

ASME B89.4.19-2021

[Revision of ASME B89.4.19-2006 (R2015)]

Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems

AN AMERICAN NATIONAL STANDARD



**The American Society of
Mechanical Engineers**

ASME B89.4.19-2021
[Revision of ASME B89.4.19-2006 (R2015)]

Performance Evaluation of Laser-Based Spherical Coordinate Measurement Systems

AN AMERICAN NATIONAL STANDARD



**The American Society of
Mechanical Engineers**

Two Park Avenue • New York, NY • 10016 USA

Date of Issuance: April 11, 2022

This Standard will be revised when the Society approves the issuance of a new edition.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this Standard. Interpretations are published on the Committee web page and under <http://go.asme.org/InterpsDatabase>. Periodically certain actions of the ASME B89 Committee may be published as Cases. Cases are published on the ASME website under the B89 Committee Page at <http://go.asme.org/B89committee> as they are issued.

Errata to codes and standards may be posted on the ASME website under the Committee Pages to provide corrections to incorrectly published items, or to correct typographical or grammatical errors in codes and standards. Such errata shall be used on the date posted.

The B89 Committee Page can be found at <http://go.asme.org/B89committee>. There is an option available to automatically receive an e-mail notification when errata are posted to a particular code or standard. This option can be found on the appropriate Committee Page after selecting "Errata" in the "Publication Information" section.

ASME is the registered trademark of The American Society of Mechanical Engineers.

This code or standard was developed under procedures accredited as meeting the criteria for American National Standards. The standards committee that approved the code or standard was balanced to ensure that individuals from competent and concerned interests had an opportunity to participate. The proposed code or standard was made available for public review and comment, which provided an opportunity for additional public input from industry, academia, regulatory agencies, and the public-at-large.

ASME does not "approve," "rate," or "endorse" any item, construction, proprietary device, or activity. ASME does not take any position with respect to the validity of any patent rights asserted in connection with any items mentioned in this document, and does not undertake to insure anyone utilizing a standard against liability for infringement of any applicable letters patent, nor does ASME assume any such liability. Users of a code or standard are expressly advised that determination of the validity of any such patent rights, and the risk of infringement of such rights, is entirely their own responsibility.

Participation by federal agency representatives or persons affiliated with industry is not to be interpreted as government or industry endorsement of this code or standard.

ASME accepts responsibility for only those interpretations of this document issued in accordance with the established ASME procedures and policies, which precludes the issuance of interpretations by individuals.

No part of this document may be reproduced in any form,
in an electronic retrieval system or otherwise,
without the prior written permission of the publisher.

The American Society of Mechanical Engineers
Two Park Avenue, New York, NY 10016-5990

Copyright © 2022 by
THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
All rights reserved

CONTENTS

Foreword	v
Committee Roster	vi
Correspondence With the B89 Committee	vii
Summary of Changes	ix
1	Scope	1
2	Introduction	1
3	Definitions	2
4	Specifications and Rated Conditions	4
5	Test Environment	4
6	Performance Evaluation Tests	4
7	Analysis of Performance Evaluation Tests	18
8	References	21
 Mandatory Appendix		
I	Reference Length Traceability	23
 Nonmandatory Appendices		
A	Traceability of Subsequent Measurements	25
B	Spherically Mounted Retroreflector (SMR) Tests	27
C	Refractive Index of Air	33
D	Reference Lengths for Laser Tracker System Tests and Test Value Uncertainty	37
E	Effect of Air Temperature on Laser Tracker Measurements	49
F	Laser Tracker Interim Testing	55
 Figures		
6.4.4.1-1	Laser Tracker and Reference Interferometer Alignment	17
6.4.4.1-2	Cosine Error Versus Offset C From Reference Line	17
7.1-1	Form 4-2 With Example Default Method Data	19
7.3.1-1	Least-Squares Line Fit to 12 Short Reference Lengths	20
7.4.2-1	Form 4-2 With Example Alternative Method Data	22
B-2.1-1	Microscope Schematic for Measuring Lateral Centering Error	28
B-2.2-1	Setup for Measuring Radial Centering Error	28
B-3-1	Beam Orientations That Minimize Effects of Dihedral Angle Errors	30
B-3-2	Laser Path With Unintended Offset Between Incoming and Outgoing Beams	31
B-3-3	Path of Laser Beam in Cube-Corner Retroreflector	31
B-3-4	Top View of Laser Beam Path in Cube-Corner Retroreflector	31
B-3-5	Top View of Cube Corner With Extended Lines of Intersection	32
B-3-6	Laser Beams Superimposed on Top View of Dihedral Prism	32

B-3-7	Encoder Runout Pattern	32
C-5-1	Refractivity for Standard Dry Air	36
D-6-1	Schematic of Laser Rail System	45
D-6.2-1	Illustrating the Origin of Abbé Errors	46
D-6.2-2	Abbé Error Versus Carriage Angular Motion for Various Values of Abbé Offset	47
E-2.3-1	Change in Refractive Index Versus Transverse Distance, x	52
E-2.3-2	Angle of Laser Beam Versus Distance Traveled	53
E-2.3-3	Transverse Displacement of Laser Beam Versus Distance Traveled	53
E-2.3-4	Example of Fractional Error Versus Distance	54
F-5.1.2-1	Scale Bar With Three Nests for Interim Testing	56
F-5.1.2-2	Five Test Positions to Perform the Interim Check of a Laser Tracker	57
F-5.2.2-1	Setup for Inclinator Tests	58
 Tables		
6.1-1	Laser Tracker Performance Evaluation Requirements	7
6.2.1-1	Horizontal Length Measurement System Test	8
6.2.1-2	Vertical Length Measurement System Test	9
6.2.1-3	Right Diagonal Length Measurement System Test	10
6.2.1-4	Left Diagonal Length Measurement System Test	11
6.3.1-1	Two-Face System Test	13
6.4.1-1	Ranging Test	14
A-2-1	Example Uncertainty Budget	26
 Forms		
4-1	Specifications of Rated and Limiting Operating Conditions	5
4-2	Manufacturer's Performance Specifications and Test Results	6

FOREWORD

ASME B89 Standards Committee on Dimensional Metrology, under procedures approved by the American National Standards Institute (ANSI), prepares standards that encompass the inspection and the means of measuring characteristics of such various geometric parameters as diameter, length, flatness, parallelism, concentricity, and squareness.

Division 4 of the B89 Committee produces standards and technical reports in the area of coordinate measuring technology, with particular focus on coordinate measuring machines (CMMs). This Standard addressing the performance evaluation of laser trackers and similar large-scale measurement systems is the work of the B89.4.19 Project Team.

Performance evaluation of a laser tracker presents challenges different from those associated with conventional Cartesian CMMs. Because of a laser tracker's very large working volume, no full-scale, three-dimensional calibrated artifacts exist, and the design of the laser beam steering subsystem is such that individual parametric errors cannot, in general, be isolated and measured individually. For any coordinate measurement system, a test of the system's ability to realize the SI unit of length, the meter, is a fundamental requirement. In a laser tracker, the length scale is often a laser interferometer (IFM), and the person checking the system's ability to realize a meter usually does not have a significantly more accurate reference interferometer with which to perform such a test.

For these reasons, the performance evaluation tests in this Standard consist primarily of point-to-point length measurements using calibrated artifacts that can be realized in a number of ways. Measured lengths are compared with the manufacturer's maximum permissible error (MPE) specifications in order to decide conformance. Realization of the SI definition of the meter can be evaluated in a number of ways, including calibration of the laser IFM, measurement of a series of short-calibrated reference lengths, or measurement of a series of long-calibrated reference lengths. Procedures are also included for testing the absolute distance measurement capability of laser trackers that include this option.

All reference lengths used in the performance evaluation tests are required to be traceable per ASME B89.7.5. Guidance is provided on how to demonstrate this traceability, as well as the traceability of subsequent point-to-point length measurements made with a laser tracker that has passed the performance evaluation tests of this Standard.

ASME B89.4.19-2021 was approved by ANSI on September 13, 2021.

ASME B89 COMMITTEE

Dimensional Metrology

(The following is the roster of the Committee at the time of approval of this Standard.)

STANDARDS COMMITTEE OFFICERS

E. Morse, *Chair*
J. Cassamassino, *Secretary*

STANDARDS COMMITTEE PERSONNEL

J. Cassamassino , The American Society of Mechanical Engineers	D. Sawyer , National Institute of Standards and Technology
T. C. Charlton, Jr. , Charlton Associates	J. R. Schmidl , Optical Gaging Products, Inc.
J. D. Drescher , UTC — Pratt and Whitney	C. Shakarji , National Institute of Standards and Technology
M. L. Fink , Retired	R. L. Thompson , U.S. Air Force Metrology and Calibration
E. Gesner , Quality Vision International, Inc.	K. L. Skinner , <i>Alternate</i> , U.S. Air Force Metrology and Calibration
G. A. Hetland , International Institute of Geometric Dimensioning and Tolerancing	B. Crowe , <i>Contributing Member</i> , CDI Engineering Solutions
M. Liebers , Professional Instruments Co.	T. E. Carpenter , <i>Honorary Member</i> , U.S. Air Force Metrology and Calibration
R. L. Long , ANSI National Accreditation Board	D. J. Christy , <i>Honorary Member</i> , Mahr Federal, Inc.
E. Morse , University of North Carolina, Charlotte	R. J. Hocken , <i>Honorary Member</i> , University of North Carolina, Charlotte
B. Parry , Consultant	M. P. Krystek , <i>Honorary Member</i> , Physikalisch-Technische Bundesanstalt
P. Pereira , Caterpillar, Inc.	B. R. Taylor , <i>Honorary Member</i> , Consultant
B. S. Pippenger , Rolls-Royce Purdue University	
J. G. Salisbury , Mitutoyo America Corp.	

SUBCOMMITTEE 4 — COORDINATE MEASURING TECHNOLOGY

E. Morse , <i>Chair</i> , University of North Carolina, Charlotte	B. S. Pippenger , Rolls-Royce Purdue University
T. E. Carpenter , U.S. Air Force Metrology and Calibration	J. B. Ross , GE Aircraft Engines
T. C. Charlton, Jr. , Charlton Associates	J. G. Salisbury , Mitutoyo America Corp.
J. Davies , Honeywell Federal Manufacturing and Technologies	J. Schlecht , North Star Imaging, Inc.
J. D. Drescher , UTC — Pratt and Whitney	J. R. Schmidl , Optical Gaging Products, Inc.
E. Gesner , Quality Vision International, Inc.	C. Shakarji , National Institute of Standards and Technology
R. L. Long , ANSI National Accreditation Board	R. L. Thompson , U.S. Air Force Metrology and Calibration
B. Parry , Consultant	E. R. Yaris , Lowell, Inc.
P. Pereira , Caterpillar, Inc.	

WORKING GROUP B89.4.19 — OPTICAL CMM EVALUATION

B. Muralikrishnan , <i>Chair</i> , National Institute of Standards and Technology	P. K. Rachakonda , National Institute of Standards and Technology
D. Bianculli , Lawrence Berkeley National Laboratory	K. W. Redman , Sierra Lobo, Inc.
R. E. Bridges , FARO Technologies	M. Saure , Leica Geosystems AG
E. Clifton , The Boeing Co.	D. Sawyer , National Institute of Standards and Technology
J. D. Drescher , UTC — Pratt and Whitney	M. Settle , Brunson Instrument Co.
R. P. Elliot, Jr. , Lockheed Martin	H. Shi , SLAC National Accelerator Laboratory, Stanford University
D. K. MacKinnon , Canadian Intellectual Property Office	K. M. Shilling , National Institute of Standards and Technology
M. Meuret , Brunson Instrument Co.	K. L. Skinner , U.S. Air Force Metrology and Calibration
K. Ni , Apple, Inc.	D. Sommers , BWX Technologies
	R. L. Thompson , U.S. Air Force Metrology and Calibration

CORRESPONDENCE WITH THE B89 COMMITTEE

General. ASME Standards are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Standard may interact with the Committee by requesting interpretations, proposing revisions or a case, and attending Committee meetings. Correspondence should be addressed to:

Secretary, B89 Standards Committee
The American Society of Mechanical Engineers
Two Park Avenue
New York, NY 10016-5990
<http://go.asme.org/Inquiry>

Proposing Revisions. Revisions are made periodically to the Standard to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Standard. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Standard. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Proposing a Case. Cases may be issued to provide alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Standard and the paragraph, figure, or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Standard to which the proposed Case applies.

Interpretations. Upon request, the B89 Standards Committee will render an interpretation of any requirement of the Standard. Interpretations can only be rendered in response to a written request sent to the Secretary of the B89 Standards Committee.

Requests for interpretation should preferably be submitted through the online Interpretation Submittal Form. The form is accessible at <http://go.asme.org/InterpretationRequest>. Upon submittal of the form, the Inquirer will receive an automatic e-mail confirming receipt.

If the Inquirer is unable to use the online form, he/she may mail the request to the Secretary of the B89 Standards Committee at the above address. The request for an interpretation should be clear and unambiguous. It is further recommended that the Inquirer submit his/her request in the following format:

- Subject: Cite the applicable paragraph number(s) and the topic of the inquiry in one or two words.
- Edition: Cite the applicable edition of the Standard for which the interpretation is being requested.
- Question: Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. Please provide a condensed and precise question, composed in such a way that a “yes” or “no” reply is acceptable.
- Proposed Reply(ies): Provide a proposed reply(ies) in the form of “Yes” or “No,” with explanation as needed. If entering replies to more than one question, please number the questions and replies.
- Background Information: Provide the Committee with any background information that will assist the Committee in understanding the inquiry. The Inquirer may also include any plans or drawings that are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in the format described above may be rewritten in the appropriate format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

Moreover, ASME does not act as a consultant for specific engineering problems or for the general application or understanding of the Standard requirements. If, based on the inquiry information submitted, it is the opinion of the Committee that the Inquirer should seek assistance, the inquiry will be returned with the recommendation that such assistance be obtained.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not “approve,” “certify,” “rate,” or “endorse” any item, construction, proprietary device, or activity.

Attending Committee Meetings. The B89 Standards Committee regularly holds meetings and/or telephone conferences that are open to the public. Persons wishing to attend any meeting and/or telephone conference should contact the Secretary of the B89 Standards Committee. Future Committee meeting dates and locations can be found on the Committee Page at <http://go.asme.org/B89committee>.

ASME B89.4.19-2021

SUMMARY OF CHANGES

Following approval by the ASME B89 Committee and ASME, and after public review, ASME B89.4.19-2021 was approved by the American National Standards Institute on September 13, 2021.

The figures, forms, and tables in ASME B89.4.19-2021 have been redesignated based on their parent paragraphs. ASME B89.4.19-2021 also includes the following changes identified by a margin note, **(21)**.

<i>Page</i>	<i>Location</i>	<i>Change</i>
1	1	Revised
1	2	Revised
2	3	Revised in its entirety
4	4	Revised
5	Form 4-1	Title and subheadings revised
6	Form 4-2	Title revised
4	5	Revised
4	6	Revised in its entirety
13	Table 6.3.1-1	Title revised
18	7	Revised in its entirety
19	Figure 7.1-1	Title revised
22	Figure 7.4.2-1	Title revised
21	8	References updated
23	Mandatory Appendix I	Revised in its entirety
25	Nonmandatory Appendix A	Revised
26	Table A-2-1	Revised
27	B-1	First sentence and subpara. (a) revised
27	B-2.1	Third paragraph revised
27	B-2.2	Second and fifth sentences revised
28	Figure B-2.2-1	General Note added
29	B-3	First, second, ninth, and tenth paragraphs revised
34	C-4	Second and fourth paragraphs revised
34	C-4.1	First sentence revised
34	C-5	First paragraph revised
37	Nonmandatory Appendix D	Revised in its entirety
49	E-1	First sentence revised
55	Nonmandatory Appendix F	Revised in its entirety
56	Figure F-5.1.2-1	Added
57	Figure F-5.1.2-2	Added
58	Figure F-5.2.2-1	Added

PERFORMANCE EVALUATION OF LASER-BASED SPHERICAL COORDINATE MEASUREMENT SYSTEMS

1 SCOPE

(21)

This Standard prescribes methods for the performance evaluation of laser-based spherical coordinate measurement systems and provides a basis for performance comparisons among such systems. Definitions, environmental requirements, and test methods are included with emphasis on point-to-point length measurements. The specified test methods are appropriate for the performance evaluation of a majority of laser-based spherical coordinate measurement systems and are not intended to replace more complete tests that may be required for special applications.

This Standard establishes requirements and methods for specifying and testing the performance of a class of spherical coordinate measurement systems called laser trackers.¹ A laser tracker is a system that directs the light from a range-measuring device to a retroreflecting target (called a retroreflector) by means of a two-axis rotary steering mechanism while monitoring the angular position of these rotary axes, thereby forming a spherical coordinate metrology system. Such a system may measure a static target, track and measure a moving target, or measure (and perhaps track) some combination of static and moving targets. This Standard can also be used to specify and verify the relevant performance tests of other spherical coordinate measurement systems that use cooperative targets, such as laser radar systems.

This Standard focuses specifically on the use of laser trackers as industrial measurement tools rather than on their use in surveying or geodesy. Specified tests are designed to evaluate the static point-to-point length measurement capabilities of these systems. The specified tests are not intended to evaluate the dynamic performance of the laser trackers. Additional tests are included that evaluate the range measurement capability of laser trackers equipped with absolute distance meters (ADMs). The tests do not evaluate workpiece thermal compensation capability and are not sensitive to spherically mounted retroreflector (SMR) imperfections.

2 INTRODUCTION

(21)

In addition to providing for the performance evaluation of laser trackers, this Standard facilitates performance comparisons among different systems by unifying the terminology and the treatment of environmental factors. It defines test methods appropriate for evaluating the performance of a majority of laser trackers, but it is not intended to replace more complete tests that may be required for special applications.

Systems that have passed the performance evaluation tests of this Standard are considered capable of producing traceable point-to-point length measurements for the conditions required herein. Application of point-to-point length measurements to a specific workpiece or measurement task may require additional testing and analysis in order to establish metrological traceability. This Standard provides technical guidance that may be useful in the calibration of laser-based spherical coordinate systems for point-to-point length measurements.

The Appendices describe various factors that should be considered when using this Standard.

(a) [Mandatory Appendix I](#) discusses metrological traceability, with particular focus on demonstrating traceability of reference lengths used in laser tracker performance evaluation. Requirements for demonstrating metrological traceability are presented per ASME B89.7.5.

(b) [Nonmandatory Appendix A](#) discusses the traceability of laser tracker point-to-point length measurements performed subsequent to a system passing the performance evaluation tests described in this Standard.

(c) [Nonmandatory Appendix B](#) describes tests and procedures for determining geometric errors in the construction of SMRs so that the suitability of a particular SMR for laser tracker performance testing can be evaluated.

(d) [Nonmandatory Appendix C](#) describes environmental factors that influence the refractive index of light in air. These factors affect the wavelength of light and should be carefully understood before proceeding with the tests described in this Standard.

¹For purposes of this Standard, the terms *spherical coordinate measurement system* and *laser tracker* will be used interchangeably, notwithstanding the ability or inability to track a target.