NIST HANDBOOK 150-2C

National Voluntary Laboratory Accreditation Program

Calibration Laboratories

Technical Guide for Time and Frequency Measurements

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September 2001

U.S. Department of Commerce
Donald L. Evans, Secretary

Technology Administration
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National Institute of Standards and Technology
Karen Brown, Acting Director

National Institute of Standards and Technology
NIST Handbook 150-2C
26 pages (September 2001)
CODEN: NIHAE2

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 2001

For sale by the Superintendent of Documents
U.S. Government Printing Office
Washington, DC 20402-9325

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Preface

The Calibration Laboratories Accreditation Program was developed by the National Voluntary Laboratory Accreditation Program (NVLAP) at NIST as a result of interest from private industry and at the request of the National Conference of Standards Laboratories. The goal of the program is to provide a means by which calibration laboratories can be assessed for competency. This voluntary program is not designed to serve as a means of imposing specific calibration procedures or minimum uncertainties on applicant laboratories; instead, the program allows for all scientifically valid calibration schemes and requires that laboratories derive and document their measurement uncertainties.

To accomplish this goal, NVLAP employs technical experts, on a contract basis, to serve as assessors in each of the following eight fields of physical metrology calibration:

- electromagnetic dc/low frequency,
- electromagnetic rf/microwave frequency,
- time and frequency,
- ionizing radiation,
- optical radiation,
- dimensional,
- mechanical, and
- thermodynamics.

NIST Handbooks 150-2A through 150-2H are technical guides for the accreditation of calibration laboratories, with each handbook corresponding to one of the eight fields of physical metrology calibration. They are intended for information and use by:

- NVLAP technical experts in assessing laboratories,
- staff of accredited laboratories,
- those laboratories seeking accreditation,
- other laboratory accreditation systems,
- users of laboratory services, and
- others needing information on the requirements and guidelines for accreditation under the NVLAP Calibration Laboratories Accreditation Program.

NOTE The Calibration Laboratories Accreditation Program has been expanded to cover chemical calibration for the providers of proficiency testing and certifiers of spectrophotometric NTRMs. (See NIST Handbooks 150-19 and 150-21.) Other NVLAP handbooks in the chemical calibration area are expected in the future.

The assessor uses NIST Handbook 150, *NVLAP Procedures and General Requirements*, and the appropriate guides (NIST Handbooks 150-2A through 150-2H) to validate that a laboratory is capable of performing calibrations within the laboratory's stated uncertainties. These technical guides and other relevant technical information support assessors in their assessments of laboratories. Along with inspecting the facilities, documentation, equipment, and personnel, the assessor can witness a calibration, have an item recalibrated, and/or examine the results of measurement assurance programs and round-robins to collect objective evidence.

NIST Handbooks 150-2A through 150-2H supplement NIST Handbook 150, which contains Title 15 of the U.S. Code of Federal Regulations (CFR) Part 285 plus all general NVLAP procedures, criteria, and policies. The criteria in NIST Handbook 150 originally encompassed the requirements of ISO/IEC Guide 25:1990 and the relevant requirements of ISO 9002 (ANSI/ASQC Q92-1987). These handbook criteria have been updated to incorporate the requirements of ISO/IEC 17025:1999. The entire series of Handbooks 150-2A through 150-2H comprises information specific to the Calibration Laboratories Program and neither adds to nor detracts from requirements contained in NIST Handbook 150.

Any questions or comments on this handbook should be submitted to the National Voluntary Laboratory Accreditation Program, National Institute of Standards and Technology, 100 Bureau Drive, Stop 2140, Gaithersburg, MD 20899-2140; phone (301) 975-4016; fax (301) 926-2884; e-mail NVLAP@nist.gov.

Acknowledgments

NIST Handbook 150-2 was first available as a draft covering all eight fields of physical metrology calibration in one volume. It has been separated into eight handbooks to allow easier updating and electronic downloading from the NVLAP web site. The preparation of these documents has been a joint effort, with input from representatives of other government agencies, laboratories, and the private sector. Acknowledgment of their efforts is in order; however, the listing of individual names is impractical. The submissions by individuals and companies offering suggestions for improvement to this document were also very welcome, as were the contributions of those who attended the public workshops.

We thank all the NIST measurement divisions for their work in writing or contributing to the individual handbooks. Listed below are those from the NIST measurement divisions who deserve special thanks for input to Handbook 150-2C, *Technical Guide for Time and Frequency Measurements*:

> Michael A. Lombardi (Frequency and Time), Dr. Donald B. Sullivan, and David A. Howe (Spectral Purity).

Additional thanks go to those who actively participated in the Technical Guide Workshop held November 1993 and to those who served as points of contact within fields of calibration. They include: Georgia L. Harris, Norman B. Belecki, Dr. Theodore D. Doiron, Robert M. Judish, Thomas C. Larason, Sally S. Bruce, and Dr. Donald B. Sullivan. A special thanks is owed to James L. Cigler for work in developing the content and format of this guide, and to Vanda White for her editorial expertise in making this a readable document.

Above all, we wish to thank Jon M. Crickenberger, the editor of the first three drafts of this document, for literally hundreds of hours of his work in creating this guide. It was he who tasked the contributors to produce the technical content, assembled the results of their efforts into a consistent format, and provided the general commentary. Without Jon's dedicated effort to this monumental task, this guide would never have been published.

NVLAP has edited the individual handbooks and made changes resulting from comments by individuals to earlier draft versions. This editing has been to a different extent for each parameter. Every effort was made to include all pertinent information relevant to an ISO/IEC 17025-derived technical guide.

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Summary

This guide presents the general technical requirements (i.e., on-site assessment and proficiency testing) of the laboratory accreditation program for calibration laboratories along with specific technical criteria and guidance applicable to time and frequency measurement. These technical guidelines are presented to indicate how the NVLAP criteria may be applied.

Any calibration laboratory (including commercial, manufacturer, university, or federal, state, or local government laboratory) engaged in calibration in time and frequency measurements listed in this handbook may apply for NVLAP accreditation. Accreditation will be granted to a laboratory that complies with the criteria for accreditation as defined in NIST Handbook 150. Accreditation does not guarantee laboratory performance – it is a finding of laboratory competence.

Fields of calibration covered: Specific calibration parameters and related stimulus and measurement devices in areas of time and frequency.

Scope of accreditation: Calibration parameter(s), range, and uncertainty level. Types of measuring and test equipment. Quality assurance system for measuring and test equipment.

Period of accreditation: One year, renewable annually.

On-site assessment: Visit by an assessor(s) to determine compliance with the NVLAP criteria before initial accreditation, in the first renewal year, and every two years thereafter. Preassessment and monitoring visits as required. All calibration parameters or general areas of calibration within the specific scope of accreditation requested will be assessed.

Assessors: Selected from technical experts with experience in the appropriate areas of calibration and quality systems assessment.

Proficiency testing (measurement assurance): Each laboratory is required to demonstrate its capability to successfully perform calibrations as part of on-site assessment or by documented successful completion of an approved Measurement Assurance Program (MAP) or round-robin correlation. Proficiency testing may be required for initial accreditation, or where other evidence of measurement assurance is not evident, and may be conducted annually thereafter. Advance notice and instructions are given before proficiency testing is scheduled.

Fees: Payments are required as listed on the NVLAP fee schedule, including the initial application fee, administrative/technical support fee, on-site assessment fee, and proficiency testing fee.

1 General information

1.1 Purpose

The purpose of this handbook is to amplify the general requirements for accreditation by NVLAP of calibration laboratories in the area of time and frequency measurements covered by the Calibration Laboratories Program. It complements and supplements the NVLAP programmatic procedures and general requirements found in NIST Handbook 150, *NVLAP Procedures and General Requirements*. The interpretive comments and additional guidelines contained in this handbook make the general NVLAP criteria specifically applicable to the Calibration Laboratories Program.

This handbook does not contain the general requirements for accreditation, which are listed in NIST Handbook 150, but rather provides guidelines for good calibration laboratory practices, which may be useful in achieving accreditation.

1.2 Organization of handbook

The handbook is organized in two sections. The first section provides additional explanations to the general procedures and requirements contained in NIST Handbook 150. The second section provides details and guidance very specific for time and frequency calibration laboratories.

1.3 Description of Calibration Laboratories Accreditation Program

On May 18, 1992, as a result of the petition and public notice process, the Director of the National Institute of Standards and Technology published in the *Federal Register* a notice of intent to develop the Calibration Laboratories Accreditation Program under the procedures of the National Voluntary Laboratory Accreditation Program . On June 2, 1994, the procedures and general requirements under which NVLAP operates, Title 15, Part 285 of the U.S. Code of Federal Regulations (CFR), were revised to:

a) expand the procedures beyond testing laboratories to include accreditation of calibration laboratories,

b) update the procedures to ensure compatibility with generally accepted conformity assurance and conformity assessment concepts,

c) incorporate international changes, especially with relevant International Organization for Standardization/International Electrotechnical Commission (ISO/IEC) documents (e.g., ISO/IEC Guides 25 (now ISO/IEC 17025:1999), 38, 43, and 58, and the ISO 9000 series), and

d) facilitate and promote acceptance of the calibration and test results between countries to avoid barriers to trade.

Calibration laboratory accreditation is offered in eight fields of physical metrology calibration covering a wide variety of parameters and includes accreditation in multifunction measuring and test equipment calibrations. Specific requirements and criteria have been established for determining laboratory qualifications for accreditation following prescribed NVLAP procedures. The criteria address quality systems, staff, facilities and equipment, test and calibration methods and procedures, manuals, records, and calibration/certification reports.

On September 18, 1992, a public workshop was held at NIST Gaithersburg and attended by a mix of private sector and government personnel. The workshop reviewed a draft handbook, which included general requirements, as well as very specific technical requirements for dc voltage calibrations at all levels. As a result of the workshop, the draft handbook was revised to take the form of a Calibration Laboratories Program Handbook, which included the general requirements for laboratories (using ISO/IEC Guide 25 as a basis), and eight companion Technical Guides covering the specific requirements for each field of calibration offered for accreditation.

On May 18, 1993, a public workshop on the revised draft program handbook was held at NIST Boulder and attended by more than 60 industry and government personnel. Comments from this workshop, as well as responses to a survey/checklist mailing, were used to prepare the final draft of the handbook, now entitled *NVLAP Procedures and General Requirements* (NIST Handbook 150), published in March 1994. [A revised NIST Handbook 150 incorporating ISO/IEC 17025:1999 is dated 2001.]

A public workshop for the Calibration Laboratories Technical Guides was held at NIST Gaithersburg, on November 22 through 24, 1993. More than 60 industry and government personnel attended and provided comments on the draft version of the Technical Guide for each of eight fields of calibration. As a result, the eight Technical Guides were incorporated into a draft Handbook 150-2, *Calibration Laboratories Technical Guide*, covering the fields being offered for accreditation. [In 2000, Handbook 150-2 (draft) was divided into eight handbooks, one for each calibration area.]

The need for technical experts to serve as assessors was advertised, and the first group of assessors was selected and trained during a four-day session held from November 16 through 19, 1993, in Gaithersburg, using materials developed by NVLAP.

The Calibration Laboratories Accreditation Program officially began accepting applications when notification was given in the *Federal Register* dated May 11, 1994. Applications are accepted and processed in accordance with procedures found in NIST Handbook 150.

1.4 References

1.4.1 The following documents are referenced in this handbook.

a) NIST Handbook 150, *NVLAP Procedures and General Requirements*; available from:

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100 Bureau Drive, Stop 2140
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Phone: (301) 975-4016
Fax: (301) 926-2884
E-mail: nvlap@nist.gov
NVLAP Web site: http://www.nist.gov/nvlap

b) ISO/IEC/BIPM (BIPM is the Bureau International des Poids et Mesures, the International Bureau of Weights and Measures) *Guide to the Expression of Uncertainty in Measurement* (GUM), 1993.

c) ISO/IEC 17025: 1999: *General requirements for the competence of testing and calibration laboratories.*

d) ISO/IEC Guide 43: 1997, *Proficiency testing by interlaboratory comparisons, Part 1 and Part 2.*

e) ISO/IEC/BIPM *International Vocabulary of Basic and General Terms in Metrology* (VIM), 1993.

ISO documents **b)** through **e)** are available from:

Global Engineering Documents (paper copies)
Order phone: (800) 854-7179

American National Standards Institute (ANSI) (electronic copies)
Electronic Standards Store
ANSI web site: http://www.ansi.org

f) NIST Technical Note 1297, *Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results.* Available on-line at http://physics.nist.gov/Document/tn1297.pdf.

g) EA-2/03, EA Interlaboratory Comparison (previously EAL-P7), Mar. 1996. Available on-line at http://www.european-accreditation.org/.

h) ANSI/NCSL Z540-1-1994, *Calibration Laboratories and Measuring and Test Equipment—General Requirements.*

i) ANSI/NCSL Z540-2-1997, *U.S. Guide to the Expression of Uncertainty in Measurement.*

j) NCSL Recommended Practice RP-7: *Laboratory Design*, 1993.

NCSL documents **h)** through **j)** are available from:

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Fax: (303) 440-3384
E-mail: info@ncslinternational.org
Web site: http://www.ncslinternational.org

k) C. D. Ehrlich and S. D. Raspberry, "Metrological Timelines in Traceability," Jour. Res. NIST, Vol. 103, No. 1, Jan-Feb, 1998.

l) C. Croarkin, Measurement Assurance Programs, Part II: Development and Implementation, NBS Special Publication 676-II (U.S. Government Printing Office, Washington, DC, 1985).

1.4.2 Additional references specific to time and frequency measurements are listed in Section 2.

1.5 Definitions

Definitions found in NIST Handbook 150 apply, but may be interpreted differently or stated differently, when necessary to amplify or clarify the meaning of specific words or phrases as they apply to specific technical criteria.

1.5.1 Proficiency Testing: Determination of laboratory performance by means of comparing and evaluating calibrations or tests on the same or similar items or materials by two or more laboratories in accordance with predetermined conditions. For the NVLAP Calibration Laboratories Accreditation Program, this entails using a transport standard as a measurement artifact, sending it to applicant laboratories to be measured, and then comparing the applicant's results to those of a reference laboratory on the same artifact.

1.5.2 Traceability: Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties. [VIM:1993, 6.10]

A single measurement intercomparison is sufficient to establish uncertainty relationships only over a limited time interval (see reference 1.4.1.(k)); internal measurement assurance (see reference 1.4.1(l)), using control (check) standards, is required to fully demonstrate that uncertainties remain within stated levels over time. For the purposes of demonstrating traceability for NVLAP accreditation, a laboratory must demonstrate not only that there is an unbroken chain of comparisons to national standards, but also that this chain is supported by appropriate uncertainties, measurement assurance, continuous standard maintenance, proper calibration procedures, and handling of standards. In this way, traceability is related to these other areas of calibration.

1.6 NVLAP documentation

1.6.1 Accreditation documents

Laboratories granted NVLAP accreditation are provided with two documents: Scope of Accreditation and Certificate of Accreditation.

The Scope of Accreditation lists the "Best Uncertainty" that an accredited laboratory can provide for a given range or nominal value within a given parameter of measurement. This "Best Uncertainty" is an statement of the smallest uncertainty that a laboratory has been assessed as capable of providing for that particular range or nominal value. The actual reported value of uncertainty for any particular measurement service that the accredited laboratory provides under its scope may vary depending on such contributors as the statistics of the test and uncertainties associated with the device under test.

1.6.2 Fields of calibration/parameters selection list

The Calibration Laboratories program encompasses eight fields of physical metrology calibration, with multiple parameters under each field. Each field is covered by a separate handbook (NIST Handbooks 150-2A through 150-2H). (Fields of accreditation under Chemical Calibration are covered by separate handbooks.) Depending on the extent of its calibration capabilities, a laboratory may seek accreditation to all or only selected fields and parameters within the scope of the program. The fields of calibration and their related parameters are given on the Fields of Calibration and Parameters Selection List, which is provided to a laboratory seeking accreditation as part of the NVLAP application package for the program. Additional fields of calibration and/or parameters may be added to the Calibration Laboratories program upon request of customer laboratories and/or if decided by NVLAP to be in the best interest of the Calibration Laboratories program.

The laboratory is requested to indicate on the Fields of Calibration/Parameters Selection List the parameter(s) for which accreditation is desired, along with appropriate ranges and uncertainties. There is also provision for an applicant laboratory to request accreditation for parameters not currently listed on the Selection List, or for accreditation of the quality system employed for assuring Measurement and Test Equipment (M & TE) used in support of product certification. Request for accreditation of quality assurance systems for M & TE will be treated as a separate field of calibration for the purpose of setting appropriate fees. Once a laboratory meets all the requirements for accreditation for the Fields of Calibration/Parameters Selection List, this information will become the basis for the Scope of Accreditation document.

1.6.3 Checklists

Checklists enable assessors to document the assessment of the laboratory against the NVLAP requirements found in NIST Handbook 150. The NVLAP Calibration Laboratories Accreditation Program incorporates the NVLAP General Operations Checklist. The questions are applicable to evaluating a laboratory's ability to operate a calibration program, and address factors such as the laboratory's organization, management, and quality system in addition to its calibration competency.

The NVLAP General Operations Checklist is numbered to correspond to the requirements in NIST Handbook 150. Comment sheets are used by the assessor to explain deficiencies noted on the checklist. Additionally, the assessor may use the sheets to make comments on aspects of the laboratory's performance other than deficiencies.

1.7 Assessing and evaluating a laboratory

1.7.1 On-site assessment

1.7.1.1 The NVLAP lead assessor will schedule with the laboratory the date for on-site evaluation, and will request the quality manual and documented quality and calibration procedures in advance of the visit to reduce time spent at the laboratory; such materials will be returned by the assessor. NVLAP and the assessor will protect the confidentiality of the materials and information provided. The laboratory should be prepared to conduct routine calibrations, have equipment in good working order, and be ready for examination according to the guidance contained in this handbook, the requirements identified in NIST Handbook 150, and the laboratory's quality manual. The assessor will need time and work space to complete assessment documentation while at the laboratory, and will discuss these needs at the opening meeting of the on-site assessment.

1.7.1.2 NVLAP technical assessors are provided with the NVLAP General Operations Checklist to help ensure the completeness, objectivity, and uniformity of the on-site assessment.

1.7.1.3 When accreditation has been requested for a considerable number of fields of calibration and parameters, the assessment may range from observing calibrations in progress, requiring repeat measurements on completed calibrations, to listening to laboratory staff describe the calibration process. The depth into which the assessor performs the assessment depends on the number of fields of calibration and associated parameters for which accreditation is requested and the time required to perform a given calibration.

1.7.1.4 The assessor, or the assessment team, does the following during a typical on-site assessment:

a) Conducts an entry briefing with the laboratory manager to explain the purpose of the on-site visit and to discuss the schedule for the day(s). At the discretion of the laboratory manager, other staff may attend the briefing.

b) Reviews quality system manual, equipment and maintenance records, record-keeping procedures, laboratory calibration reports, and personnel competency records. At least one laboratory staff member must be available to answer questions; however, the assessor may wish to review the documents alone. The assessor(s) does not usually ask to take any laboratory documents with him/her, and previously supplied documents will be returned.

c) Physically examines equipment and facilities, observes the demonstration of selected procedures by appropriate personnel assigned to perform calibrations, and interviews the personnel. The demonstrations must include preparation for calibration of devices, and the setup and use of measuring and test equipment, standards and systems.

d) Holds an exit briefing with the laboratory manager and staff to discuss the assessment findings. Deficiencies are discussed and resolutions may be mutually agreed upon. Items that must be addressed before accreditation can be granted are emphasized, and outstanding deficiencies require response to NVLAP within 30 days. Items that have been corrected during the on-site and any recommendations are specially noted.

e) Completes an On-site Assessment Report, as part of the exit briefing, summarizing the findings. The assessor(s) attaches copies of the completed checklists to this report during the exit briefing. The report is signed by the lead assessor and the laboratory's Authorized Representative to acknowledge the discussion. This signature does not necessarily indicate agreement; challenge(s) may be made through NVLAP. A copy is given to the representative for retention. All observations made by the NVLAP assessor are held in the strictest confidence.

1.7.2 Proficiency testing

1.7.2.1 Background

Once the quality system review and on-site assessment steps have been satisfactorily completed, it is necessary to gather another set of data points to aid in deciding whether or not the applicant laboratory is competent to perform calibrations within the fields of interest to the uncertainties claimed. In the eight fields of calibration covered by Handbooks 150-2A through 150-2H, there are approximately 85 parameters of interest. Under most parameters there are several subsets, referred to as ranges. For example, in the time and frequency field, the typical input frequency parameters for most laboratories fall in the range from 1 Hz to 100 MHz, with 1, 5, 10, 100 MHz the most common test frequencies. Laboratories who wish can specify higher input frequencies as parameters. In view of the many possible ranges, proficiency testing could be conducted in a multitude of areas. NVLAP reserves the right to test by sampling in any area; hence, applicant laboratories must be prepared, with reasonable notice, to demonstrate proficiency in any of a number of parameters.

1.7.2.2 Proficiency testing vs. measurement assurance

There is an important difference between proficiency testing and measurement assurance. The objective of proficiency testing is to determine through a measurement process that the laboratory's measurement compares favorably with the measurement of the audit laboratory (NIST or one designated by NVLAP), taking into account the relative uncertainties assigned by both the applicant and audit laboratories. NVLAP employs the same principle used by the European Cooperation for Accreditation and described in EA-2/03 covering international measurement audits. Note that the objective is not to determine and certify the total uncertainty of the applicant laboratory, as is done in a Measurement Assurance Program (MAP) with NIST, but to verify (through the assessment process) that the uncertainty claimed by the applicant laboratory is reasonable, and then to test that the measurement result obtained through the proficiency test is acceptable.

It is not the intention nor the mission of NVLAP to conduct MAPs or to otherwise provide traceability for laboratories. Laboratories obtain these services from the NIST measurement divisions. NVLAP assesses the implementation, application, and documentation of MAPs by laboratories. NVLAP accreditation encourages the use of MAPs by the calibration laboratory community, and MAP results produce objective evidence that NVLAP assessors look for as part of the assessment process.

1.7.2.3 Requirements

NVLAP's proficiency testing program uses a sampling approach. All applicant laboratories are required to complete an annual proficiency test in one parameter under each field of calibration for which it has applied to be accredited. For the purposes of the NVLAP Calibration Laboratories Accreditation Program, the results of the proficiency test are considered as objective evidence, along with the on-site visit, of a laboratory's ability to perform competent calibrations. Proficiency testing is conducted annually using different parameters in each field; however, those laboratories accredited in only one parameter within a field are retested in the same parameter.

1.7.2.4 Uncertainty determination

The applicant laboratory is required to perform a measurement or series of measurements on an artifact using the same calibration method, apparatus, and personnel that it uses to calibrate customers' equipment. The laboratory must be able to identify and quantify all sources of uncertainty that affect the measurement. The laboratory should attach an overall uncertainty to the measurement by combining all uncertainty contributions, in their type A and type B components, in the root-sum-squared method as described in the *Guide to the Expression of Uncertainty in Measurement* (see 1.4.1 (b)). The confidence limit used should be $k = 2$, which is equivalent to a 95% confidence probability.

1.7.2.5 Pass/fail criteria

The performance of the proficiency test is judged by calculating the error of the measurement, normalized with respect to the uncertainty of the measurement, using the following equation:

$$E_{normal} = \left| (Value_{lab} - Value_{ref}) / (Uncertainty_{ref}^2 + Uncertainty_{lab}^2)^{1/2} \right|$$

where

E_{normal} = normalized error of the applicant laboratory
$Value_{lab}$ = the value as measured by the applicant laboratory
$Value_{ref}$ = the value as measured by the reference laboratory
$Uncertainty_{ref}$ = the uncertainty of the reference laboratory
$Uncertainty_{lab}$ = the uncertainty of the applicant laboratory

To pass the proficiency test, the applicant laboratory must have a value for E_{normal} less than 1 (i.e., $E_{normal} < 1$). The results may be plotted graphically, with lines representing the limits of uncertainty of the measurements. The anonymity of each applicant laboratory will always be preserved.

1.7.2.6 Scheduling and handling

Proficiency testing is scheduled by NVLAP-designated reference laboratories. These sites are NIST laboratories or NVLAP-accredited laboratories that have been found to have the ability to perform the required proficiency tests to an uncertainty level appropriate for the laboratories they evaluate. The proficiency test is scheduled independently and not to correspond with the on-site visit. Applicant laboratories are notified in advance as to the approximate arrival time of the measurement artifact. Instructions for performing the test, reporting the results, communicating with the reference laboratory, and shipping are included along with the artifact as part of the proficiency test package. Applicant laboratories are instructed to perform all required measurements within a reasonable time and are told where to ship the artifacts once the testing has been completed.

1.7.2.7 Notification of results

NVLAP notifies each laboratory of its own results in a proficiency test. If a laboratory has been evaluated prior to the completion of the proficiency test, the status of that laboratory's accreditation is contingent upon successful completion of proficiency testing. The laboratory's accreditation status may be changed to reflect a partial accreditation, or may be completely suspended pending demonstration of the laboratory's ability to successfully complete the proficiency test at a later date.

1.7.3 Traceability

1.7.3.1 Establishing traceability

Laboratories must establish an unbroken chain of comparisons leading to the appropriate international or national standard, such that the uncertainties of the comparisons support the level of uncertainty that the laboratory gives to its customers. Generally speaking, the uncertainties of the comparisons increase as they move from a higher (international or national level) to a lower level standard. This uncertainty chain is the evidence of traceability and must be documented accordingly. Traceability does not simply mean having standards calibrated at the national laboratory, but must consider how a measurement, with its corresponding uncertainty, is transferred from the national level to the calibration laboratory's customers.

1.7.3.2 Considerations in determining traceability

Without measurement assurance, one cannot be reasonably certain that the comparisons have been transferred properly to the laboratory's customers. The measurement process itself must be verified to be in control over time. Therefore, traceability is not a static concept that, once established, may be ignored, but it is dynamic. Process control exercised in each calibration provides the assurance that a valid transfer of the international or national standard has taken place. This assurance may be accomplished through the use of tools such as check standards and control charts. Also, the laboratory's primary standards must be maintained in such a way as to verify their integrity. Examples of this may be having more than one primary standard to use for intercomparisons, monitoring the primary standard with a check or working standard (looking for changes), and verifying a primary standard on a well-characterized measurement/calibration system. Using scientifically sound measurement procedures to transfer the primary standard value to the working level and the customer's item is essential to establishing traceability. If the procedure itself yields the wrong result, there is no way the laboratory can perform a calibration traceable to the international or national standard. Handling the laboratory's standards affects the measurement process, and therefore the ability to transfer the standard's value to the customer. Examples of handling problems are dirty or improperly cleaned standards, maintaining standards in an improper environment, not maintaining custody and security, and improper handling of standards during the measurement process.

1.7.3.3 Relationship to existing standards

The above discussion illustrates how traceability is dependent on many aspects of the measurement process and therefore must be considered in all phases of calibration. It is not just coincidental that the factors addressed above are main topics of concern in ISO/IEC 17025:1999.

1.7.4 Uncertainty

NVLAP recognizes the methodology for determining uncertainty as described in the *Guide to the Expression of Uncertainty in Measurement*, published by ISO. To be NVLAP-accredited, a laboratory must document the derivation of the uncertainties that it reports to its customers. These uncertainties will appear on the scope issued to each accredited laboratory to an accuracy appropriate to the standards, procedures, and measuring devices used.

2 Criteria for accreditation

2.1 Introduction

2.1.1 Applicant laboratories are assessed using the requirements in NIST Handbook 150, *NVLAP Procedures and General Requirements*. This guide, NIST Handbook 150-2C, was developed from a NIST measurement laboratory perspective and provides examples and guidelines, not requirements, to assessors and interested calibration laboratories on good laboratory practices and recommended standards. Therefore, the guide language reflects this philosophy through the use of "shoulds" instead of "shalls" (along with other less prescriptive language) when describing criteria. The requirements presented here are not absolute since specific requirements depend on the measurement uncertainty for which an applicant laboratory wishes to be accredited. This is a business decision for each laboratory and beyond the scope of NVLAP. Simply stated, to be accredited, an applicant laboratory must have a quality system and be able to prove (and document) that it is capable of doing what it says it does (i.e., correctly calibrate to a stated uncertainty) within the framework of NIST Handbook 150. Accreditation will be granted, and therefore may be referenced in calibration reports, etc., only for those specific parameters, ranges and uncertainties using calibration methods and procedures for which a laboratory has been evaluated. Calibrations performed by a laboratory using methods and procedures not considered appropriate for the level of measurements being made, and which have not been evaluated by the accreditation process, are outside the scope of accreditation and may not be referenced as "accredited" calibrations on calibration reports, etc.

2.1.2 Section 2.2 provides specific interpretations of the NIST Handbook 150 criteria for time and frequency calibrations. Section 2.3 provides specific calibration guidelines for spectral purity measurements. This guide is dynamic in that new parameters may be added and existing criteria updated and improved.

2.2 Time and frequency

2.2.1 Scope

This section describes the criteria under which a laboratory should operate to be NVLAP-accredited as competent to perform measurements in the area of time and frequency. It also describes the procedure for performing frequency calibrations traceable to NIST and for establishing a time reference. Since any on-site frequency calibration requires an external reference signal, laboratories are encouraged to obtain the publications cited at the end of this section. These publications provide detailed information about the available reference signals, and contain information about the receiving equipment and calibration methods. Users are also invited to contact the Time and Frequency Division of NIST for assistance.

2.2.2 Accommodation and environment

2.2.2.1 A calibration service dependent on radio or satellite signals must mount an outdoor antenna. The laboratory should be arranged so that the receiver is reasonably close to the antenna. The receiver should be isolated from sources of radio interference, and should have a back-up power supply for operation during power failures.

2.2.2.2 The laboratory's main standard (oscillator) should be located where it will not be disturbed. It should run continuously (24 h/d) and should have a back-up power supply so that it remains on during local power outages. For high performance levels (better than 1 x 10^{-10}), an isolation amplifier is needed to distribute signals within and outside the laboratory.

2.2.3 Equipment and reference materials

The laboratory manager should first decide on the performance level required for traceable calibrations, then choose a reference signal that can meet the required level. In making these choices, the manager should consider the equipment and labor costs involved. Both NIST and manufacturers of receiving equipment can help decide which signal to use. There are several factors to consider before making a decision:

a) The selected radio signal should meet the performance standards claimed by the laboratory. Otherwise, calibration claims cannot be validated.

b) The chosen radio signal must be usable at the receiving site; not all radio signals are usable everywhere.

2.2.4 Calibration methods

2.2.4.1 Frequency calibrations can be made continuously or at periodic intervals. The device under test can be a stand-alone device or an oscillator embedded inside another piece of equipment. Stand-alone devices include quartz, rubidium, cesium, and hydrogen maser oscillators. Embedded devices are usually quartz or rubidium oscillators that serve as the time base for a piece of test equipment, such as a frequency counter or signal generator.

2.2.4.2 In most cases, laboratories calibrate only their best oscillator against an external reference. After its performance is known, the signal can be distributed or used to calibrate other oscillators. As a general rule, the frequency reference for a measurement should perform at least one order of magnitude better than the oscillator being calibrated. The reference frequency should be one of the sources listed in section 2.2.4.3.

2.2.4.3 The following is a short description of the four main external signals available at this writing. See the references or contact NIST if further information is required.

a) WWV/WWVH High Frequency Radio Service from NIST (zero beat method)

   1) Performance: 1 x 10^{-7} (single measurement)

   2) Equipment: Shortwave radio with headphones or meter, antenna, and harmonic generator (if needed).

   3) Method: Tune in WWV or WWVH, couple oscillator to receiver antenna and adjust oscillator for zero beat in headphones or on meter.

   4) Pros: Simple equipment. Large coverage area. Low cost. Provides time-of-day information (audio and digital time codes). The audio time code can be used for simple time interval measurements such as the calibration of stop watches and timers.

   5) Cons: Manual operation, must be done often. Cannot be done if reception is poor. No measurement data; only physical record is laboratory log. This makes uncertainty

analysis difficult. Suitable only for calibration of low-performance quartz oscillators such as those found in inexpensive test equipment.

b) WWVB Low Frequency Radio Service from NIST (60 kHz carrier frequency)

1) Performance: 1×10^{-12} (24 h average)

2) Equipment: LF tracking receiver, antenna, phase comparison measurement system, and battery backup. Phase comparison system is built into receiver in some cases. In other cases, it can be a chart recorder or a computer-controlled system that includes a time interval counter and frequency divider.

3) Method: Set up WWVB receiver and antenna. Connect LF receiver output and signal from device under test to phase comparison system. Measurement system produces either a strip chart recording or a phase plot that shows the phase shift of the device under test versus time of day. The frequency offset and stability can be derived from the slope of the phase plot.

4) Pros: Permits calibration of atomic oscillators under good conditions. Carrier frequency is directly produced and controlled by NIST. Provides time-of-day information.

5) Cons: Noise can be a problem over long signal paths (> 2000 km). Large diurnal phase steps (tens of microseconds) might appear in data if a combination of skywave and groundwave is received, since the length of the skywave path can fluctuate. Phase steps equal to a multiple of the period of the carrier frequency (16.67 μs) will occur if signal becomes weak and receiver loses tracking point. These phase steps can make data hard to interpret.

c) LORAN-C LF signals from United States Coast Guard

1) Performance: 1×10^{-12} (24 h average)

2) Equipment: LORAN-C receiver, antenna, phase comparison measurement system, and battery backup. Phase comparison system is built into receiver in some cases. In other cases it can be a chart recorder or a computer-controlled measurement system that includes a time interval counter and frequency divider.

3) Method: Set up LORAN-C receiver and antenna and tune to nearest station. Connect LORAN-C receiver output and signal from device under test to phase comparison system. Measurement system produces either a strip chart recording or a phase plot that shows the phase shift of the device under test versus time of day. The frequency offset and stability can be derived from the slope of the phase plot.

4) Pros: Permits calibration of atomic oscillators. Signals are strong and easy to receive. Pulses are modulated on 100 kHz carrier and provide a carrier tracking point. This makes it possible to identify and stay locked to the same carrier cycle if the laboratory is within 2000 km of LORAN-C transmitter.

5) Cons: Phase steps equal to a multiple of the period of the carrier frequency (10 μs) will occur if signal becomes weak and receiver loses tracking point. These phase steps can make data hard to interpret. LORAN-C service might be discontinued in 2008, so few manufacturers continue to support and sell equipment.

d) Global Positioning System (GPS) service operated by United States Department of Defense

1) Performance: 2×10^{-13} (24 h average)

2) Equipment: Receiver, antenna, time interval counter and 1 Hz divider, or integrated GPS timing receiver.

3) Method: Set up receiver and antenna. Connect GPS receiver output and signal from device under test to phase comparison system. Measurement system collects data and produces a phase plot that shows the phase shift of the device under test versus time of day. The frequency offset and stability can be derived from the slope of the phase plot.

4) Pros: GPS signals are usable nearly anywhere on earth. Better performance than WWVB or LORAN-C and more reliable reception. Provides position and time-of-day information.

5) Cons: GPS is primarily a navigation service, and not all GPS receivers are suitable for use as a time and frequency standard.

2.2.4.4 Distribution of frequency signals

Care should be exercised in the distribution of oscillator signals to avoid:

a) Degradation of performance by overloading the oscillator output.

b) Coupling unwanted signals back into the oscillator (standard).

c) Coupling noise into the distribution circuit.

2.2.4.5 Measurement errors

Most techniques (excluding the audible zero-beat method) have a measurement resolution that is many times better than errors due to radio propagation. Measurements should be made so that radio propagation delays can be averaged out over time. In general, this is easy to do for frequency measurements, but more difficult when determining time-of-day.

2.2.4.6 Time-of-day

2.2.4.6.1 Time, as in time-of-day, is not a standard even though it can be referenced to time-of-day signals maintained at national laboratories. Any frequency source can be used to derive a time-of-day signal with the same stability as the source, but the uncertainty depends upon how well the source can be synchronized to the external reference. Proper synchronization of the signal requires a knowledge of equipment and signal propagation delays. The accuracy of any timekeeping system depends upon how often the system is synchronized to the reference, the stability of the oscillator, and the distribution delays from the system to the user.

2.2.4.6.2 A number of satellite, radio, and telephone systems carry a digital time code. With the right equipment, this code can be read and used to obtain time-of-day. In some cases (WWV and WWVH radio and telephone services) the time is also sent by voice. A list of time-of-day signals is given below. It is the responsibility of the laboratory acquiring such time signals to properly account for all propagation and equipment delays. National laboratories, such as NIST, can only ensure that the time is accurate when it leaves the broadcast source.

a) Radio time-of-day signals

   1) WWV and WWVH (voice & digital code)

   2) WWVB (digital code)

   3) Global Positioning Satellite System (digital code)

b) Telephone and Internet time-of-day signals

   1) Automated Computer Time Service (Digital code for computers by telephone at Boulder, CO is 303-494-4774 and at Hawaii is 808-335-4721).

   2) WWV audio (Colorado) can be heard by dialing 303-499-7111. WWVH audio (Hawaii) can be heard by dialing 808-335-4363.

   3) NIST Internet Time Service (ITS). A list of IP addresses can be found at: http://www.boulder.nist.gov/timefreq/service/time-servers.html.

2.2.5 Certificates and reports

2.2.5.1 Calibration results are normally reported in terms of frequency offset defined as the ratio of the frequency offset or error [f(actual) - f(nameplate)] to the nameplate frequency [f(nameplate)]. The nameplate frequency is the nominal frequency stated on the oscillator or the specification sheet. The frequency offset is positive (+) if the actual frequency is greater than the nameplate frequency and negative (-) if less. Care should be taken in reporting results so that this sign is properly determined. Frequency offset is usually expressed in scientific notation since the numbers involved are small. For example, if an oscillator has a frequency offset of 1 part per billion, its frequency offset is expressed as 1×10^{-9}. The frequency uncertainty is determined by making multiple measurements of the frequency offset and performing a statistical analysis.

2.2.5.2 The averaging time used to determine frequency should always be reported. It should be long enough to produce a meaningful answer. High quality oscillators require longer averaging times. For example, the frequency of a 1×10^{-8} oscillator can be measured by averaging for a few minutes or less using a reference such as GPS, LORAN-C, or WWVB. However, measuring the performance of a 1×10^{-12} oscillator might take 24 hours or longer.

2.2.6 NIST Frequency Measurement and Analysis Service (FMAS)

NIST operates a Frequency Measurement and Analysis Service (FMAS) on a subscription basis. Subscribers to the FMAS pay a monthly fee to NIST, and in turn receive the measurement hardware and software needed to make frequency calibrations traceable to NIST at an uncertainty of 2×10^{-13}. The FMAS uses GPS signals as a reference frequency. Each subscriber's measurement system is linked to NIST by a telephone modem or Internet connection, and NIST personnel monitor all measurements from Boulder, Colorado. A monthly calibration report is sent to each subscriber. The report includes a statement of uncertainty for the device under test relative to the NIST national frequency standard.

The FMAS can benefit NVLAP customers seeking accreditation in the frequency calibration field. In some cases, it can eliminate or reduce the need for proficiency testing (and its associated fees) in the frequency calibration area.

2.2.7 References

a) The NIST Time and Frequency Division web site provides information about the current status of the NIST time and frequency services. It also includes GPS, WWVB, and LORAN-C monitoring data. Please see: http://www.boulder.nist.gov/timefreq.

b) R. E. Beehler and M. A. Lombardi, "NIST Time and Frequency Services," NIST Special Publication 432, June 1991 (new version is in preparation).

c) M. A. Lombardi, "Time and Frequency Measurement," Section III of *The Measurement, Instrumentation, and Sensors Handbook*, CRC Press: Florida, 1999.

d) M. A. Lombardi, "Traceability in Time and Frequency Metrology," *Cal Lab: The International Journal of Metrology*, pp. 33-40, September-October 1999.

2.3 Spectral purity calibrations

2.3.1 Scope

This section describes the criteria under which a calibration laboratory should operate to be NVLAP accredited for calibrations involving spectral purity in the frequency domain (amplitude modulation (AM) and phase modulation (PM) noise of signals) and the time-domain characterization of oscillators. The specifications for these quantities should be the internationally accepted ones described in reference 2.2.7 a).

2.3.2 Statistical process control

The measurement of PM and AM noise in the frequency domain involves more potential problems because the measurement laboratory does not usually have sufficient access to self-calibration or self-testing methods that ensure reliability. For this reason, the calibration laboratory should participate in a round-robin evaluation of performance of standard artifacts for both PM and AM noise measurements. These performance tests should include a determination of the system noise floor and accuracy of the phase and/or amplitude noise level. Once established and certified, time-domain characterization systems are more robust, providing sufficient control and self-testing of measurement conditions. These measurements thus require less continuous control, but it is still a good idea to occasionally perform a round-robin evaluation of the system.

2.3.3 Accommodation and environment

The laboratory conditions (temperature and humidity control) required for measurements should be those commensurate with the sensitivities of the components and oscillators used to perform the measurements. This, of course, depends upon the level of precision desired. Unless the oscillators are particularly sensitive, this usually means that a fairly standard calibration environment (±1 °C and ± 15 % RH) will be adequate.

2.3.4 Equipment and reference materials

2.3.4.1 The following are the general equipment requirements for AM and PM noise measurements:

a) Spectrum analyzer (rf) covering the carrier frequencies of interest.

b) Baseband spectrum analyzer with a calibrated power-spectral-density (PSD) routine.

c) Calibrated power meter with ± 0.5 dB accuracy.

d) PM detectors with post amplifiers.

e) AM detectors with post amplifiers.

f) Electronic counter.

g) Means to calibrate the PSD function of the spectrum analyzer in item b) above.

h) Means to calibrate the linearity of the spectrum analyzer in item b) above.

i) Means to calibrate gain as a function of frequency for amplifiers in items d) and e).

2.3.4.2 The following are the general equipment requirements for time-domain measurements:

a) Electronic counter with input for external reference oscillator.

b) Mixer with post amplifier.

c) Reference oscillator with performance better than clock/oscillator under test.

d) Isolation (active or passive) for device under test.

2.3.5 Calibration methods

2.3.5.1 AM and PM noise

The noise that limits the spectral purity of a signal is composed of two different components, AM and PM noise. To adequately specify the level of AM or PM noise on the signal, it is necessary to use measurement techniques that are sensitive to one type of noise and have good rejection of the other type of noise. In many sources, AM and PM are comparable in magnitude. The conversion of AM noise to PM noise often limits the resolution and accuracy of PM noise measurements. Since the noise processes, especially lower frequency processes, are often not white (with frequency dependence going as 1/f, $1/f^2$, etc.), the bandwidths of systems and averaging times are important. Using the IEEE or internationally accepted specification (see references) for these noises will account for this problem.

2.3.5.2 Calibration procedures for PM noise measurements

2.3.5.2.1 PM noise measurement systems can be divided into two-oscillator and single-oscillator measurement systems. The most common measurement technique for PM noise measurements is the two-oscillator method. This technique offers the widest range of carrier frequencies, the lowest noise, and the widest bandwidth for analysis. Single-oscillator systems require only one source, but have much higher noise floors close to the carrier. A problem with this technique for calibration purposes is that it is much more difficult to evaluate the noise floor because the noise in the source always contributes to the measurement. Because of this problem, two-oscillator methods are generally preferred over single-oscillator methods. More detailed descriptions of these and other measurement methods can be found in NIST Technical Note 1337 (reference 2.3.6 a)).

2.3.5.2.2 The errors that affect phase noise measurements using the two-oscillator technique are listed below. The model for confidence limits depends upon whether the analyzer uses Fast-Fourier-Transform (FFT) or a swept method.

a) Value of detector sensitivity and possible variations with frequency.

b) Value of gain and possible variations with frequency.

c) Variable phase-locked-loop effects at low frequency.

d) Non-linearity of spectrum analyzers.

e) Contributions of AM noise.

f) Inaccuracy of power-spectral-density (PSD) functions.

g) Conversion of noise at harmonics.

h) Noise contributions from the system noise floor.

i) Analysis uncertainty in separating the reference oscillator noise.

2.3.5.2.3 The calibration laboratory should indicate the biases and uncertainties for each of the nine errors for every measurement. The laboratory should ensure that sufficient data are taken to be sure that a 95 % confidence level (1.9 σ) can be properly specified.

2.3.5.2.4 It is sometimes necessary to use cross-correlation techniques to reduce the measurement noise floor so that it doesn't limit the resolution and accuracy of PM noise measurements (see reference 2.3.6 a)). The methods of reference 2.3.6 b) should be used to estimate the 95 % confidence window for statistical uncertainty of the PSD measurements. Because of the problem of AM-to-PM conversion, no PM measurement is complete without determining the AM noise and the AM-to-PM conversion factor as a function of Fourier frequency of the measurement system.

2.3.5.3 Calibration procedures for AM noise measurements

2.3.5.3.1 AM noise measurement systems usually have a high PM noise rejection and so determination of PM noise can often be neglected. It is often necessary to use cross-correlation techniques to reduce measurement noise floor enough that it does not limit the resolution and accuracy of the measurements (see 2.2.7 c)). The list below gives the errors for AM noise measurements.

a) Value of detector sensitivity and possible variations with frequency.

b) Value of gain and possible variations with frequency.

c) Conversion of noise at harmonics.

d) Noise contributions from the system noise floor.

e) Non-linearity of spectrum analyzers.

f) Inaccuracy of power-spectral-density (PSD) functions.

2.3.5.3.2 The calibration laboratory should indicate the biases and uncertainties for each of the six errors for every measurement. The laboratory should ensure that sufficient data are taken to be sure that a 95 % confidence level (1.9 σ) can be properly specified.

2.3.5.4 Time-domain calibration procedures

2.3.5.4.1 A simple time-domain characterization can be derived from a time series of direct, fixed-interval counts of the frequency. One can derive from this one of the two-sample variances (Allan variance, modified Allan variance or time variance) as a function of averaging time τ (see reference 2.3.6 a)). The computer effectively varies the averaging time by looking at successively larger intervals in the data. The direct counter method suffers from low resolution, so heterodyne measurement methods are needed to characterize high-performance clocks and oscillators. These methods are described in reference 2.3.6 a). The error considerations for these time-domain measurements are given below. Special care should be taken to isolate the oscillator under test from the measurement system. Inadequate isolation can lead to locking of the oscillator under test to the reference.

a) Aliasing effects.

b) Quantization uncertainty associated with digitization.

c) Effects of dead time in the measurement process.

d) Noise associated with the reference oscillator.

e) Distortion of results by the presence of "bright" lines in the spectrum.

f) Effects of hardware bandwidths.

2.3.5.4.2 The calibration laboratory should indicate the biases and uncertainties for each of the six errors for every measurement.

2.3.5.5 Conversion from the frequency domain to the time domain

Good time-domain characterization can be obtained through proper conversion of frequency-domain data to the time domain (see reference 2.3.6 a)). The time-domain averaging time τ in such a conversion should be limited to $1/(2\pi f)$ where f is the lowest Fourier frequency where reliable frequency-domain data are available. Reverse conversion from the time domain to the frequency domain is not reliable and should not be used.

2.3.6 References

a) D. B. Sullivan, D. W. Allan, D. A. Howe, and F. L. Walls, Eds., "Characterization of Clocks and Oscillators," NIST Tech. Note 1337, March 1990. (Available from the Superintendent of Documents, U.S. Government Printing Office, Washington, DC 20402-9325.)

b) F. L. Walls, "Reducing Errors, Complexity, and Measurement Time of PM Noise Measurements," Proceedings of the 1993 IEEE Frequency Control Symposium, Salt Lake City, UT, June 2-4, 1993, IEEE Catalogue No. 93CH3244-1.

c) L. M. Nelson, C. W. Nelson and F. L. Walls, "Relationship of AM-to-PM Noise in Selected RF Oscillators," Proceedings of the 1993 IEEE Frequency Control Symposium, Salt Lake City, UT, June 2-4, 1993, IEEE Catalogue No. 93CH3244-1.

d) F. L. Walls and E.S. Ferre-Pikal, "Measurement of Frequency, Phase Noise and Amplitude Noise," *Wiley Encyclopedia of Electrical and Electronics Engineering*, Vol. 12, pp. 459-473, John Wiley & Sons: New York, 1999.