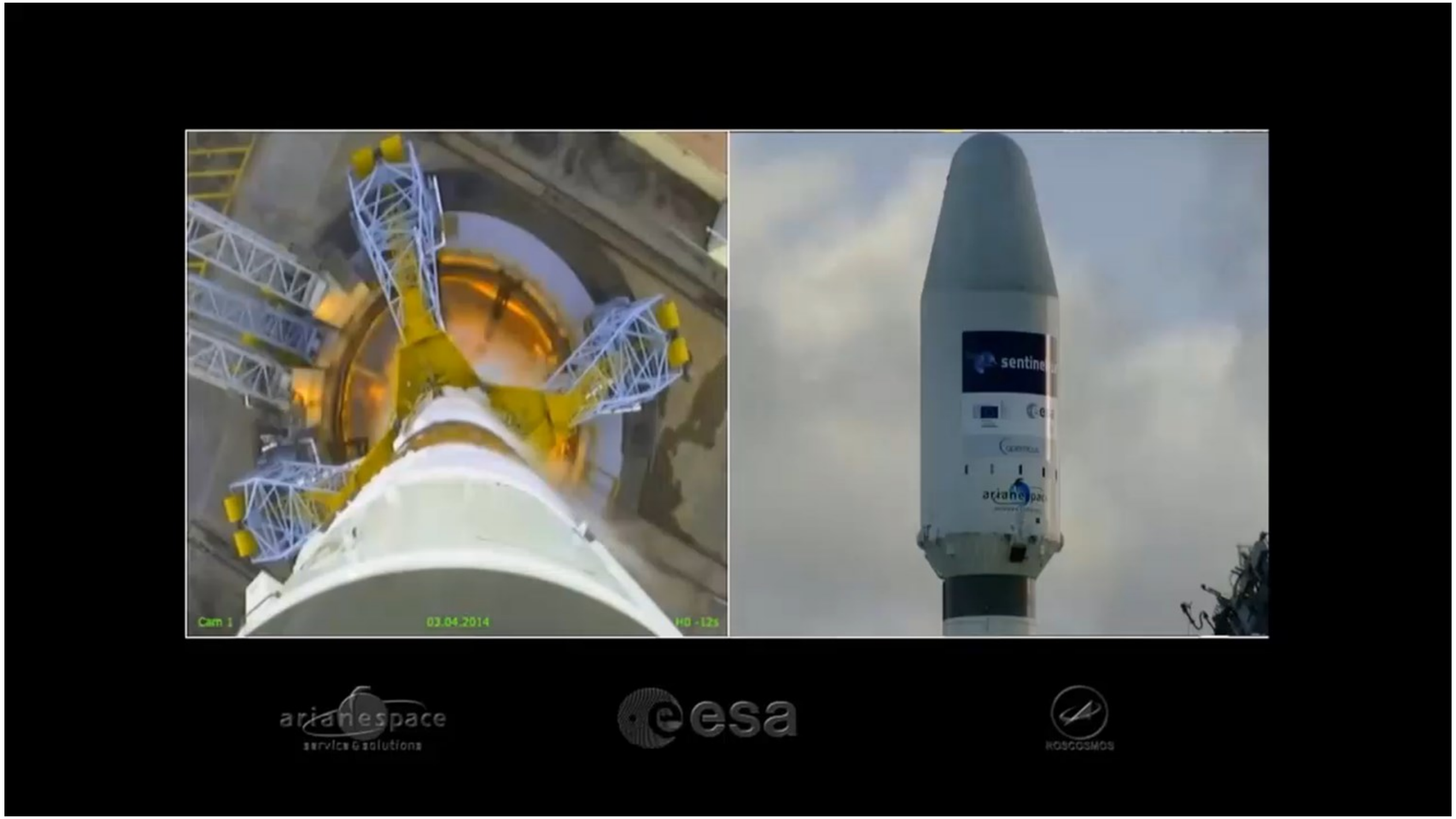
Insight Into the Sound Field During a Direct Field Acoustic Test (DFAT®)

A Carrella

Satellite Launch: a rough ride

- Ignition of Engines = Sine test (5-150Hz)
- Take-off (structure-born noise) = Acoustic Tests
- Separations (boosters, fairing, satellite) = Shocks
- For subsystems (antennae, reflectors, panels, etc) = Random + a number of tests before assembly



ARIANE V user's manual: test requirement

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S/C development approach	Model	Static	Sine vibration	Acoustic	Shock
With Structural Test Model (STM)	STM	Qual. test	Qual. test	Qual. test	Shock test characterization and analysis
	FM1	By heritage from STM *	Protoflight test	Protoflight test	Shock test characterization and analysis or by heritage*
	Subsequent FM's**	By heritage from STM *	Acceptance test (optional)	Acceptance test	By heritage* and analysis
With ProtoFlight Model	PFM = FM1	Qual test or by heritage *	Protoflight test	Protofligt test	Shock test characterization and analysis or by heritage*
	Subsequent FM's**	By heritage *	Acceptance test (optional)	Acceptance test	By heritage* and analysis

"The spacecraft authority shall demonstrate that the spacecraft structure and equipment are capable of withstanding the maximum expected launch vehicle ground and flight environments. The spacecraft compatibility must be proven by means of adequate tests."

Acoustic Testing requirements

Acoustic testing is accomplished in a reverberant chamber. The volume of the chamber with respect to that of the spacecraft shall be sufficient so that the applied acoustic field is diffuse.

VEGA Launcher's Manual

Acoustic testing is accomplished in a reverberant chamber applying the flight limit environment provided in Chapter 3 paragraph 3.2.6 and increased by the appropriate safety factors. The volume of the chamber with respect to that of the spacecraft shall be sufficient so that the applied acoustic field is diffuse.

SOUYUZ and ARIANE V Launcher's Manual

Other Users' Manual (incl. H3, Delta-IV, Falcon, Atlas-V) do not mention any diffusivity requirement – some of these mention the uniformity of the field

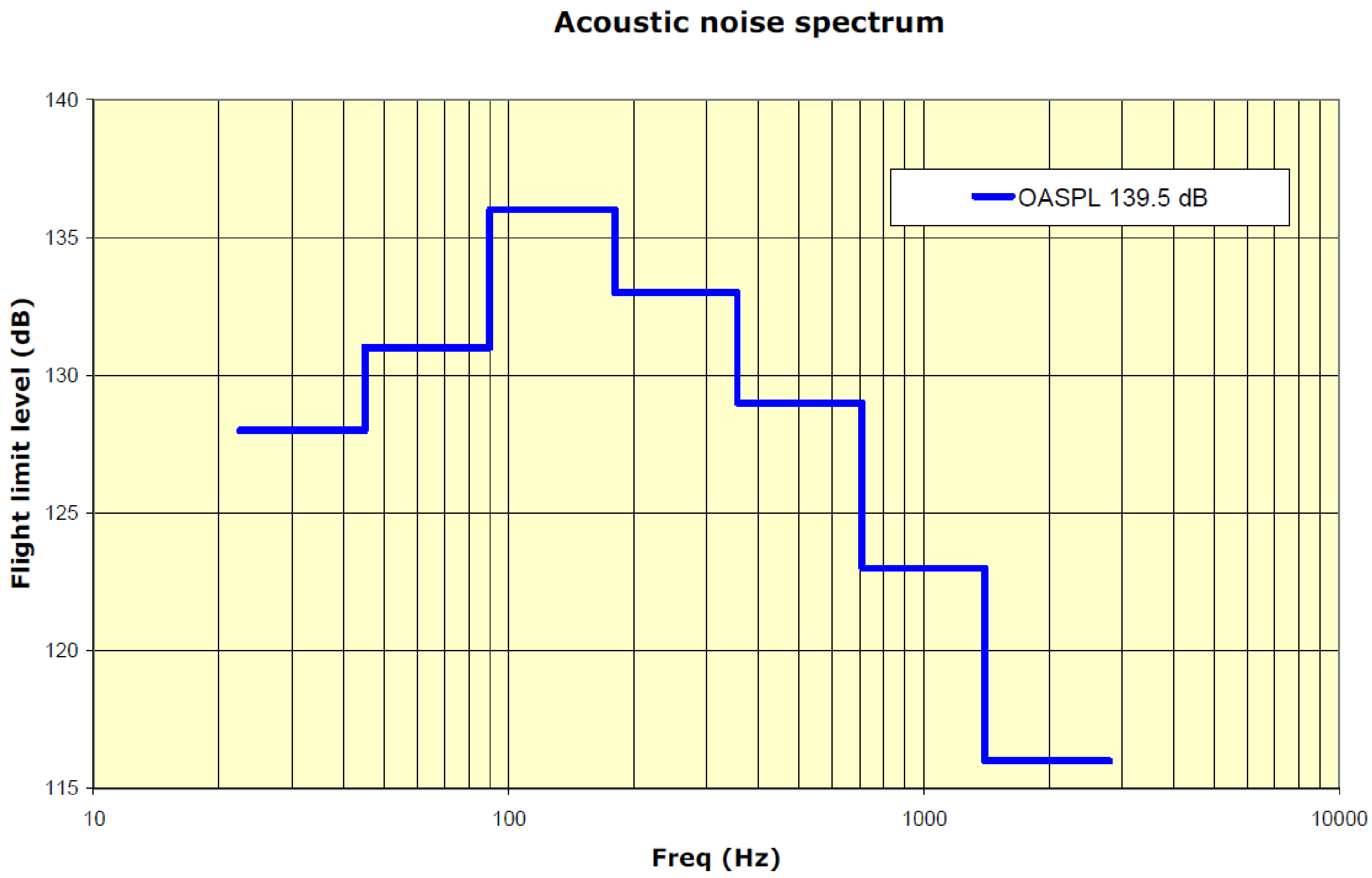
Acoustic Test (in practice)

The launch authority prescribes a spectrum/target (usually in 1/1 Oct)

Reverberant chambers (RFAT) have been used for the past 4 decades

RFAT are controlled automatically or manually

The test requires to maintain the excitation within certain tolerances on each band AND on the OASPL



Why Acoustic Test. And HOW?

WHY?

– ***Acoustic:*** *<u>Simulate wideband frequency loading experienced by S/C</u>*

– ***Structure:*** *<u>Measure vibration response for design verification, workmanship screening</u>*

HOW?

- **Reverberant Field Acoustic Testing (RFAT)** is accepted, and proven;
- The Acoustic Field of a reverberant chamber is well defined and correlates well to theoretical models of diffuse fields;

Should DFAT aim at reproducing this?

- **Direct Field Acoustic Testing (DFAT)** is an accepted alternative
- The acoustic field in DFAT is more complex than the field in RFAT
- Modern DFAT systems enable for Diffusivity Control

- What are the important data and plots to loot at?
- How can we exploit the potential of DFAT for better tests?

Ariane 6 DFAT requirement

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4.2.6.3. Acoustic vibration tests

Acoustic testing should be accomplished in an acoustic reverberant chamber. The volume of the chamber with respect to the spacecraft shall be sufficient so that the applied acoustic field is diffuse. The test measurements shall be performed at an optimum distance from the spacecraft, in order to avoid "wall effect".

In case of direct Field Acoustic Test, please contact Arianespace.

Octave band centre frequency (Hz)	Qualification Level (dB)	Protoflight Level (dB)	Acceptance level (flight) (dB)	Test tolerance (dB)
	ref: 0 dB = 2×10^{-5} Pascal			
31.5	131	131	128	-2 / +4
63	134	134	131	-1 / +3
125	139	139	136	-1 / +3
250	136	136	133	-1 / +3
500	132	132	129	-1 / +3
1000	126	126	123	-1 / +3
2000	119	119	116	-1 / +3
Overall level	142.5	142.5	139.5	
Test duration	2 minutes	1 minute	1 minute	

Table 4.3.3.3.a – Acoustic vibration test levels

- The levels provided in table 4.3.3.3.a are applicable to the Average Sound Pressure Level per octave band,
- Test tolerances allow only to cover calibration dispersion of the acoustic chamber,
- For homogeneity of the acoustic field, dispersion measured between each microphone shall be within +/-3 dB around the average SPL obtained in the octave band.

First launcher manual to acknowledge DFAT

First criterion on uniformity

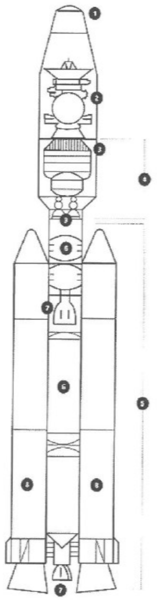
Still short of important details, but a start!

Some questions…

- … do all DFAT tests produce the same field?
- …how could one compare a DFA test with a RFA test?
- …I there a better DFAT than other?
- …what curves/plots do I need to look at during a DFAT?

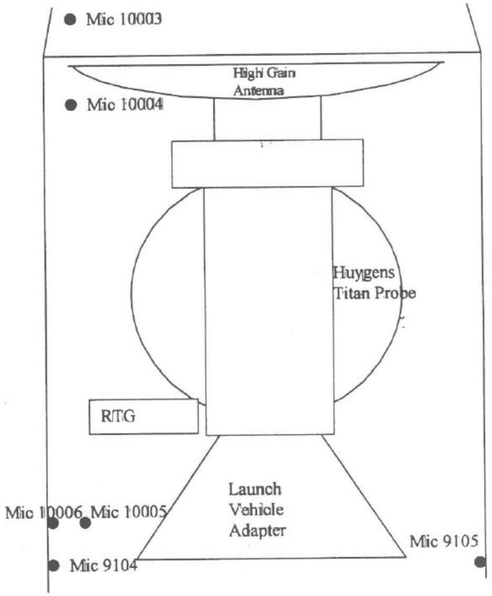
Introducing the SINC INDICATOR FUNCTION (SIF)

The original paper (SCLVD 2000, B Gardner @JPL)

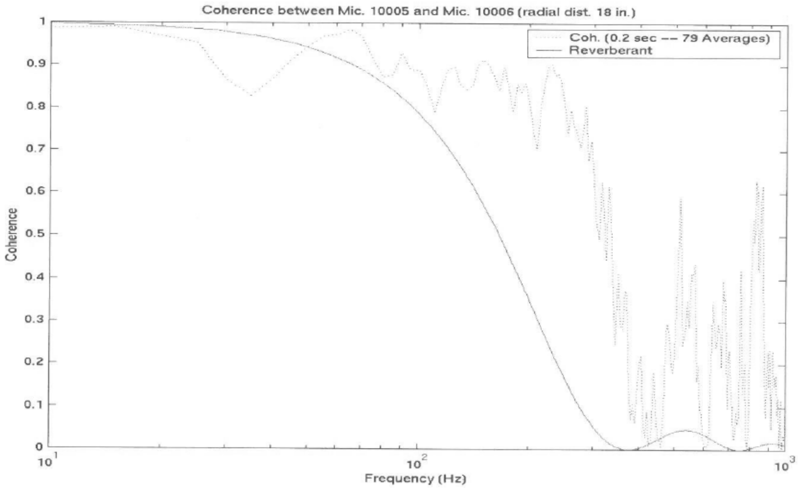


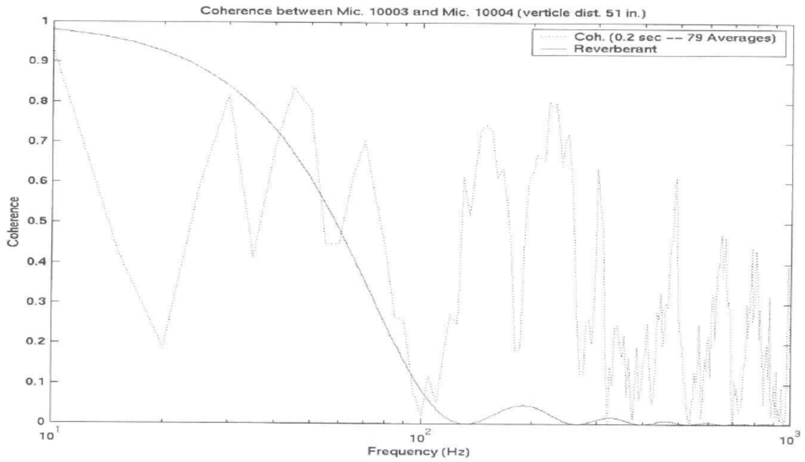
Titan IV B-33

- Launched Oct. 15, ~~1979~~ 1997
- To arrive at Saturn July, 2004
- Significantly updated acoustic blankets (to protect the RTGs)
- Cassini was a large payload (7 meters high with 4 meter diameter High gain antenna)



Measured Coherence vs. Reverberant Field





Diffuse field, Cross Spectral Density and Coherence

DIFFUSE FIELD: A diffuse field describes an acoustic field where sound waves reach the observer from all directions. The reflected sound is of similar magnitude to the direct sound when it reaches the observer, and as a result, ***does not appear to have a single source***. A microphone in a ***diffuse field measures the same magnitude regardless of orientation or location***; the sound level is the same everywhere. In a diffuse sound field, the sound pressure and the particle velocity are not in phase so the net sound intensity is zero and the sound doesn't appear to have a single source.

Diffuse Sound Field Definition (IEC 801-23-31) sound field which in a given region has statistically uniform energy density, for which the directions of propagation at any point are randomly distributed.

It can be shown that the coherence squared of a Diffuse Sound field can by expressed the by Sinc function

$$\gamma_{xy}^2 = \left(\frac{\sin(kr_{xy})}{kr_{xy}}\right)^2$$

In a vibro-acoustic random process, the **Cross-Spectral Density (CSD)** is a function of frequency which is a function of relative coherence (γ_{xy}^2) and phase (θ_{xy}) between 2 signals (or 2 points) as:

$$S_{xy} = \sqrt{\gamma_{xy}^2 S_{xx} S_{yy}}\, e^{j\theta_{xy}} \Leftrightarrow \gamma_{xy}^2 = \frac{\left|S_{xy}\right|^2}{S_{xx} S_{yy}}$$

Coherence/Diffusivity: Theory vs Experiment

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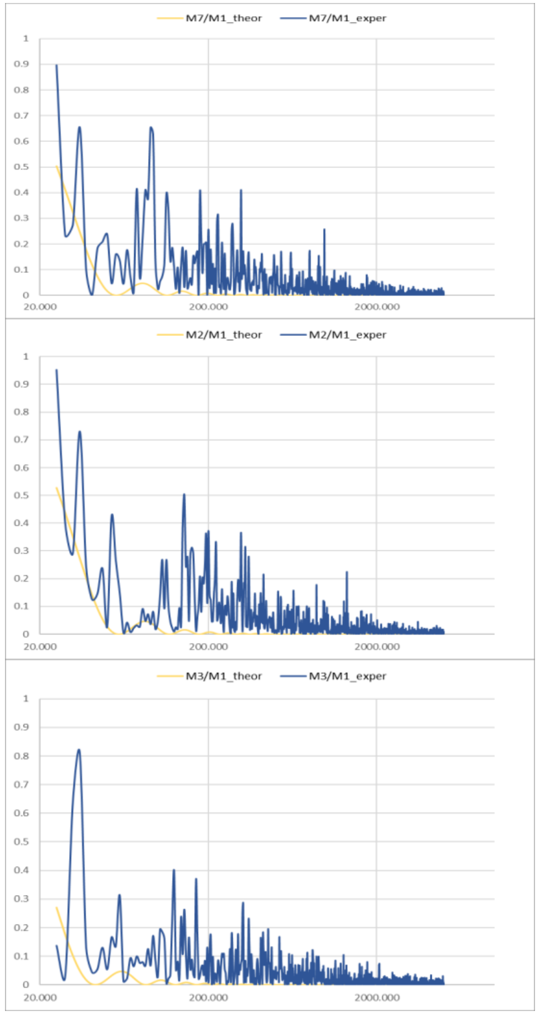
Large Reverb Chamber



Note: Mic position was not measured but inferred

Coherence

$$\gamma_{xy}^2 = \frac{|S_{xy}|^2}{S_{xx}S_{yy}}$$

Where

$|S_{xy}|$ is the Cross Spectral Density (CSD) between points x and y

S_{xx}, S_{yy} are the Auto/Power Spectral Density (PSD) of x and y

For a Diffuse Field the coherence is expressed analytically as

$$\gamma_{xy}^2 = \left(\frac{\sin(kr_{xy})}{kr_{xy}}\right)^2$$

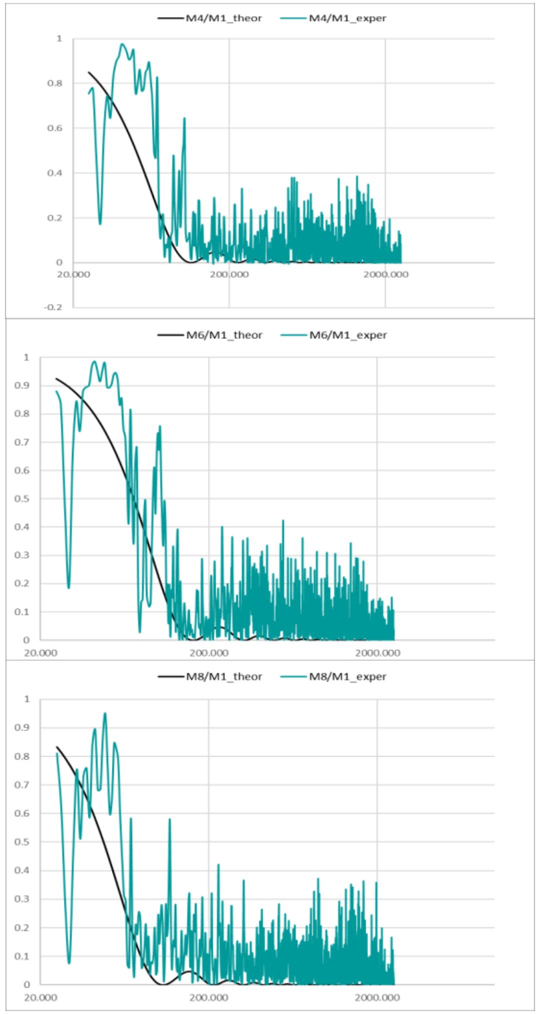
where

$k = \frac{\omega}{c} = \frac{2\pi f}{c}$

f is the frequency in Hz and c is the speed of sound

r_{xy} = distance between points/mics x and y (y = ref mic M1 in these plots)

Large Reverb Chamber



The SIF

SINC INDICATOR FUNCTION (SIF) = $1 - \overline{\Delta\gamma^2}$

where $\Delta\gamma^2 = \left\| \gamma^2 - \left(\frac{\sin(kr)}{kr}\right)^2 \right\|$ is the difference/error between the theoretical and measured coherence, and $\overline{\Delta\gamma^2}$ is the spatial average of this error, i.e. the MEAN across all the microphones

OverAll Sinc Indicator Function (OASIF) of Acoustic Field = *Avg*(SIF)

OASIF = 1 ⇔ theoretical diffuse field

Two extreme cases:

1) Reverberant Chamber: by design providing a reverberant/diffuse field ⇔ $\gamma^2 = \left(\frac{\sin(kr)}{kr}\right)^2$
2) Acoustic field generate by multiple sources using a single signal

Validating the SIF as a metric

OASIF ≈1

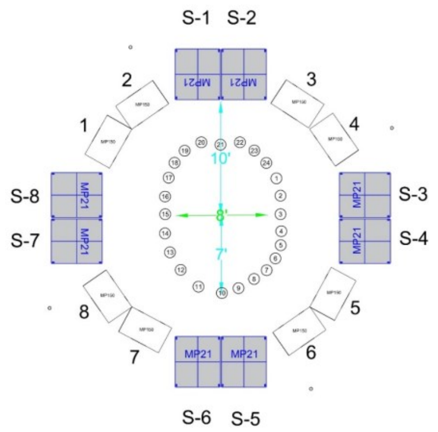
Reverberant Chambers

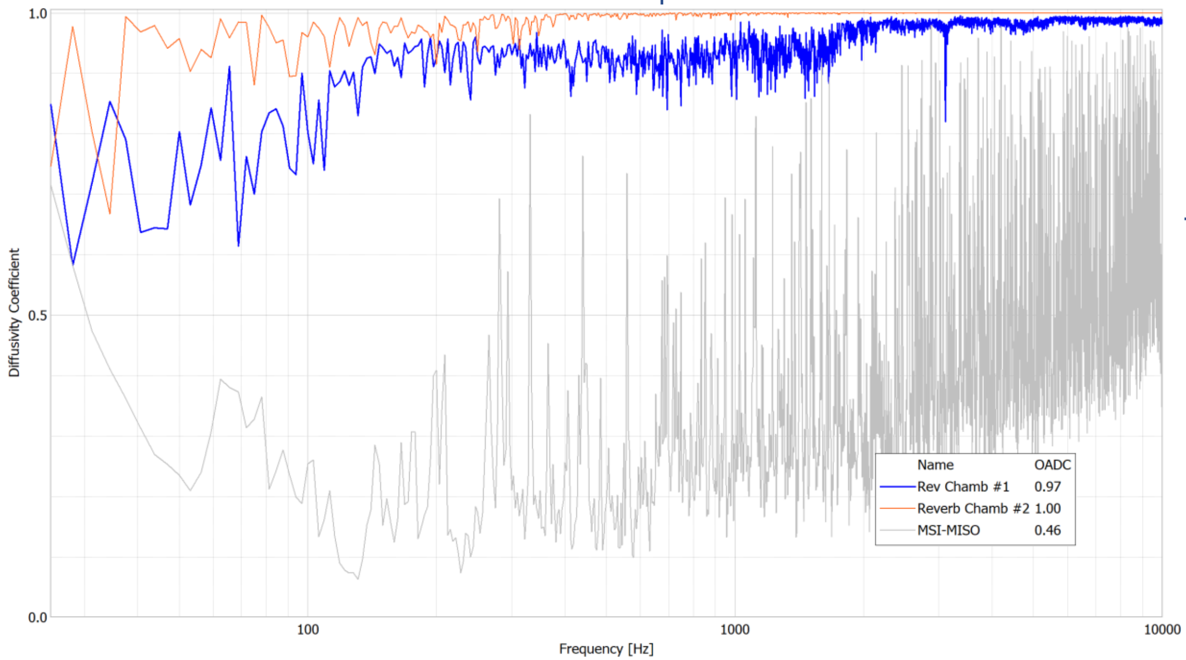
- The Acoustic Field produced by a reverberant chamber is not perfect, but close to the theoretical.
- The lower SIF is observed in the low-frequency region (where the modal density is low)

OADN <<1

MISO (Multi-Input-Single-Output) Test:

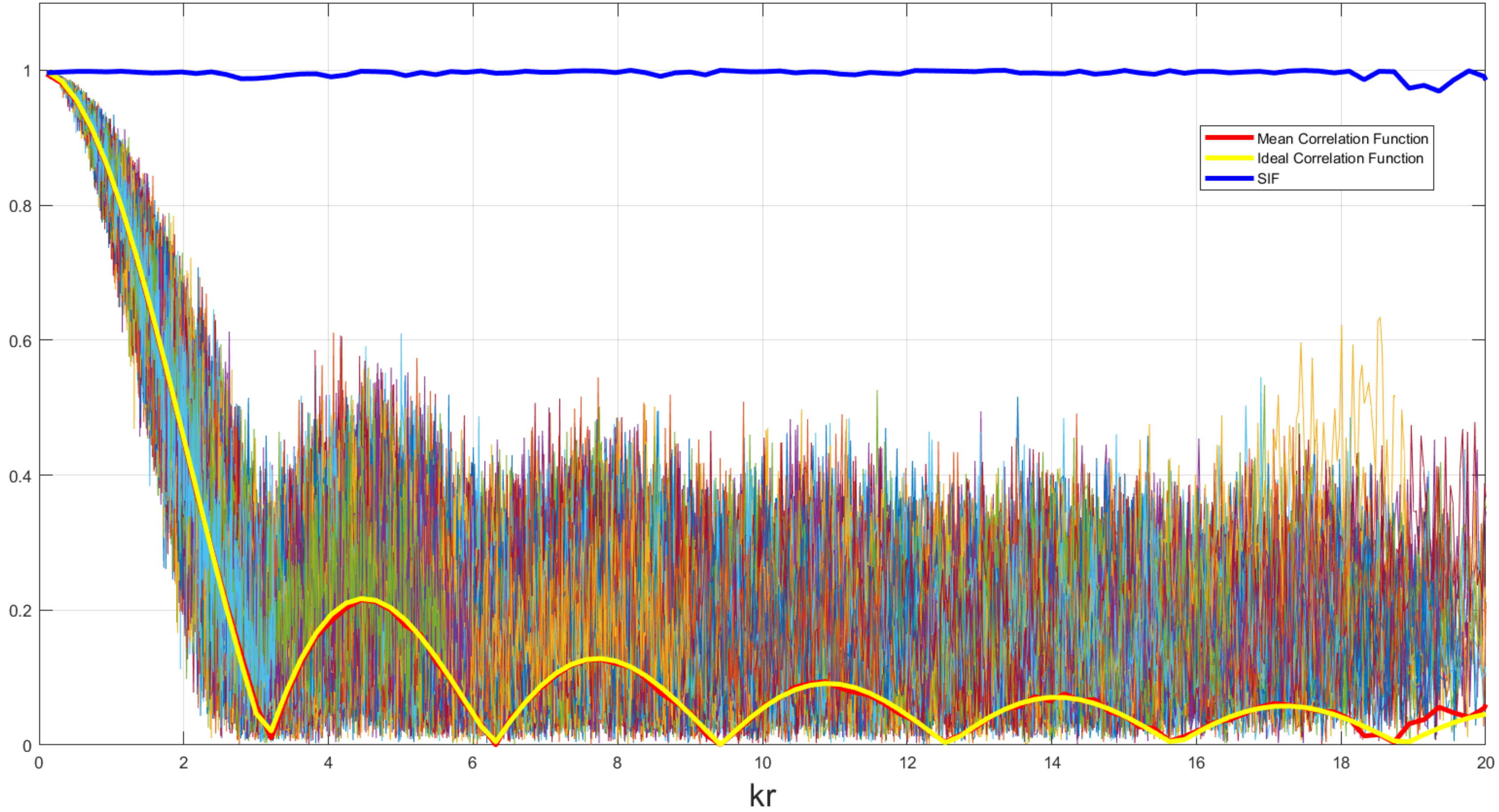
- all the 8 stacks of speakers are driven by the same drive
- It was the very first strategy used for DFAT – abandoned in favor of MIMO





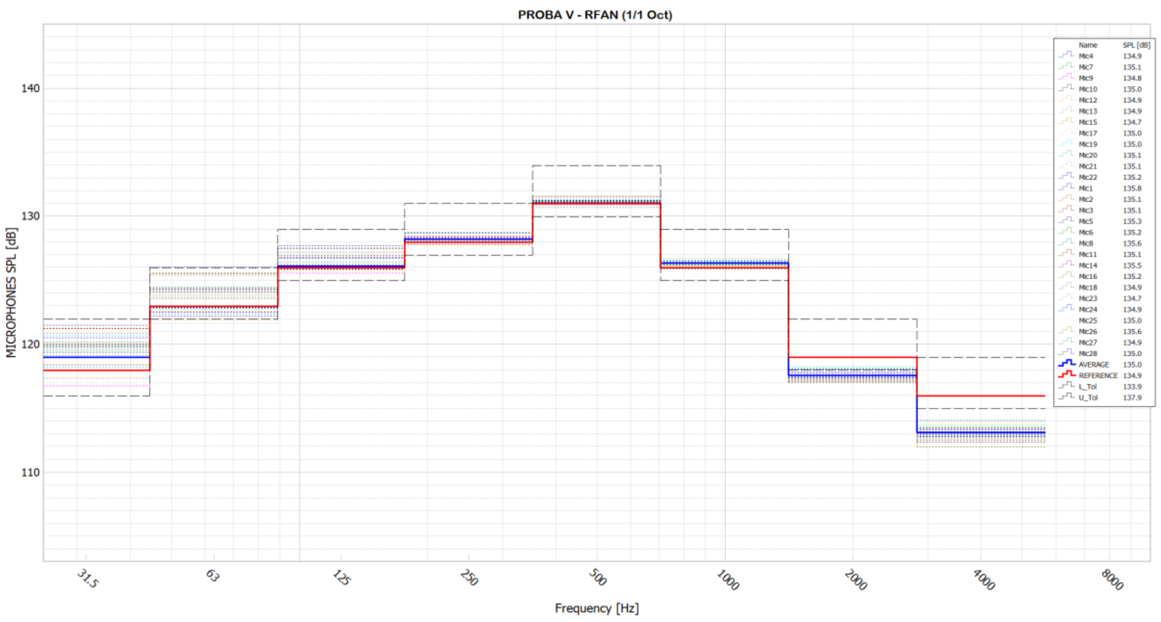
Validating the SIF as a metric

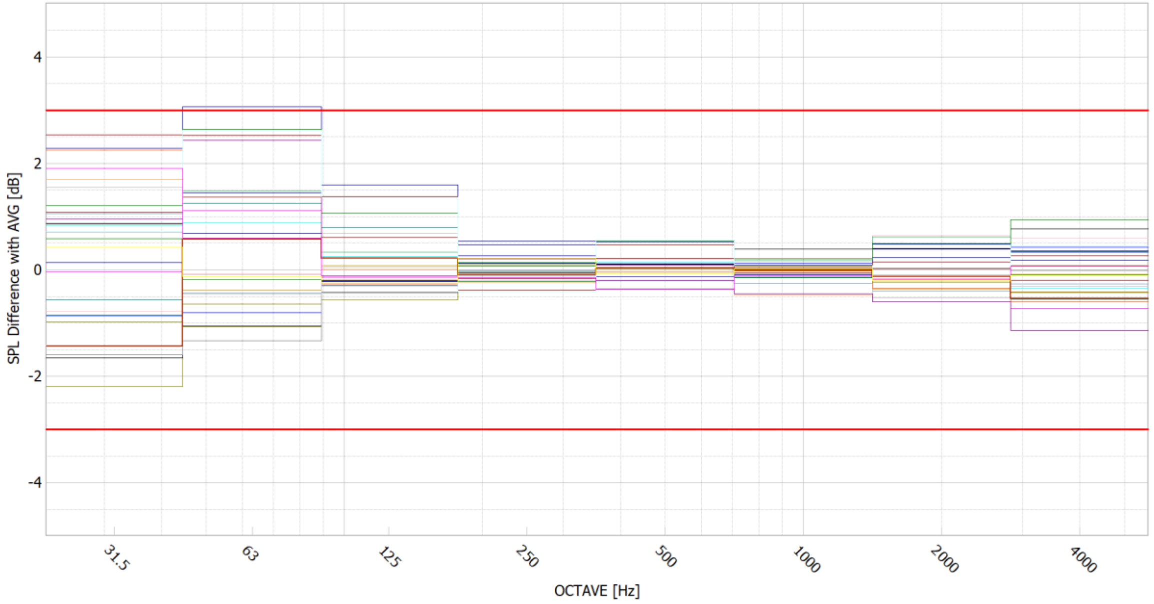
The theoretical case of Numerical Simulation

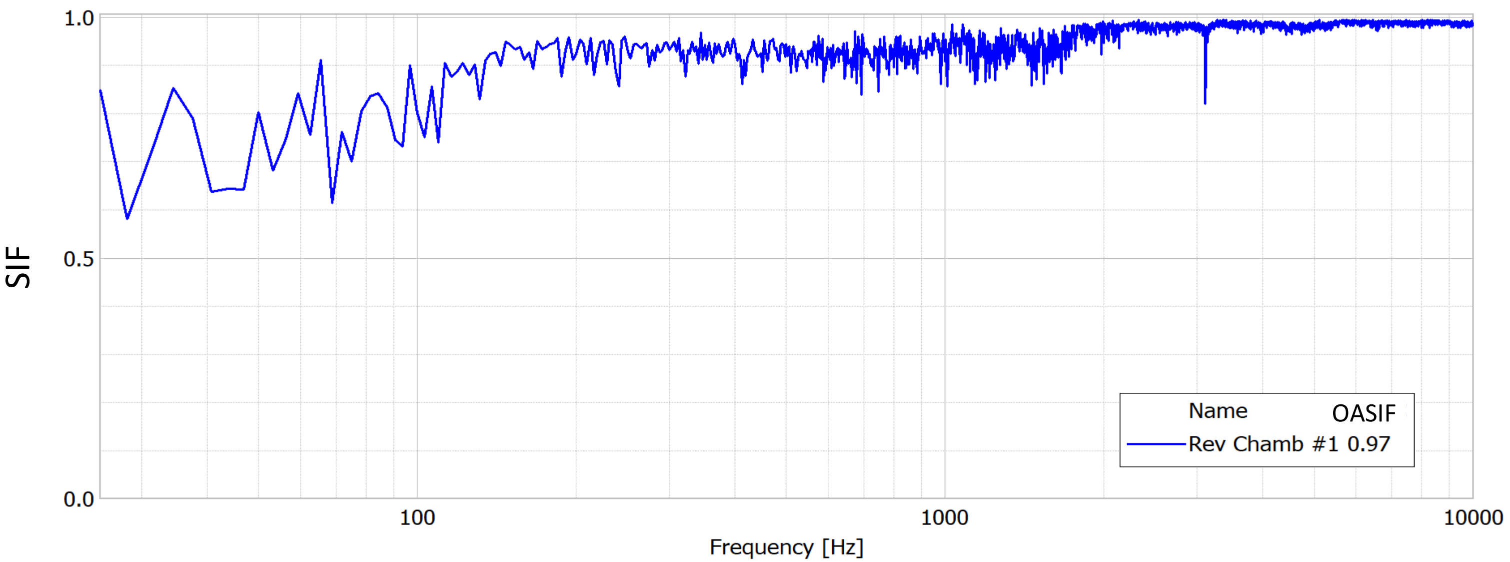


Coherence squared plot of multiple location pairs in a simulated reverberant (diffuse) field

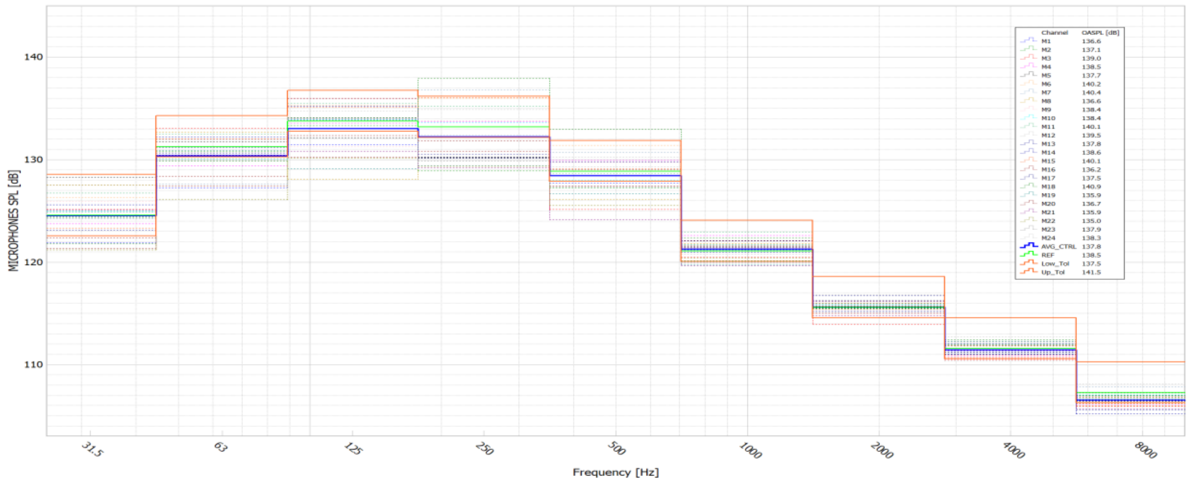
Reverberant Chamber: the standard



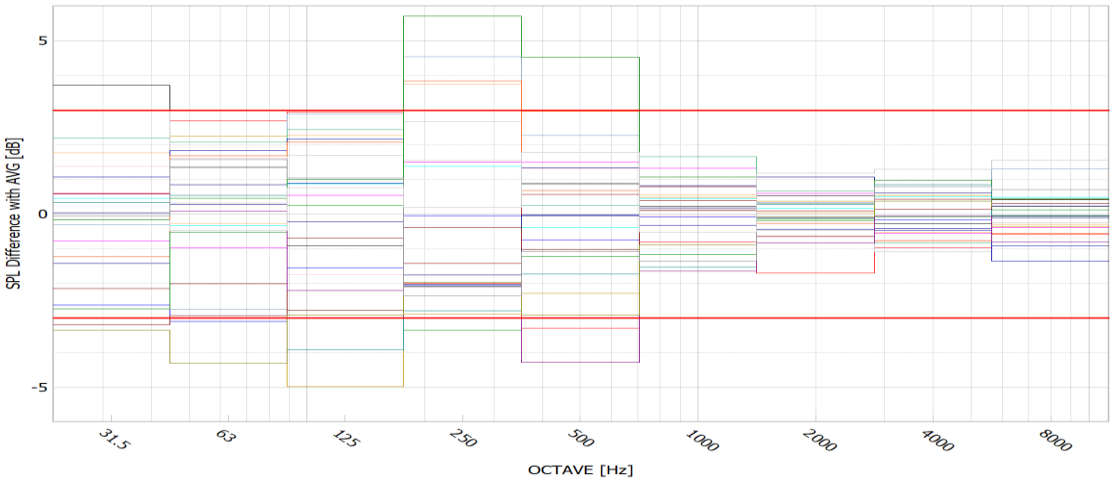




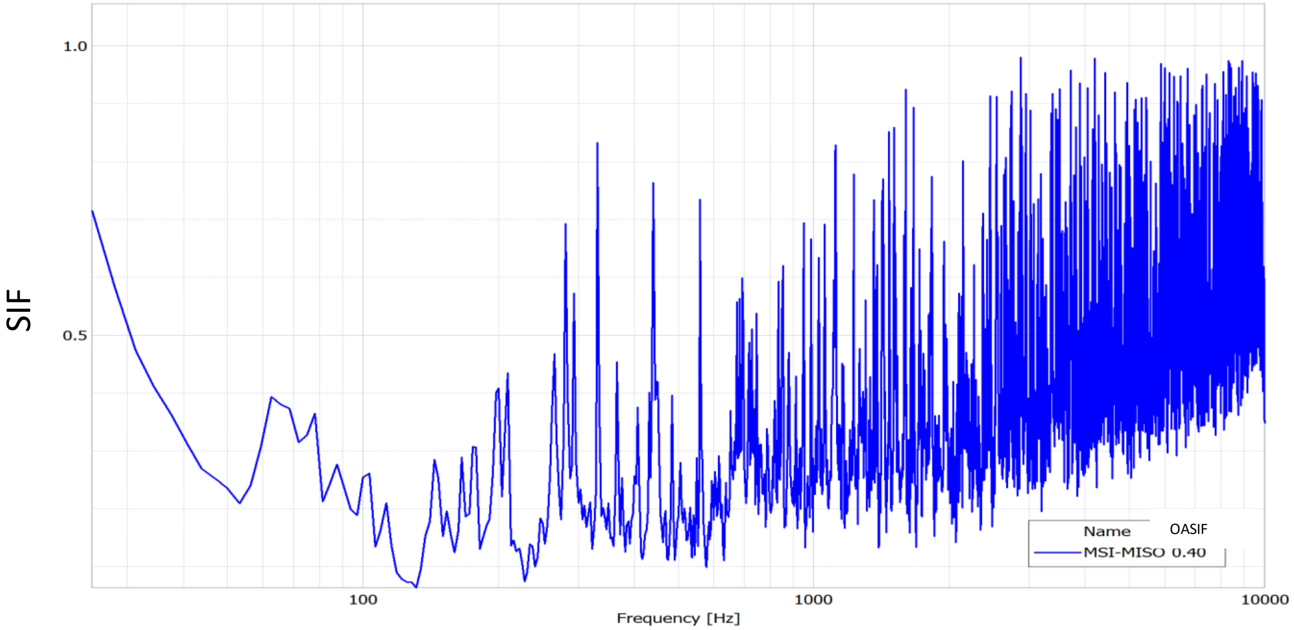
MISO



MICROPHONES SPL [dB]
140
130
120
110
31.5
63
125
250
500
1000
2000
4000
8000
Frequency [Hz]
Channel OASPL [dB]
M1 136.6
M2 137.1
M3 139.0
M4 138.5
M5 137.7
M6 140.2
M7 140.4
M8 136.6
M9 138.4
M10 138.4
M11 140.1
M12 139.5
M13 137.8
M14 138.6
M15 140.1
M16 136.2
M17 137.5
M18 140.9
M19 135.9
M20 136.7
M21 135.9
M22 135.0
M23 137.9
M24 138.3
AVG_CTRL 137.8
REF 138.5
Low_Tol 137.5
Up_Tol 141.5

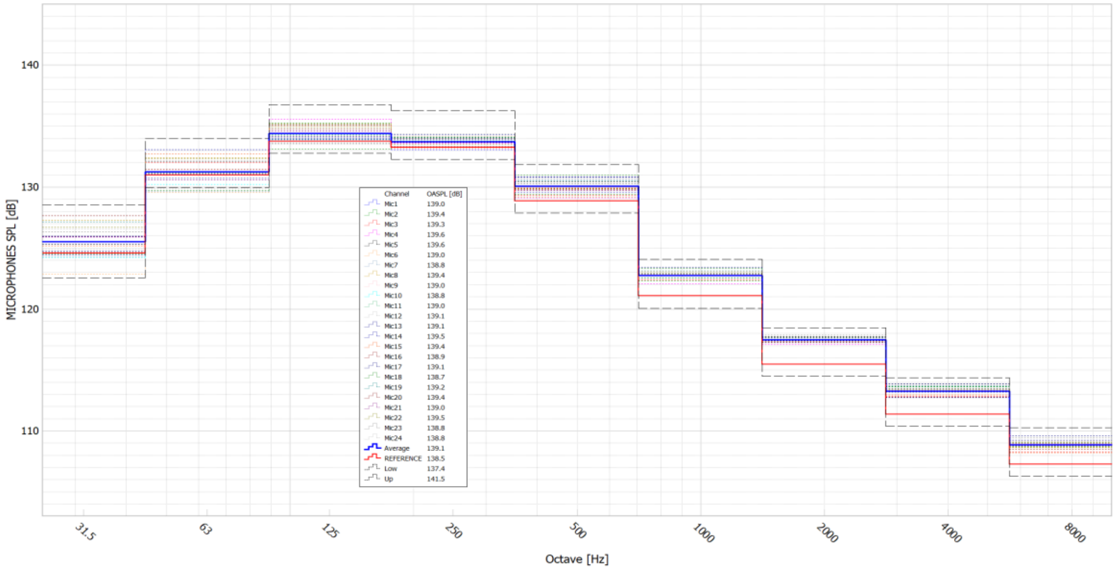


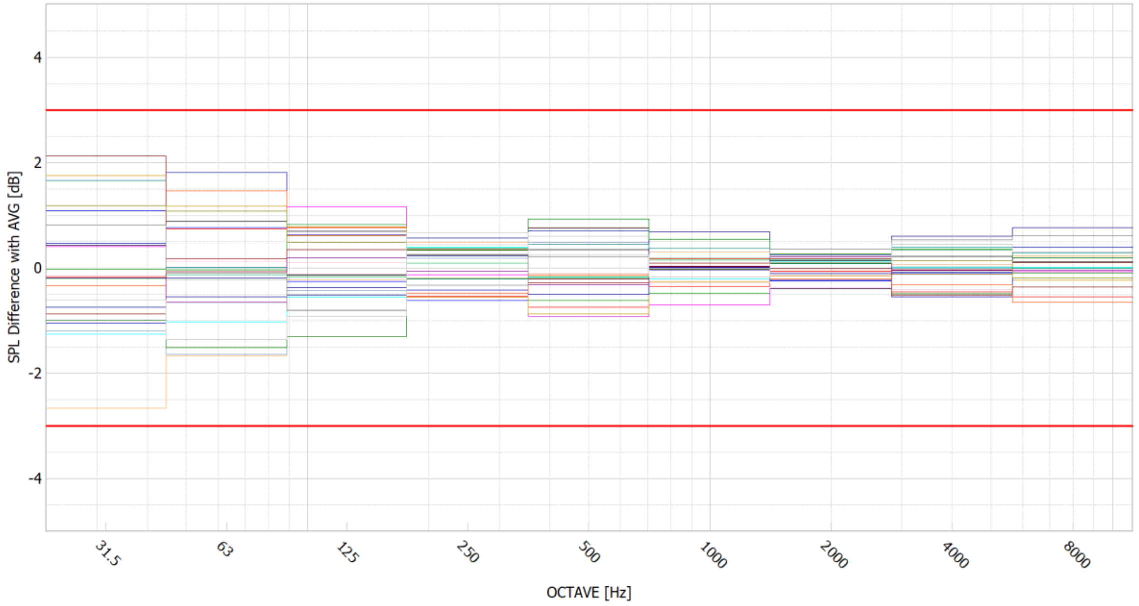
SPL Difference with AVG [dB]
5
0
-5
31.5
63
125
250
500
1000
2000
4000
8000
OCTAVE [Hz]

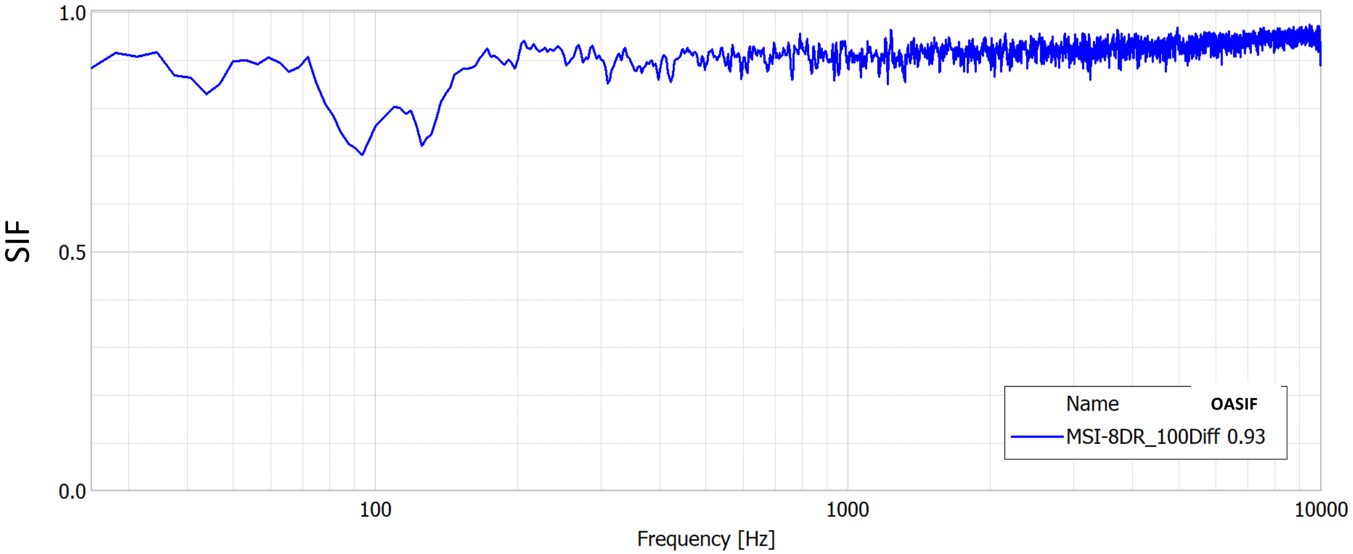


SIF
1.0
0.5
100
1000
10000
Frequency [Hz]
Name
OASIF
MSI-MISO 0.40

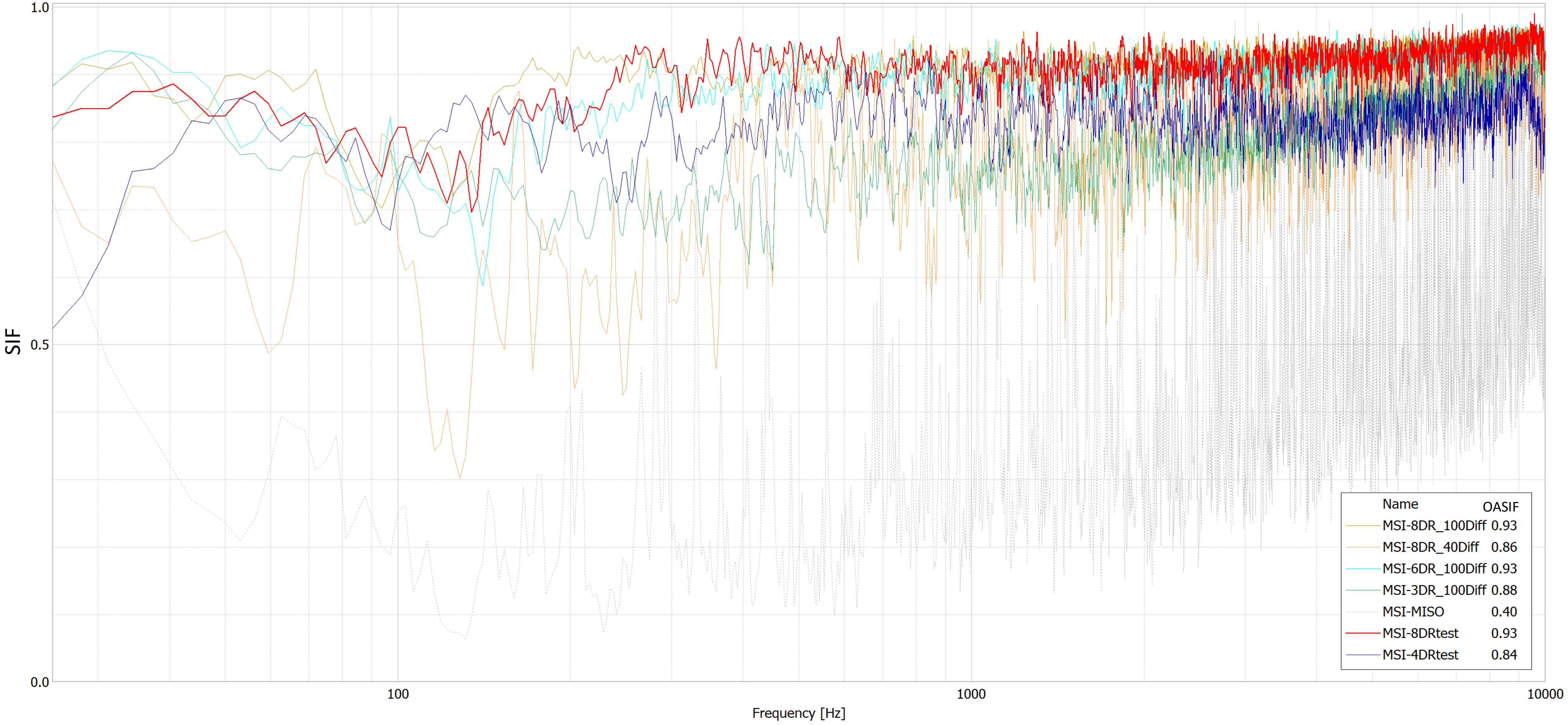
MSI 24x8 – Low Coherence







One System, many SIFs



Today's Goal: achieve an acoustic field the closest to a reverb chamber

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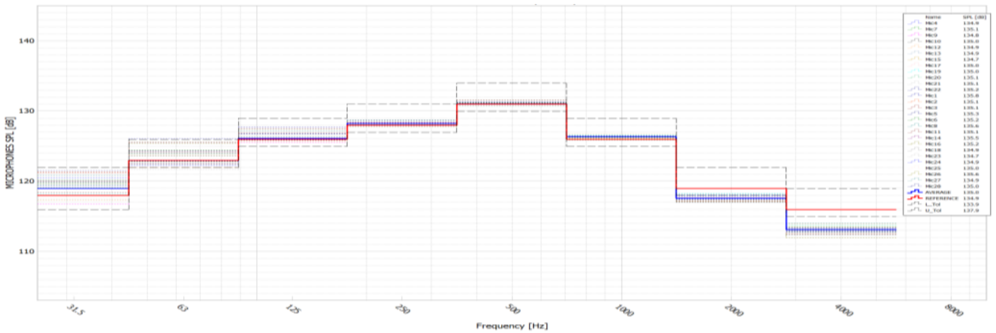
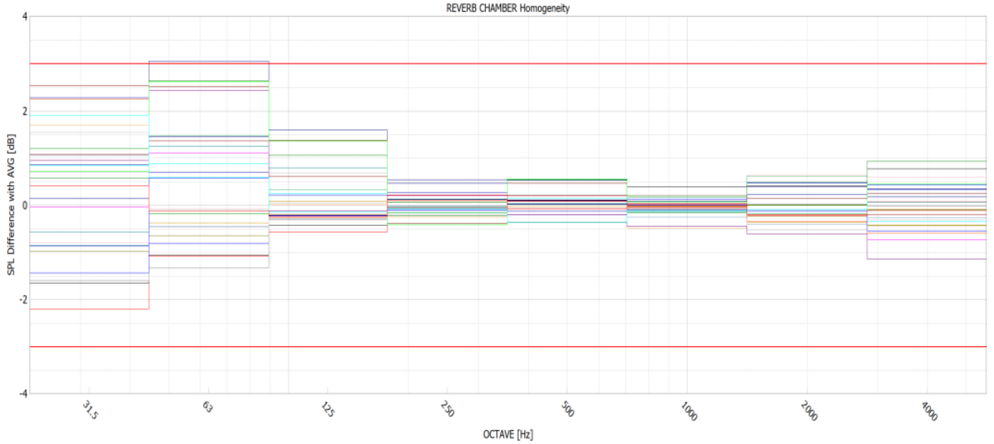
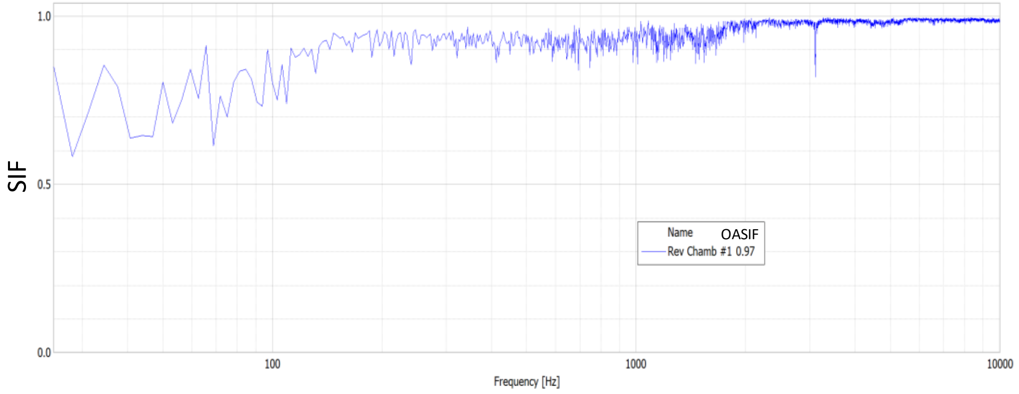
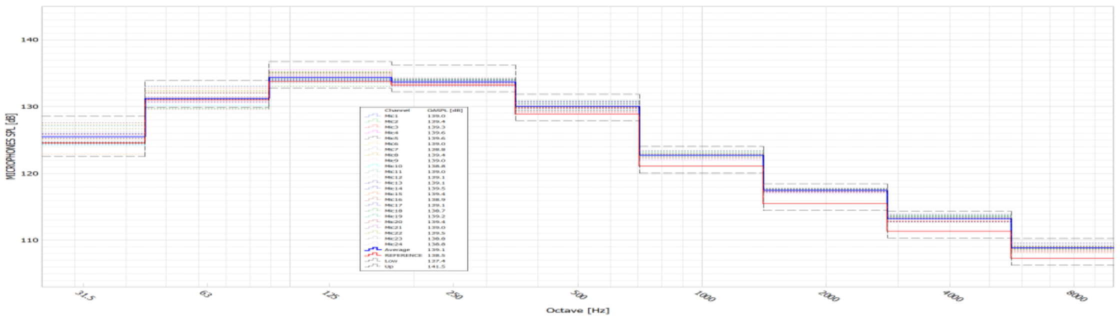
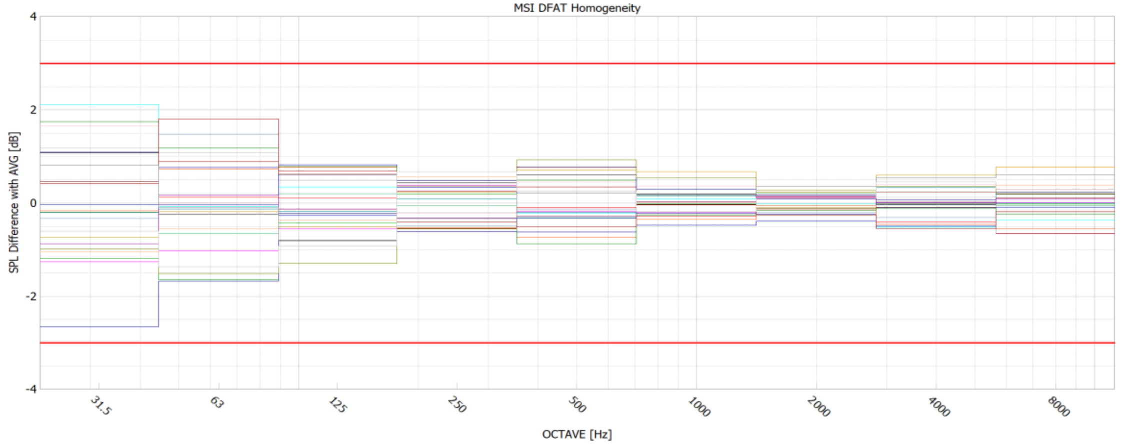
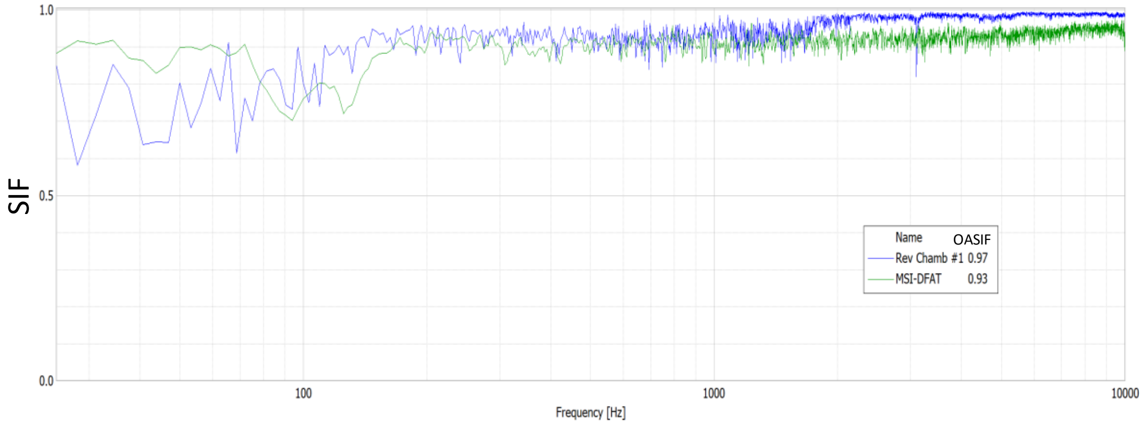






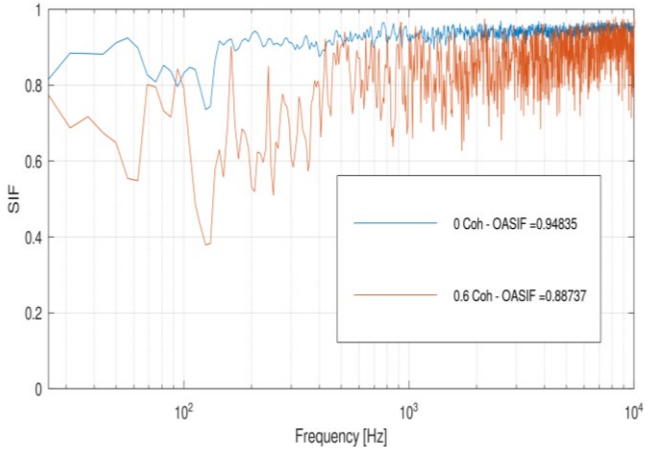




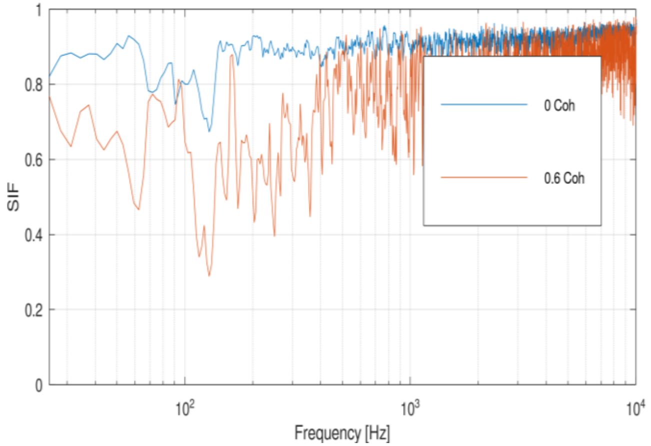


The effect of sampling frequency on OASIF

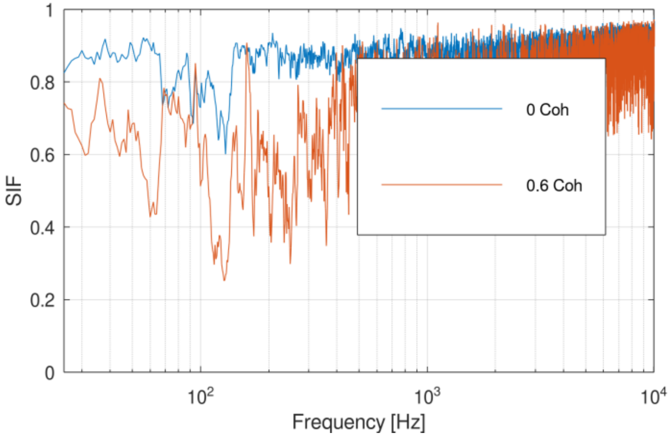
6.25 Hz res
OASIF_0 = 0.9483
OASIF_06 = 0.8874



3.125 Hz res
OASIF_0Co = 0.9344
OASIF_06Co = 0.8626



1 Hz res
OASIF_0Co = 0.9154
OASIF_06Co = 0.8365



Conclusions

- Direct Field Acoustic Testing (DFAT®) is a relatively new technology that reduces testing costs
- The Acoustic Field produced in a DFAT® changes depending on the technology used
- Looking at how close to the theoretical Sinc function is the coherence squared measured between microphones during a DFAT® test can be a metric to differentiate between 2 different DFAT tests – or 2 acoustic fields more generally
- This metric works only for relative comparisons and if the data processing is done exactly the same – the effect of the sampling frequency can produce different OASIF values
- More (controlled) cases will be necessary to generalize the concept

Thank you!

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