NUWC-NPT Technical Report 12,320
26 June 2019

Underwater Sound Reference Division (USRD) Annual Report: 2018

Steven E. Crocker
Benjamin W. Lee
Victor M. Evora
Sensors and Sonar Systems Department

NAVSEA
WARFARE CENTERS
NEWPORT

Naval Undersea Warfare Center Division Newport, Rhode Island

PREFACE

This report was prepared under Project No. SS1517, "Acoustic Facilities and Standards," principal investigator Steven E. Crocker (Code 1531). The sponsoring activity is the Underwater Sound Reference Division (Code 1531).

The technical reviewer for this report was Michael J. Obara (Code 15E).

Reviewed and Approved: 26 June 2019

Joseph F. Sheltry
Head, Sensors and Sonar Systems Department

REPORT DOCUMENTATION PAGE	*Form Approved OMB No. 0704-0188*

1. REPORT DATE (*DD-MM-YYYY*)	**2. REPORT TYPE**	**3. DATES COVERED** (*From – To*)
26-06-2019	Technical	01-01-2018 to 12-31-2018

4. TITLE AND SUBTITLE Underwater Sound Reference Division (USRD) Annual Report: 2018	**5a. CONTRACT NUMBER** **5b. GRANT NUMBER** **5c. PROGRAM ELEMENT NUMBER**
6. AUTHOR(S) Steven E. Crocker Benjamin W. Lee Victor M. Evora	**5.d PROJECT NUMBER** **5e. TASK NUMBER** **5f. WORK UNIT NUMBER**
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Undersea Warfare Center Division 1176 Howell Street Newport, RI 02841-1708	**8. PERFORMING ORGANIZATION REPORT NUMBER** TR 12,320
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Naval Undersea Warfare Center Division Underwater Sound Reference Division 1176 Howell Street Newport, RI 02841-1708	**10. SPONSORING/MONITOR'S ACRONYM** NUWCDIVNPT USRD **11. SPONSORING/MONITORING REPORT NUMBER**

12. DISTRIBUTION/AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Underwater Sound Reference Division (USRD) at the Naval Undersea Warfare Center Division Newport (NUWCDIVNPT) provides underwater acoustic measurement and calibration services to a diverse client base including other government laboratories, nongovernmental organizations, industry, and academia. Services provided by the laboratory are accredited per ISO 17025:2005 for the competence of testing and calibration laboratories. In addition, the National Institute for Standards and Technology (NIST) is coordinating with the USRD to appoint it as the U.S. designated institute (DI) for sound in water. Once designated, the USRD will provide traceability to the International System of Units (SI) through its measurement and calibration services for underwater acoustic measurements. Among its responsibilities as an accredited laboratory and (prospective) U.S. DI for sound in water, the USRD engages in a variety of activities related to its quality management system (QMS) and claimed measurement capabilities. Among these are internal audits, operator training, proficiency testing and other activities intended to maintain the laboratory's competence and to consistently deliver measurement and calibration services with known measurement uncertainties. This document is a report summarizing activities of the USRD related to its quality system and measurement capabilities throughout 2018 followed by a summary of activities planned for 2019.

15. SUBJECT TERMS

ISO 17025, quality management system, underwater acoustic metrology, acoustic transducer calibration

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			Steven E. Crocker
(U)	(U)	(U)	SAR	69	**19b. TELEPHONE NUMBER** *(Include area code)* (401) 832-6131

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LIST OF ABBREVIATIONS AND ACRONYMS

ADLP	Associate Director of Laboratory Programs
ANSI	American National Standards Institute
APTF	Acoustic Pressure Tank Facility
ARB	Assessment Review Board
ASA	Acoustical Society of America
ASTM	American Society for Testing and Materials
AUV	Acoustics, Ultrasound, and Vibration
BIPM	International Bureau of Weights and Measures
BC	Bilateral Comparison
CCAUV	Consultative Committee for Acoustics, Ultrasound and Vibration
CIPM	International Committee of Weights and Measures
CMC	Calibration and Measurement Capability
CPAR	Corrective and Preventive Action Request
CRV	Comparison Reference Value
DI	Designated Institute
DoE	Degree of Equivalence
EMI	Electromagnetic Interference

LIST OF ABBREVIATIONS AND ACRONYMS (Cont'd)

IEC	International Electrotechnical Commission
ISO	International Organization for Standardization
KC	Key Comparison
LCP	Local Calibration Procedure
LEFAC	Leesburg Facility
LOFAC	Low-Frequency Facility
METCAL	Metrology and Calibration
MoU	Memorandum of Understanding
MC	Multilateral Comparison
MEMS	Micro-Electro-Mechanical System
MRA	Mutual Recognition Arrangement
NIST	National Institute of Standards and Technology
NMI	National Metrology Institute
NPL	National Physical Laboratory
NUWCDIVNPT	Naval Undersea Warfare Center Division Newport
NVLAP	National Voluntary Laboratory Accreditation Program
OTF	Open Tank Facility
QMP	Quality Management Procedure
QMS	Quality Management System
RMO	Regional Metrology Organization
RVS	Receive Voltage Sensitivity
SI	International System of Units
SIM	Inter-American Metrology System
SN	Serial Number
TAG	Technical Advisory Group
TVR	Transmit Voltage Response
THAMES V2	Transducer and Hydrophone Acoustic Measurements and Evaluation System Version 2
UK	United Kingdom
USRD	Underwater Sound Reference Division
WG15	Work Group 15

LIST OF MATHEMATICAL SYMBOLS AND UNITS

A	Design matrix
α	Sample drawn from a multivariate Gaussian distribution
d	Degree of equivalence
dB	Decibel
δ	Uncertainty component arising from a random effect
Hz	Hertz
kHz	Kilohertz
λ	Uncertainty component arising from a systematic effect
m, m	Meter or index enumerating laboratories
M	Maximum value of index m enumerating laboratories
MHz	Megahertz
n	Index enumerating acoustic devices
N	Maximum value of index n enumerating acoustic devices
Pa	Pascal
r	Relative degree of equivalence
V	Covariance matrix
μPa	Micropascal
u	Standard uncertainty
w	Weight used to compute weighted mean y
x	Measured value
y	Weighted mean of measured values x having weights w

UNDERWATER SOUND REFERENCE DIVISION (USRD) ANNUAL REPORT: 2018

1. INTRODUCTION

The Underwater Sound Reference Division (USRD) at the Naval Undersea Warfare Center Division Newport (NUWCDIVNPT) provides underwater acoustic measurement and calibration services to other government laboratories, industry, and academia in the United States. As such, the laboratory functions as the U.S. standardizing activity for sound in water by providing the framework for a system of measurement that is traceable to primary reference standards realized and maintained by the USRD.

Certain laboratory facilities and calibration services provided by the USRD are accredited under ISO 17025:2005 (reference 1) by the National Voluntary Laboratory Accreditation Program (NVLAP) (reference 2), including acoustic measurements performed in the Open Tank Facility (OTF) and the Low Frequency Facility (LOFAC) standing wave tube (System K). Expansion of the laboratory's scope of accreditation to include calibration services provided by the USRD Acoustic Pressure Tank Facility (APTF) is planned during periodic assessment in 2019.

To maintain its accreditation, the USRD operates a quality management system (QMS) that conforms to the requirements of ISO 17025:2005. The USRD QMS includes requirements that specify processes and procedures for a wide variety of activities including internal audits, management reviews, and proficiency testing, to name a few. The USRD is also required to issue periodic reports on these activities and to make such reports available to the NVLAP. The USRD has similar reporting requirements as the National Institute of Standards and Technology (NIST) (prospective) designated institute (DI) for sound in water including dissemination of an annual report to the Inter-American Metrology System (SIM), the regional metrology organization (RMO) for the Americas.

The purpose of this document is to report significant activities carried out by the USRD in 2018 and those planned for 2019 thus satisfying certain requirements specified by ISO 17025:2005 and others related to its role at the U.S. (prospective) DI for sound in water.

2. SIGNIFICANT ACTIVITIES 2018

2.1 QUALITY SYSTEM

The most significant quality related events of 2018 included initial NVLAP assessment of the laboratory, accreditation of the laboratory per ISO 17025:2005, and an onsite peer-review of the laboratory performed by NIST in preparation for appointment of USRD as the U.S. DI for sound in water.

2.1.1 ISO 17025:2005 Accreditation

In November 2017, the USRD applied to NVLAP for the assessment needed to accredit the laboratory in accordance with ISO 17025:2005. The objective of the accreditation was for the laboratory to demonstrate that it operates a quality system that satisfies the requirements of ISO 17025. The onsite assessment, conducted on March 5-6, 2018, resulted in 11 nonconformities and 19 comments, details of which are described in the report issued by the NVLAP assessors (reference 3) at the conclusion of the visit. Nonconformities observed during the assessment were corrected over the period from March to June 2018.

Several nonconformities resulted from a lack of traceability for calibrations performed by the USRD. While USRD general purpose test equipment was maintained in accordance with the Navy Metrology and Calibration (METCAL) program and policies, performing laboratories within the Navy's METCAL system are not generally accredited under ISO 17025, thus do not provide traceability to the International System of Units (SI). As a result, the USRD was required to identify and implement a process by which traceability to the SI could be established, while also maintaining compliance with Navy METCAL program requirements.

The USRD and local METCAL laboratory developed a process to attain traceable calibrations of USRD test equipment while simultaneously satisfying the requirements of the Navy METCAL program. In short, the local METCAL laboratory continues to manage and track the calibration status of all USRD general-purpose test equipment. However, equipment through which the traceability of USRD measurements is established is identified and sent to third-party calibration laboratories having the necessary accreditation and scope. These third-party calibrations are accepted as satisfying Navy METCAL policies and returned to the USRD with the certificates issued by the performing laboratories. The USRD metrologist also reviews and approves the performing laboratory's calibration certificates to ensure evidence sufficient to establish traceability to the SI is provided. This process was developed, implemented, and used to acquire traceable calibrations of USRD test equipment, resulting in closure of this nonconformity in June 2018.

Other nonconformities identified during the initial NVLAP assessment consisted of largely administrative issues that were corrected within 30 days following the onsite assessment.

After successfully addressing nonconformities identified during the initial NVLAP assessment, the USRD accreditation was issued in July 2018. In October 2018, the accreditation scope was expanded to provide coverage for increased measurands and frequency ranges for services where data to support the claimed measurement capabilities were initially lacking.

At the conclusion of 2018, the USRD scope of accreditation included the following calibration services:

1. Primary calibration of hydrophones from 3 Hz to 2 kHz–Coupler Reciprocity.
2. Primary calibration of hydrophones from 1 kHz to 2 MHz–Free-Field Reciprocity.
3. Secondary calibration of hydrophones from 3 Hz to 1.6 kHz–Standing Wave Tube.
4. Secondary calibration of hydrophones from 1 kHz to 2 MHz–Free-Field Comparison.
5. Measurement of hydrophone normalized angular response from 1 kHz to 2 MHz.
6. Measurement of projector normalized angular response from 1 kHz to 2 MHz.
7. Measurement of projector transmitting voltage response from 1 kHz to 2 MHz.
8. Measurement of projector transmitting current response from 1 kHz to 2 MHz.

2.1.2 NIST Peer Review

The USRD and NIST are working toward appointment of the USRD as the U.S. DI for sound in water. The act of designation will formally identify USRD as the U.S. institution that maintains and disseminates national measurement standards for sound in water. Among the responsibilities to be assumed by the Navy are to participate in the activities of the International Committee for Weights and Measures, Mutual Recognition Arrangement (CIPM MRA) and to comply with its requirements. The USRD will also be responsible for "establishing and maintaining calibration and measurement capabilities…in the Bureau International des Poids et Mesures (BIPM) Key Comparison Database" (reference 4).

These responsibilities represent long-term commitments on the part of the USRD to continuously operate a vital quality management system, demonstrate technical competency, and participate in the work of international metrology organizations, including the SIM, the RMO comprised of the National Metrology Institute (NMI), and DI of 27 nations in the Americas.

Prior to designation, the USRD was required to attain accreditation under ISO 17025:2005 and to successfully complete an onsite peer review by NIST, which occurred on 25-26 October 2018. The conduct of the review was similar in content to the NVLAP assessment, but it was conducted by an Assessment Review Board (ARB) comprised of the agency's quality manager and two scientists from different NIST laboratory programs. The NIST ARB identified seven nonconformities and three comments related to the quality system and measurement capabilities of the USRD. The most significant nonconformity was the lack of sufficient internal audit activities leading up to the peer review. This and all other nonconformities were resolved by USRD within 30 days of the review and closed by the ARB in early December 2018. (reference 5)

At year's end, the USRD had successfully demonstrated that it operated a vital QMS and possessed the claimed measurement capabilities. Activities remaining to be completed prior to formal appointment of USRD as the U.S. DI for sound in water included review and approval of the designation by the NIST Associate Director for Laboratory Programs (ADLP), publication of a notice in the Federal Register, and execution of a memorandum of understanding (MOU) between the Department of the Navy (NUWCDIVNPT) and the Department of Commerce (NIST) (reference 4).

2.1.3 Internal Audits and Reviews

The USRD performed an internal audit of its quality system on 26-28 November 2018. The audit was conducted by personnel assigned to NUWCDIVNPT headquarters (Code 00Q) with extensive experience in quality systems. Neither auditor was administratively assigned to the USRD, thus ensuring the objectivity of the audit results. The internal audit was focused on quality related activities of the USRD since its previous internal audit conducted in 2017.

The audit results did not include any nonconformities or noncompliance. The auditors did identify three operational improvements for USRD to consider. The areas where improvements were suggested were personnel training, incorporating elements of the NUWCDIVNPT QMS such as quality management procedures (QMP) into the USRD quality system, and improvements to the USRD Corrective and Preventive Action Request (CPAR) process. While none of these improvements were incorporated in 2018, they will be taken into consideration during revision of the USRD quality system in 2019 in conjunction with changes needed for compliance with ISO 17025:2017.

2.1.4 Corrective and Preventive Actions

The USRD maintains an active program for the identification and resolution of CPARs. Twelve new CPARs were opened in 2018, eight of which were created during the NVLAP assessment, two were opened in response to customer feedback, and two were identified by USRD personnel during normal operations (see appendix A, table A-1). All of the CPARs opened in 2018 were resolved and closed before the end of the year.

The CPARs generated in response to customer feedback (i.e., 0019 and 0020) both related to calibrations performed in the LOFAC. In one case (CPAR 0019), USRD received customer feedback that calibrations performed in two different facilities (one of which was LOFAC) over a range of hydrostatic pressure and temperature did not appear to be consistent. A root-cause investigation identified a lack of technical proficiency for certain members of the LOFAC engineering staff. The CPAR was resolved through personnel reassignments, additional training, and increased surveillance of work performed in this laboratory. In addition, once the laboratory's operations were restored, the affected devices were calibrated again without charge to the customer.

The second CPAR resulting from customer feedback (CPAR 0020) was generated when an excessive level of 60-Hz line noise was affecting the low-frequency calibration result. While checks of grounding and shielding in the LOFAC did not identify a root cause for the line noise that was attributable to the laboratory's equipment, it was found that susceptibility of the device to 60-Hz line noise was somewhat reduced in one of the laboratory's (unaccredited) traveling wave tube measurement systems. In addition to providing calibration services in the customer's preferred measurement system, the USRD provided suggestions to reduce susceptibility of the customer's device to 60-Hz line noise. The recommended design changes were incorporated by the customer resulting in a significant reduction in the susceptibility of the customer's device.

Appendix A, table A-2 summarizes results for 19 CPARs that were closed during 2018. In addition to closing all CPARs that were opened in 2018, seven CPARs opened in 2017 were also closed. None of the CPARs opened in 2017 were the result of customer feedback. Instead, all were related to internal audits and other quality activities as the USRD adopted its quality system and prepared for its initial NVLAP assessment.

2.1.5 Personnel Training and Qualifications

The USRD established policies and procedures for the training and qualification of laboratory personnel for OTF and LOFAC. The objective of the training program is to formalize the requirements to be satisfied before an operator is authorized to perform a given calibration service without supervision. The USRD manager maintains measurement personnel records to include satisfaction of training requirements and qualified operator lists.

The training requirements are defined for each of the calibration services listed within the scope of the laboratory's accreditation. For example, the training required for qualification to perform unsupervised calibrations includes:

- Objectives of the training curriculum, including specific procedure.
- Required reading:
    - Quality Management System (i.e., QM-USRD-001 Quality Manual).
    - Theory (e.g., relevant texts and methods such as International Electrotechnical Commission (IEC) 60565 (reference 6)).
    - Practice (e.g., system operators manual and local calibration procedure).
- On-the-job training (e.g., minimum time in training and number of calibrations).
- Practical examination (e.g., specified calibrations and crane operator certification).

In addition to initial qualification of laboratory personnel, continued proficiency is monitored by the performance of laboratory spot checks and through the execution of an annual proficiency testing program (see section 2.2.4). Thus, the USRD QMS includes policies and procedures to periodically verify that each laboratory and its assigned personnel are capable of delivering the claimed measurement capabilities within the uncertainties published in the laboratory's scope.

2.2 METROLOGY AND CALIBRATION SERVICES

2.2.1 Laboratory Workload Summary

The USRD began issuing ISO 17025:2005 compliant calibration certificates following its accreditation in July 2018, issuing 63 certificates between July and December. The vast majority of these certificates were issued for calibrations of 14 different transducer models that were shipped to U.S. customers as part of the USRD transducer standards leasing program. It is anticipated the volume of accredited calibrations will increase significantly in the coming years as demand for calibrations of customer-owned transducers increases, and the laboratory's scope continues to expand to include calibrations performed with other measurement systems such as the APTF and the low-frequency traveling wave tubes.

2.2.2 Laboratory Upgrades and Improvements

There were no major improvements to USRD laboratory facilities in 2018, although planning for future upgrades did occur. The most significant planning effort addressed work to support expansion of accredited calibration services at low frequency to include two traveling wave tubes operated by the LOFAC (reference 7). At present, only the LOFAC standing wave tube is accredited to perform hydrophone calibrations at frequencies ranging from 3 Hz to 1600 Hz. Addition of the traveling wave tubes to the laboratory's scope will increase the maximum hydrostatic pressure for low-frequency calibrations from 13.8 MPa to 68.9 MPa, or equivalent ocean depths of 1.39 km to 6.92 km. In addition to increasing the environmental conditions for the accredited calibration services, the traveling wave tubes provide calibration services using a plane-progressive acoustic wave field for measurement of hydrophone response as opposed to the standing wave field currently employed.

Planning for an upgrade to, or replacement of, the reciprocity coupler used to perform primary calibration of the laboratory's Type H48 reference measuring hydrophones was also begun. Objectives of that effort include measurement of complex sensitivity (reference 8), operation at frequencies less than 3 Hz, uncertainty reduction, and general improvements to workflow efficiency.

The USRD has recently added an experienced engineer (and Ph.D. candidate) to its technical staff to lead these upgrades. In addition to improving the laboratory's measurement capabilities, the associated research and development will be performed as partial fulfillment of the academic requirements for the Ph.D. degree in ocean engineering at the University of Rhode Island.

2.2.3 Uncertainty Statements

Uncertainty statements for calibration services within the laboratory's scope of accreditation were developed, reviewed, and approved during the NVLAP assessment and NIST peer review conducted in March and November, respectively (references 3, 5). They provide detailed descriptions of the individual uncertainty components upon which measurement uncertainties published by the NVLAP in the USRD scope of accreditation were derived as specified in references 9 and 10. Complete statements of measurement uncertainty for the calibration services listed in section 2.1.1 constitute a set of controlled documents that are maintained in accordance with the USRD quality system. A summary of the uncertainty statements for the OTF and the LOFAC are provided in appendix B as tables B-1 and B-2, respectively.

A new uncertainty study was begun in 2018 for calibrations performed in the APTF. Calibration services covered by the study included primary and secondary calibration of hydrophones, transmitting voltage response of projectors, and transmitting current response of projectors over a frequency range of 1 kHz to 250 kHz in a variety of ocean environments (i.e., hydrostatic pressure and temperature). The study was conducted to support the addition of calibration services provided by the APTF to the laboratory's scope during periodic assessment by the NVLAP scheduled for late 2019. The uncertainty statements were also used during intercomparisons performed as part of the 2018 proficiency testing program in which the APTF was a participant. A summary of the APTF uncertainty statements is provided in appendix B as table B-3.

2.2.4 Proficiency Testing

The USRD operates a proficiency testing program that is modeled on the key comparisons (KC) performed by the Consultative Committee for Acoustics, Ultrasound, and Vibration (CCAUV). The program employs a series of intercomparisons between and among a set of participating laboratories. While all of the laboratories included in the 2018 program were associated with the USRD, it is anticipated the scope of the program will expand to include other Navy laboratories and eventually include non-Navy laboratories as well.

The objectives of the proficiency testing program are to 1) establish the equivalence of underwater acoustic calibrations and measurements performed by the participating laboratories, and 2) identify root causes and corrective actions in cases where that equivalence cannot be demonstrated through intercomparisons.

2.2.4.1 Proficiency Testing Program Plan. The 2018 proficiency testing program included a series of calibrations among USRD laboratories including the LOFAC, OTF, APTF, and LEFAC. The calibrations performed are listed in table 1 and include the dates, transducers, methods, frequency ranges, and environmental parameters that were applicable to each transducer calibration. The resulting calibration data and uncertainty estimates were analyzed to yield a set of bilateral and multilateral comparisons between and among the participants. The bilateral comparisons were performed between a laboratory accredited in accordance with ISO 17025:2005 (i.e., LOFAC and OTF) and a laboratory for which accreditation will be sought in the future (i.e., APTF and LEFAC). Multilateral comparisons were performed among all of the laboratories that perform calibrations in an acoustic free-field (i.e., OTF, APTF, and LEFAC).

Seventeen separate calibrations were performed using five different transducer standards in four laboratories as inspection of table 1 shows. The data were grouped and analyzed to yield six bilateral comparisons (see table 2) and two multilateral comparisons (see table 3) using statistical methods that were consistent with those employed in a prior CCAUV key comparison (references 11, 12), details of which are described in appendix C. In particular, the comparisons were arranged and calibration data were processed to yield a combined, relative degree of equivalence (DoE) for each laboratory and calibration service, evaluated at preferred one-third octave band center frequencies (reference 13).

Table 1. Laboratory Intercomparison Calibrations

		Transducer		Calibration		Frequency		Environment	
Facility	Date Complete	Type	Serial Number	Measurand	Method	Min (kHz)	Max (kHz)	Temp. (°C)	Pres. (kPa)
OTF [1]	08/27/18	H52	84	RVS [2]	Secondary	1	200	20	101
	08/27/18	H56	125	RVS	Secondary	1	80	20	101
	08/27/18	F37	A117	RVS	Secondary	1	50	20	101
	08/27/18	F37	A117	TVR [3]	Secondary	1	50	20	101
	09/05/18	H52	80	RVS	Primary	1	250	20	101
	09/05/18	F42D	145	RVS	Primary	1	250	20	101
LOFAC [1]	10/09/18	H52	84	RVS	Secondary	0.003	1.6	20	345
	10/09/18	H56	125	RVS	Secondary	0.003	1.6	20	345
	10/09/18	F37	A117	RVS	Secondary	0.003	1.6	20	345
APTF	05/07/18	H52	80	RVS	Primary	1	250	18	101
	05/07/18	F42D	145	RVS	Primary	1	250	18	101
	11/23/18	F37	A117	RVS	Secondary	1	50	20	101
	11/23/18	F37	A117	TVR	Secondary	1	50	20	101
LEFAC	10/01/18	H52	84	RVS	Secondary	0.02	100	22	243
	10/01/18	H56	125	RVS	Secondary	0.02	80	22	243
	10/01/18	F37	A117	RVS	Secondary	0.02	50	22	243
	10/01/18	F37	A117	TVR	Secondary	1	50	22	243

[1] ISO 17025:2005 accredited

[2] RVS – Receive voltage sensitivity (dB re 1V/uPa)

[3] TVR – Transmitting voltage response (dB re 1uPa·m/V)

Table 2. Bilateral Comparisons

OTF—APTF						
	Transducer		Calibration		Frequency (kHz)	
ID	Type	Ser. No.	Measurand	Method	Min	Max
BC-1	H52	80	RVS	Primary	1	250
	F42D	145	RVS	Primary	1	250
BC-2	F37	A117	RVS	Secondary	1	50
BC-3	F37	A117	TVR	Secondary	1	50

OTF—LEFAC						
	Transducer		Calibration		Frequency (kHz)	
ID	Type	Ser. No.	Measurand	Method	Min	Max
BC-4	H52	84	RVS	Secondary	1	100
	H56	125	RVS	Secondary	1	80
	F37	A117	RVS	Secondary	1	50
BC-5	F37	A117	TVR	Secondary	1	50

LOFAC—LEFAC						
	Transducer		Calibration		Frequency (kHz)	
ID	Type	Ser. No.	Measurand	Method	Min	Max
BC-6	H52	84	RVS	Secondary	0.02	1.6
	H56	125	RVS	Secondary	0.02	1.6
	F37	A117	RVS	Secondary	0.02	1.6

Table 3. Multilateral Comparisons

OTF—APTF—LEFAC						
	Transducer		Calibration		Frequency (kHz)	
ID	Type	Ser. No.	Measurand	Method	Min	Max
MC-1	F37	A117	RVS	Secondary	1	50
MC-2	F37	A117	TVR	Secondary	1	50

Arguably the most important comparison performed in 2018 was bilateral comparison 1 (see table 2, BC-1) conducted by the OTF and APTF for the primary calibration of hydrophones. The relative importance of this comparison derives from the fact that all other calibration services provided by the USRD rely on accurate and precise primary calibrations of the reference measuring hydrophones used in its laboratories and disseminated to U.S. customers. As inspection of table 2 shows, the comparison included two hydrophones (i.e., Type F42D and Type H52) with significantly different sensitivities that were calibrated over the frequency range of 1 kHz to 250 kHz. In order to condense the calibration data into a single concise metric, the evaluation was performed to yield a combined, relative DoE for each laboratory.

The generalized DoE of each participant is expressed quantitatively by two terms, 1) the deviation of the laboratory's calibration result from the comparison reference value (CRV), and 2) the uncertainty of this deviation at the 95% level of confidence. The CRV was determined as the weighted mean of the sensitivities measured by the participants where the weights were determined from the inverse of the measurement variances (and covariances) derived from the laboratory's uncertainty statements. Each laboratory's deviation was then normalized by the

CRV to yield a fractional deviation that would facilitate combining results of different devices to yield a single, combined DoE and to support its expression in decibels. Thus, the evaluation yields an average value of the degree of equivalence (and uncertainty) for each laboratory in decibels. Appendix B provides a detailed description of the statistical procedures used in the evaluation of comparisons involving one or more transducers calibrated by two or more laboratories.

2.2.4.2 Bilateral Comparisons Between OTF and APTF. Results of bilateral comparison 1 (BC-1) are shown in figure 1 The upper panels illustrate the sensitivities measured by each of the participants and the CRV calculated using those sensitivities and the respective uncertainty statements. The two lower panels summarize the comparison results as the degree of equivalence (markers) and uncertainty (error bars).

Figure 1c provides comparison results for the OTF where the DoE varied from -0.34 to 0.09 dB and the uncertainties ranged from 0.26 to 0.45 dB. Expressed this way, the ideal value of the DoE would be 0 dB, indicating the sensitivity measured by the laboratory was exactly equal to the comparison reference value (an event with vanishingly small probability). In the usual case where the DoE is not exactly zero, the result is considered satisfactory provided that the 95% confidence interval of the estimate spans zero. This is illustrated in the figure where the DoE error bars overlap the value of 0 dB, as was the case for all of the OTF measurements, except the measurement at 63 kHz (annotated with a red marker). In comparisons involving two or more laboratories, the calibrations are said to be equivalent when the 95% confidence interval for the estimated DoE includes 0 dB.

Figure 1d shows the comparison results for the APTF where the DoE varied from -0.11 to 0.68 dB and the uncertainties ranged from 0.30 to 0.61 dB. In this case, the result included three outliers (i.e., 63, 80 and 160 kHz). As inspection of the figure shows, uncertainties in the value of the DoE at the upper end of the frequency band were greater in the APTF than in the OTF, a direct consequence of the greater measurement uncertainties in this band for the APTF (reference 14). Nonetheless, the presence of multiple outliers in the APTF comparison result suggests the laboratory's uncertainty statements in this frequency band may have been underestimated and will be closely monitored in future comparisons.

The result of BC-1 was that primary calibrations performed by the OTF and APTF were equivalent over the frequency band of 1 to 50 kHz. Equivalence was not clearly established above 50 kHz where the comparison was not satisfactory in 3 out of 7 frequencies evaluated. Detailed results of the comparison are illustrated in appendix D (figures D-1 through D-4), and detailed in table D-1 where the CRVs, DoEs, and the associated uncertainties are all tabulated. Laboratories and frequencies for which the equivalence of the calibration results were not established are indicated in red.

Bilateral comparisons between the OTF and APTF for secondary calibrations of hydrophones (BC-2) and transmitting voltage response of projectors (BC-3) successfully established equivalence for the respective calibration services provided by the laboratories. Comparison results for secondary calibration of hydrophones are provided in appendix D (as figures D-5 through D-7, and table D-2. Comparison results for measurement of transmitting voltage response of projectors are provided in figures D-8 through D-10, and table D-3.

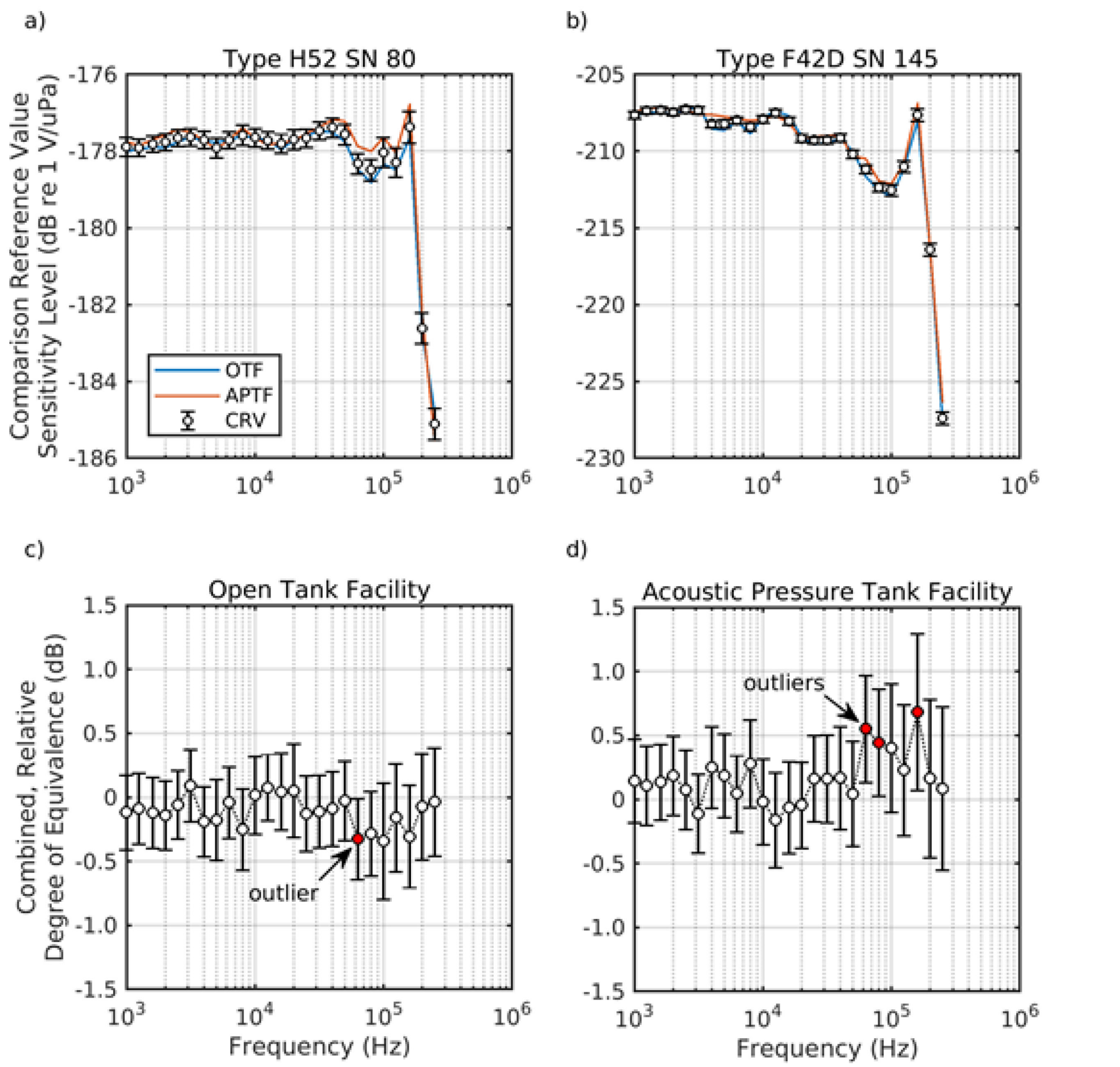

Figure 1. HLF-1D Transducer and Specifications

2.2.4.3 Bilateral Comparisons Between OTF and LEFAC. Bilateral comparisons between the OTF and LEFAC for secondary calibrations of hydrophones (BC-4) and transmitting voltage response of projectors (BC-5) were performed. However, these comparisons did not have the same level of engineering rigor as existed for comparisons between the OTF and APTF because a reliable uncertainty estimate for measurements performed by the LEFAC was not available. A rigorous uncertainty statement for the LEFAC was not produced because there are no immediate plans to seek ISO 17025 accreditation of this laboratory. As a result, USRD laboratories that provide accredited calibration services (i.e., OTF and LOFAC) have received the greatest attention, followed by the APTF for which accreditation will be requested during the 2019 NVLAP assessment.

The measurement system used at the LEFAC is not the Transducer and Hydrophone Acoustic Measurement and Evaluation System, Version 2 (THAMES V2) system used in other

USRD laboratories. As a result, the LEFAC measurement system lacks a rigorous analysis of uncertainty propagation for the electrical measurements required when calibrating underwater acoustic transducers. In addition, the more comprehensive studies needed to develop reliable measurement uncertainty estimates, to include evaluation of the Type A and Type B components, have not been conducted. Instead, these comparisons used an ad hoc uncertainty estimate where the Type A part was estimated as varying from 3% to 5% across a range of frequencies spanning 20 Hz to 100 kHz. Note that these values are significantly greater than the Type A uncertainty components (based on repeated measurements) for other USRD laboratories in part to allow for potential motion among the equipment deployed from the floating barge on which the laboratory resides. The Type B uncertainty component estimate was similar to other USRD laboratories. However, it had an additional allowance for uncertainty in distance measurements and an additional term to account for boundary reflections at low frequencies where it is not practicable to eliminate them using time-gated, tone bursts. Thus, the combined standard uncertainty included in the ad hoc estimate varied from 5.0% to 8.7% over the indicated frequency band. The LEFAC uncertainty estimates assumed for the purpose of these comparisons are summarized in appendix B (table B-4).

The bilateral comparison between the OTF and LEFAC for secondary calibrations of hydrophones (BC-4) was performed with favorable results. The DoE for both laboratories was consistent for all frequencies, albeit using an uncertainty estimate for the LEFAC that lacked the rigor employed for other USRD laboratories. Results of this comparison are illustrated in appendix D (figures D-11 through D-15), and detailed in table D-4.

The bilateral comparison between the OTF and LEFAC for measurement of transmitting voltage response (BC-5) showed a non-negligible departure from statistical equivalence for frequencies greater than 20 kHz as suggested by review of figure D-16, where the measurements of the two laboratories diverged. Inspection of figures D-17 and D-18 further illustrate the departure where the test for statistical equivalence between the two laboratories was not satisfied beyond 20 kHz. While it is generally not possible to attribute the lack of equivalence to a particular laboratory based solely on the results of a single bilateral comparison, the 2018 proficiency testing program included a variety of comparisons, some of which may shed light on the lack of equivalence observed in this case.

A bilateral comparison for projector transmit voltage response (TVR) was also performed between the OTF and APTF with satisfactory results (BC-3). Comparison of the CRV estimated during the two comparisons shows that both were well within the estimated uncertainties from 1 kHz to 20 kHz. Above this frequency, the CRV estimate for the OTF–LEFAC comparison decreased relative to the OTF–APTF comparison, reaching a maximum difference of 1.77 dB at 40 kHz, a direct result of the lower TVR measured by the LEFAC (see figure D-16). This suggests the observed lack of equivalence was attributable to the LEFAC, as opposed to the OTF, which had previously demonstrated equivalence with the APTF for the same measurement. A similar result was observed during a multilateral comparison among the OTF–APTF–LEFAC using the same calibration data as discussed in this section.

2.2.4.4 Bilateral Comparison Between LOFAC and LEFAC. A bilateral comparison was performed between the OTF and LEFAC for secondary calibrations of hydrophones (BC-6). The comparison employed three different devices and was completed with favorable results. Note that the CRV was generally weighted more heavily toward the LOFAC data because of its low measurement uncertainty relative to the ad hoc estimate assembled to facilitate participation of the LEFAC in the proficiency testing program. For example, inspection of figure D-19 for calibrations of a Type H52 hydrophone shows the CRV closely tracked the LOFAC data, while the LEFAC measurements showed non-negligible deviations, including one of about 0.8 dB due to 60 Hz line noise picked up by the Type H52 hydrophone when calibrated at the LEFAC. Interestingly, the agreement between the two laboratories was much improved for calibrations of a Type H56 hydrophone as shown in figure D-20, likely a result of its lower susceptibility to electromagnetic interference (EMI). Calibration results for a Type F37 transducer are shown in figure D-21.

Comparison results are shown in figures D-22 and D-23, and detailed in table 18 where the larger uncertainties associated with the LEFAC are clearly evident. In all cases the condition required for equivalence was satisfied.

While the comparisons were satisfactory, the CRV for the different devices at first may appear to be anomalous. In particular, the CRV for the Type H52 (figure D-19) and Type H56 (Figure D-20) hydrophones at 1.6 kHz were not intermediate between the sensitivities reported by the two laboratories, as would be expected if the CRV were evaluated as a simple, weighted mean of two measurements. In both cases, the CRV was about 0.3 dB less than both of the measured values. Inspection of Type F37 data (figure D-21) shows the CRV was 0.6 dB less than the sensitivity measured by the LEFAC, and 0.7 dB greater than the LOFAC measurement, intermediate between the two measurements, as might be expected.

While these CRV values may appear to be anomalous, they are not. They are the correct result of the evaluation method employed. As described in the derivation of the statistical procedures (appendix C, section C.3), the measurement results were not all regarded as mutually independent. On the contrary, it was assumed that different measurements made by the same laboratory might be correlated owing to common Type B uncertainties that may introduce a systematic effect to the result. Thus, a large deviation from the CRV for one measurement (e.g., Type F37) may produce correlated deviations in other measurements made by the same laboratory (e.g., Types H52 and H56) if the Type B uncertainty component is non-negligible (relative to the Type A component).

Table 4 shows the uncertainty components for the laboratories at 1.6 kHz, where the combined standard uncertainties were similar at 5.34% and 4.81% for the LOFAC and LEFAC, respectively. While the combined uncertainties were similar, their apportionment between Type A and Type B were quite different. For example, the combined standard uncertainty for the LOFAC measurement was dominated by the Type A part (i.e., 5.16% versus 1.39%). However, the Type B part of the combined uncertainty (i.e., 3.76%) for the LEFAC measurement was greater than the Type A part (i.e., 3.00%), thus evaluation of the CRV included a covariance among the measurements performed at the LEFAC that was driven by the Type B part of the combined uncertainty.

Table 4. LOFAC and LEFAC Measurement Uncertainties at 1.6 kHz

Laboratory	Fractional Standard Uncertainties at 1.6 kHz		
	Type A (%)	Type B (%)	Combined (%)
LOFAC	5.16	1.39	5.34
LEFAC	3.00	3.76	4.81

This seemingly anomalous result is due in part to the ad hoc nature of the LEFAC uncertainty budget compared to the more rigorous evaluation of uncertainties for measurements performed in the LOFAC. A more thorough treatment of LEFAC measurement uncertainty, to include the repeated measurements needed for a reliable estimate of the Type A uncertainty component, may yield a different result. Thus, the value of a proficiency testing program based on laboratory comparisons depends strongly on rigorous, comprehensive estimates of measurement uncertainty, including reliable estimates for the Type A part describing random effects and the Type B part describing systematic effects in the current measurement process (reference 9).

2.2.4.5 Multilateral Comparisons Among OTF, APTF, and LEFAC. Data collected during the proficiency testing program were also evaluated to yield two multilateral comparisons among the OTF, APTF, and LEFAC for calibrations of a Type F37 transducer. The first comparison (MC-1) evaluated secondary calibrations of receive sensitivity as illustrated in figure D-24. Equivalence was demonstrated for all three laboratories as shown in figures D-25 through D-27, and detailed in table D-7.

Comparison results for measurement of transmitting voltage response (MC-2) showed a non-negligible divergence among the laboratories above 20 kHz. As shown by inspection of figure D-28, measurement results of OTF and APTF were closely grouped, whereas measurement results provided by LEFAC diverged systematically above 20 kHz. Degree of equivalence estimates were uniformly satisfactory for the OTF (see figure D-29), and satisfactory for the APTF at all frequencies except 31.5 and 40 kHz (see figure D-30). Comparison results for LEFAC satisfied the condition for equivalence only for frequencies less than 20 kHz (figure D-31). Results are detailed in table D-8.

Consideration of results for comparisons between the OTF–APTF (BC-3), OTF–LEFAC (BC-5), and among OTF–APTF–LEFAC (MC-2) suggests that equivalence was successfully demonstrated for OTF and APTF at all frequencies, and for the LEFAC at frequencies less than 20 kHz. While a definitive root cause for deviations in the LEFAC transmitting voltage response measurements is not known, the observed behavior was consistent with misalignment of the Type F37 transducer's normalized angular response pattern (reference 15) during the TVR measurements. For example, a vertical misalignment of about 10° would introduce a systematic bias in the measured TVR of about -1, -3, and -5 dB at 10, 25, and 35 kHz, respectively. Thus, vertical misalignment of the Type F37 transducer of less than 10° would be sufficient to produce the observed behavior. Given that LEFAC calibrations are performed at a nominal depth of 14.5 m with transducers frequently suspended from cables, vertical misalignment on the order of a few degrees is quite plausible.

2.3 EXTERNAL ACTIVITIES

The USRD has a long history of support for international and U.S. national metrology activities. It has provided technical expertise to standards writing committees including those responsible for IEC 60565 (reference 6) and ANSI/ASA S1.20 (reference 16). In addition, the USRD has provided a subject matter expert in underwater sound to NIST for every meeting of the CCAUV since its inception.

The most significant change in USRD's external activities in 2018 relates to IEC Technical Committee 87: Ultrasonics. Specifically, USRD became an active member (with voting rights) of the American Society of Testing and Materials (ASTM) Technical Advisory Group (TAG) to IEC TC87 and supports work group 15 (WG15) for underwater acoustics, including development and maintenance of IEC 60565 for hydrophone calibrations.

In addition to direct support to metrology related activities, USRD metrology staff serve on the faculty of the Ocean Engineering Department at the University of Rhode Island teaching sonar system engineering and serving on academic committees for graduate students matriculating for both masters and doctoral degrees.

3. PLANNED ACTIVITIES 2019

3.1 QUALITY SYSTEM

Activities planned for 2019 include migration of the quality system to the ISO 17025:2017 standard, NVLAP assessment, expansion of the scope of the laboratory's accreditation to include calibration services provided by the APTF and continued coordination with NIST leading to appointment of the USRD as the U.S. DI for sound in water.

3.1.1 ISO 17025:2017 Accreditation

The USRD will be assessed by NVLAP against the ISO 17025:2017 standard in late 2019. Accordingly, the quality system will be revised to conform to the newer standard and implemented for all administrative activities and calibration services provided by the USRD. The most significant change in the new standard is the requirement to implement a risk management program to support operation of the laboratory. Implementing risk management within the USRD will be accomplished by adopting the existing risk management processes employed throughout NUWCDIVNPT. Consequently, it should not be disruptive to laboratory operations.

The USRD will also expand the scope of its accreditation to include calibration services provided by the APTF. The planned expansion will include primary and secondary calibration of hydrophones, transmitting voltage response, and transmitting current response of projectors over a range of simulated oceanic environments characterized by temperature and hydrostatic pressure. The accredited frequency range will extend from 1 kHz to 250 kHz.

3.1.2 Designated Institute

Coordination between NIST and the USRD leading to appointment of the laboratory as the U.S. DI for sound in water will continue throughout 2019. All USRD milestones leading to designation are complete, having concluded with the NIST peer review conducted on 25-26 October 2018. Work remaining to complete the designation process resides within NIST as prescribed in reference 4.

Pending formal designation, the USRD will continue to support the activities of NIST in international metrology activities including attendance at a meeting of the SIM in July, and a meeting of the CCAUV in September.

3.1.3 Internal Audits and Reviews

Internal audits and reviews in 2019 will focus on parts of the QMS that have been recently revised and on calibration services not previously accredited (i.e., APTF). Planned changes to the QMS, and those under consideration, include:

1. Revisions for compliance with ISO 17025:2017.
2. Scope expansion to include calibration services provided by the APTF.
3. Incorporation of comments resulting from the 2018 NVLAP assessment.
4. Incorporation of comments resulting from the 2018 NIST peer review.
5. Incorporation of operational improvements resulting from the prior internal audit.

In preparation for the 2019 NVLAP assessment, the internal audits will focus on the first two items, compliance with ISO 17025:2017 and an onsite audit of the APTF. Once the QMS has been updated, but prior to the NVLAP assessment, a document audit will be performed against ISO 17025:2017, NIST HB-150 (reference 17), and NIST HB 150-2 (reference 18). In addition, an onsite internal audit of APTF will be conducted. This activity will occur after the launch of the QMS within the APTF but prior to the 2019 assessment. The APTF local calibration procedures LCP-009 (reference 19) and LCP-010 (reference 20) will be reviewed and verified as transducer calibrations are performed. This activity will emulate the NVLAP assessment process to prepare laboratory personnel and to acquaint them with the process.

3.1.4 Personnel Training and Qualifications

USRD personnel training processes will continue as currently defined by the quality system but with the addition of a component for laboratory personnel assigned to the APTF, as well as consideration of operational improvements suggested during the 2018 internal audit.

Also under consideration for incorporation in 2019 is inclusion of proficiency test program events as elements within the internal audit process. These events provide an ideal opportunity to conduct onsite audits of laboratory operations as part of the USRD quality system because the USRD operates a robust (and expanding) proficiency testing program consisting of laboratory intercomparisons.

3.2 METROLOGY AND CALIBRATION SERVICES

3.2.1 Proficiency Testing

The USRD proficiency testing program consists of laboratory comparisons as described in section 2.2.4. However, whereas the 2018 program consisted of comparisons between and among USRD laboratories, the 2019 program will expand to include participation by other government laboratories that provide testing and measurement services in underwater sound.

Table 5 shows two bilateral comparisons planned for 2019. The first (BC-1) will compare results for primary calibrations of hydrophones between the USRD OTF and APTF. While only the OTF is currently accredited, it is anticipated that accreditation of the APTF will have been completed by the end of the calendar year. So this comparison is intended to demonstrate the equivalence of primary hydrophone calibrations performed using the method of three-transducer, spherical wave reciprocity. This comparison will be performed in accordance with IEC 60565 (reference 6) for the USRD laboratories that offer this as an accredited calibration service (or soon will).

Also shown in table 5 is BC-2 between the USRD OTF and another government laboratory (Lab-A). The objective of this comparison is to provide proficiency test coverage for calibrations performed at high frequencies ranging from 100 kHz to 2 MHz.

Multilateral comparisons planned for 2019 are shown in table 6. The first two (MC-1 and MC-2) include eight participants, four of which are USRD laboratories and four of which are other government laboratories (i.e., Laboratories A, D, K, and L). Measurements to be performed during these comparisons include receive voltage sensitivity (RVS) of hydrophones (dB re 1V/μPa) and transmitting voltage response of projectors (dB re 1μPa·m/V). The objective of MC-3 is to demonstrate the equivalence of hydrophone calibrations performed near the upper end of the accredited measurand range (i.e., -140 dB re 1V/μPa) for USRD laboratories.

Table 5. Bilateral Comparisons 2019

NUWC-USRD: OTF // APTF						
	Transducer		Calibration		Frequency (kHz)	
ID	Type	Ser. No.	Measurand	Method	Min	Max
BC-1	H52	80	RVS	Primary	1	250
	F42D	145	RVS	Primary	1	250

NUWC-USRD: OTF // LAB-A						
	Transducer		Calibration		Frequency (kHz)	
ID	Type	Ser. No.	Measurand	Method	Min	Max
BC-2	E27	213	RVS	Secondary	100	500
	E8	7	RVS	Secondary	400	2000

Table 6. Multilateral Comparisons 2019

NUWC-USRD: OTF // LOFAC // APTF // LEFAC LAB-A // LAB-D // LAB-K // LAB-L						
	Transducer		Calibration		Frequency (kHz)	
ID	Type	Ser. No.	Measurand	Method	Min	Max
MC-1	H52	84	RVS	Secondary	0.02	160
	F37	A117	RVS	Secondary	0.02	40
MC-2	F37	A117	TVR	Secondary	1	40

NUWC-USRD: OTF // LOFAC // APTF // LEFAC						
	Transducer		Calibration		Frequency (kHz)	
ID	Type	Ser. No.	Measurand	Method	Min	Max
MC-3	H64	2	RVS	Secondary	0.02	25

3.2.2 Laboratory Upgrades and Improvements

The most significant activity planned for 2019 relates to the overhaul and modernization of the USRD low-frequency measurement systems. The particular focus of this capital project is a pair of traveling wave tubes used for a variety of acoustic measurements including hydrophone calibrations performed in simulated oceanic environments (i.e., temperature and hydrostatic pressure) using low-frequency traveling wave fields. Various project activities are planned to occur from 2019 to 2023, culminating in accreditation of these measurement system capabilities in accordance with ISO 17025:2017 during a future NVLAP assessment. At the time of writing, this capital project was in the proposal stage for consideration, and potential award, during 2019 (reference 7).

3.3 EXTERNAL ACTIVITIES

Significant external activities related to underwater acoustic metrology occurring in 2019 include meetings of the Inter-American Metrology System (SIM) and the biennial meeting of the Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV).

A representative of the USRD attended the spring meeting of the SIM on 1-3 April 2019 in San Jose, Costa Rica. The USRD objective in attending the meeting was to help prepare for the presentation and defense of its quality system and measurement capabilities at a future meeting. The most probable meeting for USRD to satisfy these requirements will be held in Santiago, Chile in the spring of 2020.

The USRD will also support a SIM workshop for laboratory personnel working in acoustics, ultrasound, and vibration (AUV) to be hosted by NIST on 9-11 July 2019 in Gaithersburg, Maryland. Topics to be discussed during the meeting are quite broad, ranging from micro-mechanical-electrical systems (MEMS) sensor calibrations to interferometric-based primary calibrations. The USRD was invited to speak on the subject of underwater acoustic calibration services and future needs.

The most significant external activity planned for 2019 is the twelfth meeting of the CCAUV scheduled for 24-27 September 2019 in Paris, France. The USRD plans to provide an expert in underwater sound to assist the NIST delegate as it has since the committee's inaugural meeting. Among the subjects to be discussed at this meeting is the status of an ongoing KC piloted by the National Physical Laboratory (NPL) of the United Kingdom (UK) for primary calibration of hydrophones. The USRD is a participant in this comparison, having completed its measurements in June 2016.

4. CONCLUSIONS

The USRD provides underwater acoustic calibration services that are accredited in accordance with ISO 17025:2005. Laboratory accreditation was gained in 2018 as a prerequisite for NIST to nominate the USRD to serve as the U.S. DI for sound in water. This report describes a variety of activities required for a vital quality system and to ensure the claimed measurement capabilities are maintained.

The most significant event of 2018 was the initial accreditation, and subsequent expansion, of calibration services provided by the USRD. This milestone was followed closely by a successful peer review of the laboratory by NIST personnel, including the agency's quality manager and scientists from two different laboratory programs. At the conclusion of 2018, the USRD had satisfied its requirements for nomination as a designated institute (reference 4). Tasks remaining to be completed were related to vetting and acceptance of the laboratory's capabilities within NIST and formal nomination leading to designation.

Once designated by NIST, the USRD must then take up the activities leading to its participation in the MRA and publication of its calibration and measurement capabilities (CMC) at the BIPM. The path to these milestones includes the presentation, defense, and acceptance of the laboratory's quality system and measurement capabilities by the SIM, the RMO for the Americas. While 2018 began with USRD working toward initial ISO accreditation, it ended with the laboratory preparing to gain formal recognition as a (prospective) U.S. designated institute at the regional and international levels.

Among the responsibilities USRD will have as a designated institute is to serve as the pilot laboratory for the key comparisons, regional comparisons, supplementary comparisons, and pilot studies on which the international equivalence of measurements is established. Toward this end, the USRD reorganized its proficiency testing program to emulate the processes and statistical procedures employed by international metrology organizations, the CCAUV in particular. The newly renovated program was used in 2018 for several comparisons between and among USRD laboratories with good results. Based on that experience, the USRD extended an invitation to several other government laboratories to participate in the 2019 proficiency testing program and received a good response. Beyond 2019, the USRD anticipates further expansion of its proficiency testing program to non-governmental laboratories based in the U.S. before taking on the challenges associated with piloting regional or international comparisons.

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APPENDIX A
CORRECTIVE AND PREVENTIVE ACTION REQUESTS

Table A-1. Corrective and Preventive Action Requests (CPAR) Opened in 2018

CPAR No.	Type	Description
0019	Corrective	System K/APTF (Cust.: G. Crabtree)
0020	Corrective	LOFAC – Sys. K 60 Hz noise (Cust.: D. Haralson)
0021	Corrective	[NVLAP Assessment] LOFAC Vacuum pump, QMS compliance
0022	Corrective	[NVLAP Assessment] Minor QMS documentation updates
0023	Corrective	[NVLAP Assessment] Equipment Calibrations/Measurement Traceability
0024	Corrective	[NVLAP Assessment] Central document access (Robin's RDTE computer)
0025	Corrective	[NVLAP Assessment] Records management retention times
0026	Corrective	[NVLAP Assessment] Equipment records – 17025 compliance
0027	Corrective	[NVLAP Assessment, comment] Handling, receiving, and inspection of customer items
0028	Corrective	[NVLAP Assessment, comment] QA of data, aggregation, and analysis (e.g. control charts)
0029	Corrective	OTF – cable hookup error (Cust.: HTI)
0030	Corrective	Coupler – vacuum chamber stirrer

Table A-2. Corrective and Preventive Action Requests (CPAR) Closed in 2018

CPAR No.	Type	Description	Resolution
0001	Corrective	Update and sign LCPs	LCP drafts were completed; added review and approval by USRD Manager.
0003	Corrective	Establish USRD personnel training requirements, policies, and procedures	The USRD Manager and USRD Metrologist created personnel training requirements and a competency/surveillance/spot check procedure. Employees deemed proficient were "grandfathered" in and certified by the USRD Manager to perform calibration work in their respective facilities. Personnel who needed additional training followed new USRD training program.

Table A-2. Corrective and Preventive Action Requests (CPAR) Closed in 2018 (Cont'd)

CPAR No.	Type	Description	Resolution
0004	Corrective	Complete measurement uncertainty budgets for NVLAP scope of accreditation (OTF, LOFAC Sys. K, reciprocity coupler)	The USRD Metrologist submitted measurement uncertainty budgets to NVLAP which were approved for NVLAP scope of accreditation.
0006	Corrective	[2017 internal audit] Co-mingled out-of-cal, inactive, and in-cal test and measurement equipment; general laboratory housekeeping	Resolved equipment and housekeeping issues; added periodic checks (i.e., spot checks) of housekeeping and equipment for facilities.
0007	Corrective	Formalize 2018 Round Robin/proficiency testing plan	USRD Metrologist created 2018 Round Robin plan and updated QMS documents with additions and changes to USRD Round Robin planning policies/procedures.
0009	Corrective	Establish software validation policies and procedures	Created new QP-USRD-020 and implemented into QMS.
0010	Corrective	[2017 internal audit] More rigorous tracking and scheduling of calibration of USRD internal reference standards	Updated and implemented QP-USRD-002.
0011	Corrective	[2017 internal audit] Additional QA/surveillance (e.g., spot checks)	Added spot checks to USRD QMS.
0012	Corrective	[2017 internal audit, 2018 NVLAP Assessment] QMS document updates	Addressed minor QMS document updates in response to internal audit and NVLAP assessment nonconformities.
0018	Corrective	Low frequency primary calibrations – measurement offset	Added procedure of comparing incoming H48 reference standard calibration to outgoing H48.
0019	Corrective	System K/APTF (Cust.: G. Crabtree)	Updated System K technical procedures; updated System K post-processor; assigned J. Whitacre as primary technical PoC for G. Crabtree; re-calibrated customers devices free-of-charge.

Table A-2. Corrective and Preventive Action Requests (CPAR) Closed in 2018 (Cont'd)

CPAR No.	Type	Description	Resolution
0020	Corrective	LOFAC (Cust.: D. Haralson)	Calibration moved to Sys. L and a new calibration memo was issued; USRD agreed to calibrate customer's future TB-23 work in Sys. L; J. Whitacre assigned to oversee all future TB-23 work; USRD looking into EMI study of LOFAC.
0021	Corrective	[NVLAP Assessment] LOFAC Vacuum pump, QMS compliance	LCP-005 was updated to include an alternate method of applying vacuum to the standing wave tank. The issue was also analyzed and discussed at a branch meeting.
0022	Corrective	[NVLAP Assessment] Minor QMS documentation updates	Minor corrections and updates to USRD QMS documents were made in response to NVLAP assessment findings. The updated documents were submitted to NVLAP.
0023	Corrective	[NVLAP Assessment] Equipment Calibrations/Measurement Traceability	New procedures and policies were established to obtain 17025-accredited calibrations for critical test and measurement equipment.
0024	Corrective	[NVLAP Assessment] Central document access (Robin's RDTE computer)	The USRD Manager was given the login credentials for RDTE computer where USRD reports are stored.
0025	Corrective	[NVLAP Assessment] Records management retention times	QMS documents were updated to include retention times for all types of USRD records.
0026	Corrective	[NVLAP Assessment] Equipment records – 17025 compliance	USRD equipment records were updated to meet 17025 requirements.
0029	Corrective	OTF – cable hookup error (Cust.: HTI)	J. Whitacre provided technical assistance to M. Bergeron; defective units were sent back to HTI and the replacement units were calibrated.

Table A-2. Corrective and Preventive Action Requests (CPAR) Closed in 2018 (Cont'd)

CPAR No.	Type	Description	Resolution
0030	Corrective	Coupler – vacuum chamber stirrer	LCP-004 was updated to make use of the stirrer optional; the stirrer was not repaired or replaced; however, a stirrer was added to a list of desired equipment procurements for the coupler.

APPENDIX B
LABORATORY UNCERTAINTY STATEMENT SUMMARIES

Evaluation of measured data collected during the USRD proficiency testing program requires not only laboratory measurement results, but it also requires detailed estimates of measurement uncertainty for each of the calibration services considered. Estimation of measurement uncertainty was generally performed in accordance with *NIST Technical Note 1297: Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results* (reference 9), although with varying rigor depending on the maturity of the laboratory's measurement services and accreditation status. For example, uncertainty statements for the OTF and LOFAC are the most reliable having been rigorously developed and reviewed by NVLAP assessors and by the NIST ARB in 2018. Uncertainty statements for the APTF are rigorous but have not yet been reviewed by either NVLAP or the NIST ARB. Finally, the uncertainty statements for the LEFAC consist of ad hoc estimates that were assembled only to facilitate the laboratory's participation in the USRD proficiency testing program.

The summaries provided as tables B-1 through B-4 present only the Type A and Type B components together with the combined standard uncertainty computed as the root-sum-of-squares of the two components (A and B). Uncertainty components are generally grouped into two categories (or types) according to the method used to estimate their numerical values:

A. Those which are evaluated by statistical methods, and
B. Those which are evaluated by other means.

These categories somewhat over-simplify the case, as there is not always a simple correspondence between the classification of uncertainty components into these categories and the commonly used classification of uncertainty components as random and systematic. In particular, the category for an uncertainty component should be determined by the use made of the corresponding quantity and how that quantity appears in the mathematical model of the measurement process. Thus, the terms random uncertainty and systematic uncertainty can be misleading when generally applied. An alternate nomenclature suggested by reference 9 is that a Type A component arises from a random effect in the current measurement process, while a Type B component arises from a systematic effect in the current measurement process.

While the significance of this distinction may not be obvious, it can be clarified by consideration of a simple example. USRD uncertainty studies include a series of repeated measurements for a given acoustic transducer. The system and equipment are disassembled and reassembled between each measurement so that variations due to factors such as noise, entrained air, transducer rigging, and alignment may be characterized by the variance of the measurement result, yielding an estimate for the Type A component. Other sources of measurement uncertainty may not be detected by this process of repeated measurements. These include calibration errors in reference standards, biases in positioning equipment, transducer transient response and other factors that may give rise to a systematic effect in the current measurement process, and so are classified as Type B uncertainties. As a result, calibration measurements performed by a given laboratory may not be mutually independent random variables but may be correlated due to common Type B uncertainty components, a factor that should be considered when comparing measurement results between and among different laboratories as discussed in appendix C.

Table B-1. Uncertainty Statements: Open Tank Facility

Frequency (kHz)	Hydrophones						Projectors		
	Primary Calibration			Secondary Calibration			Transmit Voltage Response		
	Type A (%)	Type B (%)	Comb. Std. Uncert. (%)	Type A (%)	Type B (%)	Comb. Std. Uncert. (%)	Type A (%)	Type B (%)	Comb. Std. Uncert. (%)
1.00	1.21	1.50	1.93	0.95	3.12	3.26	0.95	3.27	3.41
1.25	0.95	1.50	1.78	0.95	3.00	3.14	0.95	3.16	3.30
1.60	0.95	1.50	1.78	0.95	2.96	3.11	0.95	3.12	3.26
2.00	0.77	1.50	1.69	1.22	2.97	3.21	1.20	3.14	3.36
2.50	0.68	1.50	1.65	1.72	2.95	3.41	1.70	3.11	3.55
3.15	0.90	1.50	1.75	1.68	3.01	3.45	1.70	3.17	3.60
4.00	0.91	1.50	1.75	1.55	3.01	3.39	2.55	3.17	4.07
5.00	1.60	1.50	2.19	2.19	2.98	3.70	2.67	3.14	4.12
6.30	0.92	1.50	1.76	1.64	2.99	3.41	1.64	3.15	3.55
8.00	1.71	1.50	2.27	1.70	2.94	3.40	1.70	3.11	3.54
10.0	1.17	1.56	1.95	1.31	2.90	3.18	1.30	3.02	3.29
12.5	1.04	1.30	1.66	1.17	2.77	3.01	1.17	3.07	3.28
16.0	1.09	1.56	1.90	1.19	3.00	3.23	1.20	3.28	3.49
20.0	2.06	1.56	2.58	1.44	2.98	3.31	1.44	3.26	3.56
25.0	1.15	1.56	1.94	0.85	2.95	3.07	0.80	3.23	3.32
31.5	0.82	1.58	1.78	0.85	2.97	3.09	0.85	3.25	3.36
40.0	1.00	1.58	1.87	1.77	3.16	3.62	1.77	3.42	3.85
50.0	1.12	1.64	1.99	1.98	3.20	3.76	1.98	3.45	3.98
63.0	1.16	1.73	2.08	2.97	3.07	4.27	2.97	3.34	4.47
80.0	1.40	1.73	2.23	3.38	3.30	4.72	3.38	3.55	4.90
100	3.08	1.73	3.53	3.08	3.33	4.54	3.08	3.58	4.72
125	2.62	1.73	3.14	2.62	3.40	4.29	2.62	3.80	4.61
160	2.58	1.64	3.06	3.56	3.31	4.86	1.33	3.95	4.17
200	1.95	2.05	2.82	1.95	3.31	3.84	1.95	3.96	4.41
250	2.10	2.00	2.90	2.10	3.32	3.93	2.10	3.97	4.49
315	1.74	2.00	2.65	1.74	3.32	3.75	1.74	3.96	4.33
400	2.05	2.00	2.86	2.05	3.34	3.92	2.05	3.98	4.48
500	2.08	2.00	2.88	2.22	3.43	4.08	2.08	4.06	4.56
630	1.42	2.00	2.45	2.34	3.21	3.97	2.19	4.17	4.71
800	0.80	2.00	2.15	3.10	3.25	4.50	3.10	3.51	4.68
1000	1.23	1.98	2.33	3.93	3.38	5.18	3.93	3.63	5.35
1250	1.85	2.03	2.75	5.38	3.68	6.52	5.38	4.00	6.70
1600	3.65	2.10	4.21	8.63	4.87	9.91	8.63	5.23	10.09
2000	6.21	2.19	6.58	10.89	7.02	12.96	10.89	7.38	13.16

Table B-2. Uncertainty Statement: Low-Frequency Facility

Frequency (Hz)	Hydrophones		
	Secondary Calibration		
	Type A (%)	Type B (%)	Comb. Std. Uncert. (%)
3.00	2.49	1.87	3.11
4.00	2.53	1.87	3.15
5.00	1.42	1.87	2.35
6.30	1.57	1.87	2.44
8.00	1.49	1.87	2.39
10.0	1.13	1.87	2.19
12.5	1.15	1.39	1.80
16.0	0.81	1.39	1.61
20.0	0.67	1.39	1.54
25.0	0.50	1.39	1.48
31.5	0.57	1.39	1.50
40.0	0.80	1.39	1.60
50.0	1.25	1.39	1.87
63.0	1.53	1.39	2.07
80.0	2.05	1.39	2.48
100	1.26	1.39	1.88
125	1.05	1.39	1.74
160	0.75	1.39	1.58
200	1.21	1.39	1.85
250	0.99	1.39	1.71
315	0.86	1.39	1.64
400	0.94	1.39	1.68
500	1.88	1.39	2.34
630	2.87	1.39	3.18
800	2.36	1.39	2.74
1000	3.22	1.39	3.5
1250	3.44	1.39	3.71
1600	5.16	1.39	5.34

Table B-3. Uncertainty Statements: Acoustic Pressure Tank Facility

Frequency (kHz)	Hydrophones						Projectors		
	Primary Calibration			Secondary Calibration			Transmit Voltage Response		
	Type A (%)	Type B (%)	Comb. Std. Uncert. (%)	Type A (%)	Type B (%)	Comb. Std. Uncert. (%)	Type A (%)	Type B (%)	Comb. Std. Uncert. (%)
1.00	1.34	1.62	2.10	2.18	2.00	2.96	2.59	2.40	3.53
1.25	1.08	1.62	1.95	1.76	2.00	2.67	2.27	2.40	3.30
1.60	0.73	1.62	1.78	1.20	2.00	2.33	1.99	2.40	3.11
2.00	1.04	1.62	1.93	1.70	2.00	2.63	2.01	2.40	3.12
2.50	1.04	1.64	1.94	1.69	2.12	2.71	2.04	2.34	3.11
3.15	1.33	1.56	2.05	2.16	2.12	3.03	2.14	2.34	3.17
4.00	1.28	1.56	2.02	2.09	2.12	2.98	2.32	2.34	3.30
5.00	1.45	1.56	2.13	2.38	2.12	3.19	3.13	2.34	3.91
6.30	0.85	1.64	1.85	1.40	2.12	2.54	2.01	2.34	3.09
8.00	1.09	1.78	2.09	1.78	2.35	2.95	2.29	2.55	3.42
10.0	0.60	1.92	2.01	0.98	2.35	2.54	2.31	2.69	3.54
12.5	0.83	2.15	2.30	1.35	2.83	3.14	2.79	2.91	4.03
16.0	0.59	2.08	2.16	0.97	2.83	2.99	2.71	2.91	3.98
20.0	0.59	1.95	2.04	0.96	2.65	2.81	2.33	2.73	3.59
25.0	0.63	1.89	1.99	1.03	2.65	2.84	2.28	2.73	3.56
31.5	0.80	1.89	2.05	1.31	2.65	2.95	2.27	2.73	3.55
40.0	0.99	2.21	2.42	1.61	3.24	3.62	2.63	3.04	4.02
50.0	1.28	2.21	2.55	2.08	3.24	3.85	2.72	3.04	4.08
63.0	0.94	2.21	2.40	1.53	3.24	3.58	2.69	3.04	4.06
80.0	1.11	2.21	2.47	1.82	3.24	3.72	2.74	3.04	4.09
100	1.69	2.56	3.07	2.76	3.87	4.75	3.48	3.39	4.85
125	2.07	2.56	3.29	3.38	3.87	5.14	4.41	3.39	5.56
160	3.00	2.61	3.97	4.89	3.87	6.24	4.63	3.39	5.74
200	2.88	2.98	4.14	4.70	4.53	6.53	5.70	3.77	6.84
250	3.20	2.98	4.37	5.23	4.53	6.92	6.42	3.77	7.45

Table B-4. Uncertainty Statements: Leesburg Facility

Frequency (kHz)	Hydrophones			Projectors		
	Secondary Calibration			Transmit Voltage Response		
	Type A (%)	Type B (%)	Comb. Std. Uncert. (%)	Type A (%)	Type B (%)	Comb. Std. Uncert. (%)
20.0	3.00	5.37	6.15	3.00	5.37	6.15
25.0	3.00	5.35	6.13	3.00	5.35	6.13
31.5	3.00	5.33	6.12	3.00	5.33	6.12
40.0	3.00	5.34	6.12	3.00	5.34	6.12
50.0	3.00	5.37	6.15	3.00	5.37	6.15
63.0	3.00	5.45	6.22	3.00	5.45	6.22
80.0	3.00	5.53	6.29	3.00	5.53	6.29
100	3.00	5.69	6.43	3.00	5.69	6.43
125	3.00	5.46	6.23	3.00	5.46	6.23
160	3.00	4.16	5.13	3.00	4.16	5.13
200	3.00	4.09	5.07	3.00	4.09	5.07
250	3.00	4.20	5.16	3.00	4.20	5.16
315	3.00	4.14	5.12	3.00	4.14	5.12
400	3.00	4.11	5.09	3.00	4.11	5.09
500	3.00	4.13	5.10	3.00	4.13	5.10
630	3.00	3.96	4.97	3.00	3.96	4.97
800	3.00	4.52	5.42	3.00	4.52	5.42
1000	3.00	4.22	5.17	3.00	4.22	5.17
1250	3.00	3.84	4.87	3.00	3.84	4.87
1600	3.00	3.76	4.81	3.00	3.76	4.81
2000	3.00	3.76	4.81	3.00	3.76	4.81
2500	3.00	3.72	4.78	3.00	3.72	4.78
3150	3.00	3.70	4.77	3.00	3.70	4.77
4000	3.00	3.75	4.80	3.00	3.75	4.80
5000	3.00	3.75	4.80	3.00	3.75	4.80
6300	3.00	4.34	5.27	3.00	4.34	5.27
8000	3.00	4.13	5.11	3.00	4.13	5.11
10000	4.00	5.58	6.87	4.00	5.58	6.87
12500	4.00	5.46	6.77	4.00	5.46	6.77
16000	4.00	5.36	6.69	4.00	5.36	6.69
20000	4.00	5.44	6.75	4.00	5.44	6.75
25000	4.00	6.46	7.59	4.00	6.46	7.59
31500	4.00	6.23	7.40	4.00	6.23	7.40
40000	5.00	6.18	7.95	5.00	6.18	7.95
50000	5.00	6.20	7.97	5.00	6.20	7.97
63000	5.00	7.07	8.66	5.00	7.07	8.66
80000	5.00	7.09	8.68	5.00	7.09	8.68
100000	5.00	7.14	8.72	5.00	7.14	8.72

APPENDIX C
CALCULATING COMBINED DEGREES OF EQUIVALENCE

C.1 INTRODUCTION

The USRD proficiency testing program is based on round-robin comparisons of results from several laboratories, each of which calibrates a specified number of acoustic transducers. Given the large amount of data generated during a comparison, a meaningful and statistically valid method to summarize the result is required. The method employed by the USRD was adapted from the first key comparison (KC) for hydrophone calibrations conducted by the CCAUV at the BIPM and published by the UK's NPL in its final report as the pilot laboratory for the CCAUV.W-K1 comparison (reference 11). The following discussion differs from NPL's treatment primarily by generalizing the approach to accommodate arbitrary numbers of participating laboratories and acoustic transducers as opposed to the more specific circumstances of the key comparison for which the method was reported by the NPL. Thus, the USRD proficiency testing program is modeled closely on practices that have been accepted by the CCAUV for its key comparisons.

A software application implementing the following method was developed by the USRD to support ongoing proficiency testing, to include varying numbers of participating laboratories, acoustic transducers, calibration methods, measurands, and frequency ranges.

C.2 CALCULATING COMPARISON REFERENCE VALUES AND DEGREES OF EQUIVALENCE FOR MUTUALLY INDEPENDENT MEASUREMENTS

In order to obtain a useful method to combine data from different acoustic transducers (i.e., devices) in the calculation of the degrees of equivalence between (and among) separate laboratories, it is useful to consider first the situation where the calibrations are mutually independent. In this case, the calibrations have no common sources of uncertainty and the resulting data are uncorrelated. This is not the case for data collected during the comparisons reported in this report. However, it is simpler and provides a useful introductory example.

Correlation of measured data results when calibrations from a given laboratory share common Type B uncertainties that may influence estimates for the comparison reference values and degrees of equivalence. Section C.3 describes a method to combine data for different devices that accounts for correlations in the measured data.

C.2.1 Individual Degrees of Equivalence for Mutually Independent Measurements

Suppose, for $m = 1, 2, \ldots, M$, and $n = 1, 2, \ldots, N$, that $x_{m,n}$ denotes the measurement made by laboratory, m, of device, n, at a particular frequency, and $u_{m,n} = u\left(x_{m,n}\right)$ is the standard uncertainty associated with $x_{m,n}$. It is assumed that $x_{m,n}$, $m = 1, 2, \ldots, M$, $n = 1, 2, \ldots, N$ are the available measurements so that association of index, m, with "laboratory" and index, n, with "device" is used throughout. As such, the following development allows for arbitrary numbers of laboratories and devices in order to facilitate future comparisons where these numbers are expected to vary over time. To that end, the software application implementing the method described here is inherently scalable in that it imposes no restrictions on the number of participant laboratories, the number of devices calibrated, the range of the measurand, or the range of frequencies included in the comparison.

In this section, all the measurements are regarded as mutually independent, such that

1. There is no correlation between the measurements made by different laboratories, and
2. There is no correlation between different measurements made by the same laboratory.

An analysis of the measurements to evaluate CRVs and DoEs for which condition 2 above does not hold is presented in section C.3.

A consequence of condition 2 above is the measurements relating to the different devices may be treated independently. A consequence of condition 1 is the weighted mean, y_n, of the laboratories' measurements corresponding to device, n, provides a method for determining the comparison reference value.

For $n = 1, 2, \ldots, N$, y_n is evaluated from

$$y_n = \frac{\sum_{m=1}^{M} w_m x_{m,n}}{\sum_{m=1}^{M} w_m}, \qquad w_m = \frac{1}{u_{m,n}^2}, \tag{C-1}$$

with associated uncertainty, $u\left(y_n\right)$, determined from

$$\frac{1}{u^2\left(y_n\right)} = \sum_{m=1}^{M} \frac{1}{u_{m,n}^2}. \tag{C-2}$$

If a chi-squared test of the overall consistency of the data with the weighted mean model is passed, then y_n may be accepted as the comparison reference value and $u\left(y_n\right)$ as the standard uncertainty associated with the comparison reference value. The DoE of laboratory, m, for device, n, is then evaluated from

$$d_{m,n} = x_{m,n} - y_n, \tag{C-3}$$

with associated standard uncertainty $u\left(d_{m,n}\right)$ given by

$$u^2\left(d_{m,n}\right) = u^2\left(x_{m,n}\right) - u^2\left(y_n\right). \tag{C-4}$$

The degree of equivalence between laboratory, m, and m' for device, n, is then

$$d_{m,m',n} = x_{m,n} - x_{m',n}, \tag{C-5}$$

with its associated standard uncertainty, $u\left(d_{m,m',n}\right)$, given by

$$u^2\left(d_{m,m',n}\right) = u^2\left(x_{m,n}\right) + u^2\left(x_{m',n}\right). \tag{C-6}$$

In this analysis, comparison reference values with associated uncertainties were estimated using the weighted mean model for each device measured by the laboratories at a particular frequency. Furthermore, DoEs for each laboratory and each pair of laboratories, with associated uncertainties, were evaluated separately for each device. Consideration is now given to how the evaluation of a single (combined) DoE for each laboratory and each pair of laboratories, with associated uncertainties, may be estimated using calibration data from more than one device.

C.2.2 Combined, Relative Degree of Equivalence for Mutually Independent Measurements

The approach is to determine an "average" value of the DoEs for each laboratory (and each pair of laboratories) expressed as a proportion of the respective comparison values. Relative values are considered because the devices used in the comparison are intended to be different and, consequently, the sensitivities evaluated for the devices (comparison reference values, degrees of equivalence, etc.) are not comparable in absolute terms. Furthermore, it is common in the field of acoustics to express differences between calibration values, and the uncertainties associated with the calibration values, in relative terms expressed either as percentages or in decibels (relative to a reference level).

Defining for $m = 1, 2, \ldots, M$ and $n = 1, 2, \ldots, N$, the relative DoE

$$r_{m,n} = \frac{d_{m,n}}{y_n}, \tag{C-7}$$

with associated relative standard uncertainty

$$u\left(r_{m,n}\right) = \frac{u\left(d_{m,n}\right)}{y_n}, \tag{C-8}$$

then the combined, relative DoE, r_m, for laboratory, m, is evaluated as the weighted mean of the values $r_{m,n}$

$$r_m = \frac{\sum_{n=1}^{N} w_n r_{m,n}}{\sum_{n=1}^{N} w_n}, \qquad w_n = \frac{1}{u^2\left(r_{m,n}\right)}, \tag{C-9}$$

with associated uncertainty, $u\left(r_m\right)$, determined from

$$\frac{1}{u^2\left(r_m\right)} = \sum_{n=1}^{N} \frac{1}{u^2\left(r_{m,n}\right)}. \tag{C-10}$$

C.3 CALCULATING COMPARISON REFERENCE VALUES AND DEGREES OF EQUIVALENCE FOR MUTUALLY DEPENDENT MEASUREMENTS

A generalization of the analysis presented in section C.2 is now considered to allow for mutual dependencies between the measurements made of the different devices by the same laboratory. Recall that the mutual dependence of measurements performed in a given laboratory is a result of those measurements sharing a common set of Type B uncertainty components.

The assumption that measurements performed in different laboratories are mutually independent, thus uncorrelated, remains in place.

The aim is to undertake an analysis of the data to evaluate

1. A comparison reference value for each device with associated uncertainty,
2. A relative DoE for each laboratory with associated uncertainty, and
3. A relative DoE for each pair of laboratories and associated uncertainty.

C.3.1 Individual Degrees of Equivalence for Mutually Dependent Measurements

A model for the $M \times N$ measurements is supposed in the form

$$x_{m,n} = y_n + \alpha_{m,n},\ m = 1, \ldots, M,\ n = 1, \ldots, N, \tag{C-11}$$

where y_n is the comparison reference value (i.e., estimate of the measurand's true value) for device n, and the $\alpha_{m,n}$ are samples from a multivariate Gaussian distribution with zero mean and covariance matrix V of order $M \times N$. The matrix V has the variances $u^2_{m,n} = u^2(x_{m,n})$ as its diagonal elements, and the covariances $u(x_{m,n}, x_{m',n})$ for $m \neq m'$, and $u(x_{m,n}, x_{m,n'})$ for $n \neq n'$, as its off-diagonal elements.

The measurements made by laboratories m and m' $(m \neq m')$ are still assumed mutually independent (condition 1 of section C.2), and so $u(x_{m,n}, x_{m',n}) = 0,\ n = 1, \ldots, N$. To evaluate $u(x_{m,n}, x_{m,n'}),\ n \neq n'$, one writes

$$\begin{aligned} \alpha_{m,n} &= \lambda_m + \delta_{m,n}, \\ \alpha_{m,n'} &= \lambda_m + \delta_{m,n'}, \end{aligned} \tag{C-12}$$

where λ_m is a common (systematic) effect associated with the measurements $x_{m,n}$ and $x_{m,n'}$, and $\delta_{m,n}$ and $\delta_{m,n'}$ are (random) effects independent of each other and λ_m. The random and systematic effects are assumed to correspond to, respectively, the components of uncertainty provided by each laboratory for each measurement from a Type A and a Type B evaluation. For the analysis described in the following, both components are assumed to be available, and

$$u(x_{m,n}, x_{m,n'}) = u(\alpha_{m,n}, \alpha_{m,n'}) = u^2(\lambda_m),\ m = 1, \ldots, M, \tag{C-13}$$

Suppose N devices have been measured by M laboratories. The DoEs, $\mathbf{d}_m$ for the N devices calibrated by the m^{th}laboratory and associated covariance matrix V_m are

$$
\mathbf{d}_m = \begin{bmatrix} x_{m,1} - y_1 \\ x_{m,2} - y_2 \\ \vdots \\ x_{m,N} - y_N \end{bmatrix}, \tag{C-14}
$$

and

$$
V_m = \begin{bmatrix} u^2(x_{m,1}) & u(x_{m,1}, x_{m,2}) & \cdots & u(x_{m,1}, x_{m,N}) \\ u(x_{m,2}, x_{m,1}) & u^2(x_{m,2}) & \cdots & u(x_{m,2}, x_{m,N}) \\ \vdots & \vdots & \ddots & \vdots \\ u(x_{m,N}, x_{m,1}) & u(x_{m,N}, x_{m,2}) & \cdots & u^2(x_{m,N}) \end{bmatrix}, \tag{C-15}
$$

Estimates for the comparison reference values, $\mathbf{y}$, are obtained by solving the least-squares problem

$$
\min_{\mathbf{y}} \sum_{m=1}^{M} \mathbf{d}_m V_m^{-1} \mathbf{d}_m. \tag{C-16}
$$

If M laboratories each calibrate N devices, then the vector of measurements $\mathbf{x}$ and design matrix A are

$$
\mathbf{x} = \begin{bmatrix} x_{1,1} \\ x_{1,2} \\ \vdots \\ x_{1,N} \\ x_{2,1} \\ x_{2,2} \\ \vdots \\ x_{2,N} \\ \vdots \\ x_{M,1} \\ x_{M,2} \\ \vdots \\ x_{M,N} \end{bmatrix}, \; A = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ 1 & 0 & \cdots & 0 \\ 0 & 1 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & \cdots & 0 \\ 0 & 1 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}, \tag{C-17}
$$

the comparison reference values, $\mathbf{y}$, degrees of equivalence, $\mathbf{d}$ and covariance, V, are

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}, \ \mathbf{d} = \begin{bmatrix} \mathbf{d}_1 \\ \vdots \\ \mathbf{d}_M \end{bmatrix}, \ V = \begin{bmatrix} V_1 & & \\ & \ddots & \\ & & V_M \end{bmatrix}, \tag{C-18}$$

and equation (C-16) can be written as

$$\sum_{m=1}^{M} \mathbf{d}_m^T V_m^{-1} \mathbf{d}_m = \mathbf{d}^T V^{-1} \mathbf{d} = (\mathbf{x} - A\mathbf{y})^T V^{-1} (\mathbf{x} - A\mathbf{y}), \tag{C-19}$$

where T is the transpose operator.

The least-squares estimate for the comparison reference values $\mathbf{y}$ are then

$$\mathbf{y} = \left(A^T V^{-1} A\right)^{-1} A^T V^{-1} \mathbf{x}, \tag{C-20}$$

with the associated uncertainty matrix given by

$$V_{\mathbf{y}} = \left(A^T V^{-1} A\right)^{-1}. \tag{C-21}$$

The vector, $\mathbf{y}$, contains the comparison reference values $y_1, y_2, \cdots, y_N$ for the N devices. The diagonal elements of the associated uncertainty matrix, V_y, contain the variances associated with these values and the off-diagonal elements their covariance. The values correspond to those obtained in the previous section, but their evaluation accounts for the mutual dependencies between the measurements made by the same laboratory on the devices.

Note, in the case the N measurements $x_{m,1}, x_{m,2}, \cdots, x_{m,N}$ performed by the m^{th} laboratory are mutually independent, V_i will be a diagonal matrix, and the least-squares problem for $\mathbf{y}$ reduces to

$$\min_{\mathbf{y}} \left(\sum_{m=1}^{M} \frac{(x_{m,1} - y_1)^2}{u_{m,1}^2} + \sum_{m=1}^{M} \frac{(x_{m,2} - y_2)^2}{u_{m,2}^2} + \cdots + \sum_{m=1}^{M} \frac{(x_{m,N} - y_N)^2}{u_{m,N}^2} \right), \tag{C-22}$$

with $y_1, y_2, \cdots, y_N$ given by the (usual) "weighted means" of the data. It should likewise be noted that equation (C-20) is a generic statement of the solution to a least-squares problem with design matrix, A, and vector of observations, $\mathbf{x}$, with associated uncertainty matrix, V.

The uncertainty matrix, $V_{\mathbf{d}}$, associated with $\mathbf{d}$ evaluated at the solution is, after a few lines of algebra,

$$V_{\mathbf{d}} = V - A\left(A^T V^{-1} A\right)^{-1} A^T, \tag{C-23}$$

Now, $\mathbf{d}_m$ contains the degrees of equivalence $d_{m,1}, d_{m,2}, \ldots, d_{m,N}$ for laboratory m for calibration of the N devices. The estimates correspond to those obtained in the previous section, but their evaluation also accounts for the mutual dependencies between the measurements made by each laboratory of the different devices. The sub-matrix $V_{\mathbf{d},m}$ of V_d relating to $\mathbf{d}_m$ contains the variances and covariance associated with the degrees of equivalence $d_{m,1}, d_{m,2}, \ldots, d_{m,N}$ evaluated in this way.

C.3.2 Combined, Relative Degree of Equivalence for Mutually Dependent Measurements

To determine a single DoE for laboratory m, proceed as in the previous section but account for the mutual dependence between $d_{m,1}, d_{m,2}, \ldots, d_{m,N}$ by defining

$$r_{m,1} = \frac{d_{m,1}}{y_1},\ r_{m,2} = \frac{d_{m,2}}{y_2},\ \ldots\ , r_{m,N} = \frac{d_{m,N}}{y_N}, \tag{C-24}$$

with associated uncertainty matrix

$$V_{\mathbf{r},m} = \begin{bmatrix} u^2(d_{m,1})/y_1^2 & u(d_{m,1}, d_{m,2})/y_1 y_2 & \cdots & u(d_{m,1}, d_{m,N})/y_1 y_N \\ u(d_{m,2}, d_{m,1})/y_2 y_1 & u^2(d_{m,2})/y_2^2 & \cdots & u(d_{m,2}, d_{m,N})/y_2 y_N \\ \vdots & \vdots & \ddots & \vdots \\ u(d_{m,N}, d_{m,1})/y_N y_1 & u(d_{m,N}, d_{m,2})/y_N y_2 & \cdots & u^2(d_{m,N})/y_N^2 \end{bmatrix}, \tag{C-25}$$

The combined, relative degree of equivalence, r_m, for laboratory m is then obtained by solving the least-squares problem

$$\min_{r_m} (\mathbf{r}_m - \mathbf{A} r_m)^T V_{\mathbf{r},m}^{-1} (\mathbf{r}_m - \mathbf{A} r_m), \tag{C-26}$$

where $\mathbf{A}$ is the $N \times 1$ vector $\mathbf{A} = [1, 1, \ldots, 1]^T$.

Finally, equation (C-26) is minimized in a least-squares sense to yield an estimate for the combined, relative DoE for the m^{th} laboratory as

$$r_m = \left(\mathbf{A}^T V_{\mathbf{r},m}^{-1} \mathbf{A}\right)^{-1} \mathbf{A}^T V_{\mathbf{r},m}^{-1} \mathbf{r}_m, \tag{C-27}$$

with the associated variance given by

$$V_{r_m} = \left(\mathbf{A}^T V_{\mathbf{r},m}^{-1} \mathbf{A}\right)^{-1}. \tag{C-28}$$

APPENDIX D
PROFICIENCY TEST PROGRAM RESULTS

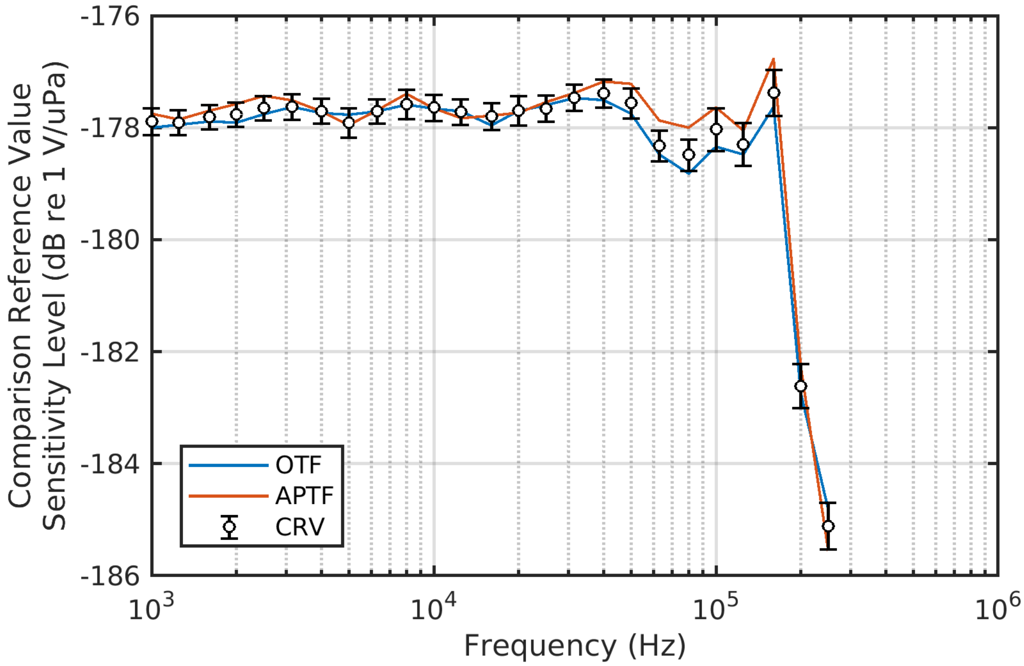

Figure D-1. Comparison BC-1 – Type H52 SN 80 – Receive Voltage Response

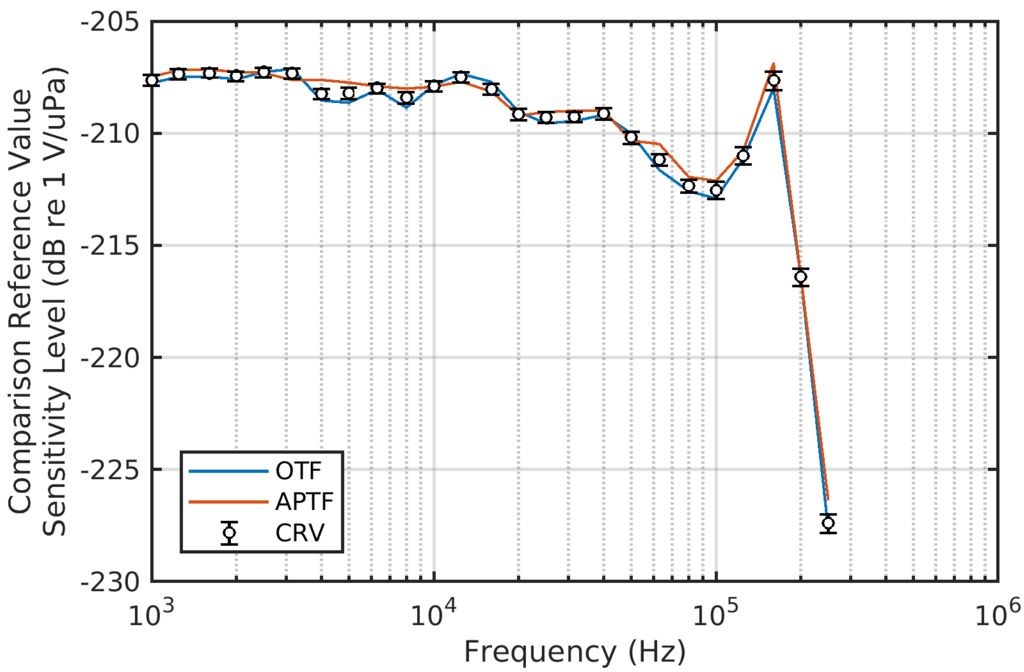

Figure D-2. Comparison BC-1 – Type F42D SN 145 – Receive Voltage Response

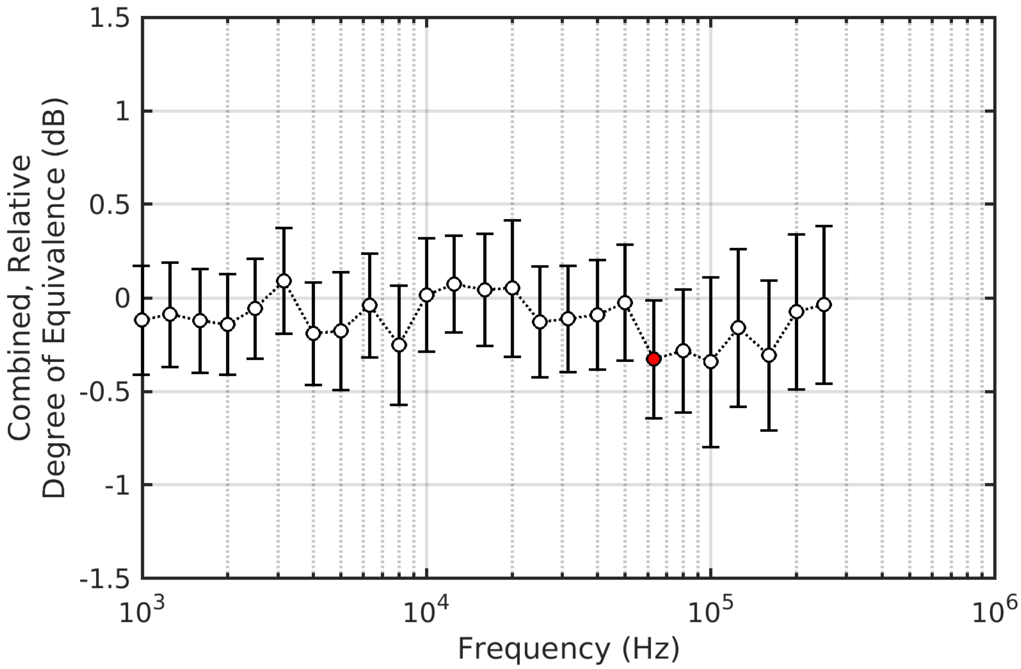

Figure D-3. Comparison BC-1 – Degree of Equivalence – OTF

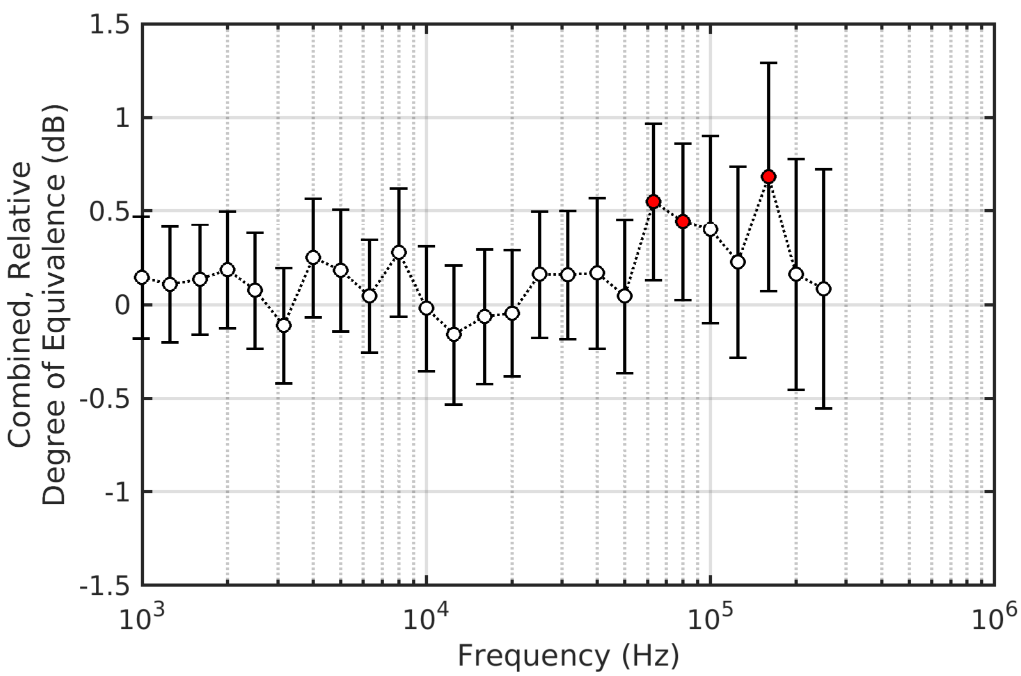

Figure D-4. Comparison BC-1 – Degree of Equivalence – APTF

Table D-1. Comparison BC-1 – Hydrophones – Primary Calibration

BC-1	Comparison Reference Value				Combined, Relative Degree of Equivalence			
	H52 SN 80		F42D SN 145		OTF		APTF	
Frequency kHz	M dB V/uPa	2u dB	M dB V/uPa	2u dB	r_m dB	$2u_m$ dB	r_m dB	$2u_m$ dB
1.00	-177.89	0.24	-207.64	0.24	-0.12	0.29	0.14	0.33
1.25	-177.91	0.23	-207.35	0.23	-0.09	0.28	0.11	0.31
1.60	-177.81	0.22	-207.32	0.22	-0.12	0.28	0.13	0.30
2.00	-177.77	0.22	-207.45	0.22	-0.14	0.27	0.19	0.31
2.50	-177.65	0.21	-207.27	0.21	-0.06	0.27	0.08	0.31
3.15	-177.63	0.23	-207.33	0.23	0.09	0.28	-0.11	0.31
4.00	-177.70	0.23	-208.23	0.23	-0.19	0.27	0.25	0.32
5.00	-177.91	0.26	-208.21	0.26	-0.18	0.31	0.18	0.33
6.30	-177.71	0.22	-207.99	0.22	-0.04	0.28	0.05	0.30
8.00	-177.58	0.26	-208.40	0.26	-0.25	0.32	0.28	0.34
10.0	-177.64	0.23	-207.90	0.23	0.02	0.30	-0.02	0.33
12.5	-177.72	0.23	-207.50	0.23	0.07	0.26	-0.16	0.37
16.0	-177.80	0.24	-208.03	0.24	0.04	0.30	-0.06	0.36
20.0	-177.69	0.26	-209.16	0.26	0.05	0.37	-0.04	0.34
25.0	-177.66	0.23	-209.28	0.23	-0.13	0.30	0.16	0.34
31.5	-177.46	0.23	-209.26	0.23	-0.11	0.28	0.16	0.34
40.0	-177.38	0.25	-209.13	0.25	-0.09	0.29	0.17	0.40
50.0	-177.56	0.27	-210.18	0.27	-0.03	0.31	0.04	0.41
63.0	-178.32	0.27	-211.18	0.27	-0.33	0.31	0.55	0.42
80.0	-178.49	0.28	-212.35	0.28	-0.28	0.33	0.44	0.42
100	-178.03	0.38	-212.54	0.38	-0.34	0.45	0.40	0.50
125	-178.30	0.38	-211.00	0.38	-0.16	0.42	0.23	0.51
160	-177.37	0.41	-207.65	0.41	-0.31	0.40	0.68	0.61
200	-182.61	0.40	-216.41	0.40	-0.07	0.41	0.16	0.62
250	-185.11	0.41	-227.39	0.41	-0.04	0.42	0.08	0.64

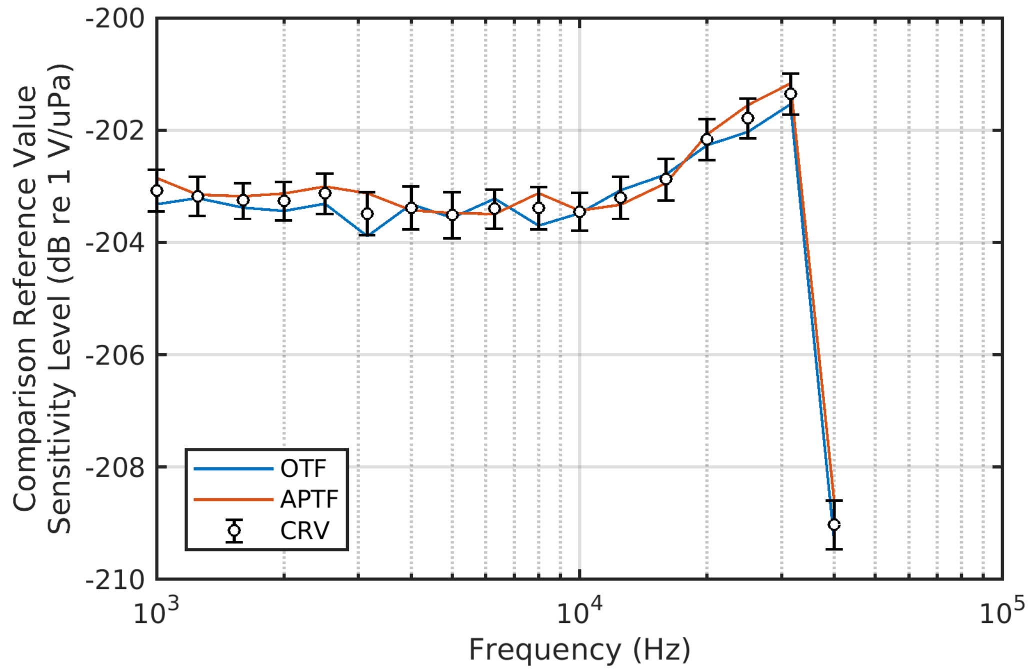

Figure D-5. Comparison BC-2 – Type F37 SN A117 – Receive Voltage Response

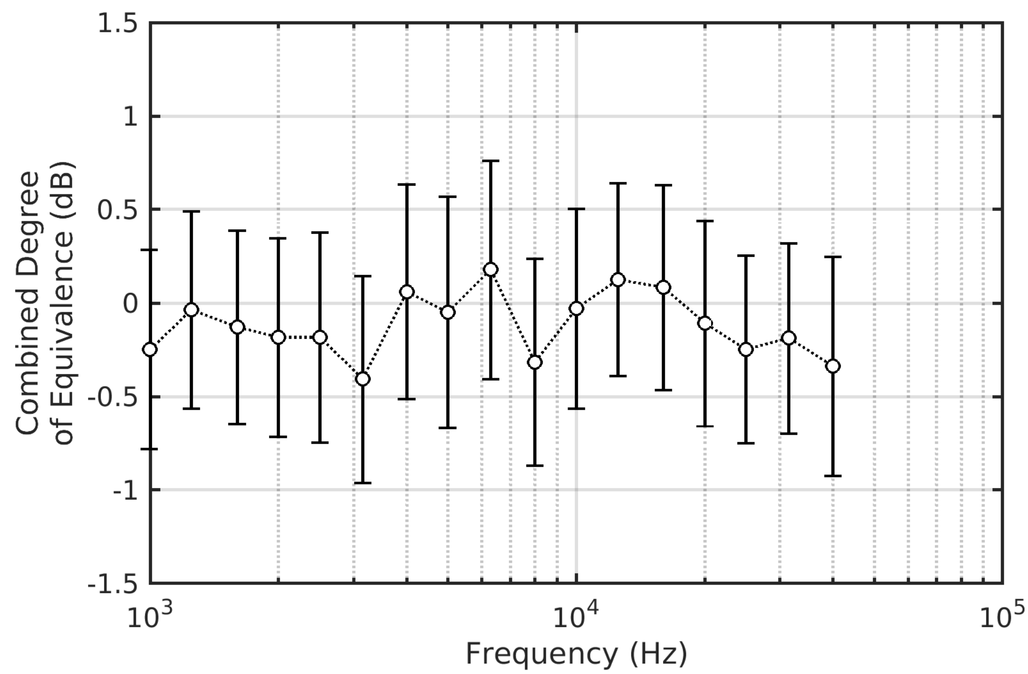

Figure D-6. Comparison BC-2 – Degree of Equivalence – OTF

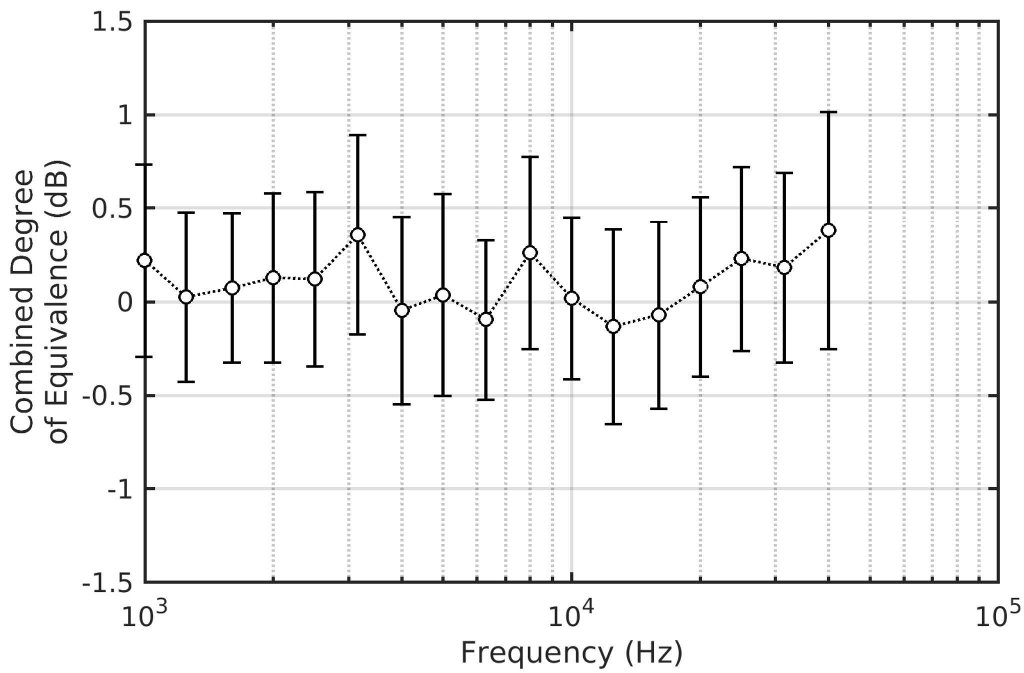

Figure D-7. Comparison BC-2 – Degree of Equivalence – APTF

Table D-2. Comparison BC-2 – Hydrophones – Secondary Calibration

BC-2	Comparison Reference Value		Relative Degree of Equivalence			
	F37 SN A117		OTF		APTF	
Frequency kHz	M dB V/uPa	2u dB	r_m dB	$2u_m$ dB	r_m dB	$2u_m$ dB
1.00	-203.07	0.37	-0.25	0.53	0.22	0.51
1.25	-203.17	0.35	-0.04	0.53	0.03	0.45
1.60	-203.25	0.32	-0.13	0.52	0.07	0.40
2.00	-203.26	0.35	-0.18	0.53	0.13	0.45
2.50	-203.13	0.36	-0.18	0.56	0.12	0.46
3.15	-203.48	0.39	-0.41	0.55	0.36	0.53
4.00	-203.38	0.38	0.06	0.57	-0.05	0.50
5.00	-203.51	0.41	-0.05	0.62	0.04	0.54
6.30	-203.40	0.35	0.18	0.58	-0.09	0.43
8.00	-203.38	0.38	-0.32	0.55	0.26	0.51
10.0	-203.45	0.34	-0.03	0.53	0.02	0.43
12.5	-203.20	0.37	0.13	0.52	-0.13	0.52
16.0	-202.87	0.37	0.08	0.55	-0.07	0.50
20.0	-202.16	0.36	-0.11	0.55	0.08	0.48
25.0	-201.78	0.35	-0.25	0.50	0.23	0.49
31.5	-201.35	0.36	-0.19	0.51	0.18	0.51
40.0	-209.02	0.43	-0.34	0.58	0.38	0.63

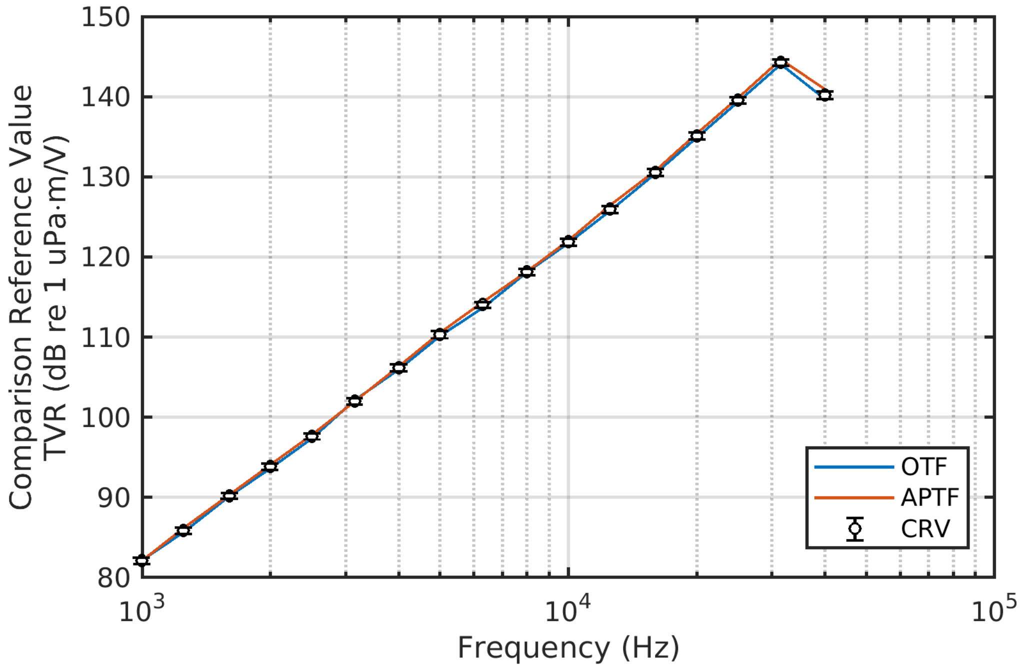

Figure D-8. Comparison BC-3 –Type F37 SN A117 – Transmitting Voltage Response

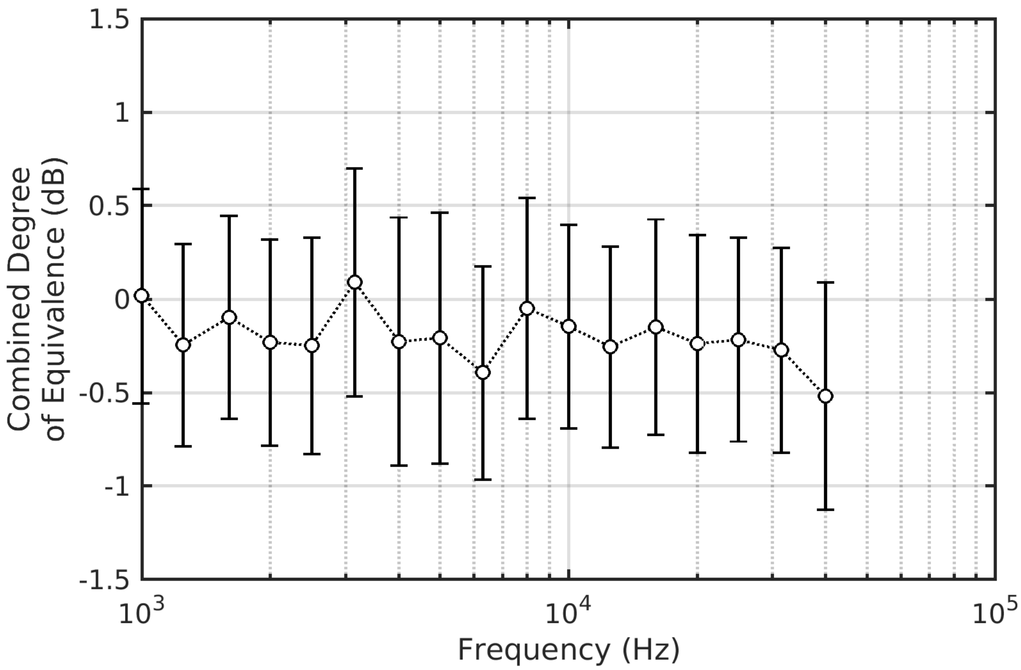

Figure D-9. Comparison BC-3 – Degree of Equivalence – OTF

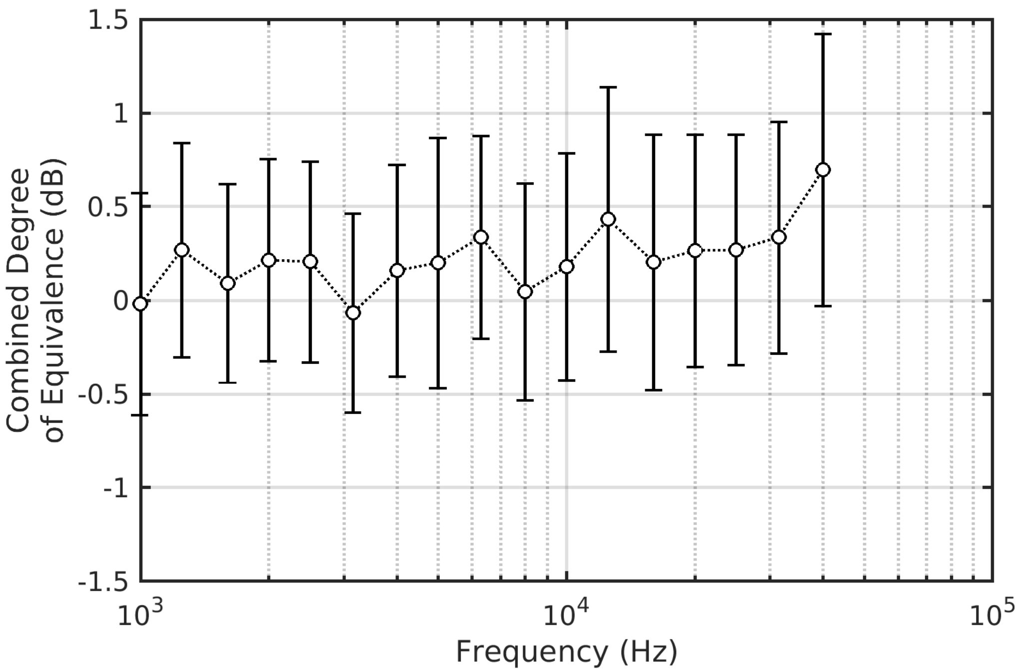

Figure D-10. Comparison BC-3 – Degree of Equivalence – APTF

Table D-3. Comparison BC-3 – Projectors – Transmitting Voltage Response

BC-3	Comparison Reference Value		Relative Degree of Equivalence			
	F37 SN A117		OTF		APTF	
Frequency kHz	S dB uPa·m/V	2u dB	r_m dB	$2u_m$ dB	r_m dB	$2u_m$ dB
1.00	82.13	0.42	0.02	0.57	-0.02	0.59
1.25	85.89	0.40	-0.25	0.54	0.27	0.57
1.60	90.22	0.38	-0.10	0.54	0.09	0.53
2.00	93.85	0.39	-0.23	0.55	0.22	0.54
2.50	97.59	0.40	-0.25	0.58	0.21	0.54
3.15	102.03	0.40	0.09	0.61	-0.07	0.53
4.00	106.19	0.43	-0.23	0.66	0.16	0.57
5.00	110.35	0.48	-0.21	0.67	0.20	0.67
6.30	114.04	0.40	-0.39	0.57	0.34	0.54
8.00	118.15	0.42	-0.05	0.59	0.05	0.58
10.0	121.88	0.41	-0.15	0.54	0.18	0.61
12.5	125.97	0.43	-0.25	0.54	0.43	0.71
16.0	130.56	0.44	-0.15	0.58	0.20	0.68
20.0	135.13	0.43	-0.24	0.58	0.26	0.62
25.0	139.57	0.41	-0.22	0.55	0.27	0.62
31.5	144.31	0.41	-0.27	0.55	0.34	0.62
40.0	140.21	0.47	-0.52	0.61	0.70	0.73

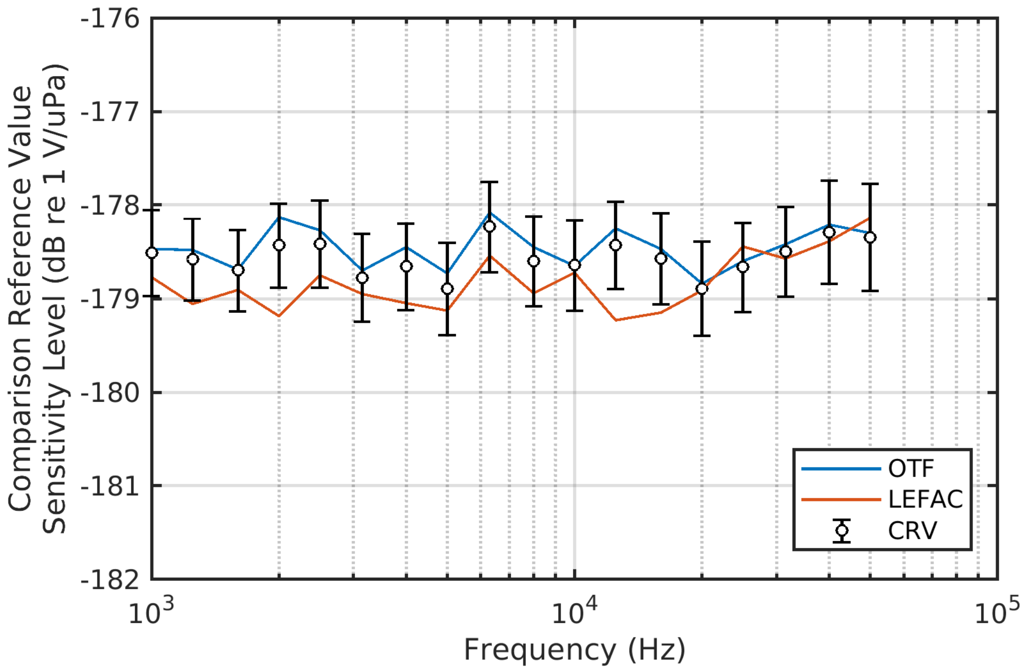

Figure D-11. Comparison BC-4 – Type H52 SN 84 – Receive Voltage Response

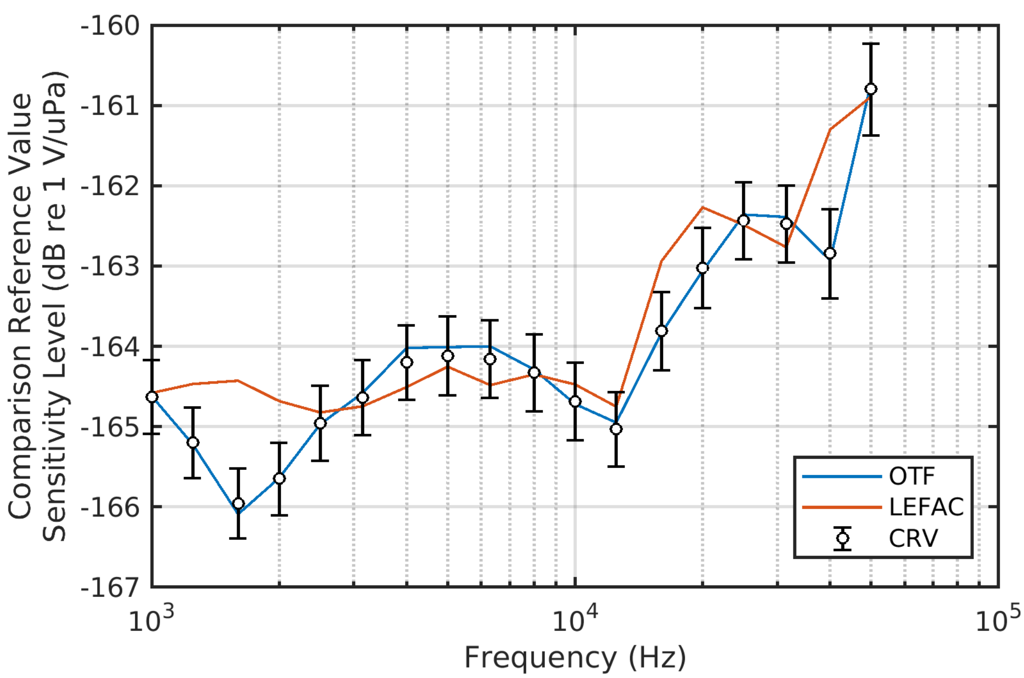

Figure D-12. Comparison BC-4 – Type H56 SN 125 – Receive Voltage Response

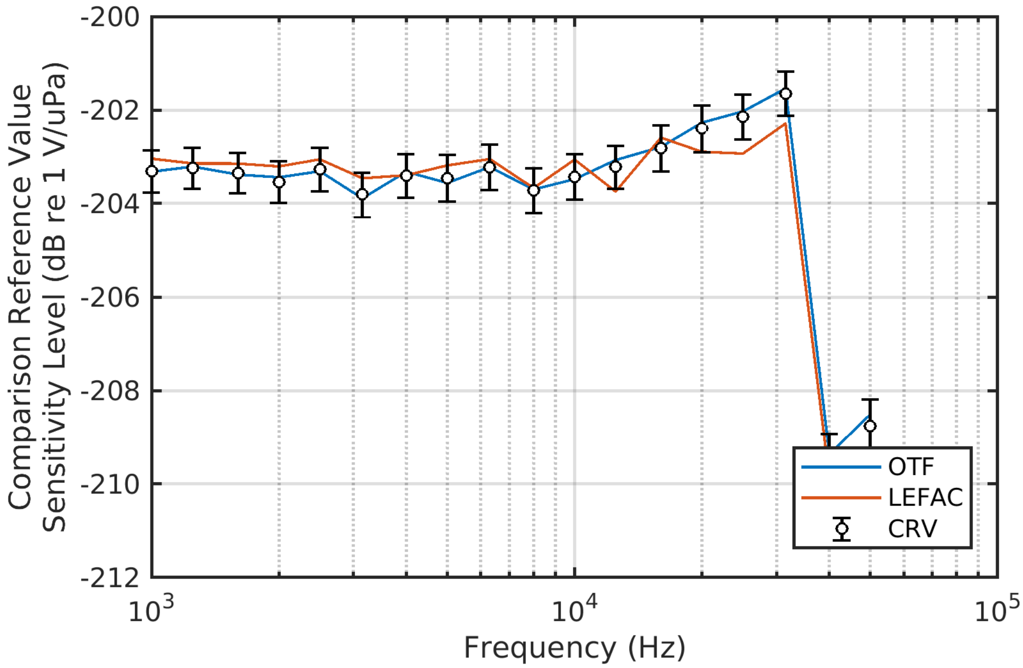

Figure D-13. Comparison BC-4 – Type F37 SN 117 – Receive Voltage Response

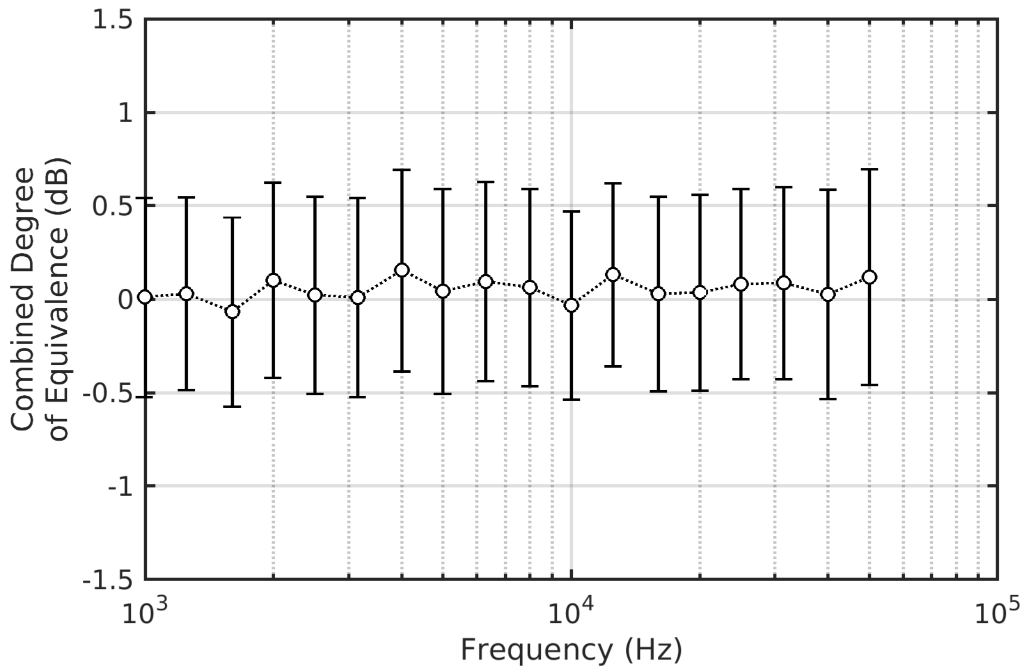

Figure D-14. Comparison BC-4 – Degree of Equivalence – OTF

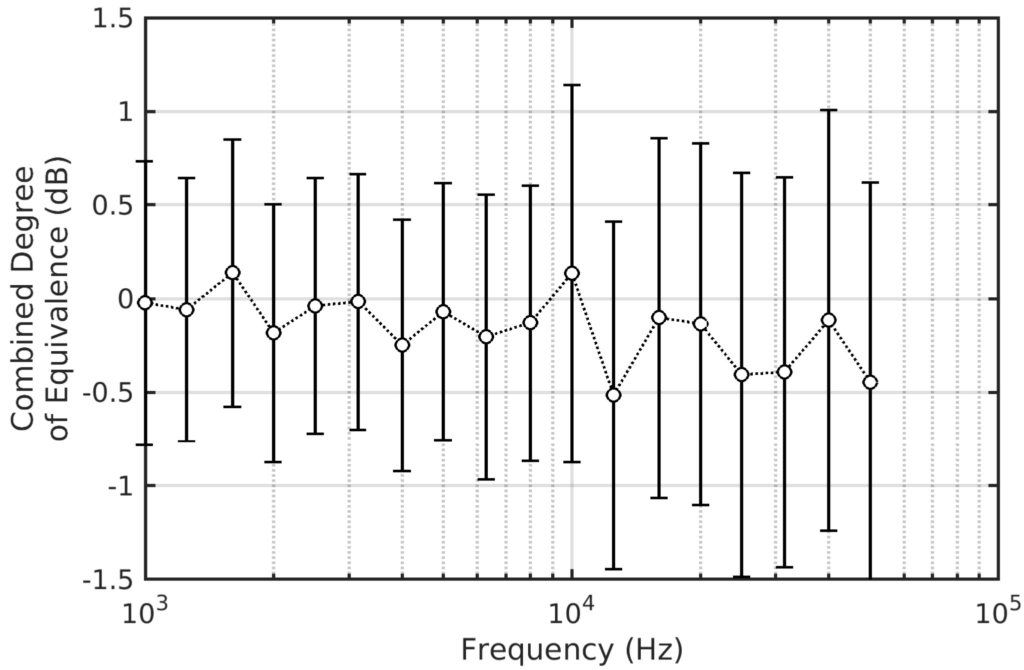

Figure D-15. Comparison BC-4 – Degree of Equivalence – LEFAC

Table D-4. Comparison BC-4 – Hydrophones – Secondary Calibration

BC-4	Comparison Reference Value						Combined, Relative Degree of Equivalence			
	H52 SN 84		H56 SN 125		F37 SN A117		OTF		LEFAC	
Frequency kHz	M dB V/uPa	2u dB	M dB V/uPa	2u dB	M dB V/uPa	2u dB	r_m dB	$2u_m$ dB	r_m dB	$2u_m$ dB
1.00	-178.51	0.46	-164.63	0.46	-203.31	0.46	0.01	0.53	-0.02	0.76
1.25	-178.58	0.44	-165.20	0.44	-203.25	0.44	0.03	0.52	-0.06	0.70
1.60	-178.70	0.43	-165.95	0.43	-203.34	0.43	-0.07	0.50	0.14	0.71
2.00	-178.43	0.45	-165.65	0.45	-203.53	0.45	0.10	0.52	-0.18	0.69
2.50	-178.42	0.47	-164.95	0.47	-203.27	0.47	0.02	0.53	-0.04	0.68
3.15	-178.78	0.47	-164.64	0.47	-203.81	0.47	0.01	0.53	-0.02	0.68
4.00	-178.66	0.46	-164.20	0.46	-203.41	0.46	0.15	0.54	-0.25	0.67
5.00	-178.89	0.50	-164.12	0.50	-203.45	0.50	0.04	0.55	-0.07	0.69
6.30	-178.23	0.48	-164.16	0.48	-203.22	0.48	0.10	0.53	-0.20	0.76
8.00	-178.60	0.48	-164.33	0.48	-203.72	0.48	0.06	0.53	-0.13	0.74
10.0	-178.64	0.48	-164.68	0.48	-203.43	0.48	-0.03	0.50	0.14	1.01
12.5	-178.43	0.46	-165.03	0.46	-203.22	0.46	0.13	0.49	-0.52	0.93
16.0	-178.57	0.49	-163.81	0.49	-202.81	0.49	0.03	0.52	-0.10	0.96
20.0	-178.89	0.50	-163.02	0.50	-202.39	0.50	0.04	0.52	-0.14	0.97
25.0	-178.66	0.48	-162.43	0.48	-202.14	0.48	0.08	0.51	-0.40	1.08
31.5	-178.49	0.48	-162.48	0.48	-201.64	0.48	0.09	0.51	-0.39	1.04
40.0	-178.29	0.55	-162.84	0.56	-209.48	0.55	0.03	0.56	-0.12	1.12
50.0	-178.34	0.57	-160.80	0.57	-208.76	0.57	0.12	0.58	-0.45	1.07

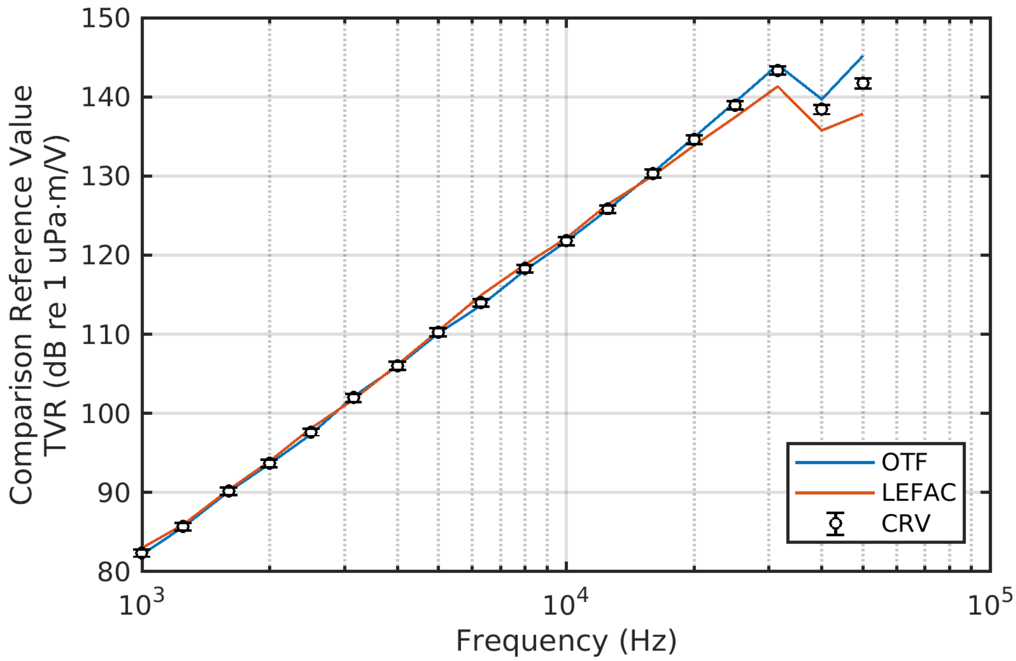

Figure D-16. Comparison BC-5 – F37 SN A117 – Transmitting Voltage Response

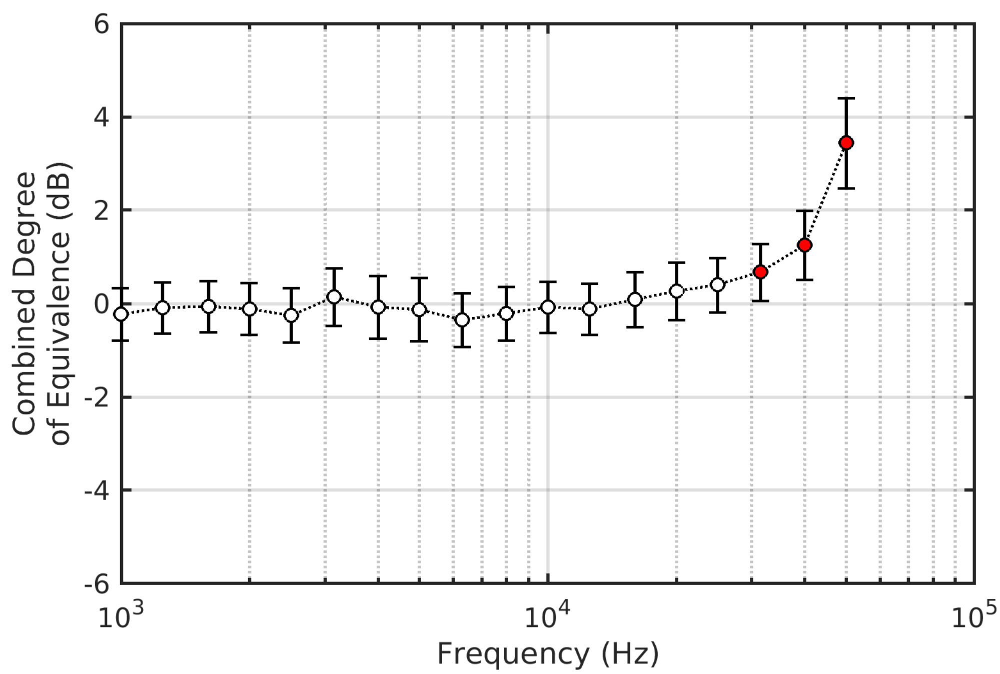

Figure D-17. Comparison BC-5 – Degree of Equivalence – OTF

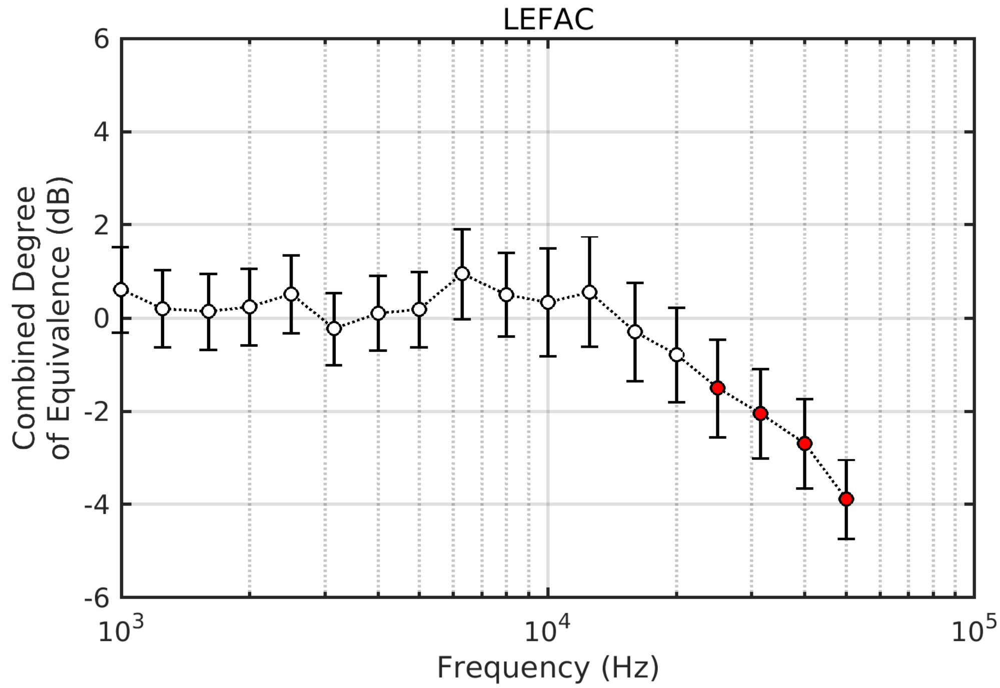

Figure D-18. Comparison BC-5 – Degree of Equivalence – LEFAC

Table D-5. Comparison BC-5 – Projectors – Transmitting Voltage Response

BC-5	Comparison Reference Value		Relative Degree of Equivalence			
	F37 SN A117		OTF		LEFAC	
Frequency kHz	S dB uPa·m/V	2u dB	r_m dB	$2u_m$ dB	r_m dB	$2u_m$ dB
1.00	82.38	0.48	-0.23	0.56	0.61	0.91
1.25	85.73	0.46	-0.09	0.55	0.20	0.83
1.60	90.18	0.46	-0.06	0.54	0.14	0.81
2.00	93.73	0.47	-0.11	0.56	0.24	0.82
2.50	97.59	0.48	-0.25	0.58	0.51	0.84
3.15	101.98	0.49	0.14	0.61	-0.23	0.77
4.00	106.04	0.52	-0.08	0.67	0.11	0.81
5.00	110.27	0.53	-0.13	0.68	0.18	0.81
6.30	114.00	0.50	-0.35	0.57	0.95	0.97
8.00	118.31	0.49	-0.21	0.58	0.50	0.89
10.0	121.80	0.50	-0.07	0.55	0.34	1.16
12.5	125.84	0.50	-0.12	0.54	0.56	1.17
16.0	130.32	0.52	0.09	0.59	-0.30	1.06
20.0	134.63	0.53	0.26	0.62	-0.79	1.01
25.0	138.95	0.51	0.40	0.58	-1.51	1.04
31.5	143.36	0.52	0.68	0.61	-2.04	0.96
40.0	138.44	0.59	1.25	0.74	-2.69	0.96
50.0	141.74	0.65	3.44	0.97	-3.89	0.84

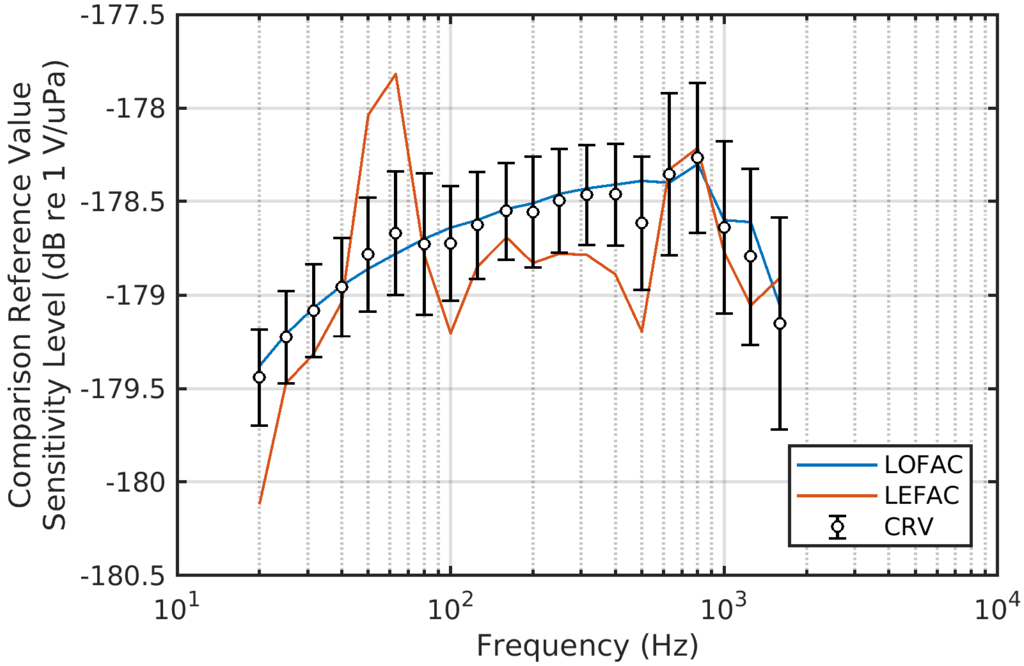

Figure D-19. Comparison BC-6 – Type H52 SN 84 – RVS

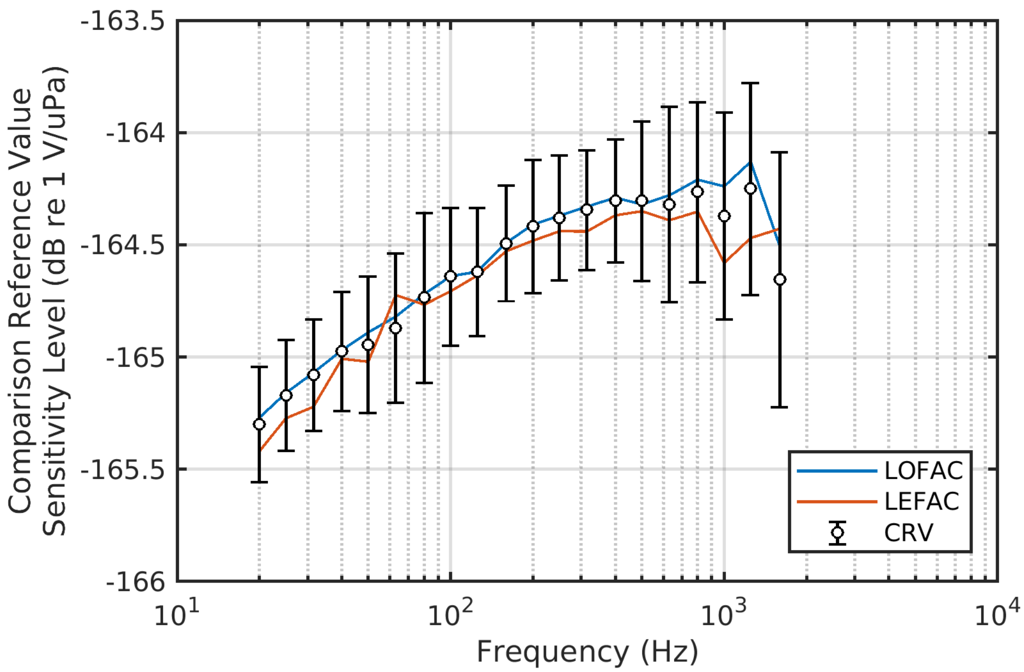

Figure D-20. Comparison BC-6 – Type H56 SN 125 – RVS

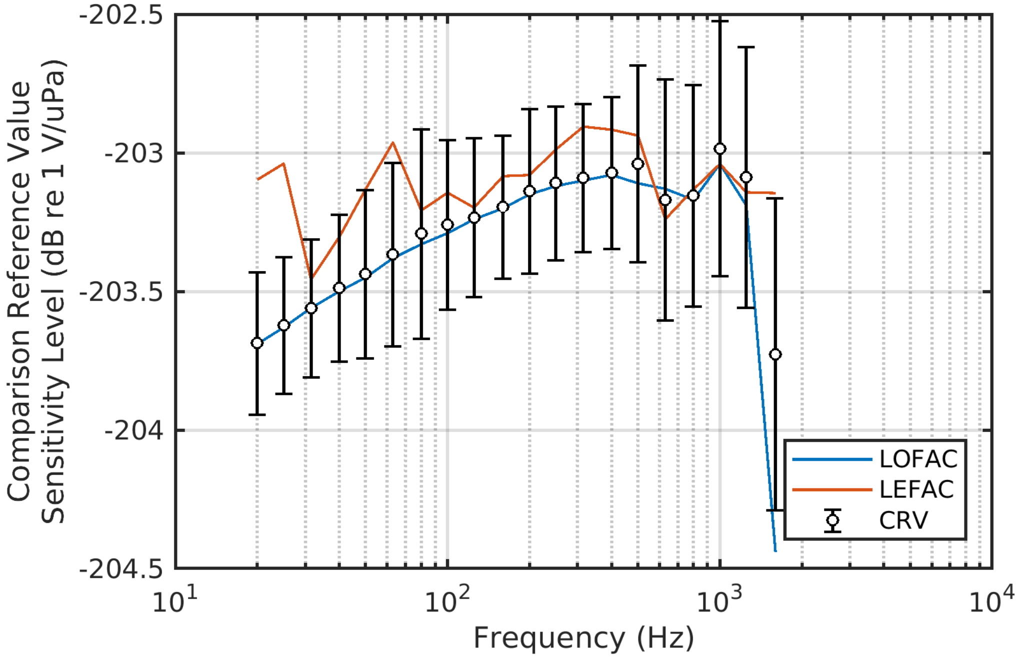

Figure D-21. Comparison BC-6 – Type F37 SN A117 – RVS

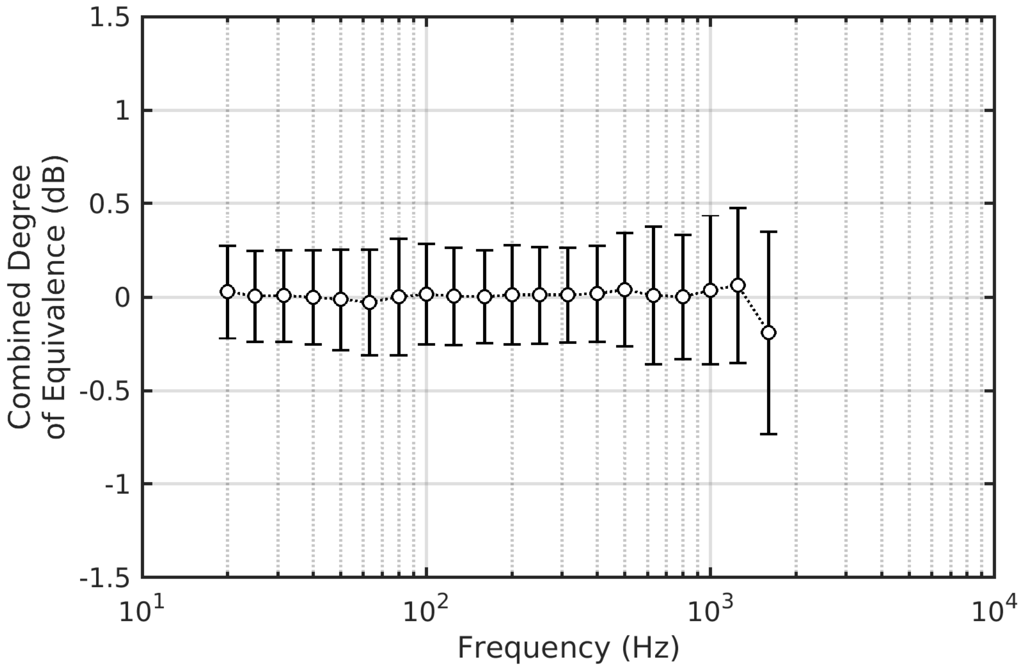

Figure D-22. Comparison BC-6 – Degree of Equivalence – LOFAC

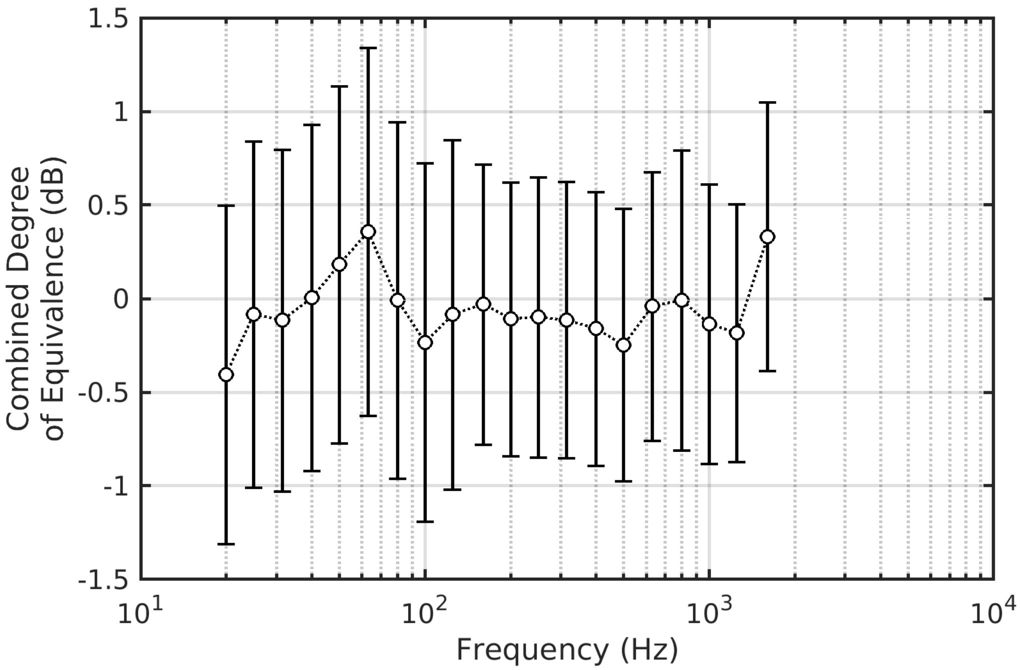

Figure D-23. Comparison BC-6 – Degree of Equivalence – LEFAC

Table D-6. Comparison BC-6 – Hydrophones – Secondary Calibration

BC-6	Comparison Reference Value						Combined, Relative Degree of Equivalence			
Frequency Hz	H52 SN 84		H56 SN 125		F37 SN A117		LOFAC		LEFAC	
	M dB V/uPa	2u dB	M dB V/uPa	2u dB	M dB V/uPa	2u dB	r_m dB	$2u_m$ dB	r_m dB	$2u_m$ dB
20.0	-179.44	0.26	-165.30	0.26	-203.69	0.26	0.03	0.25	-0.41	0.90
25.0	-179.22	0.25	-165.17	0.25	-203.62	0.25	0.01	0.24	-0.08	0.92
31.5	-179.08	0.25	-165.08	0.25	-203.56	0.25	0.01	0.24	-0.12	0.91
40.0	-178.96	0.26	-164.97	0.26	-203.49	0.26	0.00	0.25	0.01	0.93
50.0	-178.78	0.30	-164.94	0.30	-203.44	0.30	-0.01	0.27	0.18	0.95
63.0	-178.67	0.33	-164.87	0.33	-203.37	0.33	-0.03	0.28	0.36	0.98
80.0	-178.73	0.38	-164.73	0.38	-203.29	0.38	0.00	0.31	-0.01	0.95
100	-178.72	0.31	-164.64	0.31	-203.26	0.31	0.02	0.27	-0.23	0.96
125	-178.63	0.29	-164.62	0.29	-203.23	0.29	0.01	0.26	-0.09	0.93
160	-178.55	0.26	-164.49	0.26	-203.19	0.26	0.00	0.25	-0.03	0.75
200	-178.56	0.30	-164.42	0.30	-203.14	0.30	0.01	0.27	-0.11	0.73
250	-178.50	0.28	-164.38	0.28	-203.11	0.28	0.01	0.26	-0.10	0.75
315	-178.46	0.27	-164.34	0.27	-203.09	0.27	0.01	0.25	-0.11	0.74
400	-178.46	0.27	-164.30	0.27	-203.07	0.27	0.02	0.26	-0.16	0.73
500	-178.61	0.36	-164.30	0.36	-203.04	0.36	0.04	0.30	-0.25	0.73
630	-178.35	0.43	-164.32	0.43	-203.17	0.43	0.01	0.37	-0.04	0.72
800	-178.27	0.40	-164.26	0.40	-203.15	0.40	0.00	0.33	-0.01	0.80
1000	-178.64	0.46	-164.37	0.46	-202.98	0.46	0.04	0.40	-0.14	0.75
1250	-178.79	0.47	-164.25	0.47	-203.09	0.47	0.06	0.41	-0.18	0.69
1600	-179.15	0.57	-164.65	0.57	-203.73	0.56	-0.19	0.54	0.33	0.72

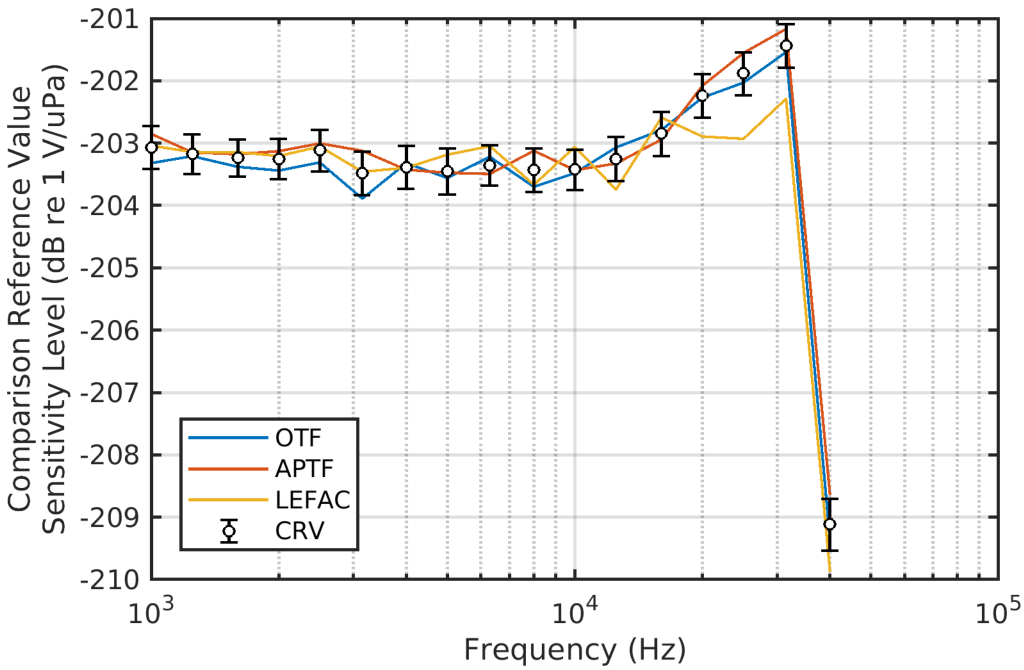

Figure D-24. Comparison MC-1 – Type F37 SN A117 – RVS

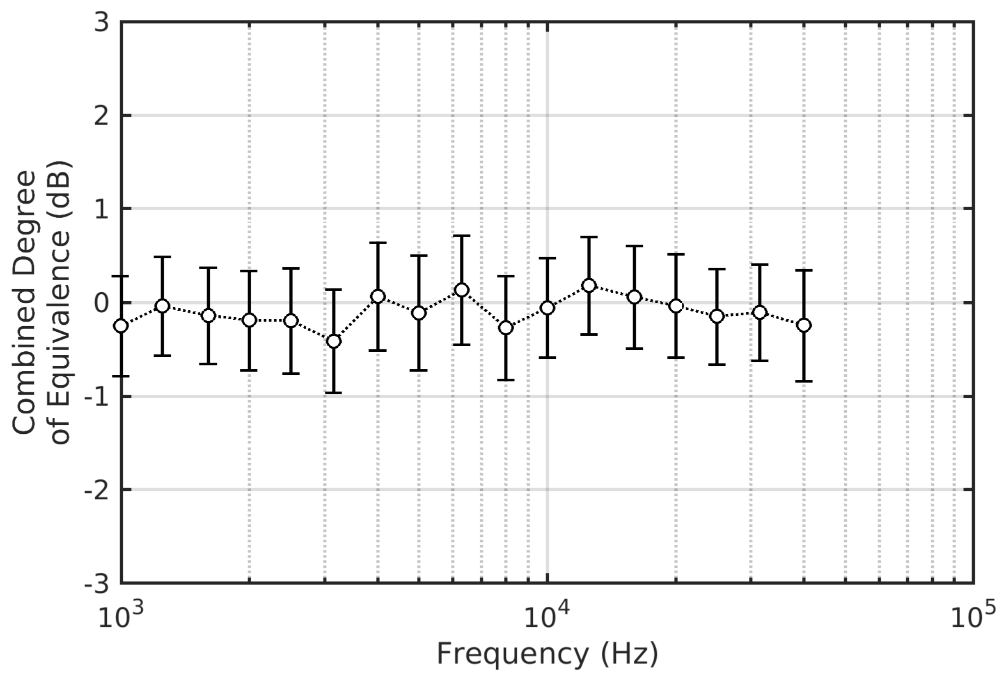

Figure D-25. Comparison MC-1 – Degree of Equivalence – OTF

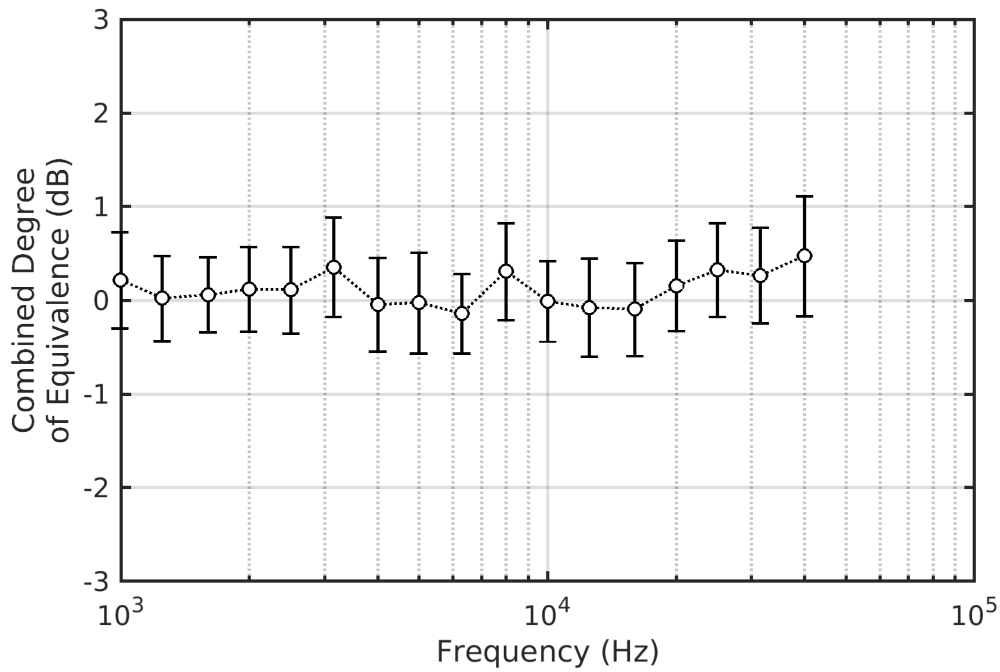

Figure D-26. Comparison MC-1 – Degree of Equivalence – APTF

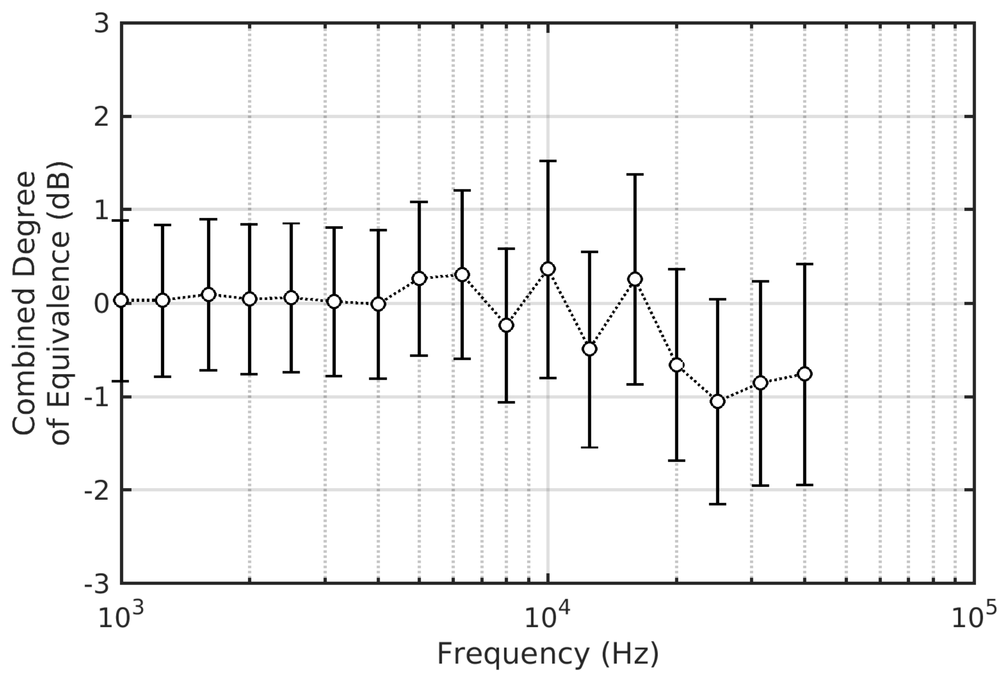

Figure D-27. Comparison MC-1 – Degree of Equivalence – LEFAC

Table D-7. Comparison MC-1 – Hydrophones – Secondary Calibration

MC-1	Comparison Reference Value		Relative Degree of Equivalence					
	F37 SN A117		OTF		APTF		LEFAC	
Frequency kHz	M dB V/uPa	2u dB	r_m dB	$2u_m$ dB	r_m dB	$2u_m$ dB	r_m dB	$2u_m$ dB
1.00	-203.07	0.34	-0.25	0.53	0.22	0.51	0.03	0.86
1.25	-203.17	0.32	-0.04	0.53	0.02	0.45	0.03	0.81
1.60	-203.24	0.30	-0.14	0.52	0.06	0.40	0.09	0.81
2.00	-203.25	0.32	-0.19	0.53	0.12	0.45	0.04	0.80
2.50	-203.11	0.33	-0.20	0.56	0.11	0.46	0.06	0.80
3.15	-203.48	0.35	-0.41	0.55	0.36	0.53	0.02	0.79
4.00	-203.38	0.35	0.06	0.57	-0.04	0.50	-0.01	0.80
5.00	-203.45	0.37	-0.11	0.61	-0.03	0.54	0.26	0.82
6.30	-203.36	0.32	0.14	0.58	-0.14	0.42	0.31	0.90
8.00	-203.43	0.35	-0.27	0.55	0.31	0.52	-0.24	0.82
10.0	-203.42	0.33	-0.06	0.53	-0.01	0.43	0.36	1.16
12.5	-203.25	0.35	0.18	0.52	-0.08	0.52	-0.49	1.05
16.0	-202.85	0.35	0.06	0.55	-0.10	0.50	0.26	1.12
20.0	-202.24	0.35	-0.03	0.55	0.16	0.48	-0.66	1.02
25.0	-201.88	0.34	-0.15	0.51	0.33	0.50	-1.05	1.10
31.5	-201.44	0.35	-0.10	0.51	0.27	0.51	-0.85	1.09
40.0	-209.11	0.41	-0.25	0.59	0.47	0.64	-0.76	1.18

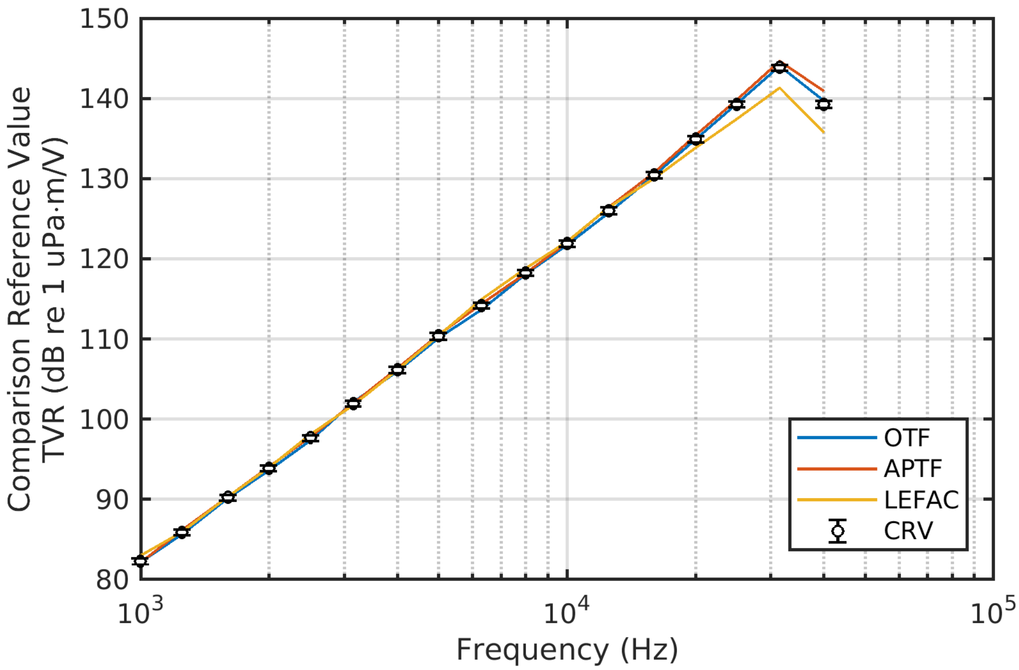

Figure D-28. Comparison MC-2 – Type F37 SN A117 – Transmitting Voltage Response

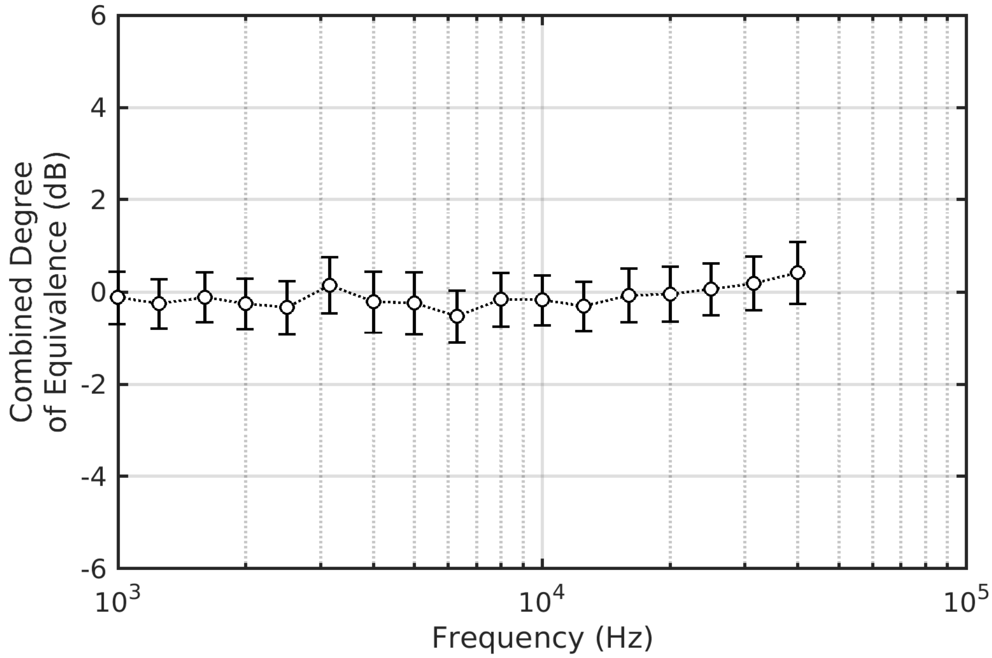

Figure D-29. Comparison MC-2 – Degree of Equivalence – OTF

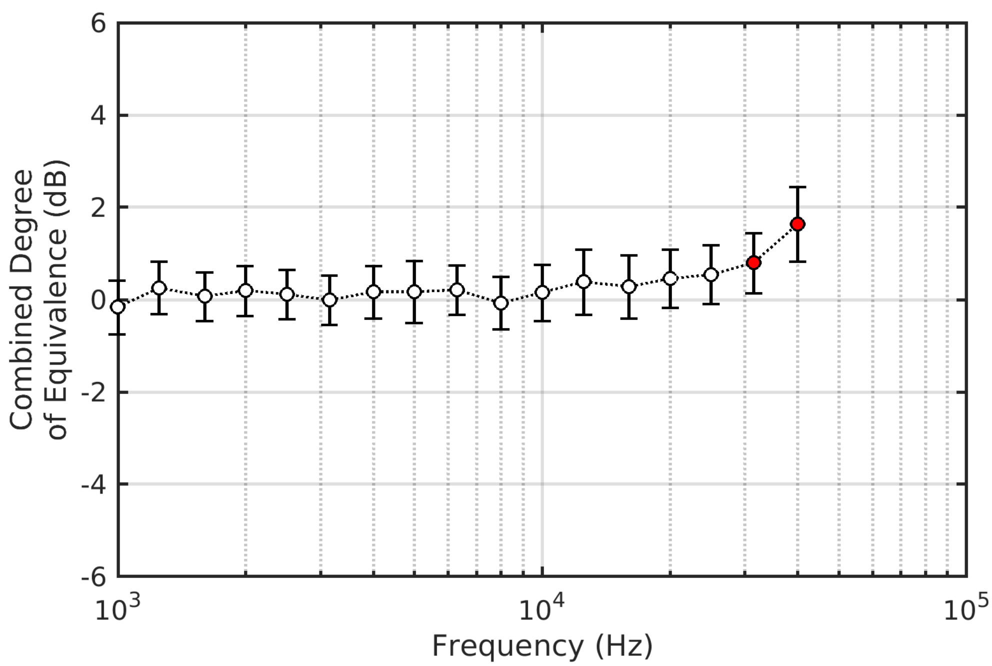

Figure D-30. Comparison MC-2 – Degree of Equivalence – APTF

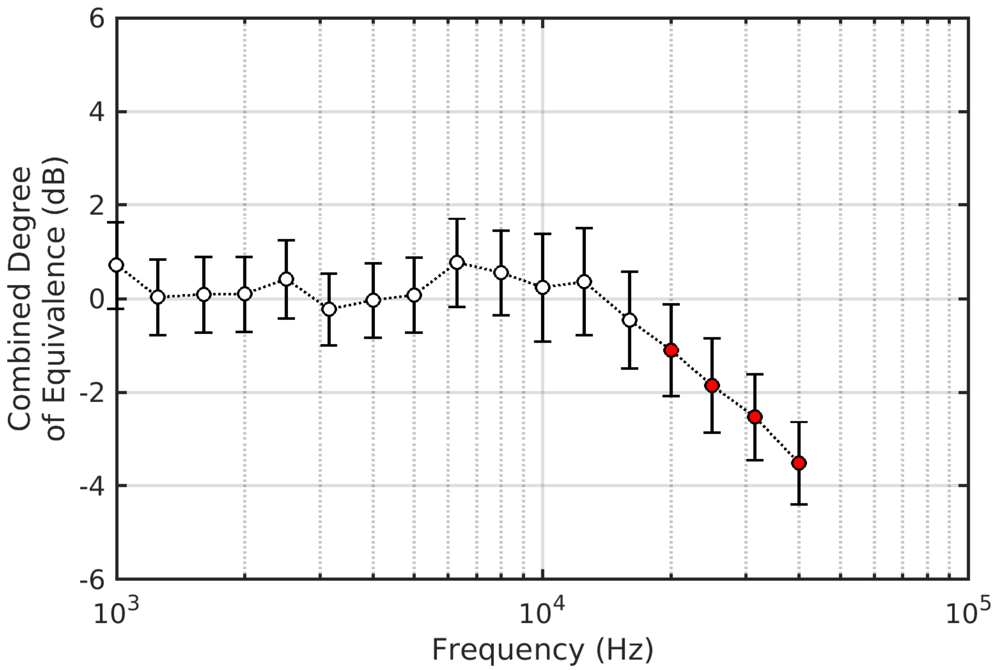

Figure D-31. Comparison MC-2 – Degree of Equivalence – LEFAC

Table D-8. Comparison MC-2 – Projectors – Transmitting Voltage Response

MC-2	Comparison Reference Value		Relative Degree of Equivalence					
	F37 SN A117		OTF		APTF		LEFAC	
Frequency kHz	S dB uPa·m/V	2u dB	r_m dB	$2u_m$ dB	r_m dB	$2u_m$ dB	r_m dB	$2u_m$ dB
1.00	82.27	0.38	-0.12	0.57	-0.16	0.58	0.72	0.92
1.25	85.89	0.36	-0.25	0.54	0.26	0.57	0.04	0.81
1.60	90.23	0.35	-0.11	0.54	0.07	0.53	0.09	0.81
2.00	93.87	0.35	-0.25	0.55	0.19	0.54	0.10	0.81
2.50	97.68	0.36	-0.34	0.57	0.11	0.53	0.42	0.83
3.15	101.97	0.36	0.15	0.61	-0.01	0.53	-0.22	0.77
4.00	106.18	0.38	-0.22	0.66	0.17	0.57	-0.03	0.79
5.00	110.37	0.41	-0.23	0.67	0.17	0.67	0.08	0.80
6.30	114.17	0.36	-0.52	0.56	0.21	0.53	0.77	0.95
8.00	118.26	0.38	-0.16	0.58	-0.07	0.57	0.56	0.90
10.0	121.91	0.39	-0.18	0.54	0.15	0.60	0.24	1.15
12.5	126.02	0.40	-0.30	0.53	0.38	0.70	0.37	1.15
16.0	130.48	0.41	-0.07	0.58	0.28	0.69	-0.45	1.04
20.0	134.94	0.40	-0.05	0.59	0.46	0.63	-1.10	0.98
25.0	139.29	0.39	0.06	0.56	0.54	0.63	-1.85	1.01
31.5	143.85	0.40	0.19	0.58	0.80	0.65	-2.53	0.91
40.0	139.27	0.45	0.42	0.67	1.64	0.80	-3.51	0.88

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