Calibration at the U.S. Navy Underwater Sound Reference Division (USRD) and considerations for in-situ calibration of hydrophones deployed at sea

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NAVSEA NAVAL SEA SYSTEMS COMMAND WARFARE CENTERS NEWPORT
USRD UNDERWATER SOUND REFERENCE DIVISION

10 September 2025

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International Traceability of Underwater Sound: Key Comparisons

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Dissemination to U.S. Government, Industry, Academic Customers

Calibration at the U.S. Navy Underwater Sound Reference Division (USRD) and considerations for in-situ calibration of hydrophones deployed at sea

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BIPM

USRD
Primary
(Reciprocity)

Coupler

Open Tank

Pressure Tank

Standards Lab

Calibration at the U.S. Navy Underwater Sound Reference Division (USRD) and considerations for in-situ calibration of hydrophones deployed at sea

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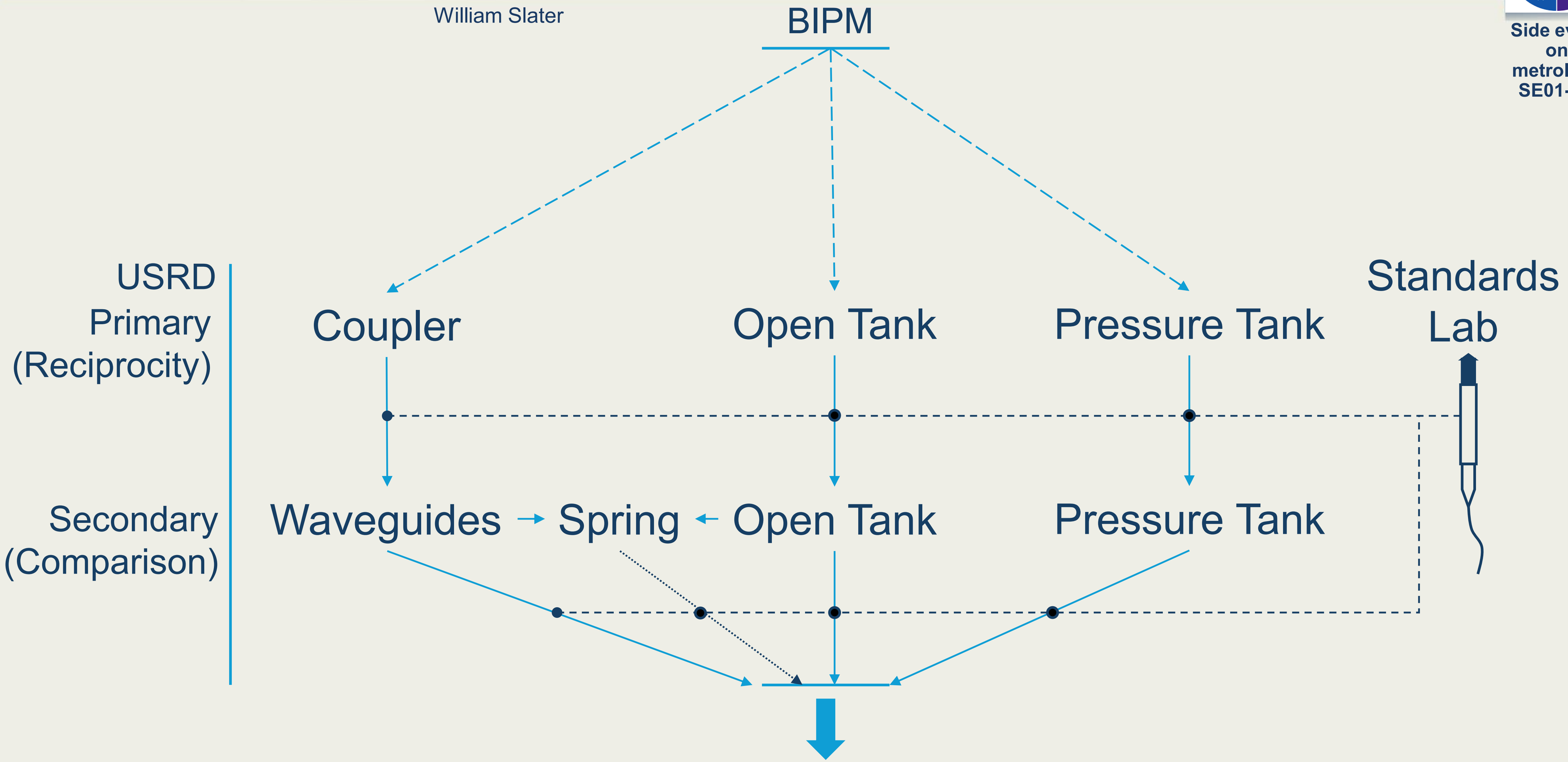
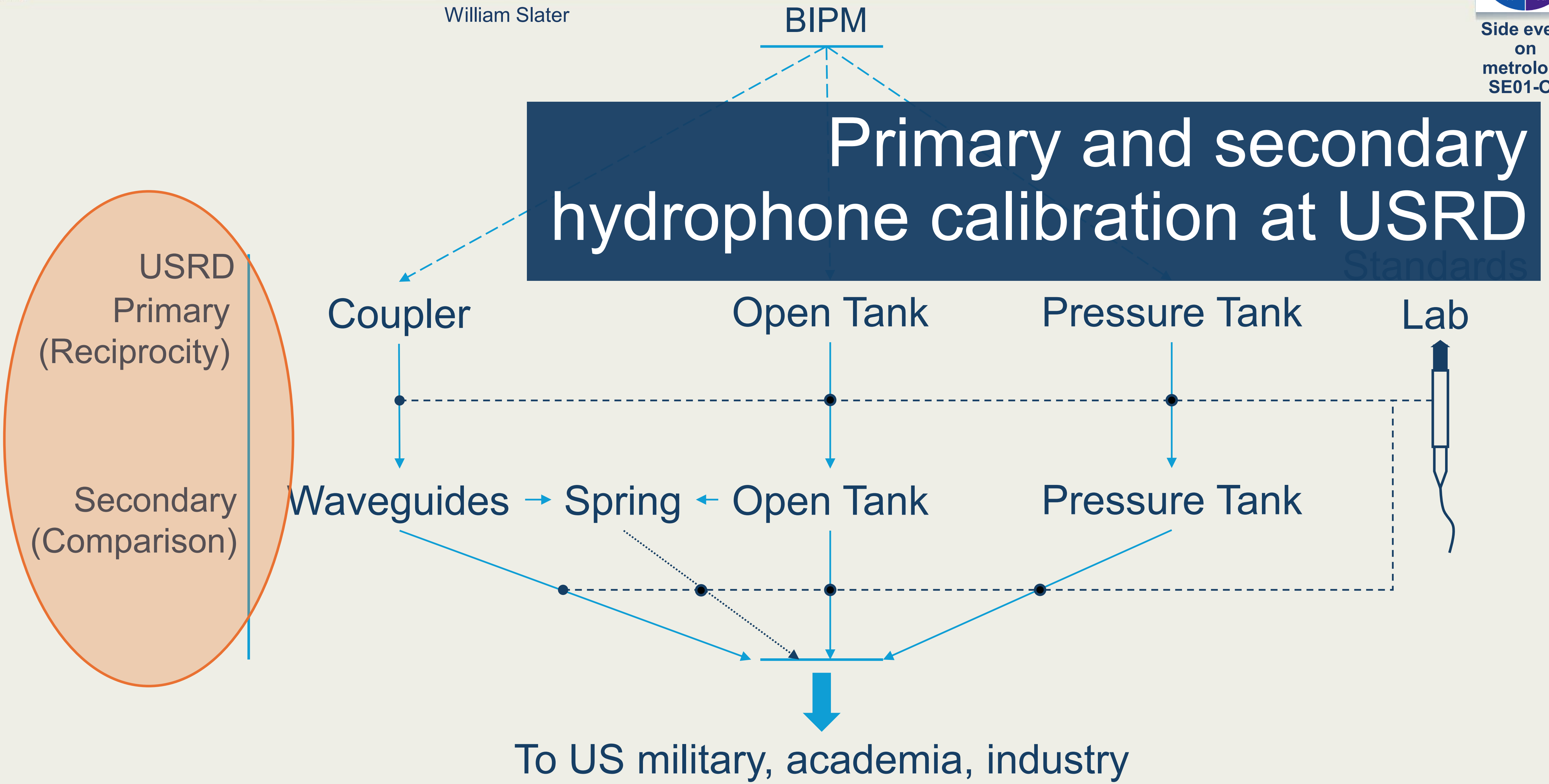


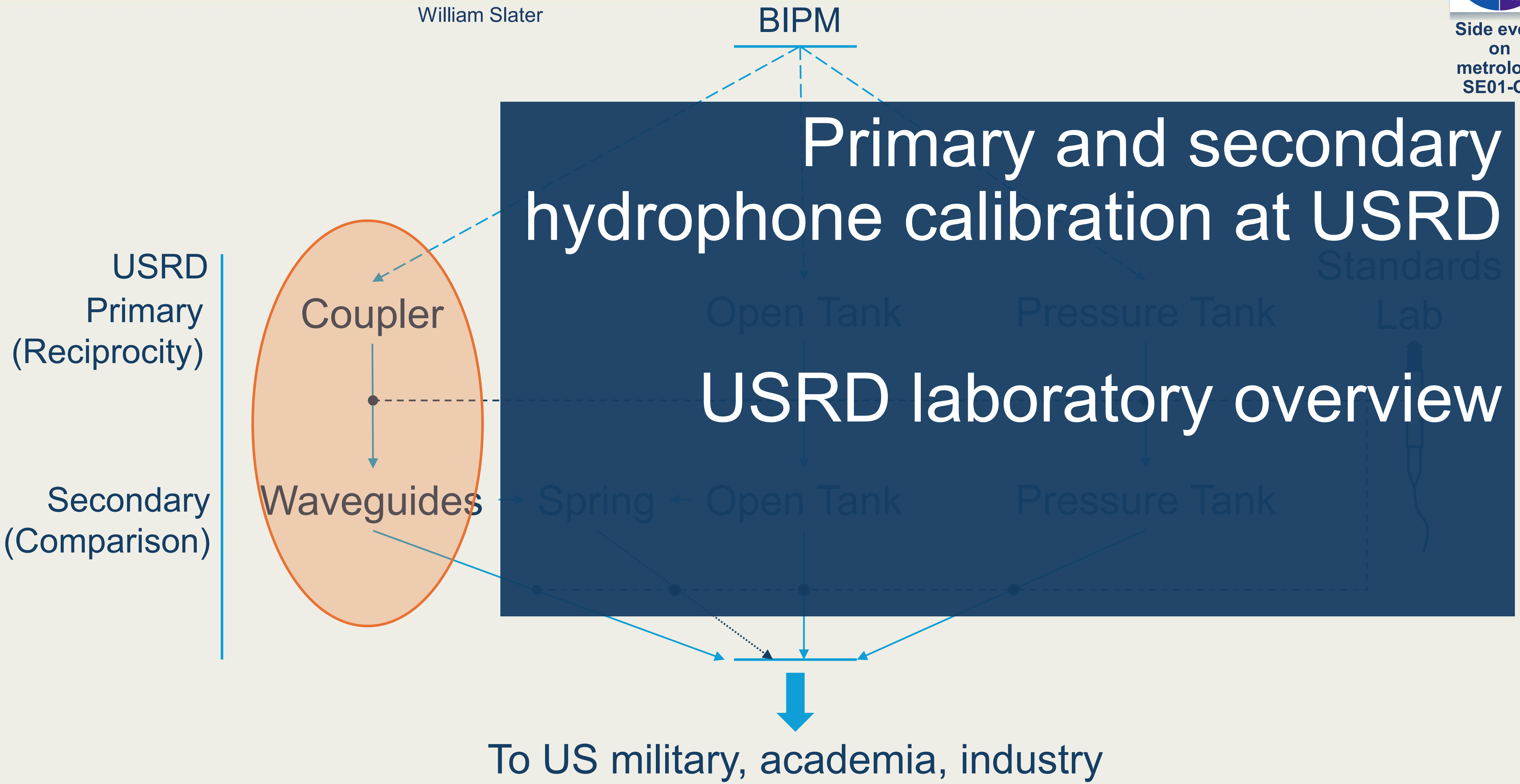
To US military, academia, industry

Primary and secondary hydrophone calibration at USRD



Primary and secondary hydrophone calibration at USRD

USRD laboratory overview



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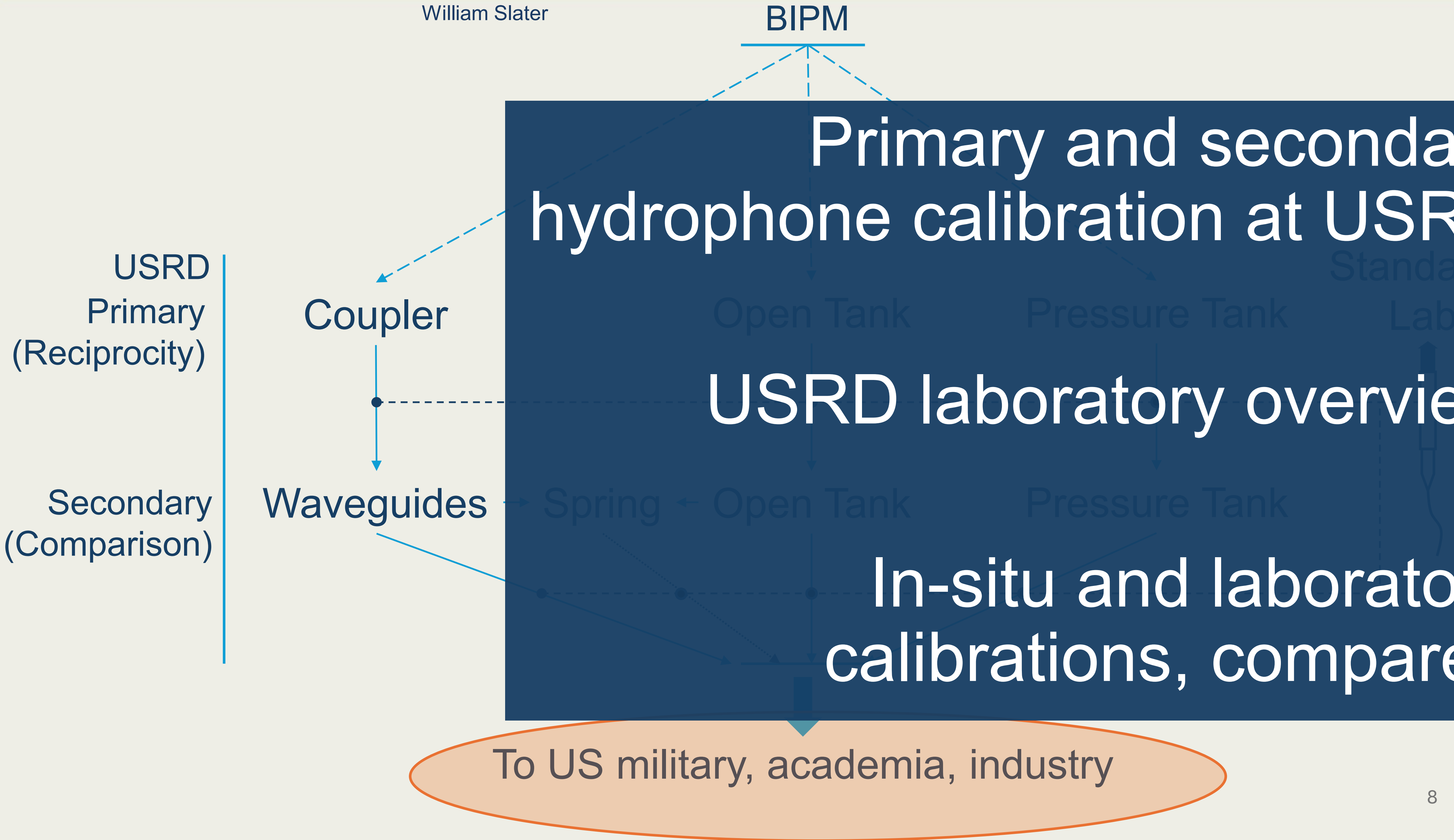
Primary and secondary hydrophone calibration at USRD

USRD laboratory overview

In-situ and laboratory calibrations, compared



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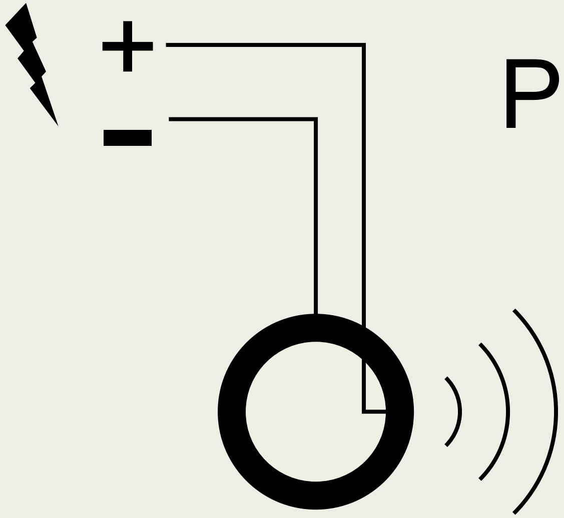
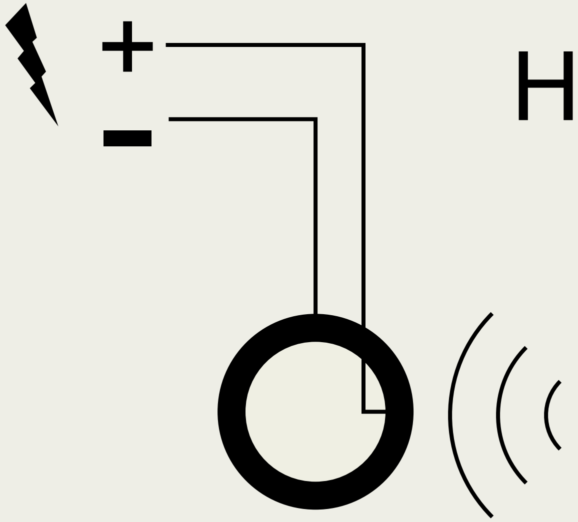


Projector (transmitting response)

$$\frac{\text{pressure}}{\text{current (or voltage)}}$$

*Pa*m/A*
or
*dB re 1 µPa * m / A*



Hydrophone (sensitivity)

$$\frac{\text{voltage}}{\text{pressure}}$$

V/Pa
or
dB re 1 V / µPa

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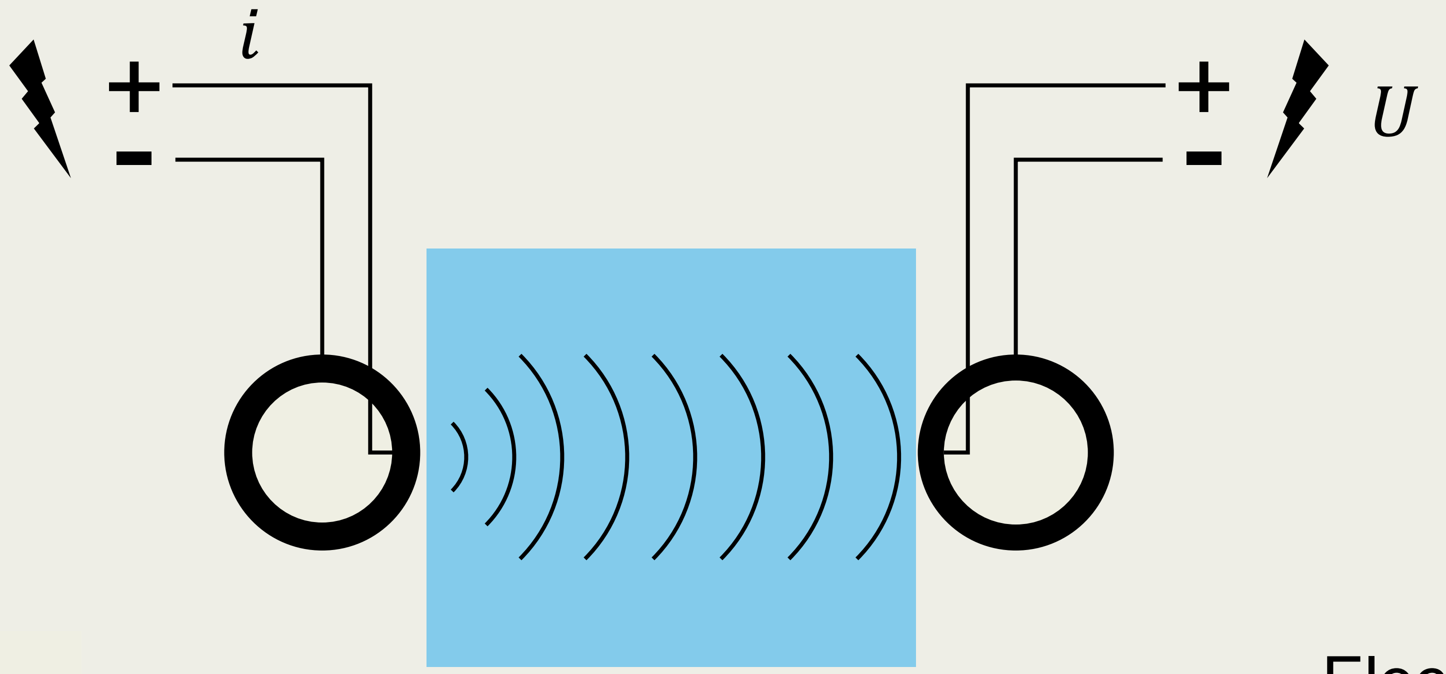

Voltage from receiver

$$Z = \frac{U}{i}$$

Electrical Transfer Impedance

Current to projector

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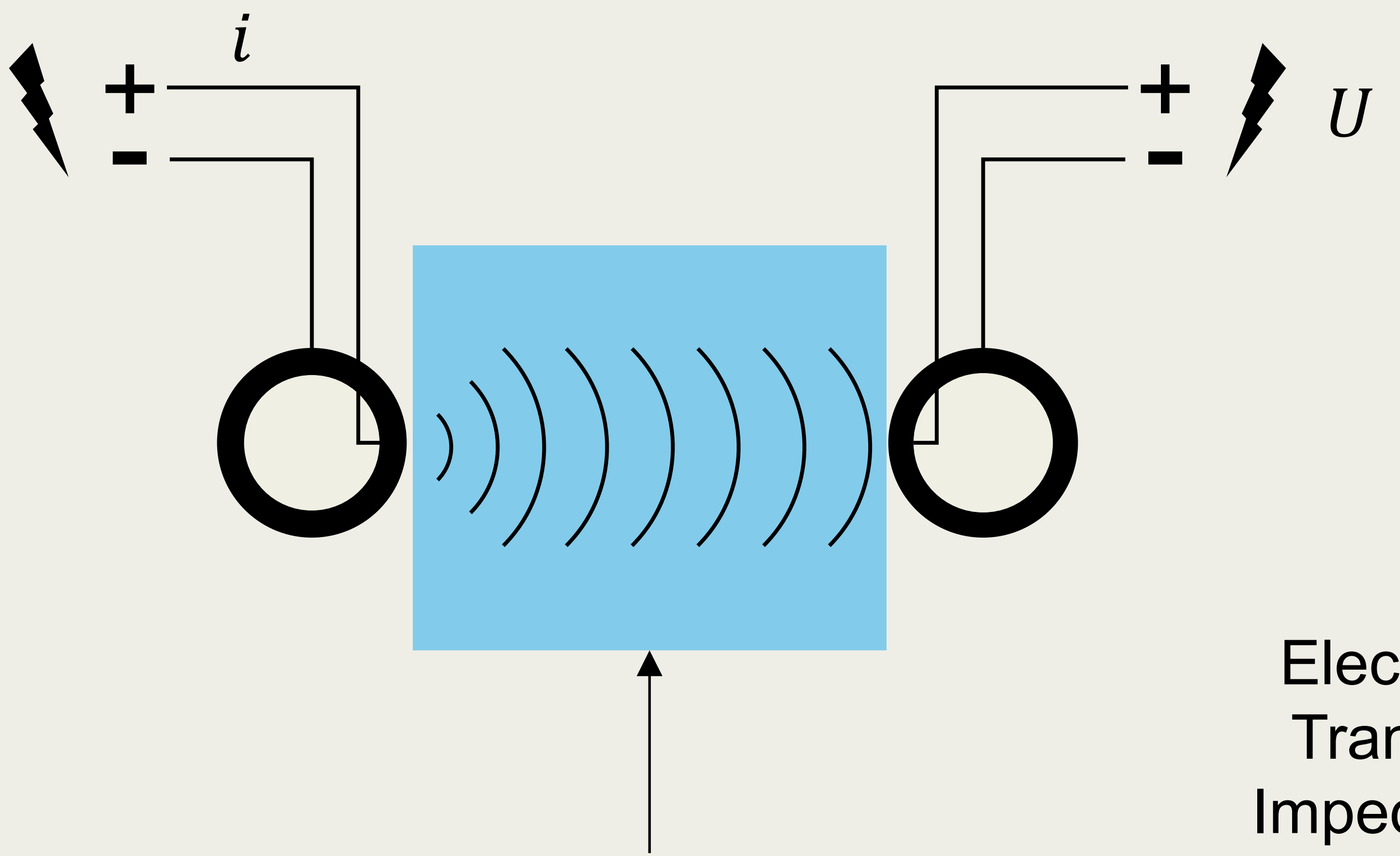

But what is the acoustic pressure here?

Voltage from receiver

$$Z = \frac{U}{i}$$

Electrical Transfer Impedance

Current to projector

Reciprocity

Reciprocal

Transducer

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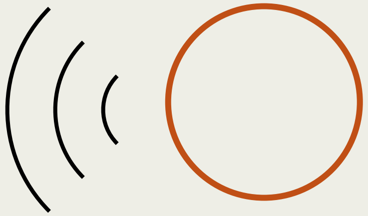
Reciprocity

Reciprocal

Transducer



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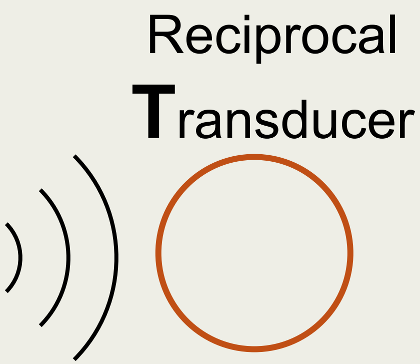
Reciprocity



Reciprocity

Reciprocal **T**ransducer

$$J = \frac{\text{transmitting response}}{\text{sensitivity}}$$

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Reciprocity

Reciprocal **T**ransducer

$$J = \frac{\text{transmitting response}}{\text{sensitivity}}$$

$$J = \frac{2d}{\rho f}$$

Distance, density, frequency

$$J = 2\pi f C$$

Frequency, compliance (bulk modulus)

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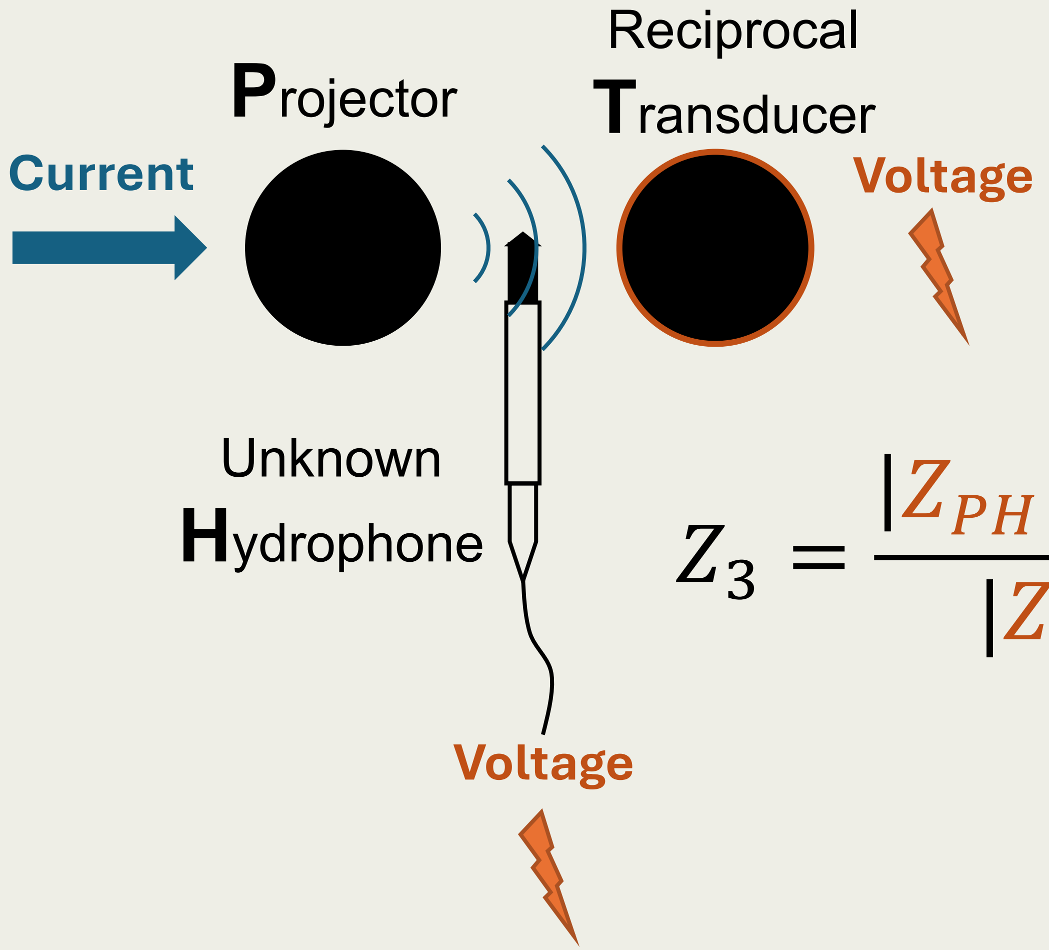
Reciprocity



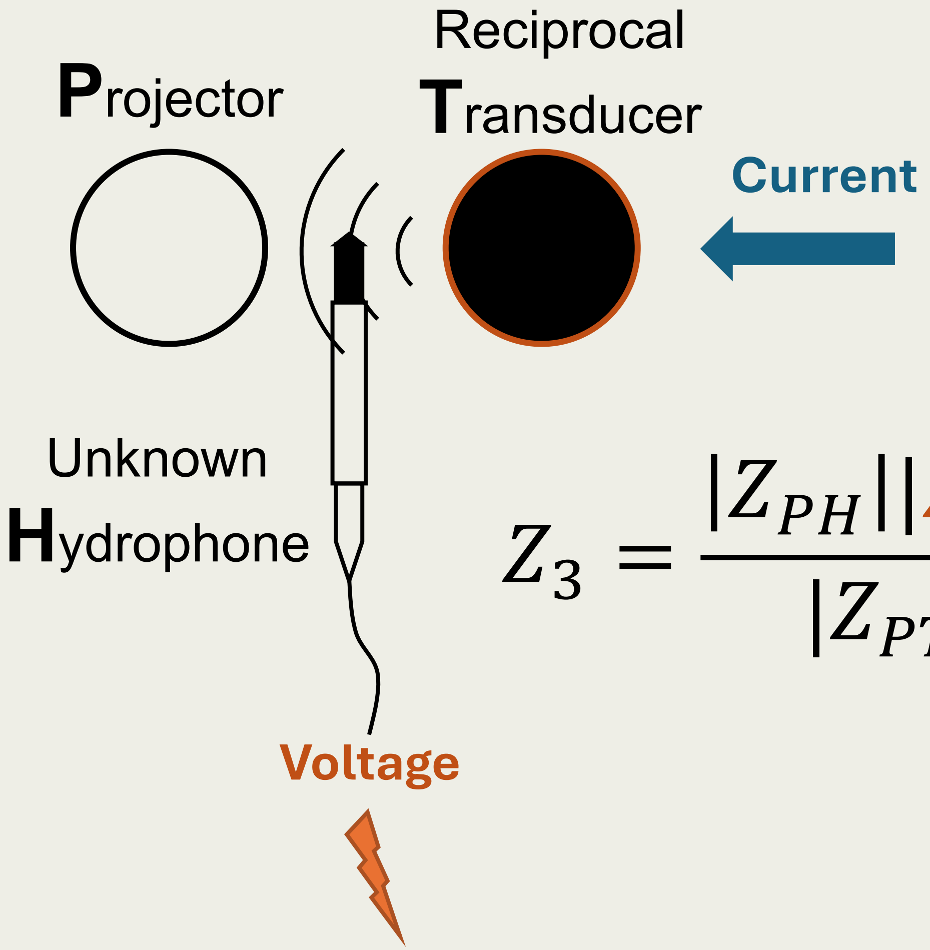
$$Z_3 = \frac{|Z_{PH}||Z_{TH}|}{|Z_{PT}|}$$

$$J = \frac{\text{transmitting response}}{\text{sensitivity}}$$

$$J = \frac{2d}{\rho f}$$ Distance, density, frequency

$$J = 2\pi f C$$ Frequency, compliance (bulk modulus)

Reciprocity



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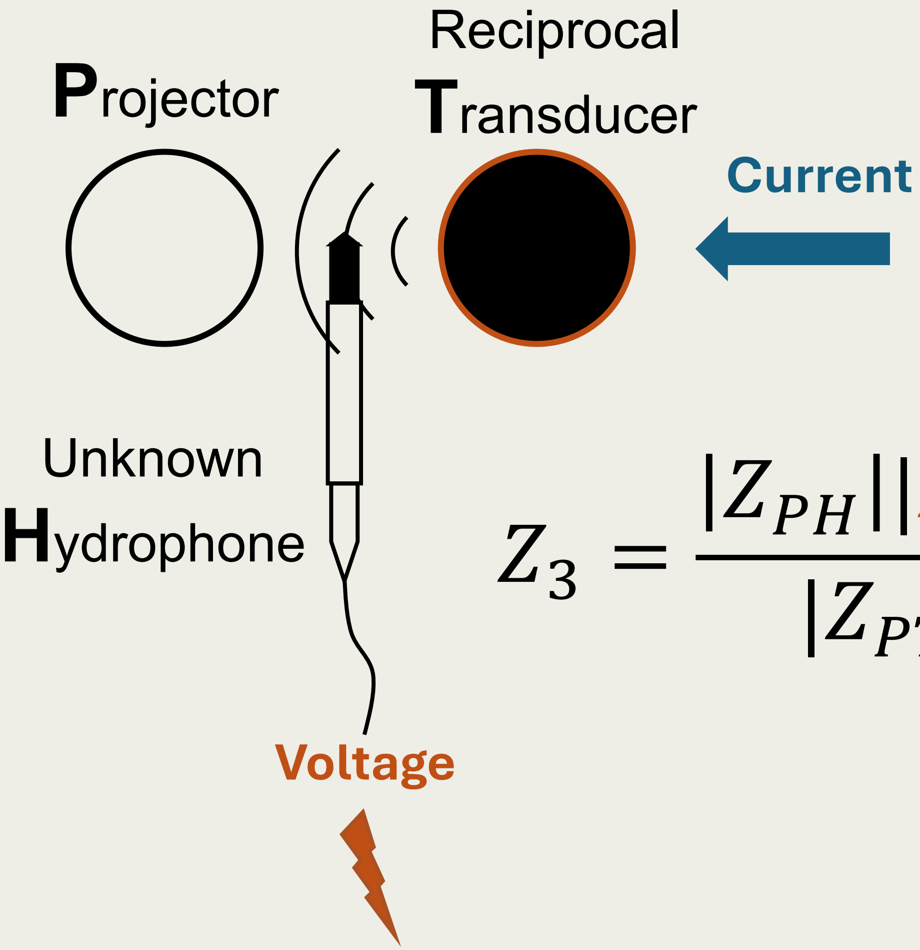
Reciprocity



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$$J = \frac{2d}{\rho f}$$ Distance, density, frequency

$$J = 2\pi f C$$ Frequency, compliance (bulk modulus)

Sensitivity = $\sqrt{J Z_3}$

Reciprocity Parameter (J)

Electrical transfer impedances (Z_3)

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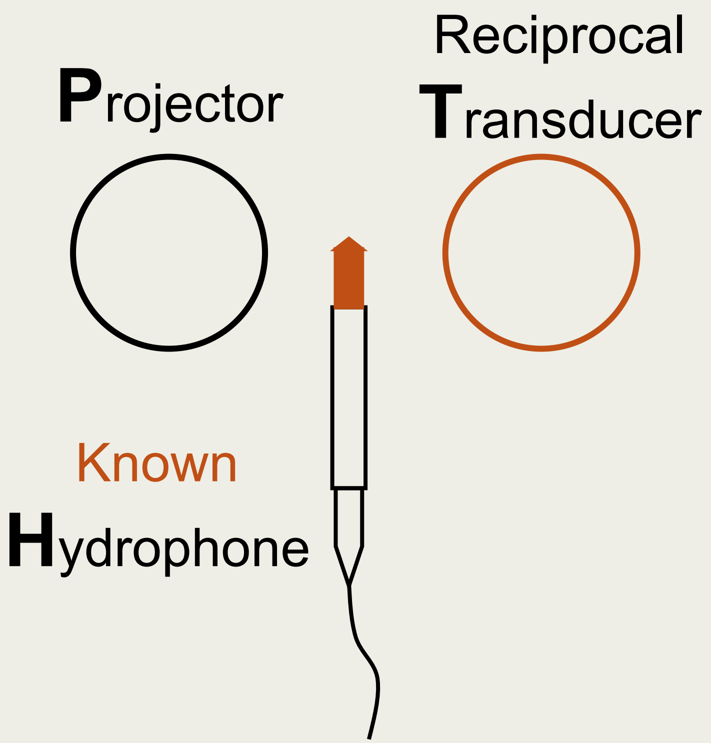
Reciprocity



Now we have a transducer sensitivity without reference to the sensitivity of another transducer - a primary calibration of sensitivity.

$$\text{Sensitivity} = \sqrt{J Z_3}$$

Reciprocity Parameter

Electrical transfer impedances

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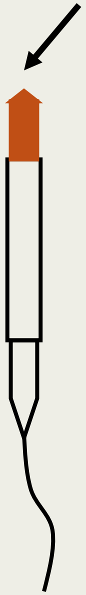
Comparison, Side-by-side

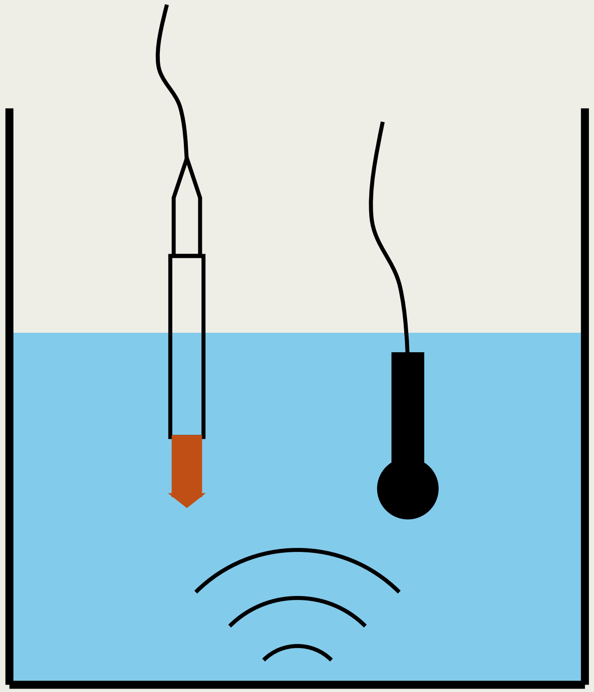
M
(dB re 1V/μPa)



Sensitivity = MZ

Reference Sensitivity

Voltage and Current ratios



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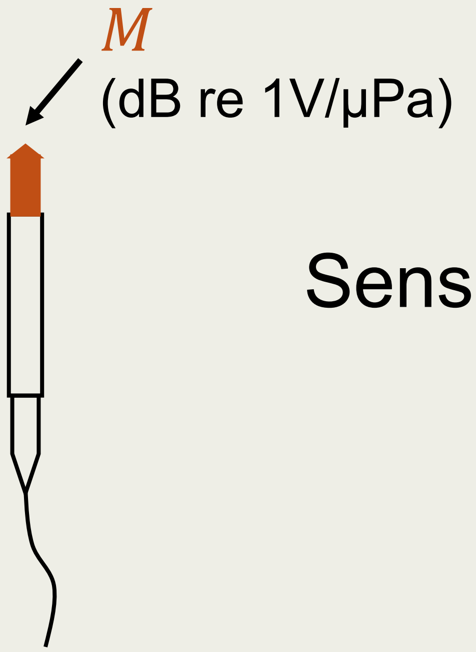
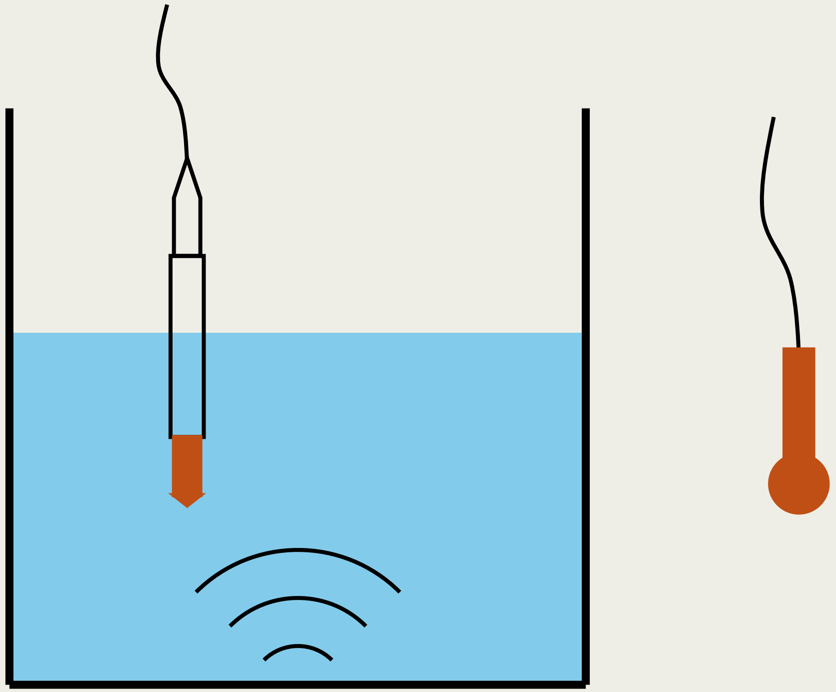
Comparison, Side-by-side



Sensitivity = MZ

Reference Sensitivity

Voltage and Current ratios



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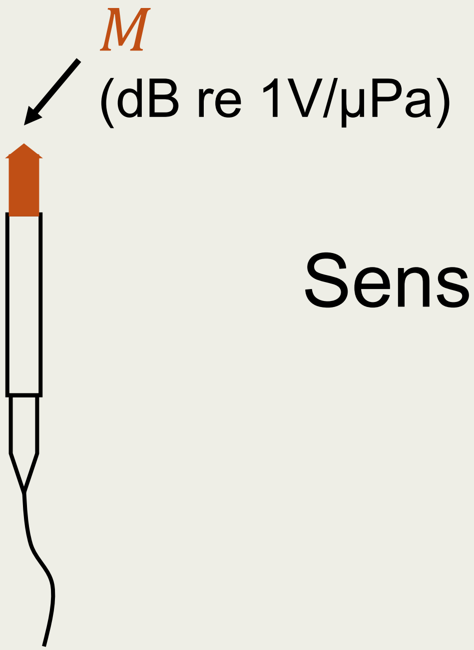
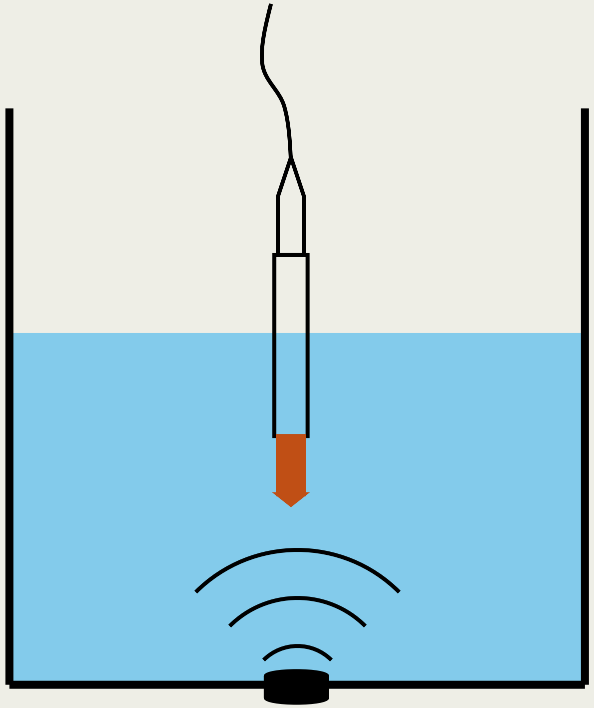
Comparison Replacement



Sensitivity = MZ

Reference Sensitivity (M)

Voltage and Current ratios (Z)



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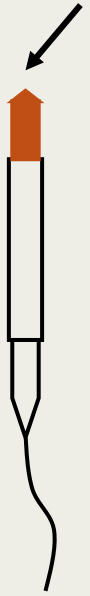
Comparison Replacement

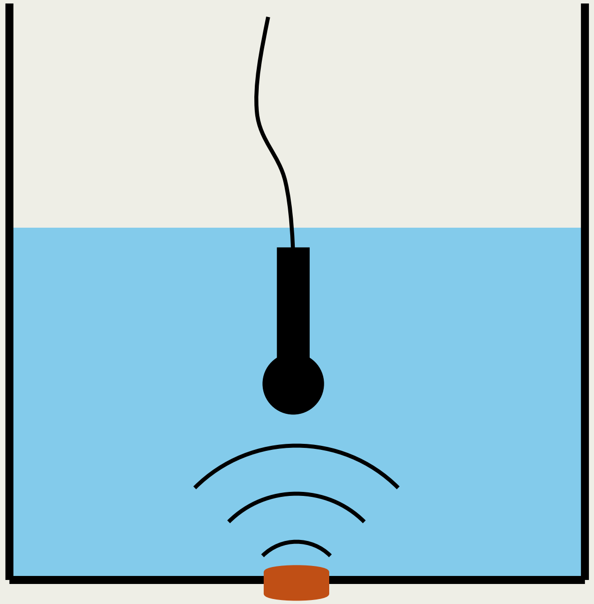
M
(dB re 1V/μPa)



Sensitivity = MZ

Reference Sensitivity

Voltage and Current ratios



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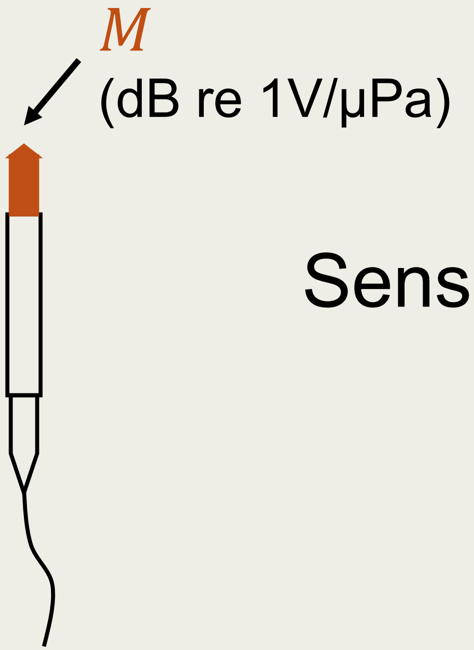
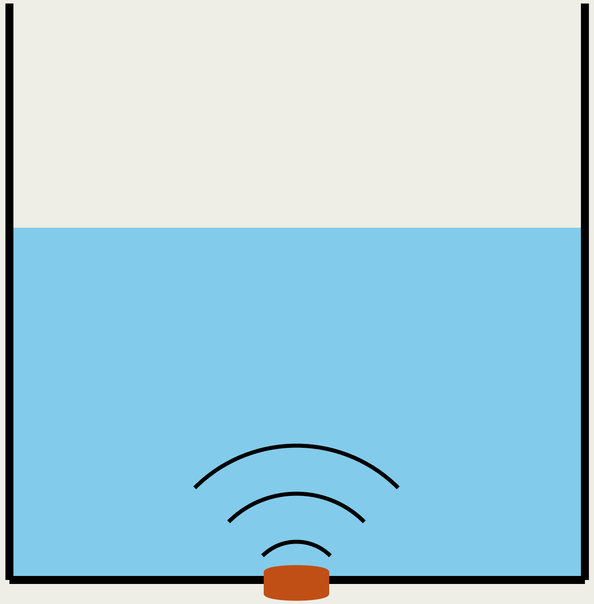
Comparison Replacement

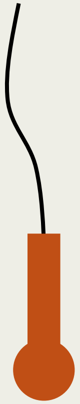


Sensitivity = MZ

Reference Sensitivity

Voltage and Current ratios





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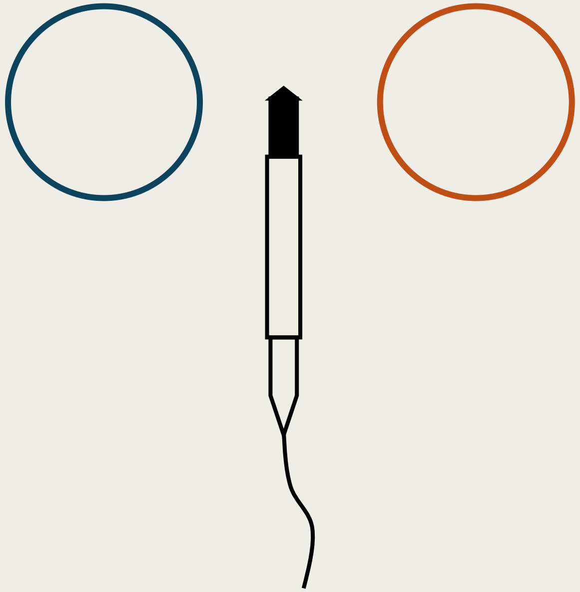
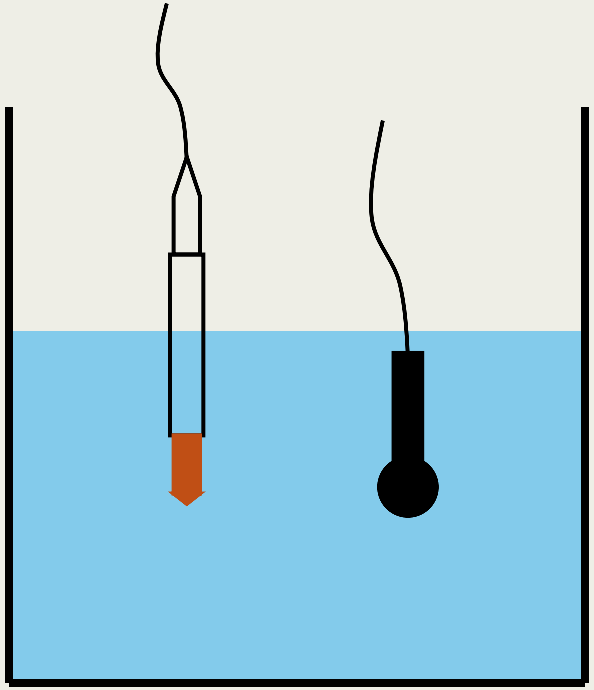
IEC 60565-1 (2020) and IEC 60565-2 (2019)

Primary



Sensitivity = $\sqrt{JZ_3}$

Secondary



Sensitivity = MZ

Calibration at the U.S. Navy Underwater Sound Reference Division (USRD) and considerations for in-situ calibration of hydrophones deployed at sea

Uncertainty Sources from IEC 60565-1 (2020)

Sources of uncertainty specific to free-field reciprocity calibrations [40] to [43]:

1) uncertainty of any assumptions about the acoustic field, e.g. that the field is a spherical-wave field (this can be checked by varying the separation distance between **transducers** and checking that the product of **electrical transfer impedance** and distance is invariant, see 8.2.9.2);
2) non-reciprocal behaviour by **transducers** which can be evaluated by checking the equivalence of the Z_{PT} and Z_{TP} electrical transfer impedances (see 8.2.9.1);
3) uncertainties in the measurement of the separation distance;
4) uncertainties in the values for acoustic frequency (required to calculate the reciprocity parameter);
5) uncertainty in the values for water density (required to calculate the reciprocity parameter).

Sources of uncertainty specific to comparison calibration:

6) uncertainties in the calibration of the reference **hydrophone** (a major source of uncertainty in a comparison calibration);
7) uncertainty caused by short-term instability of any auxiliary **transducers** used for comparison calibrations (e.g. instability of the output of a **transducer** used as a **projector** in a comparison calibration);
8) uncertainty caused by potential instability of the reference **hydrophone** in comparison calibrations (i.e. variation in the sensitivity of the reference device since the previous absolute calibration);
9) differences in environmental conditions for the comparison calibration compared with those that existed during the absolute calibration of the reference **hydrophone**, which would cause a change in sensitivity for the reference **hydrophone** (e.g. temperature, depth, mounting/rigging, etc.).

Sources of uncertainty specific to **hydrophone** calibration by calibrated **projector** method:

10) uncertainty of any assumptions about the acoustic field produced by the **projector**, e.g. that the field is a spherical-wave (the calibrated **projector** method is more sensitive to lack of free-field conditions than comparison with a calibrated **hydrophone**, for example, due to interference from boundary reflections);
11) uncertainties in the measurement of the separation distance;
12) lack of stability in the **projector** electrical drive conditions, including lack of linearity if the **projector** is driven with a **signal** different than that used in its own absolute calibration;
13) instability of the calibrated **projector** (i.e. variation in sensitivity of reference device since previous absolute calibration);
14) differences in environmental conditions for the calibration compared with those that existed during the absolute calibration of the reference **projector** which would cause a change in sensitivity for the reference **hydrophone** (e.g. temperature, depth, mounting/rigging, etc.).

Sources of uncertainty common to all above methods [4], [40] to [43]:

15) lack of steady-state conditions, especially where bursts of single-frequency sound waves are used (the resonance frequency and Q-factors of the **transducers** and the echo-free time of the tank will influence this contribution);
16) interference from acoustic reflections, leading to a lack of free-field conditions;
17) lack of **acoustic far-field** conditions;
18) the spatial averaging effects of the **hydrophones** under calibration due to their finite size and the lack of perfect plane-wave conditions;
19) misalignment, particularly at high frequencies where the **hydrophone** response will be far from omnidirectional;
20) acoustic scattering from the **hydrophone** mount (or vibrations picked up and conducted by the mount);
21) uncertainty in measurement of the receive voltage (including uncertainty due to the measuring instrumentation (voltmeter, digitizers, etc.);
22) uncertainty of the gains of any amplifiers, filters, and digitizers used;
23) uncertainties in the measurement of the drive current or voltage;
24) uncertainties due to the lack of linearity in the measurement system (the use of a calibrated attenuator to equalize the measured **signals** can significantly reduce this contribution);
25) uncertainty of any electrical **signal** attenuators used;
26) electrical noise including RF pick-up;
27) uncertainty of any electrical loading corrections made to account for loading by extension cables and preamplifiers;
28) bubbles or air clinging to **transducers** (this should be minimized by adequate wetting and soaking of **transducers**);
29) environmental conditions, such as water temperature and depth of immersion (corrections need not be included for these if the calibration results specify the conditions and state that the calibration is only valid for the conditions stated).

Sources of Uncertainty

Primary

Voltage measurement

Positioning, orientation, and fixturing

Fluid volume, density, sound speed

$$J = 2\pi f C$$

Boundary compliance

$$\mathrm{C} = \frac{V}{\rho c^2} + C_b$$

Secondary

Voltage measurement

Positioning, orientation, and fixturing

(Primary calibration)

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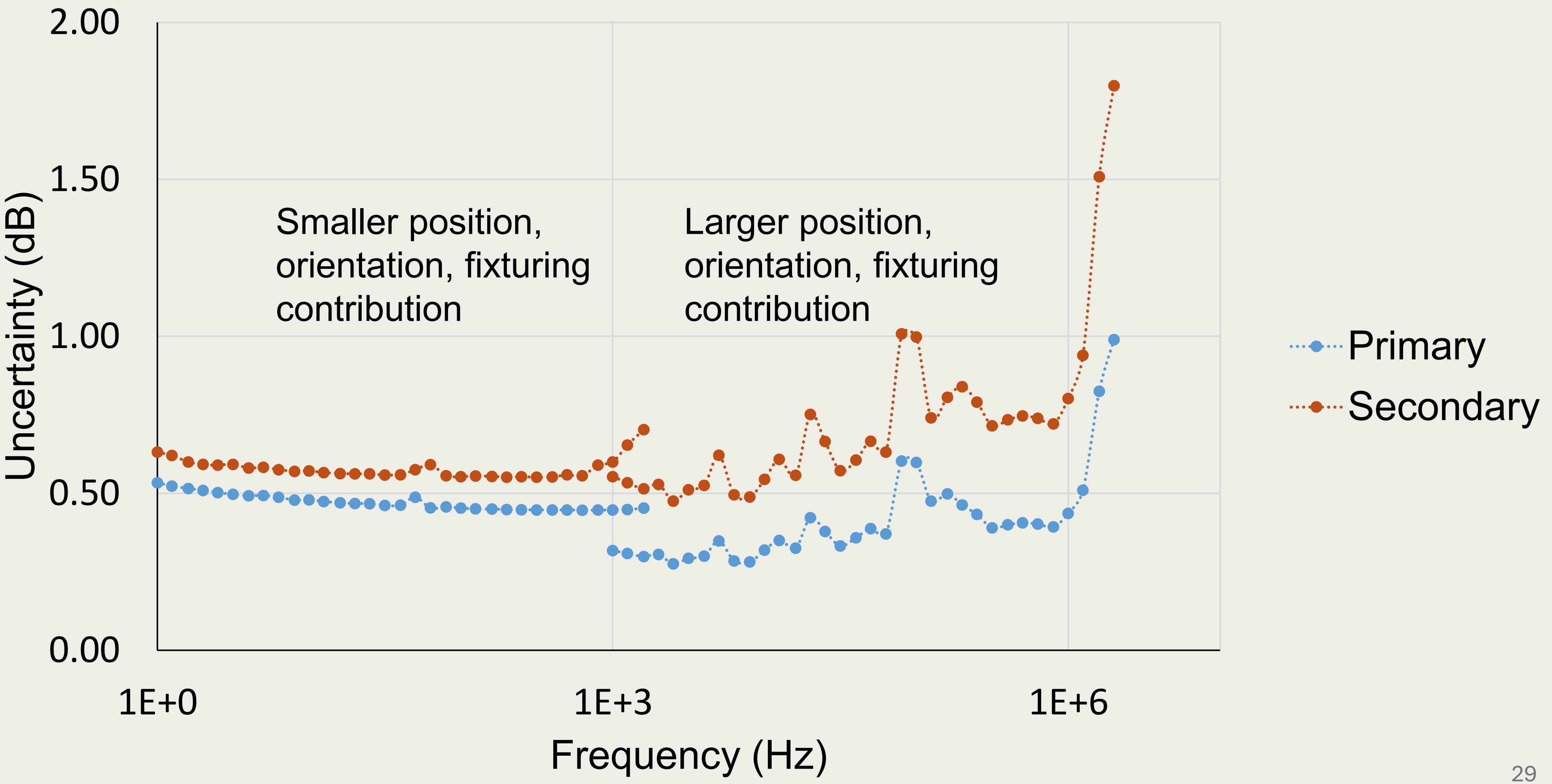
Uncertainty Contribution of Primary and Secondary Calibration



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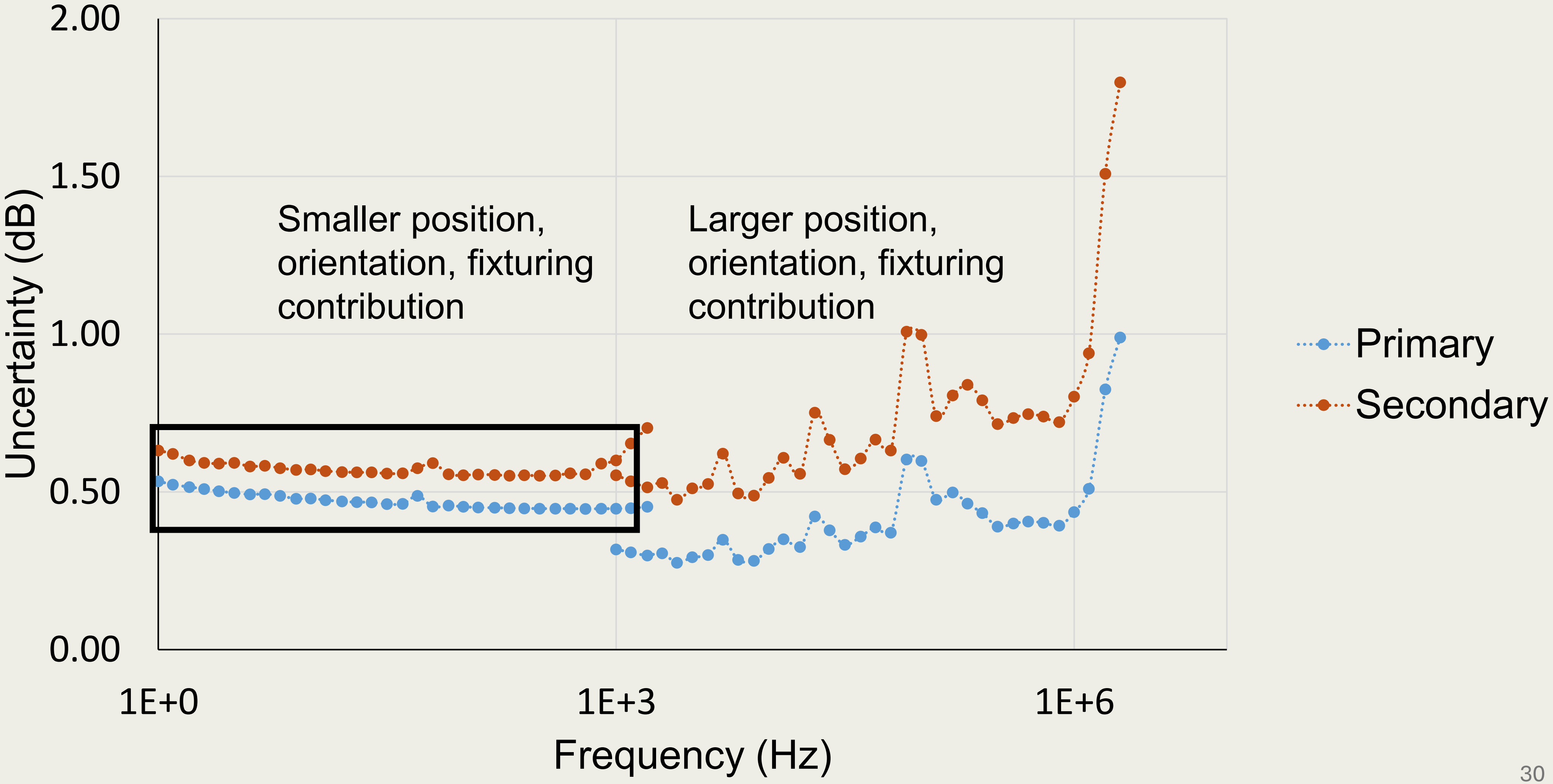
Uncertainty Contribution of Primary and Secondary Calibration



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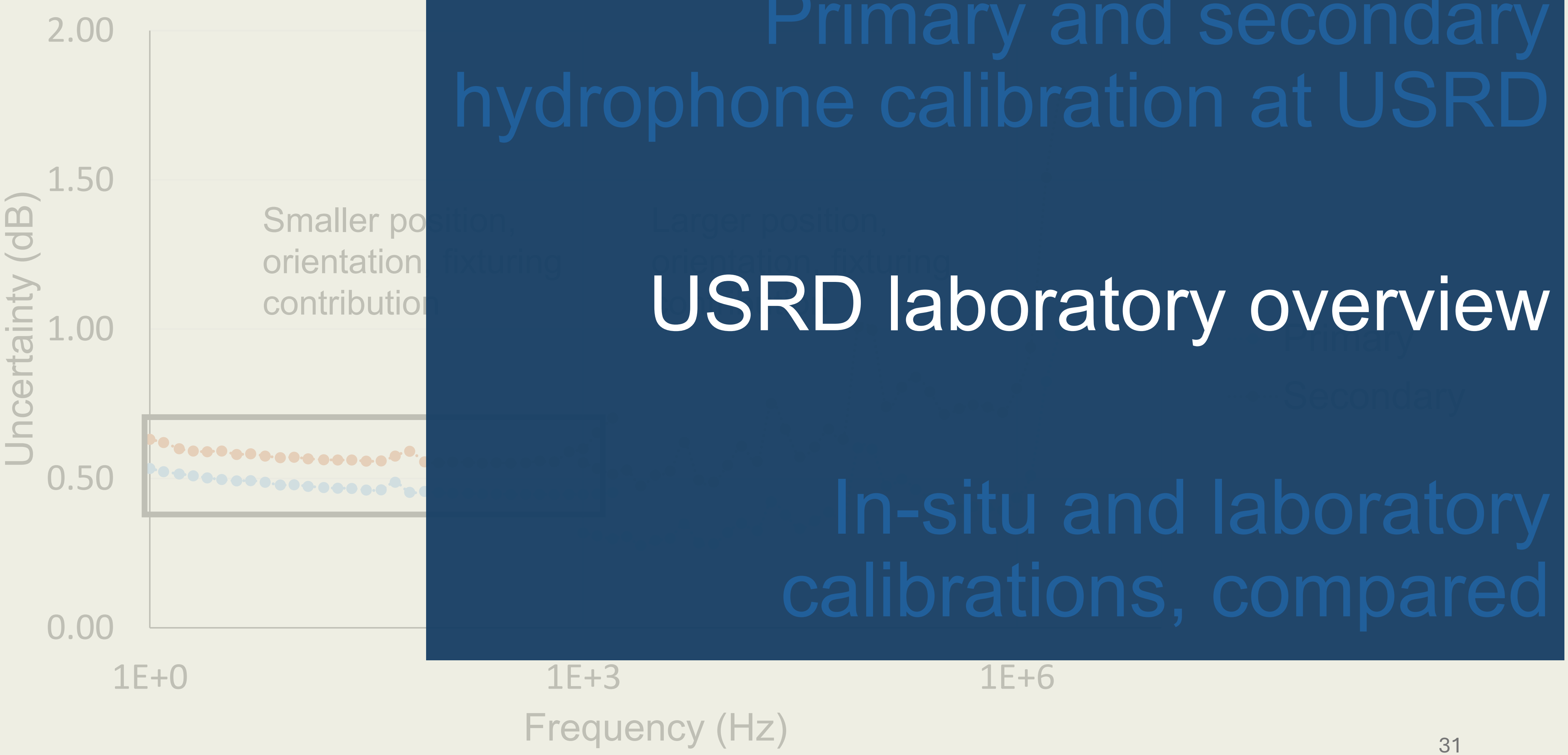
Uncertainty Contribution of Primary and Secondary Calibration



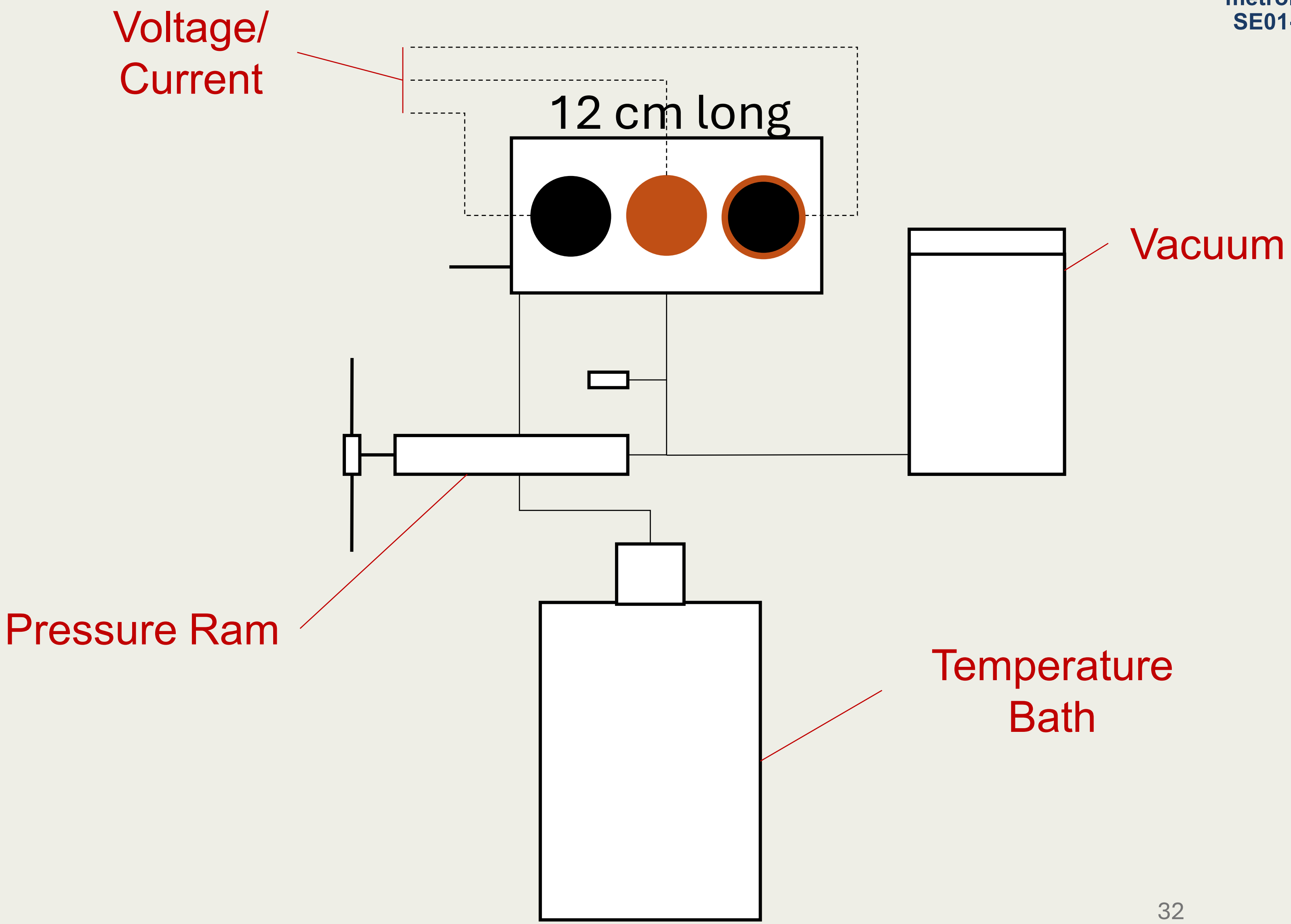
Primary and secondary hydrophone calibration at USRD

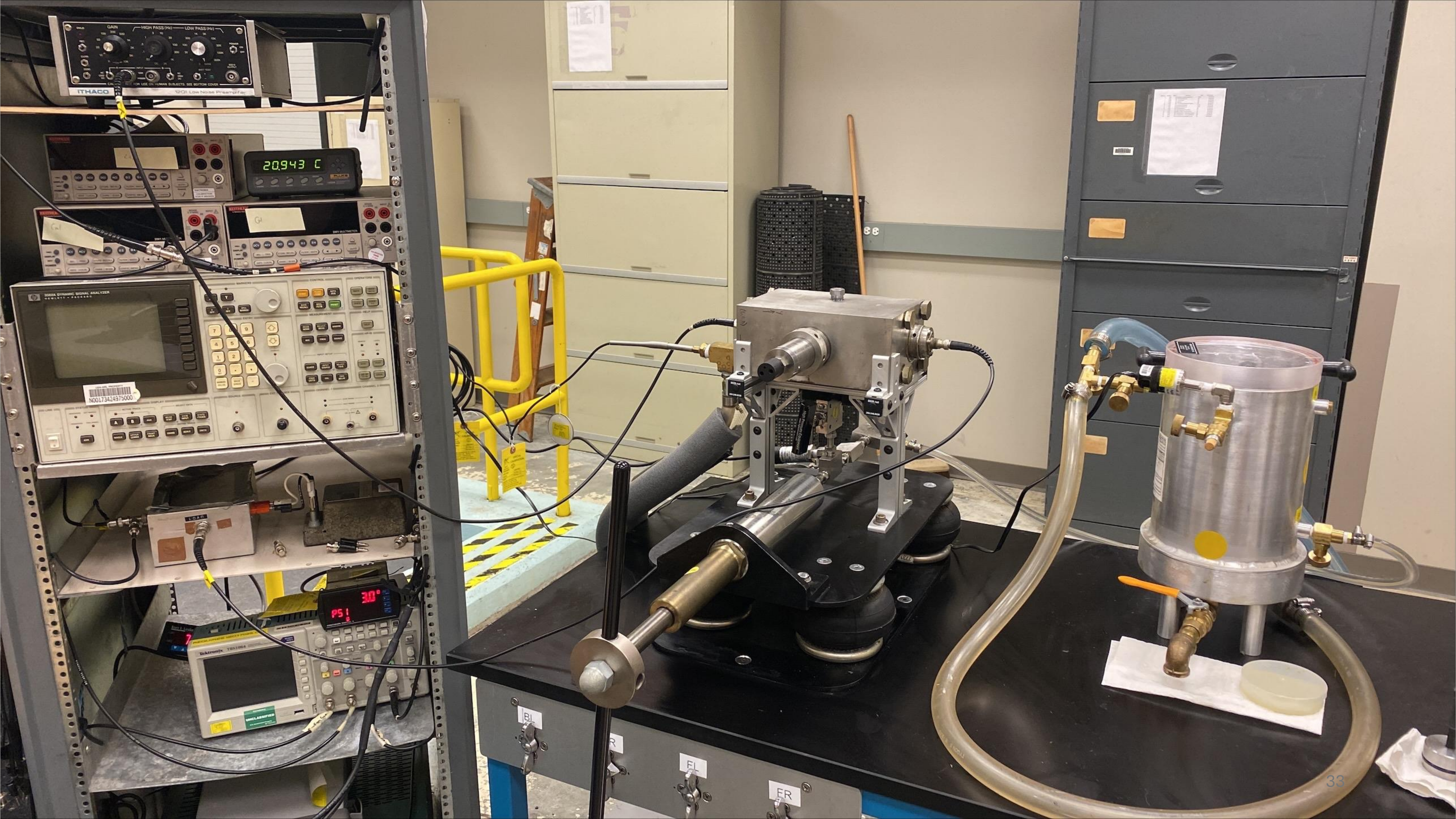
USRD laboratory overview

In-situ and laboratory calibrations, compared

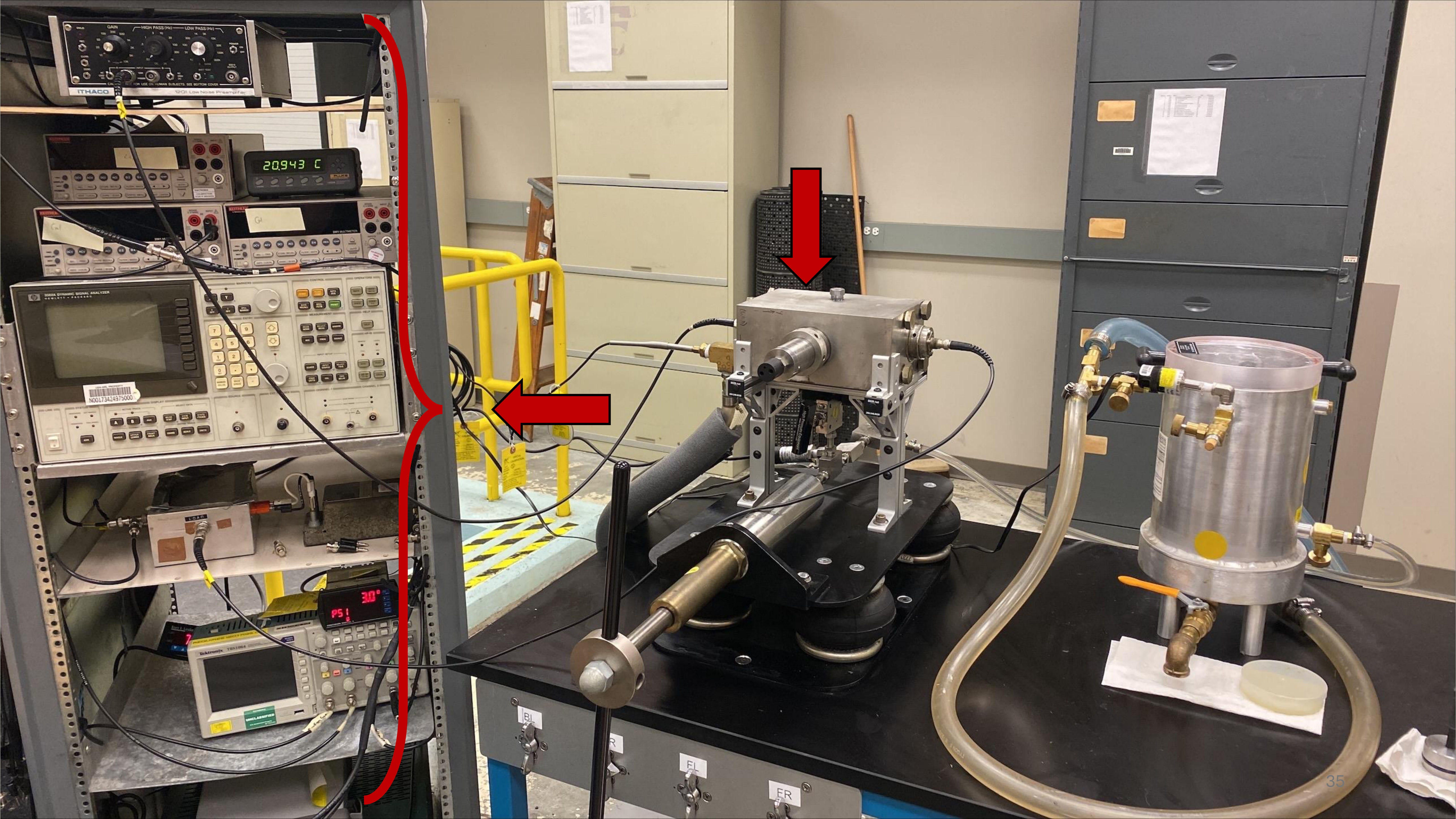
Primary Calibration: Coupler Reciprocity

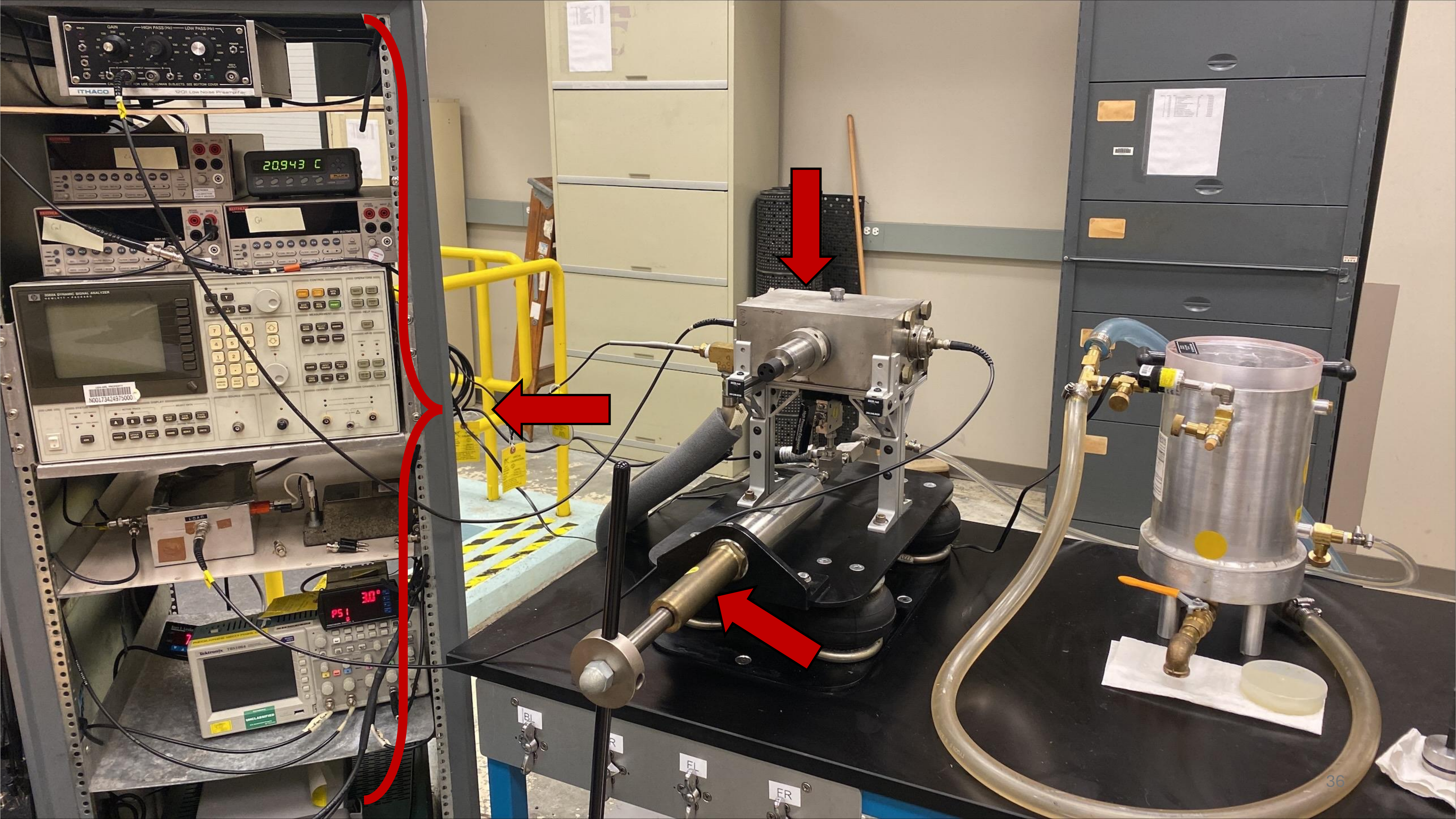
1 Hz to 2 kHz

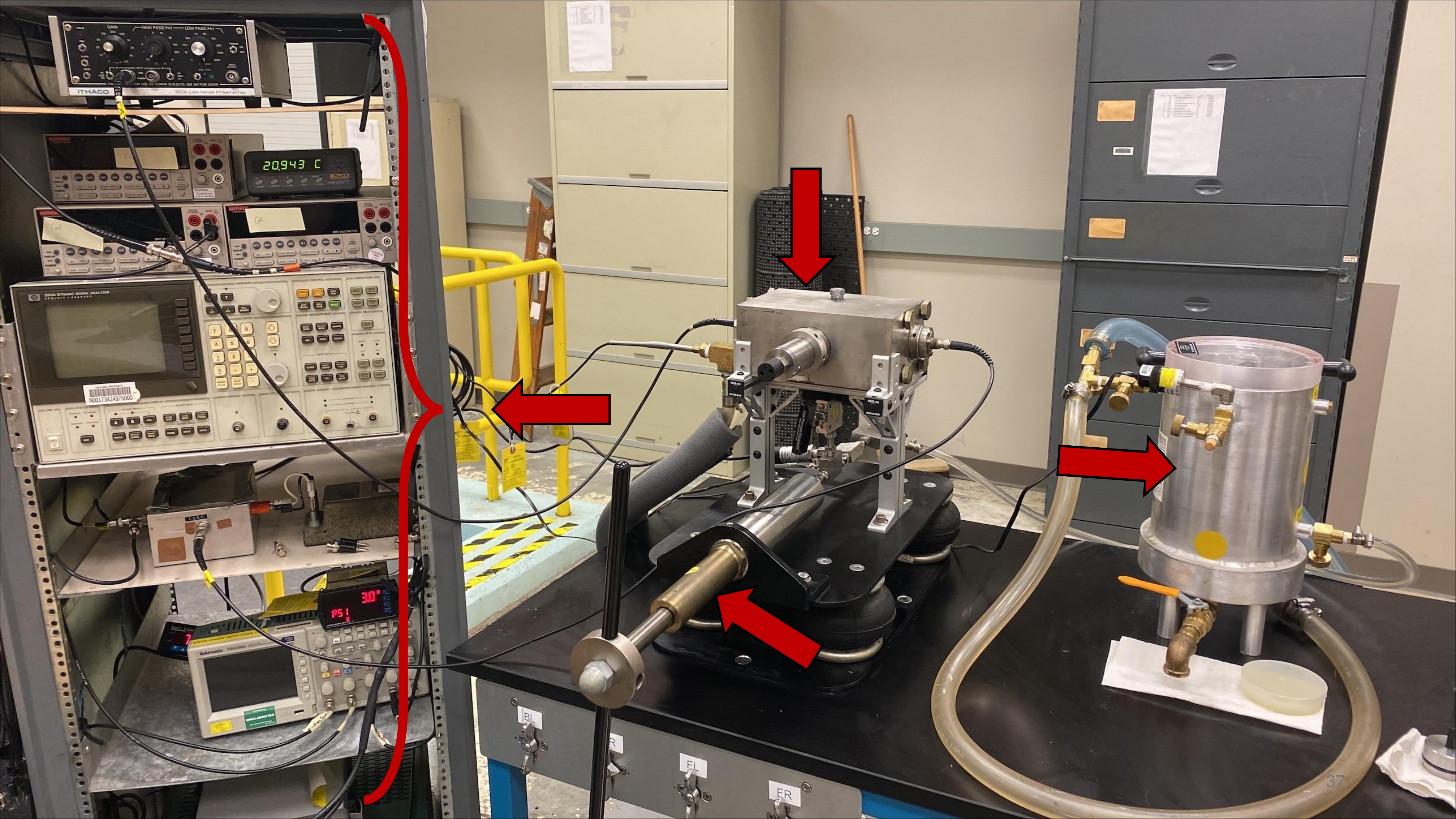



ITHACO
1201 Low Noise Preamplifier
20.943 C
N00173424975000
LOAD
PS1
Tektronix
BL
FL
FR


ITHACO
1201 Low Noise Preamplifier
20.943 C
3.0°
PS1
BL
FL
ER



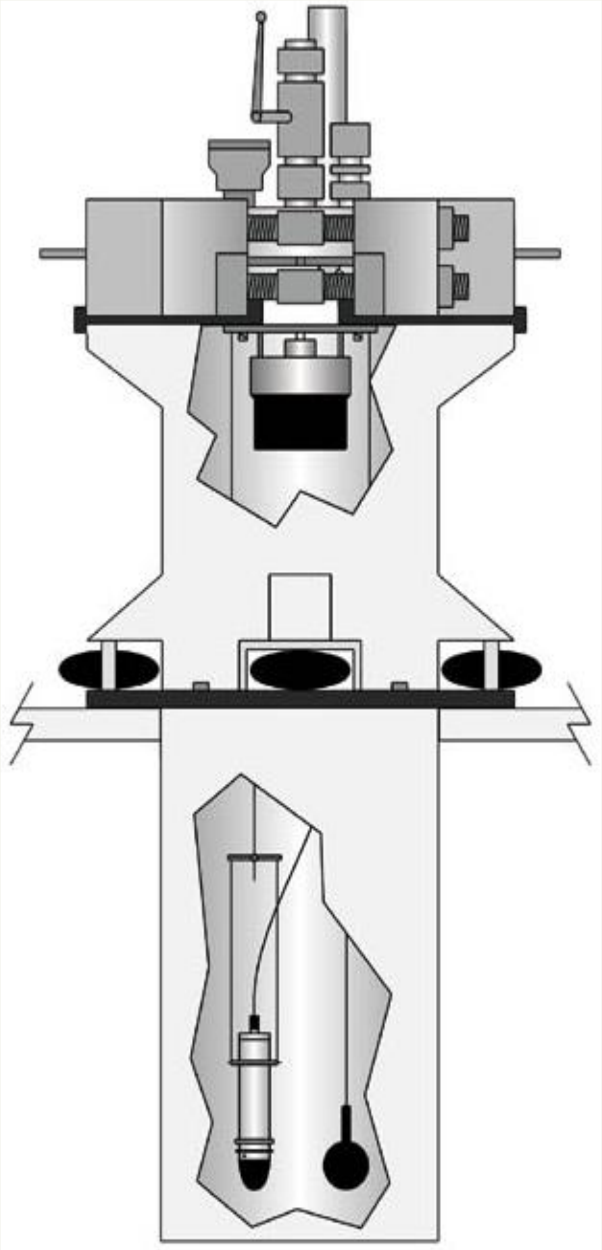

ITHACO
20.943 C
LOAD
PSI
Tektronix
BL
FL
ER

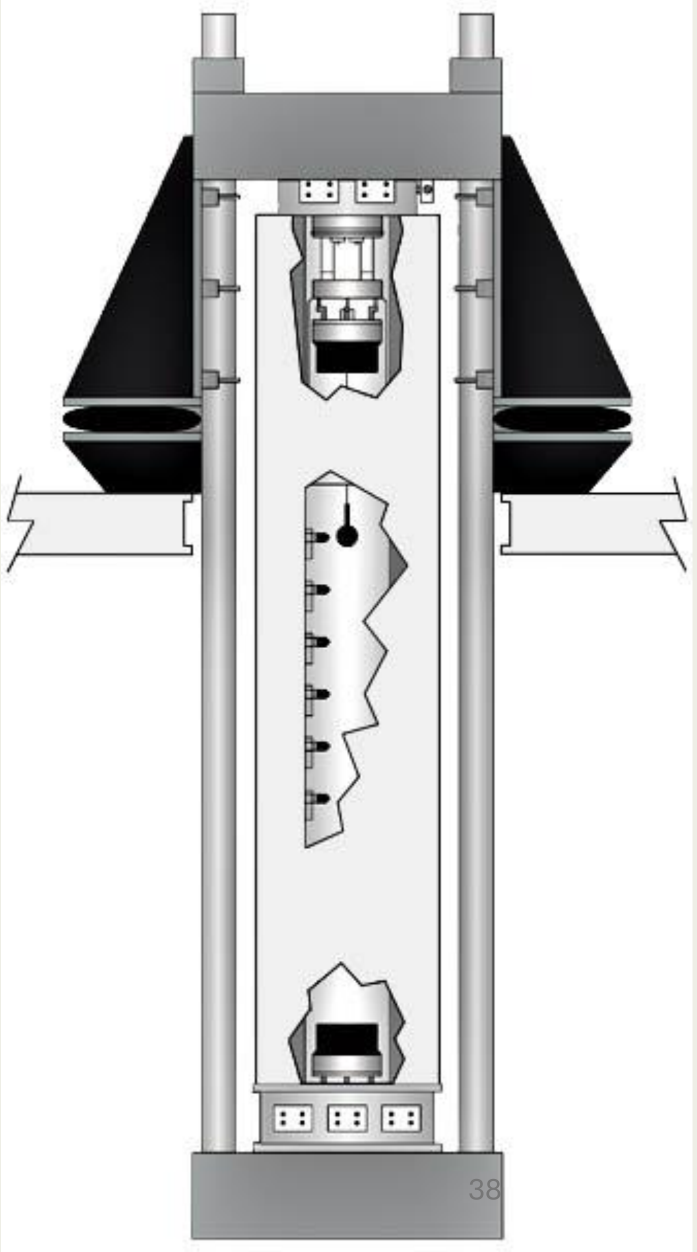

ITHACO
1201 Low Noise Preamplifier
20.943 C
N00173424975000
LOAD
PSI
BL
FL
FR

Secondary Calibration: "System J, K, L" Waveguides

1 Hz to 2 kHz

20 - 38 cm diameter





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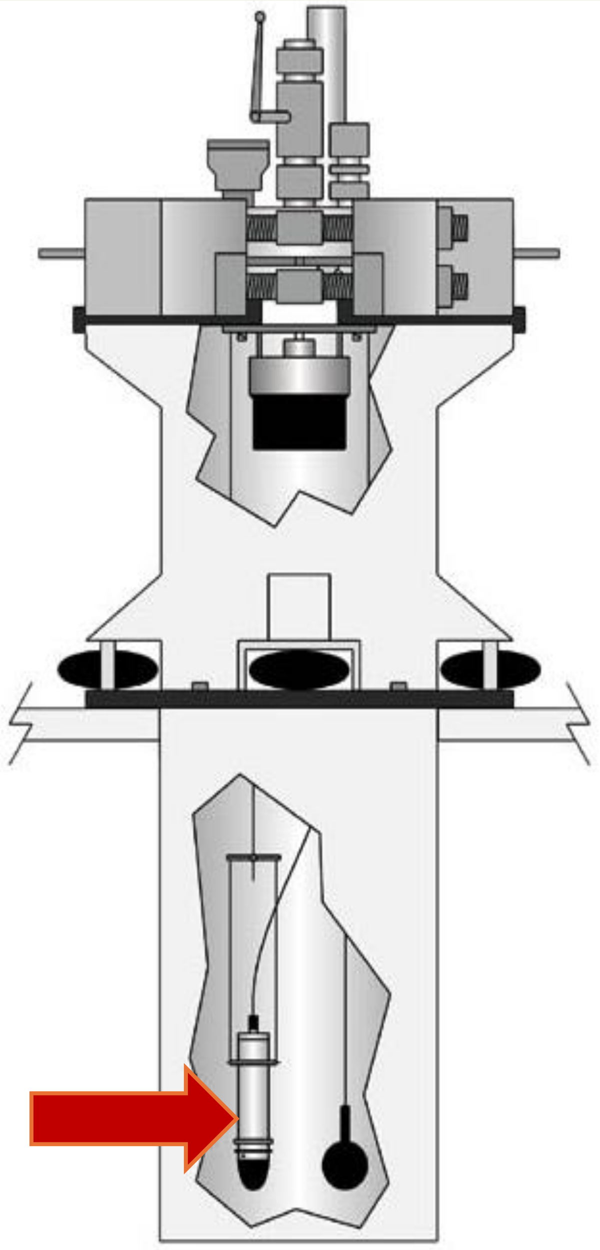

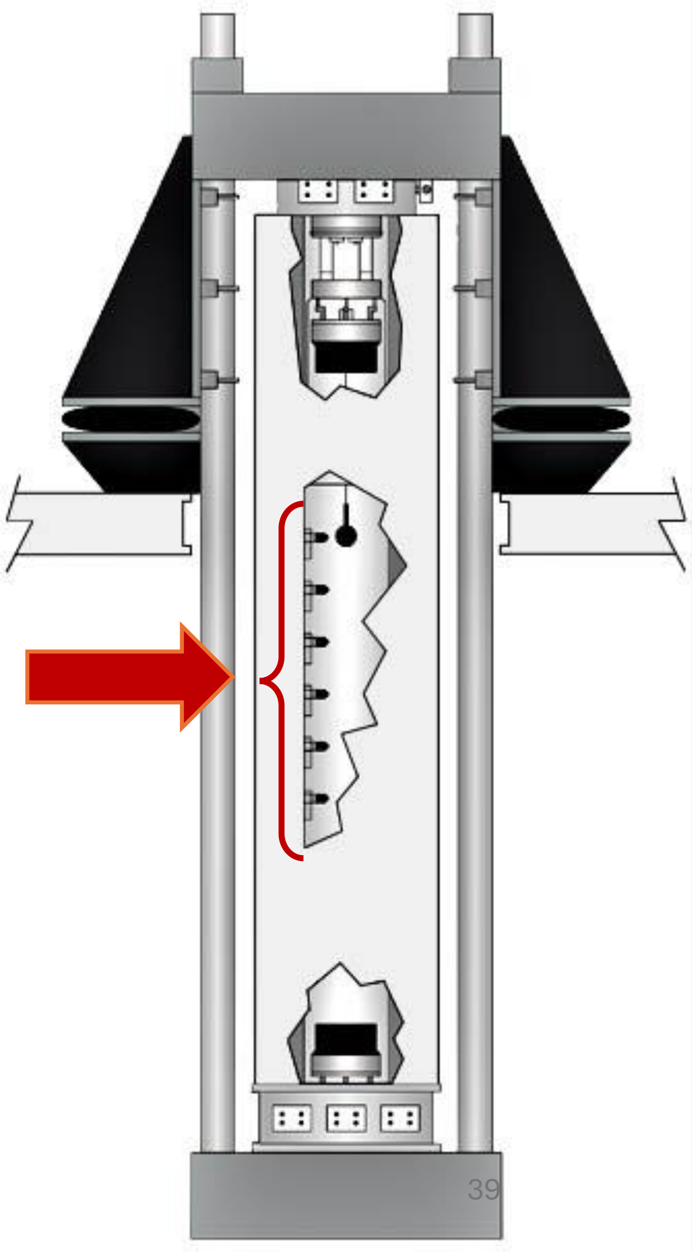

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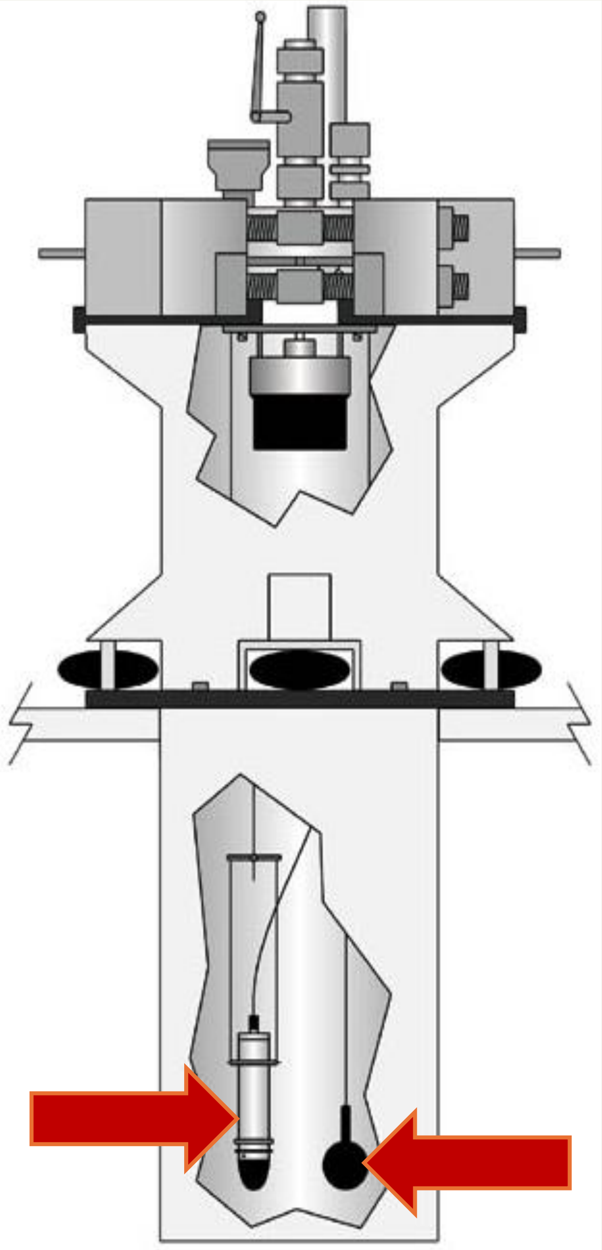
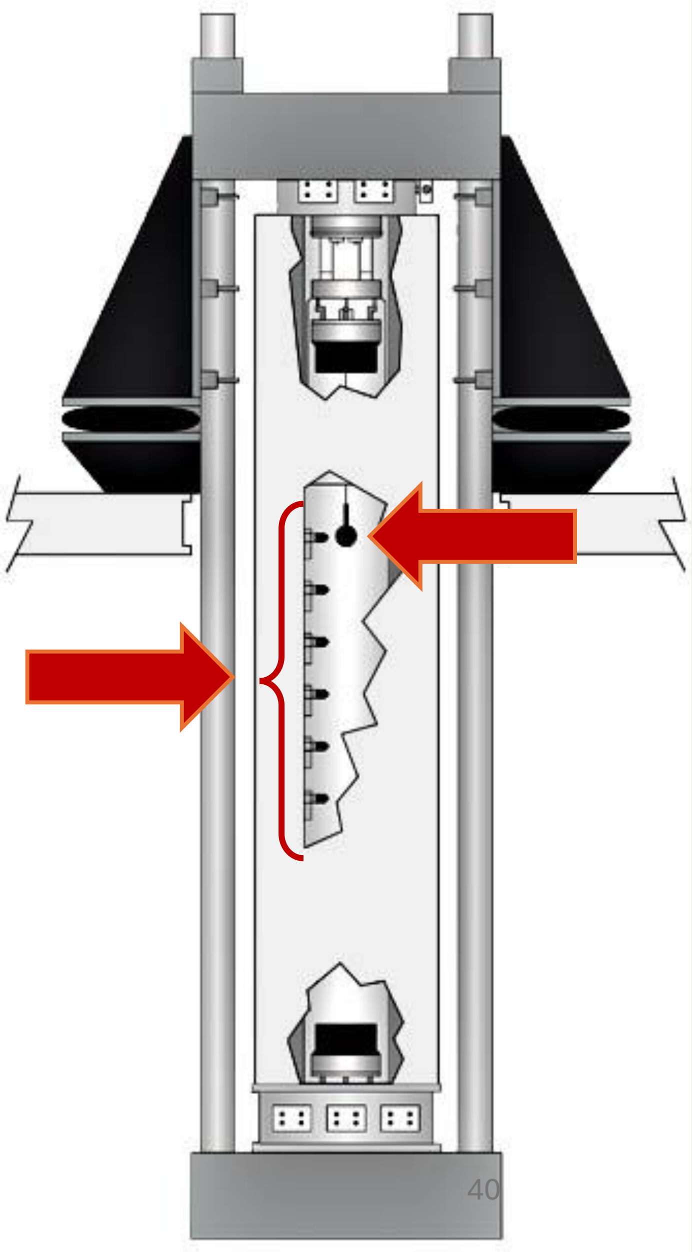
1 Hz to 2 kHz

20 - 38 cm diameter





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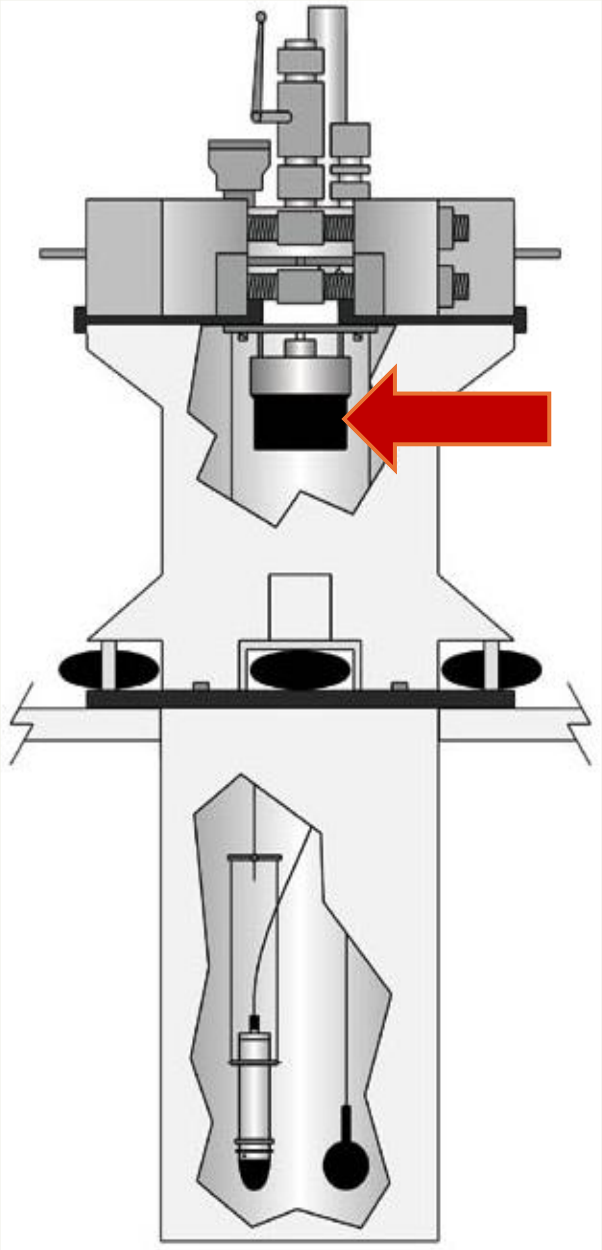
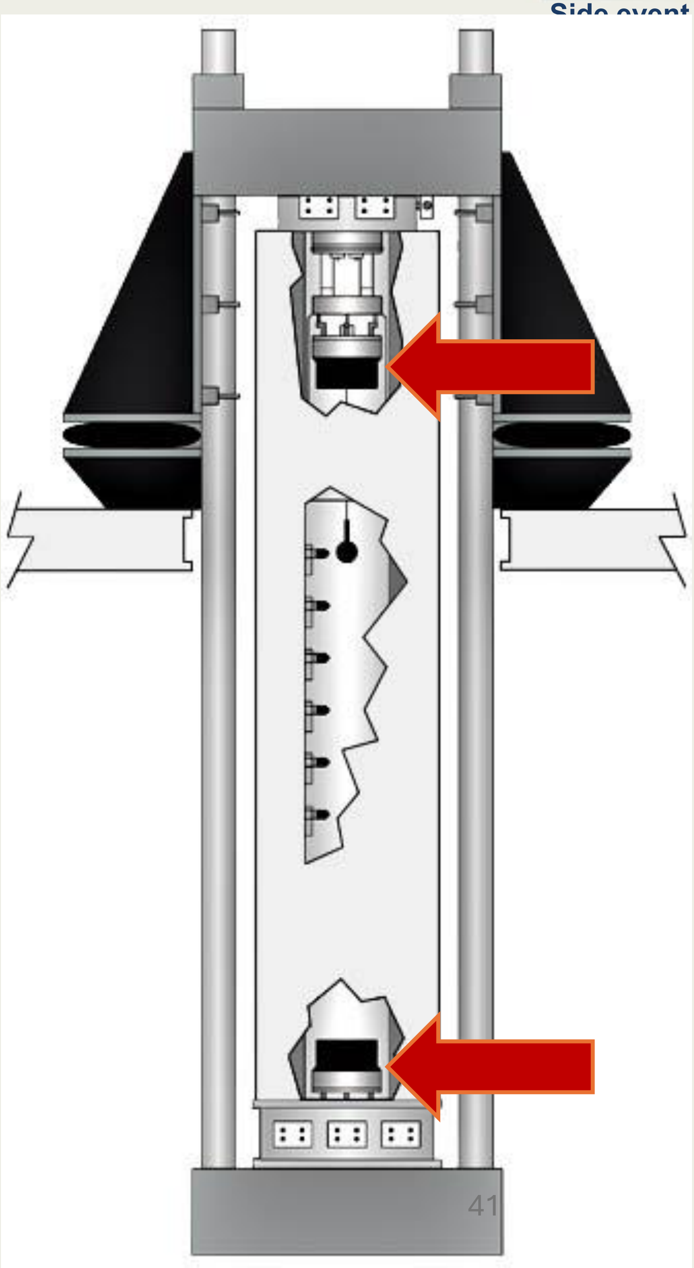
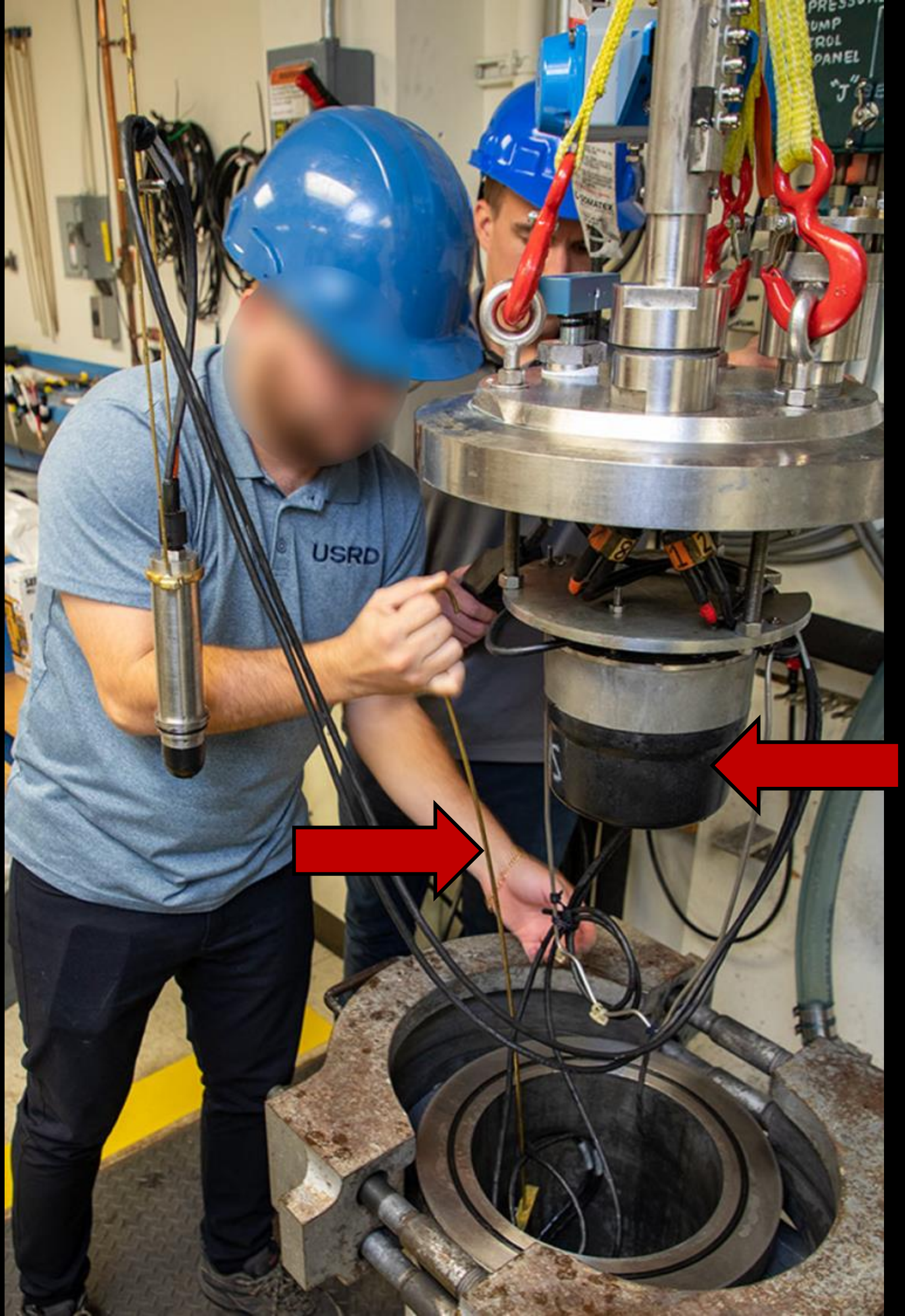
Secondary Calibration: "System J, K, L" Waveguides

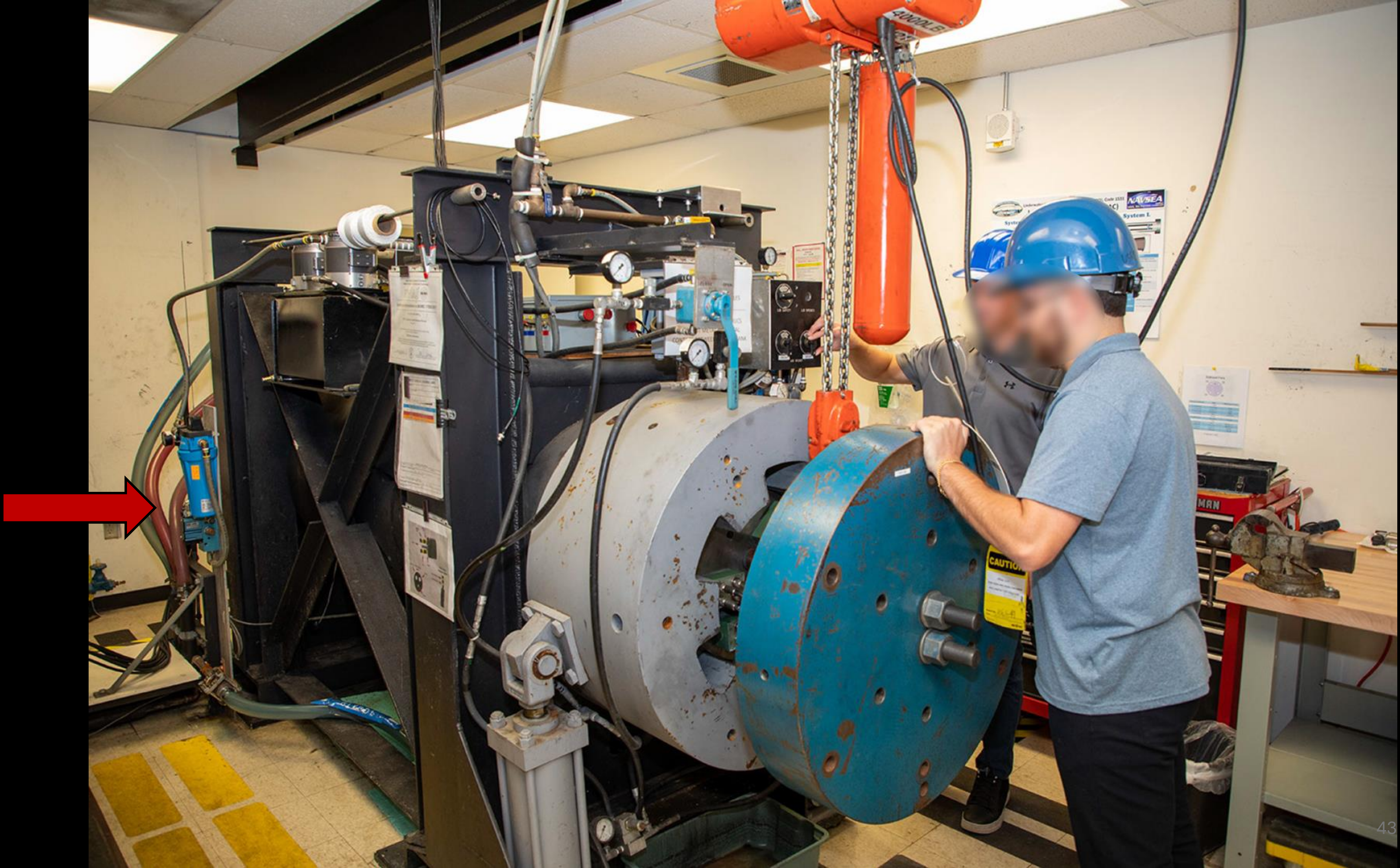
1 Hz to 2 kHz

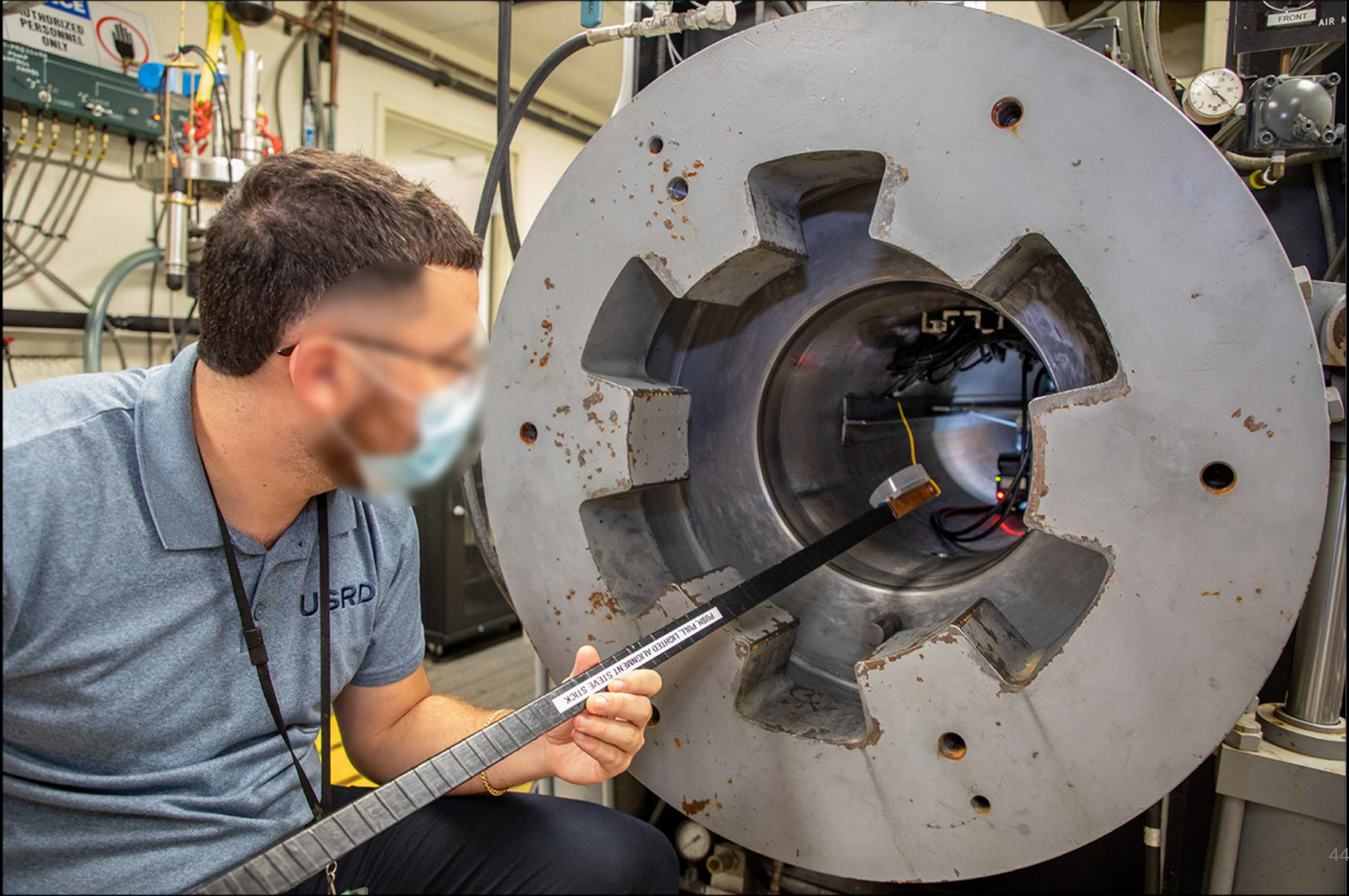
20 - 38 cm diameter






USRD


4000LB
NAVSEA
CAUTION

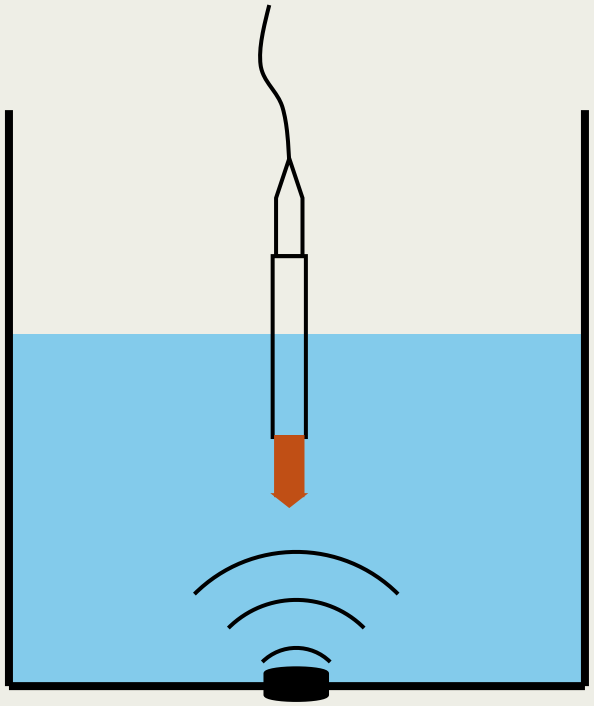

PERSONNEL
ONLY
FRONT
USRD
PUSH, PULL, LIGHTED ALIGNMENT STEVE STICK

Primary and secondary hydrophone calibration at USRD

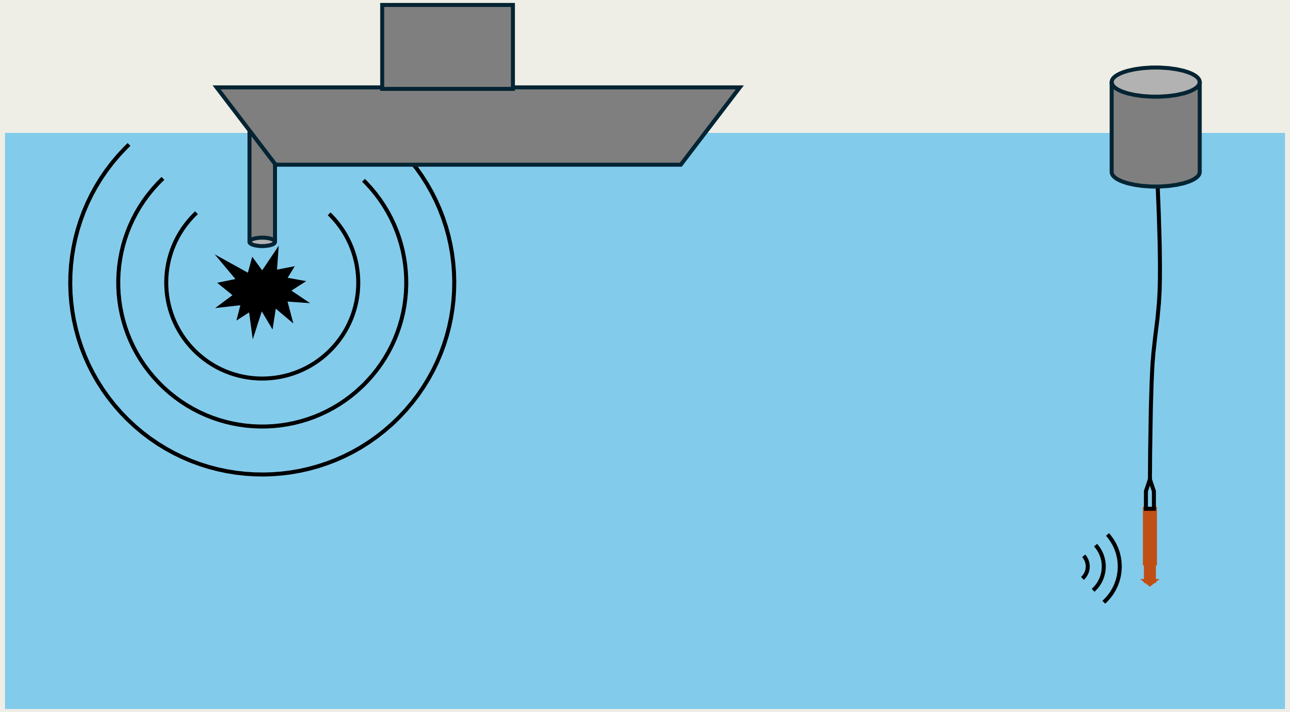
USRD laboratory overview

In-situ and laboratory calibrations, compared

Comparison: IEC 60565-1 (2020) 9.5, Projector calibration using a calibrated hydrophone

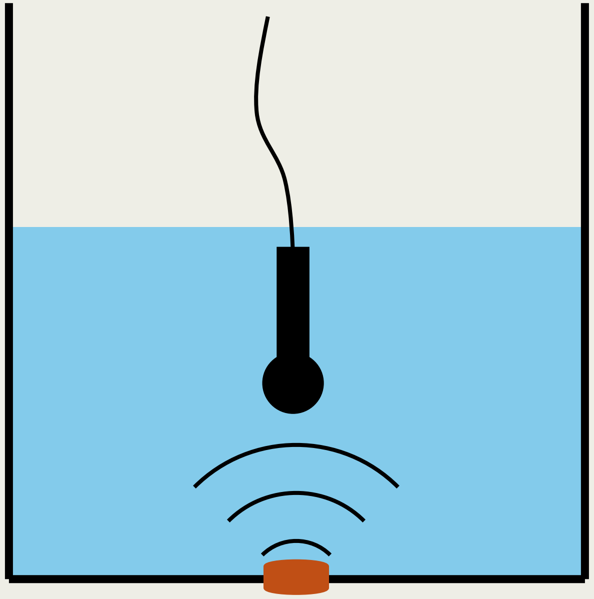


$$|S| = \frac{d_R |Z_{PR}|}{|M_R|}$$

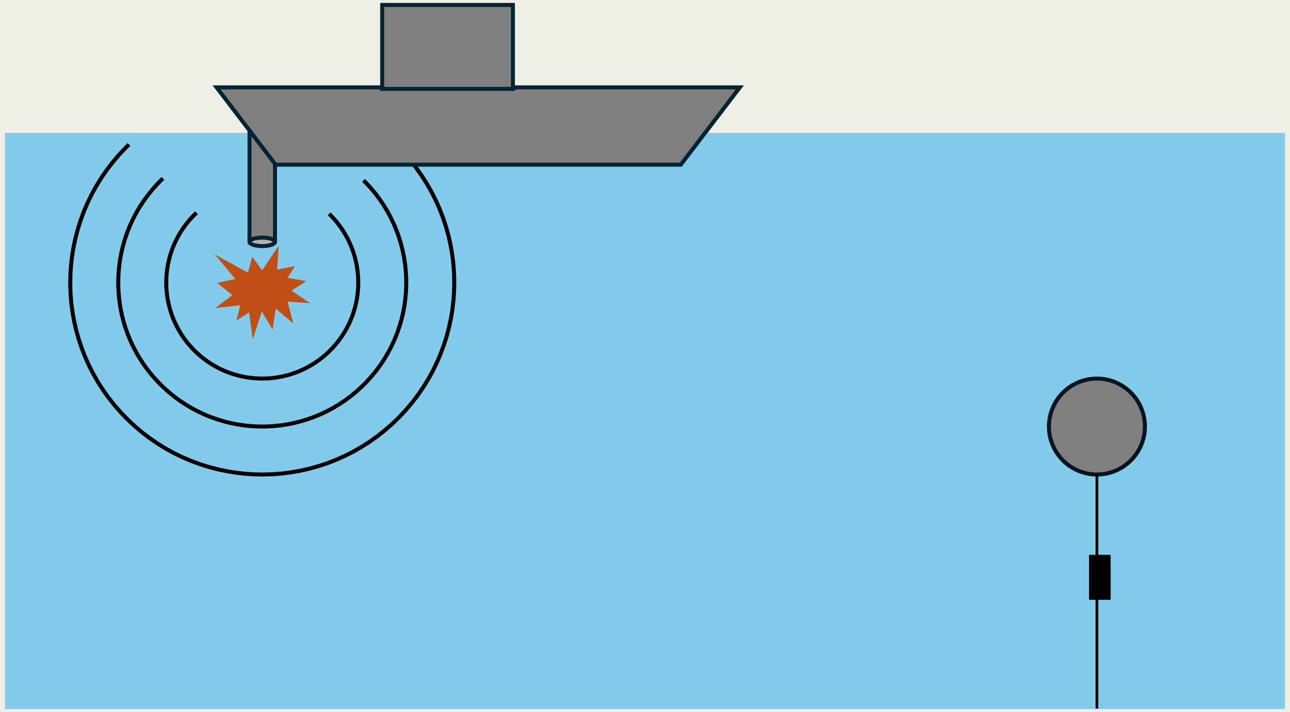


Measure the transmitting response of the source with a known reference hydrophone

Comparison: IEC 60565-1 (2020) 9.5, Hydrophone calibration using a calibrated projector



$$|M_H| = \frac{d_H |Z_{PH}|}{|S|}$$



Measure the sensitivity of the unknown hydrophone with the known source

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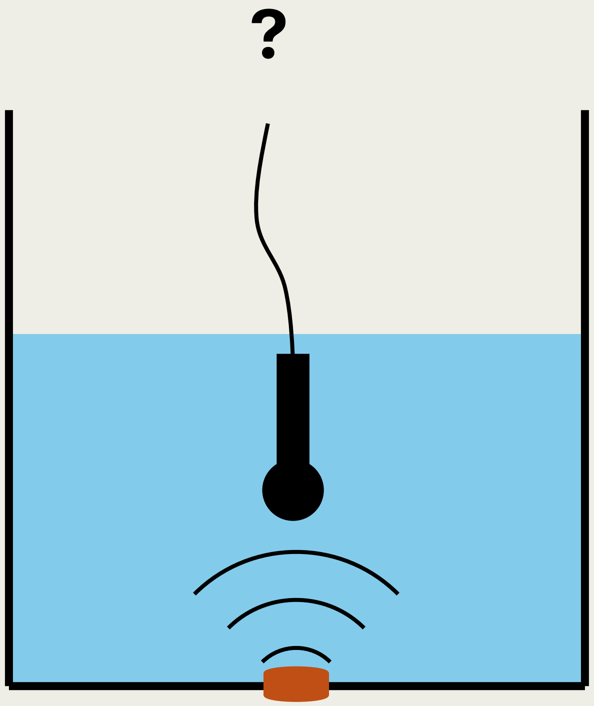
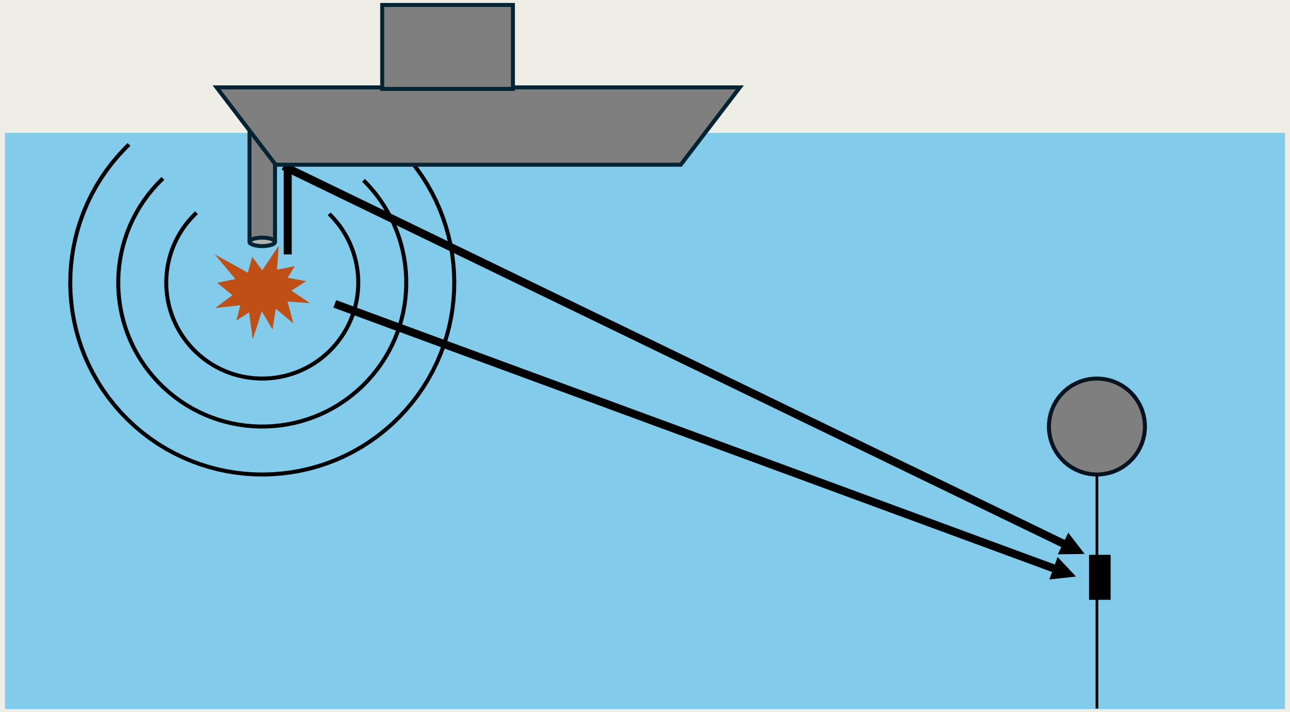
Comparison: IEC 60565-1 (2020) 9.5, Hydrophone calibration using a calibrated projector



$$|M_H| = \frac{d_H |Z_{PH}|}{|S|}$$



Correct for surface interference

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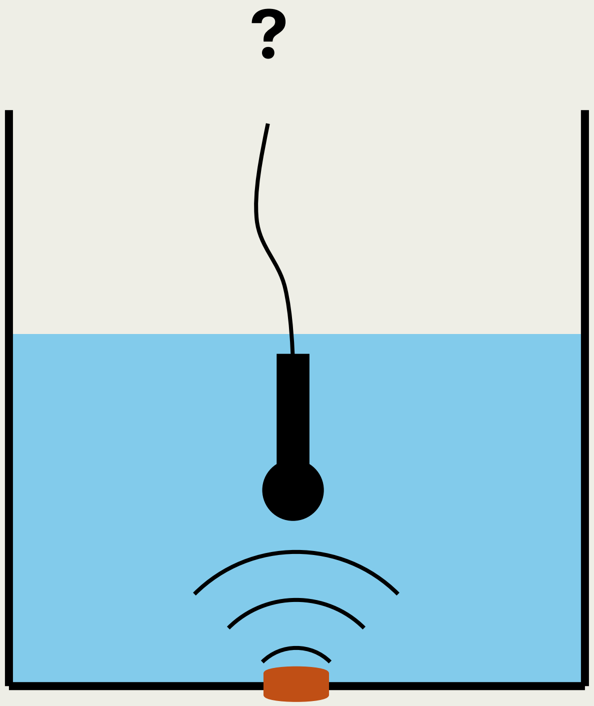
Comparison: IEC 60565-1 (2020) 9.5, Hydrophone calibration using a calibrated projector



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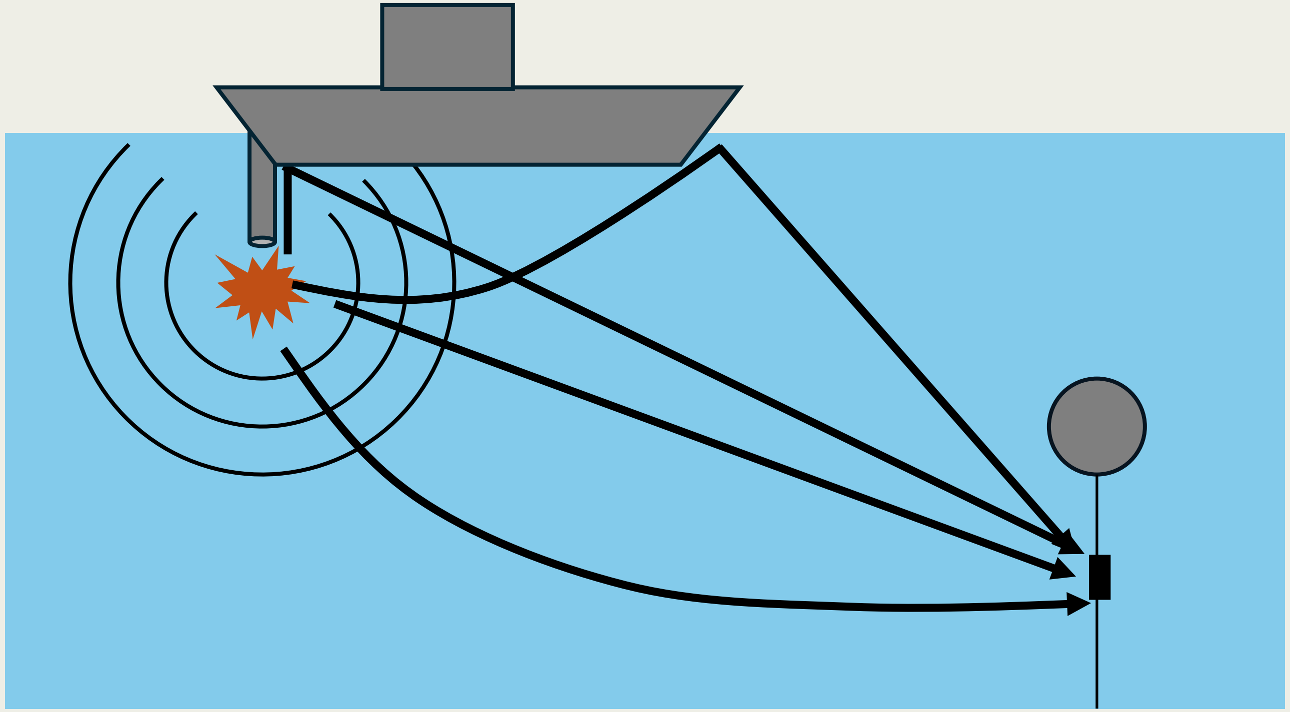
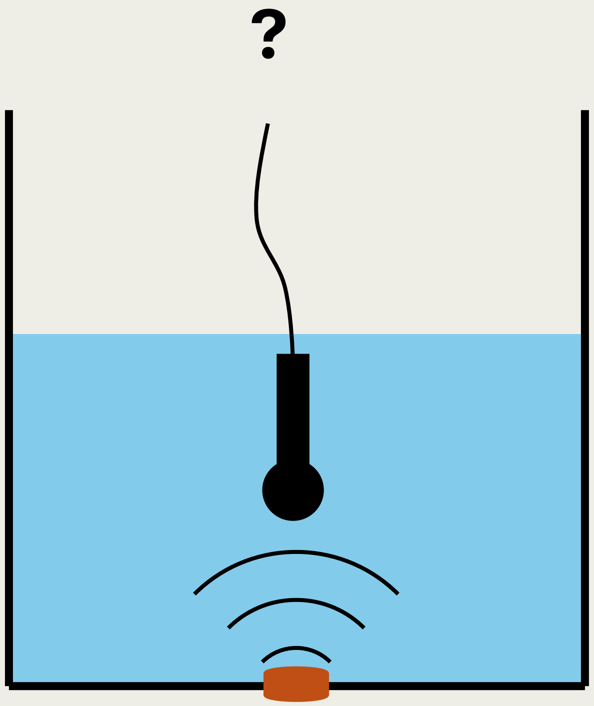
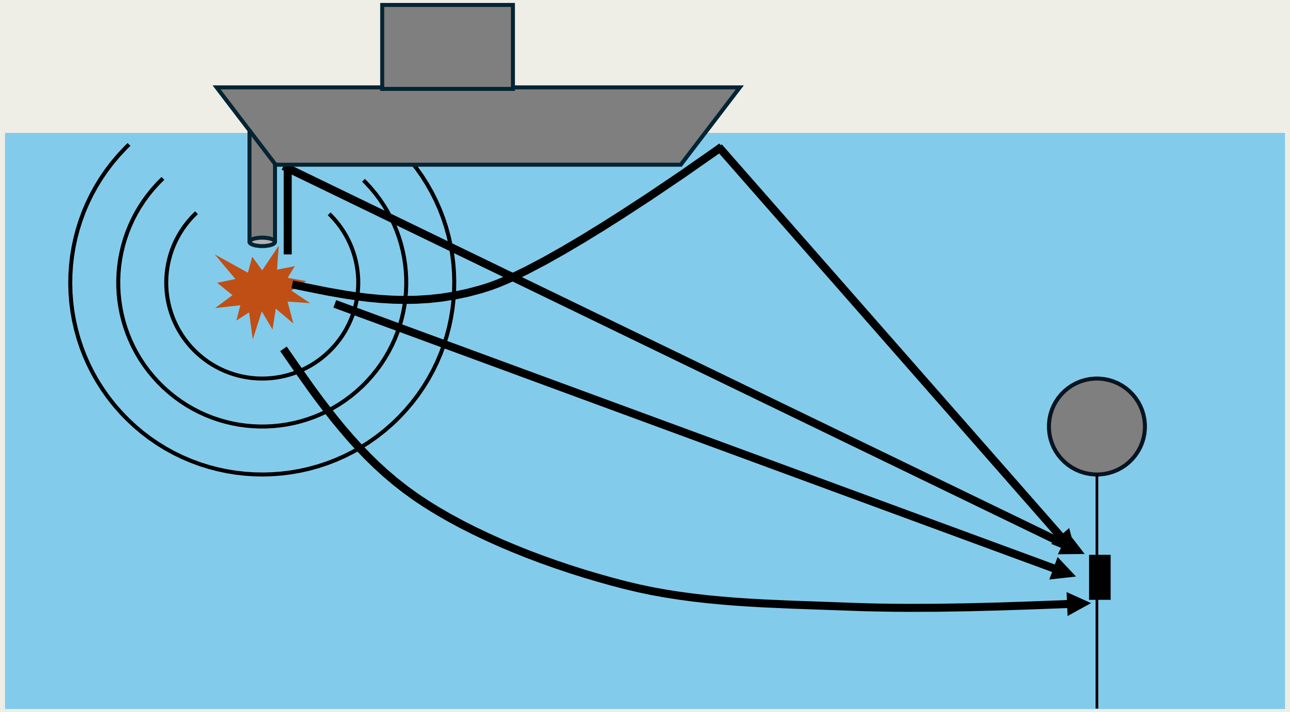


Separate direct from multipath and reflected arrivals

Comparison: IEC 60565-1 (2020) 9.5, Hydrophone calibration using a calibrated projector





Harben and Rodgers, "Calibration of Hydrophone Stations: Lessons Learned From The Ascension Island Experiment," 2000.
Crocker et al., "Geoacoustic inversion of ship radiated noise in shallow water using data from a single hydrophone," 2014.

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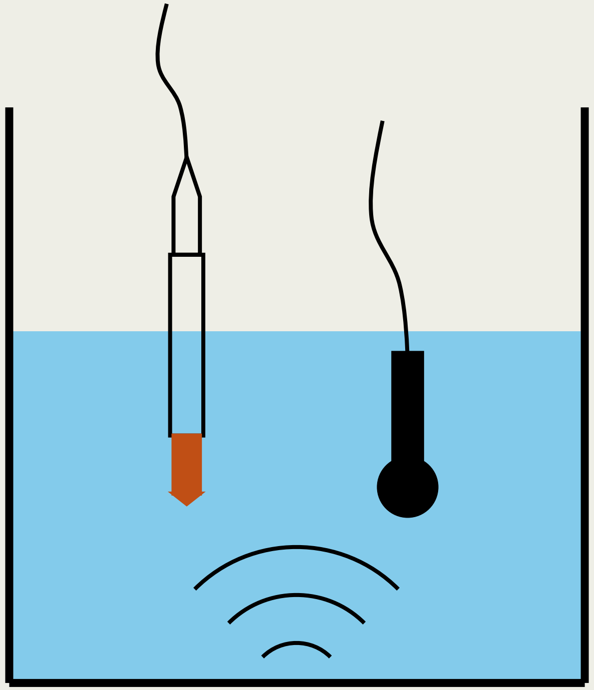
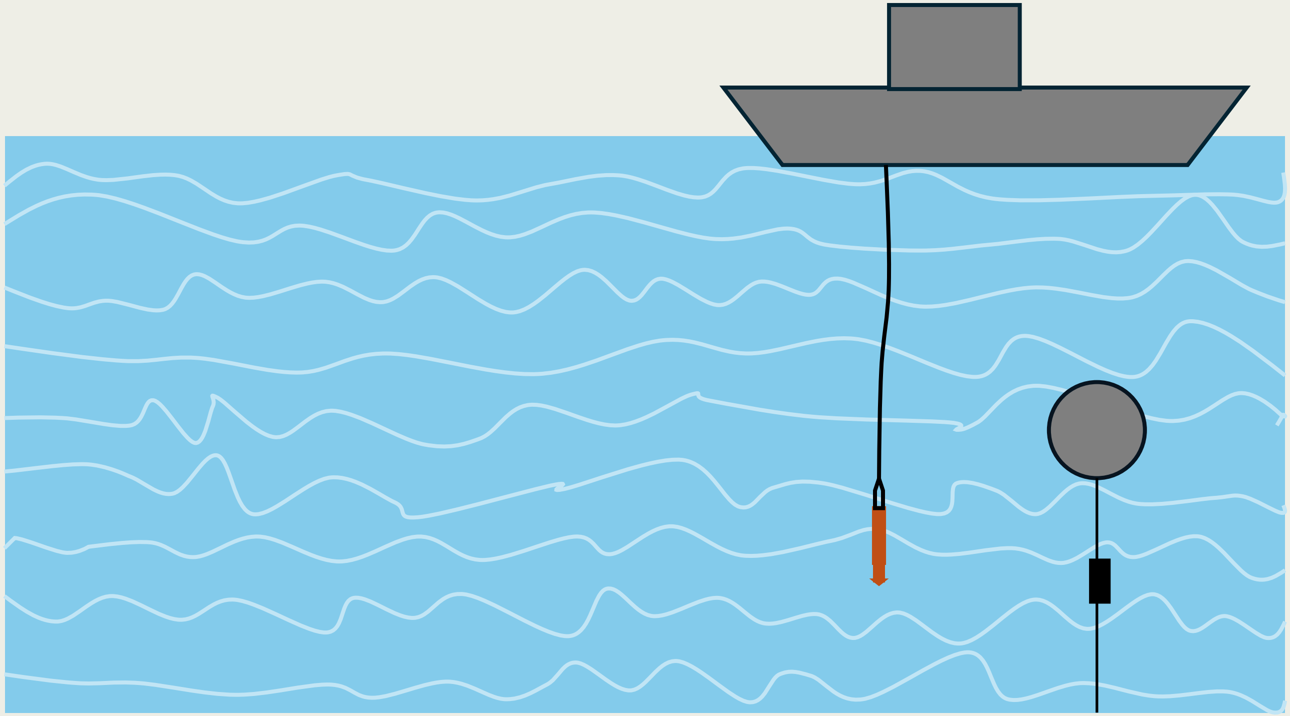
Comparison: IEC 60565-2 (2019) 8.5, 10.4 Relative calibration



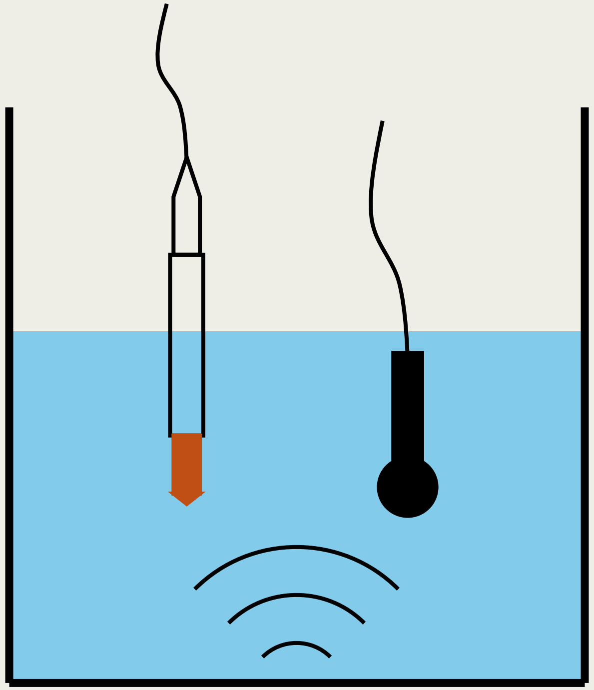


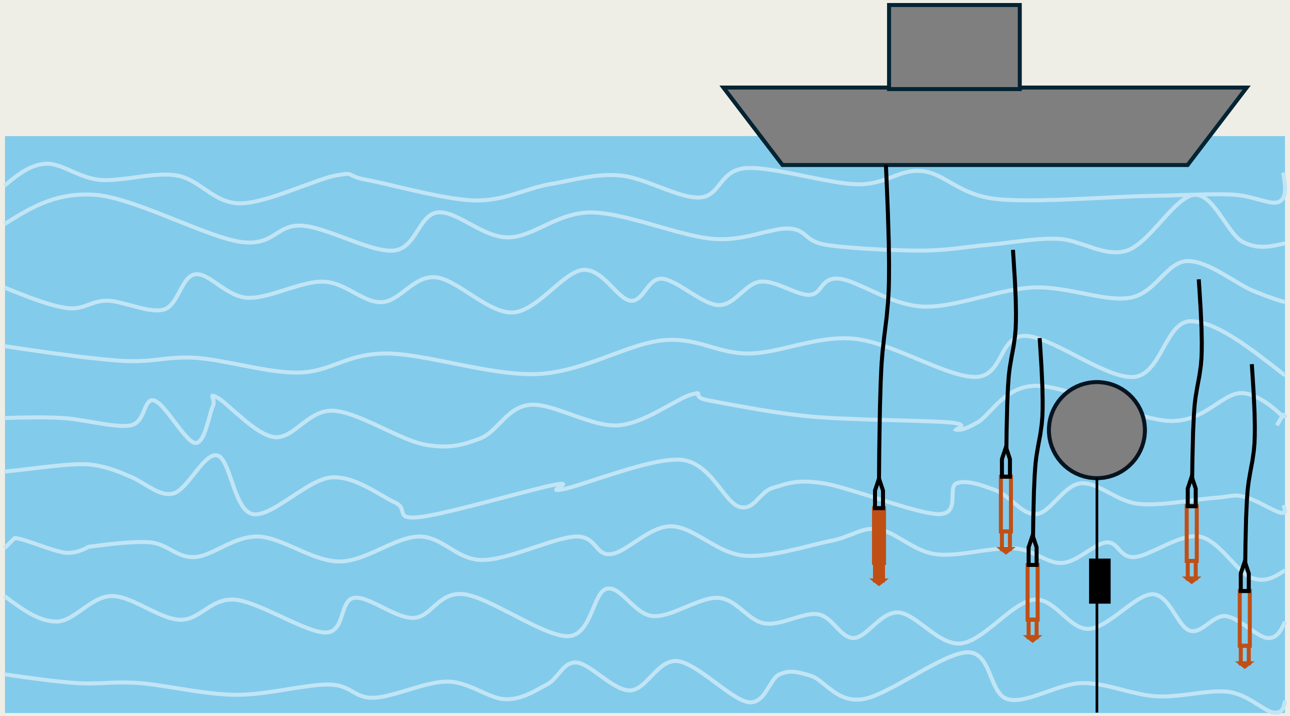
Ratio of voltages

$$|M_H| = \frac{U_H}{U_R} |M_R|$$

Co-located hydrophones are exposed to the same acoustic pressure. Using ambient noise in the ocean, a reference hydrophone near the unknown hydrophone could be used for in-situ calibration. How close is close enough?

Comparison: IEC 60565-2 (2019) 8.5, 10.4 Relative calibration





P. Harris et al., “Study of the in-situ calibration of hydroacoustic sensors,” NPL Report AC 24, National Physical Laboratory, Teddington, UK, Dec. 2023.
S. Crocker and R. Smalley, “System and Method for the Calibration of a Hydrophone Line Array in a Quasi-Diffuse Ambient Sound Field” U.S. Patent 11,209,571, Dec. 28, 2021.

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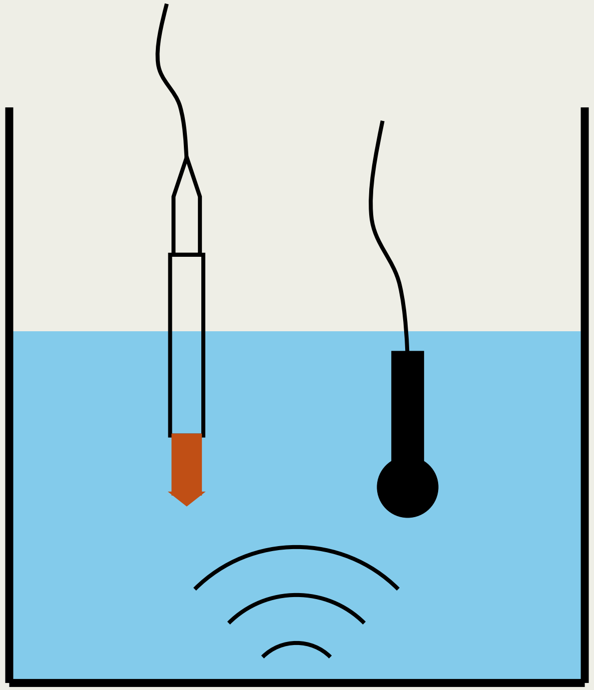
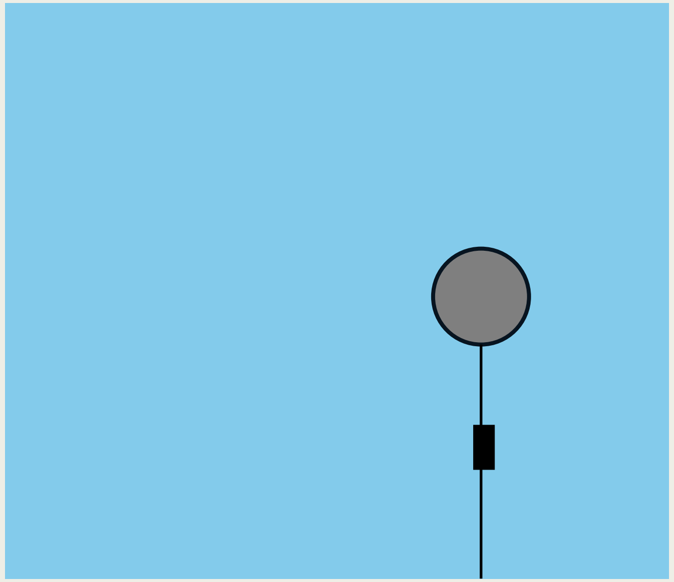
Reciprocity, in situ: IEC 60565-1 (2020) 8, with empirical reciprocity parameter J



Calibrate hydrophone in the laboratory



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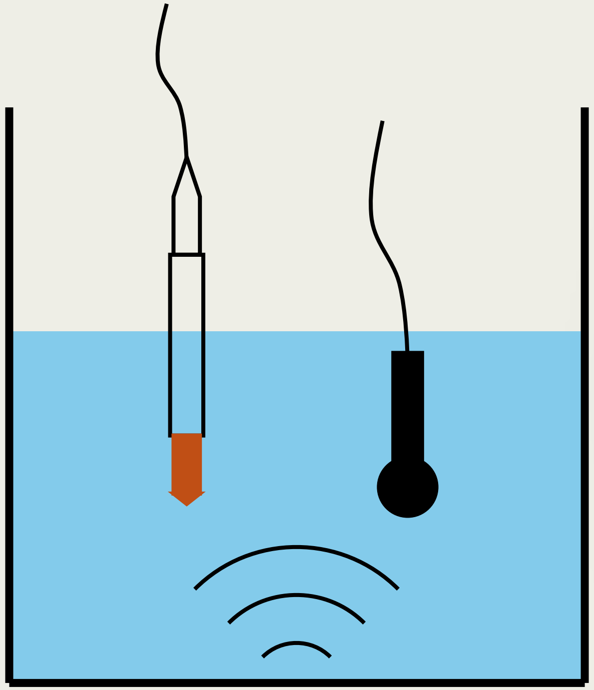
Reciprocity, in situ: IEC 60565-1 (2020) 8, with empirical reciprocity parameter J

$$J = \frac{M^2}{Z_3}$$



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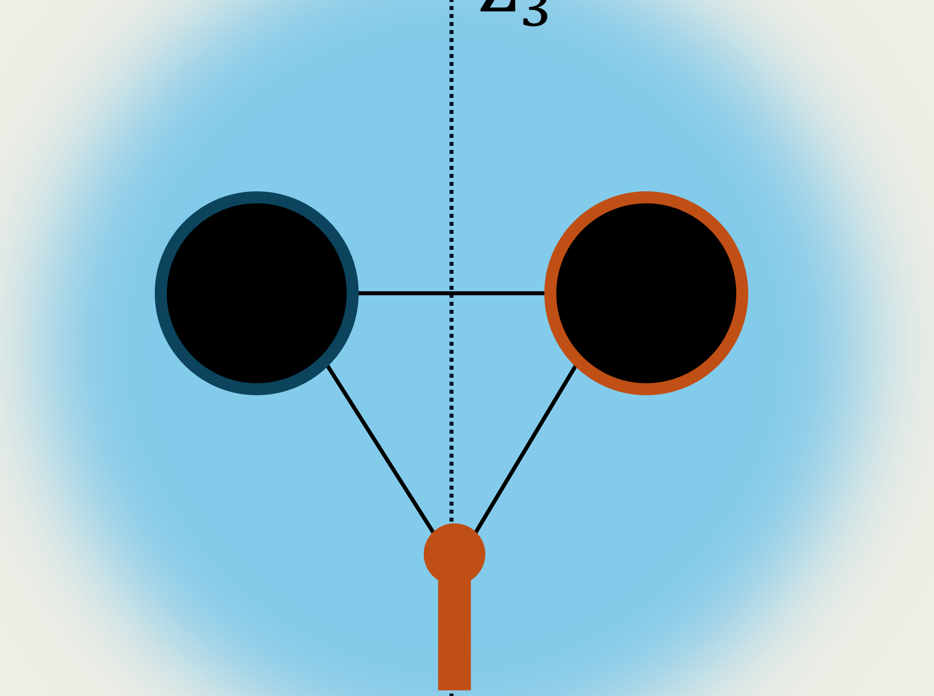
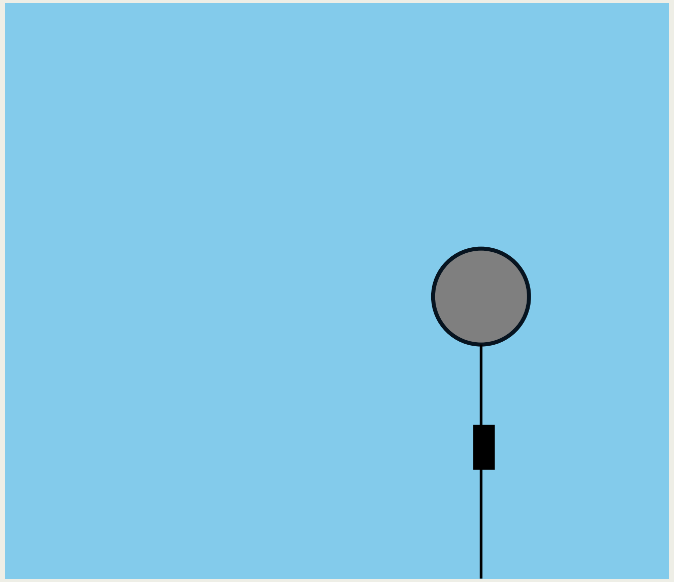


Build reciprocal assembly with calibrated hydrophone. Upon deployment, perform reciprocity calibration with known M, solve for



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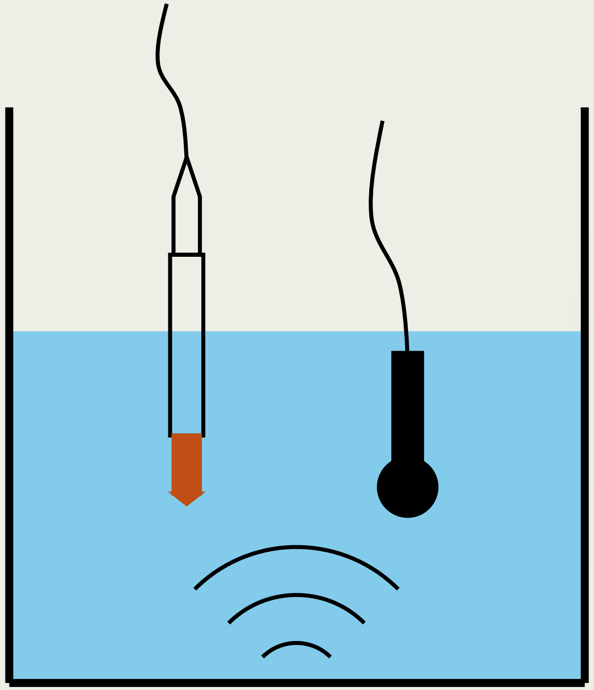
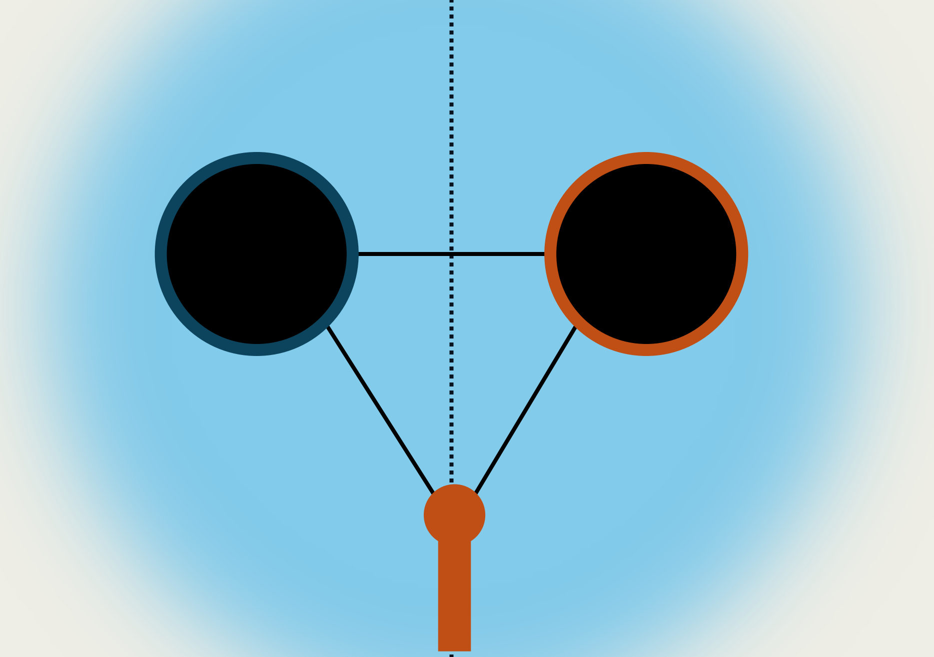
Reciprocity, in situ: IEC 60565-1 (2020) 8, with empirical reciprocity parameter J



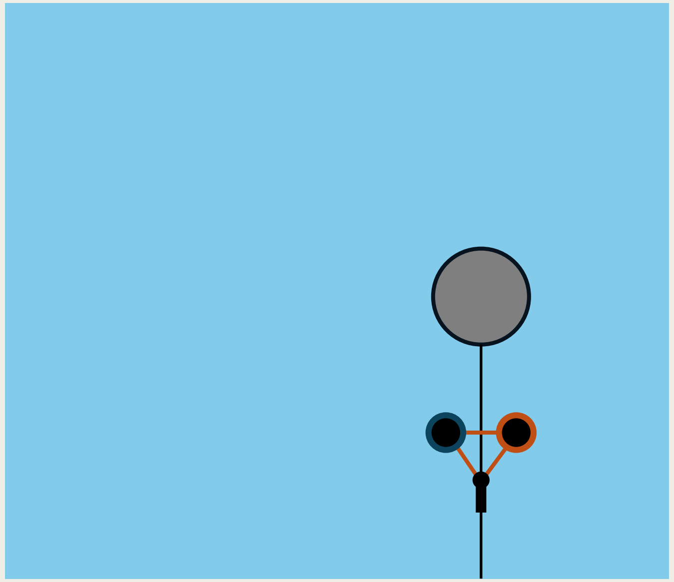
Calibrate hydrophone in the laboratory

$$J = \frac{M^2}{Z_3}$$



Build reciprocal assembly with calibrated hydrophone. Upon deployment, perform reciprocity calibration with known M, solve for

$$M = \sqrt{J Z_3}$$



Future reciprocity calibrations solve for M from previously measured J.

Calibration at the U.S. Navy Underwater Sound Reference Division (USRD) and considerations for in-situ calibration of hydrophones deployed at sea

William Slater

June 28, 1966 R. W. VANHOESEN ET AL 3,257,839

RECIPROCITY CALIBRATION OF LOW FREQUENCY RANGE RECORDING HYDROPHONES IN SITU

Filed Dec. 27, 1962 2 Sheets-Sheet 1

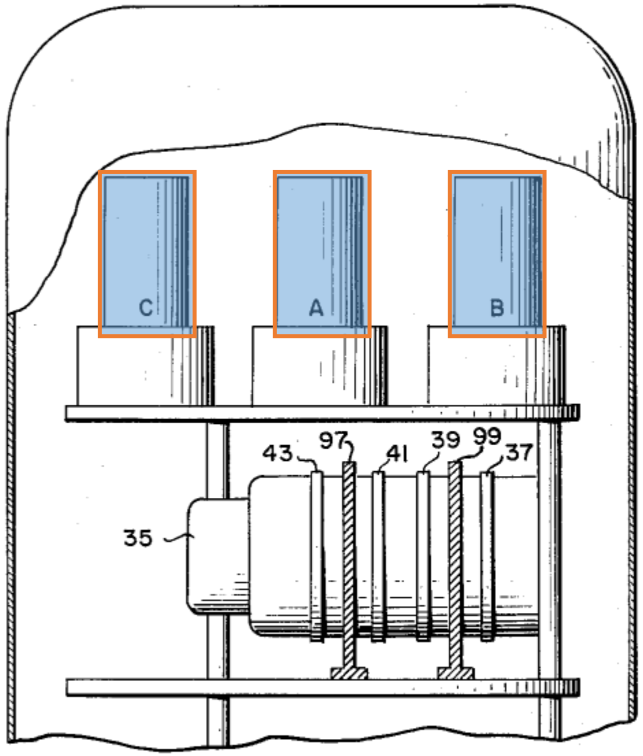
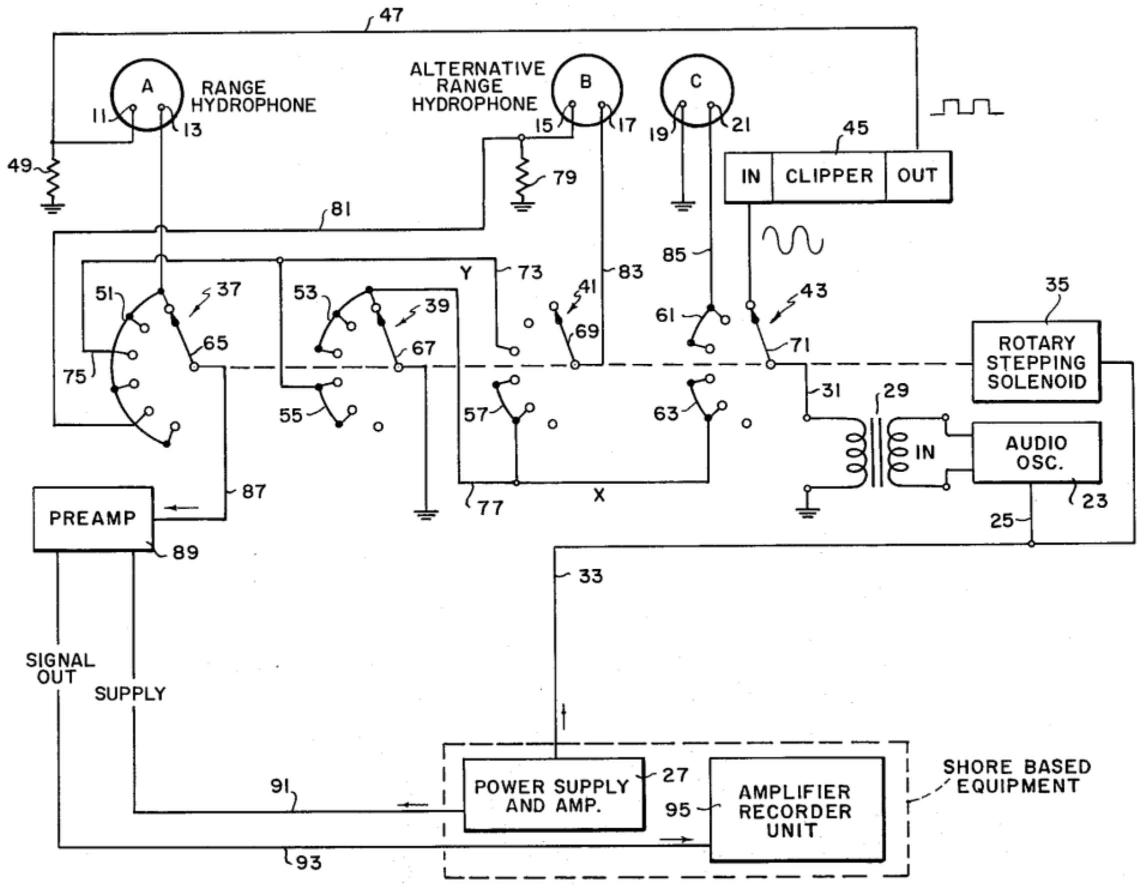


FIG. 3.

FIG. 2.



INVENTORS
RICHARD W. VANHOESEN, DECE. BY FRANCES R. VANHOESEN, ADMIN.
AND MARVIN S. WEINSTEIN.
BY
AGENT.

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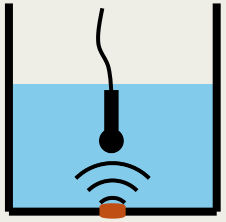
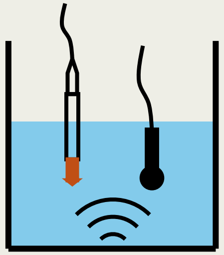
Additional Uncertainty



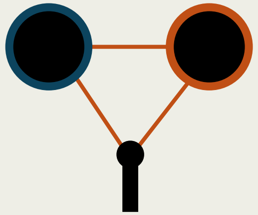
IEC 60565 uncertainty sources made more difficult:

separation distance measurement, transmission loss, isolating direct path signals



New sources of uncertainty, characterizable through statistics:

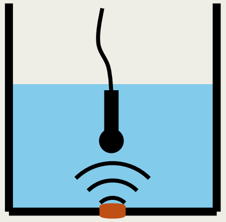
How close must the unknown and reference hydrophone be? What if an array of references are used?



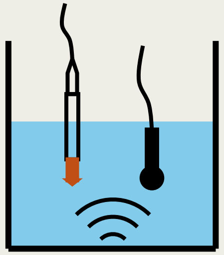
Design and characterization of a new device:

How stable are the in-situ boundary conditions and what transducers could support such a calibration?

References



- P. Harben and A. Rodgers, "Calibration of Hydrophone Stations: Lessons Learned from the Ascension Island Experiment", Proceedings of the 22nd Annual DoD/DoE Seismic Research Symposium, New Orleans, Louisiana, Sep. 2000.
- S. Crocker et al., "Geoacoustic inversion of ship radiated noise in shallow water using data from a single hydrophone," J. Acoust. Soc. Am., Vol. 136, 2014, doi: 10.1121/1.4898739.



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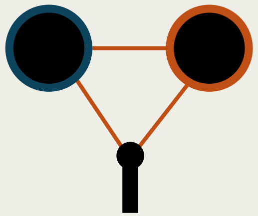

- R. Bobber, "General Reciprocity Parameter," J. Acoust. Soc. Am., Vol. 39, No. 4, pp. 680-687, 1966.
- R. Van Hoesen and M. Weinstein, "Reciprocity Calibration of Low Frequency Range Recording Hydrophones In Situ," U.S. Patent 3,257,839, Jun. 28, 1966.

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Backup

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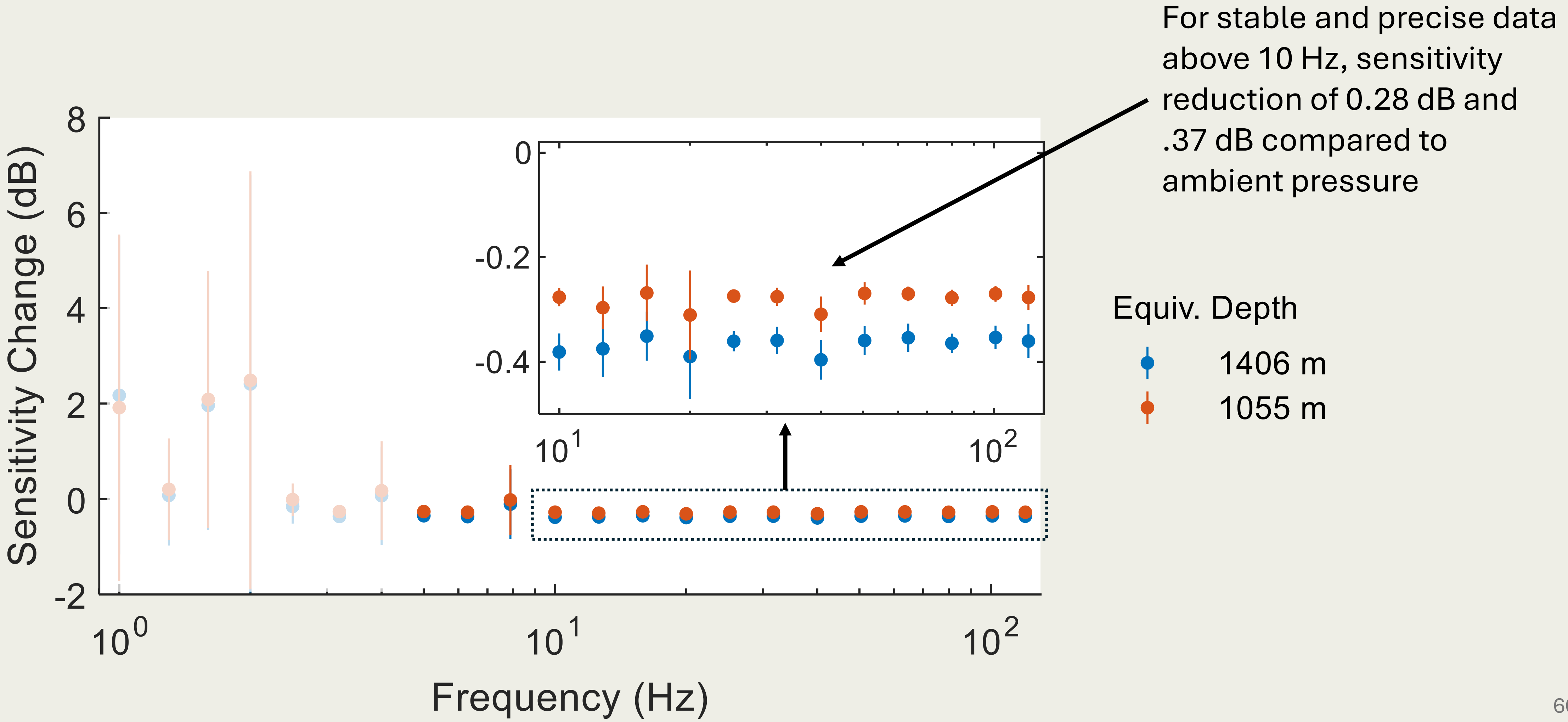
Mean sensitivity change from ambient to pressure at depth from calibrations of seven IMS Hydrophones in 2016



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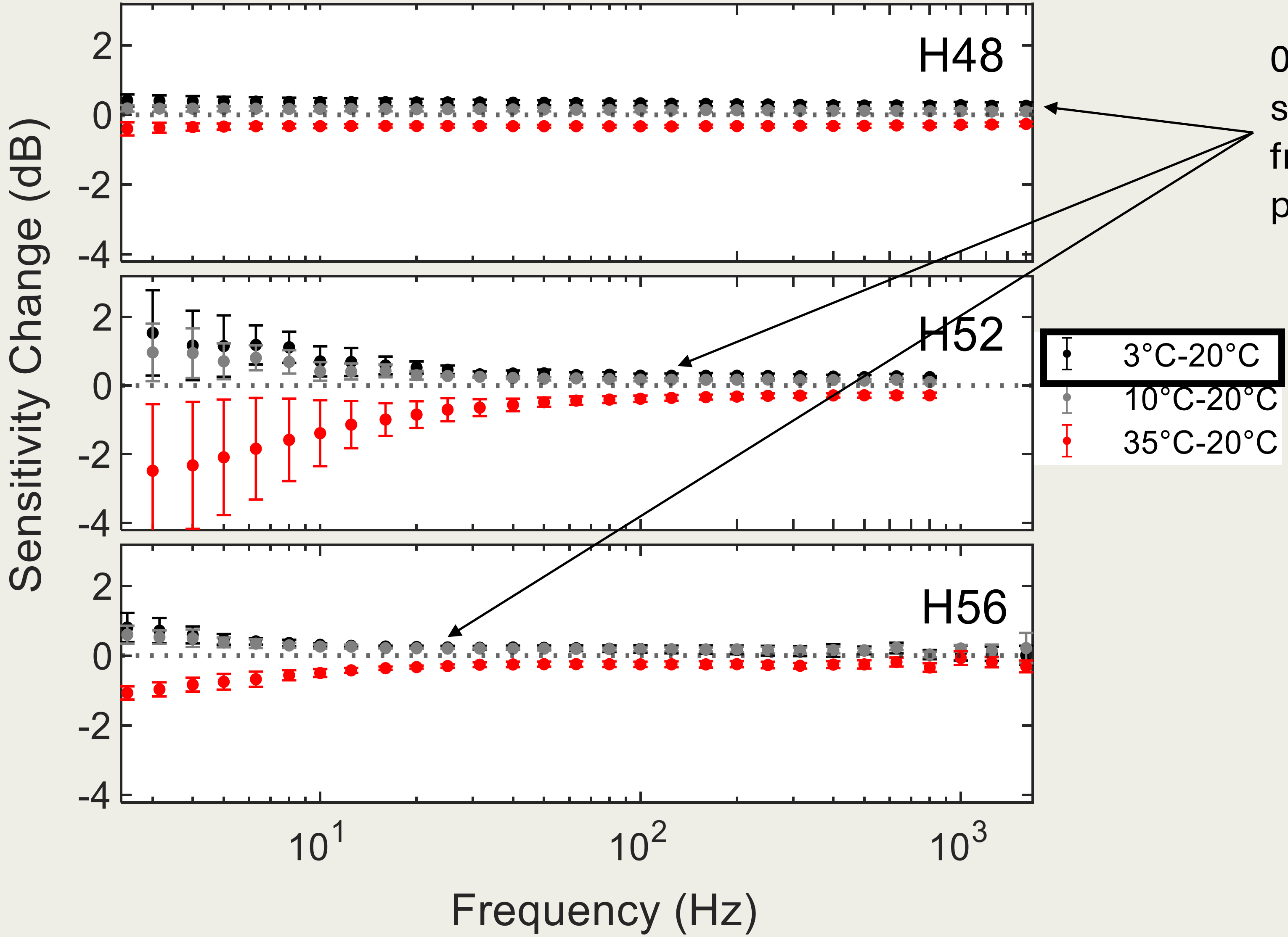
Sensitivity Change With Temperature For a population of USRD Type H48, H52, and H56 hydrophones



0.25 dB to 0.35 dB increase in sensitivity between 20°C to 3°C at frequencies above the preamplifier roll off regions.