



IEEE Standard for Measuring the Imaging Performance of Active Millimeter-Wave Systems for Security Screening of Humans

IEEE Instrumentation and Measurement Society

Developed by the
Radiation and Nuclear Instrumentation and Systems Committee

IEEE Std N42.59™-2024

STANDARDS

IEEE Standard for Measuring the Imaging Performance of Active Millimeter-Wave Systems for Security Screening of Humans

Developed by the

Radiation and Nuclear Instrumentation and Systems
of the
IEEE Instrumentation and Measurement Society

Approved 12 November 2024

IEEE SA Standards Board

Recognized as an American National Standard

Abstract: Established in this standard are test methods and test objects for measuring the imaging performance of active millimeter wave (MMW) radio frequency systems for security screening of humans. This standard applies to security screening systems that inspect people who are not inside vehicles, containers, or enclosures. Specifically, this standard applies to systems used to detect objects carried on the body of the individual being screened. The purpose of this standard is to provide standard test objects and methods of evaluating and reporting imaging quality characteristics. The quality of the data that is used for automated threat recognition is the primary concern.

Keywords: body scanner, contrast resolution, contrast scaling, depth response, dynamic range, effective depth resolution, field of view, IEEE N42.59, illumination coverage, illumination uniformity, imaging performance, lateral resolution, millimeter wave, personnel scanner, reflectivity mapping, security screening

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2025 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 18 April 2025. Printed in the United States of America.

IEEE is a registered trademark in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 979-8-8557-1939-0 STD27759
Print: ISBN 979-8-8557-1940-6 STDPD27759

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <https://www.ieee.org/about/corporate/governance/p9-26.html>.

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

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE Standards documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page (<https://standards.ieee.org/ipr/disclaimers.html>), appear in all IEEE standards and may be found under the heading “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents are developed within IEEE Societies and subcommittees of IEEE Standards Association (IEEE SA) Board of Governors. IEEE develops its standards through an accredited consensus development process, which brings together volunteers representing varied viewpoints and interests to achieve the final product. IEEE standards are documents developed by volunteers with scientific, academic, and industry-based expertise in technical working groups. Volunteers involved in technical working groups are not necessarily members of IEEE or IEEE SA and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE makes no warranties or representations concerning its standards, and expressly disclaims all warranties, express or implied, concerning all standards, including but not limited to the warranties of merchantability, fitness for a particular purpose and non-infringement. IEEE Standards documents do not guarantee safety, security, health, or environmental protection, or compliance with law, or guarantee against interference with or from other devices or networks. In addition, IEEE does not warrant or represent that the use of the material contained in its standards is free from patent infringement. IEEE Standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity, nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document should rely upon their own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: THE NEED TO PROCURE SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus balloting process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English language version published by IEEE is the approved IEEE standard.

Use by artificial intelligence systems

In no event shall material in any IEEE Standards documents be used for the purpose of creating, training, enhancing, developing, maintaining, or contributing to any artificial intelligence systems without the express, written consent of IEEE SA in advance. “Artificial intelligence” refers to any software, application, or other system that uses artificial intelligence, machine learning, or similar technologies, to analyze, train, process, or generate content. Requests for consent can be submitted using the Contact Us form.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE SA Standards Board Operations Manual is not, and shall not be considered or inferred to be, the official position of IEEE or any of its committees and shall not be considered to be, or be relied upon as, a formal position of IEEE or IEEE SA. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that the presenter’s views should be considered the personal views of that individual rather than the formal position of IEEE, IEEE SA, the Standards Committee, or the Working Group. Statements made by volunteers may not represent the formal position of their employer(s) or affiliation(s). News releases about IEEE standards issued by entities other than IEEE SA should be considered the view of the entity issuing the release rather than the formal position of IEEE or IEEE SA.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE or IEEE SA. However, **IEEE does not provide interpretations, consulting information, or advice pertaining to IEEE Standards documents.**

Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its Societies and subcommittees of the IEEE SA Board of Governors are not able to provide an instant response to comments or questions, except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in evaluating comments or revisions to an IEEE standard is welcome to join the relevant IEEE SA working group. You can indicate interest in a working group using the Interests tab in the Manage Profile & Interests area of the [IEEE SA myProject system](#).¹ An IEEE Account is needed to access the application.

Comments on standards should be submitted using the [Contact Us](#) form.²

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not constitute compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

¹ Available at: <https://development.standards.ieee.org/myproject-web/public/view.html#landing>.

² Available at: <https://standards.ieee.org/about/contact/>.

Data privacy

Users of IEEE Standards documents should evaluate the standards for considerations of data privacy and data ownership in the context of assessing and using the standards in compliance with applicable laws and regulations.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under U.S. and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, neither IEEE nor its licensors waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate licensing fees, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400; <https://www.copyright.com/>. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit [IEEE Xplore](#) or [contact IEEE](#).³ For more information about the IEEE SA or IEEE's standards development process, visit the IEEE SA Website.

Errata

Errata, if any, for all IEEE standards can be accessed on the [IEEE SA Website](#).⁴ Search for standard number and year of approval to access the web page of the published standard. Errata links are located under the Additional Resources Details section. Errata are also available in [IEEE Xplore](#). Users are encouraged to periodically check for errata.

³ Available at: <https://ieeexplore.ieee.org/browse/standards/collection/ieee>.

⁴ Available at: <https://standards.ieee.org/standard/index.html>.

Patents

IEEE standards are developed in compliance with the [IEEE SA Patent Policy](#).⁵

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE SA Website at <https://standards.ieee.org/about/sasb/patcom/patents.html>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

IMPORTANT NOTICE

Technologies, application of technologies, and recommended procedures in various industries evolve over time. The IEEE standards development process allows participants to review developments in industries, technologies, and practices, and to determine what, if any, updates should be made to the IEEE standard. During this evolution, the technologies and recommendations in IEEE standards may be implemented in ways not foreseen during the standard's development. IEEE standards development activities consider research and information presented to the standards development group in developing any safety recommendations. Other information about safety practices, changes in technology or technology implementation, or impact by peripheral systems also may be pertinent to safety considerations during implementation of the standard. Implementers and users of IEEE Standards documents are responsible for determining and complying with all appropriate safety, security, environmental, health, data privacy, and interference protection practices and all applicable laws and regulations.

⁵ Available at: <https://standards.ieee.org/about/sasb/patcom/materials.html>.

Participants

At the time this standard was completed, the Imaging Performance of Active Millimeter-Wave Systems Working Group had the following membership:

Sherif Ahmed, *Chair*
Lee Spanier, *Vice Chair*
Douglas McMakin, *Vice-chair*
Jack Glover, *Secretary*
Lawrence Hudson, *Technical Editor*

Andrew Aceti
Laura Aume
Ra'id Awadallah
Jeffrey Barber
Richard Burdette
Stephen Cockey
Robert Flacco
Andrew Foland
William Garrett
Christopher Gregory

Frank Gumbmann
Michael Jennings
Angela Lundberg
Linda Marchese
Barry Masters
Yonas Nebiyeloul-Kifle
Joseph Palma
Nicholas Paulter
Chondrea Richard
Colin Sanford

Georg Schnattinger
Firas Shaikh
David Sheen
Barry Smith
Steve Smith
Scott Trosper
James Weatherall
Christoph Weiskopf

The following members of the individual Standards Association balloting group voted on this standard. Balloters may have voted for approval, disapproval, or abstention.

William Garrett
Jack Glover
John Hawkins
Werner Hoelzl
Efthymios Karabetsos
Piotr Karocki
Richard Kouzes
Greg Luri

Linda Marchese
Jon Martens
Darren McCarthy
Douglas McMakin
Nicholas Ortyl
Satoshi Oyama
Bansi Patel
Donivan Porterfield

Cam Posani
Georg Schnattinger
Jhony Sembiring
Lee Spanier
Walter Struppler
Mark Sturza
Peter Vouras

When the IEEE SA Standards Board approved this standard on 12 November 2024, it had the following membership:

David J. Law, *Chair*
Jon Walter Rosdahl, *Vice Chair*
Gary Hoffman, *Past Chair*
Alpesh Shah, *Secretary*

Sara R. Biyabani
Ted Burse
Stephen Dukes
Doug Edwards
J. Travis Griffith
Guido R. Hiertz
Ronald W. Hotchkiss
Hao Hu

Yousef Kimiagar
Joseph L. Koepfinger*
Howard Li
Xiaohui Liu
John Haiying Lu
Kevin W. Lu
Hiroshi Mano
Paul Nikolich

Robby Robson
Lei Wang
F. Keith Waters
Sha Wei
Philip B. Winston
Don Wright

*Member Emeritus

Introduction

This introduction is not part of IEEE Std N42.59-2024, IEEE Standard for Measuring the Imaging Performance of Active Millimeter-Wave Systems for Security Screening of Humans.

This standard is the responsibility of the Accredited American Standards Committee on Radiation Instrumentation, N42. The standard was approved on N42 letter ballot.

Contents

1. Overview	1
1.1 Scope	1
1.2 Purpose	2
1.3 Word usage	2
2. Definitions, acronyms, and abbreviations	3
2.1 Definitions	3
2.2 Acronyms and abbreviations	4
3. General testing requirements	5
3.1 Environmental	5
3.2 System mode	5
3.3 Test object placement	5
3.4 Data for analysis	6
3.5 Measurement coordinate system	6
4. Test procedures for image quality	7
4.1 General	7
4.2 Test report	8
4.3 Lateral resolution	10
4.4 Effective depth resolution and depth response	14
4.5 Illumination coverage and uniformity	22
4.6 Contrast scaling and contrast resolution	29
4.7 Minimum detectability	36
Annex A (normative) Detailed test article drawings	42
Annex B (informative) Detailed drawings for fixturing the test objects	51
Annex C (informative) Sample test report	82
C.1 Introduction	82
C.2 Lateral resolution	83
C.3 Effective depth resolution and depth response	86
C.4 Illumination coverage and uniformity	90
C.5 Contrast scaling and contrast resolution	93
C.6 Minimum detectability	95
Annex D (informative) Statistical guidance on multiple scans, summary statistics, and comparison of results	97

IEEE Standard for Measuring the Imaging Performance of Active Millimeter-Wave Systems for Security Screening of Humans

1. Overview

This document establishes standard test methods and test objects for measuring the imaging performance of active millimeter wave (MMW) radio frequency systems for security screening of humans. The quality useability of the data for automated analysis is the primary concern. This standard does not address the system's ability to use image data to automatically detect explosives or other threat materials, which is typically security sensitive and verified by an appropriate regulatory body. The procedures in this standard should not be construed as an all-inclusive measure of performance for all situations. Depending on the circumstances and detection needs, users may continue to generate their own requirements and are encouraged to do so. Rather, it is hoped that this standard will provide consistent definitions of metrics and procedures for their measurement and offer an accepted procedure for periodic quality control testing that is complementary to threat-based testing and evaluation.

Four annexes are included. Annex A (normative) provides mechanical drawings of the image-quality test objects while Annex B provides a drawing package for fixturing the test objects (informative). A sample test report form is given in Annex C (informative). Annex D (informative) offers statistical guidance on multiple scans, summary statistics, and comparison of test results to determine meaningful performance changes.

1.1 Scope

This standard applies to security screening systems that utilize millimeter wave (MMW) radiation to actively inspect persons who are not inside vehicles, containers, or enclosures. The standard is applicable to systems used to detect concealed objects carried on the body of the individual being screened at a security checkpoint. This standard addresses monostatic, bistatic, or multistatic MMW systems. Walk-through systems can be tested using the standard.

This document focuses on the imagery that is presented to an Automated Threat Recognition (ATR) algorithm, not the imagery presented to a human screener. This standard applies to systems that are primarily imaging but that also may have complementary functionality such as materials discrimination. This standard does not address how to test these complementary functions. The standard describes the tools, objectively-analyzed test methods, and image quality metrics for characterizing the imaging performance of the system but not for its operational performance.

For the purposes of this standard, the test objects herein are appropriately applied to characterize systems that use radiation from 3 GHz to 150 GHz (100 mm to 2 mm wavelength).

The standard is limited to tests related to image quality or functional factors that affect image quality. It does not, for example, include tests or requirements for electrical safety, or electromagnetic interference or immunity. This standard does not specify minimum or baseline performance requirements (pass-fail thresholds).

1.2 Purpose

The primary purpose of this standard is to describe the tools and methods to measure the technical imaging performance of a particular millimeter wave screening system through its life cycle. These tools and methods were developed by subject matter experts to address aspects of image quality thought to be relevant to threat detection. In general, this standard is not intended as a methodology for comparing different types of systems against one another nor should technical performance be conflated with threat detection, although the two are related. One may also compare a particular system that has been certified for detection to systems produced subsequently that are functionally equivalent, e.g., the same vendor, model, and configuration of hardware, firmware, and software; or one may wish to determine that technical performance of a particular system has not changed with respect to changes in hardware, firmware, or software. Other use cases include guidance to vendors for gauging improvements during system development and the registration of technical performance at the time of certification by a regulatory body to ensure this performance is maintained through factory-acceptance testing, site-acceptance testing, fault testing, or operational-readiness testing.⁶

The image quality provided to the operator is not necessarily the same as that used by the automated analysis. For example, the data may be altered, for the purpose of reducing the resources required for rendering the image on the screen, before being presented to the operator. The data used in the automated analysis may also be altered in various ways that are appropriate for a given threat-recognition algorithm. The user of this standard may wish to separately assess the quality of the images presented to the system's operator.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{7,8}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶ For additional use cases, see The Case for Technical-Performance Standards for Radiation Inspection Systems, Larry Hudson, Journal of Testing and Evaluation 46, (2018) pp. 8-16, <https://doi.org/10.1520/JTE20170329>.

⁷ The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁸ The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

2. Definitions, acronyms, and abbreviations

2.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁹

bistatic: In the context of MMW screening, a system with a transmitter and a receiver that are separated by a distance comparable to the expected target distance.

center frequency f_c : The center frequency¹⁰ is equal to $f_c = (f_H + f_L) / 2$, where f_H and f_L respectively designate the upper and lower frequencies in the system's frequency band. Designating f_M as the frequency at which the maximum radiation emission occurs within the band, f_H and f_L correspond, respectively, to the outermost frequencies at which the radiation level drops by 10 dB below f_M .

NOTE—The system bandwidth is $(f_H - f_L)$.

center wavelength λ_c : Equal to the wavelength at the center frequency: $\lambda_c = c / f_c$, where c is the speed of light in air.

column average: The array $C(j)$ computed from the grayscale pixel values of a rectangular ROI, $\mathcal{R}$, with n rows and m columns, indexed by i and j respectively, using: $C(j) = \frac{\sum_{i=1}^n \mathcal{R}(i, j)}{n}$

contrast resolution: A measure of the extent to which targets with similar reflectivity can be distinguished as having distinct grayscale values in a MMW image.

NOTE—In this document, the contrast resolution metric is measured from the width of a histogram of a target region of nominally uniform reflectivity.

contrast scaling: The mapping of the reflected signal to the grayscale values in a MMW imaging system.

depth: A direction perpendicular to the y-axis and intersecting the center of the imaging aperture.

NOTE 1—Figure 1 and Figure 2 define the system axes.

NOTE 2—In radar physics, this is also called range.

depth response: The full width at half maximum in the depth direction of the reflected signal that is obtained from imaging a thin, highly-reflective object using a MMW system.

effective depth resolution: The measured spatial resolution in the depth direction.

horizontal illumination coverage: A measure of the visible width of a vertical cylinder in the x-z plane in a MMW image.

NOTE 1—Figure 1 and Figure 2 define the system axes.

imaging aperture: The physical extent of the opening through which the radar system receives and/or transmits electromagnetic waves that contribute to the image. It is a surface that includes all antenna positions that contribute to generating the image. The imaging aperture may span only part of the total aperture, for example, when a system creates an image from a particular angle using only some of the antenna data.

lateral resolution: A measure of the extent to which closely spaced objects can be separately distinguished in directions perpendicular to the depth axis.

⁹IEEE Standards Dictionary Online is available at: <http://dictionary.ieee.org>. An IEEE account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

¹⁰The definitions of the center frequency, center wavelength, and bandwidth are consistent with the FCC definition [393764 UWB Compliance Measurements (fcc.gov)].

minimum detectability: The size of the smallest sphere consistently detected above noise in a MMW image.

monostatic: In the context of MMW screening, a system with collocated transmitter(s) and receiver(s).

multistatic: In the context of MMW screening, a system with bistatic components or spatially separated monostatic ones that are capable of cross-measurements.

row average: The array $R(i)$ computed from the grayscale pixel values of a rectangular ROI, $\mathcal{R}$, with n rows

and m columns, indexed by i and j respectively, using:
$$R(i) = \frac{\sum_{j=1}^m \mathcal{R}(i, j)}{m}.$$

sheet resistance: The electrical resistance to current flow across a thin, flat material, such as a thin film or a sheet of metal.

NOTE—This quantity is expressed in the conventional units Ω/sq , the electrical resistance between two opposite edges of a square-shaped material.

system: The instrument under test, specifically a security screening device that uses millimeter-wave radiation to actively screen persons for anomalies including explosives or other contraband.

vertical field of view: A measure of the vertical extent of the inspection volume using the image signal response from a uniform object.

NOTE—In this document, the vertical direction is defined as the direction of the y axis (see Figure 1 and Figure 2) of a MMW system.

vertical illumination uniformity: A measure of image signal homogeneity measured vertically along an extended uniform object.

2.2 Acronyms and abbreviations

2D two dimensional

3D three dimensional

ATR automated threat recognition

NOTE—The ATR is an algorithm intended to automatically detect objects of interest or anomalies.

DFT discrete Fourier transform

FOV field of view

ITO indium tin oxide

MMW millimeter wave

MTF modulation transfer function

MVP maximum value projection

RAM radar absorbing material

RMSE root mean square error

ROI region of interest

NOTE—An ROI is a contiguous subset of pixels in a two-dimensional image or a contiguous subset of voxels in a three-dimensional image. In this document, a 2D ROI is a square or rectangle, and a 3D ROI is a cuboid.

3. General testing requirements

3.1 Environmental

These tests shall be conducted under ambient temperature and humidity conditions defined as 15 °C to 35 °C (59 °F to 95 °F) and non-condensing humidity. The temperature and relative humidity shall be reported with the testing results.

If performance is required outside of the above specified environmental conditions, the user should not assume that reported image quality performance metrics are equivalent to those reported under ambient conditions. The user may wish to require testing outside of ambient conditions or request engineering analysis to measure performance in the field.

3.2 System mode

System components and adjustments should be as for the standard commercial product in normal security screening operation mode; any deviations shall be noted by the testers in the test report. If the system is approved to operate under more than one configuration, the user may want to request the test be carried out at all appropriate settings. Evaluation is to be based on images or other data normally used in standard mode of operation. A calibration of the system shall be carried out prior to any testing. Any recalibration shall be allowed according to the standard operation of the system. Changes in image reconstruction software should be followed by gathering a new baseline measurement set. Alternatively, new baseline results may be recomputed offline if the data are available and unaffected by the system software changes.

3.3 Test object placement

Except as otherwise specified in the test methods prescribed in 4.3 to 4.7, the tests shall be performed with:

- Mechanically robust fixturing to ensure reproducible placement of the test objects within the scan volume
- The bottom of the test object 100 cm above the floor of the system under test
- The front of the test object shall nominally face the center of the imaging aperture
- The front of the test object shall coincide with the part of a typical scanned person that is closest to the center of the imaging aperture
- For systems where the person is stationary, see the vendor manual or floor markings for guidance
- For systems where the scanned person is in motion, such as walk-through systems, the test object shall be placed at multiple positions representative of where the person is imaged e.g., entrance, center, and exit positions

If this language is inapplicable to the system under test, then consult with the system manufacturer about test object placement.

If a system produces separate images using independent hardware systems, then images from each independent hardware system shall be separately tested. For example, if the front and back of the passenger are illuminated by separate antenna arrays, then a set of image quality metrics shall be produced by separate analysis of images of both the front and the back. If a system provides a set of images from the same hardware system and of the same reconstruction method, but from different angles, then the test methods need only be applied to images taken from one of these angles.

The system shown in Figure 1, for example, creates images of a person using two sets of imaging hardware (front and back). For each set of imaging hardware, multiple images are created from different angles. When collecting test data from the front imaging hardware, place a test object facing in the positive z direction, coinciding with the front of the person, 100 cm above the floor of the scanner. When testing the back imaging hardware, the test objects would face in the negative z direction, coinciding with the back of the person, and at the same height. Two full sets of image quality metrics would be calculated (front and back).

Detailed information shall be given in the test report, sufficient to allow another tester to reproduce the placement of the test objects. While the normative position of the test objects is as described above, the testers may also elect to measure performance at other locations within the inspection volume.

Guidance related to the fixturing of the test objects is the subject of informative Annex B.

3.4 Data for analysis

The methods in the standard shall be applied to the image data that are sent to the Automated Target Recognition (ATR) algorithm of the system under test. These data are not to be otherwise filtered, scaled, or smoothed except as specified in the test methods. A system under test may send 2D grayscale imagery, 3D grayscale imagery, and/or other data to the ATR. The effective depth resolution and depth response tests can only be applied to 3D data (integer or floating point); the depth tests (4.4) are therefore not applicable to systems that only utilize 2D data. All the other image quality tests can be applied to systems that produce 2D or 3D data. If complex valued data are produced, the magnitude of the complex values shall be used with the analysis methods of this standard.

In the cases where systems produce 3D data, but the test methods operate upon 2D data, a Maximum Value Projection (MVP) of the 3D data shall be made in the depth direction. Depending on the system, the values may correspond to power, intensity or some other quantity. A regularly spaced 2D set of parallel projections shall pass through the 3D voxel data. The maximum value encountered along each projection is used to assemble a 2D MVP image for analysis.

3.5 Measurement coordinate system

The locations described in each test method are described in terms of the coordinate planes for cylindrical (Figure 1) and flat panel (Figure 2) MMW imaging systems. The x - y plane, nominally the plane of inspection, bisects the MMW imaging system into two symmetric halves with the origin at the geometrical center of the floor of the MMW imaging system. The geometrical center of a cylindrical system is the point that is equidistant from front surface of the rotating antenna mast of the MMW imaging system. The geometrical center of a flat panel system is defined as the point at which the diagonals formed by the inside corners of the panels intersect. The front surface of each test object shall be oriented to be parallel to the x - y plane. The tester may additionally decide to test in places other than where described in the normative test methods; in such cases, the data shall be treated separately and all deviations from the test methods shall be recorded.

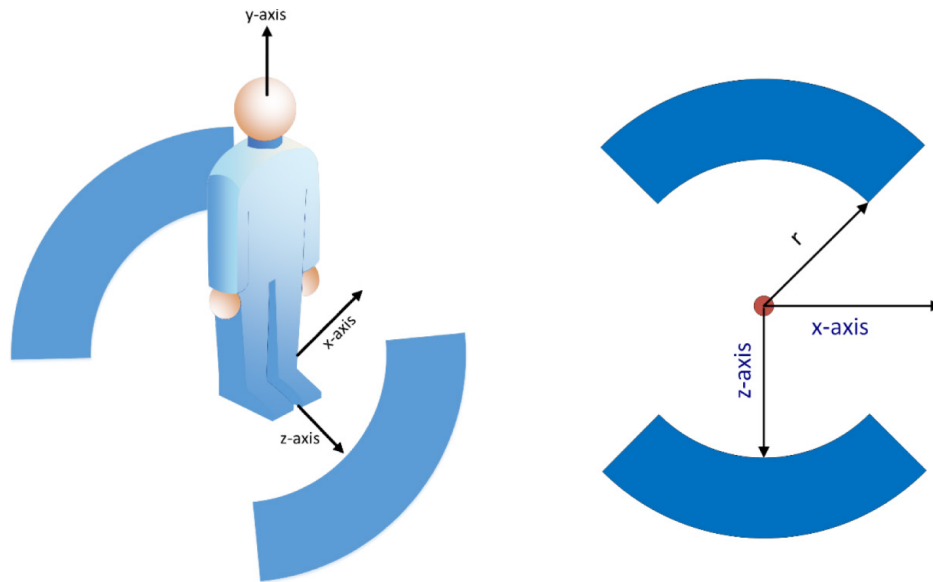


Figure 1—Reference diagram of a cylindrical MMW imaging system showing the x , y , and z axes of the measurement coordinate system

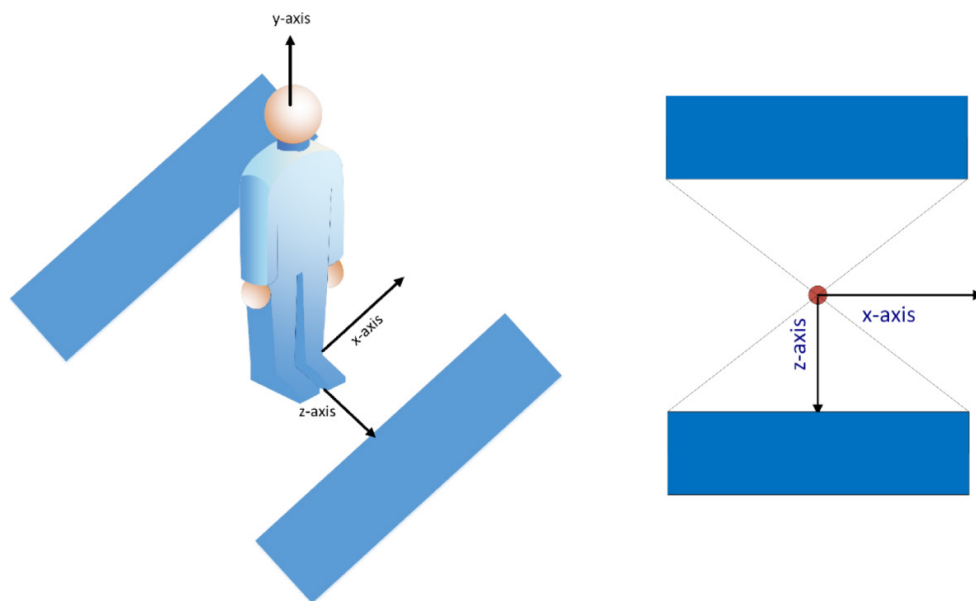


Figure 2—Reference diagram of a planar MMW imaging system showing the x , y , and z axes of the measurement coordinate system

4. Test procedures for image quality

4.1 General

This document specifies standard test objects, test object placement, test methods and objective algorithms for measuring the image quality metrics listed in Table 1. Normative mechanical drawings of the test objects are given in Annex A; Annex B gives notional examples of fixturing.

Table 1—Description of the image quality tests and metrics

Image quality tests	What is being measured?	Test object description
Lateral resolution (horizontal and vertical)	Image spatial resolution lateral to the plane of the test object	Bar chart and slot pattern in a metal sheet
Effective depth resolution and depth response	Image spatial resolution in the depth direction (range) and impulse response; each may be sensitive to loss of system bandwidth	A wedge consisting of a partially-transmissive front sheet and a metal reflector behind it; for depth response, an object of high reflectivity
Illumination coverage and uniformity	Falloff along the horizontal axis; homogeneity and extent along the vertical direction being imaged	Cylinder with reflective surface, marked with angular fiducials
Contrast scaling and contrast resolution	Relative reflectivity as a function of sheet resistance of different materials	A set of reference standards with reflectivities ranging from 0 to 1
Minimum detectability	Smallest reflective object that can be detected above the noise floor of the system	Metal spheres in polystyrene foam

4.2 Test report

4.2.1 Purpose

Manufacturers may produce several models under the same general product name, and they may perform differently under different environmental conditions. When interpreting results, it is important to ensure comparison is between functionally equivalent systems (or the same system over time) with similar hardware and software configurations and under similar environmental conditions. This subclause (4.2) specifies the minimum information that shall be included about the system and the evaluation conditions in the test report. The final test report shall also include the results of the test methods outlined in 4.3 to 4.7.

4.2.2 System data

The following data should be available from the manufacturer of the system, or in some cases, provided by the system itself. It is not intended that the tester acquire any of the data to record for this section.

4.2.2.1 General information

The following items shall appear on the covering page (Figure 3) of the final test report:

- a) Test method: State that the evaluation was carried out in accordance with this standard or any variances there from.
- b) Manufacturer: Record the name of the company producing the system.
- c) Model: Record the full model name/number for the system.
- d) Serial number: Record the serial number for the system under test.
- e) Configuration: Describe the configuration of the system under test. Is it mobile or stationary? What is the geometry of the system?
- f) Scanning mode: Describe the system's intended mode of operation. (static target, walk through, range of azimuthal angular scan, focal plane or holographic imaging, etc.)

4.2.2.2 Hardware information

In addition to the general items noted in 4.2.2.1, the pixel and/or voxel spacings of the imagery shall be reported. It is also desirable to report the system center frequency and bandwidth and the imaging aperture geometry.

4.2.2.3 System software

Record the manufacturer's version numbers for each element of software included for data acquisition and control, data reconstruction, etc. Additionally, specify operating system version number and any other software that the system employs.

4.2.3 Evaluation environmental data

The following data are related to the environment in which the testing was carried out. In general, the evaluation is based on a single scanning of each test object and reporting the results of the tests. In cases where many scans would be taken, such as establishing a baseline expectation for a particular scanner, the environmental data should be modified to show the date, time, temperature, etc. for the beginning of the scanning and for its end.

The following data shall be provided:

- a) Local date: Record the local date of the testing.
- b) Local time: Record the local time for the start of the testing.
- c) Location: Record the address and location of the testing.
- d) Ambient temperature: Record the temperature of the environment surrounding the system in °C.
- e) Ambient humidity: Record the relative humidity of the environment surrounding the system.
- f) Personnel: Record the names and affiliations of the personnel conducting the testing.
- g) Contact details: Record a telephone number or email address where the lead of the testing team may be contacted in case of questions about the evaluation.
- h) Test object manufacturer: Record the manufacturer of the test articles used in the testing.
- i) Test object serial numbers: If available, record the unique serial numbers for each of the test objects used for the testing, and/or dates acquired and provider.

4.2.4 Comments and deviations in methods of evaluation

Under the comments section, the testers should note any issues or problems encountered. Some of the test methods described in this standard may explicitly permit the tester to use alternate approaches of calculating evaluation results. In such cases, the test report shall specify which analysis methods were modified and the description of these modifications. Otherwise, this standard shall be applied using the normal security screening operation mode of the system, using the normative test objects and methods; any variations shall be clearly noted and the rationale for deviation should be indicated where informative (e.g., "the system was operated without its air conditioner running to simulate operation in a hotter climate"). Record any other information necessary for another tester to reproduce the results.

4.2.5 Presentation of results

The general information outlined in this section shall be included in the test report of results of the image evaluation methods specified in this standard. Figure 3 shows an example format, but other formats for the presentation of these data are acceptable. An example of a full test report is given in Annex C.

Image Quality Report	
Evaluated in accordance with IEEE N42.59 American National Standard for Measuring the Imaging Performance of Active Millimeter-Wave Systems for Security Screening of Humans	
General Information	
<u>System Under Test</u> Manufacturer: _____ Model: _____ Serial Number: _____ Configuration: _____ Scanning Mode: _____ <u>Software Version</u> Operating System: _____ Reconstruction: _____ Other info: _____ <u>Evaluation Conditions</u> Local Time: _____ Date: _____ Location: _____ _____ _____ Ambient Temperature (°C): _____ Ambient Humidity: _____ Comments and deviations: _____ _____ _____	<u>Hardware information</u> Center frequency: _____ Bandwidth: _____ Geometry of imaging aperture: _____ _____ Other details of note: _____ _____ Pixel/voxel spacing: x: _____ y: _____ z: _____ <u>Other information:</u> Testing Personnel: _____ _____ _____ Contact details: _____ Test Object Manufacturer: _____ Test Article S/Ns: _____

Figure 3—Format example for test report cover page (general information)

4.3 Lateral resolution

4.3.1 Purpose

This test assesses the spatial resolution of the imaging system in the plane parallel to the front face of the test object. Spatial resolution is an image quality metric that quantifies the ability of a system to separately distinguish small, closely-spaced objects. Bar and slot test objects are conventionally used to measure the contrast transfer function by quantifying the peak-to-trough contrast in the image, but this test method uses Fourier techniques to measure the modulation transfer function (MTF).

4.3.2 Test object description

For this assessment, there are two standard test objects that have bar patterns with widths varying from 20 mm to 1 mm. The designs of the test objects are shown in Figure 4. Each test object consists of a series of bar patterns cut from 0.5 mm thick general-purpose stainless-steel sheet (e.g., unified numbering system (UNS) designation S30200, S30400, S31600, or equivalent). Circular fiducial holes are positioned 30 mm from

either end of the rows of slots (see Figure 4). The circular fiducials have a diameter of 10 mm. If the system cannot reliably detect the fiducials, then it is acceptable to construct an alternate version of the test object with 20 mm diameter fiducials. If the system cannot resolve the bar patterns, then it is acceptable to construct alternate versions of the test objects that are scaled up by an appropriate factor (the factor shall be recorded). The test object(s) design shall be chosen so that some of the measured MTF values are above 0.2 and some are below 0.2, so that the metric of interest can be calculated. If this can be achieved by making measurements with only one of the test objects, then that is acceptable.

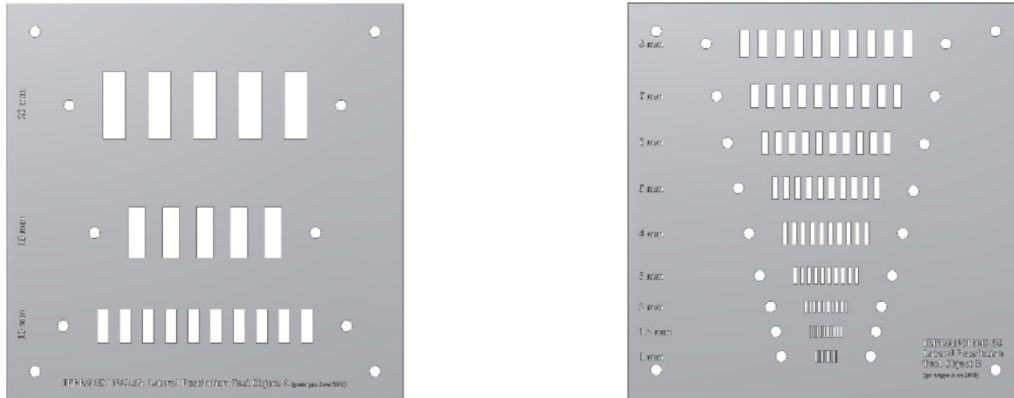


Figure 4—The standard lateral resolution test objects

The bar patterns in Figure 4 are divided between two square test objects, referred to as Test Objects A (left) and B (right). The test objects measure horizontal lateral resolution when oriented in the manner shown here.

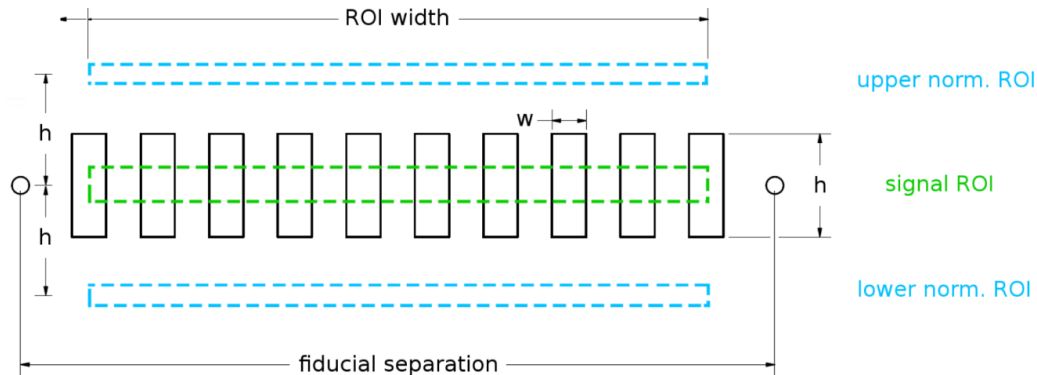


Figure 5—A diagram showing the position and size of the signal ROI, the upper normalization ROI, and the lower normalization ROI for a particular test pattern

4.3.3 Test method

This section describes a test method to measure the Modulation Transfer Function (MTF). The test method can be used to measure spatial resolution at any position in the scanning volume, but the standard test object placement is described in 3.3. This lateral resolution test is sensitive to alignment of the test object about the y axis, so the tester should be careful to place the test object consistently and align using a tolerance appropriate for the system under test. The test method is written for measurement of the horizontal lateral resolution, in other words, under the assumption that the test object is oriented so that the long axes of the slots are vertical (as shown in Figure 4). The tester shall also determine the vertical lateral resolution by making measurements with the test object rotated 90 degrees from what is shown in Figure 4 following the procedure below.

- a) Using a lateral resolution test object (Figure 4), collect a set of Q (with $Q \geq 5$) independent images for the horizontal lateral resolution tests, obtained by placing and removing the test object from the

inspection volume between image acquisitions. When measuring the vertical lateral resolution, collect a set of Q independent images with the test object rotated 90 degrees then digitally rotate the images by 90 degrees so that the long axis of the slots are vertical. This allows the same analysis procedure to be used for both the horizontal and vertical lateral resolution tests.

- b) For every image and bar pattern width, compute the MTF values and associated uncertainties using steps c) to h). We define m as the number of slots in the pattern, w as the width of the slots in millimeters, and h as the height of the slots in millimeters. The spatial frequency of the test pattern is $f = 1/(2w)$.
- c) The separation of the fiducials in mm, d_{MM} , is known from the design drawings of the test objects (see Annex A). Determine the positions of the centers of the fiducials in the image to within ± 1 pixel in the horizontal and vertical directions and calculate the distance between the centers, d_{PX} , in units of pixels. This information shall be used to compute $\alpha = d_{PX}/d_{MM}$, a coefficient that is used to convert ROI sizes from millimeters to pixels.
- d) Select the signal ROI from the image. This ROI should be centered at the midpoint between the centers of the two fiducial holes. The width of the ROI shall be taken to be $\alpha \cdot w \cdot (2m - 2)$ pixels, rounded to the nearest integer, and the height of the ROI, given in units of pixels, shall be the smallest integer greater than or equal to $\alpha \cdot h/3$.
- e) Select the normalization ROIs from the image. The upper and lower normalization ROIs have the same horizontal extent as the signal ROI but are vertically offset by $+h$ and $-h$, respectively (see Figure 5). The height of the normalization ROIs, given in units of pixels, shall be the smallest integer greater than or equal to $\alpha \cdot h/6$.
- f) Perform a column average of the signal ROI to produce $S_i(x)$, where x is an index in units of pixels, and i is an index for the i^{th} image of the test object. The length of $S_i(x)$ will be denoted N and measured in pixels. Perform a column average of the upper and lower normalization ROIs to produce $U_i(x)$ and $L_i(x)$, respectively. Compute the bar profile function $B_i(x)$ of image i using,

$$B_i(x) = \frac{2S_i(x)}{U_i(x) + L_i(x)},$$

- g) Compute $MTF_i(f)$, the value of the MTF derived from the i^{th} image at spatial frequency f , associated with the m -bar pattern,

$$MTF_i(f) = \frac{\pi}{N} \left| \hat{B}_i(m-1) \right|,$$

where $\hat{B}_i(m-1)$ is the $(m-1)^{th}$ element of the Discrete Fourier Transform of $B_i(x)$ and the first element of $\hat{B}_i(m)$ is $\hat{B}_i(0)$ (i.e., the indices start with a zero).

- h) For each image, compute the $MTF20_i$ by finding the spatial frequency at which the $MTF_i(f)$ drops below 0.2 when linearly interpolated with respect to f (see Figure 6). If all or none of the $MTF_i(f)$ values are above 0.2, then an $MTF20_i$ should not be reported for that image and the user should consider using an alternate version of the test object (see 4.3.3). Convert the $MTF20_i$ value to millimeters by using the equation in 4.3.3b.

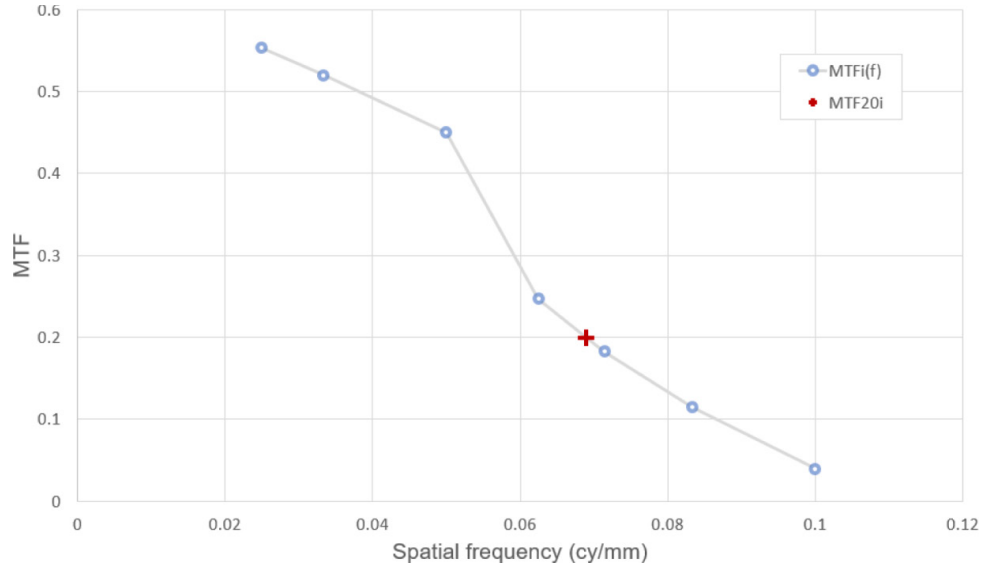


Figure 6—MTF_i(f) data derived from one image of test objects A and B

In Figure 6, the linearly interpolated MTF value crosses 0.2 at a spatial frequency of 0.069 cy/mm (see red cross). The reported MTF20_i value is therefore 7.2 mm.

- i) For each spatial frequency, f , compute the mean, $\overline{MTF(f)}$, of the Q reported values of the $MTF(f)$.

$$\overline{MTF(f)} = \frac{1}{Q} \sum_{i=1}^Q MTF_i(f)$$

- j) For each spatial frequency, compute the standard deviation, $\sigma_{\overline{MTF(f)}}$, of the Q reported values of the $MTF(f)$ using

$$\sigma_{\overline{MTF(f)}} = \sqrt{\frac{1}{Q-1} \sum_{i=1}^Q (MTF_i(f) - \overline{MTF(f)})^2}$$

- k) Compute $\overline{MTF20}$ by taking the mean of the $MTF20_i$ values for all images for which a value was reported.

$$\overline{MTF20} = \frac{1}{Q'} \sum_{i=1}^{Q'} MTF20_i$$

where Q' is the number of images for which an $MTF20$ was reported.

- l) Estimate the standard deviation of the $MTF20_i$ values using

$$\sigma_{\overline{MTF20}} = \sqrt{\frac{1}{Q'-1} \sum_{i=1}^{Q'} (MTF20_i - \overline{MTF20})^2}$$

4.3.4 Presentation of results

All the measured values of the non-zero $\overline{MTF(f)}$ values and their uncertainties $\sigma_{\overline{MTF(f)}}$ shall be reported for informative purposes. The results should also be plotted.

Table 2—Example lateral resolution results

Bar width (mm)	Spatial frequency (cycles/mm)	$\overline{MTF(f)}_H$	$\sigma_{\overline{MTF(f)},H}$	$\overline{MTF(f)}_V$	$\sigma_{\overline{MTF(f)},V}$
20 mm	0.0250	0.aaa	0.aaa	0.aaa	0.aaa
15 mm	0.0333	0.bbb	0.bbb	0.bbb	0.bbb
⋮	⋮	⋮	⋮	⋮	⋮
$w_{\min}$	$f_{\max}$	0.zzz	0.zzz	0.zzz	0.zzz

NOTE—The subscript *H* indicates horizontal lateral resolution results, whereas *V* indicates vertical.

The values of $\overline{MTF20}$ and their uncertainty $\sigma_{\overline{MTF20}}$ in the horizontal and vertical axes are the primary metrics of interest resulting from this analysis (see Table 3 for an example reporting template).

Table 3—Example lateral resolution MTF20 results

Metric	Image 1 (mm)	Image 2 (mm)	Image 3 (mm)	...	Image <i>Q</i> (mm)	$\overline{MTF20}$ (mm)	$\sigma_{\overline{MTF20}}$ (mm)
MTF20 _H							
MTF20 _V							

A discussion of determination of a statistically significant change of a metric can be found in Annex D.

4.4 Effective depth resolution and depth response

4.4.1 Purpose

The effective depth resolution and depth response tests assess the depth response of the millimeter-wave imaging system. The depth resolution test characterizes the ability of the system to resolve two reflections that are closely spaced in depth. The depth response characterizes the effective width of the response from a single reflection. Both metrics can be used to assess the performance of the system in the depth dimension. The two tests may both be useful, or one may be preferred for certain systems. For example, a narrow band system may be difficult to assess with the depth resolution test object, but the depth response test can be applied effectively.

4.4.1.1 Effective depth resolution

The depth resolution is a fundamental performance parameter of three-dimensional millimeter-wave imaging systems. It describes the ability of MMW imaging systems to resolve closely spaced objects in depth or perpendicular to the imaging aperture. In security-screening applications, the depth resolution is relevant to the ability of the system to resolve the front and back surfaces of thin dielectric sheets of materials or clothing barriers. Typically, the larger a system's operational frequency bandwidth the better an imaging system can resolve the front and the back surfaces of thin dielectric materials; lower bandwidth MMW imaging systems may not have this ability.

The theoretical depth resolution for active, coherent, millimeter-wave imaging is given by

$$\delta_z = \frac{c}{2B}$$

where: δ_z is the theoretical depth resolution (in mm), c is the speed of light in air (3×10^{11} mm/sec), and B is the bandwidth of the imaging system (in Hz). In practice, the realized or effective depth resolution is somewhat larger than predicted and can depend upon system design and other system parameters. It can also be affected by various imaging artifacts, especially interference effects near the resolution limit.

4.4.1.2 Depth response

Another metric that is sensitive to changes in system bandwidth is “depth response” or “impulse response.” This is the reflected response from a target at a fixed depth. Examples include a point scatterer, flat plate, or cylinder. For a significant signal response, flat plate or cylindrical test objects are preferred. A flat plate should be placed in the imaging region and aligned so that it nominally faces the center of the imaging aperture. If a cylinder is chosen, it should be placed within the imaging region with its axis aligned vertically. Placement of test objects is discussed in greater detail in 3.3.

The depth response allows analysis of the width of the focused response along the depth axis, as well as analysis and display of imaging artifacts that deviate from a typical response. The expected width of the depth response profile is on the same order as the depth resolution and is expected to be inversely proportional to the bandwidth of the system. Evaluating the depth response width and profile shape provides a second metric related to the depth resolution and can provide insight into the frequency response and consistency of the millimeter-wave imaging system under test.

4.4.2 Test object description

4.4.2.1 Effective depth resolution

The effective depth resolution can be determined using a test fixture that produces two reflections having nominally the same amplitude over a range of fixture separations. Equal-amplitude reflections can be generated using a flat partially transmissive dielectric material placed in front of a flat metal plate. A wedge-shaped test object consisting of a partially reflective sheet over a metallic surface shall be used.

Figure 7 shows two implementations of the wedge depth resolution test object. A thin sheet of partially reflective and partially-transmissive dielectric material (e.g., ITO on a polymer substrate) is positioned in front of a flat metal plate to form a wedge in a free-standing, angled configuration. The sheet resistance of the ITO sheet is selected to be $Z_{sh} = 300 \Omega/\text{sq}$ such that the reflection magnitude from the front surface is approximately equal to the reflection from the metal plate (back surface); the reflection of the ITO sheet is frequency independent to first order. The thickness of the ITO shall be less than 200 μm . The angle between the front and back surfaces should be relatively small; this is typically 3° to 4° . The analyzable width (direction perpendicular to MMW beam) of these test objects shall be at least 10 pixels. The reflecting surfaces must be free of effects arising from edges and fixturing. In Figure 7(a), the ITO sheet and metal plate are separated by a very low dielectric polystyrene foam. In Figure 7(b), the wedge is designed with a metal frame to support the ITO film sheet in front of the metal plate. The minimum and maximum separations between the plates are determined by the wedge angle and the separations, d , and shall span a range of separations of at least $0.5\delta_z < d < 2\delta_z$. The maximum separation shall be at least 6 depth pixels.

4.4.2.2 Depth response

The depth response will be measured using the metal-coated cylinder that is used for the illumination coverage metric or a flat metal plate similar in height and width of the cylindrical test object.

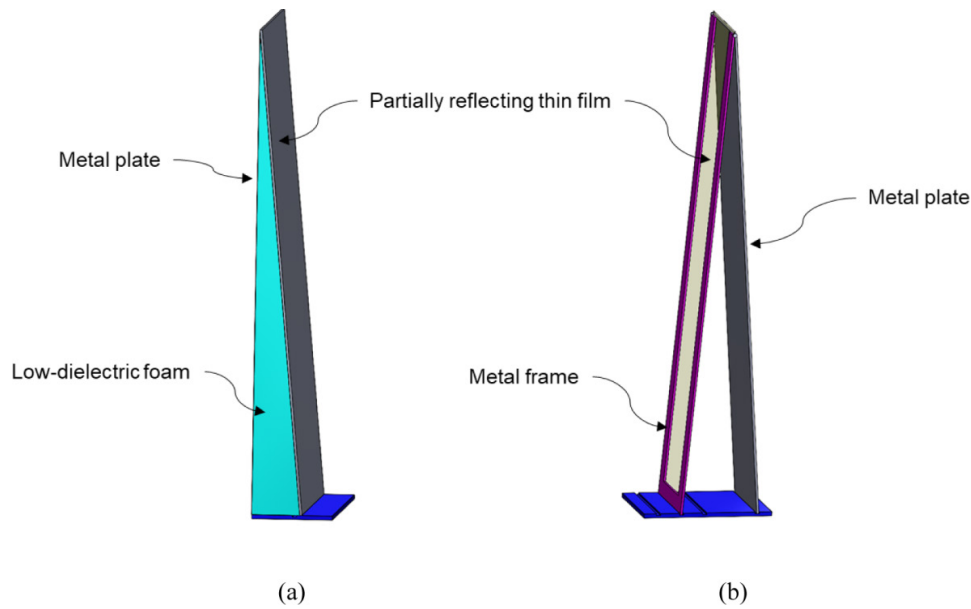


Figure 7—Wedge depth resolution test objects permit multiple depth resolution measurements with a single image: (a) metal copper tape and thin sheet partial reflector attached to a low-dielectric, polystyrene foam wedge (b) thin sheet partial reflector attached to metal frame and attached to a metal plate with adjustable hinge at top

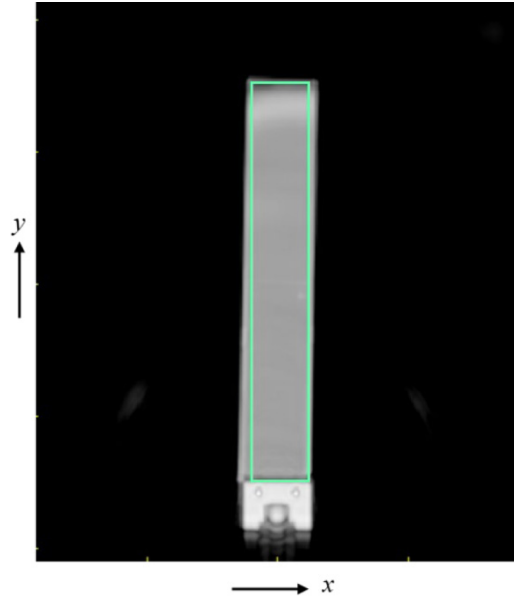
4.4.3 Test method

4.4.3.1 Effective depth resolution

The test method for measuring depth resolution follows three basic steps: an image set is collected, modulation curves are generated, then separation metrics are calculated.

a) Collect image set

1. Position the wedge test object following the guidance in 3.3 except that when placed for scanning, the test object shall be oriented such that its long axis nominally aligns with the y axis (Figure 1 and Figure 2) and both faces of the wedge are facing the center of the imaging aperture to within the wedge angle. Collect a set of Q ($Q \geq 5$) independent volumetric images obtained by placing and removing the wedge from the inspection volume between acquisitions. Figure 8 shows the typical orientation of the test object with the thin-sheet reflector facing the source along the z direction, tilted a few degrees from the +z axis which is out of the page. The associated x and y axes are also labeled in this maximum value projection (MVP) of a reconstructed image of the wedge test object.
2. Establish a three-dimensional ROI from which to generate modulation curve data. The ROI is selected based on features in the image and the known dimensions of the test object/fixture including the known sheet-to-plate separations. In the y dimension, the top of the ROI is selected to align with the known minimum plate separation, and the bottom is selected to align with the known maximum plate separation. If required, fiducial marks should be placed to assist with this alignment. In the x dimension, the ROI should be selected to enclose the central 50% to 90% of the wedge object response so that edge effects are not significant. In the z dimension, the ROI is selected to enclose the responses from both surfaces and should span at least 1.5 times the known maximum plate separation of the test object being imaged. Two views of the ROI are illustrated with a green box in Figure 8 and Figure 9.



NOTE—Shown on a logarithmic (dB) scale with 30 dB of dynamic range displayed (similarly for Figure 9 and Figure 12).

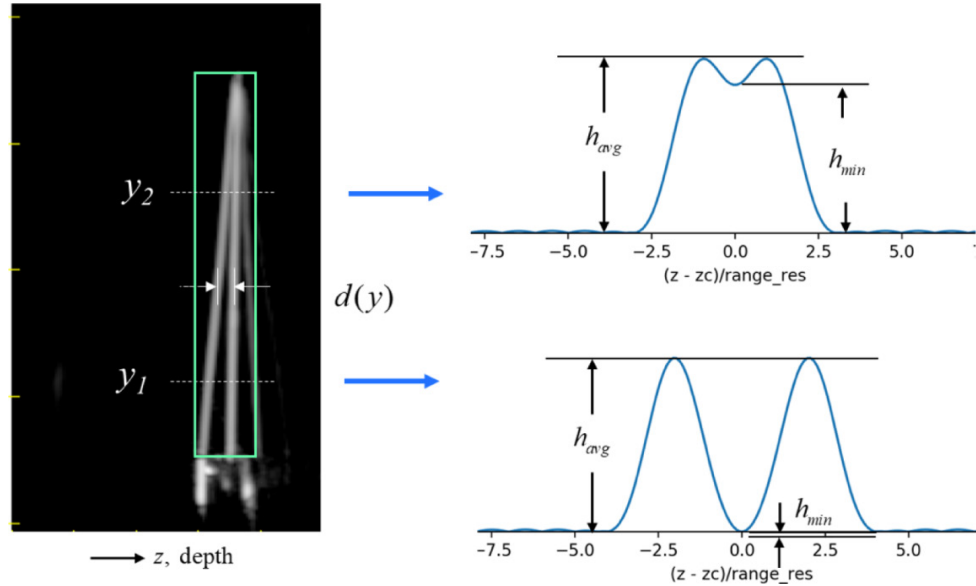
Figure 8—The maximum value projection (MVP) of a 3D MMW image of the wedge test object showing a front view and green ROI relevant to modulation curve generation

b) Generate modulation curves

- 1) Project the 3D ROI into two dimensions (the y-z plane) by averaging over voxel values in the x direction (as shown on the left side of Figure 9). Each row is indexed in the y direction and the columns are indexed in the z direction.
- 2) Calculate the modulation depth between the two surfaces of the wedge for each height, y . Modulation depth assumes that the response comprises two maxima separated by a minimum. If the two maxima have values h_1 and h_2 , and the minimum has value h_{min} , then the modulation depth is defined by $M = (h_{avg} - h_{min}) / h_{avg}$ where $h_{avg} = (h_1 + h_2) / 2$. The maxima may be ambiguous for complex depth responses, so the following algorithm is to be used to uniquely compute a modulation depth. This algorithm relies on the *a priori* knowledge of the peak separation, which is known for the depth resolution test object. The d values of the test object shall be derived from a priori knowledge of the dimensions and geometry of the wedge test object and using wedge features that can serve as length-scaling fiducials in the 2D image.
 - i) Operating on each y-axis row, let $h(z)$ be the grayscale value at depth z , where the known wedge separation is $d(y)$. Linear interpolation should be used at this step to increase the sampling precision by a factor of at least 10 to compensate for coarsely sampled depth data and increase the accuracy of the modulation depth calculation.
 - ii) Determine the location of the first maximum by finding the value, z_1 , that maximizes the following quantity: $h(z_1) + h(z_1 + d)$. The location of the second maximum is at $z_2 = z_1 + d$.
 - iii) Let $h_{avg} = (h(z_1) + h(z_2)) / 2$
 - iv) Let h_{min} be the minimum value of h that occurs between z_1 and z_2 .

- v) Calculate the modulation depth using $M = (h_{avg} - h_{min}) / h_{avg}$. An example is shown in Figure 9.

Repeat 1) and 2) for each of the Q scans.



NOTE—Green ROI (left) and examples related to computation of the modulation depth profile from two rows at heights y_1 and y_2 .

Figure 9—A side view of the wedge test object

c) Calculate separation metrics

Four measures of effective depth resolution shall be recorded. The first is found by traversing the $M(d)$ curve (defined above in step v) from the direction of largest wedge separation to the smallest separation, as shown with the red arrows in Figure 10. Report the value of d where $M(d)$ first becomes less than specified values of $M = 25\%$, $M = 40\%$, $M = 55\%$ and $M = 70\%$ as indicators of the effective depth resolution in mm for each of the Q images. For example, use the notation $d(M = 25\%)$ for the 25% value.

Due to coherence and other effects, a composite depth criterion has been found to be sensitive to bandwidth loss for many MMW systems, namely averaging the d values associated with the four different percent losses of modulation (see Figure 11). As above, each value of d is determined by traversing the curve starting from largest wedge separation moving to the smallest separation until $M(d)$ first becomes less than the indicated percentage loss. Report $\bar{d} \equiv [d(M = 25\%) + d(M = 40\%) + d(M = 55\%) + d(M = 70\%)]/4$ in mm for each of the Q images.

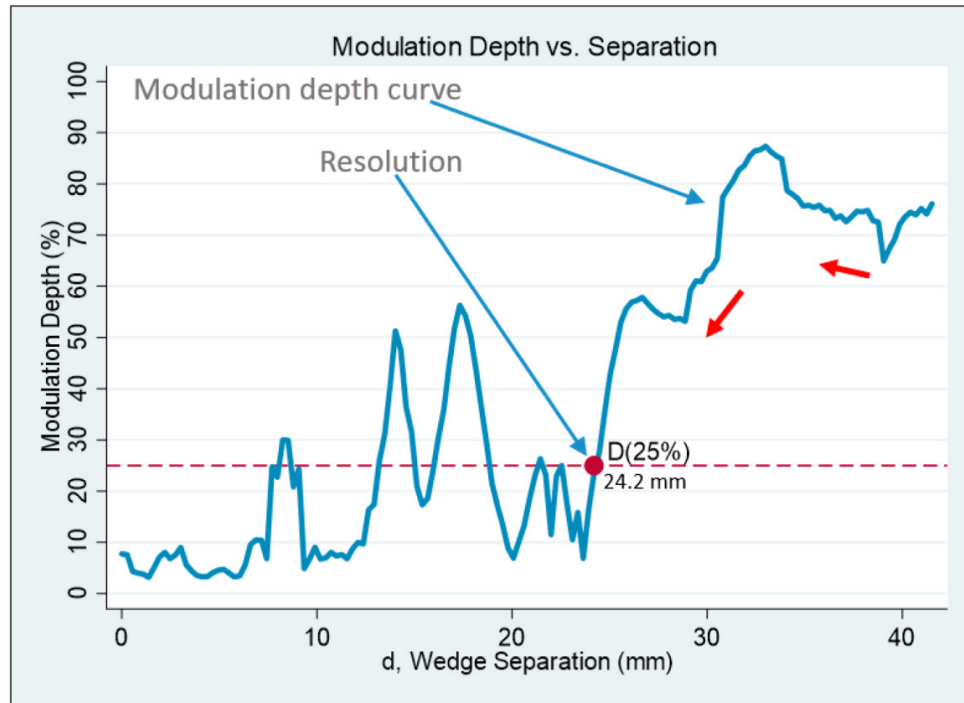


Figure 10—Determining an effective depth resolution for a modulation depth curve with a 25% modulation depth criterion

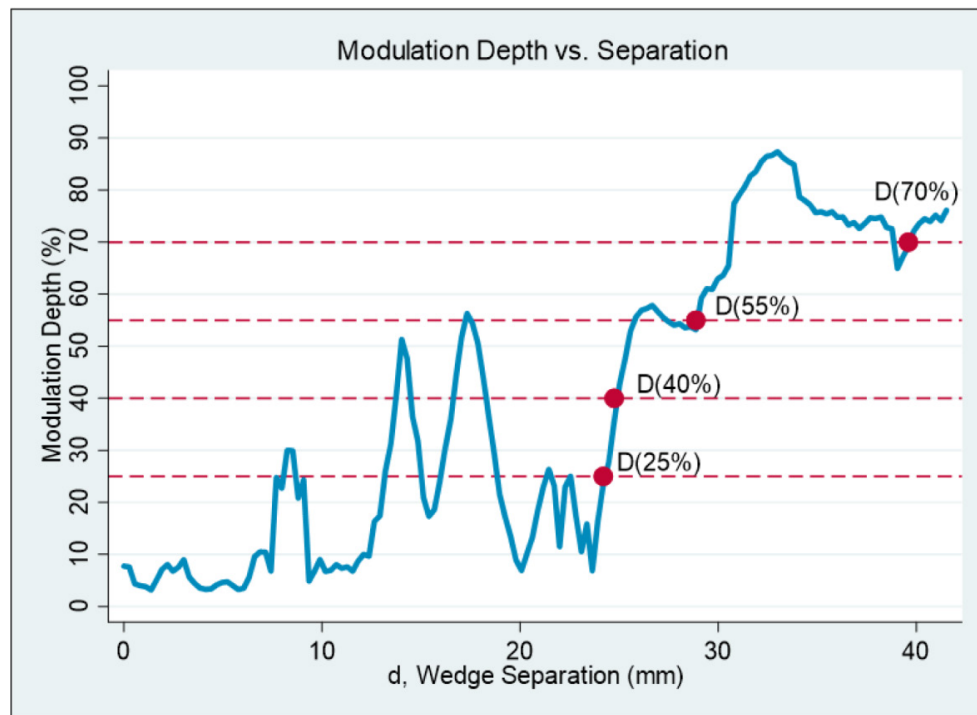


Figure 11—Determining $\bar{d}$ from a modulation depth curve

A discussion of determination of a statistically significant change of these metrics can be found in Annex D.

4.4.3.2 Depth response using the cylinder test object

The methods for computing the depth response follows two basic steps: collecting a set of Q images of a single reflecting surface then computing the width of peaks.

a) **Collect image set**

Place the cylinder test object of 4.5.2 in the inspection volume following the guidance in 3.3. Collect a set of Q ($Q \geq 5$) independent volumetric images, placing and removing the test object between acquisitions. If a reflective plate is used instead of the cylinder, it should be oriented normal to the $+z$ axis when imaged by a planar system.

b) **Calculate widths of response peak**

- 1) Determine the center of the cylinder image in x , and the y range of the height of the cylinder; this is illustrated in the left side of Figure 12 with vertical and horizontal dotted lines.
- 2) Extract the x -centered (y, z) slice for analysis as illustrated in the right side of Figure 12.
 - i) For each vertical location ($y = y_1$ to y_2) of the (y, z) slice, plot $h(z)$, the voxel values as a function of z position to find the width of the profiles at an amplitude approximately equal to 0.708 of the profile maximum value (see Figure 13; here the data have been normalized to 1, but that is not required).

NOTE—The value of 0.708 corresponds to -3 dB from the maximum.

- ii) Let h_{max} be the maximum profile value which occurs at the position z_{max} .
- iii) Determine z_{left} , the minimum z value where the linearly interpolated depth profile has a value of $0.708 * h_{max}$.
- iv) Determine z_{right} , the maximum z value where the linearly interpolated depth profile has a value of $0.708 * h_{max}$.
- v) Calculate the average response width for image i and height y_j , $W_i(y_j) = z_{right} - z_{left}$.
- vi) Calculate the average peak width for the i^{th} image, $\bar{W}_i$, by averaging over all y_j values.

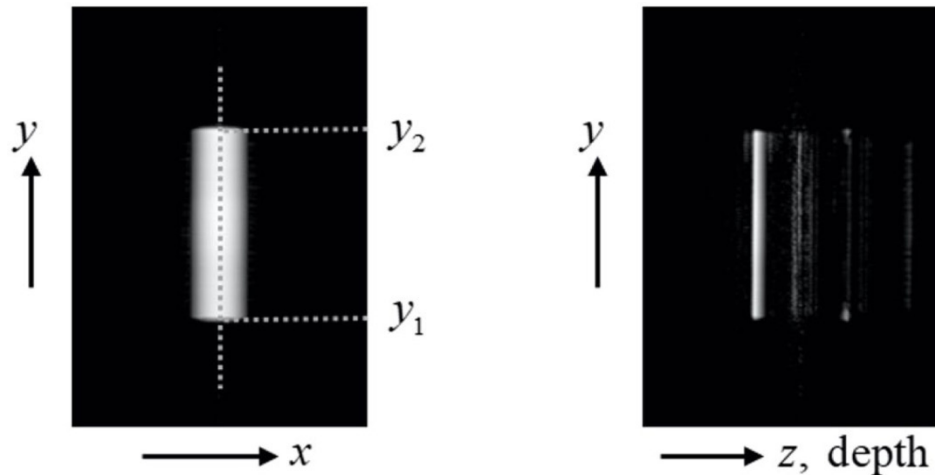
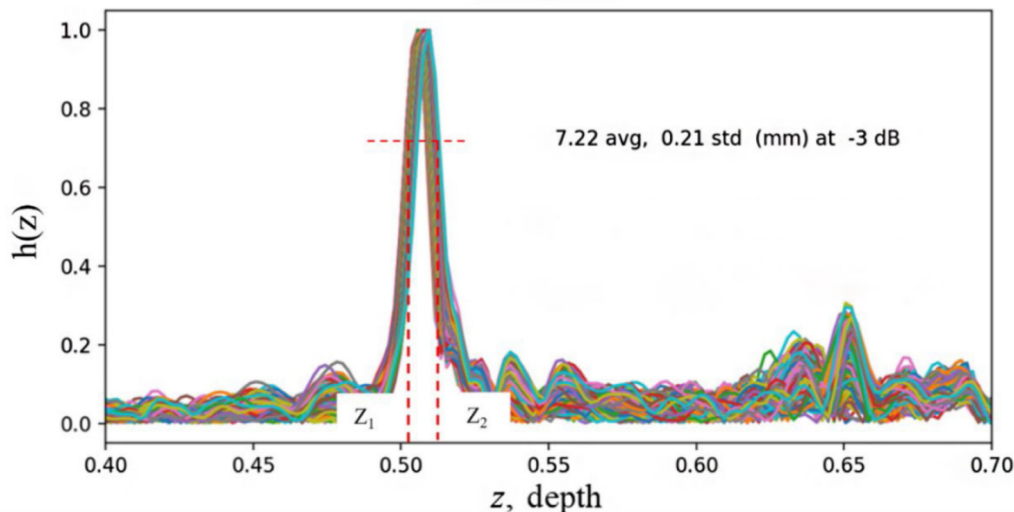


Figure 12—MMW image of a cylindrical test object, front and side view along with x, y, and z coordinates



NOTE—Each profile has been normalized to have a maximum value of 1.

Figure 13—Depth profiles from MMW imagery of depth response from a cylindrical test piece

A discussion of determination of a statistically significant change of a metric can be found in Annex D.

4.4.4 Presentation of results

4.4.4.1 Effective depth resolution

Show the following for each of the Q independent wedge-object images and compute the mean and standard deviation.

- Show the plot of $M(d)$ for the range of available separations, d .
- Report $\bar{d} \equiv [d(M = 25\%) + d(M = 40\%) + d(M = 55\%) + d(M = 70\%)] / 4$ in mm.
- Report the mean and standard deviation of $\bar{d}$ computed from the Q independent image acquisitions (Table 4).

Table 4—Example depth resolution results

Metric	Image 1	Image 2	...	Image Q	Mean	SD
$\bar{d}$						

4.4.4.2 Depth response

Show the following for each of the Q independent images and compute the mean and standard deviation.

- Record which depth-response test object was employed (cylinder or plate).
- Plot the depth response over the range of available depths.
- Report each of the Q average response widths, $\bar{W}_i$, as well as the mean and standard deviation of these values (Table 5).

Table 5—Example depth response results

Metric	Image 1	Image 2	...	Image Q	Mean	SD
$\bar{W}_i$						

4.5 Illumination coverage and uniformity

4.5.1 Purpose

MMW imaging systems typically produce a three-dimensional image, or multiple two-dimensional perspectives such that when all images are aggregated it is possible to detect most unexpected objects that are hidden by the clothing of the person being scanned. Illumination of the scan volume may be with normal incidence, oblique incidence, or a combination of both, and thus the apparent uniformity of illumination will differ between different models of MMW imaging systems. The test described in this clause provides a method for characterizing the illumination of a three-dimensional object when scanned by an MMW imaging system. This procedure can be used to quantify changes in illumination coverage as a machine's hardware or software is changed purposefully, or over time with the intent of capturing drift as well as some types of failure modes. A single test object will be used to evaluate horizontal illumination coverage, vertical illumination uniformity, and vertical field of view (coverage).

4.5.2 Test object description

A representative test object for the assessment of illumination coverage is shown below in Figure 14. It shall take the shape of a reflective cylinder $30 \text{ cm} \pm 2 \text{ cm}$ in diameter and $\geq 60 \text{ cm}$ in length. The object is most easily fabricated using a hollow form or standard tube of cardboard or plastic that has been coated (e.g., foil wrapped or spray painted) to produce a metallic reflective surface. A solid foam cylinder may be another convenient choice. Care should be taken to produce a uniformly smooth surface relative to the wavelength of the reflected radiation from the scanner. At the top or bottom of the test cylinder, contrasting fiducials shall be uniformly placed to establish an absolute reference for reproducible presentation with respect to the scanner and with ≤ 15 degree angular gauge to provide a *post hoc* diagnostic of the angle subtended, and to assist in test object orientation, in the imagery under test.



Figure 14—Example illumination coverage test object

4.5.3 Test method

- The test object shall be placed following the guidance in 3.3 except as otherwise specified in this section. The long axis of the cylinder shall be coincident with the y axis (see Figure 1 and Figure 2 for reference). Orient the reference fiducial marks so that they are facing towards the imaging aperture; the test object is not intended to be rotated.
- Acquire an image of the test object.
- Using the angular fiducial marks, report the best estimate of the angle, in degrees, subtended by the imagery that will be analyzed in this image quality test.

4.5.3.1 Horizontal illumination coverage

- Using the two-dimensional grayscale image produced in step a) of 4.5.3, select a ROI that is centered on the test object image, with the horizontal extent of the ROI to be about twice the width of the cylinder and the vertical extent of the ROI to enclose the central third to two-thirds of the cylinder (see left side of Figure 15). While the test results are generally insensitive to the exact size and location of the ROI, the intent is to try to integrate over various types of imaging artifacts that may affect the computation of the illumination coverage. The location and dimensions of the ROI should be reported as specified in 4.5.4.