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Underwater Sound Reference Division (USRD) Annual Report: 2019

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PREFACE

This report was prepared under NUWC Division Newport Network Activity No. 400000062661/0010 for 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).

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14. ABSTRACT

The Underwater Sound Reference Division (USRD) at the Naval Undersea Warfare Center Division, Newport is the institute designated by the National Institute of Standards and Technology (NIST) to hold national measurement standards for sound in water, to disseminate those standards in the United States, and to provide traceability to the International System of Units. Thus, the USRD resides at the top of the U.S. national metrology system within the limited scope of its designation—the acoustic pascal in water. National measurement standards delegated to the USRD are disseminated through the laboratory's calibration services to industry, government, and academic institutions in the United States and internationally. As a NIST designated institute, the USRD must conform to the requirements of ISO/IEC 17025 and maintain its accreditation through periodic assessment of the laboratory by the National Voluntary Laboratory Accreditation Program. The laboratory engages in activities required by its quality management system and claimed measurement capabilities, including internal audits, operator training, proficiency testing, and other activities intended to ensure the consistent delivery of calibration services with known measurement uncertainties. This report summarizes the activities of the USRD related to its quality system and measurement capabilities throughout 2019, followed by a summary of activities planned for 2020.

15. SUBJECT TERMS

ISO/IEC 17025, Quality Management System, Underwater Acoustic Metrology, Calibration, Designated Institute

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TABLE OF CONTENTS

| Section | Page |
|--|------|
| LIST OF ILLUSTRATIONS | ii |
| LIST OF TABLES | iii |
| LIST OF ABBREVIATIONS AND ACRONYMS | iii |
| LIST OF MATHEMATICAL SYMBOLS AND UNITS | iv |
| 1 INTRODUCTION | 1 |
| 2 SIGNIFICANT ACTIVITIES IN 2019 | 3 |
| 2.1 Laboratory Status | 3 |
| 2.2 Quality System..... | 3 |
| 2.2.1 ISO/IEC 17025:2005 Accreditation..... | 3 |
| 2.2.2 Internal Audit | 3 |
| 2.2.3 Management Review | 4 |
| 2.2.4 Corrective and Preventive Actions | 4 |
| 2.2.5 Personnel Training and Qualifications..... | 5 |
| 2.2.6 Statistical Process Control System Research..... | 6 |
| 2.3 Metrology and Calibration Services | 7 |
| 2.3.1 Laboratory Workload Summary | 7 |
| 2.3.2 Laboratory Upgrades and Improvements..... | 8 |
| 2.3.3 Uncertainty Statements | 8 |
| 2.3.4 Proficiency Testing | 8 |
| 2.4 External Activities | 14 |
| 3 PLANNED ACTIVITIES 2020..... | 15 |
| 3.1 Laboratory Status | 15 |
| 3.2 Quality System..... | 15 |
| 3.2.1 ISO/IEC 17025:2017 Accreditation..... | 15 |
| 3.2.2 Internal Audits and Reviews..... | 16 |
| 3.2.3 Personnel Training and Qualifications..... | 16 |
| 3.3 Metrology and Calibration Services | 16 |
| 3.3.1 Proficiency Testing | 16 |
| 3.3.2 Laboratory Upgrades and Improvements..... | 16 |
| 3.4 External Activities | 16 |
| 4 CONCLUSION..... | 19 |
| APPENDIX A—CORRECTIVE AND PREVENTIVE ACTION REQUESTS | A-1 |
| APPENDIX B—CALCULATING COMBINED DEGREES OF EQUIVALENCE | B-1 |

TABLE OF CONTENTS (Cont'd)

| Section | Page |
|---|------|
| APPENDIX C—LABORATORY UNCERTAINTY STATEMENT SUMMARIES.... | C-1 |
| APPENDIX D—PROFICIENCY TEST PROGRAM RESULTS | D-1 |
| REFERENCES | R-1 |

LIST OF ILLUSTRATIONS

| Figure | Page |
|---|------|
| 1 Statistical Process Control Chart | 7 |
| 2 Bilateral Comparison 1—Primary Calibration of Hydrophones | 10 |
| 3 BC-1 Measurements: 2019 and 2018..... | 12 |
| 4 BC-1 Degrees of Equivalence with 2018 Data Included..... | 12 |
| D-1 BC-1: Type H52 SN 80—Receive Voltage Sensitivity..... | D-1 |
| D-2 BC-1: Degree of Equivalence—OTF..... | D-1 |
| D-3 BC-1: Degree of Equivalence—APTF | D-2 |
| D-4 BC-2: Type H64 SN 2—Receive Voltage Sensitivity..... | D-4 |
| D-5 BC-2: Degree of Equivalence—OTF..... | D-4 |
| D-6 BC-2: BC-2: Degree of Equivalence—APTF..... | D-5 |
| D-7 MC-1: Type F37—Receive Voltage Sensitivity..... | D-6 |
| D-8 MC-1: Type H64—Receive Voltage Sensitivity | D-6 |
| D-9 MC-1: Degree of Equivalence—OTF..... | D-7 |
| D-10 MC-1: Degree of Equivalence—APTF | D-7 |
| D-11 MC-1: Degree of Equivalence—LOFAC | D-8 |
| D-11 MC-2: Type F37—Receive Voltage Sensitivity..... | D-9 |
| D-12 MC-2: Degree of Equivalence—LOFAC | D-9 |
| D-13 MC-2: Degree of Equivalence—LEFAC..... | D-10 |
| D-14 MC-2: Degree of Equivalence—OTF..... | D-10 |
| D-15 MC-2: Degree of Equivalence—APTF | D-11 |
| D-16 MC-3: Type H52—Receive Voltage Sensitivity | D-13 |
| D-17 MC-3: Degree of Equivalence—LOFAC | D-13 |
| D-18 MC-3: Degree of Equivalence—LEFAC..... | D-14 |
| D-19 MC-3: Degree of Equivalence—OTF..... | D-14 |
| D-20 MC-4: Type F37—Transmitting Voltage Response..... | D-16 |
| D-21 MC-4: Degree of Equivalence—OTF..... | D-16 |
| D-22 MC-4: Degree of Equivalence—APTF | D-17 |
| D-23 MC-4: Degree of Equivalence—LEFAC..... | D-17 |

LIST OF TABLES

| Table | Page |
|--|------|
| 1 Summary of Corrective and Preventive Actions | 5 |
| 2 Proficiency Test Program Comparisons | 9 |
| C-1 Uncertainty Statements: Open Tank Facility..... | C-2 |
| C-2 Uncertainty Statement: Low-Frequency Facility..... | C-3 |
| C-3 Uncertainty Statements: Acoustic Pressure Tank Facility..... | C-4 |
| C-4 Uncertainty Statements: Leesburg Facility..... | C-5 |
| D-1 BC-1: Comparison Results | D-3 |
| D-2 BC-2: Comparison Results | D-5 |
| D-3 MC-1: Comparison Results..... | D-8 |
| D-4 MC-2: Comparison Results..... | D-12 |
| D-5 MC-3: Comparison Results..... | D-15 |
| D-6 MC-4: Comparison Results..... | D-18 |

LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|--------|--|
| APTF | Acoustic Pressure Tank Facility |
| ARB | Assessment Review Board |
| AUV | Acoustics, Ultrasound and Vibration |
| BC | Bilateral Comparison |
| BIPM | International Bureau of Weights and Measures |
| CAPA | Corrective and Preventive Action |
| CCAUV | Consultative Committee for Acoustics, Ultrasound and Vibration |
| CIPM | International Committee of Weights and Measures |
| CMC | Calibration and Measurement Capability |
| Comb. | Combined |
| CPAR | Corrective and Preventive Action Request |
| CRV | Comparison Reference Value |
| DI | Designated Institute |
| DoE | Degree of Equivalence |
| ECD | Estimated Completion Date |
| IEC | International Electrotechnical Commission |
| ISO | International Organization for Standardization |
| KCDB | Key Comparison Database |
| LEFAC | Leesburg Facility |
| LOFAC | Low-Frequency Facility |
| Max. | Maximum |
| MC | Multilateral Comparison |
| Meas. | Measurement |
| METCAL | Metrology and Calibration |
| Min. | Minimum |

LIST OF ABBREVIATIONS AND ACRONYMS (Cont'd)

| | |
|------------|---|
| MOU | Memorandum of Understanding |
| MRA | Mutual Recognition Arrangement |
| NIST | National Institute of Standards and Technology |
| NPL | National Physical Laboratory |
| NUWC | Naval Undersea Warfare Center |
| NUWCDIVNPT | Naval Undersea Warfare Center Division, Newport |
| NVLAP | National Voluntary Laboratory Accreditation Program |
| OTF | Open Tank Facility |
| QMS | Quality Management System |
| QSTF | Quality System Task Force |
| RMO | Regional Metrology Organization |
| RVS | Receive Voltage Sensitivity |
| SI | International System of Units |
| SIM | Inter-American Metrology System |
| SN | Serial Number |
| Std. | Standard |
| TAG | Technical Advisory Group |
| THAMES V2 | Transducer and Hydrophone Acoustic Measurement and Evaluation System, Version 2 |
| TVR | Transmit Voltage Response |
| UARC | University Affiliated Research Center |
| UCL | Upper Control Limit |
| UK | United Kingdom |
| Uncert. | Uncertainty |
| USRD | Underwater Sound Reference Division |

LIST OF MATHEMATICAL SYMBOLS AND UNITS

| | |
|----------------------|--|
| A | Design matrix |
| <i>d</i> | Distance between acoustic centers of two projectors |
| <i>d</i> | Degree of equivalence |
| d | Degrees of equivalence |
| <i>f</i> | Frequency |
| <i>i_p</i> | Projector input current |
| <i>m</i> | Index enumerating laboratories |
| <i>M</i> | Maximum value of index <i>m</i> enumerating laboratories |
| <i>MD</i> | Mahalanobis distance |
| MPa | Megapascal |
| <i>n</i> | Index enumerating acoustic devices |
| <i>N</i> | Number of frequencies at which the acoustic transfer impedance was collected |

LIST OF MATHEMATICAL SYMBOLS AND UNITS (Cont'd)

| | |
|--------------|---|
| N | Maximum value of index n enumerating acoustic devices |
| r | Relative degree of equivalence, singular instance |
| \mathbf{r} | Relative degree of equivalence, vector of instances |
| \mathbf{V} | Covariance matrix |
| u | Standard uncertainty |
| w | Weight used to compute weighted mean y |
| x | Measured value |
| y | Weighted mean of measured values x having weights w |
| Z | Impedance |
| α | Sample drawn from a multivariate Gaussian distribution |
| δ | Uncertainty component arising from a random effect |
| e_h | Hydrophone output voltage |
| λ | Uncertainty component arising from a systematic effect |

UNDERWATER SOUND REFERENCE DIVISION (USRD) ANNUAL REPORT: 2019

1. INTRODUCTION

The Underwater Sound Reference Division (USRD) at the Naval Undersea Warfare Center (NUWC) Division, Newport, RI, is the institute designated by the National Institute of Standards and Technology (NIST) to hold national measurement standards for sound in water, to disseminate those standards in the United States, and to provide traceability for underwater acoustic measurements and calibrations to the International System of Units (SI). Thus, the USRD resides at the top of the U.S. national metrology system for physical quantities within the limited scope of its designation—the acoustic pascal in water (reference 1).

To function as a NIST designated institute, references 2 and 3 require that the (delegated) national measurement standards are disseminated through measurement and calibration services that are accredited under ISO/IEC 17025.* Thus, traceable measurements for sound in water performed in 2019 were accredited under ISO/IEC 17025:2005 (reference 4) by the National Voluntary Laboratory Accreditation Program (NVLAP) (reference 5). This included acoustic measurements performed in an open tank facility (OTF) and a low-frequency facility (LOFAC), both of which were tasked with primary and secondary calibrations of underwater acoustic transducers. It was through the calibrations performed in these facilities that the USRD disseminated measurement standards for sound in water to other government laboratories, industry, and academia in the United States and internationally.

To maintain its accreditation, the USRD operated a quality management system (QMS) that conformed to the requirements of ISO/IEC 17025:2005. The USRD QMS included requirements that specified processes and procedures for a wide variety of activities, including internal audits, management reviews, and proficiency testing, to name a few. The USRD was also required to issue periodic reports of these activities and to make such reports available to the NVLAP, to the NIST Quality Manager, and to the Inter-American Metrology System (SIM) (reference 6)—the regional metrology organization (RMO) for the Americas.

The purpose of this document is to report significant activities carried out by the USRD in 2019 and those planned for 2020, thus satisfying certain requirements specified by ISO/IEC 17025:2005 and other requirements related to its role as the U.S. designated institute for sound in water.

*ISO/IEC 17025 is a standard promulgated jointly by the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC).

2. SIGNIFICANT ACTIVITIES IN 2019

2.1 LABORATORY STATUS

The most significant events of 2019 were related to the appointment of the USRD as the NIST designated institute (DI) for sound in water. In particular, a memorandum of understanding (MOU) was executed between NIST and the U.S. Navy in September 2019 that named NUWC-USRD as the U.S. designated institute for sound in water (reference 7). This was followed in November 2019 by NIST's notice to the International Committee for Weights and Measures, Mutual Recognition Arrangement (CIPM-MRA) that it had designated the USRD as the U.S. institute responsible for national measurement standards for "acoustics: sound in water" (reference 8).

2.2 QUALITY SYSTEM

2.2.1 *ISO/IEC 17025:2005 Accreditation*

Throughout 2019, the USRD continued to operate under its initial accreditation, which was valid through June 2020. The scope of the laboratory's accreditation included the following measurement and 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.

The USRD had planned (reference 9) to revise its quality management system in 2019 for conformance to the updated requirements of ISO/IEC 17025:2017 (reference 10). However, implementation of the new quality system was postponed until the following year. Instead, the laboratory developed and implemented certain quality processes (e.g., statistical process controls, and "risks and opportunities") required by the 2017 version of the standard so that their feasibility and effectiveness could be confirmed prior to enshrining them in a revised quality system.

2.2.2 *Internal Audit*

The USRD received an internal audit of its quality system on 21–25 October 2019 (reference 11). The laboratory was audited as part of a larger quality system functional audit across all of NUWC Division Newport activities and processes. The functional audit was conducted by personnel from various NUWC Division Newport departments, each with relevant experience in quality systems. Auditors were not 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 2018.

The audit results included a finding of noncompliance in the Corrective and Preventive Action Request (CPAR) process, which was assessed as ineffective. It was determined that the process was ineffectively managed, which rendered it less useful for its intended purpose. It was also noted that this had been a recurring issue, as identified in references 12 and 13.

The audit identified the following specific issues requiring attention:

- The status of corrective actions not maintained as current
- Estimated completion dates not updated
- Numerous actions with past due estimated completion dates
- Corrective actions not assigned to a person for action.

In response to the audit findings, Corrective and Preventive Action Request (CPAR) 0041 (“CAPA Process Ineffectiveness”) was opened on 5 November 2019. The root cause was determined to be a “lack of management oversight” (see CPAR-0041 in appendix A). The corrective actions addressed each of the specific issues identified in the audit and implemented planned, periodic review of all open CPAR at monthly branch meetings with responsible persons providing updates for progress. CPAR-0041 was closed on 16 December 2019.

2.2.3 Management Review

The laboratory’s quality system requires the USRD manager to conduct a management review annually. The review was initially planned to take place in the fourth quarter of 2019, following migration of the quality system to ISO/IEC 17025:2017. Scheduling of the review was intended to provide an early self-assessment and to identify any issues that might have arisen following deployment of the revised quality system. However, as discussed in section 2.2.1, formal introduction of the new quality system was delayed until the first quarter of 2020 to allow for development of new quality processes, such as the statistical process controls required to monitor the laboratory’s calibration services. As a result, the USRD management review was also postponed until early 2020 to follow introduction of the revised quality system and to precede the NVLAP assessment scheduled for the second quarter of 2020.

2.2.4 Corrective and Preventive Actions

The USRD maintains a program for the identification and resolution of Corrective and Preventive Action Requests (CPAR). The CPAR process is used to facilitate the prevention, identification, tracking, and resolution of laboratory operations that do not conform to the requirements of the USRD QMS. The process is also used to identify and resolve elements within the USRD QMS that do not conform to the requirements of ISO/IEC 17025:2005.

At the start of 2019, there were 17 open CPAR, with a median age of 10 months. Over the course of the year, six CPAR were closed at a median age of 11.5 months and six CPAR

were opened. Thus, at the end of the year, 17 CPAR were open, with a median age of 13 months. Table 1 provides a summary of open action requests at the start and the end of the year. As inspection of the table shows, the median age of open actions increased from 10 to 13 months over the course of the year.

As noted in section 2.2.2, the USRD corrective action process was assessed as “ineffective” during an internal audit performed in November 2019. As the year came to a close, an effort to address this issue was underway, and a number of corrective actions were ready for closure in the early part of 2020.

Table 1. Summary of Corrective and Preventive Actions

| Date | Number of CPAR Open | CPAR Age (Months) | | |
|-------------|---------------------|-------------------|--------|---------|
| | | Minimum | Median | Maximum |
| 1 Jan 2019 | 17 | 1 | 10 | 19 |
| 31 Dec 2019 | 17 | 4 | 13 | 31 |

2.2.5 Personnel Training and Qualifications

The USRD has established policies and procedures for the training and qualification of laboratory personnel for OTF and LOFAC calibrations. 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 the satisfaction of training requirements and lists of qualified operators.

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 completion of the following:

- Objectives of the training curriculum, including the specific procedure
- Required reading:
 - Quality Management System (i.e., QM-USRD-001 Quality Manual)
 - Theory (i.e., relevant texts and methods such as IEC 60565 (references 14, 15))
 - Practice (i.e., system operator’s manual and local calibration procedure)
- On-the-job training (i.e., minimum time in training and number of calibrations)
- Practical examination (i.e., specified calibrations and crane operator certifications).

In addition to initial qualification of laboratory personnel, continued proficiency is monitored by the performance of laboratory spot checks and through execution of an annual proficiency testing program (see section 2.3.4). 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 as published in the laboratory’s scope (reference 16).

Laboratory personnel assignments were stable throughout 2019. Thus, no initial operator qualifications were issued.

2.2.6 *Statistical Process Control System Research*

While not required by ISO/IEC 17025:2005 (reference 4), the USRD conducted research and development to support deployment of statistical procedures designed to ensure the validity of its measurements. The project was undertaken to prepare for migration of the USRD quality system to ISO/IEC 17025:2017 (reference 10), which does require process controls based on statistical analysis of laboratory data. An initial study of a method to develop Shewhart type control charts (reference 17) for frequency-dependent acoustic measurements was completed.

An analysis method based on the Mahalanobis distance (reference 18) was successfully deployed for secondary calibrations performed in the open tank facility. The procedure makes use of the acoustic transfer impedance measured while calibrating a hydrophone in accordance with reference 14. The acoustic transfer impedance Z , as applied to the free-field calibration method, is given by

$$Z = \frac{e_h}{i_p} d, \quad (1)$$

where e_h is the voltage output by a calibrated reference measuring hydrophone, i_p is the current input to an acoustic projector, and d is the distance between their acoustic centers. Since the Type A uncertainty for secondary calibration of a hydrophone is controlled by the variance of the acoustic transfer impedance measurements, it is an ideal parameter for the monitoring and control of laboratory operations. However, because the impedance is measured at a large number of frequencies, a method to reduce those data to yield a metric suitable for monitoring with a Shewhart type of control chart was needed.

The transfer impedance data needed to develop a process model representing the in-control condition were collected over a period of 3½ months in 2019. Each frequency-dependent measurement of acoustic transfer impedance was treated as a single measure in an N -dimensional parameter space. The dispersion of these measurements was characterized by the distance from the mean location in that parameter space to each individual measurement. The measure used was the Mahalanobis distance (reference 18) because it accounts for the variance and covariance of the underlying data, as opposed to the Euclidean distance which does not. Once a sufficient number of measurements representing the in-control condition were collected, a process model was computed and used to monitor continuing laboratory operations.

Once deployed, a process control algorithm was used to compute the Mahalanobis distance between each subsequent impedance measurement and the mean of data included in the process model. This distance was compared to an upper control limit (UCL) estimated to include the 99th percentile measurement. In cases where the Mahalanobis distance to the mean transfer impedance measurement was less than the UCL, the process was assessed to be *in-control*, whereas those that exceeded the UCL were assessed as *out-of-control*.

Figure 1 shows the control chart used to monitor the acoustic transfer impedance measurements in the open tank facility over a frequency range of 1 to 10 kHz. Each marker represents an N -dimensional measurement, where N is the number of frequencies at which the acoustic transfer impedance was collected and MD^2 is the square of its distance from the mean location in the N -dimensional parameter space (i.e., Mahalanobis distance). The process model was defined using data collected from 1 August to 14 November 2019, shown by the highlighted area in the figure. Three outliers were rejected from the process model, based on Hotelling's T^2 test (reference 19) with a critical value of 0.01. Subsequent measurements were compared to the UCL and assessed accordingly. As shown in the figure, acoustic transfer impedance measurements performed after 14 November were all assessed as in-control.

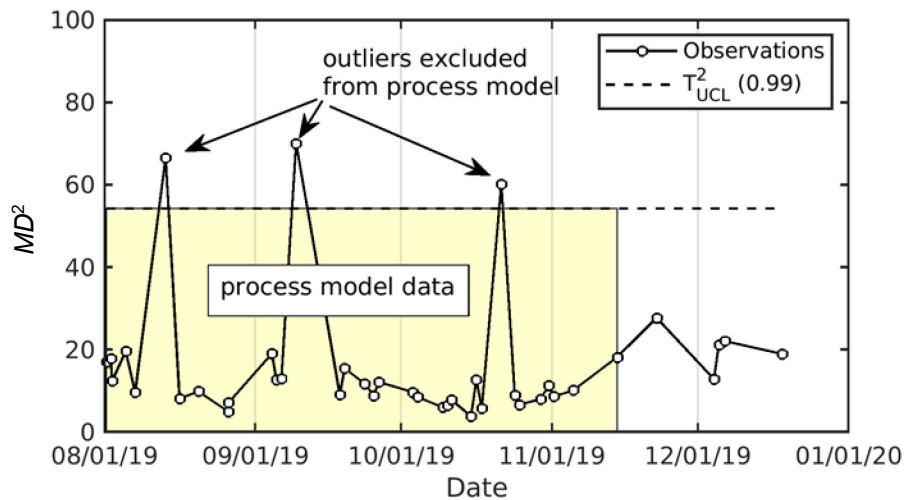


Figure 1. Statistical Process Control Chart

2.3 METROLOGY AND CALIBRATION SERVICES

2.3.1 Laboratory Workload Summary

The USRD began issuing ISO/IEC 17025:2005 compliant calibration certificates following its initial accreditation in July 2018, after which it issued 63 certificates through December of that year. In 2019, the USRD issued 391 calibration certificates for accredited services, 374 of which were for calibration of the underwater acoustic transducers that are disseminated to U.S. customers through a leasing program operated by the laboratory. Although the USRD standards leasing program has operated for many years to support the work of the Government, academia, and industry, these transducers now support a framework of metrological traceability to a U.S. national measurement standard.

2.3.2 Laboratory Upgrades and Improvements

There were no major improvements to USRD laboratory facilities in 2019. Although the laboratory identified and proposed a capital improvement project to enhance measurement capabilities at low frequency, the project was not funded. The low-frequency project remains a priority for the laboratory, and the proposal will be resubmitted for consideration in 2020.

The project involves recapitalization and modernization of two traveling-wave tubes operated by the USRD (reference 20). These systems provide the capability to calibrate transducers in a plane-progressive wave field at a very low frequency (i.e., 3 Hz). The operating environment during calibration includes temperatures from 3 to 35 °C and hydrostatic pressures up to 68.9 megapascals (MPa), equivalent to an ocean depth of 6.92 km. These measurement systems represent a unique capability for calibrating and characterizing underwater acoustic transducers in realistic environments, including operation at full ocean depth. On completion of this project, the laboratory would seek to expand the scope of its accredited services to include these two measurement systems.

2.3.3 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 of 2018, respectively (references 13, 21). In preparation for an upcoming assessment in the second quarter of 2020, the laboratory has implemented minor revisions to the uncertainty statements for its accredited services. In addition, uncertainty statements were developed to support expansion of the USRD scope to include calibration of hydrophones (primary and secondary) and projectors over the frequency range of 1 kHz to 250 kHz in the acoustic pressure tank facility (APTF) as described in reference 22.

2.3.4 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 2019 program conformed to most requirements of ISO 17043:2010 (reference 23). The program employed a series of intercomparisons between and among a set of participating laboratories. Although participation in the 2018 program was limited to USRD laboratories, the 2019 program was expanded to include other Navy facilities. Further expansion to include university affiliated research centers (UARC) was planned for 2020.

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 cause(s) and corrective actions in cases where that equivalence cannot be demonstrated through intercomparisons.

2.3.4.1 Proficiency Testing Program Plan. The 2019 proficiency testing program included a series of calibrations among USRD laboratories and four other Navy laboratories. USRD data and results are provided in this report; results for other Navy activities are reported in reference 24.

The comparisons performed among USRD laboratories are listed in table 2, which includes the participants, transducers, methods, and frequency ranges. The resulting calibration data and uncertainty estimates were analyzed to yield two bilateral and four multilateral comparisons between and among the participating laboratories. The bilateral comparisons were performed between the OTF and the APTF for primary and secondary calibrations of hydrophones. The multilateral comparisons were performed among all of the laboratories for applicable calibration services at common frequency sets.

Table 2. Proficiency Test Program Comparisons

| ID | Laboratories | | Transducer | | Calibration | | Frequency | |
|------|--------------|-------|------------|------|-------------|-----------|-----------|---------|
| | | | Type | SN | Meas. | Method | Min. | Max. |
| BC-1 | OTF | APTF | H52 | 80 | RVS | Primary | 1,000 | 250,000 |
| BC-2 | OTF | APTF | H64 | 2 | RVS | Secondary | 1,000 | 25,000 |
| MC-1 | OTF | APTF | F37 | A117 | RVS | Secondary | 1,000 | 1,600 |
| | LOFAC | | H64 | 2 | | | | |
| MC-2 | OTF | APTF | F37 | A117 | RVS | Secondary | 20 | 31,500 |
| | LOFAC | | | | | | | |
| MC-3 | OTF | LOFAC | H52 | 84 | RVS | Secondary | 20 | 100,000 |
| | LEFAC | | | | | | | |
| MC-4 | OTF | APTF | F37 | A117 | TVR | Secondary | 1,000 | 40,000 |
| | LEFAC | | | | | | | |

Notes:

Min. and max. frequencies are given in Hertz.

RVS: Receive voltage sensitivity (dB re 1 V/μPa).

TVR: Transmitting voltage response (dB re 1 μPa m/V).

Data collected for the comparisons listed in table 2 were analyzed using statistical methods employed in international key comparisons (references 25, 26) performed under the auspices of the International Committee of Weights and Measures, Mutual Recognition Arrangement (CIPM-MRA). Details of the statistical procedures are provided in appendix B. Calibration data for each comparison were processed to yield a degree of equivalence (DoE) for each laboratory, evaluated at preferred 1/3rd-octave-band center frequencies (reference 27).

The degree of equivalence represents the difference between a laboratory's measurement of a particular quantity and a comparison reference value (CRV). The degree of equivalence is expressed quantitatively by two terms: (1) the deviation of the laboratory's calibration result from the CRV and (2) the uncertainty of this deviation at the 95% level of confidence. In these comparisons, the CRV was calculated as the weighted mean of the sensitivities measured by the participants. The weights were determined from the inverse of the measurement variances (and covariances) that were computed using 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 C 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.

2.3.4.2 Bilateral Comparison 1: Primary Calibration of Hydrophones. Results of bilateral comparison 1 (BC-1) are shown in figure 2. Panel 2(a) shows the receive voltage sensitivity (RVS) measured by each of the participants, the CRV calculated using those sensitivities, and the respective uncertainty statements. Panels 2(b) and 2(c) summarize the comparison results as the degree of equivalence (markers) and uncertainty (error bars).

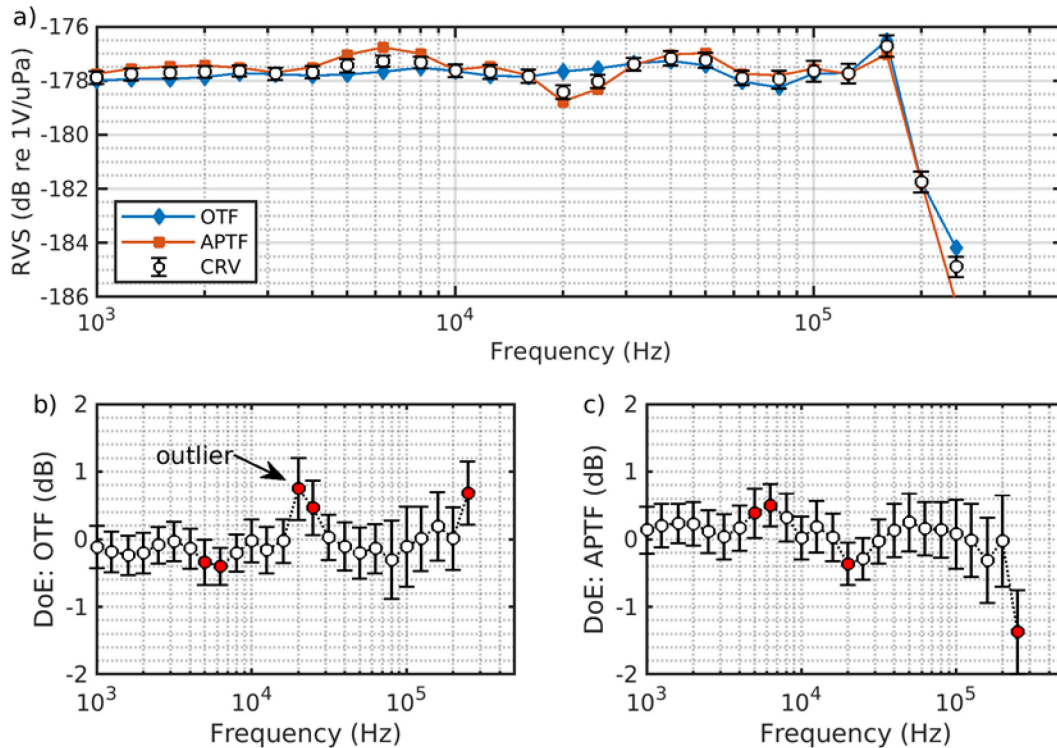


Figure 2. Bilateral Comparison 1—Primary Calibration of Hydrophones

Figure 2(b) provides comparison results for the OTF, where the DoE varied from -0.34 to 0.75 dB and the uncertainties ranged from 0.27 to 0.59 dB. Expressed this way, the ideal value of the DoE would be 0 dB, indicating that 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 when 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 most of the OTF measurements, except those 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 2(c) shows the comparison results for the APTF, where the DoE varied from -1.37 to 0.51 dB and the uncertainties ranged from 0.29 to 0.68 dB. In this case, the result included four outliers. As inspection of these three plots shows, the frequencies for which equivalence was not established were 5.0 – 6.3 kHz, 20 – 25 kHz, and 250 kHz. The frequency in the last of these three cases was located above the first resonance of the Type H52 hydrophone, in the region where the sensitivity varies most strongly with frequency. Increased variation in the performance of this model of hydrophone above 80 kHz is well established, as reported in reference 25, and is likely to have contributed to the relatively large dispersion between measurements performed in the two laboratories.

It is not usually possible to attribute the divergence in two measurements performed as part of a bilateral comparison to one of the two laboratories. However, the BC-1 comparison was also performed in 2018 and provides an additional data set with the potential to add information to the measurements submitted by each laboratory. Figure 3 provides an expanded view of the calibrations performed for comparison BC-1 in 2018 in addition to the 2019 measurements. As the figure shows, there were significant deviations in the 2019 APTF data at 5.0 – 6.3 kHz and 20 – 25 kHz relative to the other calibration results, including the previous APTF result (i.e., from 2018). Also shown in the figure is the influence that these measurements had on the comparison reference values in each year. Thus, the increase in deviations in 2019 between the laboratory measurements was correlated with the APTF data annotated in figure 3.

Data for the BC-1 comparison was reprocessed to include the 2018 data shown in figure 3. This effectively resulted in a multilateral comparison including data from both laboratories in both 2018 and 2019. The resulting comparison reference values for 2019 are shown in figure 4, where the deviations at frequencies less than 250 kHz mirrored those observed in the APTF measurements of 2019 (see figure 3). While the CRV shown in figures 2(b) and 2(c) confirm that measurements performed by the two laboratories were not equivalent to within the stated measurement uncertainties, they provide no indication of the cause. However, when prior year data are considered as shown in figures 4(a) and 4(b), the deviations were more clearly attributable to the APTF measurements.

This comparison result suggests that the APTF would benefit from increased emphasis on the validity of its measurements. Note that the APTF was not an accredited laboratory in 2019, and did not participate in some of the metrological activities used to ensure the validity of USRD measurements. For example, the APTF performed measurement system calibrations and primary calibrations of its reference measuring standards annually, as opposed to semi-annually as was done in the accredited laboratories. In addition, the APTF did not participate in as many proficiency test comparisons as the accredited laboratories.

The reduced participation of the APTF in certain metrological activities was a consequence of intense demand for its services. At the conclusion of 2019, the laboratory had a backlog of work that extended into early 2021. As a result, the time made available for metrological activities has generally coincided with annual maintenance, during which the laboratory was not available to external customers. However, the result of this comparison suggests that the success of the APTF as an accredited laboratory will require that it participate in the activities designed to ensure the validity of its measurements at the same level as other USRD laboratories. This change in laboratory operations would require time dedicated to the

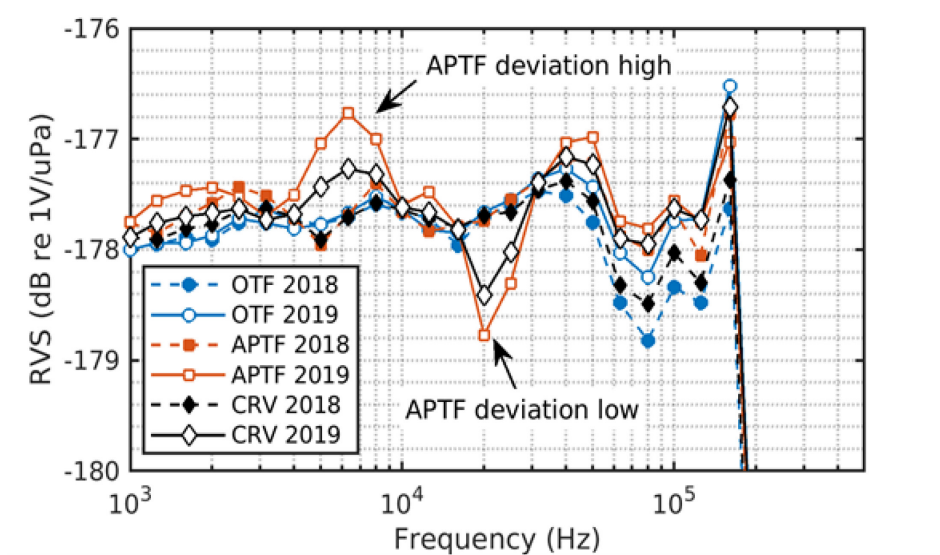


Figure 3. BC-1 Measurements: 2019 and 2018

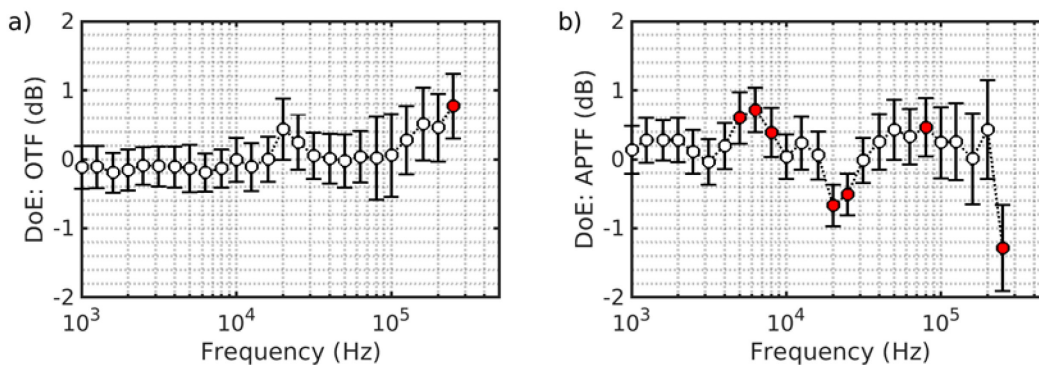


Figure 4. BC-1 Degrees of Equivalence with 2018 Data Included

metrological activities that ensure the validity of USRD measurements and a minor decrease in availability of the APTF to external customers. More specifically, it is estimated that adding 1 week per year (in addition to the week currently allocated to maintenance) would be sufficient to address some of the issues noted in the 2019 proficiency test program result for primary calibration of hydrophones.

Finally, the results presented in appendix D for the 2018 proficiency testing program does not include prior year results. Only data from 2019 is reported, as shown in figure 3 and in figures D-1 through D-3. Results for BC-1 are listed in table D-1. Thus, data reported in appendix D shows only the deviations between the two laboratories, not the likely cause of those deviations.

2.3.4.3 Bilateral Comparison 2: Secondary Calibration of Hydrophones. Bilateral comparison 2 (BC-2) was based on secondary calibrations of a Type H64 hydrophone by the OTF and APTF

over a frequency band of 1 to 25 kHz. This comparison demonstrated the equivalence of calibrations for a high-sensitivity hydrophone (i.e., -144 dB re 1 V/ μ Pa) near the upper limit for the scope of the USRD laboratory accreditation. The comparison results are provided in appendix D, in figures D-4 through D-5 and table D-2. The comparison was fully successful in that the measurements performed by both laboratories were equivalent at all frequencies.

2.3.4.4 Multilateral Comparison 1: Secondary Calibration of Hydrophones. Multilateral comparison 1 (MC-1) was designed to establish the equivalence of secondary hydrophone calibrations over the small range of frequencies (f) spanning 1.0 to 1.6 kHz. The importance of this frequency band is that it represents the range where two different calibration methods overlap. These include the free-field calibrations (reference 14) performed in the OTF and APTF, where $f \geq 1.0$ kHz, and the pressure calibrations (reference 15) performed in the LOFAC standing wave tube, where $f \leq 1.6$ kHz. Customer calibrations that span the range $1.0 \leq f \leq 1.6$ kHz require the use of both free-field and pressure methods. Therefore, laboratory measurements in the overlapping frequency range are particularly important because data from two laboratories, using two different measurement methods, appear on the same calibration certificate where small differences tend to be noticed, even when those differences are well-within the stated uncertainties.

The comparison employed two hydrophones: a Type F37 passive device with a nominal sensitivity of -203 dB re 1 V/ μ Pa and a high-sensitivity (preamplified) Type H64 hydrophone with a nominal sensitivity of -144 dB re 1 V/ μ Pa. A combined, relative degree of equivalence was computed for each laboratory at each frequency.

Results of the comparison are provided in appendix D, in figures D-7 through D-11 and table D-3. The equivalence of measurements performed by the OTF, APTF, and LOFAC was demonstrated in all cases except for the APTF at a frequency of 1.6 kHz where the DoE was 0.50 dB, while its uncertainty was only 0.49 dB—a deviation of only 0.01 dB from the requirement that the 95% confidence interval of the DoE must span zero before equivalence can be established. Thus, the comparison was largely successful in establishing the equivalence of USRD measurements in an important frequency band that is common to all of the laboratories.

2.3.4.5 Multilateral Comparison 2: Secondary Calibration of Hydrophones. Multilateral comparison 2 (MC-2) was used to establish the equivalence of secondary calibrations performed on the (passive) Type F37 transducer. All four of the USRD laboratories participated at frequency levels across at least part of the frequency band from 20 Hz to 31.5 kHz. The results are provided in appendix D, in figures D-11 through D-15 and summarized in table D-4.

The comparison successfully established the equivalence among the laboratories, with only isolated deviations noted at the upper end of the LOFAC frequency band, the lower end of the LEFAC frequency band, and at 6.3 kHz in the APTF. The APTF deviation was likely traceable to the primary calibration of the APTF primary reference standard as noted in the results for BC-1 (see section 2.3.4.2).

2.3.4.6 Multilateral Comparison 3: Secondary Calibration of Hydrophones. Multilateral comparison 3 (MC-3) was used to establish the equivalence of secondary calibrations of hydrophones among the LOFAC, LEFAC, and OTF. The calibrations were performed on a

Type H52 hydrophone over the frequency band from 20 Hz to 100 kHz, and equivalence was successfully demonstrated by all laboratories at all frequencies. Comparison results are provided in appendix D, in figures D-16 through D-19 and summarized in table D-5.

2.3.4.7 Multilateral Comparison 4: Transmitting Voltage Response of Projectors. Multilateral comparison 4 (MC-4) was used to establish equivalence for the measurement of the transmitting voltage response (TVR) of a Type F37 transducer. The participating laboratories were the OTF, APTF, and LEFAC. The comparison showed that the measurements were not equivalent among the laboratories in more cases than would be expected from random chance alone. A specific cause was not identified. The results are provided in appendix D, in figures D-20 through D-23 and summarized in table D-6.

2.4 EXTERNAL ACTIVITIES

The USRD has a long history of support for international and U.S. national metrological activities. It has provided technical expertise to standards writing committees: in particular, IEC Technical Committee 87: Ultrasonics. In addition, the USRD has provided a subject matter expert in underwater sound to NIST for every meeting of the CCAUV since its inception.

Among the external activities supported by the USRD in 2019 were the following:

- Inter-American Metrology System (SIM) Quality System Task Force (QSTF):
 - Hotel Bougainvillea, Santo Domingo, Costa Rica
 - 1–3 April 2019.
- U.S. Technical Advisory Group (TAG): IEC Technical Committee 87:
 - Hilton Orlando Bonnet Creek, Orlando, Florida
 - 5 April 2019.
- Acoustics, Ultrasound and Vibration (AUV) Workshop:
 - National Institute of Standards and Technology, Gaithersburg, Maryland
 - 9–11 July 2019.
- • Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV)
 - International Bureau of Weights and Measures (BIPM), Sèvres, France
 - 24–27 September 2019.
- International Electrotechnical Commission (IEC) General Meeting
 - Shanghai International Convention Center, Shanghai, China
 - 21–25 October 2019.

In addition to direct support to metrology-related activities, the USRD metrology staff serves on the faculty of the Ocean Engineering Department at the University of Rhode Island, where they teach sonar system engineering and serve on academic committees for graduate students matriculating for both the master's and doctoral degrees.

3. PLANNED ACTIVITIES 2020

3.1 LABORATORY STATUS

USRD activities planned for 2020 include migration of the quality system to the ISO/IEC 17025:2017 standard, periodic assessment by the NVLAP, and expanding the scope of the laboratory's accredited calibration services. In addition, the laboratory plans to present its quality system and measurement capabilities at an upcoming meeting of the Inter-American Metrology System (SIM), which will ultimately lead to publication of the laboratory's calibration and measurement capabilities (CMC) in the International Committee for Weights and Measures (CIPM) Key Comparison Database (KCDB).

3.2 QUALITY SYSTEM

3.2.1 ISO/IEC 17025:2017 Accreditation

The USRD is scheduled to be assessed by NVLAP against the ISO/IEC 17025:2017 standard in the second quarter of 2020. Thus, the quality system will be revised to conform with the newer standard and implemented for all administrative activities, laboratory operations, and calibration services provided by the USRD. The most significant changes in the new standard are the requirements to implement a risk management program to support operation of the laboratory and to employ statistical methods to ensure the validity of its measurements.

Implementing risk management within the USRD will be accomplished by adopting the existing risk management processes employed throughout NUWC Division Newport. As a result, disruption of laboratory operations is unlikely.

With regard to statistical process controls, an initial system was developed and deployed for secondary calibration of hydrophones in the OTF as described in section 2.2.6. The method, based on multidimensional distributions of acoustic transfer impedance measurements, was shown to be suitable for monitoring high-volume production calibration services. It is less useful when applied to low-volume operations because of the time required to collect data sufficient to produce a reliable process model. Thus, additional methods are required to provide a comprehensive system for monitoring and controlling all USRD measurement and calibration services. While some progress had been made in this area at the end of 2019, the remaining effort is planned for completion in the first quarter of 2020, prior to the scheduled NVLAP assessment.

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 and measurement of both the 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.

3.2.2 *Internal Audits and Reviews*

Internal audits and reviews in 2020 will focus on parts of the QMS that were previously identified as requiring additional attention (e.g., the CPAR process), were revised for conformance with ISO/IEC 17025:2017, or have had less operational exposure to the USRD QMS (e.g., the APTF). In addition, USRD has planned to significantly increase its laboratory audits with a goal of performing two each month, so that each laboratory will be audited semi-annually.

3.2.3 *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.

3.3 METROLOGY AND CALIBRATION SERVICES

3.3.1 *Proficiency Testing*

The USRD proficiency testing program consists of laboratory comparisons as described in section 2.3.4. However, whereas the 2019 program consisted of comparisons between and among USRD and other Navy laboratories, the 2020 program will expand to include participation by university affiliated research centers (UARC) that provide testing and measurement services in underwater sound.

3.3.2 *Laboratory Upgrades and Improvements*

The most significant activity planned for 2020 relates to the development of a new reciprocity coupler for primary calibration of hydrophones at low frequency. The existing system, although functional, incorporates certain non-optimal design features that will be improved by a new design. The most significant design enhancement will be the removal of all elastic materials with low compliance from the working fluid volume (e.g., sealing O-rings, transducer mounts, and wire insulation). It should be noted that the time required to develop, deploy, and validate a new primary reference standard is expected to be significant (i.e., more than 1 year).

The USRD will also resubmit its capital improvement project proposal (reference 20) for the overhaul and modernization of the USRD low-frequency measurement systems.

3.4 EXTERNAL ACTIVITIES

The USRD is scheduled to participate in several technical meetings related to underwater acoustic metrology in 2020. However, some (or all) of these events may be disrupted, postponed, or canceled due to an ongoing international health crisis.

The USRD was scheduled to attend a meeting of the U.S. Technical Advisory Group (TAG) to IEC Technical Committee 87 on 20 March 2020. Although it was originally scheduled to occur in New York prior to the start of the 2020 meeting of the American Institute of Ultrasound in Medicine (AIUM), the TAG meeting was rescheduled as a video teleconference.

Laboratory staff were scheduled to participate in a meeting of IEC Technical Committee 87: Ultrasonics in Madrid, Spain, during 15–19 June 2020. Significant activities to be supported at this meeting include two new work projects for the development of international standards. The first project involves development of an international standard for primary and secondary calibrations of acoustic motion sensors. The second work project is for development of an international standard for the calibration of underwater, autonomous noise recorders.

Two representatives of the laboratory were scheduled to attend the International Conference on Underwater Acoustics in Southampton, United Kingdom, during 6–10 July 2020, to present papers on metrology and measurements. Following the meeting, USRD staff were scheduled to visit the National Physical Laboratory (NPL) to discuss topics of mutual interest.

Finally, the USRD planned to attend the fall meeting of the Inter-American Metrology System (SIM), where its quality system and measurement capabilities were to be presented for approval. Once this milestone is successfully completed, the USRD will continue work toward the publication of its calibration and measurement capabilities in the CIPM Key Comparison Database (KCDB) (reference 28).

4. CONCLUSION

The USRD serves as the NIST designated institute for sound in water and holds national measurement standards within the limited scope of its designation. As such, the laboratory disseminates U.S. standards for the acoustic pascal in water through its accredited calibration services. In its first full year as an accredited laboratory, the USRD issued 391 calibration certificates conforming to the requirements of ISO/IEC 17025:2005.

The most significant milestone in 2019 was the designation whereby NIST formally delegated responsibility for the realization and maintenance of national measurement standards for sound in water to the USRD. The designation applies over a range of frequencies extending from 3 Hz to 2 MHz. Accredited calibration services at frequencies less than 1.6 kHz were provided over a range of environmental conditions characterized by hydrostatic pressure and temperature. Accredited calibration services above 1.6 kHz were only available at the ambient conditions provided in an open tank facility (OTF). The USRD also operated non-accredited measurement systems that provide unique capabilities, including an acoustic pressure tank facility (APTF); two low-frequency, traveling-wave tubes; and an open water acoustic test facility in Leesburg, FL. These capabilities are planned to be incorporated into the portfolio of accredited services, beginning with the APTF in 2020. Addition of the traveling-wave tubes will be sought after an overhaul and modernization.

The USRD has organized and executed a successful proficiency testing program that was expanded to include participants from other Navy activities that provide underwater acoustic measurement and calibration services. The program successfully established the equivalence of calibrations performed by USRD laboratories in most of the intercomparisons. Where the statistical condition for equivalence could not be shown, corrective actions were identified to increase laboratory proficiency. The most significant action identified was to increase participation by the APTF in metrology related activities so that it operates at the same level as the other accredited laboratories.

Also identified in 2019 was the need for greater attention to the Corrective and Preventive Action Request (CPAR) program. While a review of the laboratory's activities showed that it usually addressed issues identified in its operations, the record-keeping needed to manage an effective program was lacking. In response, the USRD instituted changes that include regularly scheduled review by the USRD manager and greater emphasis on involving the engineering staff to supplement quality assurance personnel. The objective of these changes was to enhance the ability to identify, track, correct, and close issues related to laboratory operations so as to ensure the quality and consistency of calibration services provided by the USRD.

Looking forward to 2020, the most significant milestone planned is the presentation and defense of the USRD quality system and measurement capabilities to the Inter-American Metrology System (SIM)—the Regional Metrology Organization (RMO) for the Americas. The approval and endorsement of the SIM is a prerequisite to publication of the laboratory's calibration and measurement capabilities (CMC) in the International Bureau of Weights and Measures (BIPM) Key Comparison Database (KCDB). As a formal requirement, it is

publication of CMC in the KCDB that will establish the traceability of USRD calibrations and measurements to the International System of Units (SI).

Establishing SI traceability for U.S. measurements in underwater sound was among the foremost of the NIST objectives in designating the USRD to hold a national measurement standard in its stead. Thus, it is in 2020 that the overarching objective for deployment of the USRD quality system, laboratory accreditation, MOU between the Navy and NIST, and the NIST designation itself may be accomplished.

APPENDIX A
CORRECTIVE AND PREVENTIVE ACTION REQUESTS

Note: The content of this appendix is reproduced unedited in its original form.

CPAR-0002: Supplementary Facility Procedures

Opened: May 30, 2017

Closed: N/A

Age: 31 months

This item was identified during the 2017 USRD internal audit when it was found that several laboratory processes lacked formal procedures. An extensive program to generate procedures for existing laboratory processes and those for which accreditation would be sought at a future date was undertaken. The corrective action was nearly complete at the end of 2019 and slated for closure in the first quarter of 2020.

CPAR-0004: USRD Measurement Uncertainty

Opened: May 31, 2017

Closed: January 10, 2019

Age: 19 months

This item was identified soon after introduction of the USRD quality management system and prior to initial accreditation. It remained open throughout the time required to perform and document the uncertainty studies that underpin the laboratory's scope of accreditation. The corrective action was completed with review and approval of USRD uncertainty statements during initial NVLAP assessment (March 2018) and NIST peer review (October 2018).

CPAR-0007: Round Robin Planning

Opened: May 31, 2017

Closed: January 10, 2019

Age: 19 months

This item was identified soon after introduction of the USRD quality management system and prior to initial accreditation. The initial action taken was to continue an informal round-robin program that had been in place at USRD for many years, supplemented by the claim that USRD participation in international key comparisons constituted adequate proficiency testing. In 2018, the USRD established a formal proficiency testing program throughout its laboratories. The program was modeled after the first international key comparison for primary calibration of hydrophones (reference 25). Results were reported in the 2018 annual report (reference 9).

CPAR-0013: Records Management

Opened: June 2, 2017

Closed: N/A

Age: 31 months

This item was identified prior to the initial NVLAP assessment. The records management of USRD needs to be updated to comply with both the USRD and NUWC quality manuals. As was noted in the Internal Audit Guide, not all USRD records had a defined retention requirement. While the actions required to correct this item were completed early in the USRD quality processes, this item was not administratively closed due to oversight. This oversight was in the process of being corrected at the end of 2019, with formal closure expected in the first quarter of 2020.

CPAR-0014: USRD Measurement Request Form

Opened: June 7, 2017

Closed: N/A

Age: 31 months

This item was identified during calibration of a customer device in which the desired frequency set was not accurately communicated to the performing laboratory. The initial approach to address the issue was an attempt to develop a better “measurement request form.” However, it was subsequently determined that, since the optimal content of the form may depend on the customer’s technical knowledge and that customer knowledge varies widely, a better approach would be to assist customers when completing measurement requests. It was found that increased person-to-person contact when defining the customer’s measurement request was effective when gathering the required information. While the actions required to correct this item were largely completed in 2018, this item was not administratively closed due to oversight. This oversight was in the process of being addressed at the end of 2019, with formal closure expected in the first quarter of 2020.

CPAR-0015: USRD Environmental Policies and Procedures

Opened: June 13, 2017

Closed: N/A

Age: 31 months

This item was identified prior to the initial NVLAP assessment. As cited in the most recent internal audit guide, the USRD QM is unclear or contradicts the actual practices of USRD regarding monitoring and maintaining acceptable environmental conditions for calibration laboratory facilities. The policies and procedures should be reviewed and the documentation and/or lab practices modified to agree with each other. This issue was also noted by NVLAP assessors during the initial assessment. While the actions required to correct this item were completed in 2019, this item was not administratively closed before the end of the year. Formal closure is expected in the first quarter of 2020.

CPAR-0017: OTF Angular Measurements

Opened: June 30, 2017

Closed: N/A

Age: 30 months

This item was identified prior to the initial NVLAP assessment. At the time, it was reported that “OTF currently has the capability to measure directional response but this capability is not part of the initial scope of accreditation. However, USRD would like to add this capability to the NVLAP scope of accreditation in the future.” While measurement of normalized directional response was added to the scope of USRD’s accreditation in November 2018, a commercial laboratory with the capability to provide an accredited calibration for the rotator head (i.e., angular measurements) was not found. This omission must be resolved, otherwise USRD may need to request withdrawal of normalized angular response measurements from the scope of accredited services.

CPAR-0018: LOFAC Primary References

Opened: December 2, 2017

Closed: January 9, 2019

Age: 13 months

This item was identified during replacement of Type H48 (serial number 1) reference hydrophone in the standing wave tube (System K) with a newly calibrated device (ser. no. 4). Shortly after installation of H48 serial number 4, it was discovered that its sensitivity appeared to be 0.5 to 0.7 dB too low. This was determined when attempting to calibrate a check standard (DT-369 serial number 12-0732R) used for a particular program. Investigation did not identify the root cause for the calibration error. However, the calibration was performed immediately after moving the coupler to a new laboratory and it may not have been operating correctly following the move. To prevent future occurrences, the sound field in the standing wave tube is measured with both the expiring and newly calibrated hydrophones installed to verify that measurements of the acoustic pressure agree to within the stated measurement uncertainties. This procedure has been formalized in USRD QP-21. Also included in this QP is the ongoing use of a check standard to monitor system performance over time.

CPAR-0023: Equipment Calibrations and Traceability

Opened: March 14, 2018

Closed: January 9, 2019

Age: 10 months

This item was identified during the initial NVLAP assessment. General purpose test equipment used by the USRD had been calibrated in the local Navy Metrology and Calibration Laboratory (METCAL), which is not accredited to any quality standard. A process was developed in conjunction with the METCAL laboratory whereby general purpose test equipment through which USRD establishes traceability to the SI are sent out to ISO/IEC 17025 accredited, commercial laboratories for calibration.

CPAR-0027: Receiving, Handling, and Inspection of Customer Items

Opened: March 14, 2018

Closed: N/A

Age: 21 months

This item was identified during the initial NVLAP assessment where it was noted that “there is not a specific instruction as to the identifying method being the specific model and serial number,” and other details of receipt inspection were missing. The root causes were determined to be the informality of historical USRD operating practices and insufficient familiarity of USRD personnel with the requirements of ISO/IEC 17025:2005. USRD QP-015 was revised to address the assessment comments.

CPAR-0028: QA of Data, Control Charts

Opened: March 14, 2018

Closed: N/A

Age: 21 months

This item was identified during the initial NVLAP assessment where it was commented that “the lab collects a large amount of QA data that is not aggregated in a way that trends are detectable,” and that “control charts are one means to perform robust analysis of QA data which is easily monitored.” This issue increased in urgency with new requirements in ISO/IEC 17025:2017

relating to validation of measurement results. The root cause was that, as a first time applicant, the USRD QA program was still maturing. The corrective action was the development of a comprehensive system of statistical process controls developed and operated by the USRD metrologist. The system was first applied to calibrations performed in the open tank facility in November 2019. Work to develop and implement similar methods for other laboratories was in progress at the end of 2019, with completion expected in the first quarter of 2020.

CPAR-0029: HTI Cable Hookup Error

Opened: April 18, 2018

Closed: January 10, 2019

Age: 9 months

This item was identified during calibration of a customer device when laboratory personnel applied 24 VDC to a signal line, resulting in damage to the device. The root cause was determined to be that “the operator only read the first part of the documentation provided by the customer,” and that “incorrect assumptions” were made about labels on the customer’s device. The corrective actions included notification to the customer of the error and retraining of facility personnel with respect to use of documentation for customer devices.

CPAR-0031: Cross-Facility Review Process

Opened: May 5, 2018

Closed: N/A

Age: 20 months

This item was identified when a calibration of a USRD leased standard was performed in two facilities (i.e., LOFAC and OTF) as needed to cover the entire frequency range for the device. However, sensitivities measured at the set of frequencies covered by both facilities (i.e., the overlap) did not agree to within the stated measurement uncertainty. A review of the procedure for the handling of data reported on calibration certificates found a total of 10 different issues that contribute to an inefficient process whereby calibration data from two facilities are published on the same certificate. A set of root causes and corrective actions were identified and deployed in 2019. Verification of the effectiveness remained in progress at the end of the year.

CPAR-0032: Bias in Primary Calibrations in Reciprocity Coupler

Opened: November 20, 2018

Closed: N/A

Age: 13 months

This item was identified when comparing the results of secondary calibrations performed with a Type H48 hydrophone as the reference, with the sensitivity expected for a number of small, passive devices (i.e., no preamplifier). In short, theory holds that the sensitivity of the passive devices should be independent of frequency when the devices are small with respect to an acoustic wavelength and operated well below their first resonance. However, the secondary calibrations showed a frequency-dependent trend as large as 0.8 dB that was attributed to the Type H48 reference hydrophone’s primary calibration and not to the receive response of the passive devices themselves. An investigation showed that the cause of the frequency-dependent bias in Type H48 sensitivity measured in the reciprocity coupler was due to the presence of highly compliant, elastic materials in the coupler (i.e., Buna-N rubber transducer mounts and neoprene O-rings, and wire insulation). A temporary procedure for calibration of Type H48

hydrophones was developed and deployed. Uncertainties included on calibration certificates for the H48 were increased to account for uncertainty in the applied correction. Uncertainties for devices calibrated using the H48 as the reference were likewise increased. An effort to design and manufacture a new reciprocity coupler was initiated.

CPAR-0033: Training Improvements

Opened: December 3, 2018

Closed: N/A

Age: 13 months

This item was identified during an internal audit where it was found that “the current training practices are not adequately formalized.” The root cause was determined to be that “USRD did not have a formally documented training program prior to implementation of its Quality Management System and is continuing to ... improve.” Changes to personnel training were implemented in 2019, and a successful audit was completed in August 2019. At the end of the year, formal closure was expected in the first quarter of 2020.

CPAR-0034: NUWC QMS Integration

Opened: December 3, 2018

Closed: N/A

Age: 13 months

This item was identified during an internal audit where it was found that the USRD QMS could be improved by incorporating elements of the NUWC DIVNPT QMS and supporting quality management procedures (QMP). Specific examples of QMP that should be referenced in the USRD QMS included QMP-01 Reporting of Problems and QMP-03 Cause Analysis & Cause Category Assignment. The root cause was identified as lack of familiarity with the NUWC QMS while the USRD QMS was under development. Corrective actions including updates to QP-USRD-003, -004 and -006 were completed in 2019. Formal closure of this CPAR was expected in the first quarter of 2020.

CPAR-0035: Improvements to USRD CPAR Process

Opened: December 3, 2018

Closed: N/A

Age: 13 months

This item was identified during an internal audit where it was found that the “USRD Corrective and Preventive Action process requires improvement.” Specific examples of issues included “findings and recommendations” not listed in the CPAR log, tracking of open and closed CPAR in separate spreadsheet files, and items listed in the “closed” spreadsheet indicated as “In-Progress” in the Status field. The planned actions included “changes will be implemented in FY2019.”

CPAR-0036: Adjustments to USRD Calibration Program

Opened: January 22, 2019

Closed: N/A

Age: 11 months

The Starrett tape measures purchased and used by USRD do not have recommended calibration intervals or expiration dates. While the lack of a calibration expiration does not necessarily

conflict with the USRD QMS, the USRD would like to explicitly define a policy to prevent possible nonconformities and confusion.

CPAR-0037: OTF-HPM Testing Offset

Opened: June 24, 2019

Closed: N/A

Age: 6 months

This item was identified following calibration of a customer device. This was a custom measurement, not within the scope of the laboratory's accreditation. The issue was that the measured sensitivity of the device appeared to be "significantly lower than it should have been." The facility lead recognized the issue and forwarded preliminary data to the Navy customer without comment. The facility lead did not notify the USRD manager, quality manager, or metrologist of the apparent discrepancy. When requested by the customer to recalibrate the device, its sensitivity was within specification. Subsequent investigation did not identify the root cause for the calibration error. The corrective action identified was that "extra care is taken to ensure everything is properly set up and data looks reasonable. If an issue is discovered, the customer is notified much sooner." Formal closure of this CPAR was expected in the first quarter of 2020.

CPAR-0038: THAMES V2 Algorithm Error

Opened: August 2, 2019

Closed: N/A

Age: 5 months

This item was identified during preparations to add calibration services provided by the acoustic pressure tank facility (APTF) to the USRD scope of accreditation. The THAMES V2 system uses an incorrect value for the density of water when performing primary calibrations of hydrophones using the method of three-transducer, spherical wave reciprocity. In addition, the system does not account for changes in water density in response to temperature and hydrostatic pressure. "Given the existence of a known, systematic, and correctable error in the calibration algorithm, the system must be updated as a prerequisite to NVLAP accreditation."

CPAR-0039: Transducer and Customer Item Shipping, Handling and Tracking

Opened: July 26, 2019

Closed: N/A

Age: 5 months

This item was identified when USRD personnel provided shipping instructions to a customer that did not comply with the USRD QP-015. The QP requires all incoming customer items (except for large items received directly at the APTF) to be received on the USRD loading dock. Instead, the customer was instructed to ship their items to be calibrated directly to the performing laboratory (i.e., OTF). This resulted in the requirements for receipt inspection, calibration request generation, and tracking to be bypassed.

CPAR-0040: OTF Measurement Inconsistencies, Suspected Air Problems

Opened: August 13, 2019

Closed: N/A

Age: 4 months

This item was identified when calibration certificates were rejected by the USRD metrologist due to apparent discrepancies between the sensitivities measured by the OTF and the historical values measured previously. The discrepancies were consistent with the presence of air bubbles on or near the acoustic transducers. An investigation showed a number of potential contributions, including introduction of air while removing and adding water to the tank, improper (or nonexistent) maintenance on the tank filter, and surface scratches and defects on the acoustic transducers. Several changes to OTF operating procedures were implemented, including the elimination of regular discharge and refill of water from the tank, a contract order for repair of the filter, and a request for the affected transducers to be rebuilt by standards (i.e., remove and replace transducer encapsulation/potting and cable strain reliefs). In addition, a statistical process control system, deployed to provide control charts to monitor the validity of OTF measurements, was shown to be successful. Formal closure of this CPAR was expected in the first quarter of 2020.

CPAR-0041: CAPA Process Ineffectiveness

Opened: November 5, 2019

Closed: December 10, 2019

Age: 1 month

This item was identified during an internal audit where it was determined that the Corrective and Preventive Action (CAPA) was ineffective. The audit identified several specific issues including corrective actions not maintained current, estimated completion dates not updated, actions with past due completion dates, and corrective actions not assigned to responsible persons. The root cause was determined to be a “lack of management oversight.” The corrective action reported was that “all CAPA items have been updated with ECD’s and Assignee(s)” and other actions, including monthly updates on the process at scheduled branch meetings.

APPENDIX B CALCULATING COMBINED DEGREES OF EQUIVALENCE

B.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 Consultative Committee for Acoustics, Ultrasound and Vibration (CCAUV) at the International Bureau of Weights and Measures (BIPM) and published by the United Kingdom's (UK) National Physical Laboratory (NPL) in its final report as the pilot laboratory for the CCAUV.W-K1 comparison (reference 25). 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 that includes varying numbers of participating laboratories, acoustic transducers, calibration methods, measurands, and frequency ranges.

B.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 first consider 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 document. It is however 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 B.3 describes a method to combine data for different devices that accounts for correlations in the measured data.

B.2.1 Individual Degrees of Equivalence for Mutually Independent Measurements

Suppose, for $m = 1, 2, \dots, M$ and $n = 1, 2, \dots, N$, that $x_{m,n}$ denotes the measurement made by laboratory m of device n at a particular frequency, and $u_{m,n} = u(x_{m,n})$ is the standard uncertainty associated with $x_{m,n}$. It is assumed that $x_{m,n}$, $m = 1, 2, \dots, M$, and $n = 1, 2, \dots, N$ 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. Toward 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 comparison reference values (CRV) and degrees of equivalence (DoE) for which condition 2 above does not hold is presented in section B.3.

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

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

$$y_n = \frac{\sum_{m=1}^M w_m x_{m,n}}{\sum_{m=1}^M w_m}, \quad w_m = \frac{1}{u_{m,n}^2}, \quad (\text{B-1})$$

with associated uncertainty $u(y_n)$ determined from

$$\frac{1}{u^2(y_n)} = \sum_{m=1}^M \frac{1}{u_{m,n}^2}. \quad (\text{B-2})$$

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 $u(y_n)$ as the standard uncertainty associated with the comparison reference value. The degree of equivalence of laboratory m for device n is then evaluated from

$$d_{m,n} = x_{m,n} - y_n, \quad (\text{B-3})$$

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

$$u^2(d_{m,n}) = u^2(x_{m,n}) - u^2(y_n). \quad (\text{B-4})$$

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

$$d_{m,m',n} = x_{m,n} - x_{m',n}; \quad (\text{B-5})$$

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

$$u^2(d_{m,m',n}) = u^2(x_{m,n}) + u^2(x_{m',n}). \quad (\text{B-6})$$

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, degrees of equivalence and the associated uncertainties were evaluated separately for each device. Consideration is now given to how the evaluation of a single (combined) degree of equivalence and uncertainty may be estimated for each laboratory by using calibration data from more than one device.

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

The approach is to determine an “average” value of the degrees of equivalence for each laboratory expressed as a proportion of the respective comparison values. Relative values are considered because the devices used in the comparison are (and 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. Further, 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).

If the relative degree of equivalence is defined for $m = 1, 2, \dots, M$ and $n = 1, 2, \dots, N$, as

$$r_{m,n} = \frac{d_{m,n}}{y_n}, \quad (\text{B-7})$$

with associated relative standard uncertainty

$$u(r_{m,n}) = \frac{u(d_{m,n})}{y_n}, \quad (\text{B-8})$$

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

$$r_m = \frac{\sum_{n=1}^N w_n r_{m,n}}{\sum_{n=1}^N w_n}, \quad w_n = \frac{1}{u^2(r_{m,n})}, \quad (\text{B-9})$$

with associated uncertainty $u(r_m)$ determined from

$$\frac{1}{u^2(r_m)} = \sum_{n=1}^N \frac{1}{u^2(r_{m,n})}. \quad (\text{B-10})$$

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

A generalization of the analysis presented in section B.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 degree of equivalence for each laboratory with associated uncertainty, and
3. a relative degree of equivalence for each pair of laboratories and associated uncertainty.

B.3.1 Individual Degrees of Equivalence for Mutually Dependent Measurements

Suppose a model for the $M \times N$ measurements in the form

$$x_{m,n} = y_n + \alpha_{m,n}, \quad m = 1, \dots, M, \quad n = 1, \dots, N, \quad (\text{B-11})$$

where y_n is the comparison reference value (i.e., the 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 \mathbf{V} of order $M \times N$. The matrix \mathbf{V} has the variances $u_{m,n}^2 = u^2(x_{m,n})$ 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.

It is still assumed that the measurements made by laboratories m and m' (i.e., $m \neq m'$) are mutually independent (condition 1 of section B.2); so $u(x_{m,n}, x_{m',n}) = 0$, $n = 1, \dots, N$. To evaluate $u(x_{m,n}, x_{m,n'})$, $n \neq n'$, $\alpha_{m,n}$ is written as

$$\alpha_{m,n} = \lambda_m + \delta_{m,n}; \quad \alpha_{m,n'} = \lambda_m + \delta_{m,n'}; \quad (\text{B-12})$$

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 the components of uncertainty provided by each

laboratory for each measurement from a Type A and a Type B evaluation, respectively. For the analysis described below, both components are assumed to be available, and

$$u(x_{m,n}, x_{m,n'}) = u(\alpha_{m,n}, \alpha_{m,n'}) = u^2(\lambda_m), \quad m = 1, \dots, M. \quad (\text{B-13})$$

Suppose N devices have been measured by M laboratories. The degrees of equivalence \mathbf{d}_m for the N devices calibrated by the m^{th} laboratory are

$$\mathbf{d}_m = \begin{bmatrix} x_{m,1} - y_1 \\ x_{m,2} - y_2 \\ \vdots \\ x_{m,N} - y_N \end{bmatrix}, \quad (\text{B-14})$$

and the associated covariance matrix \mathbf{V}_m is

$$\mathbf{V}_m = \begin{bmatrix} u^2(x_{m,1}) & u(x_{m,1}, x_{m,2}) & \cdots & u(x_{m,1}, x_{m,N}) \\ u(x_{m,2}, x_{m,1}) & u^2(x_{m,2}) & \cdots & u(x_{m,2}, x_{m,N}) \\ \vdots & \vdots & \ddots & \vdots \\ u(x_{m,N}, x_{m,1}) & u(x_{m,N}, x_{m,2}) & \cdots & u^2(x_{m,N}) \end{bmatrix}. \quad (\text{B-15})$$

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

$$\min_{\mathbf{y}} \sum_{m=1}^M \mathbf{d}_m^T \mathbf{V}_m^{-1} \mathbf{d}_m. \quad (\text{B-16})$$

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

$$\mathbf{x} = \begin{bmatrix} x_{1,1} \\ x_{1,2} \\ \vdots \\ x_{1,N} \\ x_{2,1} \\ x_{2,2} \\ \vdots \\ x_{2,N} \\ \vdots \\ x_{M,1} \\ x_{M,2} \\ \vdots \\ x_{M,N} \end{bmatrix}, \quad \mathbf{A} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 0 & 1 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ 1 & 0 & \cdots & 0 \\ 0 & 1 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \\ \vdots & \vdots & \vdots & \vdots \\ 1 & 0 & \cdots & 0 \\ 0 & 1 & & 0 \\ \vdots & & \ddots & \vdots \\ 0 & 0 & \cdots & 1 \end{bmatrix}, \quad (\text{B-17})$$

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

$$\mathbf{y} = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_N \end{bmatrix}, \quad \mathbf{d} = \begin{bmatrix} \mathbf{d}_1 \\ \vdots \\ \mathbf{d}_M \end{bmatrix}, \quad \mathbf{V} = \begin{bmatrix} \mathbf{V}_1 & & \\ & \ddots & \\ & & \mathbf{V}_M \end{bmatrix}, \quad (\text{B-18})$$

and equation (B-16) can be written as

$$\sum_{m=1}^M \mathbf{d}_m^T \mathbf{V}_m^{-1} \mathbf{d}_m = \mathbf{d}^T \mathbf{V}^{-1} \mathbf{d} = (\mathbf{x} - \mathbf{A}\mathbf{y})^T \mathbf{V}^{-1} (\mathbf{x} - \mathbf{A}\mathbf{y}), \quad (\text{B-19})$$

where T is the transpose operator.

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

$$\mathbf{y} = (\mathbf{A}^T \mathbf{V}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{V}^{-1} \mathbf{x}, \quad (\text{B-20})$$

with the associated uncertainty matrix given by

$$\mathbf{V}_y = (\mathbf{A}^T \mathbf{V}^{-1} \mathbf{A})^{-1}. \quad (\text{B-21})$$

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

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

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

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

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

$$\mathbf{V}_d = \mathbf{V} - \mathbf{A} (\mathbf{A}^T \mathbf{V}^{-1} \mathbf{A})^{-1} \mathbf{A}^T. \quad (\text{B-23})$$

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

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

To determine a single degree of equivalence for laboratory m , the process is the same as in the previous section but accounts for the mutual dependence between $d_{m,1}, d_{m,2}, \dots, d_{m,N}$ by defining

$$r_{m,1} = \frac{d_{m,1}}{y_1}, r_{m,2} = \frac{d_{m,2}}{y_2}, \dots, r_{m,N} = \frac{d_{m,N}}{y_N}, \quad (\text{B-24})$$

with associated uncertainty matrix

$$\mathbf{V}_{\mathbf{r},m} = \begin{bmatrix} u^2(d_{m,1})/y_1^2 & u(d_{m,1}, d_{m,2})/y_1 y_2 & \cdots & u(d_{m,1}, d_{m,N})/y_1 y_N \\ u(d_{m,2}, d_{m,1})/y_2 y_1 & u^2(d_{m,2})/y_2^2 & \cdots & u(d_{m,2}, d_{m,N})/y_2 y_N \\ \vdots & \vdots & \ddots & \vdots \\ u(d_{m,N}, d_{m,1})/y_N y_1 & u(d_{m,N}, d_{m,2})/y_N y_2 & \cdots & u^2(d_{m,N})/y_N^2 \end{bmatrix}. \quad (\text{B-25})$$

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

$$\min_{r_m} (\mathbf{r}_m - \mathbf{A}r_m)^T \mathbf{V}_{\mathbf{r},m}^{-1} (\mathbf{r}_m - \mathbf{A}r_m), \quad (\text{B-26})$$

where \mathbf{A} is the $N \times 1$ vector $\mathbf{A} = [1, 1, \dots, 1]^T$, and $\mathbf{r}_m = [r_{m,1}, r_{m,2}, \dots, r_{m,N}]^T$.

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

$$r_m = (\mathbf{A}^T \mathbf{V}_{\mathbf{r},m}^{-1} \mathbf{A})^{-1} \mathbf{A}^T \mathbf{V}_{\mathbf{r},m}^{-1} \mathbf{r}_m, \quad (\text{B-27})$$

with the associated variance given by

$$V_{r_m} = (\mathbf{A}^T \mathbf{V}_{\mathbf{r},m}^{-1} \mathbf{A})^{-1}. \quad (\text{B-28})$$

APPENDIX C LABORATORY UNCERTAINTY STATEMENT SUMMARIES

Evaluation of measured data collected during the USRD proficiency testing program requires not only laboratory measurement results but also 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 29), although with varying rigor depending on the maturity of the laboratory’s measurement services and accreditation status. For example, uncertainty statements for the Open Tank Facility (OTF) and Low-Frequency Facility (LOFAC) are the most reliable, having been rigorously developed and reviewed by NVLAP assessors and by the NIST Assessment Review Board (ARB) in 2018. Uncertainty statements for the Acoustic Pressure Tank Facility (APTF) are rigorous but have not yet been reviewed by either NVLAP or the NIST ARB. Finally, the uncertainty statements for the Leesburg Facility (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 C-1 through C-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:

1. Type A—those that are evaluated by statistical methods, and
2. Type B—those that are evaluated by other means.

These categories somewhat oversimplify 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 29 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*.

Although 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, and 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 thus are classified as Type B uncertainties. As a result, calibration measurements performed by a given laboratory may not be mutually independent random

variables: they 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 B.

Table C-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 | 0.88 | 1.64 | 1.86 | 1.44 | 2.95 | 3.29 | 0.89 | 3.27 | 3.39 |
| 1.25 | 0.76 | 1.64 | 1.81 | 1.24 | 2.92 | 3.17 | 0.64 | 3.24 | 3.30 |
| 1.60 | 0.61 | 1.64 | 1.75 | 1.00 | 2.88 | 3.05 | 0.88 | 3.21 | 3.33 |
| 2.00 | 0.72 | 1.64 | 1.79 | 1.18 | 2.91 | 3.14 | 0.65 | 3.23 | 3.30 |
| 2.50 | 0.63 | 1.48 | 1.61 | 1.04 | 2.62 | 2.81 | 0.70 | 2.97 | 3.05 |
| 3.15 | 0.87 | 1.48 | 1.71 | 1.42 | 2.68 | 3.03 | 1.15 | 3.03 | 3.24 |
| 4.00 | 0.95 | 1.48 | 1.76 | 1.55 | 2.71 | 3.12 | 1.52 | 3.05 | 3.41 |
| 5.00 | 1.41 | 1.48 | 2.04 | 2.31 | 2.90 | 3.71 | 2.43 | 3.23 | 4.04 |
| 6.30 | 0.77 | 1.48 | 1.67 | 1.25 | 2.65 | 2.93 | 1.31 | 3.00 | 3.28 |
| 8.00 | 0.72 | 1.48 | 1.65 | 1.18 | 2.64 | 2.89 | 1.13 | 2.99 | 3.20 |
| 10.0 | 1.01 | 1.58 | 1.87 | 1.65 | 2.78 | 3.23 | 1.52 | 3.24 | 3.58 |
| 12.5 | 1.32 | 1.58 | 2.06 | 2.16 | 2.91 | 3.63 | 1.93 | 3.35 | 3.87 |
| 16.0 | 0.64 | 1.80 | 1.91 | 1.04 | 3.15 | 3.31 | 0.45 | 3.41 | 3.44 |
| 20.0 | 1.73 | 1.80 | 2.49 | 2.82 | 3.53 | 4.52 | 0.61 | 3.77 | 3.81 |
| 25.0 | 1.32 | 1.80 | 2.23 | 2.15 | 3.35 | 3.98 | 0.52 | 3.60 | 3.63 |
| 31.5 | 0.76 | 1.80 | 1.95 | 1.24 | 3.17 | 3.41 | 0.66 | 3.43 | 3.49 |
| 40.0 | 0.94 | 1.88 | 2.11 | 1.54 | 3.27 | 3.61 | 1.03 | 3.52 | 3.67 |
| 50.0 | 1.29 | 1.88 | 2.28 | 2.10 | 3.39 | 3.99 | 1.17 | 3.63 | 3.82 |
| 63.0 | 1.10 | 1.88 | 2.18 | 1.79 | 3.32 | 3.77 | 1.76 | 3.57 | 3.98 |
| 80.0 | 2.57 | 2.51 | 3.59 | 4.20 | 4.49 | 6.15 | 2.86 | 4.99 | 5.75 |
| 100 | 2.53 | 2.51 | 3.56 | 4.13 | 4.47 | 6.09 | 2.51 | 4.97 | 5.57 |
| 125 | 1.45 | 2.41 | 2.81 | 2.38 | 3.76 | 4.45 | 1.59 | 4.35 | 4.63 |
| 160 | 1.80 | 2.34 | 2.95 | 2.94 | 3.87 | 4.86 | 2.23 | 4.44 | 4.97 |
| 200 | 1.73 | 2.12 | 2.74 | 2.83 | 4.21 | 5.07 | 2.51 | 4.06 | 4.77 |
| 250 | 1.49 | 2.07 | 2.55 | 2.44 | 4.10 | 4.77 | 2.43 | 3.94 | 4.63 |
| 315 | 1.21 | 1.95 | 2.29 | 1.98 | 3.81 | 4.29 | 1.07 | 3.64 | 3.79 |
| 400 | 1.32 | 1.95 | 2.35 | 2.16 | 3.85 | 4.41 | 1.03 | 3.68 | 3.82 |
| 500 | 1.39 | 1.95 | 2.39 | 2.27 | 3.87 | 4.49 | 1.38 | 3.70 | 3.95 |
| 630 | 1.35 | 1.95 | 2.37 | 2.20 | 3.86 | 4.44 | 2.12 | 3.69 | 4.25 |
| 800 | 1.25 | 1.95 | 2.31 | 2.04 | 3.82 | 4.33 | 1.35 | 3.65 | 3.89 |
| 1000 | 1.68 | 1.95 | 2.57 | 2.75 | 3.98 | 4.84 | 1.92 | 3.82 | 4.28 |
| 1250 | 2.31 | 1.94 | 3.02 | 3.78 | 4.29 | 5.71 | 2.20 | 4.22 | 4.76 |
| 1600 | 4.58 | 1.96 | 4.98 | 7.48 | 5.84 | 9.48 | 6.27 | 5.89 | 8.60 |
| 2000 | 5.70 | 1.99 | 6.04 | 9.31 | 6.76 | 11.50 | 7.20 | 6.92 | 9.98 |

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

| Frequency (Hz) | Hydrophones | | |
|-------------------|-----------------------|---------------|---------------------------|
| | Secondary Calibration | | |
| | Type A (%) | Type B (%) | Comb. Std. Uncert. (%) |
| 3.00 | 1.08 | 2.96 | 3.14 |
| 4.00 | 0.59 | 2.94 | 3.00 |
| 5.00 | 0.78 | 2.94 | 3.04 |
| 6.30 | 0.47 | 2.93 | 2.97 |
| 8.00 | 0.45 | 2.92 | 2.96 |
| 10.0 | 0.56 | 2.92 | 2.98 |
| 12.5 | 0.33 | 2.92 | 2.93 |
| 16.0 | 0.28 | 2.91 | 2.92 |
| 20.0 | 0.25 | 2.90 | 2.91 |
| 25.0 | 0.29 | 2.91 | 2.93 |
| 31.5 | 0.32 | 2.89 | 2.91 |
| 40.0 | 0.29 | 2.90 | 2.92 |
| 50.0 | 0.45 | 3.00 | 3.04 |
| 63.0 | 1.90 | 2.88 | 3.45 |
| 80.0 | 0.31 | 2.89 | 2.91 |
| 100 | 0.24 | 2.88 | 2.89 |
| 125 | 0.60 | 2.87 | 2.93 |
| 160 | 0.54 | 2.86 | 2.92 |
| 200 | 0.34 | 2.86 | 2.88 |
| 250 | 0.53 | 2.86 | 2.91 |
| 315 | 0.38 | 2.85 | 2.88 |
| 400 | 0.50 | 2.85 | 2.89 |
| 500 | 0.80 | 2.85 | 2.96 |
| 630 | 0.72 | 2.85 | 2.94 |
| 800 | 0.99 | 3.02 | 3.18 |
| 1000 | 0.82 | 3.02 | 3.13 |
| 1250 | 1.82 | 3.03 | 3.54 |
| 1600 | 2.56 | 3.06 | 3.99 |

Table C-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 | 1.50 | 2.01 | 2.18 | 2.83 | 3.58 | 1.52 | 3.13 | 3.48 |
| 1.25 | 1.08 | 1.50 | 1.85 | 1.76 | 2.72 | 3.25 | 1.17 | 3.03 | 3.24 |
| 1.60 | 0.73 | 1.50 | 1.67 | 1.20 | 2.61 | 2.87 | 0.89 | 2.92 | 3.05 |
| 2.00 | 1.04 | 1.50 | 1.83 | 1.70 | 2.71 | 3.20 | 0.56 | 3.01 | 3.06 |
| 2.50 | 1.04 | 1.52 | 1.84 | 1.69 | 2.81 | 3.28 | 0.63 | 2.98 | 3.05 |
| 3.15 | 1.33 | 1.44 | 1.95 | 2.16 | 2.88 | 3.61 | 0.62 | 3.05 | 3.11 |
| 4.00 | 1.28 | 1.44 | 1.93 | 2.09 | 2.86 | 3.55 | 1.14 | 3.03 | 3.24 |
| 5.00 | 1.45 | 1.44 | 2.04 | 2.38 | 2.95 | 3.78 | 2.29 | 3.11 | 3.86 |
| 6.30 | 0.85 | 1.52 | 1.74 | 1.40 | 2.75 | 3.08 | 0.79 | 2.92 | 3.02 |
| 8.00 | 1.09 | 1.68 | 2.00 | 1.78 | 3.08 | 3.56 | 0.93 | 3.08 | 3.22 |
| 10.0 | 0.60 | 1.78 | 1.88 | 0.98 | 3.00 | 3.16 | 1.13 | 3.12 | 3.32 |
| 12.5 | 0.83 | 2.03 | 2.19 | 1.35 | 3.58 | 3.82 | 1.57 | 3.50 | 3.84 |
| 16.0 | 0.59 | 1.95 | 2.04 | 0.97 | 3.49 | 3.62 | 1.64 | 3.41 | 3.78 |
| 20.0 | 0.59 | 1.82 | 1.91 | 0.96 | 3.26 | 3.40 | 1.13 | 3.33 | 3.52 |
| 25.0 | 0.63 | 1.75 | 1.86 | 1.03 | 3.23 | 3.39 | 1.12 | 3.30 | 3.49 |
| 31.5 | 0.80 | 1.75 | 1.92 | 1.31 | 3.27 | 3.52 | 0.98 | 3.34 | 3.48 |
| 40.0 | 0.99 | 2.09 | 2.31 | 1.61 | 3.98 | 4.29 | 1.03 | 3.81 | 3.95 |
| 50.0 | 1.28 | 2.09 | 2.45 | 2.08 | 4.06 | 4.56 | 0.95 | 3.90 | 4.01 |
| 63.0 | 0.94 | 2.09 | 2.29 | 1.53 | 3.97 | 4.25 | 1.23 | 3.80 | 4.00 |
| 80.0 | 1.11 | 2.09 | 2.37 | 1.82 | 4.01 | 4.40 | 1.18 | 3.85 | 4.03 |
| 100 | 1.69 | 2.46 | 2.98 | 2.76 | 4.89 | 5.61 | 1.63 | 4.51 | 4.80 |
| 125 | 2.07 | 2.46 | 3.21 | 3.38 | 5.03 | 6.06 | 2.94 | 4.67 | 5.52 |
| 160 | 3.00 | 2.51 | 3.91 | 4.89 | 5.50 | 7.36 | 2.38 | 5.17 | 5.69 |
| 200 | 2.88 | 2.89 | 4.08 | 4.70 | 6.09 | 7.70 | 3.92 | 5.56 | 6.80 |
| 250 | 3.20 | 2.89 | 4.31 | 5.23 | 6.25 | 8.15 | 4.71 | 5.73 | 7.42 |

Table C-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 D
PROFICIENCY TEST PROGRAM RESULTS

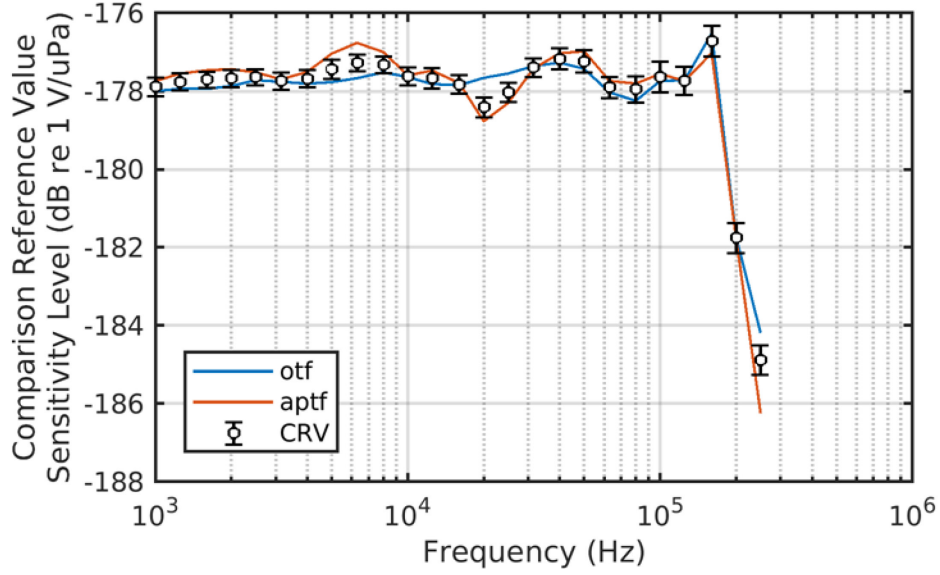


Figure D-1. BC-1: Type H52 SN 80—Receive Voltage Sensitivity

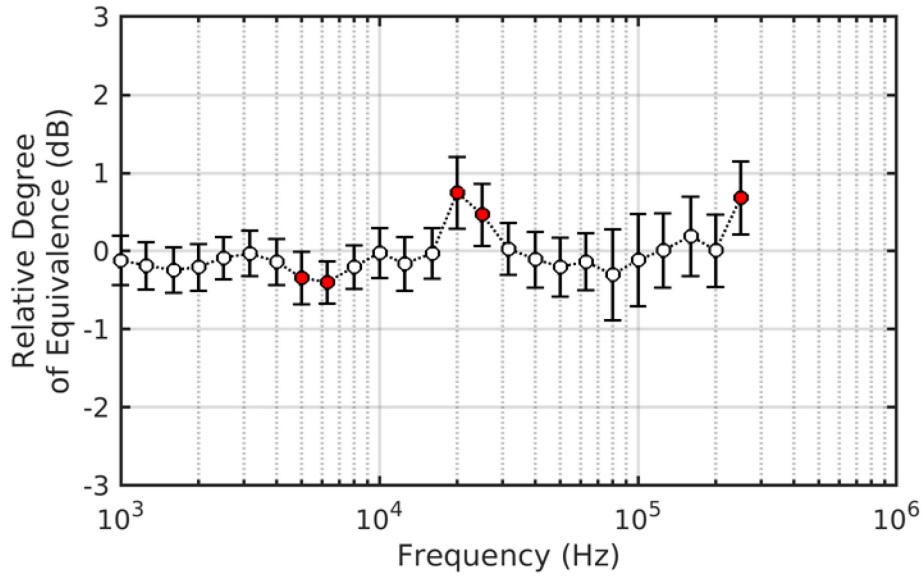


Figure D-2. BC-1: Degree of Equivalence—OTF

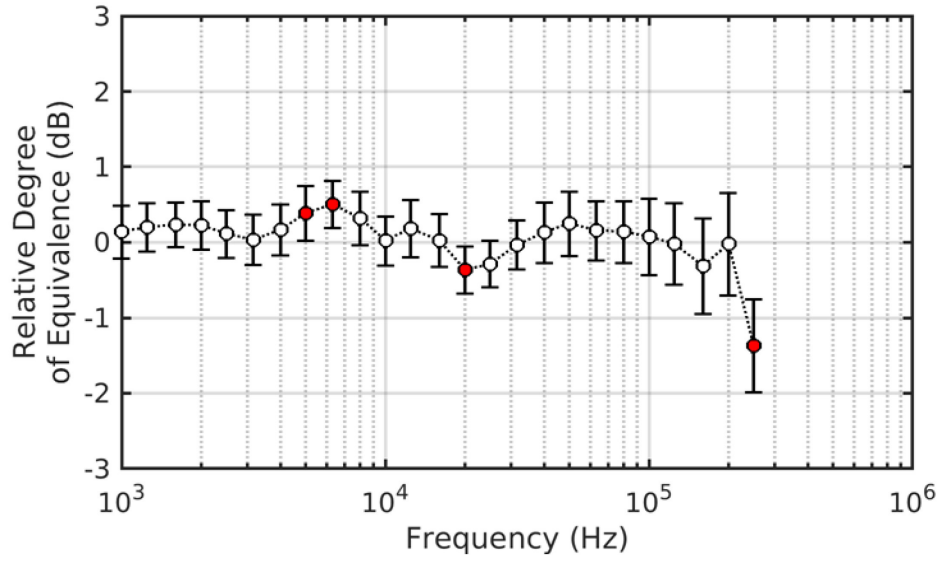


Figure D-3. BC-1: Degree of Equivalence—APTF

Table D-1. BC-1: Comparison Results

| BC-1 | Comparison Reference Value | | Relative Degree of Equivalence | | | |
|---------------|----------------------------|----------|--------------------------------|-----------------------|----------------------|-----------------------|
| | H52 SN 80 | | OTF | | APTF | |
| Frequency kHz | M dB V/uPa | 2u dB | r _m dB | 2u _m dB | r _m dB | 2u _m dB |
| 1,000 | -177.89 | 0.23 | -0.11 | 0.31 | 0.14 | 0.35 |
| 1,250 | -177.76 | 0.22 | -0.18 | 0.30 | 0.20 | 0.32 |
| 1,600 | -177.70 | 0.21 | -0.24 | 0.29 | 0.23 | 0.29 |
| 2,000 | -177.67 | 0.22 | -0.20 | 0.30 | 0.23 | 0.32 |
| 2,500 | -177.63 | 0.21 | -0.09 | 0.27 | 0.12 | 0.32 |
| 3,150 | -177.73 | 0.22 | -0.03 | 0.29 | 0.04 | 0.33 |
| 4,000 | -177.68 | 0.22 | -0.13 | 0.30 | 0.17 | 0.34 |
| 5,000 | -177.43 | 0.25 | -0.34 | 0.33 | 0.39 | 0.36 |
| 6,300 | -177.27 | 0.21 | -0.40 | 0.27 | 0.51 | 0.31 |
| 8,000 | -177.32 | 0.22 | -0.20 | 0.28 | 0.32 | 0.35 |
| 10,000 | -177.62 | 0.23 | -0.02 | 0.32 | 0.02 | 0.32 |
| 12,500 | -177.66 | 0.26 | -0.16 | 0.34 | 0.19 | 0.38 |
| 16,000 | -177.82 | 0.24 | -0.03 | 0.32 | 0.03 | 0.35 |
| 20,000 | -178.41 | 0.26 | 0.75 | 0.46 | -0.36 | 0.31 |
| 25,000 | -178.02 | 0.24 | 0.47 | 0.40 | -0.29 | 0.31 |
| 31,500 | -177.39 | 0.23 | 0.03 | 0.33 | -0.03 | 0.33 |
| 40,000 | -177.16 | 0.27 | -0.11 | 0.35 | 0.13 | 0.40 |
| 50,000 | -177.23 | 0.29 | -0.20 | 0.38 | 0.25 | 0.43 |
| 63,000 | -177.90 | 0.27 | -0.13 | 0.37 | 0.16 | 0.40 |
| 80,000 | -177.95 | 0.34 | -0.30 | 0.58 | 0.14 | 0.41 |
| 100,000 | -177.63 | 0.39 | -0.11 | 0.59 | 0.08 | 0.51 |
| 125,000 | -177.73 | 0.36 | 0.01 | 0.48 | -0.01 | 0.54 |
| 160,000 | -176.71 | 0.40 | 0.19 | 0.51 | -0.31 | 0.63 |
| 200,000 | -181.75 | 0.39 | 0.01 | 0.46 | -0.02 | 0.68 |
| 250,000 | -184.87 | 0.38 | 0.68 | 0.47 | -1.37 | 0.62 |

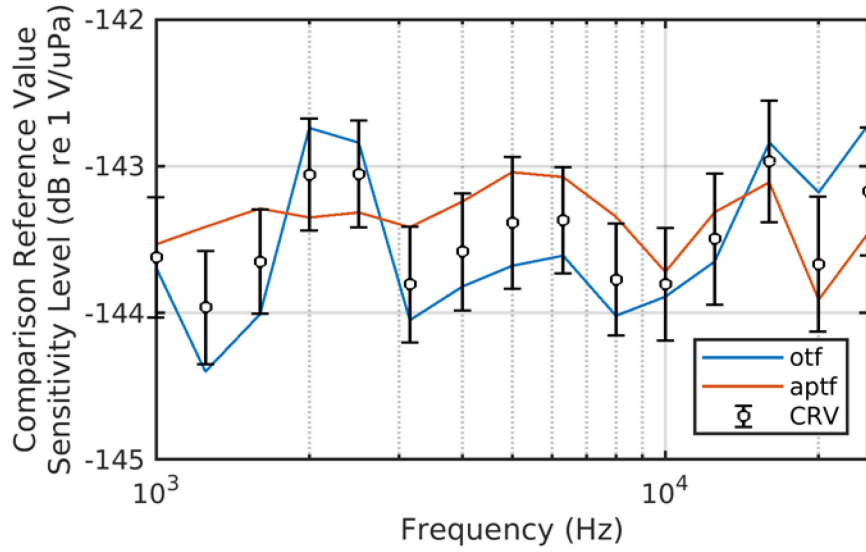


Figure D-4. BC-2: Type H64 SN 2—Receive Voltage Sensitivity

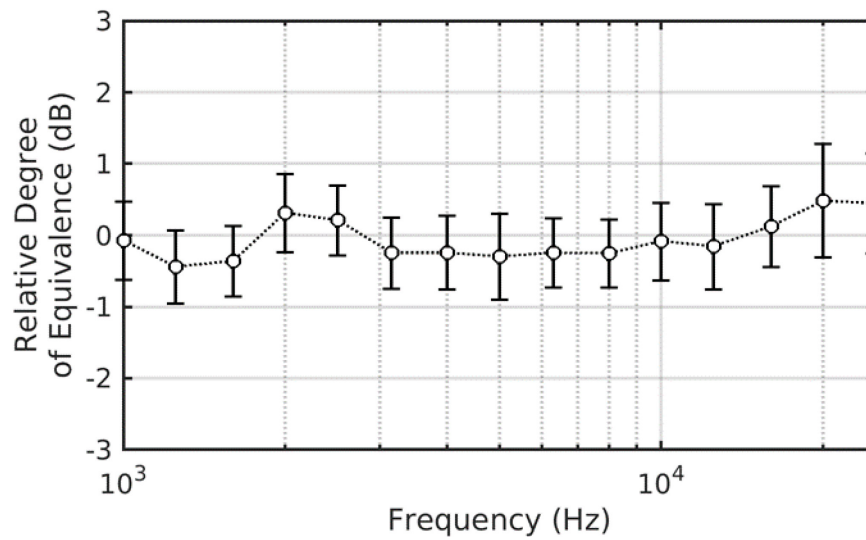


Figure D-5. BC-2: Degree of Equivalence—OTF

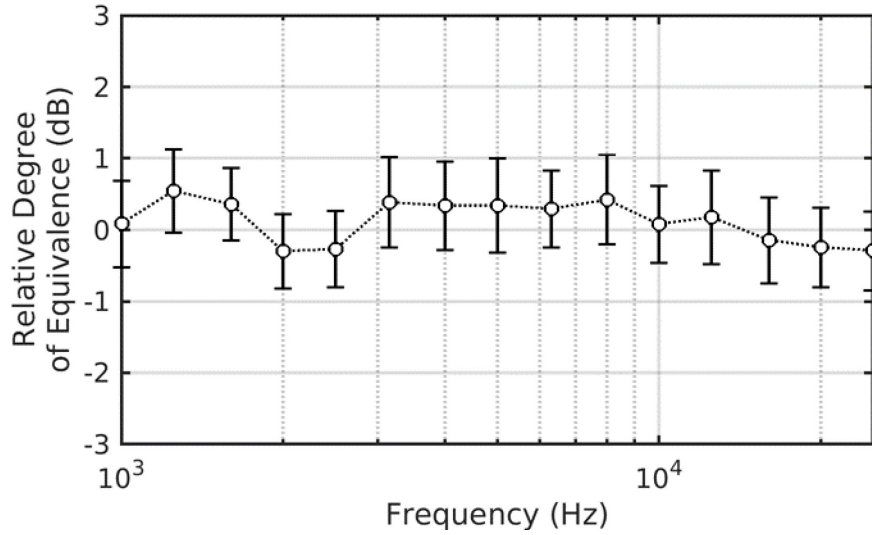


Figure D-6. BC-2: Degree of Equivalence—APTF

Table D-2. BC-2: Comparison Results

| BC-2 Frequency Hz | Comparison Reference Value | | Combined, Relative Degree of Equivalence | | | |
|-------------------------|-------------------------------|----------|---|--------------|-------------|--------------|
| | H64 SN 2 M dB V/uPa | 2u dB | OTF | | APTF | |
| | | | r_m dB | $2u_m$ dB | r_m dB | $2u_m$ dB |
| 1,000 | -143.62 | 0.41 | -0.07 | 0.55 | 0.09 | 0.61 |
| 1,250 | -143.96 | 0.39 | -0.44 | 0.51 | 0.55 | 0.58 |
| 1,600 | -143.65 | 0.36 | -0.36 | 0.49 | 0.36 | 0.50 |
| 2,000 | -143.06 | 0.38 | 0.32 | 0.55 | -0.29 | 0.52 |
| 2,500 | -143.05 | 0.36 | 0.21 | 0.49 | -0.26 | 0.54 |
| 3,150 | -143.80 | 0.39 | -0.25 | 0.50 | 0.39 | 0.63 |
| 4,000 | -143.58 | 0.40 | -0.24 | 0.51 | 0.34 | 0.62 |
| 5,000 | -143.38 | 0.45 | -0.30 | 0.60 | 0.34 | 0.66 |
| 6,300 | -143.37 | 0.36 | -0.24 | 0.48 | 0.29 | 0.54 |
| 8,000 | -143.77 | 0.38 | -0.25 | 0.47 | 0.43 | 0.63 |
| 10,000 | -143.81 | 0.38 | -0.08 | 0.54 | 0.08 | 0.54 |
| 12,500 | -143.50 | 0.45 | -0.15 | 0.60 | 0.18 | 0.65 |
| 16,000 | -142.97 | 0.41 | 0.13 | 0.56 | -0.14 | 0.60 |
| 20,000 | -143.67 | 0.46 | 0.49 | 0.79 | -0.24 | 0.56 |
| 25,000 | -143.17 | 0.44 | 0.45 | 0.70 | -0.29 | 0.55 |

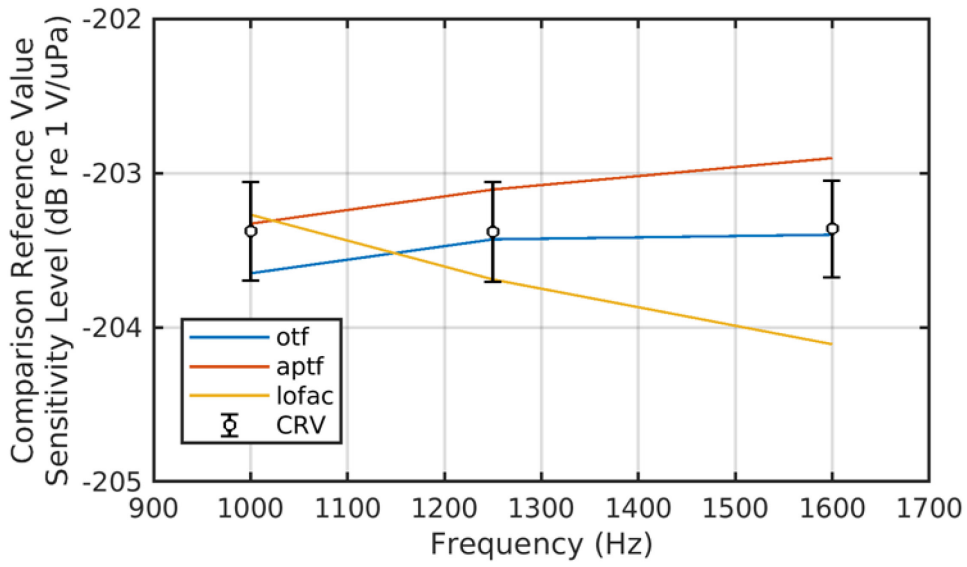


Figure D-7. MC-1: Type F37—Receive Voltage Sensitivity

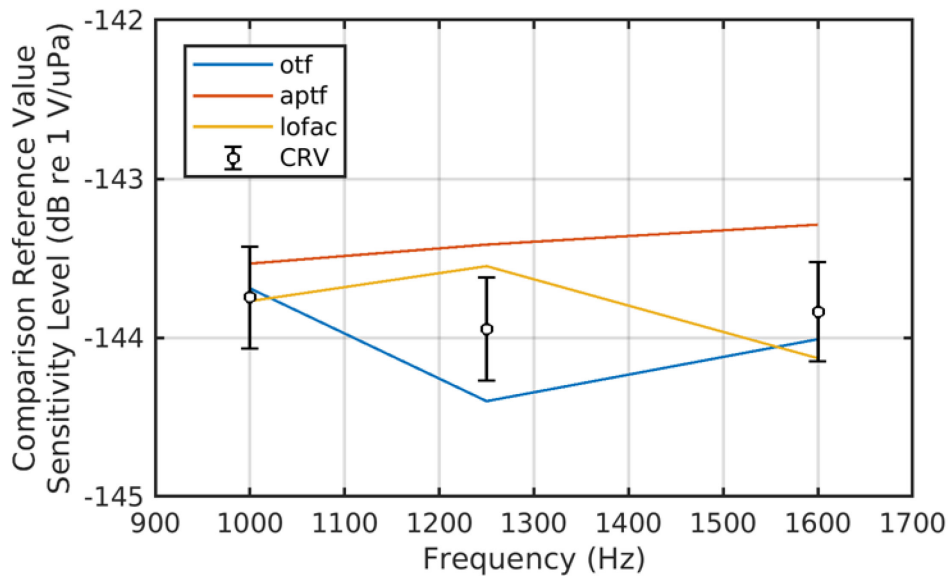


Figure D-8. MC-1: Type H64—Receive Voltage Sensitivity

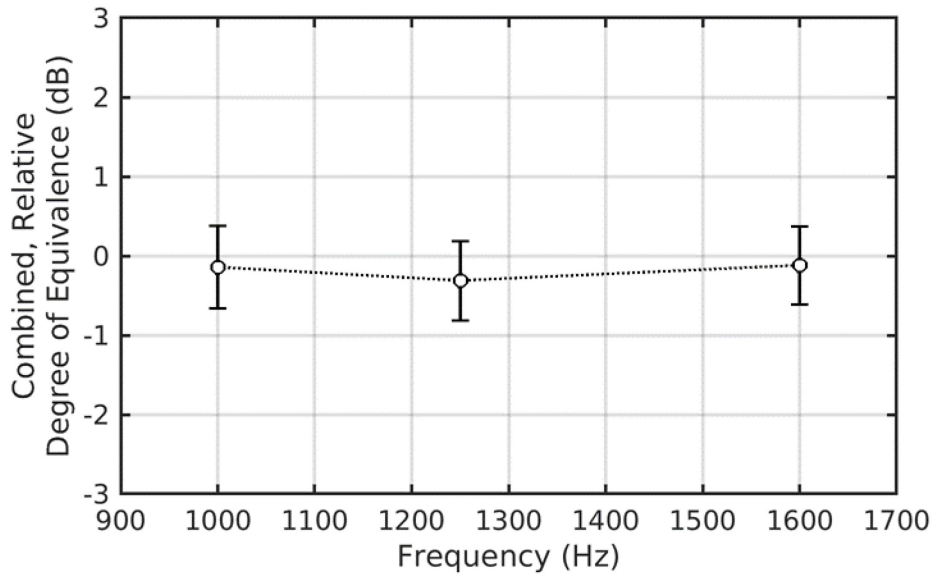


Figure D-9. MC-1: Degree of Equivalence—OTF

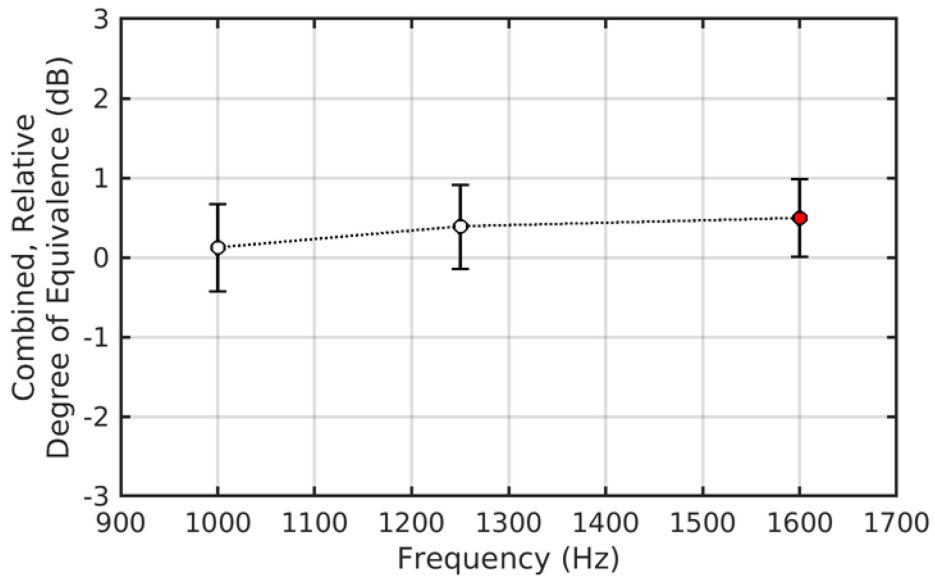


Figure D-10. MC-1: Degree of Equivalence - APTF

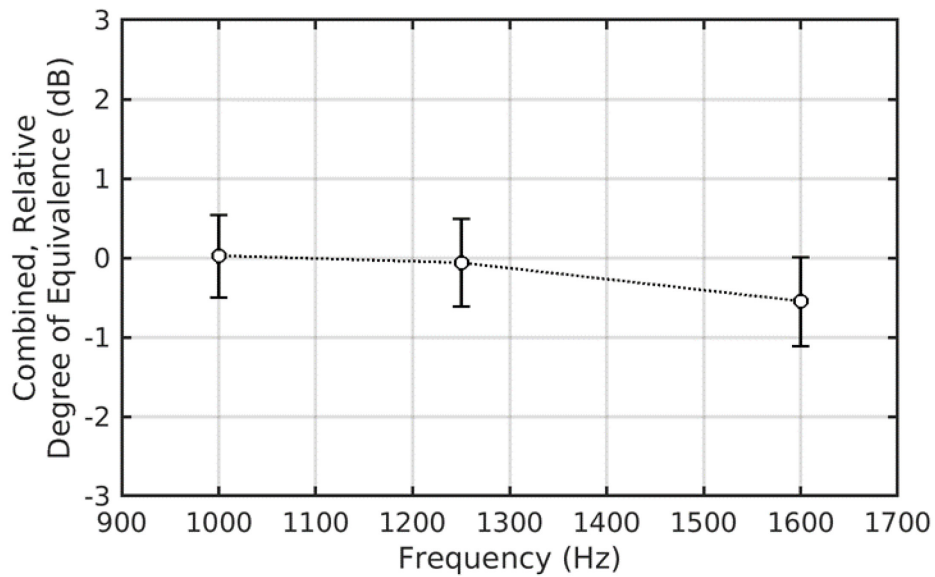


Figure D-11. MC-1: Degree of Equivalence—LOFAC

Table D-3. MC-1: Comparison Results

| MC-1 | Comparison Reference Value | | | | Combined, Relative Degree of Equivalence | | | | | |
|--------------|----------------------------|------|----------|------|--|--------|-------------|-------------|-------|--------|
| | F37 SN A117 | | H64 SN 2 | | OTF | | APTF | | LOFAC | |
| Frequency Hz | M dB | 2u | M dB | 2u | r_m | $2u_m$ | r_m | $2u_m$ | r_m | $2u_m$ |
| | V/uPa | dB | V/uPa | dB | dB | dB | dB | dB | dB | dB |
| 1,000 | -203.38 | 0.32 | -143.74 | 0.32 | -0.14 | 0.52 | 0.13 | 0.55 | 0.03 | 0.52 |
| 1,250 | -203.38 | 0.32 | -143.94 | 0.33 | -0.31 | 0.50 | 0.39 | 0.53 | -0.06 | 0.55 |
| 1,600 | -203.36 | 0.31 | -143.84 | 0.31 | -0.12 | 0.49 | 0.50 | 0.49 | -0.55 | 0.56 |

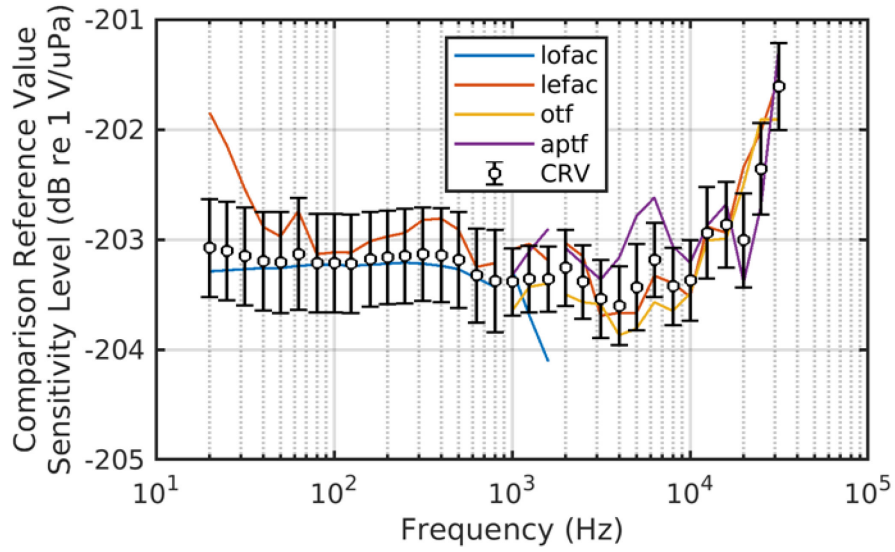


Figure D-11. MC-2: Type F37—Receive Voltage Sensitivity

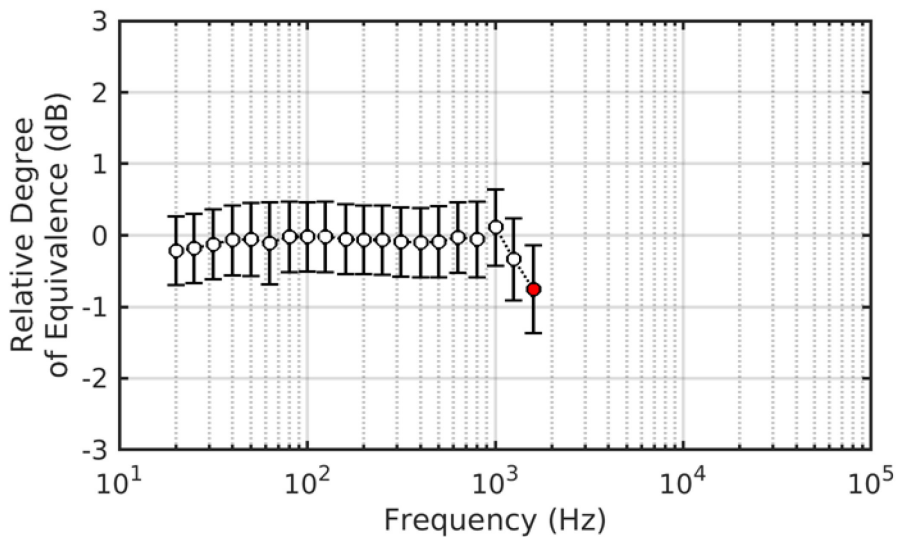


Figure D-12. MC-2: Degree of Equivalence—LOFAC

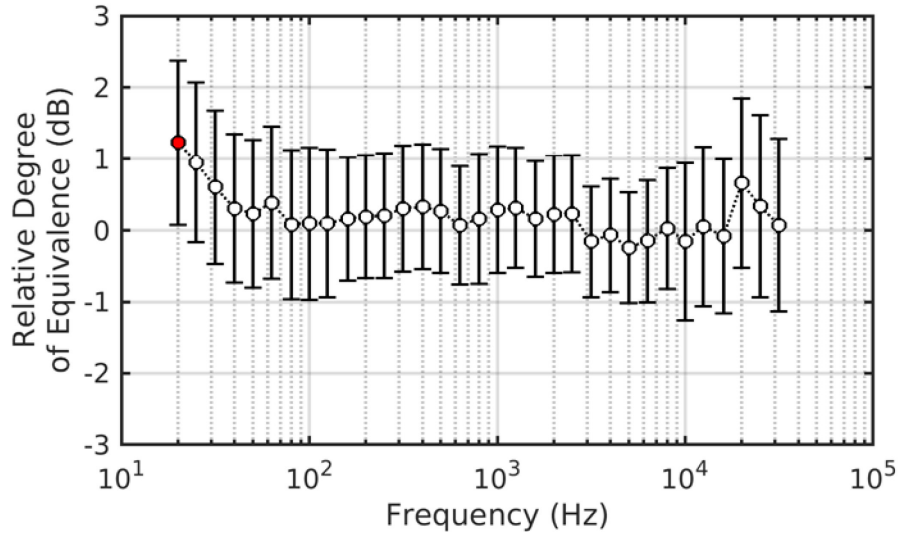


Figure D-13. MC-2: Degree of Equivalence—LEFAC

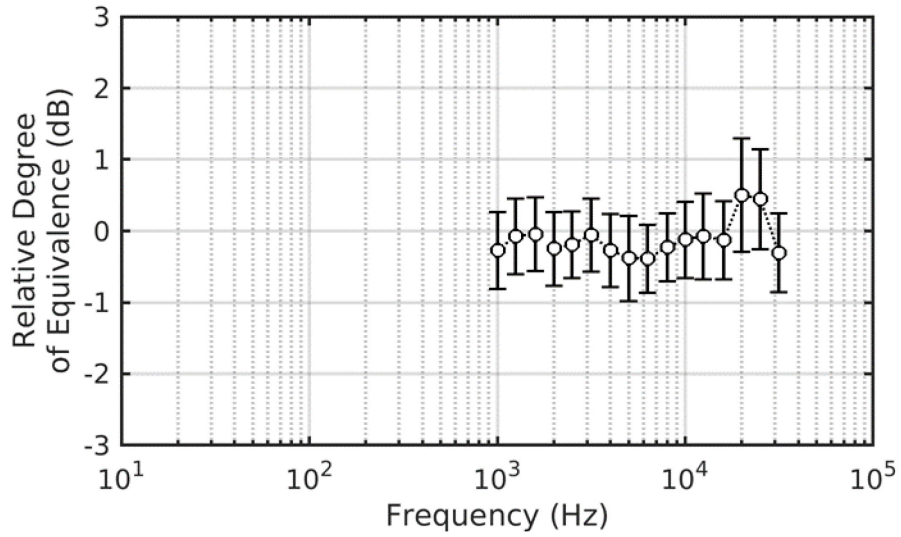


Figure D-14. MC-2: Degree of Equivalence—OTF

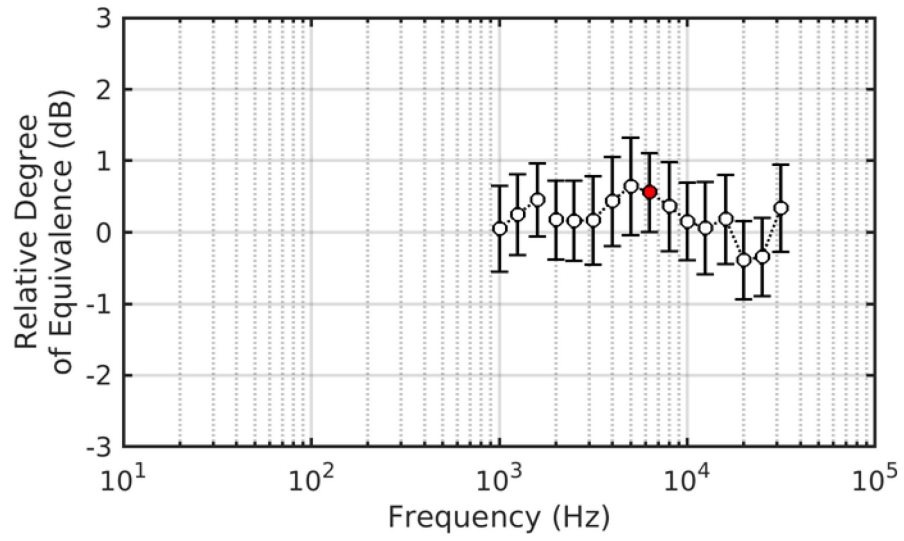


Figure D-15. MC-2: Degree of Equivalence—APTF

Table D-4. MC-2: Comparison Results

| MC-2 | Comparison Reference Value | | Relative Degree of Equivalence | | | | | | | |
|--------------|----------------------------|------|--------------------------------|-----------------|----------------|-----------------|----------------|-----------------|----------------|-----------------|
| | F37 SN A117 | | LOFAC | | LEFAC | | OTF | | APTF | |
| Frequency Hz | M dB | 2u | r _m | 2u _m | r _m | 2u _m | r _m | 2u _m | r _m | 2u _m |
| | V/uPa | dB | dB | dB | dB | dB | dB | dB | dB | dB |
| 20.0 | -203.08 | 0.45 | -0.21 | 0.48 | 1.23 | 1.15 | | | | |
| 25.0 | -203.10 | 0.45 | -0.18 | 0.48 | 0.95 | 1.11 | | | | |
| 31.5 | -203.15 | 0.45 | -0.12 | 0.48 | 0.61 | 1.07 | | | | |
| 40.0 | -203.19 | 0.45 | -0.07 | 0.49 | 0.31 | 1.04 | | | | |
| 50.0 | -203.21 | 0.46 | -0.05 | 0.51 | 0.23 | 1.03 | | | | |
| 63.0 | -203.13 | 0.51 | -0.11 | 0.57 | 0.39 | 1.06 | | | | |
| 80.0 | -203.21 | 0.45 | -0.02 | 0.49 | 0.08 | 1.04 | | | | |
| 100 | -203.21 | 0.45 | -0.02 | 0.49 | 0.09 | 1.06 | | | | |
| 125 | -203.22 | 0.45 | -0.02 | 0.49 | 0.10 | 1.03 | | | | |
| 160 | -203.18 | 0.43 | -0.05 | 0.49 | 0.16 | 0.86 | | | | |
| 200 | -203.16 | 0.42 | -0.06 | 0.48 | 0.19 | 0.86 | | | | |
| 250 | -203.15 | 0.43 | -0.06 | 0.49 | 0.21 | 0.87 | | | | |
| 315 | -203.13 | 0.43 | -0.09 | 0.48 | 0.31 | 0.88 | | | | |
| 400 | -203.14 | 0.43 | -0.10 | 0.48 | 0.33 | 0.87 | | | | |
| 500 | -203.18 | 0.43 | -0.09 | 0.49 | 0.27 | 0.87 | | | | |
| 630 | -203.32 | 0.43 | -0.03 | 0.49 | 0.07 | 0.83 | | | | |
| 800 | -203.38 | 0.46 | -0.05 | 0.53 | 0.16 | 0.91 | | | | |
| 1,000 | -203.38 | 0.31 | 0.11 | 0.53 | 0.29 | 0.88 | -0.27 | 0.54 | 0.05 | 0.60 |
| 1,250 | -203.36 | 0.30 | -0.33 | 0.57 | 0.32 | 0.84 | -0.07 | 0.53 | 0.25 | 0.56 |
| 1,600 | -203.36 | 0.30 | -0.75 | 0.61 | 0.17 | 0.81 | -0.04 | 0.51 | 0.46 | 0.51 |
| 2,000 | -203.26 | 0.35 | | | 0.22 | 0.82 | -0.24 | 0.51 | 0.18 | 0.55 |
| 2,500 | -203.38 | 0.33 | | | 0.23 | 0.81 | -0.19 | 0.47 | 0.16 | 0.56 |
| 3,150 | -203.54 | 0.36 | | | -0.16 | 0.78 | -0.05 | 0.51 | 0.17 | 0.62 |
| 4,000 | -203.60 | 0.36 | | | -0.07 | 0.79 | -0.27 | 0.51 | 0.44 | 0.63 |
| 5,000 | -203.43 | 0.39 | | | -0.24 | 0.78 | -0.38 | 0.60 | 0.64 | 0.68 |
| 6,300 | -203.18 | 0.34 | | | -0.15 | 0.86 | -0.39 | 0.47 | 0.56 | 0.55 |
| 8,000 | -203.42 | 0.35 | | | 0.03 | 0.85 | -0.23 | 0.48 | 0.37 | 0.62 |
| 10,000 | -203.37 | 0.37 | | | -0.15 | 1.10 | -0.12 | 0.54 | 0.16 | 0.54 |
| 12,500 | -202.94 | 0.42 | | | 0.05 | 1.11 | -0.07 | 0.60 | 0.07 | 0.64 |
| 16,000 | -202.86 | 0.39 | | | -0.08 | 1.08 | -0.13 | 0.55 | 0.18 | 0.62 |
| 20,000 | -203.01 | 0.43 | | | 0.66 | 1.18 | 0.51 | 0.79 | -0.39 | 0.55 |
| 25,000 | -202.36 | 0.41 | | | 0.34 | 1.27 | 0.45 | 0.70 | -0.34 | 0.55 |
| 31,500 | -201.61 | 0.40 | | | 0.08 | 1.21 | -0.30 | 0.55 | 0.34 | 0.61 |

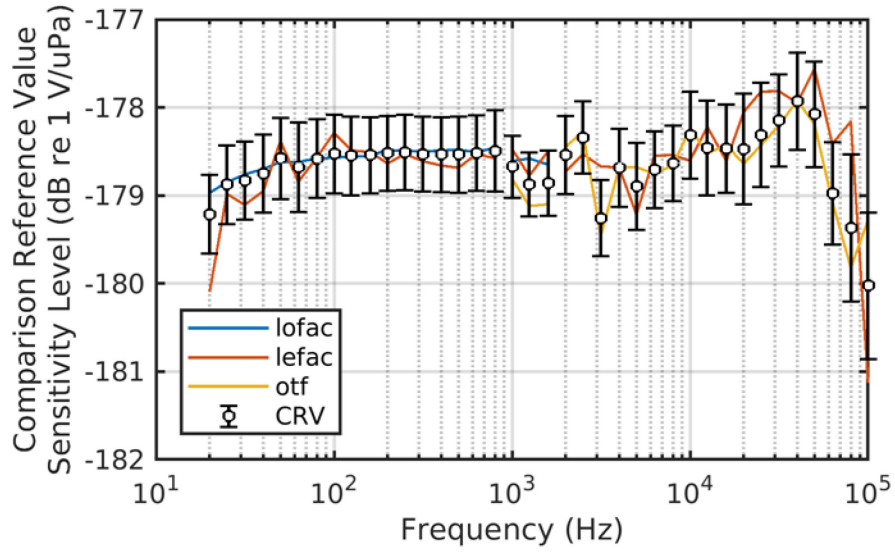


Figure D-16. MC-3: Type H52—Receive Voltage Sensitivity

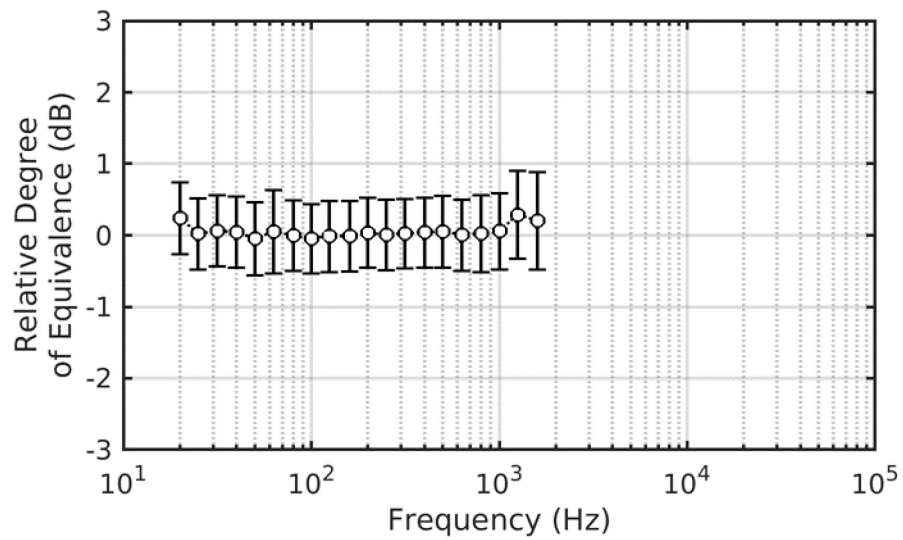


Figure D-17. MC-3: Degree of Equivalence—LOFAC

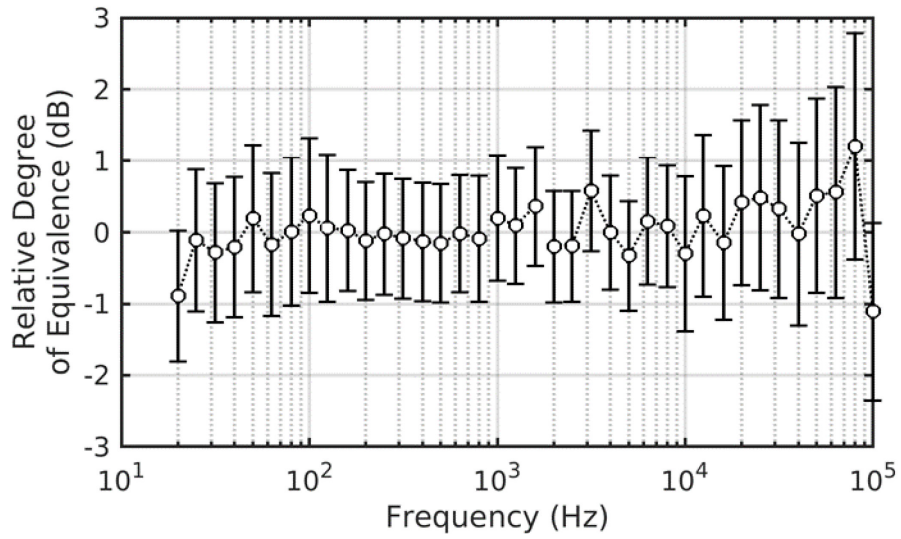


Figure D-18. MC-3: Degree of Equivalence—LEFAC

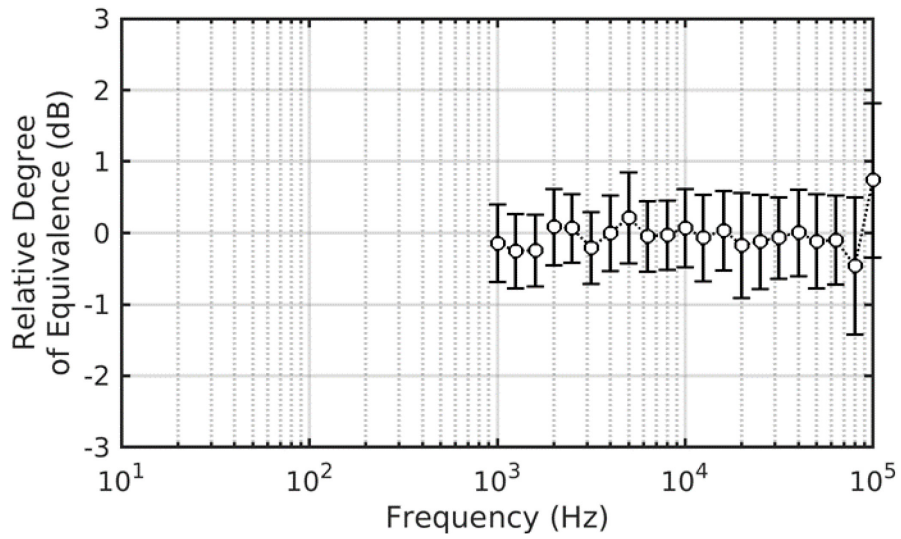


Figure D-19. MC-3: Degree of Equivalence—OTF

Table D-5. MC-3: Comparison Results

| MC-3 | Comparison Reference Value | | Relative Degree of Equivalence | | | | | |
|--------------|----------------------------|----------|--------------------------------|-----------------------|----------------------|-----------------------|----------------------|-----------------------|
| | H52 SN 84 | | LOFAC | | LEFAC | | OTF | |
| Frequency Hz | M dB V/uPa | 2u dB | r _m dB | 2u _m dB | r _m dB | 2u _m dB | r _m dB | 2u _m dB |
| 20.0 | -179.21 | 0.45 | 0.24 | 0.50 | -0.89 | 0.91 | | |
| 25.0 | -178.87 | 0.45 | 0.02 | 0.50 | -0.11 | 0.99 | | |
| 31.5 | -178.83 | 0.44 | 0.07 | 0.50 | -0.28 | 0.97 | | |
| 40.0 | -178.75 | 0.45 | 0.05 | 0.50 | -0.20 | 0.98 | | |
| 50.0 | -178.57 | 0.46 | -0.05 | 0.51 | 0.19 | 1.03 | | |
| 63.0 | -178.67 | 0.51 | 0.05 | 0.58 | -0.17 | 1.00 | | |
| 80.0 | -178.58 | 0.45 | 0.00 | 0.49 | 0.01 | 1.03 | | |
| 100 | -178.52 | 0.45 | -0.05 | 0.49 | 0.24 | 1.08 | | |
| 125 | -178.55 | 0.45 | -0.01 | 0.49 | 0.06 | 1.03 | | |
| 160 | -178.54 | 0.43 | -0.01 | 0.49 | 0.03 | 0.85 | | |
| 200 | -178.52 | 0.42 | 0.04 | 0.49 | -0.12 | 0.83 | | |
| 250 | -178.51 | 0.43 | 0.01 | 0.49 | -0.02 | 0.85 | | |
| 315 | -178.53 | 0.43 | 0.03 | 0.49 | -0.08 | 0.84 | | |
| 400 | -178.53 | 0.43 | 0.04 | 0.49 | -0.13 | 0.83 | | |
| 500 | -178.53 | 0.43 | 0.05 | 0.50 | -0.15 | 0.83 | | |
| 630 | -178.52 | 0.43 | 0.01 | 0.50 | -0.02 | 0.82 | | |
| 800 | -178.49 | 0.46 | 0.03 | 0.54 | -0.09 | 0.89 | | |
| 1,000 | -178.67 | 0.35 | 0.06 | 0.53 | 0.20 | 0.87 | -0.14 | 0.54 |
| 1,250 | -178.87 | 0.36 | 0.29 | 0.61 | 0.09 | 0.82 | -0.25 | 0.52 |
| 1,600 | -178.86 | 0.37 | 0.21 | 0.68 | 0.36 | 0.83 | -0.24 | 0.50 |
| 2,000 | -178.54 | 0.45 | | | -0.20 | 0.78 | 0.09 | 0.53 |
| 2,500 | -178.34 | 0.41 | | | -0.19 | 0.78 | 0.07 | 0.48 |
| 3,150 | -179.25 | 0.43 | | | 0.58 | 0.84 | -0.21 | 0.50 |
| 4,000 | -178.68 | 0.44 | | | 0.00 | 0.80 | 0.00 | 0.53 |
| 5,000 | -178.89 | 0.50 | | | -0.32 | 0.77 | 0.21 | 0.64 |
| 6,300 | -178.70 | 0.43 | | | 0.16 | 0.89 | -0.05 | 0.49 |
| 8,000 | -178.63 | 0.43 | | | 0.09 | 0.85 | -0.03 | 0.49 |
| 10,000 | -178.31 | 0.49 | | | -0.30 | 1.08 | 0.07 | 0.55 |
| 12,500 | -178.46 | 0.54 | | | 0.24 | 1.13 | -0.06 | 0.60 |
| 16,000 | -178.47 | 0.50 | | | -0.14 | 1.07 | 0.04 | 0.56 |
| 20,000 | -178.47 | 0.63 | | | 0.42 | 1.15 | -0.17 | 0.74 |
| 25,000 | -178.31 | 0.59 | | | 0.49 | 1.29 | -0.12 | 0.66 |
| 31,500 | -178.14 | 0.52 | | | 0.33 | 1.24 | -0.07 | 0.57 |
| 40,000 | -177.92 | 0.55 | | | -0.02 | 1.28 | 0.00 | 0.61 |
| 50,000 | -178.07 | 0.60 | | | 0.51 | 1.36 | -0.12 | 0.66 |
| 63,000 | -178.98 | 0.58 | | | 0.56 | 1.47 | -0.09 | 0.62 |
| 80,000 | -179.37 | 0.83 | | | 1.21 | 1.58 | -0.45 | 0.96 |
| 100,000 | -180.02 | 0.83 | | | -1.10 | 1.24 | 0.74 | 1.08 |

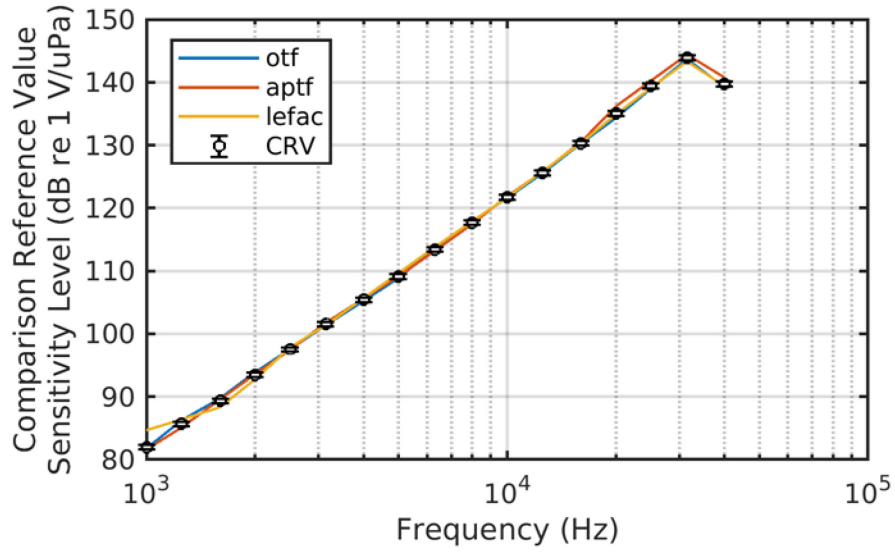


Figure D-20. MC-4: Type F37—Transmitting Voltage Response

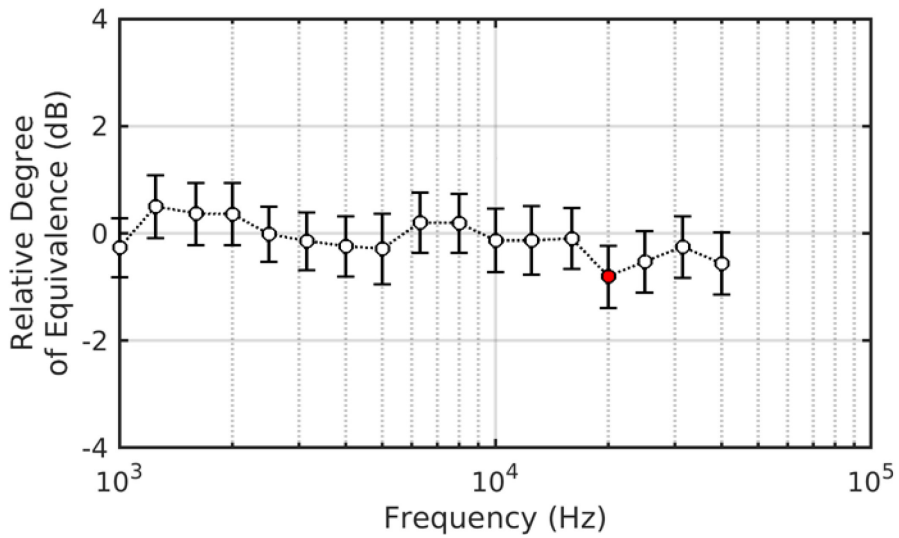


Figure D-21. MC-4: Degree of Equivalence—OTF

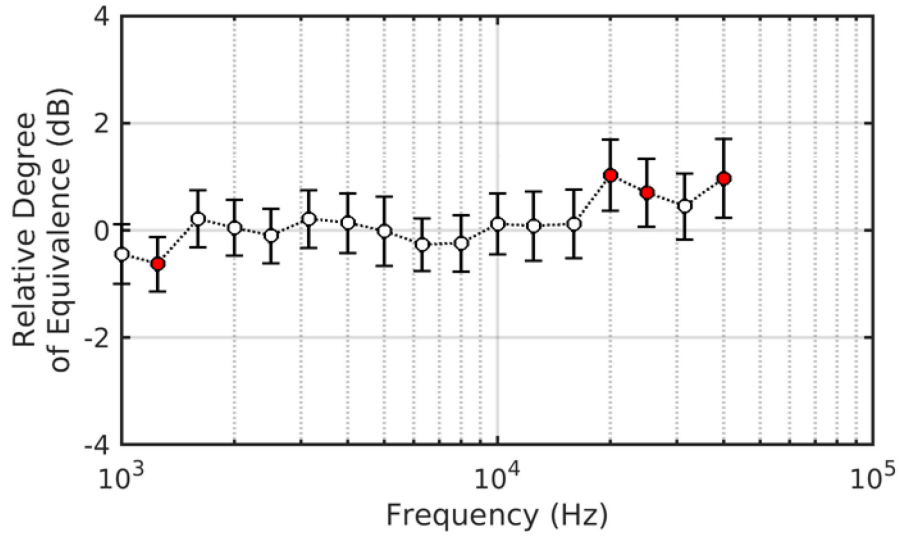


Figure D-22. MC-4: Degree of Equivalence—APTF

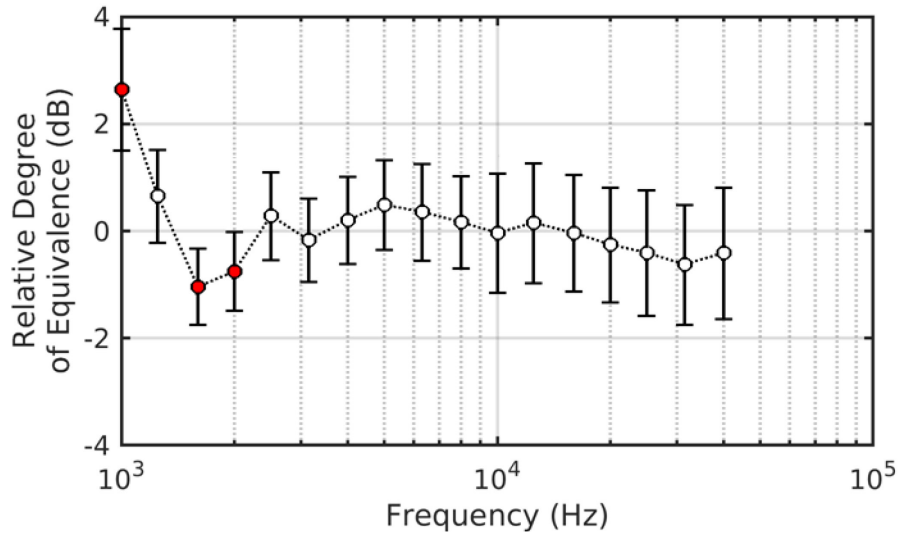


Figure D-23. MC-4: Degree of Equivalence—LEFAC

Table D-6. MC-4: Comparison Results

| MC-4 | Comparison Reference Value | | Relative Degree of Equivalence | | | | | |
|--------|----------------------------|----------|--------------------------------|-----------------------|----------------------|-----------------------|----------------------|-----------------------|
| | F37 SN A117 | | OTF | | APTF | | LEFAC | |
| | 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 |
| 1,000 | 82.03 | 0.38 | -0.26 | 0.55 | -0.44 | 0.56 | 2.64 | 1.14 |
| 1,250 | 85.71 | 0.36 | 0.50 | 0.59 | -0.63 | 0.51 | 0.65 | 0.87 |
| 1,600 | 89.36 | 0.35 | 0.37 | 0.58 | 0.22 | 0.53 | -1.04 | 0.71 |
| 2,000 | 93.52 | 0.35 | 0.36 | 0.58 | 0.05 | 0.52 | -0.75 | 0.73 |
| 2,500 | 97.55 | 0.33 | -0.01 | 0.51 | -0.10 | 0.51 | 0.28 | 0.82 |
| 3,150 | 101.58 | 0.35 | -0.15 | 0.54 | 0.22 | 0.54 | -0.16 | 0.78 |
| 4,000 | 105.47 | 0.36 | -0.24 | 0.56 | 0.14 | 0.55 | 0.21 | 0.81 |
| 5,000 | 109.19 | 0.41 | -0.29 | 0.65 | -0.02 | 0.64 | 0.49 | 0.84 |
| 6,300 | 113.44 | 0.35 | 0.21 | 0.56 | -0.26 | 0.49 | 0.35 | 0.90 |
| 8,000 | 117.73 | 0.35 | 0.19 | 0.55 | -0.24 | 0.53 | 0.17 | 0.86 |
| 10,000 | 121.74 | 0.39 | -0.13 | 0.59 | 0.12 | 0.57 | -0.04 | 1.11 |
| 12,500 | 125.64 | 0.43 | -0.13 | 0.64 | 0.08 | 0.65 | 0.15 | 1.12 |
| 16,000 | 130.36 | 0.40 | -0.09 | 0.57 | 0.12 | 0.64 | -0.03 | 1.09 |
| 20,000 | 135.14 | 0.41 | -0.81 | 0.58 | 1.03 | 0.66 | -0.25 | 1.07 |
| 25,000 | 139.52 | 0.41 | -0.53 | 0.57 | 0.71 | 0.63 | -0.41 | 1.18 |
| 31,500 | 143.94 | 0.40 | -0.25 | 0.57 | 0.45 | 0.61 | -0.62 | 1.12 |
| 40,000 | 139.79 | 0.43 | -0.56 | 0.58 | 0.97 | 0.74 | -0.41 | 1.23 |

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