NRC·CNRC

Consultative Committee for Acoustics, Ultrasound and Vibration
Evolving Needs in Metrology Workshop, 24th October 2023

Comparison of the calibration results based on acoustical and optical methods for MEMS and LS2P microphones

Triantafillos Koukoulas, Wan-Ho Cho, Fabio Saba,
Alessandro Schiavi, Giovanni Durando, Andrea Prato and Lixue Wu

National Research Council Canada | Conseil national de recherches Canada

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Canada

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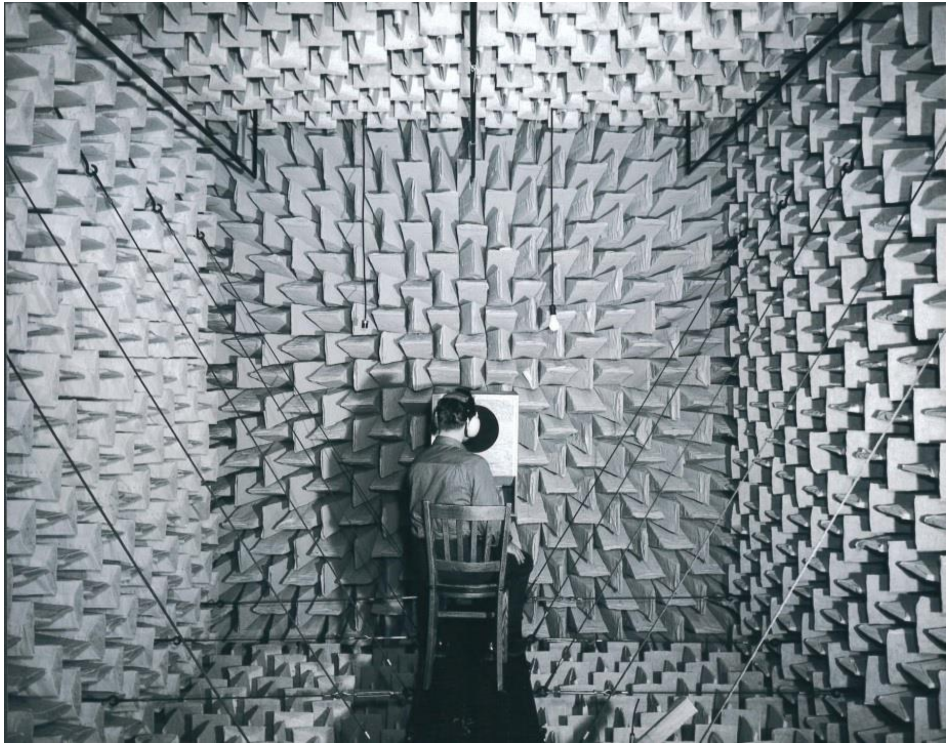
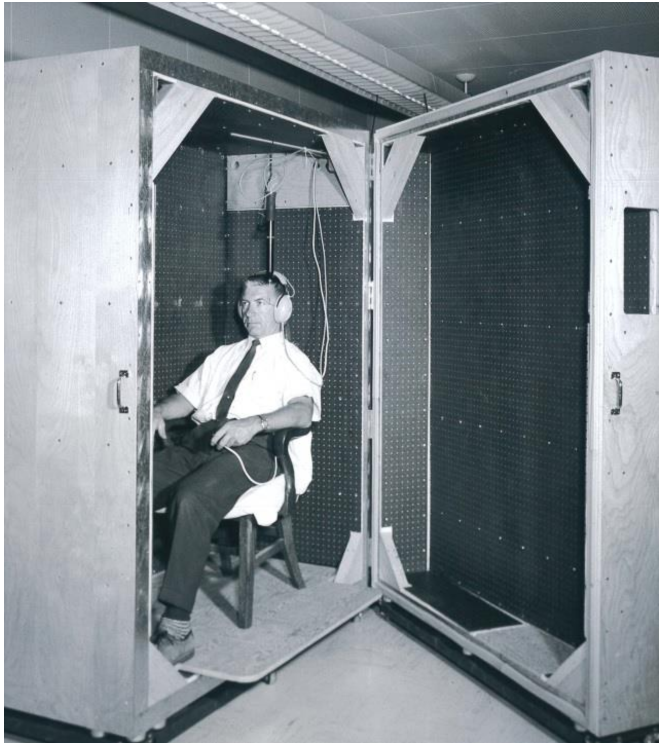
How things have changed…





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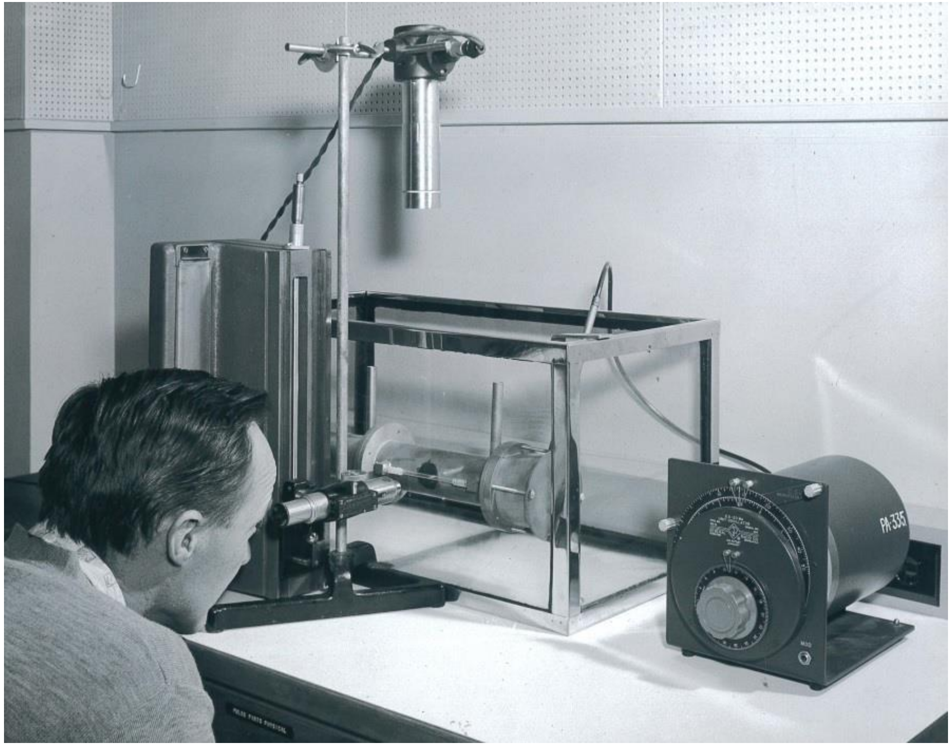
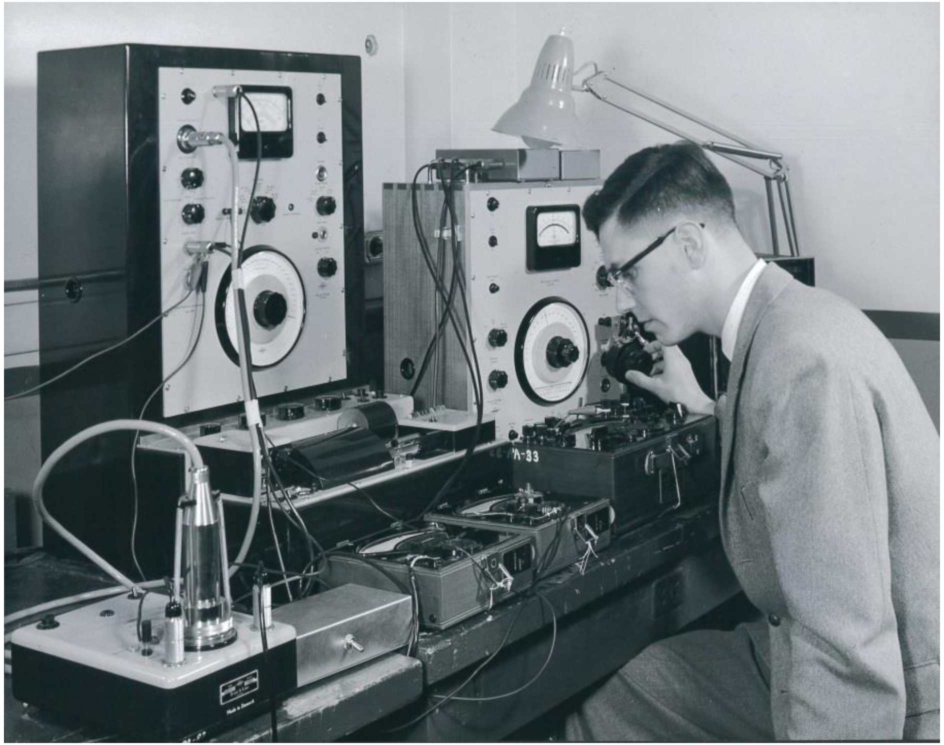
…and evolved (including the haircuts)





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Seven SI base and derived units

- All exclusively defined and traceable to combinations of fundamental constants
- This does not imply that derived units are also defined likewise

Acoustics:

- artefact (microphones and couplers) and method (reciprocity)
- dB, not direct Pa

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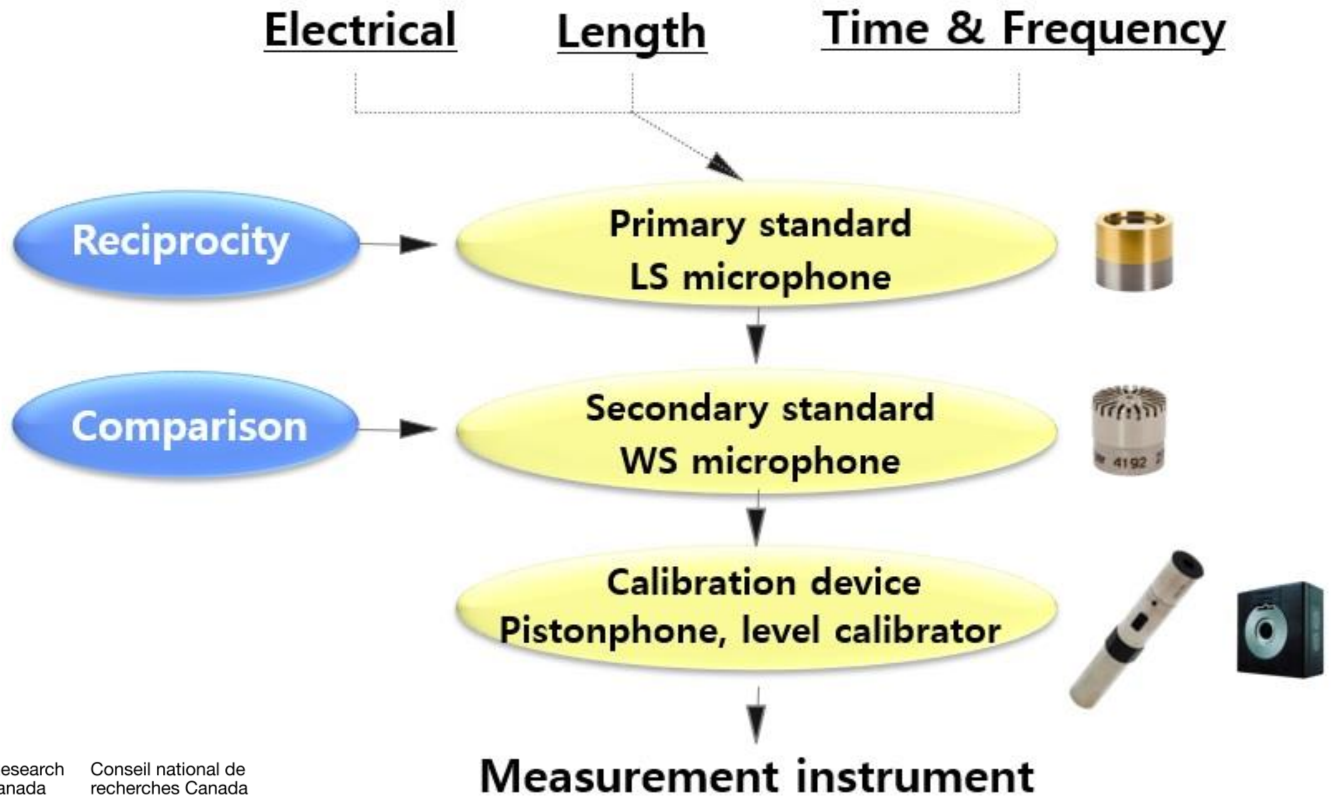
Standards, sensors and devices



Traceability of calibrations

NMI traceability

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- Not all microphones are condenser type, reciprocal, 1” or 1/2” in dimensions
- Micro-electro-mechanical systems (MEMS) microphones?

No NMI traceability

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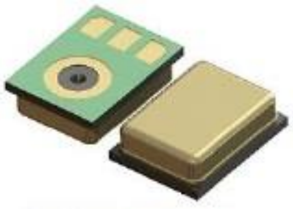

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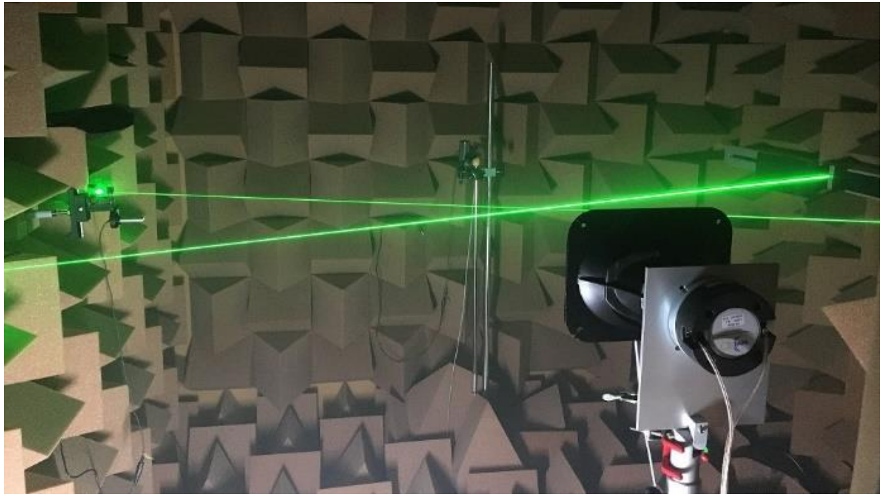
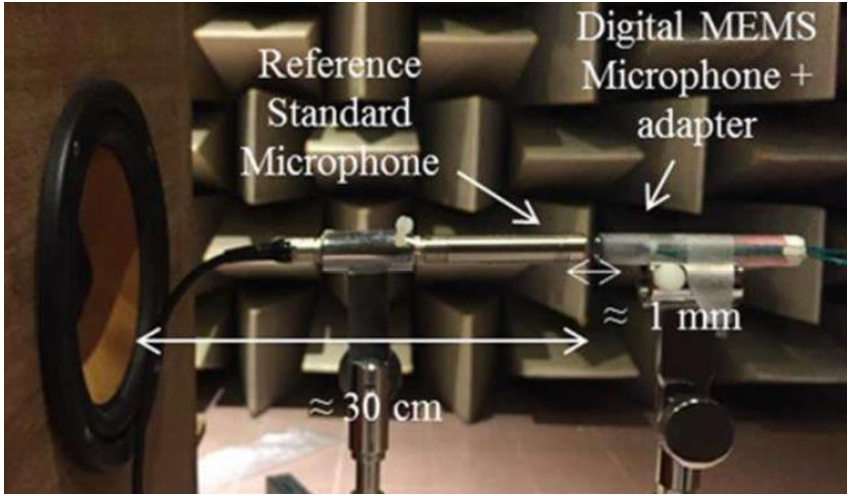
Traceability of calibrations

In 2021, NRC, KRISS and INRIM discussed a collaborative project (started in 2022):

- Photon correlation method, acoustical substitution method and pressure reciprocity
- Two MEMS microphones and one LS2P microphone





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Introduction on the absolute calibration of microphone by optical method

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KRISS

Method – Photon Correlation Method

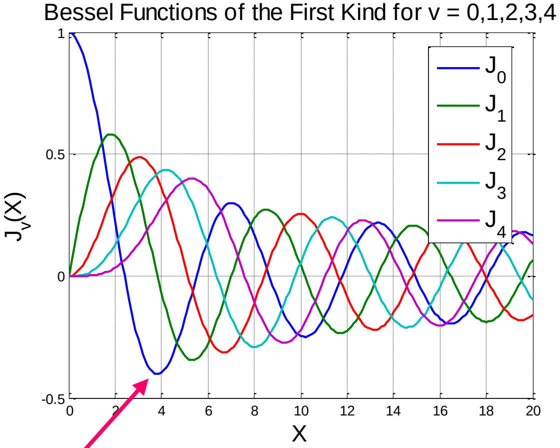
Basic theory

- Optical signal induced by fringe
  - ✓ Acoustic velocity: $u(t) = u_m \sin(\omega t)$
  - ✓ Auto correlation function (ACF):

$$R(\tau) = E\left[v(t)v(t+\tau)\right]$$

$$\propto J_0\left[\frac{2Du_m}{\omega}\sin\left(\frac{\omega\tau}{2}\right)\right]$$

Output signal of photodetector

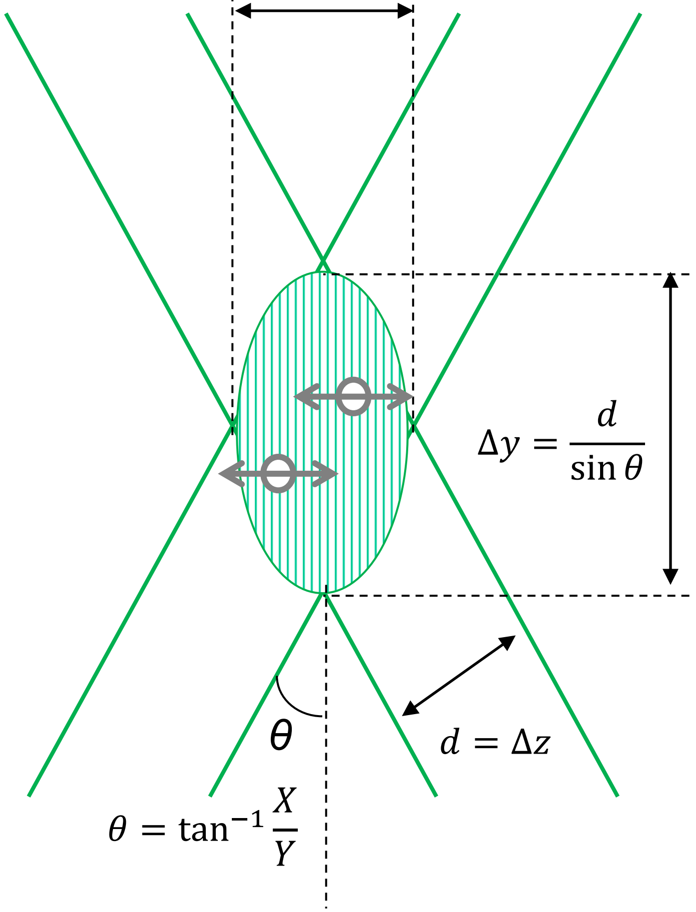


$\tau_{\min}$

$$u_m = \frac{3.832}{\frac{2D}{\omega}\sin\left(\frac{\omega}{2}\tau_{\min}\right)}$$

For free-field:

$$P = Zu_m = \rho_0 c u_m$$



Sharpe, Greated, J. Phys. D: Appl. Phys., 20, 418–423, 1987.
Sharpe, Greated, J. Phys. D: Appl. Phys., 22, 1429–1433, 1989.

Method – Photon Correlation Method

Signal processing procedure

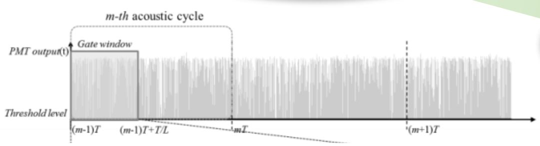
Photon count series

Gating & ACF Estimation

Phase shift

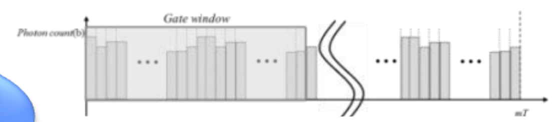
Pressure estimation

Repeat for 360°

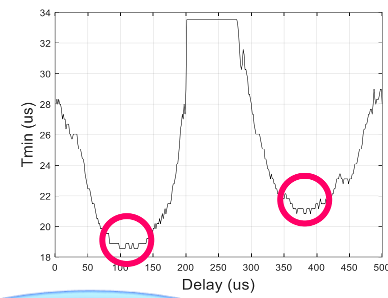


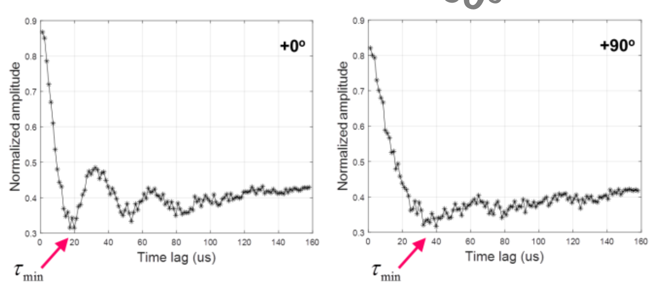
< photon count series >

< Gating & phase shift >



< Finding τ_{min} >





< Change of ACF according to phase shift >

$$u_m = \frac{3.832 f \lambda}{4\sin\theta\cdot\sin\left(\frac{\omega}{2}\tau_{min}\right)}$$

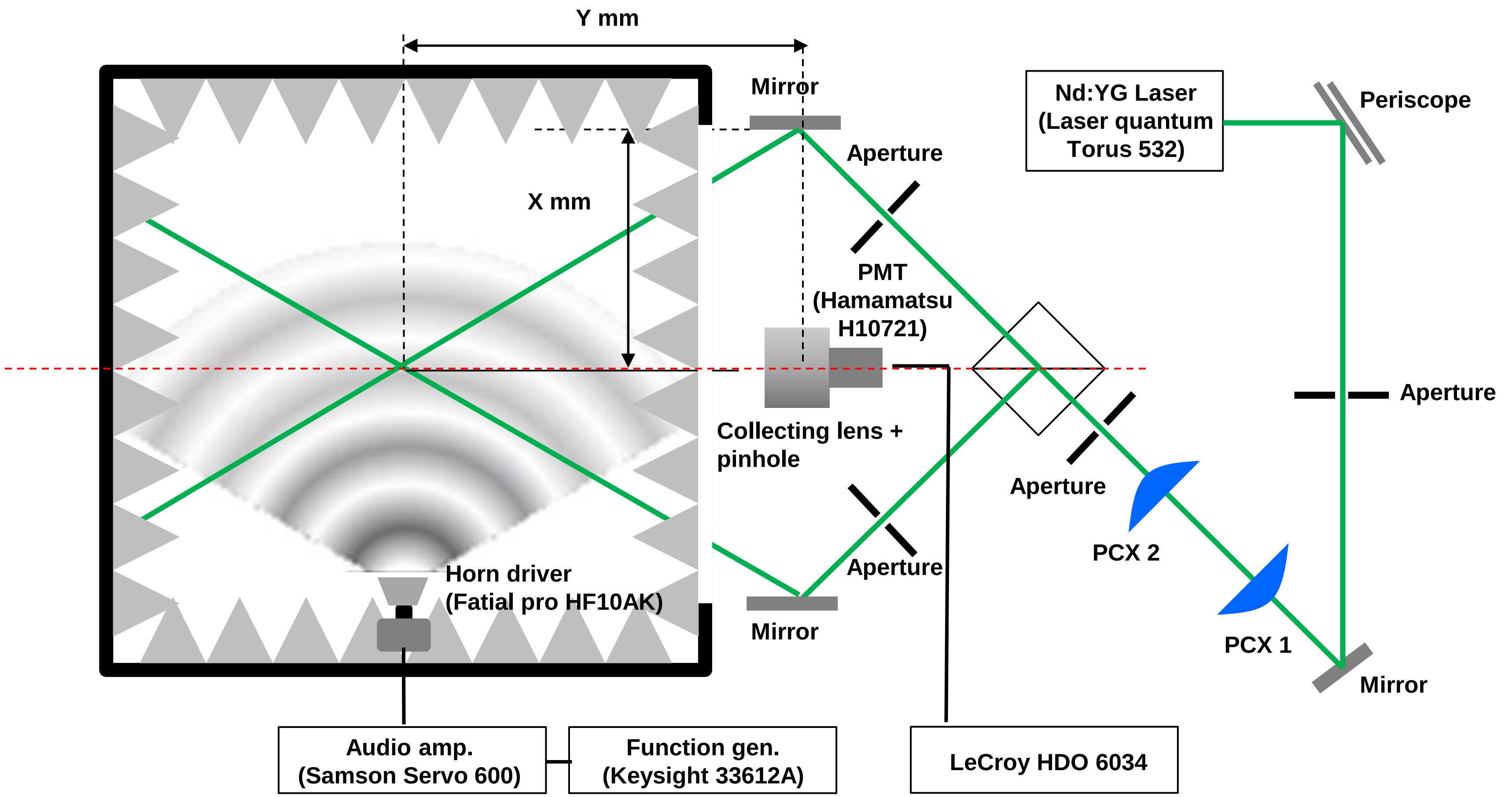
$$u(t) = u_m \sin(\omega t)$$

$$P = Zu_m = \rho_0 c u_m$$

Cho & Koukoulas, IEEE TIM, 69, 2020

System configuration

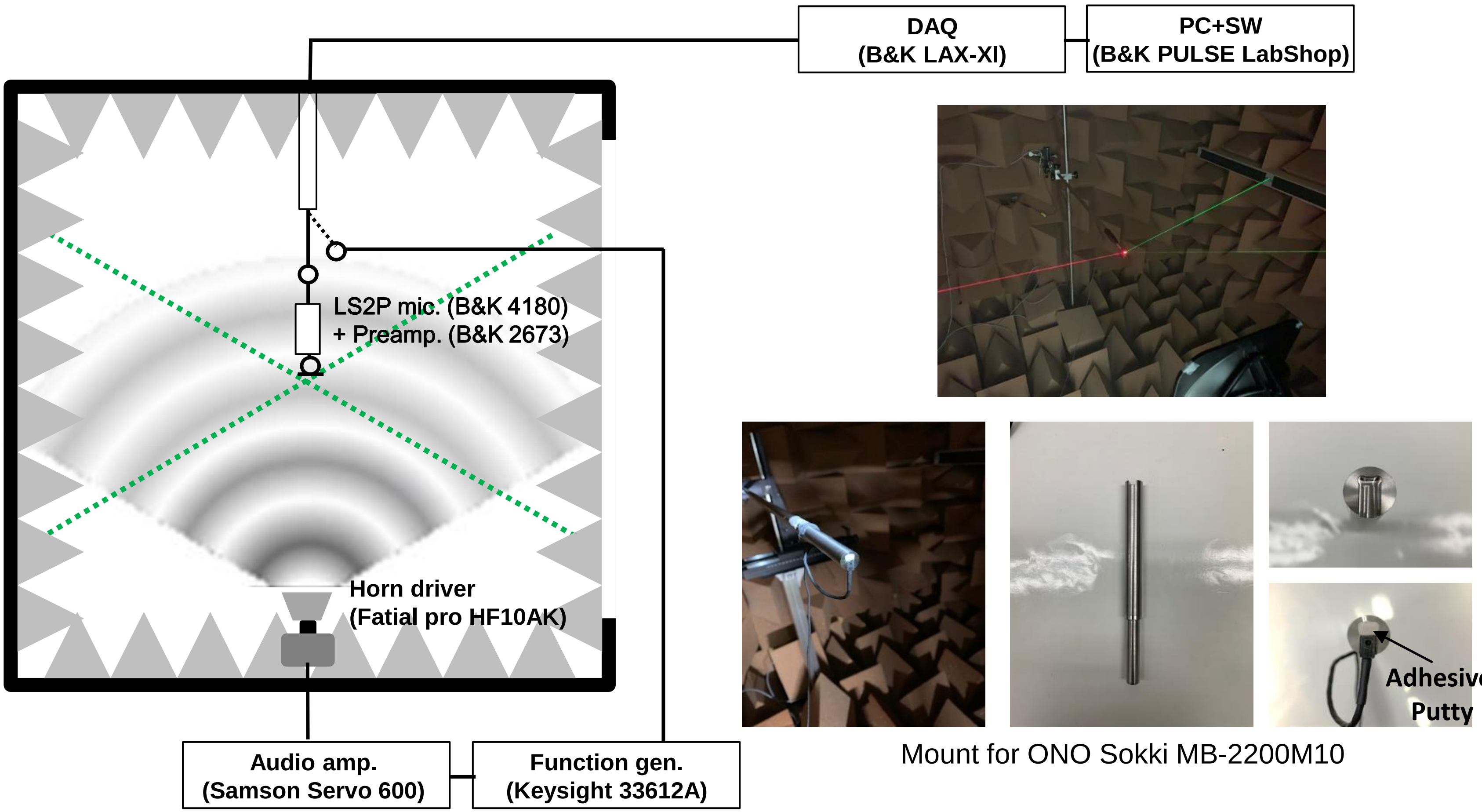
- System for the optical measurement



Cho & Koukoulas, IEEE TIM, 69, 2020

System configuration

- System for the microphone measurement

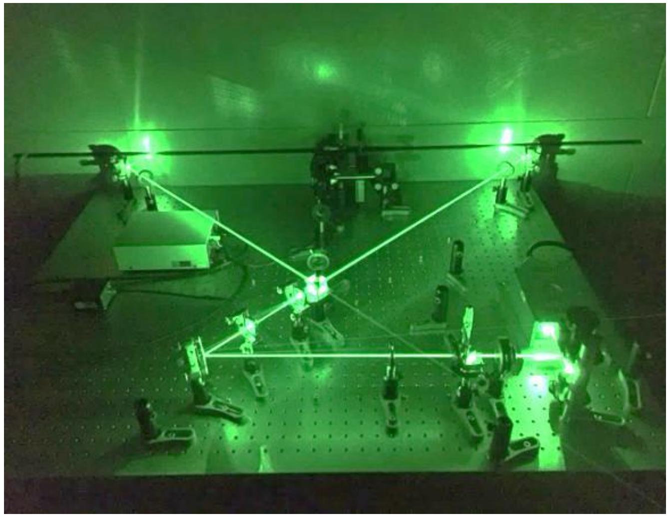


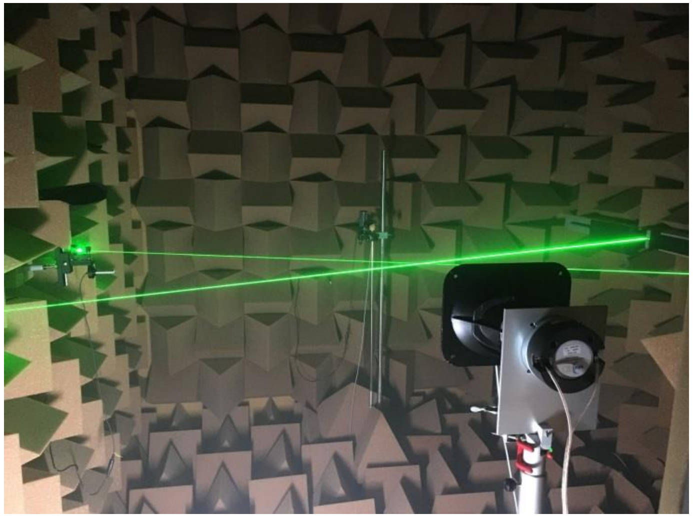
Mount for ONO Sokki MB-2200M10

Measurement System

System configuration

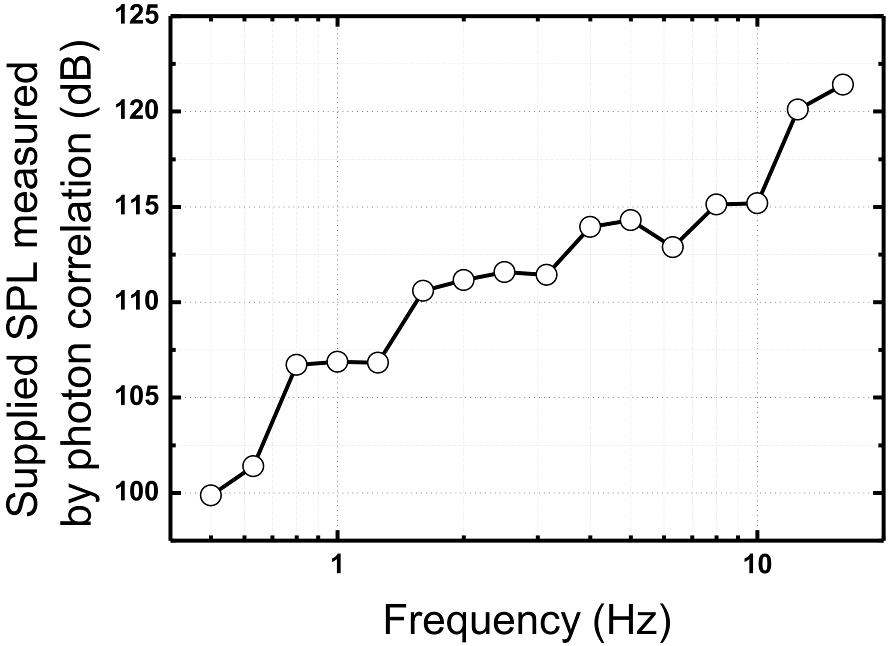
- Anechoic chamber
  - ✓ Outer dim.: 2.7 m X 2.7 m X 2.7 m
  - ✓ Low freq. cutoff: 250 Hz (Wedge length: 0.4 m)
- Instruments
  - ✓ PMT: Hamamatsu H10721
  - ✓ Horn driver:
    - 0.5 kHz – 12.5 kHz: Fatial pro HF10AK
      (Freq. range of spec.: > **<u>0.8 kHz</u>**)
    - 16 kHz – 20 kHz: Fatial pro FD371

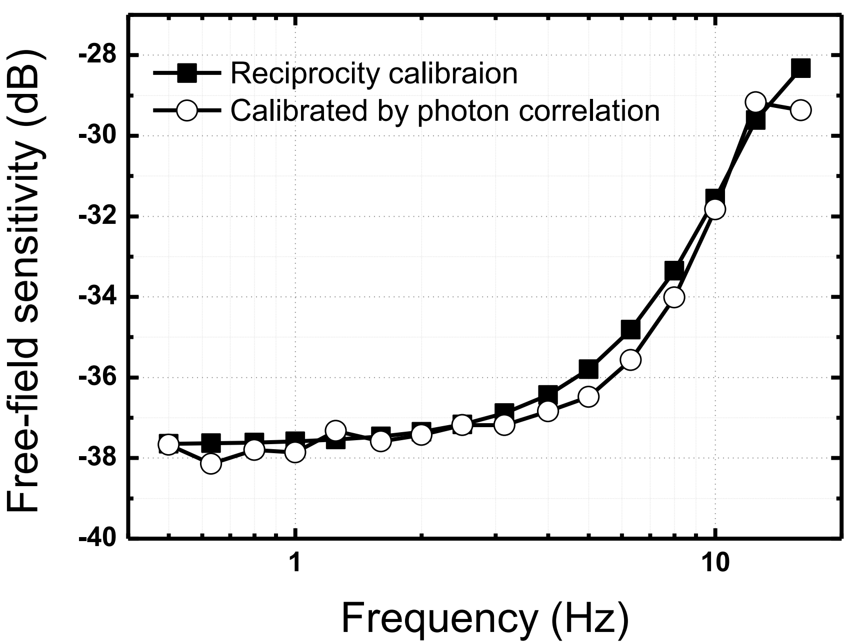




Result of previous study

- Comparison between the methods (LS2p)

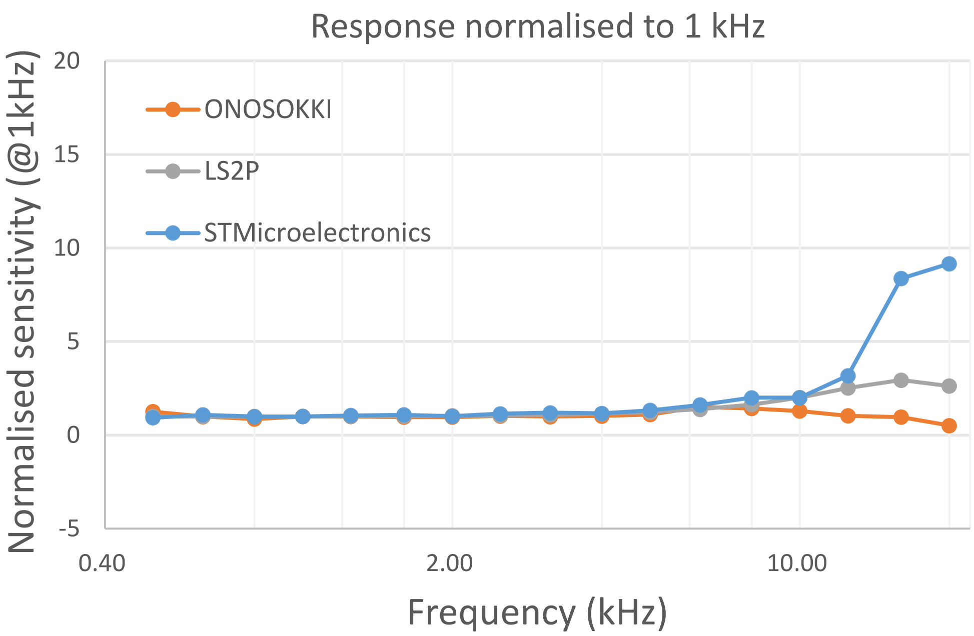




Cho & Koukoulas, IEEE TIM, 69, 2020

Result

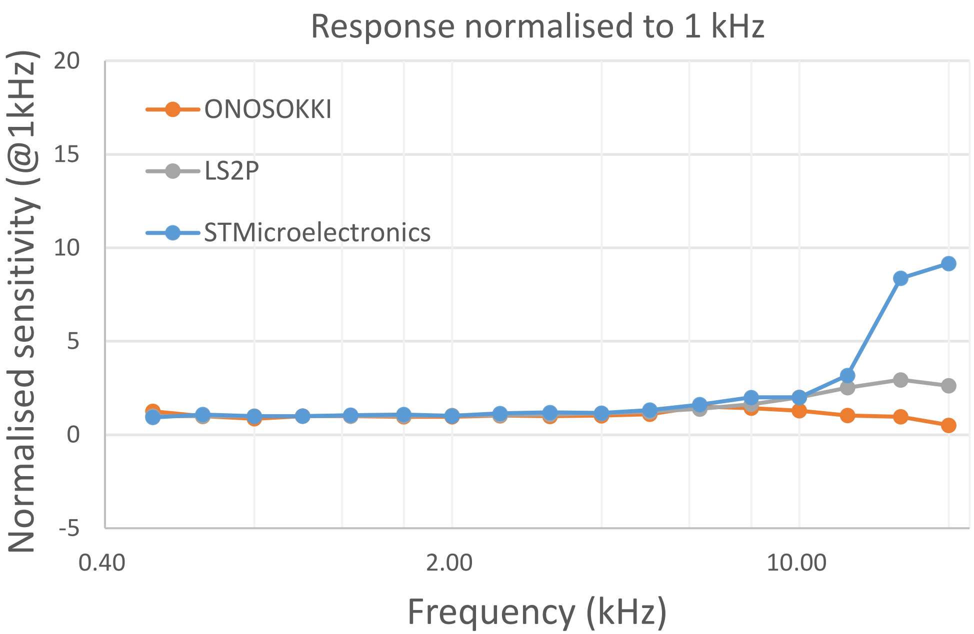
- Result of optical calibration



Freq. (kHz)	ONOSOKKI Sensitivity (norm re: 1kHz)	LS2P Sensitivity (norm re: 1 kHz)	STM Sensitivity (norm re: 1kHz)
0.50	1.25	0.99	0.93
0.63	0.99	0.99	1.08
0.80	0.86	1.00	0.99
1.00	1.00	1.00	1.00
1.25	1.00	1.01	1.04
1.60	0.96	1.01	1.08
2.00	0.96	1.03	1.01
2.50	1.02	1.05	1.15
3.15	0.99	1.08	1.19
4.00	1.02	1.14	1.16
5.00	1.10	1.23	1.33
6.30	1.50	1.38	1.61
8.00	1.42	1.63	2.00
10.00	1.29	2.01	2.00
12.50	1.03	2.52	3.18
16.00	0.96	2.94	8.37
20.00	0.51	2.62	9.17

Result

- Result of optical calibration (Uncertainty)



	ONOSOKKI	LS2P	STM	Optical
Freq.	Type A	Type A	Type A	Type B
(kHz)	(%)	(%)	(%)	(%)
0.50	7.52	5.62	2.02	0.71
0.63	4.50	5.13	4.05	0.71
0.80	2.28	0.94	1.49	0.71
1.00	1.39	1.32	1.52	0.71
1.25	2.23	1.79	1.82	0.71
1.60	0.66	0.91	1.50	0.71
2.00	1.27	0.90	1.33	0.71
2.50	2.21	1.54	1.22	0.71
3.15	4.10	4.44	2.84	0.71
4.00	3.36	1.74	2.10	0.71
5.00	4.82	4.72	3.27	1.12
6.30	2.18	0.57	2.32	1.12
8.00	3.04	2.36	1.57	1.12
10.00	2.57	2.79	1.64	1.12
12.50	6.99	4.65	1.26	1.12
16.00	2.71	2.75	1.86	1.12
20.00	3.71	3.85	2.26	1.12

Summary

Calibration of LS microphone by optical method

- Proposed method
  - ✓ Direct measurement of acoustic pressure by photon correlation method
  - ✓ Extending to sensors of non-regularized dimensions
- System implementation
  - ✓ Optical system, anechoic chamber, signal processing procedure
  - ✓ Results are compared to the result of reciprocity calibration method
- Measurement results
  - ✓ Performing the calibration of 3 different types of microphones for 0.5 kHz to 20 kHz
  - ✓ Relative high discrepancy & Type A uncertainty at near of bound frequency of sound source

Comparison of the calibration results based on acoustical and optical methods for MEMS and LS2P microphones

- Acoustical calibration methods at INRiM -

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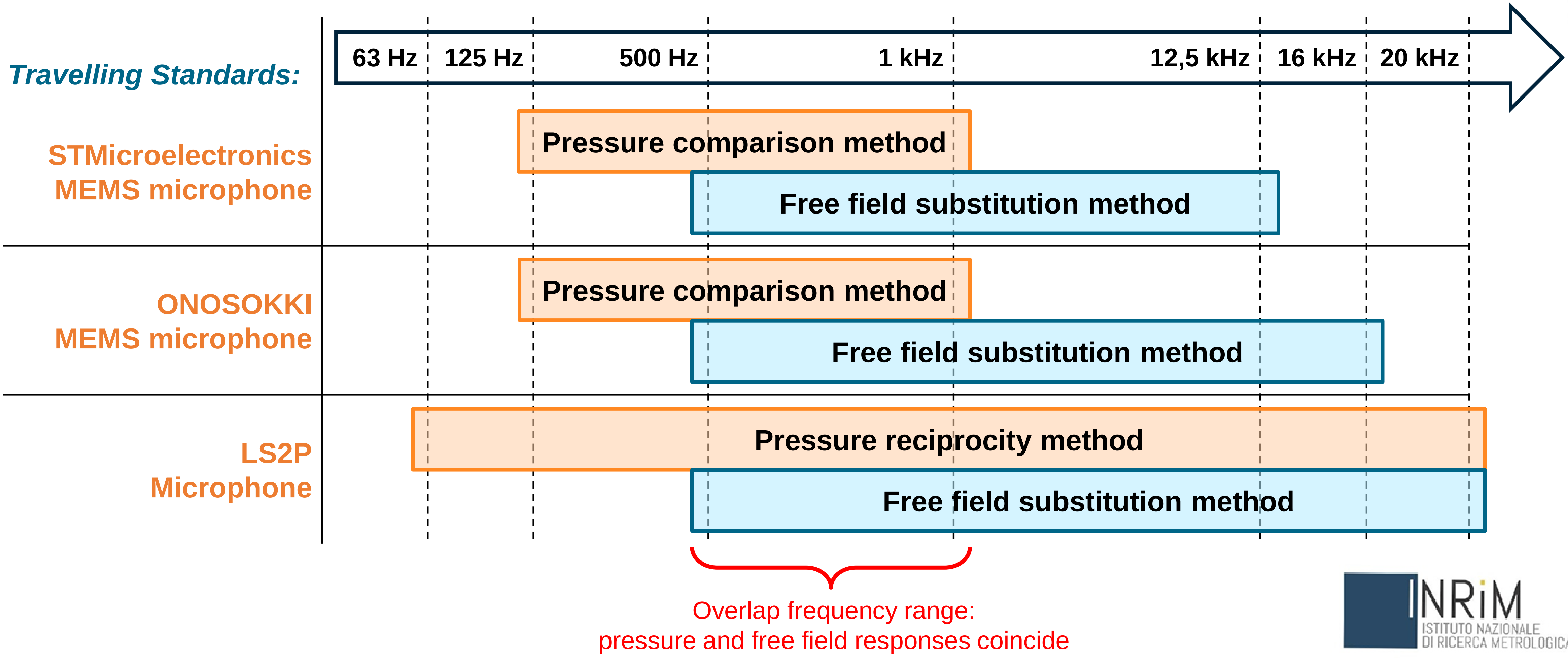
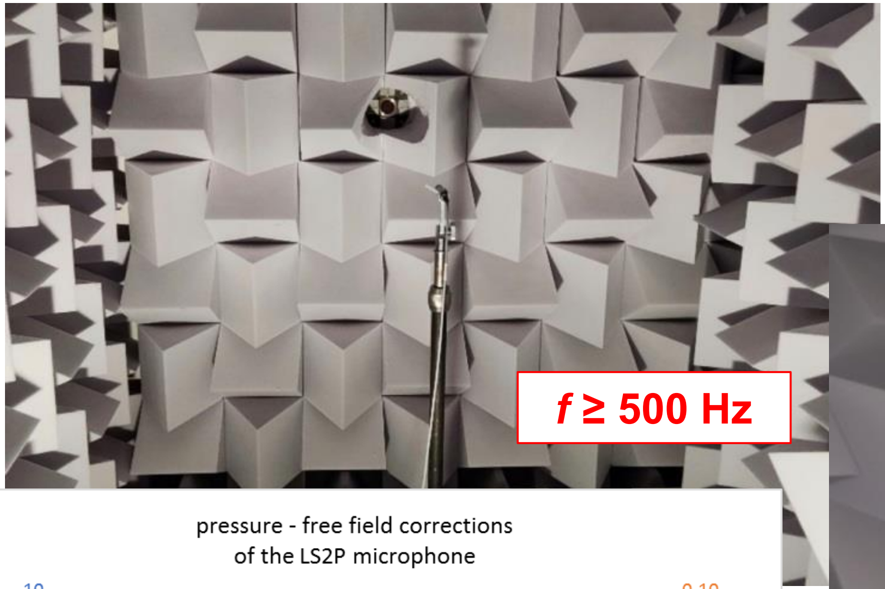
INRiM Istituto Nazionale di Ricerca Metrologica

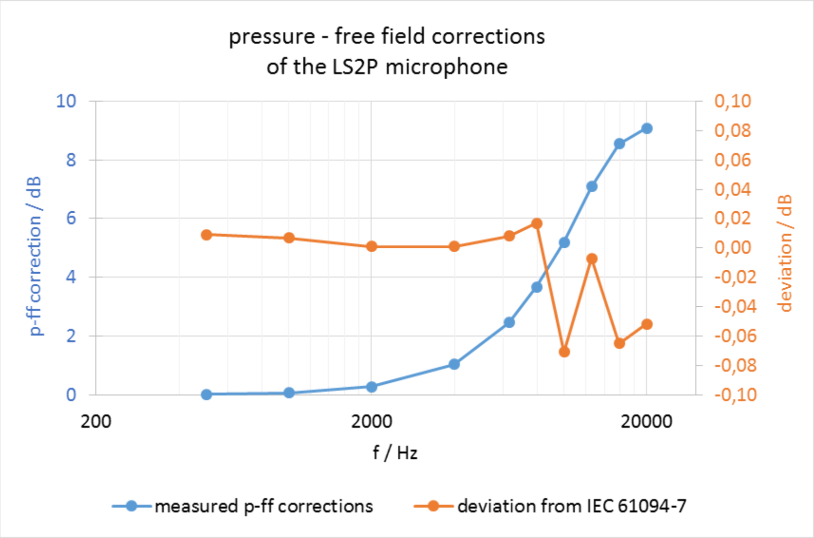
Acoustical calibration methods



Free field calibration by the substitution method

- **Secondary free-field calibration by the comparison or substitution method** (IEC 61094-8) has been performed in a small anechoic chamber (about 3,5 m^3)
- the free-field sensitivity of under-test microphones is determined from the free-field sensitivity of a reference microphone, when **both microphones are sequentially exposed to essentially the same free-field sound pressure**
- The **stability of the sound source and possible changes in the acoustic field** during measurements are taken into account by a monitor microphone
- The **lower limit of the frequency range (500 Hz)** is due to the performances of both the anechoic chamber and the sound source
- **Preliminary validation of the method** has been performed comparing the measured pressure-free field corrections of LS2P microphones, against the values provided by the IEC 61094-7 Standard





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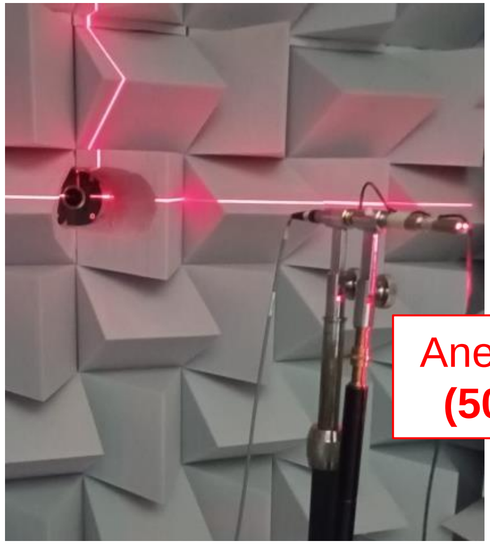
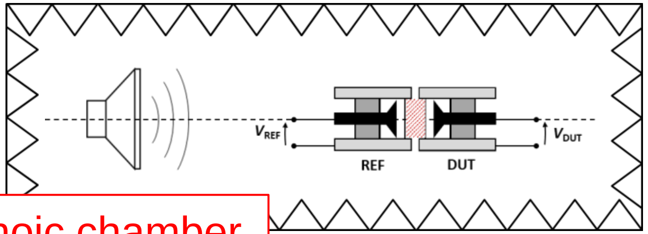
Pressure calibration by the comparison method

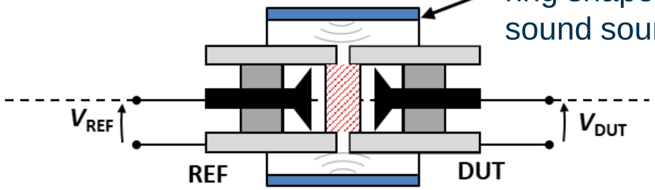
- **Secondary pressure calibration by the comparison method** (IEC 61094-5) has been performed in acoustic couplers, or in the small anechoic chamber by using proper jigs for reference and under test microphones installation
- The **simultaneous excitation method** has been preferably adopted: reference and under test MEMS microphones are simultaneously exposed to essentially the same acoustic pressure
- At frequencies lower than 1 kHz, the free field response of MEMS microphones used as travelling standards is observed to coincide with their pressure response, thus, **in the frequency range from 125 Hz to 1 kHz, pressure calibration by comparison can be effectively performed**
- Significantly different size of MEMS microphones compared to the reference (LS2P)
- **Sound field corrections** required for compensating the effect of non-uniform acoustic pressure between reference and under test microphones of different sizes are negligible for frequencies lower than 1 kHz → **verified by validated numerical modelling of the acoustic field within the small gap between microphones**



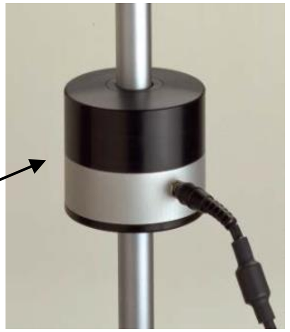
Coaxial alignment between sound source and microphones inside the anechoic chamber



Anechoic chamber
(500 – 1000) Hz



Active coupler with ring shaped build-in sound source



Brüel & Kjær WA0817
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Acoustic couplers
(125 – 1000) Hz

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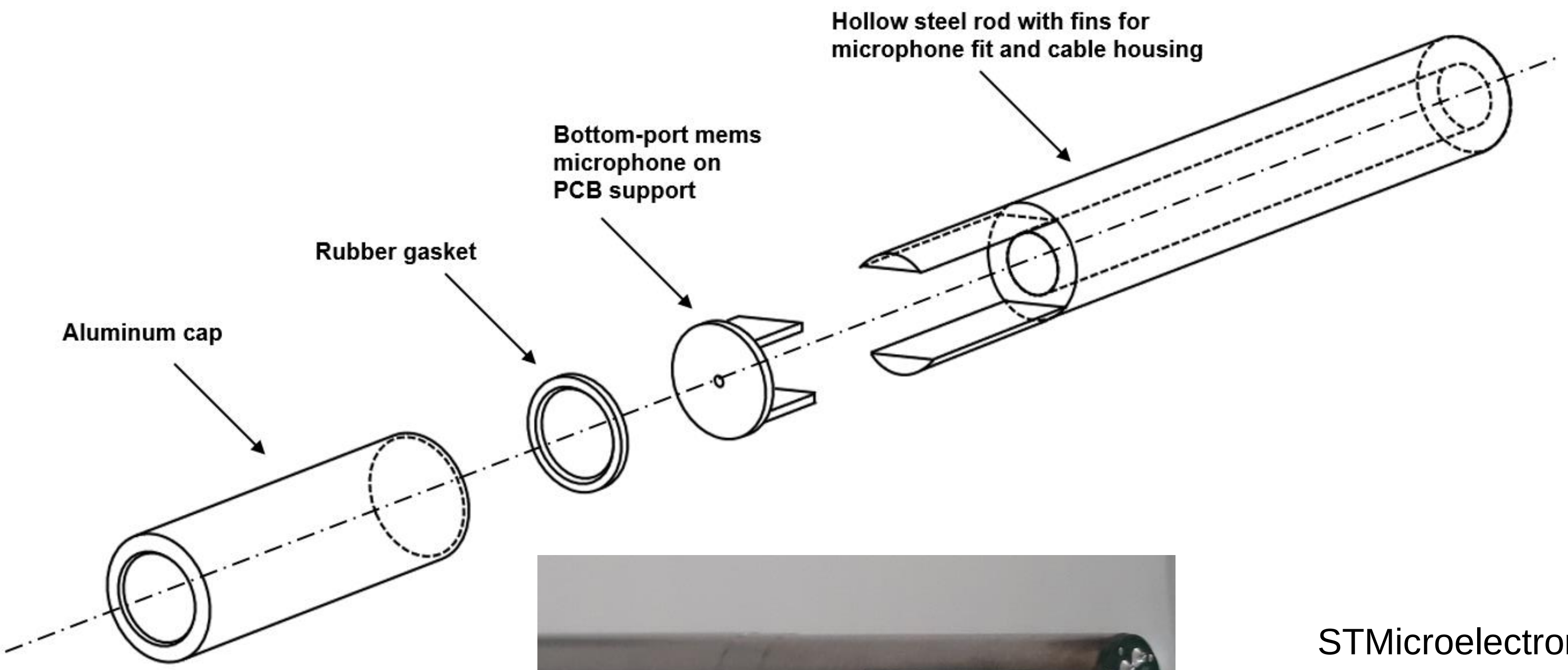
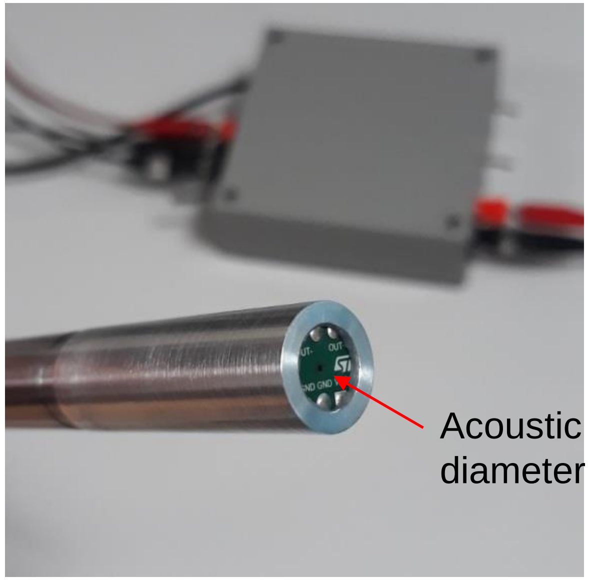
MEMS microphone mount

❖ Special mount realized to fit the STMicroelectronics MEMS microphone into comparison calibration systems



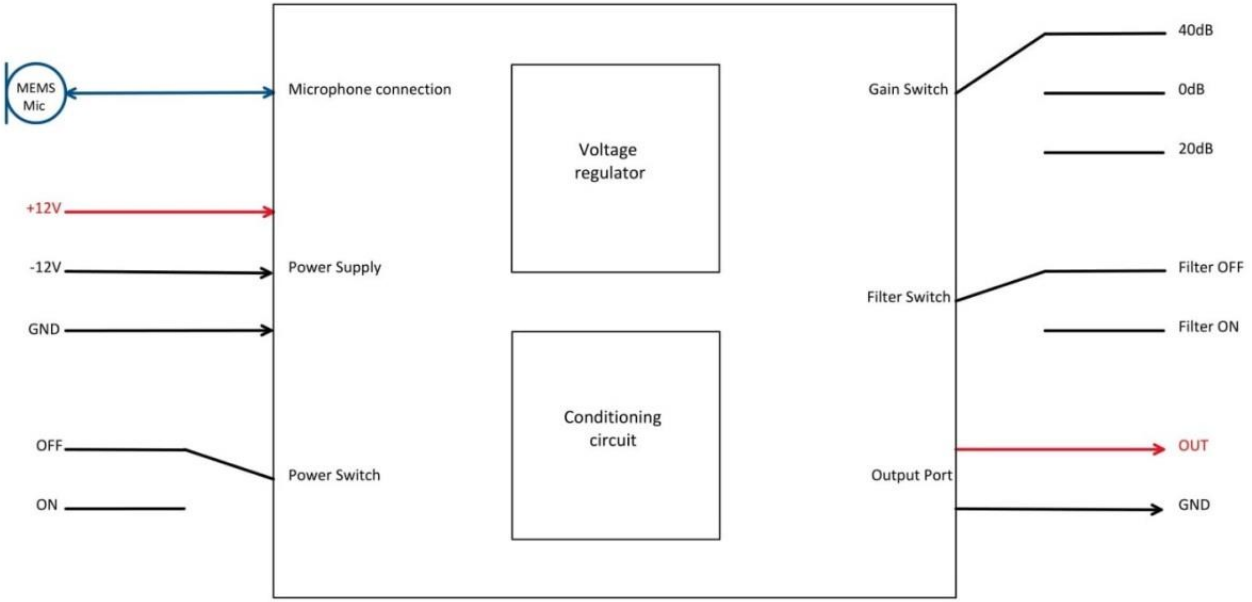


Acoustic port diameter **< 0,5 mm**

STMicroelectronics **differential analog bottom-port MEMS microphone** (ST MP23AB01DH on a 12.5 mm diameter PCB board support ST STEVAL-MKI139V5)

MEMS microphone preamplifier

- A custom-made preamplifier has been realized to provide a stable DC power supply to the STMicroelectronics MEMS microphone, and to amplify and filter its output signal



- The metrological characterization of preamplifier gains has been carried out in the frequency range of interest

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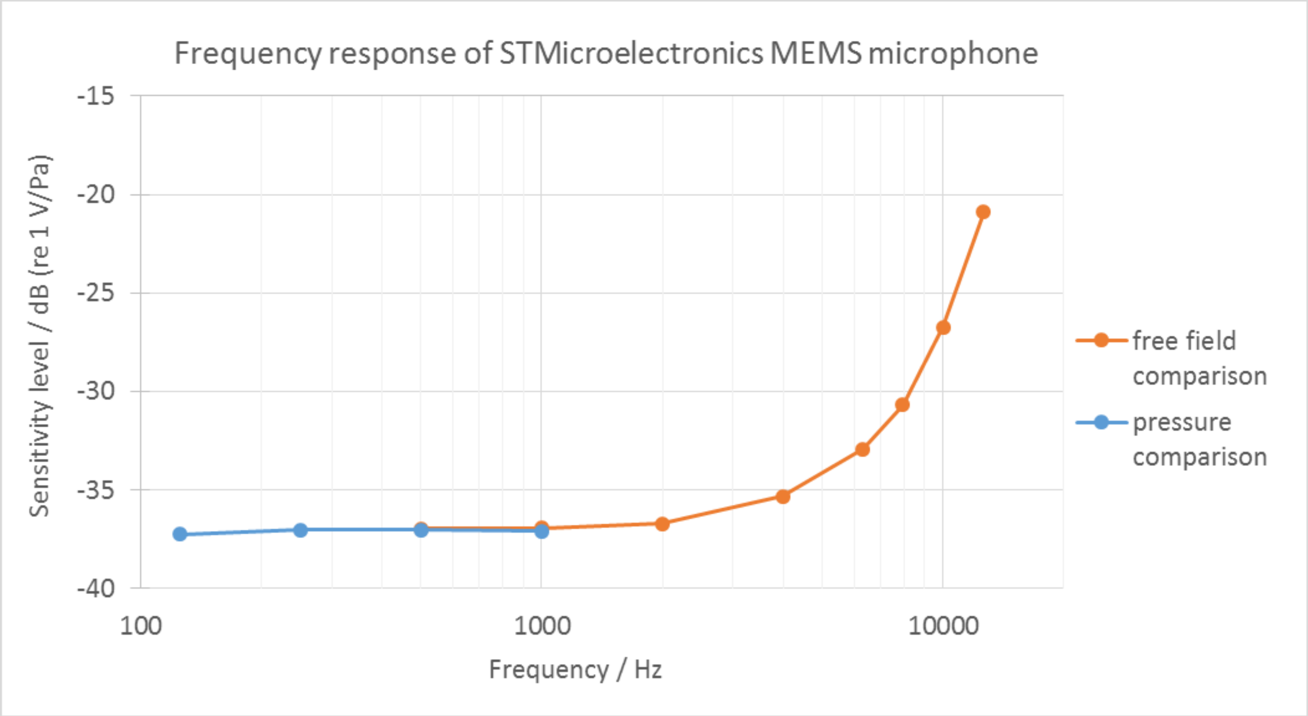
Measurement results – INRiM

❖ **STMicroelectronics MEMS microphone**

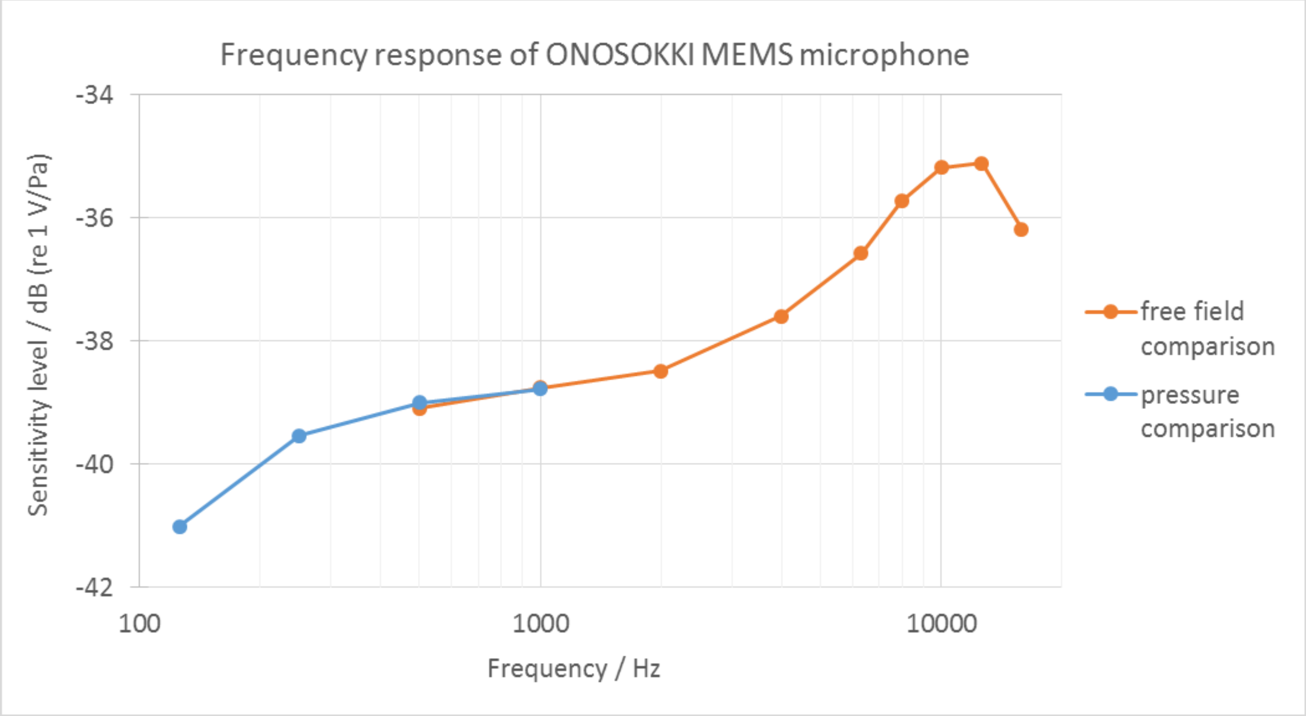
frequency Hz	S_p pressure dB (re 1 V/Pa)	$U(S_p)$ (k=2) dB	S_{ff} free field dB (re 1 V/Pa)	$U(S_{ff})$ (k=2) dB
125,89	-37,25	0,18	-	-
251,19	-37,02	0,18	-	-
501,19	-37,02	0,18	-36,96	0,19
1000,00	-37,07	0,19	-36,92	0,19
1995,26	-	-	-36,69	0,20
3981,07	-	-	-35,32	0,22
6309,57	-	-	-32,92	0,24
7943,28	-	-	-30,68	0,32
10000,00	-	-	-26,73	0,36
12589,25	-	-	-20,88	0,46



Measurement results – INRiM

❖ **ONOSOKKI MEMS microphone**

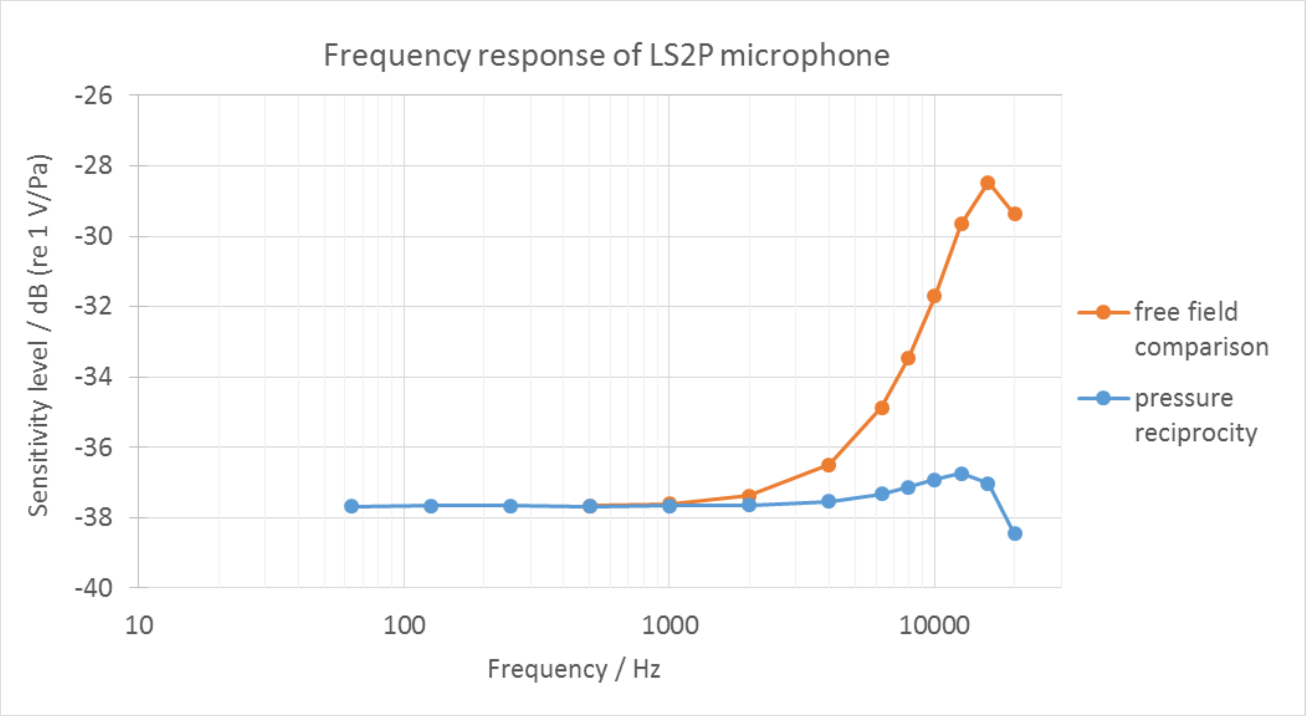
frequency	S_p pressure	$U(S_p)$ (k=2)	S_{ff} free field	$U(S_{ff})$ (k=2)
Hz	dB (re 1 V/Pa)	dB	dB (re 1 V/Pa)	dB
125,89	-41,01	0,18	-	-
251,19	-39,54	0,18	-	-
501,19	-39,00	0,18	-39,09	0,20
1000,00	-38,78	0,19	-38,75	0,30
1995,26	-	-	-38,48	0,29
3981,07	-	-	-37,60	0,26
6309,57	-	-	-36,57	0,32
7943,28	-	-	-35,73	0,42
10000,00	-	-	-35,18	0,35
12589,25	-	-	-35,11	0,55
15848,93	-	-	-36,18	0,43



Measurement results – INRiM

❖ **LS2P microphone**

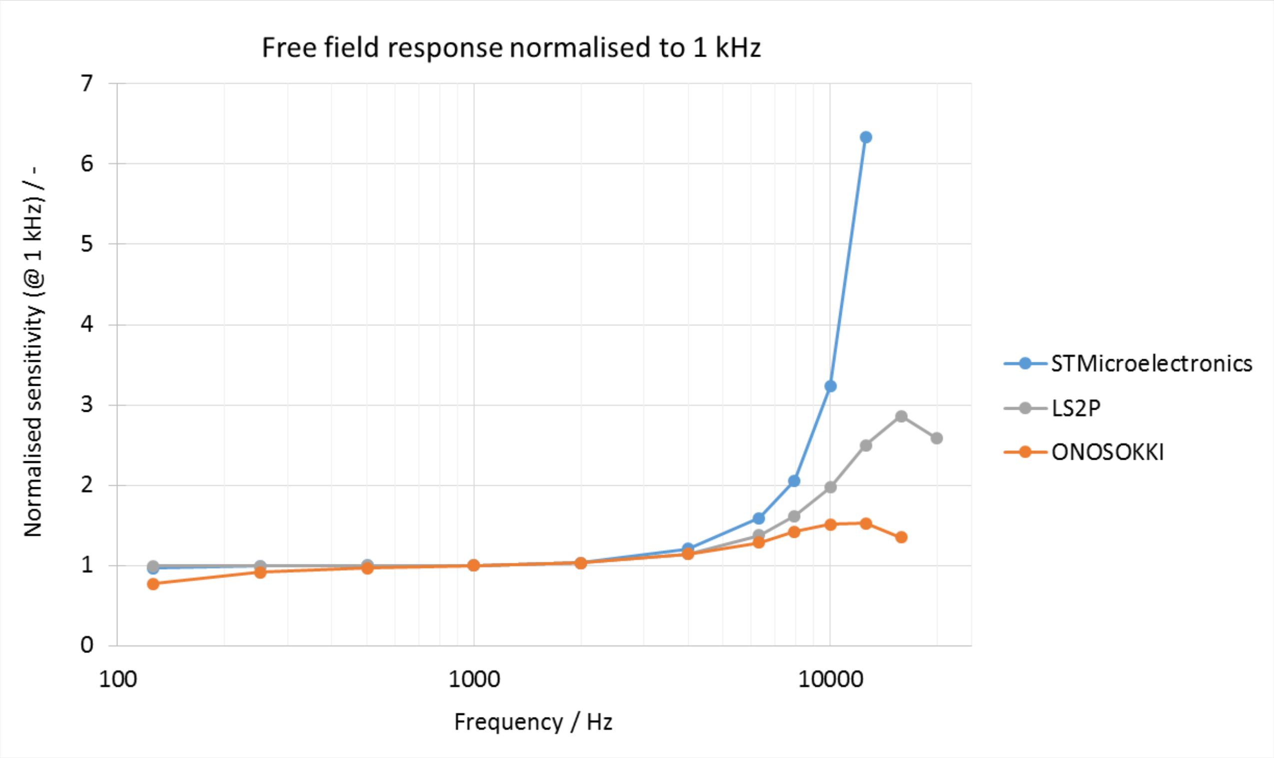
frequency	S_p pressure	$U(S_p)$ (k=2)	S_{ff} free field	$U(S_{ff})$ (k=2)
Hz	dB (re 1 V/Pa)	dB	dB (re 1 V/Pa)	dB
63,10	-37,67	0,05	-	-
125,89	-37,66	0,05	-	-
251,19	-37,67	0,05	-	-
501,19	-37,67	0,05	-37,65	0,17
1000,00	-37,67	0,05	-37,60	0,17
1995,26	-37,64	0,05	-37,38	0,20
3981,07	-37,53	0,05	-36,49	0,20
6309,57	-37,32	0,05	-34,86	0,20
7943,28	-37,14	0,05	-33,46	0,23
10000,00	-36,91	0,08	-31,71	0,32
12589,25	-36,74	0,10	-29,65	0,38
15848,93	-37,03	0,10	-28,47	0,30
19952,62	-38,46	0,15	-29,37	0,28



Results of acoustical calibrations – INRiM

❖ **Sensitivities normalised to 1 kHz (sensitivities expressed in V Pa^{-1})**

frequency	ONOSOKKI		LS2P		STMicroelectronics	
	S_{ff} norm 1 kHz	U_{rel} (k=2)	S_{ff} norm 1 kHz	U_{rel} (k=2)	S_{ff} norm 1 kHz	U_{rel} (k=2)
Hz	-	%	-	%	-	%
63,10	-	-	0,99	0,58	-	-
125,89	0,77	2,10	0,99	0,58	0,96	2,10
251,19	0,91	2,12	0,99	0,58	0,99	2,12
501,19	0,96	2,28	0,99	1,98	1,00	2,19
1000,00	1,00	3,52	1,00	2,03	1,00	2,19
1995,26	1,03	3,41	1,03	2,28	1,03	2,33
3981,07	1,14	3,08	1,14	2,35	1,20	2,51
6309,57	1,29	3,75	1,37	2,34	1,59	2,77
7943,28	1,42	4,91	1,61	2,72	2,05	3,70
10000,00	1,51	4,08	1,97	3,80	3,23	4,23
12589,25	1,52	6,48	2,50	4,47	6,34	5,45
15848,93	1,35	5,03	2,86	3,49	-	-
19952,62	-	-	2,58	3,24	-	-



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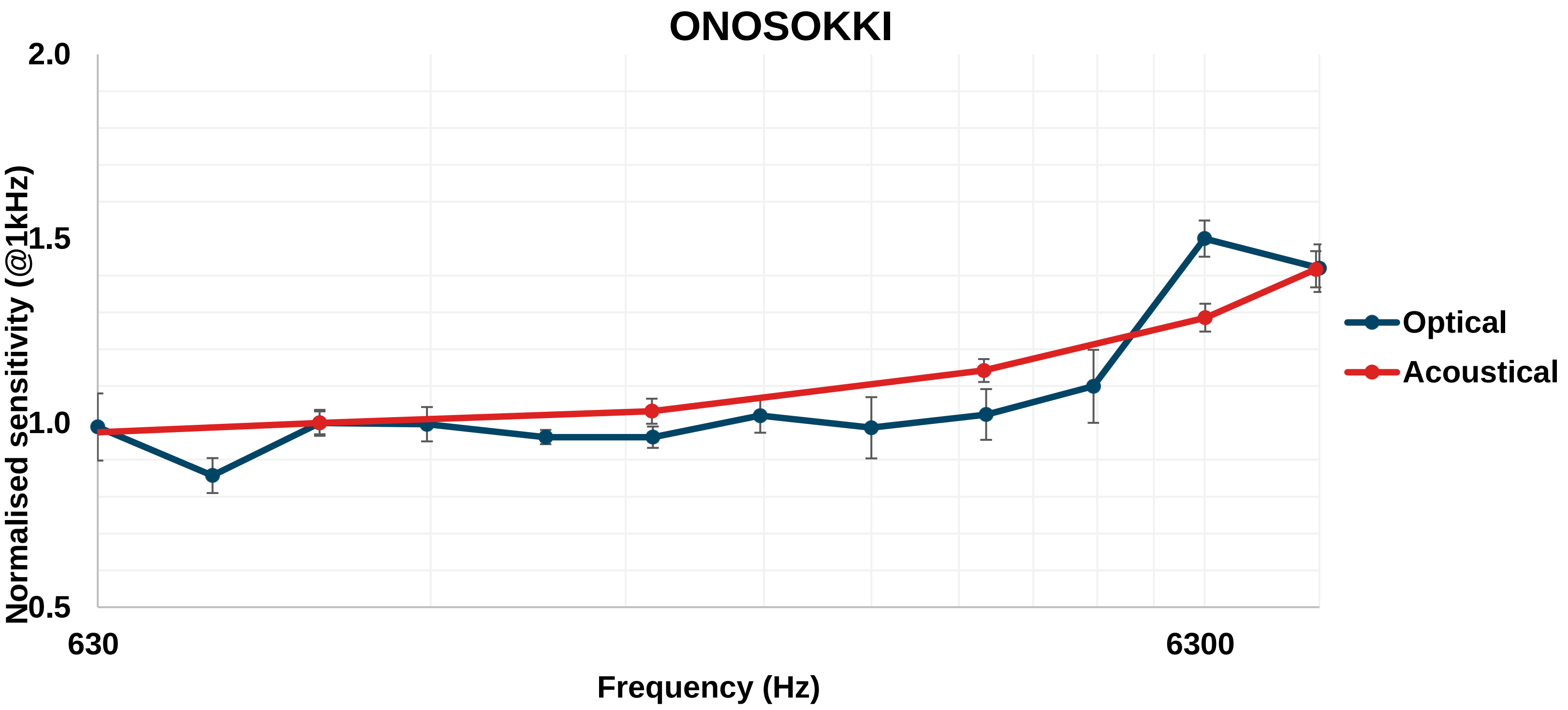
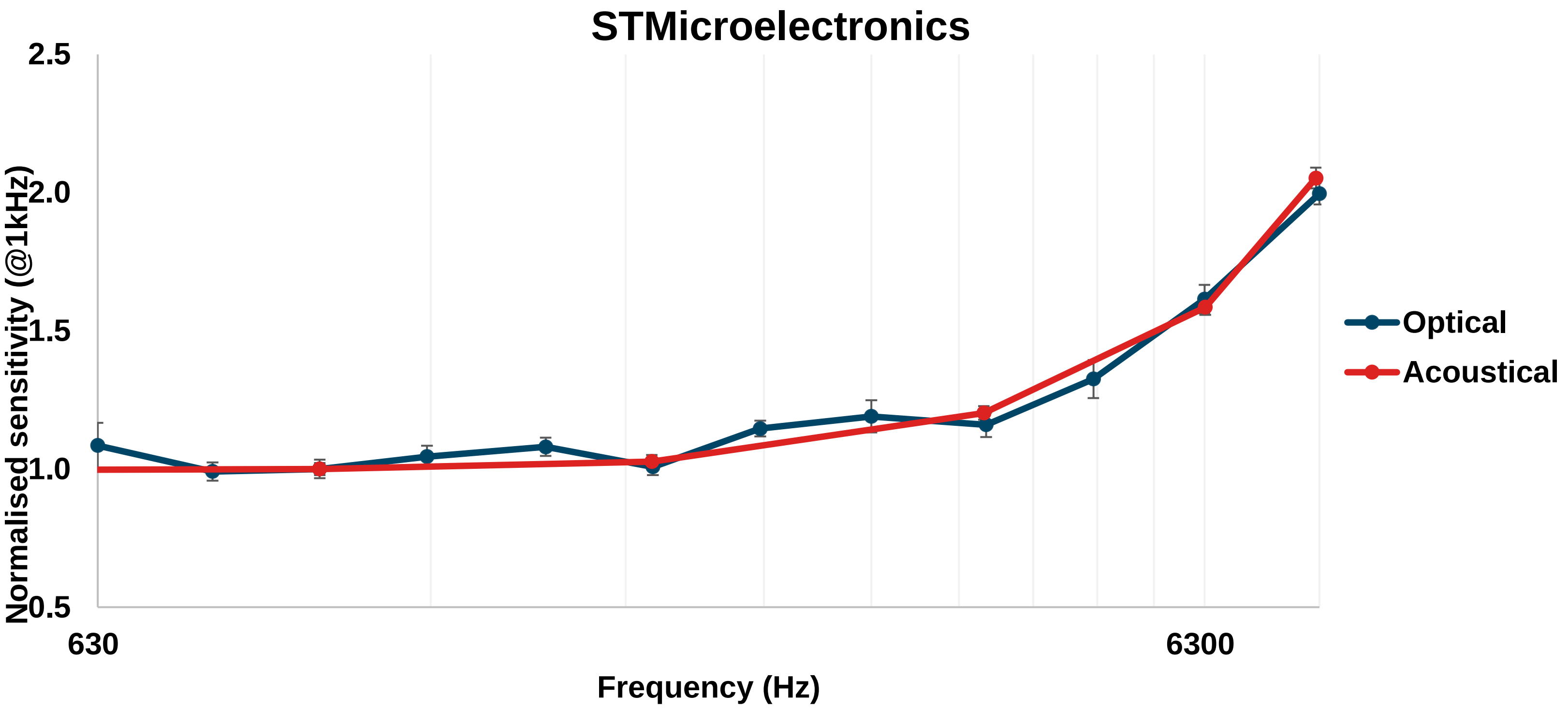
Thank you for your kind attention

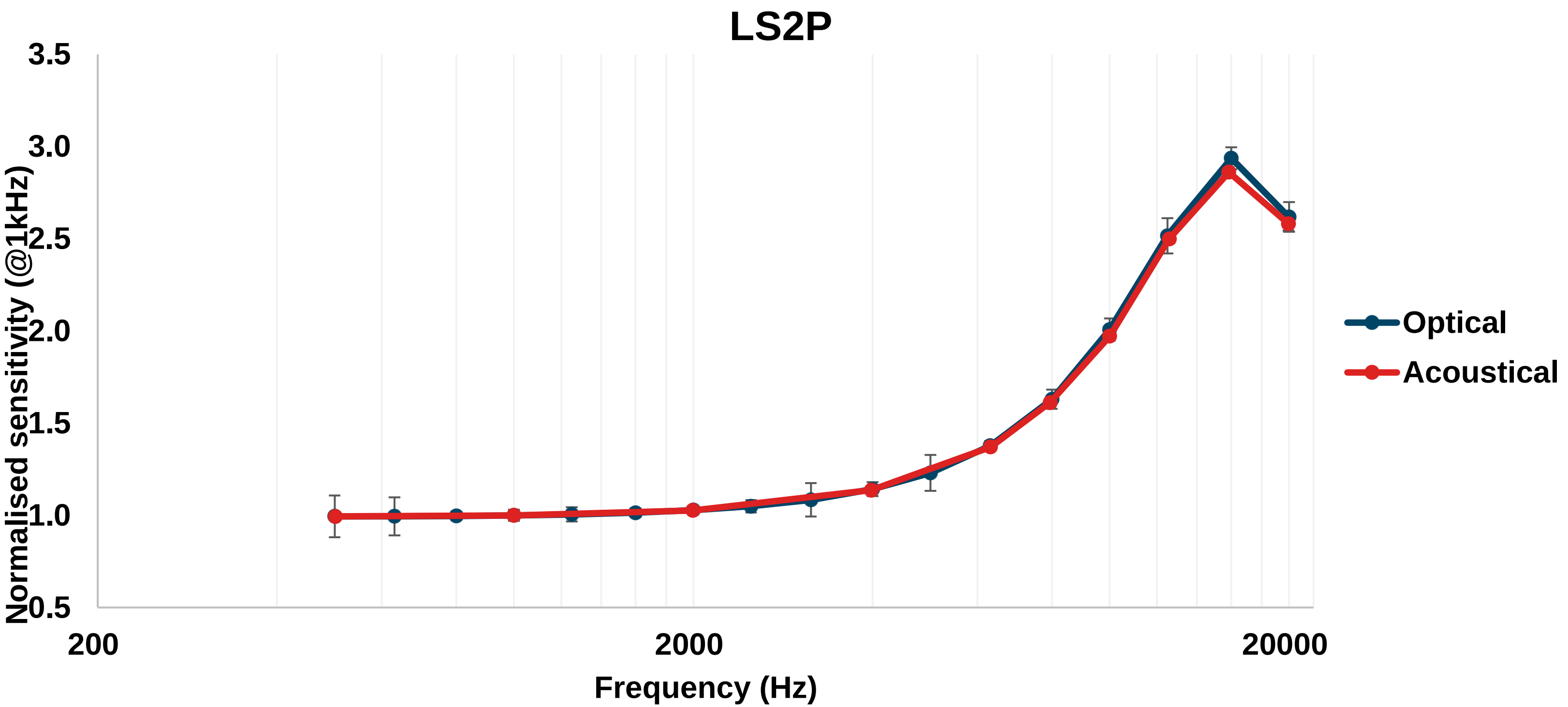
Comparison – MEMS microphone #1



Comparison – MEMS microphone #2



Comparison - LS2P microphone



Conclusions and moving forward

LS2P

- New calibration methods yield sensitivities that closely match: validation

MEMS

- Agreement in sensitivities in the range 10% for ONOSOKKI and 1% for STMicroelectronics between calibration methods
- Limited dynamic range of MEMS microphones compared to LS2P contributes to discrepancies

Next steps

- System improvements to accommodate MEMS dynamic range
- Effect of MEMS mounting and directionality
- Improvement of repeatability
- Frequency range > 8 kHz for MEMS

Thank you

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