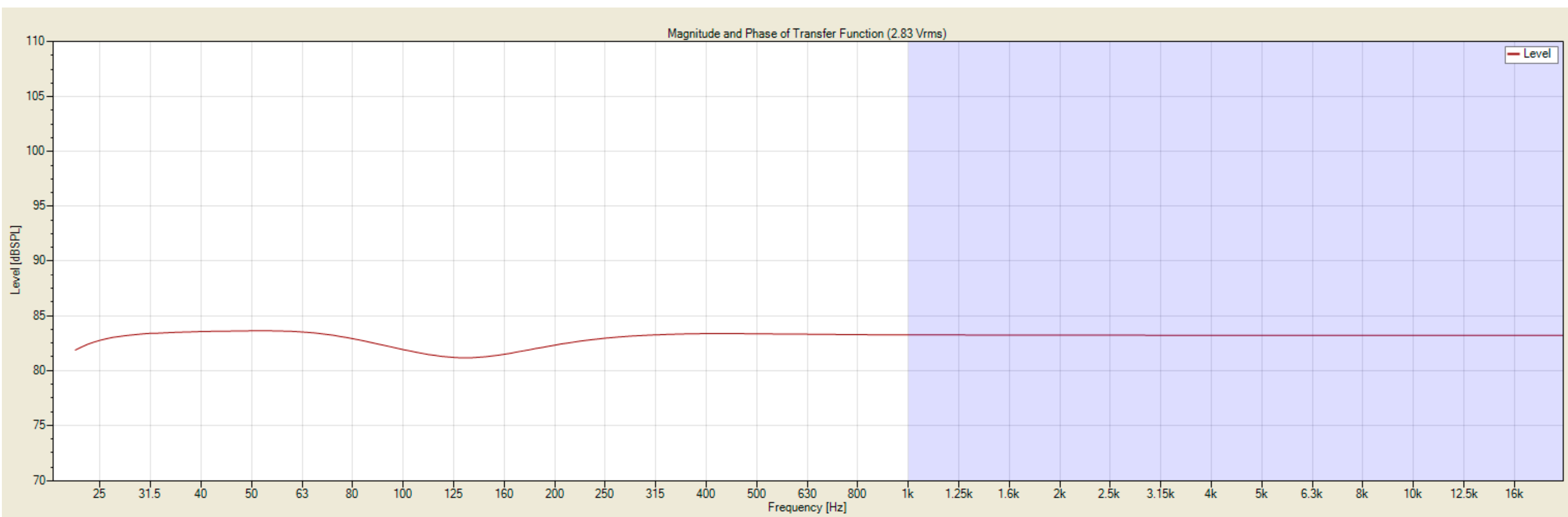


SPL Map (100 Hz) & Frequency Response



Proposed Alignment Method
Subs (6 ms delay) & Array

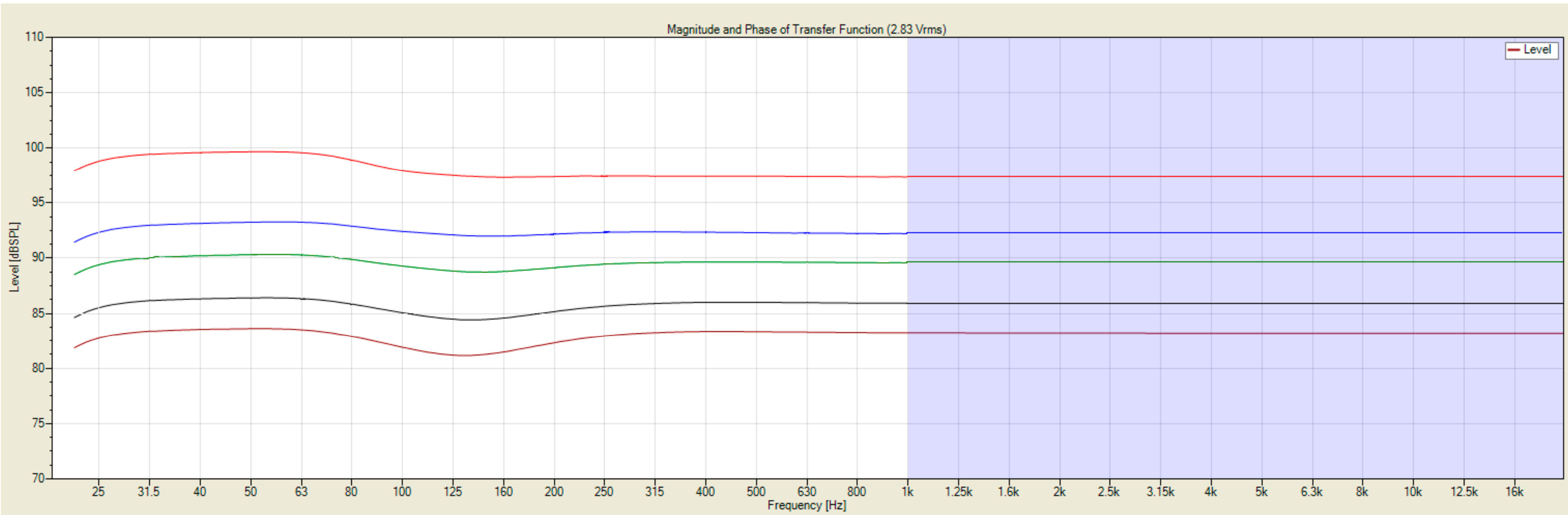
Frequency Response at
Location 5



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

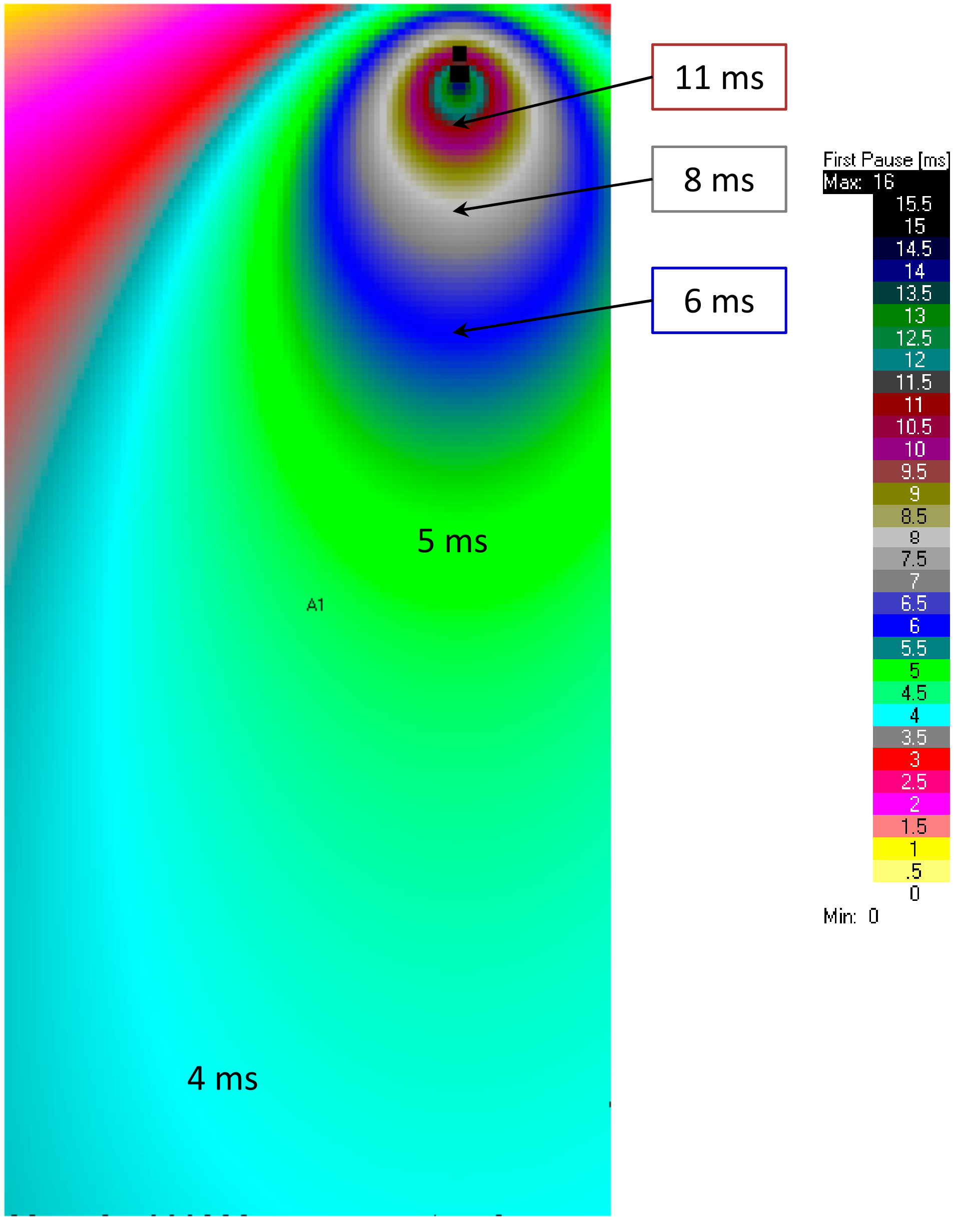
Increased SPL below 125 Hz at Location 1 is due to being much closer to ground-stacked subs than flown array

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

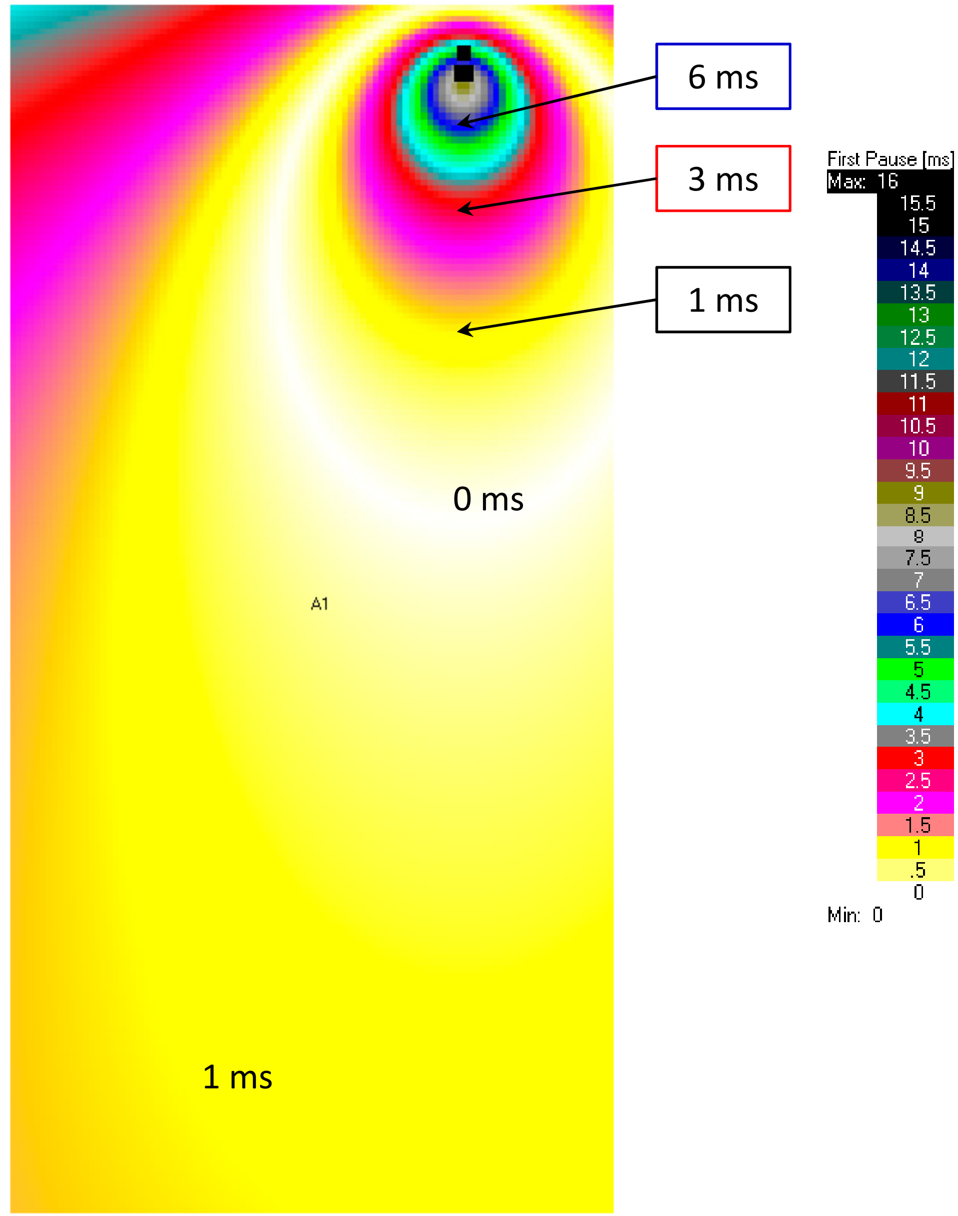
1) Let's pick the area with a 5ms difference in arrival time

2) Delay the first signal arrival by this time

3) Examine new arrival time differences

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

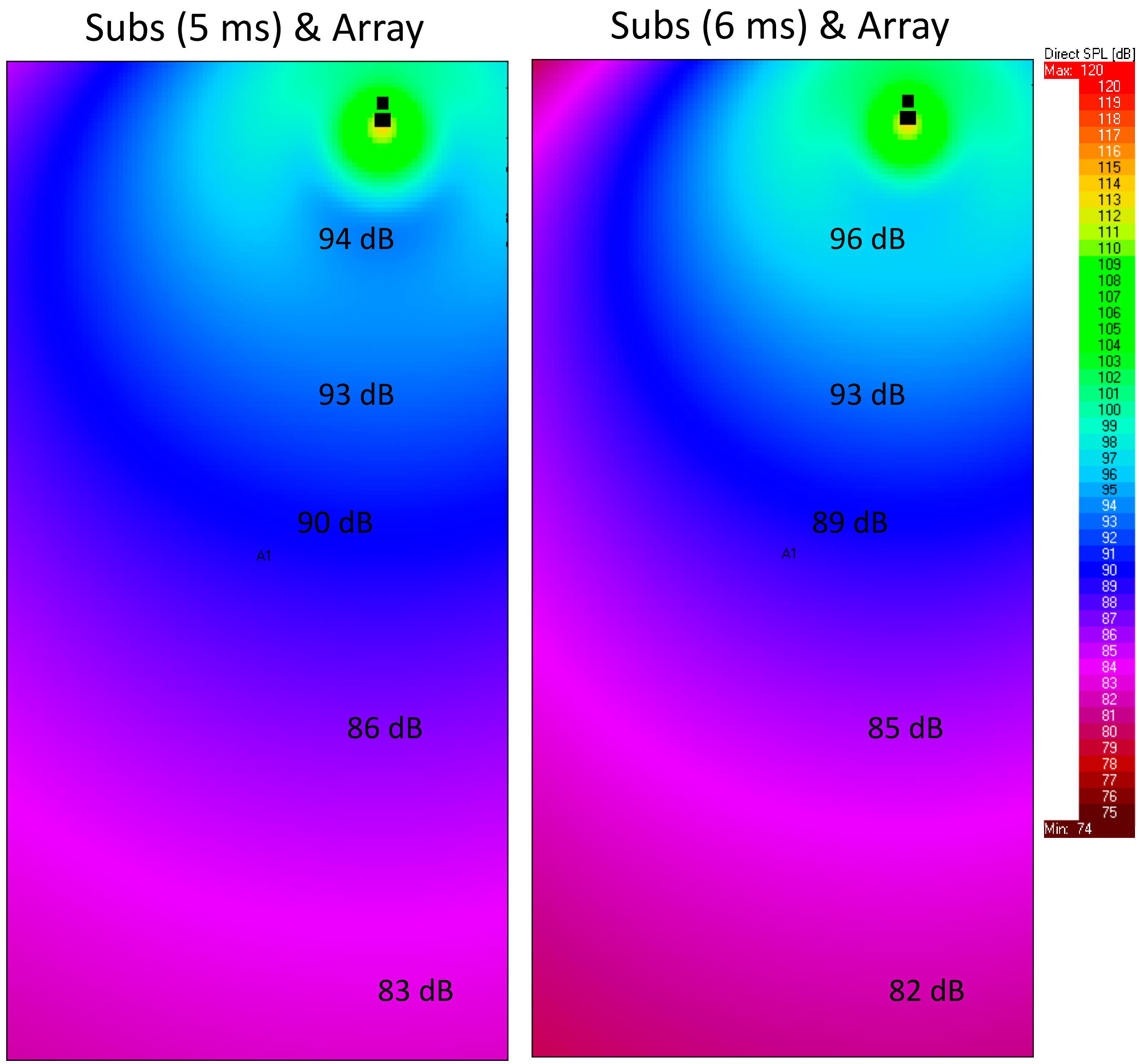
   b) Areas greater than 2.3 ms (90°) will vary by more than 3 dB



SPL Map – 100 Hz

The summation is still very good throughout the area.

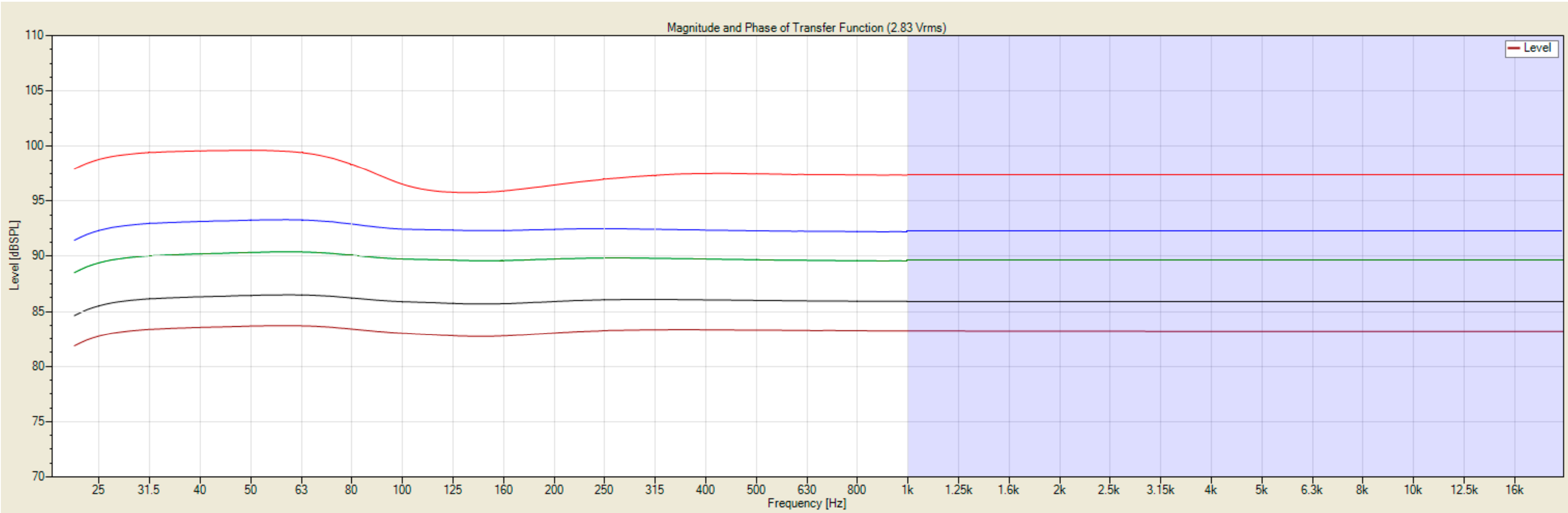
The 5 ms delay improves the middle and rear of the coverage area at the expense of the front.



Frequency Response

Frequency Response at Locations 1 – 5

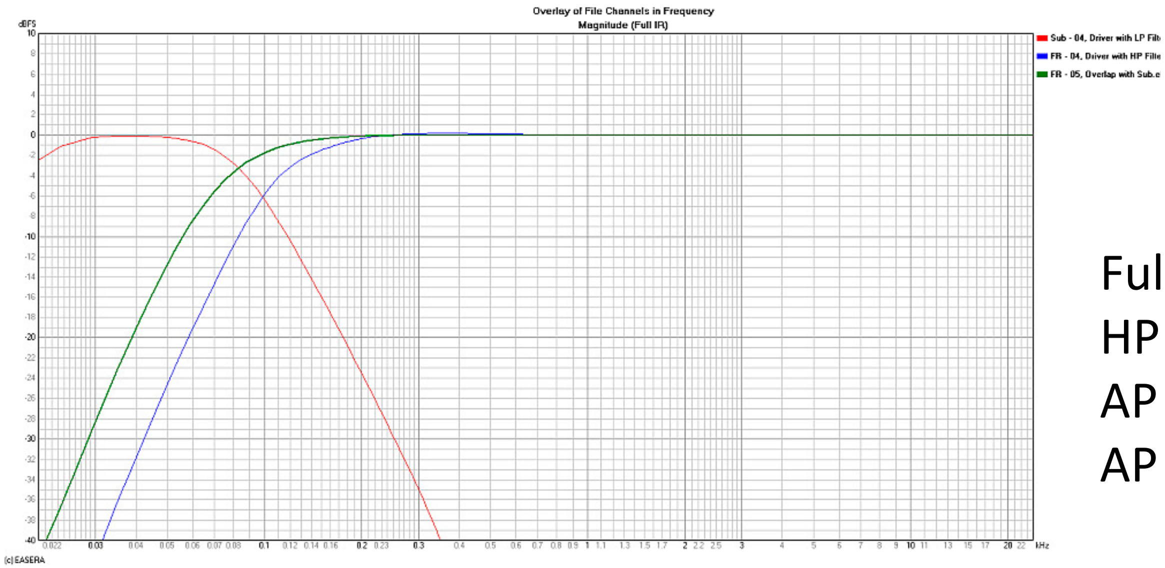
Proposed Alignment Method
Subs (5 ms delay) & Array



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

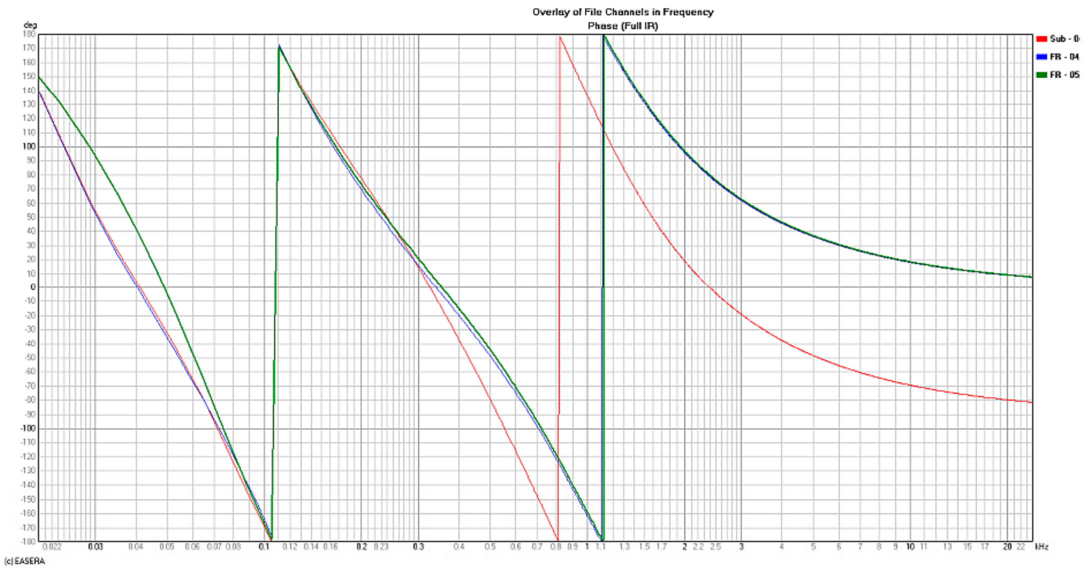
This is due to it being out of alignment by more than 1.9 ms (approx. 2.5 – 3 ms).

Full-Range Overlapping Subs



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

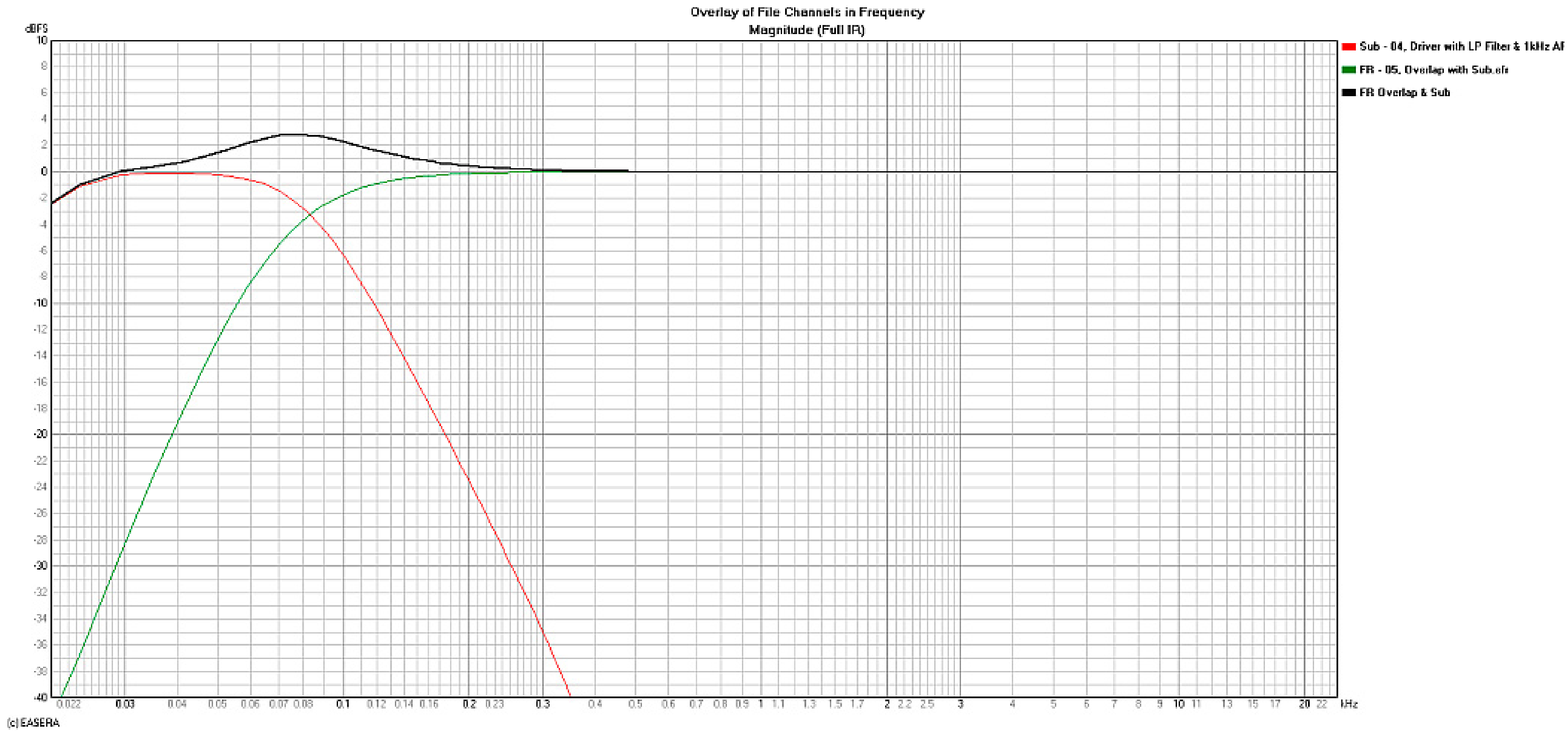
Full-Range new filtering:
HP - 75 Hz, 2nd order Butterworth
AP - 10 Hz, 1st order
AP - 80 Hz, 1st order



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

The summation is still very good throughout the area.

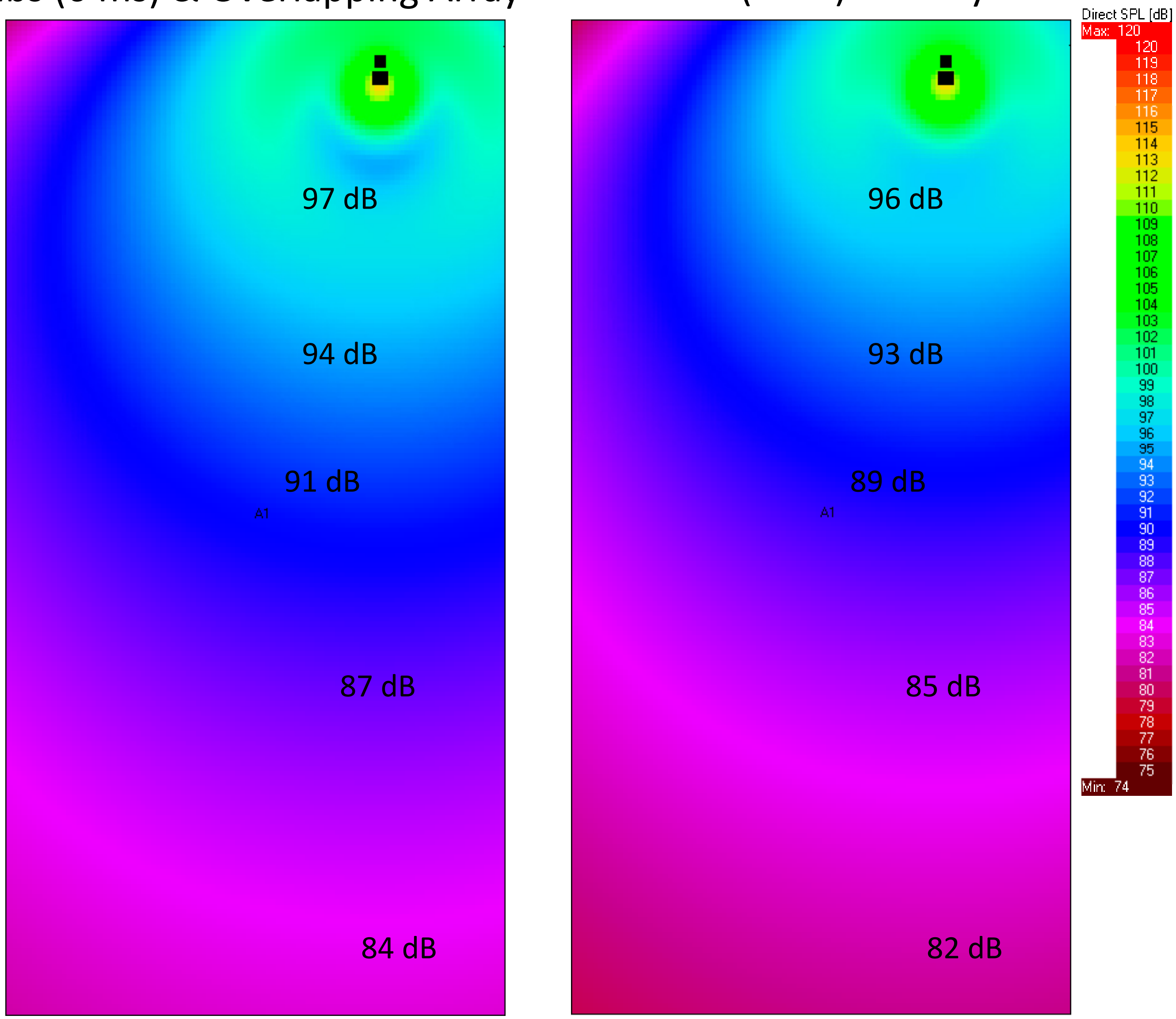
The overlapping neither significantly helps nor hurts the coverage.

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

This could have easily been achieved with system EQ.

Subs (6 ms) & Overlapping Array

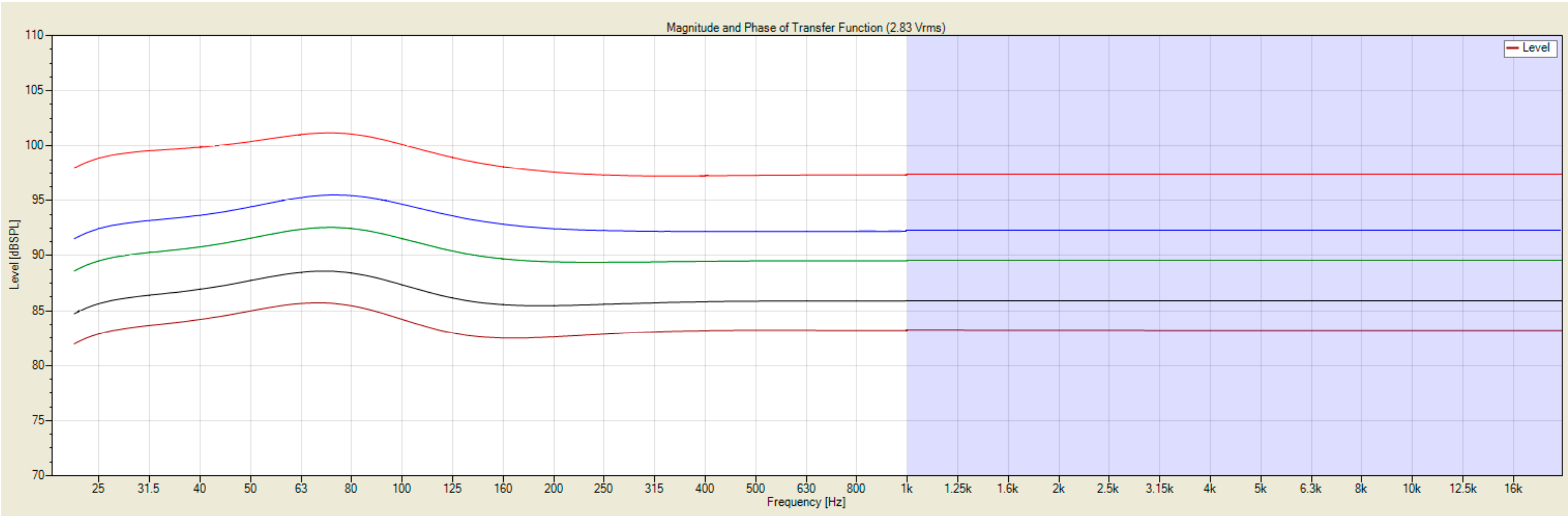
Proposed Alignment Method
Subs (6 ms) & Array



Frequency Response

Frequency Response at Locations 1 – 5

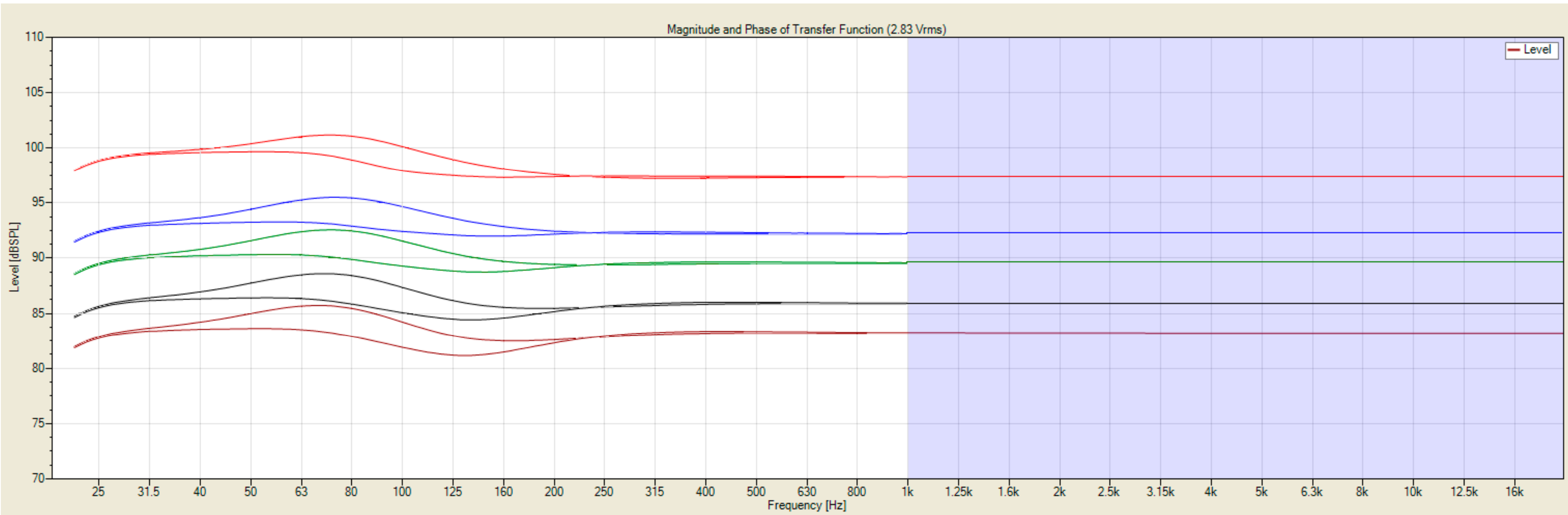
Proposed Alignment Method
Subs (6 ms delay) & Overlapping Array



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