Test Plan for Wireless Device Over-the-Air Performance

CTIA 01.72 Near-Field Phantoms

Version 8.0.0

September 2024

Use Instructions

All testing shall be performed in a CTIA Certification Authorized Test Lab and shall be initiated through one of the following methods:

1. By submitting a PTCRB or IoT Network Certified device certification request at https://certify.ptcrb.com/
2. By submitting an OTA Test Plan use request at https://certify.ctiacertification.org/

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ctiacertification.org/test-plans/

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Section 1 Introduction

1.1 Purpose

The purpose of this document is to define the phantoms used in OTA testing.

1.2 Scope

This document defines general requirements for phantoms to ensure the accurate, repeatable, and uniform OTA testing of wireless devices with phantoms.

1.3 Acronyms and Definitions

The following specialized terms and acronyms are used throughout this document.

Table 1.3-1 Acronyms and Definitions

Acronym/Term	Definition
CAD	Computer Aided Design
DUT	Device Under Test
LAA	Licensed-Assisted Access
LTE	Long Term Evolution
OCP	Open-ended Coaxial Probe
OTA	Over The Air
PDA	Personal Digital Assistant
SAM	Specific Anthropomorphic Mannequin
SAR	Specific Absorption Rate
TEM	Transverse Electromagnetic
TIS	Total Isotropic Sensitivity
TRP	Total Radiated Power
VNA	Vector Network Analyzer

1.4 Referenced Documents

The documents in this list are either cited (indicated by hyperlink references) or relevant to this test plan

Document Number, *Name*
[1] IEEE Std 1528-2003, IEEE Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head from Wireless Communications Devices: Measurement Techniques
[2] CENELEC EN 50361:2001, Basic Standard for the Measurement of Specific Absorption Rate Related to Human Exposure to Electromagnetic Fields from Mobile Phones (300 MHz - 3 GHz)
[3] CTIA 01.70, Measurement Uncertainty
[4] Thomas M. Greiner; Hand Anthropometry of US Army Personnel, Army Natick Research Development and Engineering Center, 1991 -
[5] Alvin R. Tilley and Henry Dreyfuss Associates; The Measure of Man and Woman: Human Factors in Design; Wiley, 1993
[6] B. Buchholz, T.J. Armstrong and S.A. Goldstein; Anthropometric data for describing the kinematics of the human hand, Ergonomics vol. 35, no. 3, pp. 261-273, 1992
[7] W.D. Bugbee and M.J. Botte,; Surface Anatomy of the Hand: The Relationships Between Palmar Skin Creases and Osseous Anatomy, Clinical Orthopaedics and Related Research, 296, 122-126, 1993
[8] Tissue Equivalent Material for Hand Phantoms
[9] Beard, B.B, et al., Comparisons of Computed Mobile Phone Induced SAR in the SAM Phantom to That in Anatomically Correct Models of the Human Head, IEEE Transactions On Electromagnetic Compatibility, Vol. 48, No. 2, p. 397 - 407, May 2006
[10] EN 50361:2001, Basic Standard for the measurement of Specific Absorption rate related to human exposure to electromagnetic fields from mobile phones (300 MHz - 3 GHz).
[11] Gabriel, C., Tissue Equivalent Material for Hand Head phantoms, Physics in Medicine and Biology, Vol. 52, pp. 4205 - 4210, 2007.
[12] Gregory, A.P., and Clarke, R.N., Dielectric Metrology with Coaxial Sensors, Measurement Science and Technology, Vol. 18, No. 5, pp. 1372 -1386, 2007.
[13] IEEE P1528.1™, D1.0 Draft Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Body from Wireless Communications Devices, 30 MHz - 6 GHz: General Requirements for using the Finite Difference Time Domain (FDTD) Method for SAR Calculations.
[14] IEEE P1528.3™, D2.0 Draft Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Body from Wireless Communications Devices, 30 MHz - 6 GHz: General Requirements for using the Finite Difference Time Domain (FDTD) Modeling of Mobile Phones/ Personal Wireless Devices.
[15] IEEE P1528.4™, D1.0 Draft Recommended Practice for Determining the Peak Spatial Average Specific Absorption Rate (SAR) in the Human Body from Wireless Communications Devices, 30 MHz - 6 GHz: Requirements for Using the Finite-Element Method for SAR Calculations, specifically involving Vehicle-Mounted Antennas and Personal Wireless Devices.
[16] IEEE Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Head from Wireless Communications Devices: Measurement Technique, IEEE, Inc., December 19, 2003
[17] IEEE, 1528™, SCC34 Draft Standard: Recommended Practice for Determining the Peak Spatial-Average Specific Absorption Rate (SAR) in the Human Body Due to Wireless Communications Devices: Experimental Techniques, April 2002.

Document Number, *Name*
[18] Li C-H., Ofli E., Chavannes N., and Kuster N., The Effects of Hand Phantom on Mobile Phone Antenna OTA Performance, Proc. Second European Conference on Antennas and Propagation, EuCAP 2007, Edinburgh, UK, November 11 - 16, 2007.
[19] Ofli E., Chavannes N., and Kuster N., The Uncertainties and Repeatability Limitations of Transmitter and Receiver Performance Assessments Posed by Head Phantoms, Proc. IEEE International Workshop on Antenna Technology (IWAT06), New York, pp. 349-352, 2006.
[20] CTIA 01.71, *Positioning Guidelines*
[21] Claire C. Gordon, et.al., *1988 Anthropometric Survey of US Army Personnel: Summary Statistics Interim Report*, U.S. Army Natick Research Development and Engineering Center, 1989

Section 2 Phantoms

This section provides references and specifications defining the required phantoms for simulating the human body in various use modes. The specifications include required dimensions and dielectric properties for each phantom.

Contact cpwg@ctiacertification.org to obtain phantom-related CAD files.

Companies interested in manufacturing phantoms should contact CTIA Certification at certification@ctia.org to obtain additional dielectric parameter information on the existing phantoms in order to best align the OTA performance impact of new phantoms with the OTA performance impact of the existing phantoms.

2.1 Head Phantom

2.1.1 Head Phantom Reference Information

The required head phantom is based on the Specific Anthropomorphic Mannequin (SAM) head phantom in *IEEE Std 1528-2003* [1].

The IEEE Standards Coordinating Committee 34 (SCC34) has defined a SAM head model for use in specific absorption rate (SAR) testing. The shape of this head is based on the anthropomorphic data of the 90th percentile adult male head dimensions as published by the US Army [Gorden et al., 1989], except for the distance between the back of the ear and the head.

To provide consistency between these two types of radiated measurements (SAR and TRP/TIS), a nearly identical head phantom definition will apply to all measurements made in accordance with this test plan.

Figure 2.1.1-1 shows the IEEE SCC34 SAM head model where the sections in blue indicate normative areas and the silver band indicates informative data only.

Full details of the head's construction and reference points are given in *IEEE Std 1528-2003* [1].

The shell of the head phantom should be made of low permittivity (less than 5.0), low loss material (loss tangent less than 0.05) and have a thickness of 2.0 ±0.2 mm in all areas where the handset touches (except the ear).

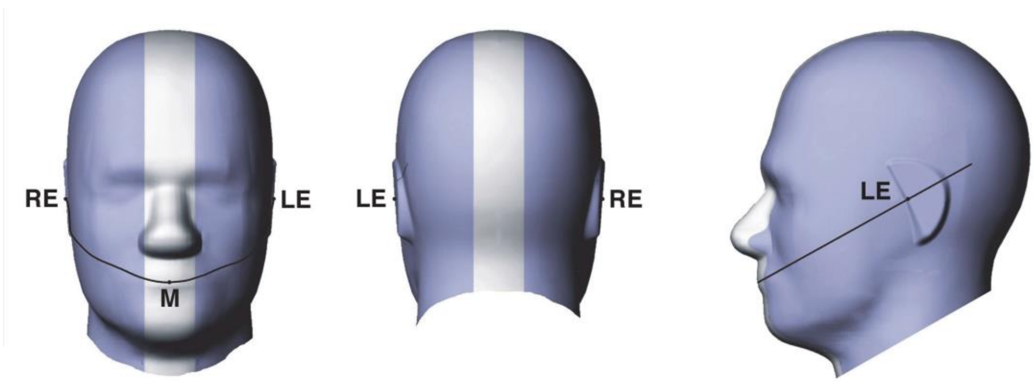

Figure 2.1.1-1 Front, Back and Side View of the SAM Head Phantom

RE and LE shown in Figure 2.1.1-1 are the Ear Reference Points for the right and left ears respectively.

2.1.2 Head Phantom Definition

For use in this test plan, this IEEE SAM head model has been extended below the neck region according to the informative data given in CENELEC EN 50361:2001 [2] so that its overall external height (from the top of the skull to bottom of the base with the head looking out horizontally) shall be 300 mm ±2 mm. The external width of the base shall be symmetrically truncated to be 225 mm ±2 mm. The head phantom appears as shown in Figure 2.1.2-1 in which the yellow areas indicate the informative CENELEC data.

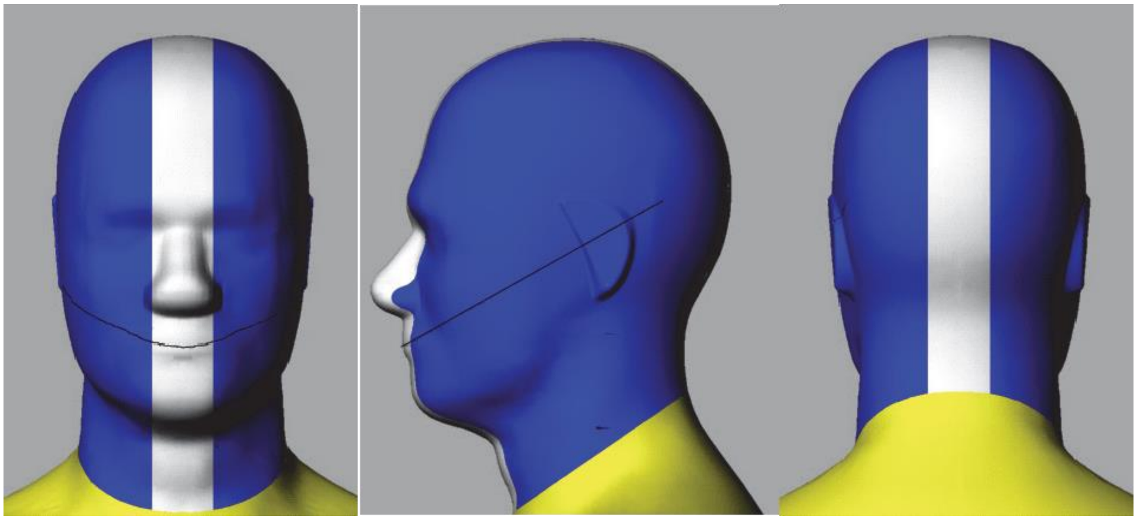

Figure 2.1.2-1 CTIA SAM Head Phantom

Figure 2.1.2-1 combined with the text above, defines the shape and size of the external shell of the head phantom, but provisions have to be made for filling/emptying the liquid contents and/or for sealing the base. No specific requirements are placed on the location of the hole(s) for filling/emptying the liquid contents of the head: these can be anywhere on or inside the head profile provided they do not obviously interfere with the measurements of this test plan. It is envisaged that either the top of the head or inside the neck region are the areas most likely to be used for this purpose. The plate that seals the base may incorporate the filling/emptying hole(s): this plate shall be made of a material with a dielectric constant of less than 5.0 and a loss tangent of less than 0.05. Whether containing the filling/emptying hole(s) (and the associated plug(s)/cap(s)/etc.) or serving as a mounting member, the plate shall additionally have a thickness of less than 13 mm and shall not extend beyond the external profile of the head phantom.

As an alternative head phantom, the IEEE SAM head model can be extended below the neck region so that its overall external height shall be 363 mm ±2 mm (without the filling cap). The external width of the base shall be symmetrically truncated to be 250 mm ±2 mm. The material in the extended region below 292 mm ±2 mm from the internal top of the IEEE SAM head shall have a dielectric constant of less than 5.0 and a loss tangent of less than 0.05. An additional uncertainty of 0.25 dB (k=2) shall be added.

The uncertainties caused by deviations from the nominal head shell dimensions shall be assessed as defined in Section 2.13.2.1 of *CTIA 01.70* [3] .

2.1.3 Head Phantom Dielectric Parameters

The IEEE SCC34 has defined the dielectric properties of the head tissue-equivalent material to be used in the head phantom for SAR measurement. To provide consistency between SAR and TRP/TIS measurement, nearly identical material dielectric property values are to be used for this test plan. The target values are given in Table 2.1.3-1 and the tolerance is ±20%.

For dielectric properties of head tissue-equivalent material at other frequencies within the frequency range, a linear interpolation method shall be used.

Dielectric materials which only comply with the requirements over a portion of the 300 MHz to 6 GHz may be used but only for tests where the band/protocol being measured is within the frequency band of compliance.

Table 2.1.3-1 Dielectric Properties of the Tissue-Equivalent Liquid

Frequency (MHz)	Target	
	ε_r	σ (S/m)
300	45.3	0.87
450	43.5	0.87
835	41.5	0.90
900	41.5	0.97
1450	40.5	1.20
1800	40.0	1.40
1900	40.0	1.40
1950	40.0	1.40
2000	40.0	1.40
2100	39.8	1.49
2450	39.2	1.80
3000	38.5	2.40
4000	37.4	3.43
5000	36.2	4.45
5200	36.0	4.65
5400	35.8	4.86
5600	35.5	5.06
5800	35.4	5.27

Frequency (MHz)	Target	
	ε_r	σ (S/m)
6000	35.1	5.48

Liquid tissue equivalent material may be used provided that the target dielectric properties are met within ±20%.

The composition of the material is not mandated provided the target dielectric properties are met within the permitted interval.

Recipes for liquid tissue equivalent material are provided in *IEEE Std 1528-2003* [1] where the main components are deionized water and sugar. Liquids are available from third parties or can mixed locally.

Care should be taken to verify the dielectric properties of the liquid tissue equivalent material at frequent enough intervals so as to guarantee compliance with the target (±20%) at the time of use for this test plan. Methods for measuring the dielectric properties are given in Section 4.

Alternatively, liquid tissue equivalent material can be replaced by gel, provided that the volume of all air bubbles in the material is below 0.13 cubic centimeters, and the dielectric properties of these materials are stable with time and certified at the point of manufacture. Methods for measuring the dielectric properties are given in Section 4.

Solid tissue equivalent material can be made from carbon loaded silicone, the dielectric properties of these materials are stable with time but must be certified at the point of manufacture following the protocol defined for the hand, i.e., a cubical sample (approximately 50 mm x 50 mm x 50 mm) for verification of stability and bulk properties and surface measurements at >20 defined positions on both sides of the head. Manufacturers of solid material head phantoms must certify that the volume of all air bubbles in the material must be below 0.13 cubic centimeters. For the purposes of this test plan, the remaining air bubbles can be assumed to have a negligible effect on the TRP/TIS.

Note: *Due to the inability to assess the measurement uncertainty of the solid tissue equivalent material for the head phantom, the use of solid head phantoms is not allowed in the test plan at this time.*

The uncertainties caused by deviations from the nominal head dielectric parameters shall be assessed as defined in Section 2.13.2.1 of *CTIA 01.70* [3].

2.1.4 Head Fixturing Requirements

The primary goal of the fixture is to allow the accurate positioning of the device under test (DUT), while also being transparent and non-reflective to RF. The material for the DUT fixturing shall have a dielectric constant of less than 5.0 and a loss tangent of less than 0.05. Any fixture meeting these material parameters may be used as long as the uncertainty assessment is done and the overall uncertainty budget is met.

The method for assessing the uncertainty for the hand phantom fixturing is described in Section 2.13.2 of *CTIA 01.70* [3] and can also be used for assessing the uncertainty for head fixturing.

No additional uncertainty assessment is needed if thin plastic “packing” tape is used to hold the DUT.

2.2 Hand Phantom

2.2.1 Hand Phantom-Reference Information

The human hand is one of the most complex parts of the human body. Detailed hand geometry not only varies from person to person, but the hand will change geometrically depending on the physical task assigned to it. Since mobile devices are used in conjunction with the hand, it is important that the hand is studied to determine the best scientific representation of the specific dimensions for a standard sized hand phantom. A large amount of published data exists regarding the human hand, but few papers address anthropometry of the hand.

2.2.2 Hand Anthropometric Research

The following articles contain information that is significant in determining the physical dimensions of a hand phantom and are used in conjunction with each other in the determination of the hand dimension parameters.

- Thomas M. Greiner; *Hand Anthropometry of US Army Personnel*, Army Natick Research Development and Engineering Center, 1991 [4]- This study, sponsored by the Anthropology Branch at NATICK, is perhaps the largest and most comprehensive modern anthropometric study available. A sample size of 2304 people and 86 anthropometric categories were photographed, digitized, and measured. Measurements were taken from a number of landmarks on the hand, including creases in the skin of the hand, the tips of fingers, and other visible locations.

- Alvin R. Tilley and Henry Dreyfuss Associates; *The Measure of Man and Woman: Human Factors in Design*; Wiley, 1993 [5]- This book contains some additional data regarding hand anthropometry to supplement the Greiner study. Although the Greiner study is mentioned, the source of the additional data in the book is unfortunately not referenced.

- B. Buchholz, T.J. Armstrong and S.A. Goldstein; "*Anthropometric data for describing the kinematics of the human hand*," Ergonomics vol. 35, no. 3, pp. 261-273, 1992 [6]- This article identifies the locations of the internal rotational joints of the fingers with respect to the skin creases that are used as measurement references in the previous two studies. This information is required to develop an articulated kinematic hand model that can be posed with anatomically correct bends in the joints.

- W.D. Bugbee and M.J. Botte,; "*Surface Anatomy of the Hand: The Relationships Between Palmar Skin Creases and Osseous Anatomy*," Clinical Orthopaedics and Related Research, 296, 122-126, 1993 [7]- This study was performed on 48 adult corpse hands and 5 live human hands. It supplements the Buchholz article with additional data on the relationship between skin creases and internal bone structure, and especially for modeling distinct carpal and metacarpal bones.

2.2.3 Hand Reference Dimensions

Based on the analysis above, the necessary dimensions of the hand components were determined. Since no one study contains all of the necessary dimensions, some combining and scaling was performed using all four references.

The hand phantom is the average of the 50th percentile of men and women as taken from the data sources cited above. The full data set including averaged hand data (per gender) and skin crease to bone joint scaling factors can be found in the references.

The hand phantom dimensions are defined in Table 2.2.3-1.

Table 2.2.3-1 Hand Phantom Dimensions

Description	Dim. (mm)	Notes
Interdigital Crotch Dimensions		
Between Digit II & III Crotch to Tip of Digit II	72.5	Greiner #10
Between Digit II & III Crotch to Tip of Digit III	80.5	Greiner #22
Between Digit III & IV Crotch to Tip of Digit IV	75.7	Greiner #34
Between Digit IV & V Crotch to Tip of Digit V	61.5	Greiner #46
Between Digit I & II Crotch to Tip of Digit I	56.5	Tilley
Major Hand and Wrist Dimensions		
Wrist Width	61.4	Greiner #64
Wrist Circumference	162.9	Greiner #65
Hand Length, Center of Wrist to Tip of Digit III	186.5	Greiner #24
Hand Circumference	200.2	Greiner #60
Palm Length: Middle Crease to Distal Palm Crease	105.7	Greiner #61
Hand Width	85.0	Greiner #63
Digit I Dimensions		
Distal Phalanx Length	29.4	Buchholz, Greiner
Proximal Phalanx Length	36.5	Buchholz, Greiner
Metacarpal Length	46.8	Buchholz, Greiner
Carpal Length	22.0	Buchholz, Greiner
DIP Width	22.3	Greiner #4
DIP Circumference	67.7	Greiner #5
Digit II Dimensions		
Distal Phalanx Length	18.1	Buchholz, Greiner
Middle Phalanx Length	26.7	Buchholz, Greiner
Proximal Phalanx Length	45.7	Buchholz, Greiner
Metacarpal Length	67.4	Buchholz, Bugbee
DIP Width	18.7	Greiner #15
PIP Width	21.5	Greiner #13
DIP Circumference	54.1	Greiner #16
PIP Circumference	64.8	Greiner #14
Carpal Length	20.6	Buchholz, Bugbee
Digit III Dimensions		
Distal Phalanx Length	20.1	Buchholz, Greiner
Middle Phalanx Length	31.7	Buchholz, Greiner
Proximal Phalanx Length	49.6	Buchholz, Greiner
Metacarpal Length	66.2	Buchholz, Bugbee
DIP Width	18.5	Greiner #27
PIP Width	20.9	Greiner #25
DIP Circumference	54.4	Greiner #28

Description	Dim. (mm)	Notes
PIP Circumference	65.5	Greiner #26
Carpal Length	17.4	Buchholz, Bugbee
Digit IV Dimensions		
Distal Phalanx Length	20.0	Buchholz, Greiner
Middle Phalanx Length	30.8	Buchholz, Greiner
Proximal Phalanx Length	45.5	Buchholz, Greiner
Metacarpal Length	60.4	Buchholz, Bugbee
DIP Width	17.2	Greiner #39
PIP Width	19.9	Greiner #37
DIP Circumference	50.3	Greiner #40
PIP Circumference	61.2	Greiner #38
Carpal Length	19.4	Buchholz, Bugbee
Digit V Dimensions		
Carpal Length	24.3	Buchholz, Bugbee
Distal Phalanx Length	17.3	Buchholz, Greiner
Middle Phalanx Length	21.8	Buchholz, Greiner
Proximal Phalanx Length	38.0	Buchholz, Greiner
Metacarpal Length	56.6	Buchholz, Bugbee
DIP Width	16.1	Greiner #51
PIP Width	17.9	Greiner #49
DIP Circumference	45.9	Greiner #52
PIP Circumference	54.2	Greiner #50

Figure 2.2.3-1 Pictorial of Human Hand with Dimension Labels

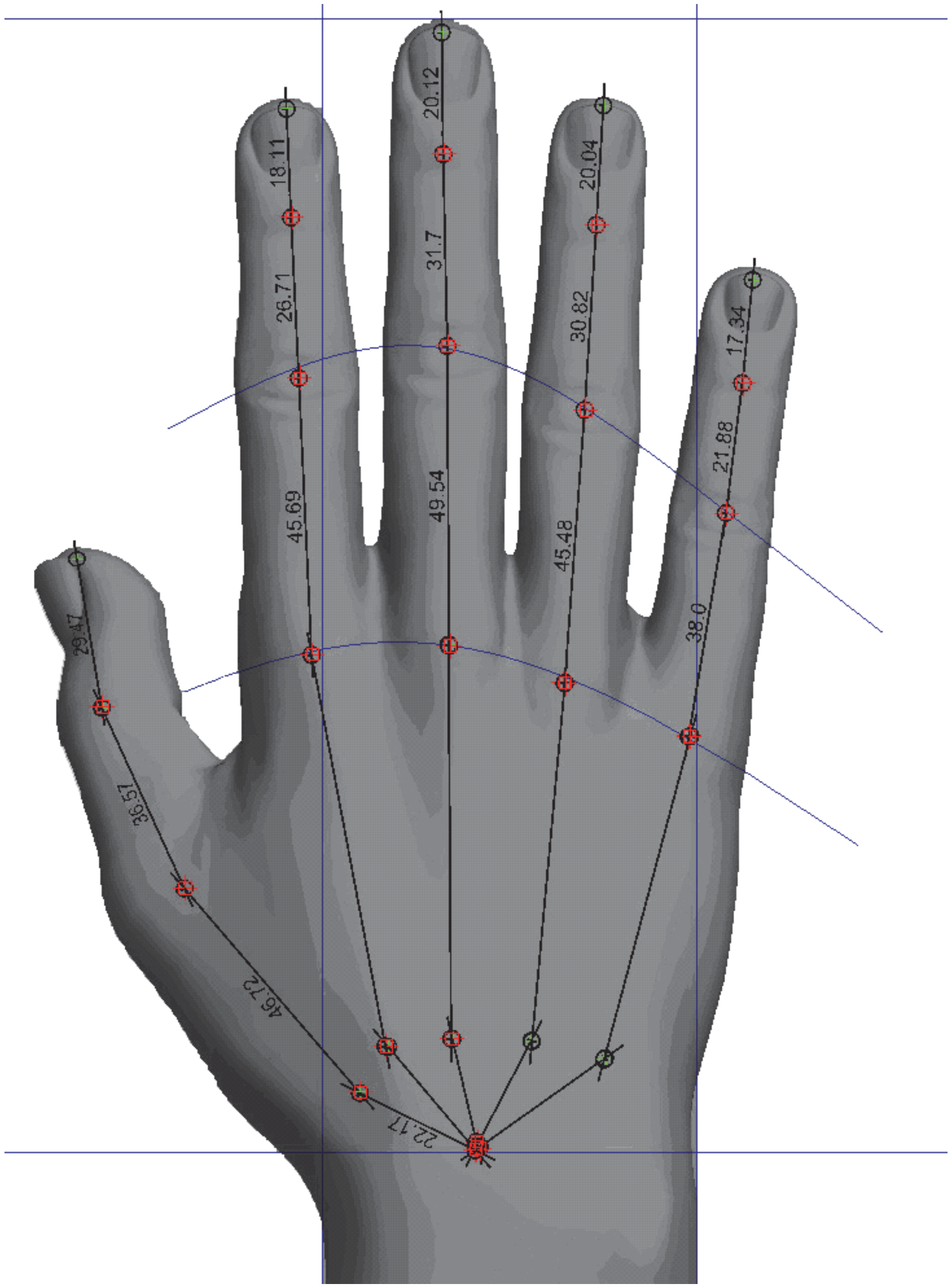

Figure 2.2.3-2 Open Hand Phantom

2.2.4 Hand Reference Dielectric Parameters

RF dielectric properties of the hand phantom are based on the dry palm human tissue measurement data as discussed in *Tissue Equivalent Material for Hand Phantoms* [8]. Table 2.2.4-1 lists the target conductivity (σ) (S/m) and relative permittivity (ε_r) for the hand phantom from 300 MHz to 6 GHz.

Table 2.2.4-1 Hand Dielectric Parameters

Frequency (MHz)	ε_r	σ (S/m)
300	37.1	0.36
450	33.9	0.43
835	30.3	0.59
900	30.0	0.62
1450	27.9	0.85
1575	27.5	0.90
1800	27.0	0.99
1900	26.7	1.04
1950	26.6	1.07
2000	26.5	1.09
2100	26.3	1.14
2450	25.7	1.32
3000	24.8	1.61
4000	23.5	2.18
5000	22.2	2.84
5200	22.0	2.98
5400	21.7	3.11
5600	21.4	3.25
5800	21.2	3.38
6000	20.9	3.52

The material composition of the hand phantom is typically silicon loaded with carbon powder. The exact ratios of these compounds are not critical as long as the required RF dielectric properties are met.

2.2.5 Dielectric Parameter Requirements

The relative permittivity of hand phantoms shall be within ±15% of the values listed in Table 2.2.4 1. The conductivity of hand phantoms shall be within ±25% of the values listed in Table 2.2.4 1. The dielectric parameters shall be determined as described in Section 2.13.2.2 of *CTIA 01.70* [3] using the methods in Section 4, across the frequency bands for which the hand phantom is to be used as outlined in Section 3. The RF dielectric parameters may be certified by the hand phantom manufacturer or determined by the test lab. The manufacturer shall provide a certificate indicating compliance over the applicable bands, including the measurement methodology and results, when they are certifying compliance with the RF dielectric parameters.

The uncertainties caused by deviations from the nominal hand dielectric parameters shall be assessed as defined in Section 2.13.2.2 of *CTIA 01.70* [3].

2.2.6 Hand Phantom Identification

The hand phantoms shall be traceable by their model and serial number. Hand phantom manufacturers shall provide a reference material block made of the same material as its associated hand phantoms, which is suitable for measuring its dielectric properties (see Section 2.13.2.2 of *CTIA 01.70* [3].) Each hand phantom shall be traceable to its associated reference material block. The identification marking of the hand phantom shall be on the back half of the hand, on the wrist, or on any side/rear mounting boss permanently attached to the hand, specifically in an area where there is no chance of interaction with the OTA measurement.

2.2.7 Hand Mechanical Requirements

The hand phantoms shall be constructed of a material that is sufficiently flexible to accommodate the range of devices specified in Sections 2.2.9 through 2.2.13. The material shall also be made sufficiently stiff that the hand grip remains constant under rotation. Adequate material stiffness of the hand phantom has been found to be necessary to maintain high repeatability of OTA measurements.

The stiffness of the hand material shall be verified by measuring the deflection of the index finger of a molded monoblock hand phantom under a given weight.

1. Position the hand phantom such that the index finger is horizontal.
2. Apply an indicator needle that extends horizontally 55 mm ±1 mm beyond the tip of the index finger.
3. Record the position of the indicator needle on a vertical scale.
4. Apply 20 g ±0.2 g of weight centered 6 mm ±0.5 mm from the tip of the index finger towards the hand.
5. Record the new position of the indicator needle on a vertical scale.

The deflection of the index finger of the hand phantom shall be between 2 and 5 mm. Deflection less than 2 mm per 20 g weight indicates a material that is too rigid. Deflection greater than 5 mm per 20 g weight indicates a material that is too soft.

Figure 2.2.7-1 shows a conformal fingertip weight container with indicator needle that shall be used for this purpose.

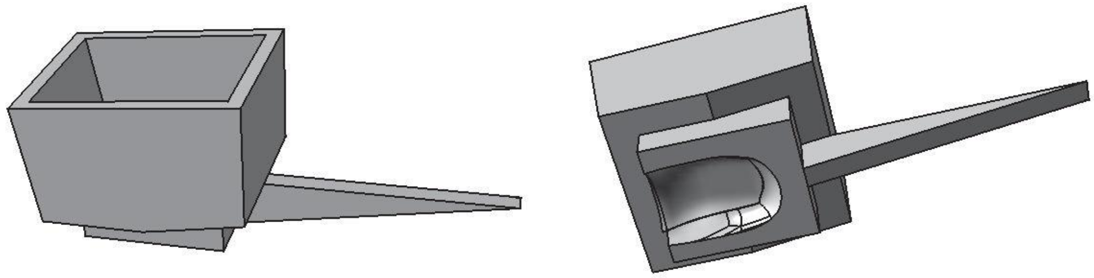

Figure 2.2.7-1 Conformal Fingertip Weight Container

The weight container is fastened to the index fingertip with cellophane tape and the hand phantom is laid on its back on a flat surface, with the indicator needle pointing to a vertical millimeter ruler as shown in Figure 2.2.7-2. The position of the needle is recorded before and after a known weight is placed in the container, and the difference is calculated to determine the deflection under load.

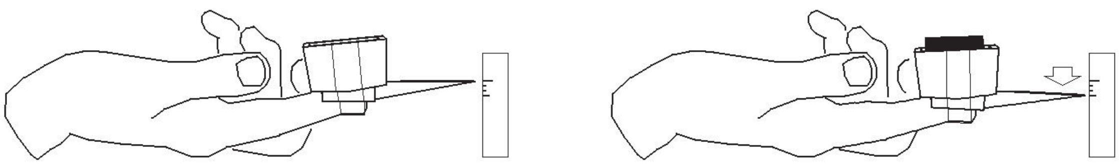

Figure 2.2.7-2 Measuring the Hand Phantom Material Stiffness

It is assumed that the other hand phantoms (i.e., fold, narrow data and PDA grips) will have similar stiffness as the monoblock hand from the same material. Therefore, a stiffness test of the monoblock hand alone is considered sufficient.

2.2.8 Hand Phantom Fixturing Requirements

The primary goal of the fixture is to allow the accurate positioning of the hand phantom and DUT, while also being transparent and non-reflective to RF. The material for the hand phantom fixturing shall have a dielectric constant of less than 5.0 and a loss tangent of less than 0.05. Any fixture meeting these material parameters may be used as long as the uncertainty assessment is done and the overall uncertainty budget is met.

The method for assessing the uncertainty for the hand phantom fixturing is described in Section 2.13.2 of *CTIA 01.70* [3].

2.2.9 Monoblock Hand Phantom

The monoblock hand phantom is suitable for use with monoblock DUTs and closed portrait slide/rotator DUTs for head and hand testing. The DUTs should have sizes within the ranges specified within Table 2.2.9-1 .

Table 2.2.9-1 Range of Monoblock-Like Device Sizes Suitable for Use with Monoblock Hand Phantom

Feature	Minimum (mm)	Maximum (mm)
Width	40	56
Length	95	none

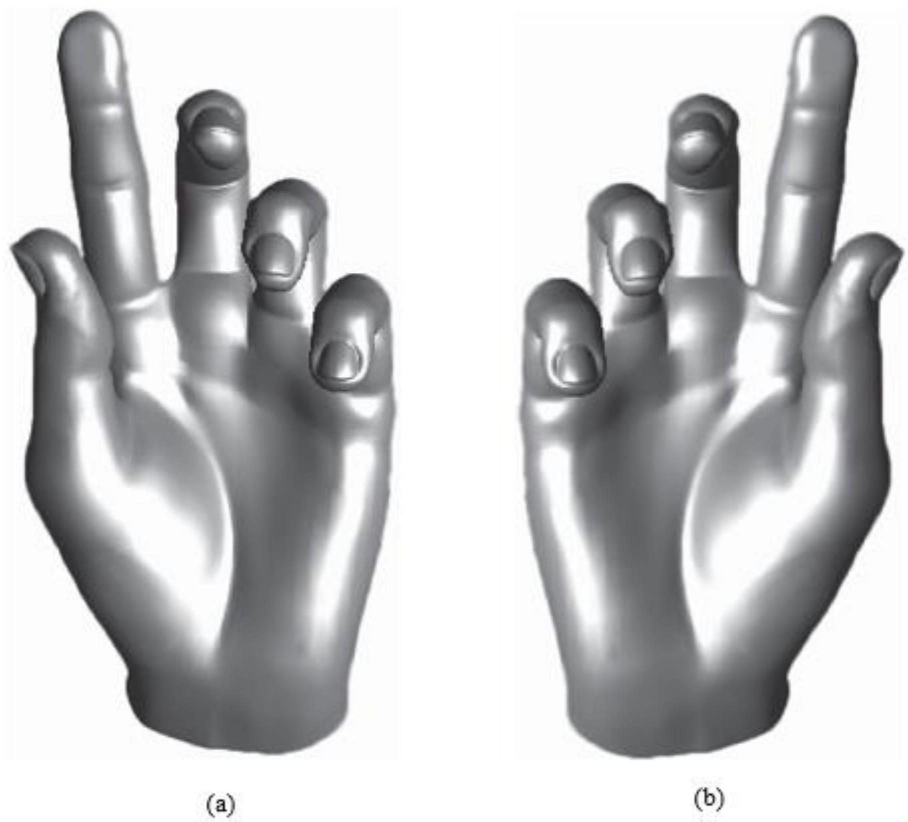

Figure 2.2.9-1 Monoblock Hand Phantom; (A) Left Hand; (B) Right Hand

2.2.10 Fold Hand Phantom

The fold hand phantom is suitable for use with fold and open portrait slide/rotator DUTs for head and hand testing, with sizes within the ranges specified within Table 2.2.10-1.

Table 2.2.10-1 Range of Fold Device Sizes Suitable for Use with Fold Hand Phantom

Feature	Minimum (mm)	Maximum (mm)
Width	40	56
Length between hinge and bottom edge	75	none

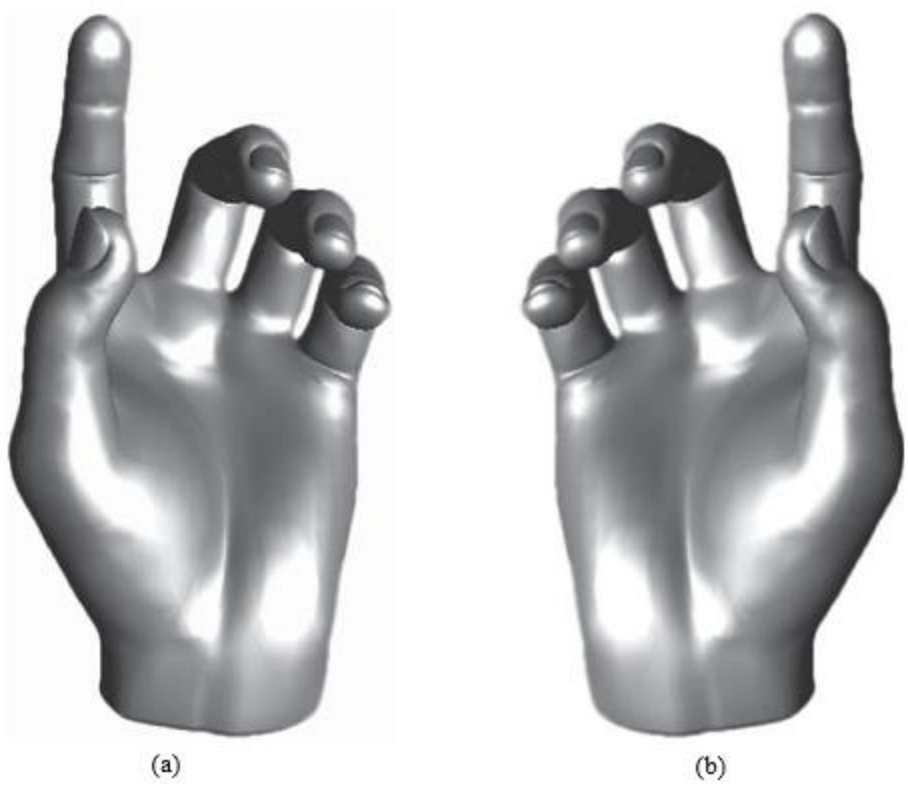

Figure 2.2.10-1 Fold Hand Phantom; (a) Left Hand; (b) Right Hand

2.2.11 Narrow Data Hand Phantom

The narrow data hand phantom is suitable for use with narrow DUTs with sizes within the ranges specified within Table 2.2.11-1 for hand only testing.

Table 2.2.11-1 Range of Narrow Data Device Sizes Suitable for Use with Narrow Data Hand Phantom

Feature	Minimum (mm)	Maximum (mm)
Width	40	56
Thickness	none	26

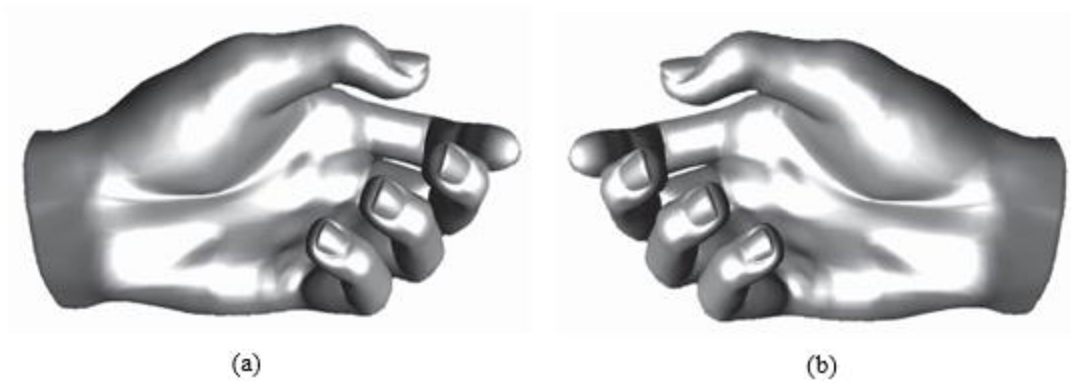

Figure 2.2.11-1 Narrow Data Hand Phantom; (A) Left Hand; (B) Right Hand

2.2.12 PDA Grip Hand Phantom

The PDA grip hand phantom is suitable for use with DUTs with sizes within the ranges specified within Table 2.2.12-1 for head and hand testing or hand only testing.

Table 2.2.12-1 Range of PDA Device Sizes Suitable for Use with PDA Hand Phantom

Feature	Minimum (mm)	Maximum (mm)
Width	56	72
Thickness	none	none

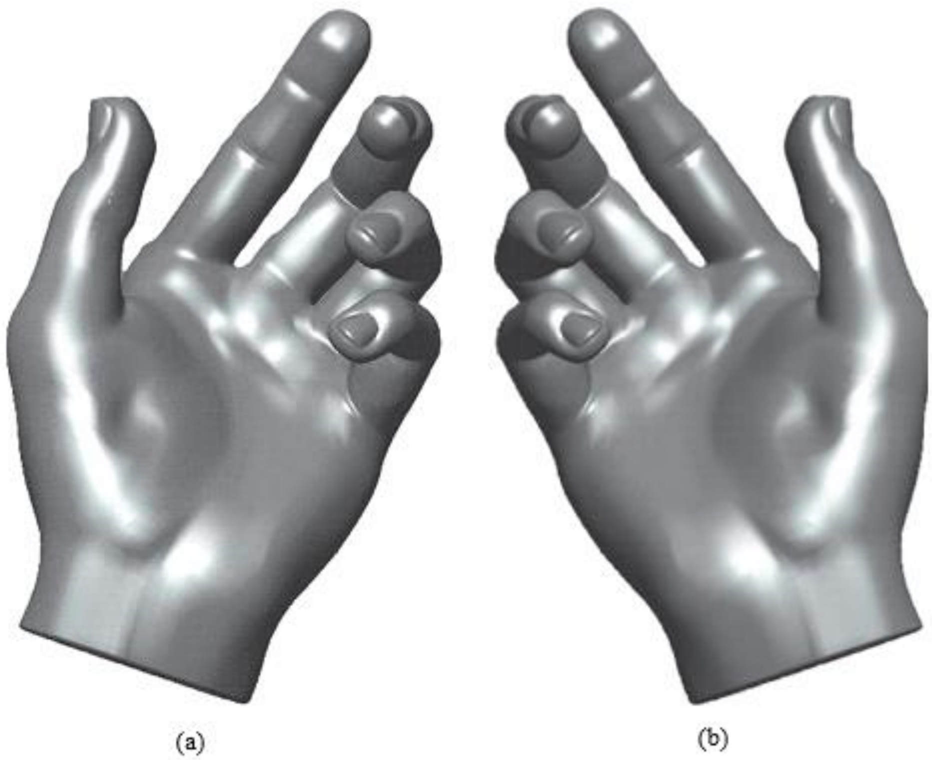

Figure 2.2.12-1 PDA Hand Phantom; (A) Left Hand; (B) Right Hand

2.2.13 Wide Grip Hand Phantom

The Wide Grip hand phantom is suitable for use with an DUT having physical dimensions falling within the ranges specified by Table 2.2.13-1 for “talk” mode (head and hand) or “data” mode (hand-only) testing.

Table 2.2.13-1 Range of DUT Sizes Suitable for use with Wide Grip Hand Phantom

Dimension	Minimum (mm)	Maximum (mm)
Width	>72	92
Thickness	none	none

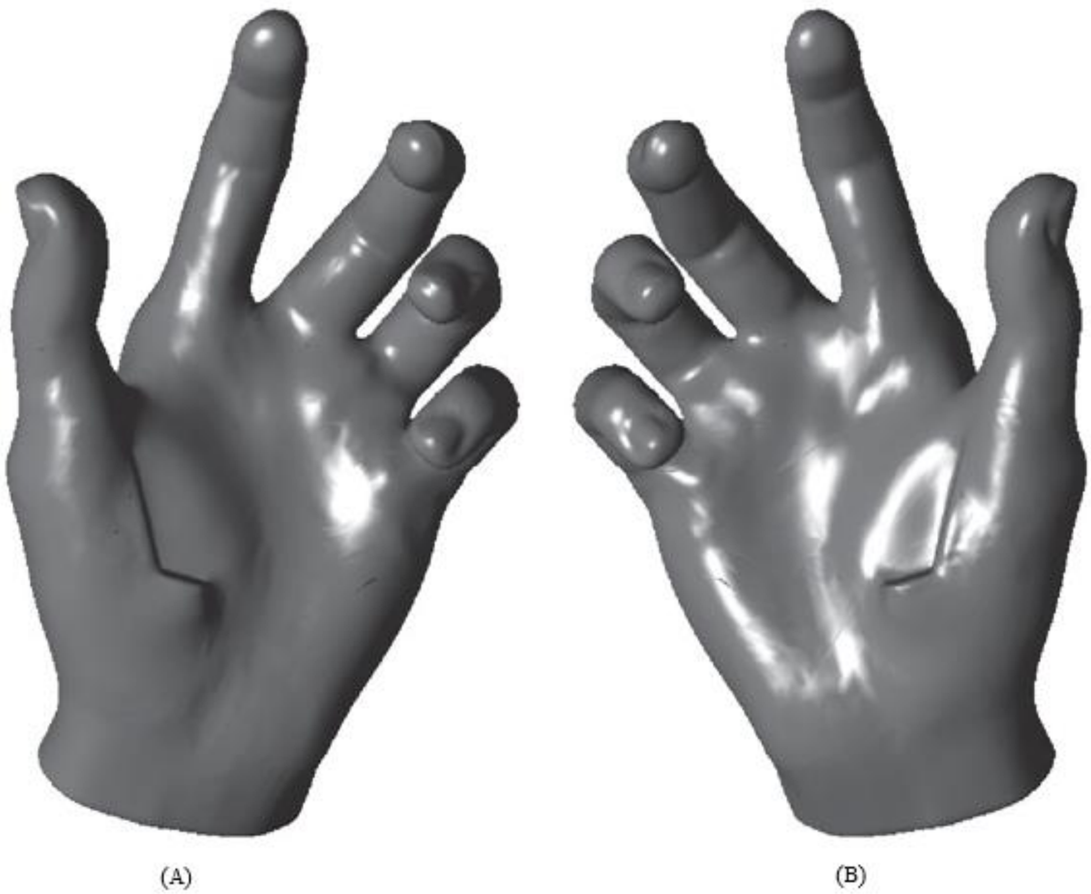

Figure 2.2.13-1 Wide Grip Hand Phantom; (A) Left Hand, (B) Right Hand

2.2.14 Alternative Hand Phantoms

Alternative hand phantoms will be allowed in the future for DUTs with form factors or sizes not covered by the current hand phantoms. These new alternative hand phantoms shall be based on human factor studies. However, the method for performing and approving these human factor studies will be determined in a future update. These alternative hand phantoms shall be based upon the existing parameters outlined in Section 2.2.3 and Section 2.2.4. All new approved hand phantoms along with their corresponding human factors studies shall be published through CTIA Certification after the associated DUT is launched in the US, thus making them available for public use.

The testing of devices with alternate hand phantoms is currently not required in this test plan.

2.3 Forearm Phantom

2.3.1 Forearm Phantom Dielectric Parameter Requirements

The relative permittivity of forearm phantoms shall be within ±15% of the values listed in Table 2.2.4 1. The conductivity of forearm phantoms shall be within ±25% of the values listed in Table 2.2.4 1. The dielectric parameters shall be determined in a manner similar to the method for evaluating hand phantoms in Section 2.13.2.2 of *CTIA 01.70* [3] using the methods in Section 4 across the frequency bands for which the forearm phantom is to be used as outlined in Section 3. The RF dielectric parameters may be certified by the forearm phantom manufacturer or determined by the test lab. The manufacturer shall provide a certificate indicating compliance over the applicable bands, including the measurement methodology and results, when they are certifying compliance with the RF dielectric parameters.

The uncertainties caused by deviations from the nominal forearm dielectric parameters shall be assessed as defined in Section 2.13.3 of *CTIA 01.70* [3].

2.3.2 Forearm Phantom Identification

The forearm phantoms shall be traceable by their model and serial number. Forearm phantom manufacturers shall provide a reference material block made of the same material as its associated forearm phantom, which is suitable for measuring its dielectric properties (see Section 2.13.3 of *CTIA 01.70* [3].) Each forearm phantom shall be traceable to its associated reference material block. The identification marking of the forearm phantom shall be on the forearm, or on any mounting boss attached to the forearm, specifically in an area where there is no chance of interaction with the OTA measurement.

2.3.3 Forearm Phantom Fixturing Requirements

The primary goal of the fixture is to allow the stable mounting of the forearm phantom and DUT in the chamber, while also being transparent and non-reflective to RF. The material for the forearm phantom fixturing shall have a dielectric constant of less than 5.0 and a loss tangent of less than 0.05. The fixturing shall be kept below the base of the forearm phantom.

No additional measurement uncertainty from the forearm phantom fixture is needed as long as the above requirements are met (See Section 2.13.3.3 of *CTIA 01.70* [3]).

2.3.4 Forearm Phantom Dimensions

The Forearm phantom consists of cylindrical and conical sections, as shown in Figure 2.3.4-1. The perimeter of the conical section is 162.7 mm at the target test location (corresponding to the 50th percentile wrist circumference), indicated by a ring marking engraved around the phantom. Elsewhere, the perimeter of the conical section varies linearly from 144.0 mm to 224.5 mm over its longitudinal length of 215 mm.

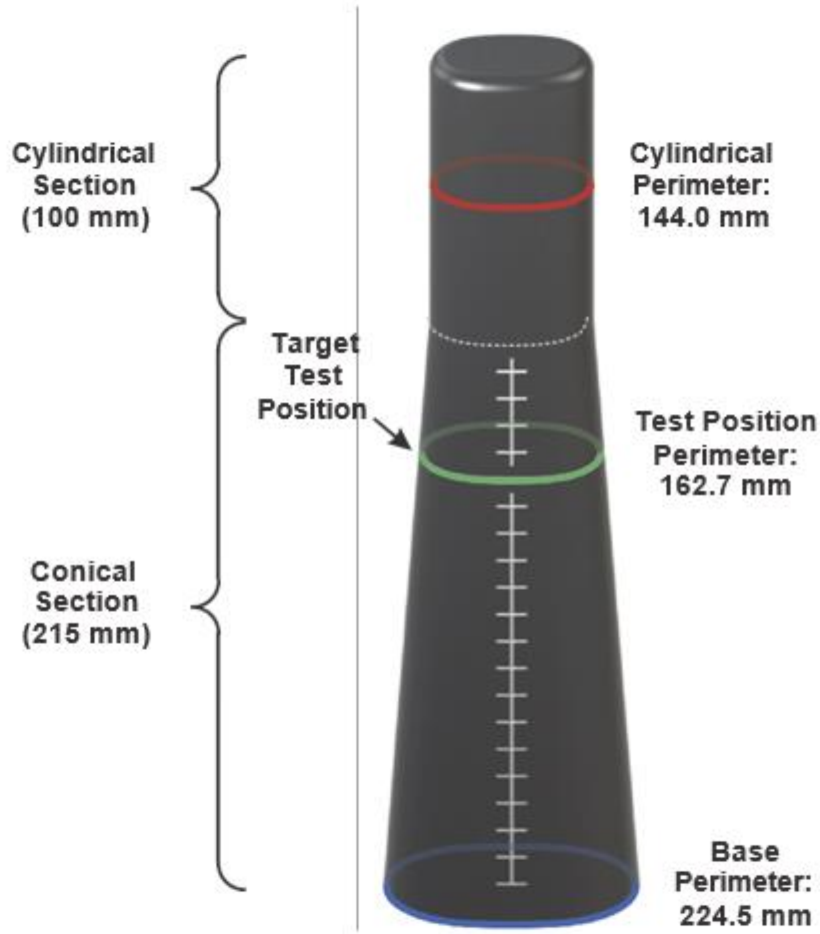

Figure 2.3.4-1 Forearm Phantom with Target Test Position

2.3.5 Forearm Phantom Reference Information

The Forearm phantom used in this test plan was selected for the following reasons:

- The anatomical hand was not included a) to enable easy positioning of wrist-worn devices onto the forearm phantom, in particular to allow fixed-circumference, rigid "bangle"-type devices to be snugly fitted at locations deviating from the target engraved marking as necessary, with minimum impact (i.e., without bringing them nearer to/farther from a hand phantom discontinuity) and b) to enable use of a single phantom for both left and right forearm testing.

- The simplified shape for the forearm was selected a) to eliminate the ulna bump in the forearm to enable repeatable positioning of wrist-worn devices on the forearm phantom and b) to enable the use of a single phantom for both left and right forearm testing.

Measurements taken from the following reference, Thomas M. Greiner; *Hand Anthropometry of US Army Personnel, Army Natick Research Development and Engineering Center,* 1991 [4], were used as a guide in defining the forearm phantom:

Table 2.3.5-1 Selection of Statistics from US Army Data on Enlisted Personnel

Body part	Mean / 50% percentile male (cm)	Mean / 50% percentile female (cm)	Model Dimension (cm)
Wrist Circumference	17.43 / 17.40	15.14 / 15.11	14.4 (smallest), 16.27 (test position)
Forearm Circumference, flexed	30.39 / 30.28	25.41 / 25.34	22.45 (base dimension)
Radiale-Stylion length	26.93 / 26.83	24.36 / 24.32	21.5 (conical section)

The wrist circumference was chosen to be the average of the mean and 50th percentile of males and females from the US Army data. The slope of the conical section taper away from the target test position (forearm circumference, flexed) was reduced in order to ensure reasonable flatness at the test location. The length of conical section (radiale-stylion length) was selected to be long enough to properly model the impact of the forearm on wrist-worn devices and to locate the wrist-worn DUT in the center of the chamber quiet zone.

2.4 Chest Phantom

2.4.1 Chest Phantom Dielectric Parameter Requirements

The relative permittivity of chest phantoms shall be within ±15% of the values listed in Table 2.2.4 1. The conductivity of chest phantoms shall be within ±25% of the values listed in Table 2.2.4 1. The dielectric parameters shall be determined in a manner similar to the method for evaluating hand phantoms in Section 2.13.2.2 of *CTIA 01.70* [3] using the methods in Section 4 across the frequency bands for which the chest phantom is to be used as outlined in Section 3. The RF dielectric parameters may be certified by the chest phantom manufacturer or determined by the test lab. The manufacturer shall provide a certificate indicating compliance over the applicable bands, including the measurement methodology and results, when they are certifying compliance with the RF dielectric parameters.

The uncertainties caused by deviations from the nominal chest phantom dielectric parameters shall be assessed as defined in Section 2.13.4 of *CTIA 01.70* [3]

2.4.2 Chest Phantom Identification

The chest phantoms shall be traceable by their model and serial number. Chest phantom manufacturers shall provide a reference material block made of the same material as its associated chest phantom, which is suitable for measuring its dielectric properties (see Section 2.13.4 of *CTIA 01.70* [3].) Each chest phantom shall be traceable to its associated reference material block. The identification marking of the chest phantom shall be on the chest phantom, or on any mounting boss attached to the chest phantom, specifically in an area where there is no chance of interaction with the OTA measurement.

2.4.3 Chest Phantom Fixturing Requirements

The primary goal of the fixture is to allow the stable mounting of the chest phantom and DUT in the chamber, while also being transparent and non-reflective to RF. The material for the chest phantom fixturing shall have a dielectric constant of less than 5.0 and a loss tangent of less than 0.05. The fixturing shall be kept below the base of the chest phantom.

No additional measurement uncertainty from the chest phantom fixture is needed as long as the above requirements are met.

2.4.4 Chest Phantom Dimensions

The Chest phantom consists of a rectangular block with curved sections on the side as shown in Figure 2.4.4 1. The overall dimensions of the chest phantom are 325 x 325 x 75 mm. The curved sections on the side have a cross section of a quarter circle with radius of 70mm.

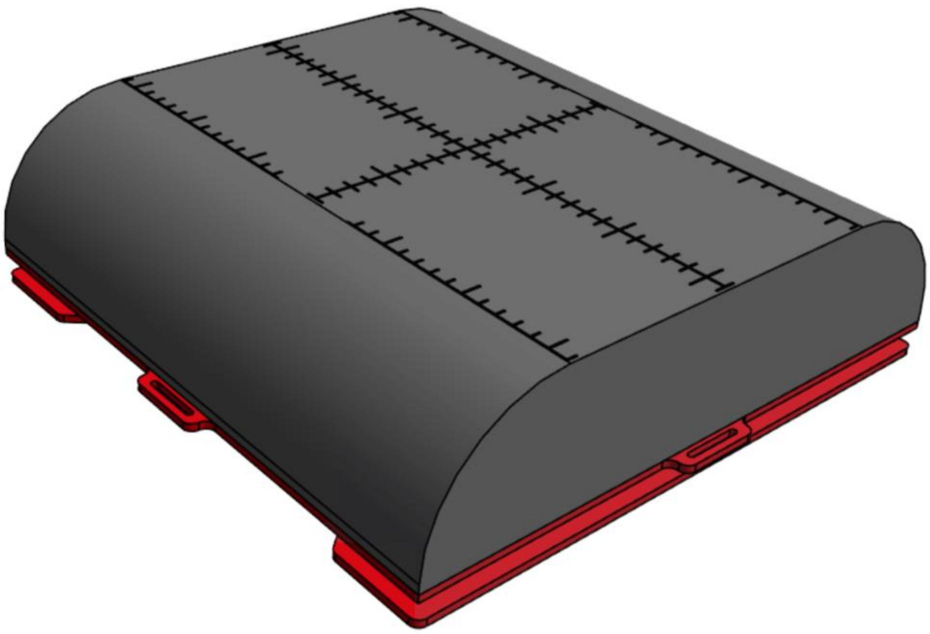

Figure 2.4.4-1 Chest Phantom with Target Test Position

2.5 Ankle Phantom

2.5.1 Ankle Phantom Dielectric Parameter Requirements

The relative permittivity of ankle phantoms shall be within ±15% of the values listed in Table 2.2.4 1. The conductivity of ankle phantoms shall be within ±25% of the values listed in Table 2.2.4 1. The dielectric parameters shall be determined in a manner similar to the method for evaluating hand phantoms in Section 2.13.2.2 of *CTIA 01.70* [3] using the methods in Section 4 across the frequency bands for which the ankle phantom is to be used as outlined in Section 3. The RF dielectric parameters may be certified by the ankle phantom manufacturer or determined by the test lab. The manufacturer shall provide a certificate indicating compliance over the applicable bands, including the measurement methodology and results, when they are certifying compliance with the RF dielectric parameters.

The uncertainties caused by deviations from the nominal ankle phantom dielectric parameters shall be assessed as defined in Section 2.13.5 of *CTIA 01.70* [3]

2.5.2 Ankle Phantom Identification

The ankle phantoms shall be traceable by their model and serial number. Ankle phantom manufacturers shall provide a reference material block made of the same material as its associated ankle phantom, which is suitable for measuring its dielectric properties (see Section 2.13.5 of *CTIA 01.70* [3].) Each ankle phantom shall be traceable to its associated reference material block. The identification marking of the ankle phantom shall be on the ankle phantom, or on any mounting boss attached to the ankle phantom, specifically in an area where there is no chance of interaction with the OTA measurement.

2.5.3 Ankle Phantom Fixturing Requirements

The ankle phantom is mounted on the 250mm radius ground plane. The method of fixing the ankle phantom to the ground plane shall enable stable mounting of the ankle phantom and EUT in the chamber, while also being transparent and non-reflective to RF. The material for the ankle phantom fixturing shall have a dielectric constant of less than 5.0 and a loss tangent of less than 0.05 and kept underneath the ankle phantom and in the ankle phantom at least 9 cm away from the target test position.

No additional measurement uncertainty from the ankle phantom fixture is needed as long as the above requirements are met.

2.5.4 Ankle Phantom Dimensions

The Ankle phantom consists of a conical section as well as a generic foot, as shown in Figure 2.5.4-1. The perimeter of the conical section is 219 mm at the target test location (corresponding to the average of the male and female ankle circumferences), indicated by a ring marking engraved around the phantom. The height at the target test location is 125mm. Elsewhere, the perimeter of the conical section varies linearly from 204mm to 371mm over its longitudinal length of 336 mm. The foot length is 257mm, which corresponds to a shoe size of 8.5 US or 40 Europe.

The ankle phantom is mounted on a circular ground plane of 250mm radius with the Z-axis of the ankle phantom, as defined in Figure 2.5-2 of *CTIA 01.71* [20], centered on the circular ground plane. The circular ground plane shall 1) consist of a metal with conductivity greater than 10e7 Siemens/m and at least 35μm in thickness, and 2) achieve flatness with less than 1° variation. Mounting holes in the ground plane for the ankle phantom are allowed as long as they are completely covered by the ankle phantom.

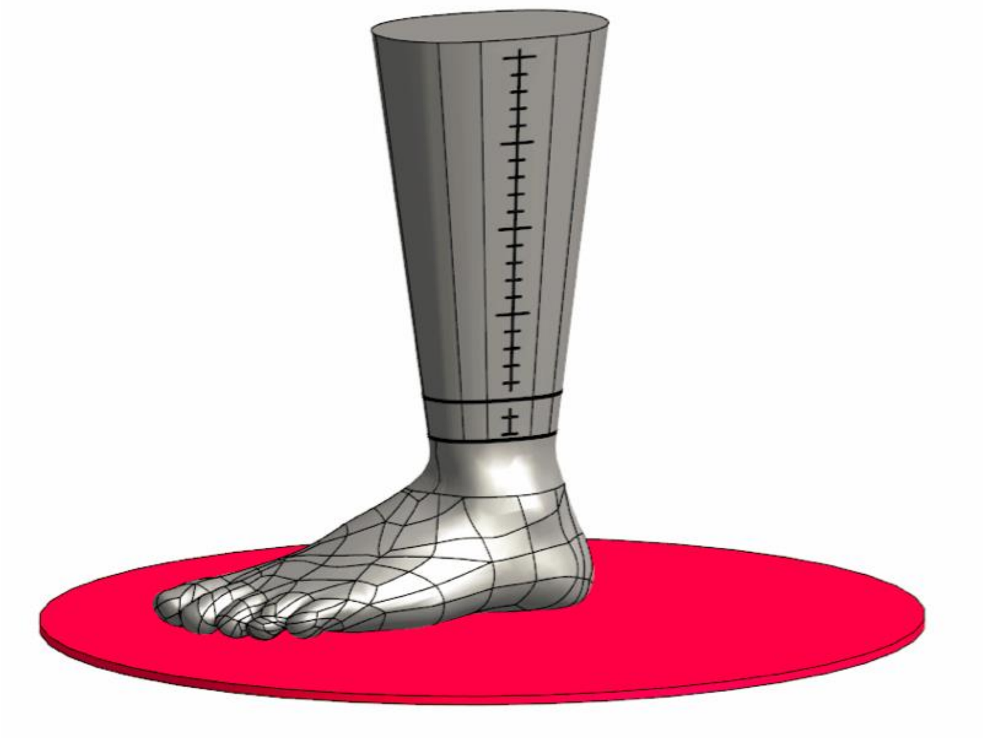

Figure 2.5.4-1 Ankle Phantom with Target Test Position

2.5.5 Ankle Phantom – Reference Information

The Ankle phantom used in this test plan was selected for the following reasons:

1) An integrated foot is included with the ankle phantom because the foot has a significant impact on the typical ankle-worn device's OTA performance and all ankle-worn devices are expected to support a band that can be opened to allow the user to wear the device on the ankle without having to fit the band over the user's foot.
2) The height of the target test position was selected to match the location where the ankle's circumference was smallest. The circumference of the ankle phantom at the target test position is not the minimum circumference of the ankle phantom.
3) The simplified shape of the leg was selected to enabled repeatable positioning of the ankle-worn devices on the ankle phantom.
4) The ankle phantom is for the left ankle, and no phantom for the right ankle is specified to minimize test time and test equipment costs. No testing for the right ankle is specified as the OTA performance is not expected to vary enough to merit the additional testing.

Measurements taken from the following reference, Claire C. Gordon, et.al., 1988 *Anthropometric Survey of US Army Personnel: Summary Statistics Interim Report*, U.S. Army Natick Research Development and Engineering Center, 1989 [21], and anthropometric data of VIP models were used as a guide in defining the ankle phantom:

Table 2.5.5-1: A Selection of Statistics from US Army Data on Enlisted Personnel and VIP Models

Body Part	50% Percentile Male (cm)	50% Percentile Female (cm)	VIP Average (cm)	Model Dimension (cm)
Ankle Circumference	22.19	20.51	22.48	21.9
Calf Circumference	37.78	35.22	37.7	37.1
Ankle height	13	12	N/A	12.5
Calf height	35.27	31.54	33.9	33.6
Foot length	26.93	24.43	N/A	25.7

Each of the following dimensions, ankle circumference, calf circumference, ankle height, calf height and foot length, were chosen to be a weighted average of the 50th percentile of males and females from the US Army data and VIP models. The slope of the conical section taper away from the target test position (ankle circumference) was selected to achieve the desired circumferences at the target test position and the top of the calf (calf circumference). The ankle height (i.e. the target test position) was set to be twice the lateral malleolus height (bump in the ankle).

Section 3 Phantom Material Selection Based on Test Frequency

The hand phantom dielectric parameter requirements are stated in Section 2.2.4 and these requirements are also used for other body phantoms. Currently, a single hand phantom material is not available that meets the dielectric parameters over the 300 MHz to 6 GHz range. Hand phantom materials exist which meet the dielectric parameters for 1) all defined test frequencies below 3 GHz range and 2) all defined test frequencies above 3 GHz. The hand phantom material is also used for forearm phantoms, ankle and chest phantoms

The head phantom dielectric parameter requirements are stated in Section 2.1.3. Currently, a single head phantom material is available that meets the dielectric parameters over the 600 MHz to 6 GHz range. At this time, the head phantom material shall comply with the dielectric parameter requirements for all band/protocols used in a test, even the band/protocols not being directly measured.

The hand phantom material shall always be selected such that its dielectric parameters meet the requirements over the frequency of the band/protocol being measured in any given test. If LTE band 13 (~700 MHz) is being measured in the head and hand or hand only position, then the hand phantom material for below 3 GHz shall be used. If LTE band 48 (3.6 GHz) is being measured in the wrist-worn position, then the hand phantom material for above 3 GHz shall be used.

There are test cases where two or more bands/protocols are operational, however there is always only one band/protocol being measured. For example, in LTE LAA with the PCC in Band 13, one band is at 700 MHz, and the other band is at 5 GHz. For the hand only use case, when the PCC in band 13 is being measured then the below 3 GHz hand phantom material shall be used and when the SCC in band 46 is being measured then the above 3 GHz hand phantom shall be used. In the case where intermediate channel relative sensitivity is being measured, the band/protocol whose sensitivity is being measured is the band/protocol that is used to select the hand phantom material.

While it is known that the use of incorrect dielectric material in the phantoms will affect the radiated performance of interfering RF signals, the impact has been assessed to be tolerable and no additional measurement uncertainty shall be assessed when a phantom with dielectric material, which is not compliant over the frequency band of an interferer, is used to measure another band/protocol for which the dielectric material is compliant.

Hand phantoms (and other solid phantoms) shall be fully compliant across the designated band of operation, which are 300 MHz to 3GHz and 3 GHz to 6 GHz, to be considered suitable for testing.

Section 4 Tissue Equivalent Dielectric Property Measurements (Normative)

This section describes the measurement of the dielectric properties of tissue-equivalent material. The head phantom is either filled with tissue simulating liquid or a solid or gel-like material. The hand is usually based on a carbon-filled silicone rubber material. This appendix intends to provide sufficient details to enable users to perform accurate measurement of the dielectric properties of liquid or solid materials including the corresponding uncertainties.

Besides relative permittivity and conductivity, the carbon-loaded polymer matrix materials used for making hand phantoms have other properties which must be carefully controlled, most notably DC resistance and stiffness. In carbon-loaded materials with increasing carbon concentrations, a point is reached, the percolation point, at which the particles are no longer completely isolated and the DC resistance of the entire macroscopic sample drops suddenly. Measurements of permittivity and conductivity on materials around this carbon concentration are believed to be subject to systematic instabilities and need careful procedures.

An additional issue is that in solids with suspended particles, natural surfaces represent a unique plane, and may contain a much-reduced particle loading compared to any other sectional plane through the solid, where particles will intersect the plane. Cutting such material may result in release of a carbon film that may also strongly affect the measurements.

The open-ended coaxial probe (OCP) technique has demonstrated an acceptable degree of consistency between labs, even around the percolation point. Moreover, the published target dielectric properties for hand materials were derived from open-ended probe measurements on a sample of human hands. The OCP method shall be used for all surface dielectric property measurements. If the transverse electromagnetic (TEM) transmission line technique is used for bulk property measurements, users shall show that their technique agrees with results obtained using the open-ended coaxial probe technique.

General procedures to evaluate dielectric parameter measurement uncertainties are provided in *Section 2.13 of CTIA 01.70* [3].

4.1 Measurement Techniques

This section intends to provide sufficient detail and a test methodology based on the OCP method to enable users to perform dielectric property measurements of hand and head phantom materials. The dielectric parameters to be determined are the complex relative permittivity of the material using the following equation:

Equation 4.1 1

$$\varepsilon_r = \varepsilon'_r - j\sigma/\omega\varepsilon_0$$

It is recommended that with each delivered hand, manufacturers will provide two test samples of the material made from the same mix as the hand, one to be kept by the user, and the other by the manufacturer. The test samples shall be of the correct dimensions, or cast in a TEM line, to lend themselves to a quick check using one of the methods below.

4.2 Open-ended Coaxial Probe (OCP) Method

Gabriel [11] has shown that data obtained on various carbon loaded materials using the open-ended coaxial measurement method encompass the required property range of proposed dielectric target values.

One additional property of the hand materials that must be considered is their rubbery nature, which makes the surfaces readily compressible. The degree to which the coaxial sensor is pressed into the surface of the test sample has a significant effect on the results obtained. Sensors with a nominal diameter of at least 7 mm are to be preferred over smaller ones in this respect.

A cylindrical sample-under-test, such as can be provided by molding inside a 20 ml plastic syringe, alleviates the concern that might exist with a flat block that probe pressure causes the material directly under the probe tip to bow away from contact.

To obtain measurement consistency, the sensor can be supported on a framework that allows measurement at either a fixed contact pressure or at a fixed sensor displacement. In both cases, as contact is increased from a light touch, the dielectric results change, but above a certain critical pressure/ penetration, stable results are obtained. Measurements shall be made in this condition. Investigations indicate that a pressure of around 500 kPa is necessary for this condition to be met, or a displacement of 3 mm. 500 kPa is equivalent to a load of 2 kg on a nominal 7 mm diameter probe.

Measurement at a fixed sensor displacement offers a considerable advantage over the fixed pressure technique by providing, at the same time, a simple measurement of the elastic modulus of the material-under-test. It is the elastic modulus which determines the ultimate stiffness of the molded hand. The NIST website at the link below shows how the deformation of a cylinder of material compressed between two plane surfaces relates to its elastic modulus.

http://emtoolbox.nist.gov/elastic/case10.asp

If, in this setup, the top plane surface is taken as the flat tip of the open-ended probe, and the lower plane is a load cell, the applied load read from the load cell for a fixed deformation relates directly to the material's elastic modulus.

Figure 4.2-1 shows the physical set-up in the case of fixed displacement, and Figure 4.2-2 the equivalent set up for fixed pressure.

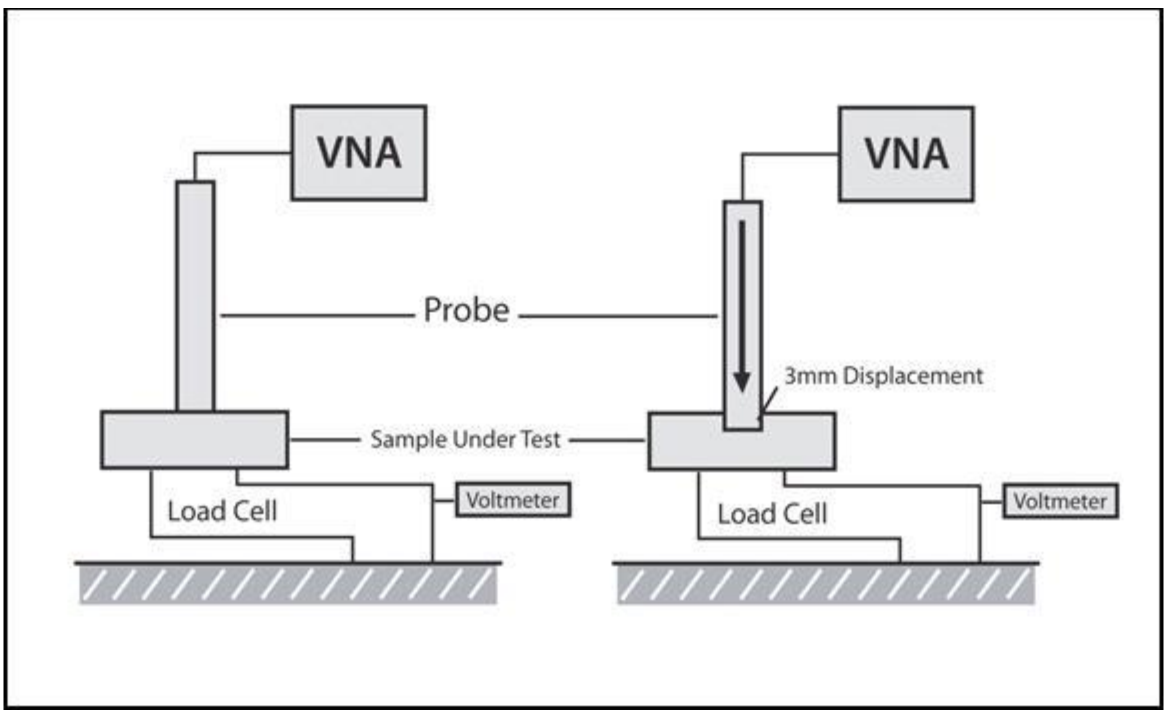

Figure 4.2-1 Setup for Fixed Displacement Measurement

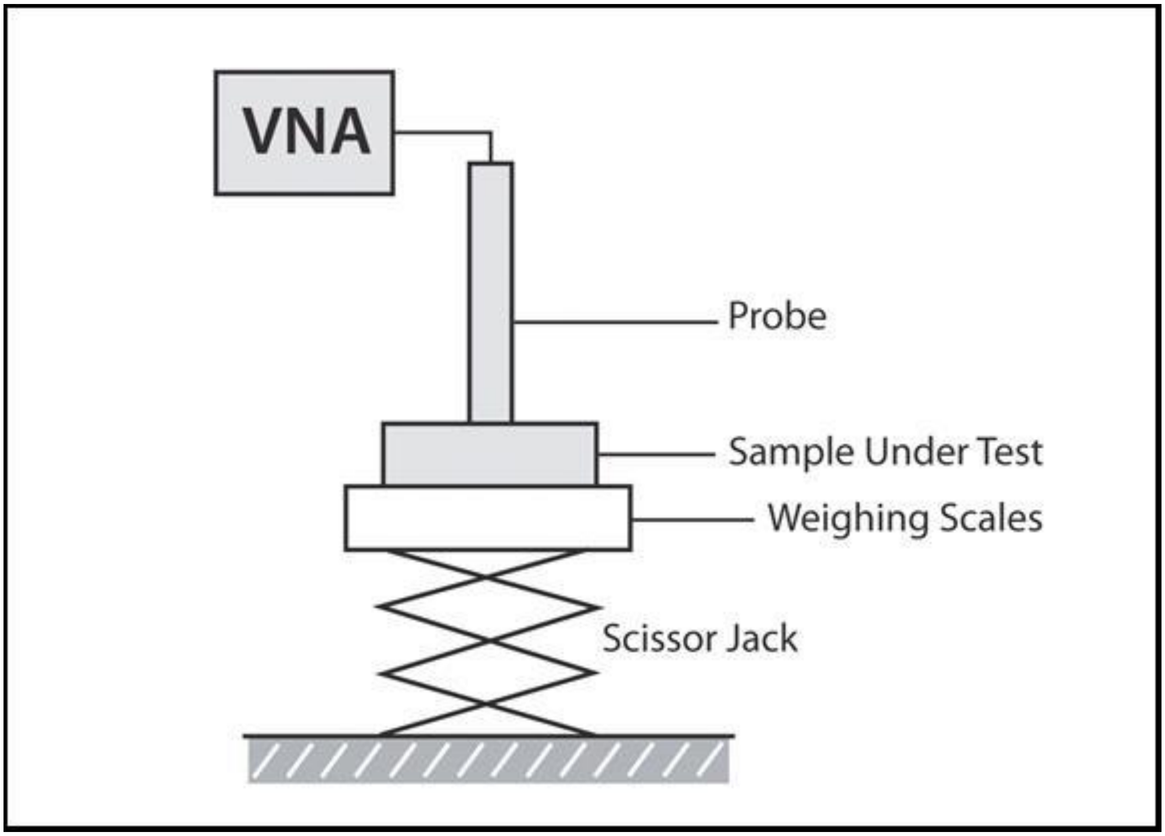

Figure 4.2-2 Setup for Fixed Pressure Measurement

Measurements are made by placing the probe in contact with the sample and measuring the admittance or reflection coefficient with respect to the open-circuit end, using a network analyzer or equivalent instrumentation. To reduce measurement uncertainty, it is recommended that the measurement be repeated at least 10 times at different positions on the test sample, to minimize bias from abnormal readings caused by particulates of the same scale size as the probe dimension.

Test procedures should specify the network analyzer calibration and settings for the required frequency range. The application software should interpret the measured data to yield the dielectric properties of the sample as a function of frequency, together with an estimate of the standard deviation. To use this technique, a probe and a software package for the network analyzer has to be developed or obtained from a commercial source. The methodology should specify the probe size and applicable frequency range.

4.2.1 OCP Equipment Set-up

The equipment consists of a probe connected to one port of a vector network analyzer. The probe is an open-ended coaxial line, as shown in Figure 4.2.1 1. Cylindrical coordinates (ρ, ϕ, z) are used where ρ is the radial distance from the axis, ϕ is the angular displacement around the axis, z is the displacement along the axis, a is the inner conductor radius, and b is the outer conductor inner radius.

Probes having the internal diameter of the outer conductor, 2b, at least 5.5 mm are to be preferred to smaller ones since preliminary findings suggest that a degree of volume averaging occurs in the material under the probe tip. A flange may be included to better represent the infinite ground-plane assumption used in admittance calculations.

The network analyzer is configured to measure the magnitude and phase of the admittance. A one-port reflection calibration is performed at the plane of the probe by placing liquids for which the reflection coefficient can be calculated in contact with the probe. Three standards are needed for the calibration, typically a short circuit, air, and de-ionized water at a well-defined temperature (other reference liquids such as methanol or ethanol may be used for calibration).

Probes with or without flanges may be used. However, care should be taken if using flanged OCPs since “flange resonances” can cause large measurement errors when the diameter of the flange is approximately equal to half a wavelength in the dielectric medium. Such effects are most pronounced for high-permittivity liquids that have a loss tangent less than approximately 0.25 (at mobile phone frequencies these include water, methanol, and dimethyl sulphoxide). Therefore, it is strongly recommended that calibration is performed in a liquid having a high loss tangent, (e.g., ethanol) unless the sensor is immersed in a suitably large volume (e.g. 10 liters) of low loss tangent fluid.

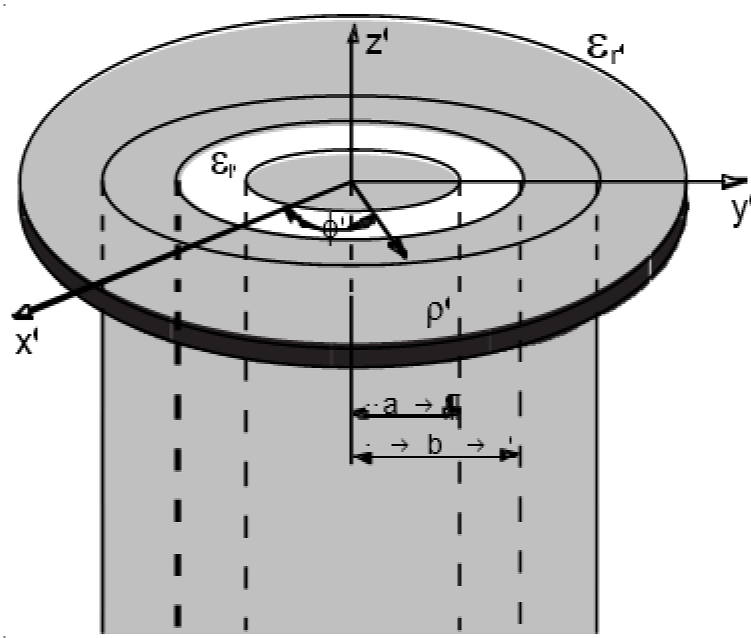

Figure 4.2.1-1 Open-Ended Coaxial Probe with Inner and Outer Radii *a* and *b*, Respectively

a is the inner conductor radius

b is the outer conductor inner radius

ε_r is the absolute permittivity of the medium outside the coaxial line

ε_i is the absolute permittivity of the medium inside the coaxial line

z is the displacement along the axis

ρ is the radial distance from the axis

ϕ is the angular displacement around the z-axis

(x, y, z) are the Cartesian coordinates

The calibration is a key part of the measurement procedure, and it is therefore important to ensure that it has been performed correctly. It can be checked by re-measuring the short circuit to ensure that a reflection coefficient of Γ = -1.0 (linear units) is obtained consistently or by a reference liquid with well known properties. The accuracy of the short-circuit measurement should be verified for each calibration at a number of frequencies. A short circuit can be achieved by gently pressing a piece of aluminum foil against the open end. For best electrical contact, the probe end should be flat and free of oxidation. Larger sensors without flanges generally have better foil short-circuit repeatability.

Measurement devices are commercially available.

4.2.2 Measurement Procedure

1. Configure and calibrate the network analyzer. Measurement uncertainty in the phase of the admittance measured by the OCP can be reduced by ensuring the calibration reference plane is located at the probe tip. This can be done by performing a full 12-term calibration with the probe replaced by an equivalent length of identical transmission line terminated at both ends (see Figure 4.2.2-1).

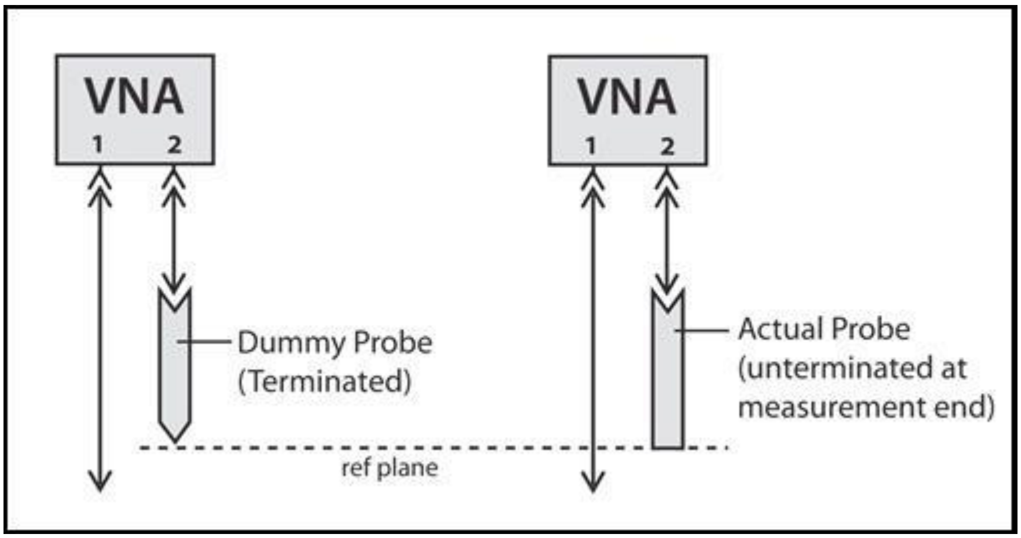

Figure 4.2.2 1 Calibration of VNA Using a Dummy Probe Whose Electrical Length is the Same as the Actual OCP

2. Replace the OCP and calibrate against an open circuit, a short circuit, and a fluid whose electrical properties are known at a reference temperature.
3. Place the sample in the measurement fixture and bring the probe squarely into contact with the surface.
4. Depending on the measurement technique chosen, either depress the probe by a fixed distance, say 3 mm, and measure the change in reading on the load cell, or place the sample on weighing scales and offer the sample up to the probe using a scissor jack until a set change in reading is obtained on the scales.
5. Measure the complex admittance with respect to the probe aperture.
6. Compute the complex relative permittivity per Equation 4.2-1 for example from the below equation.

Equation 4.2-1

$$Y = \frac{j2\omega\varepsilon_r\varepsilon_0}{[\ln(b/a)]^2}\int_a^b\int_a^b\int_0^\pi \cos\phi' \; \frac{\exp\left[-j\omega(\mu_0\varepsilon_r\varepsilon_0)^{1/2}r\right]}{r} d\phi' \; dp' \; dp$$

This expression can be computed numerically or expanded into a series and simplified. The equation is first solved for the sample wave number *k* then the sample complex permittivity, using Newton-Raphson or other iterative approximations. Other numerical approaches may be used provided the application software has been thoroughly tested and checked via measurements of reference liquids. Commercially available OCP kits typically use versions of this theory and method.

4.3 TEM Transmission Line Method

As outlined in the introduction to Section 4, the TEM transmission line method shall only be applied if it has been shown to be equivalent to the OCP method for the carbon loaded dielectric materials. This documentation shall be made available. The TEM transmission line method shall not be used for dielectric measurements of the surface of the hand phantoms.

TEM transmission line method is based on the measurement of the complex transmission coefficient of a TEM-mode coaxial transmission line filled with the test sample. The measurement of transmission coefficient is performed using a vector network analyzer to determine magnitude and phase of the scattering coefficient S_{21}. The measured data is then used to calculate the complex permittivity as a function of frequency.

4.3.1 TEM Equipment Set-up

The measuring set-up is shown in Figure 4.3.1-1. It consists of a vector network analyzer, a temperature sensor and a sample holder. The sample holder is a coaxial transmission line using the TEM dominant mode.

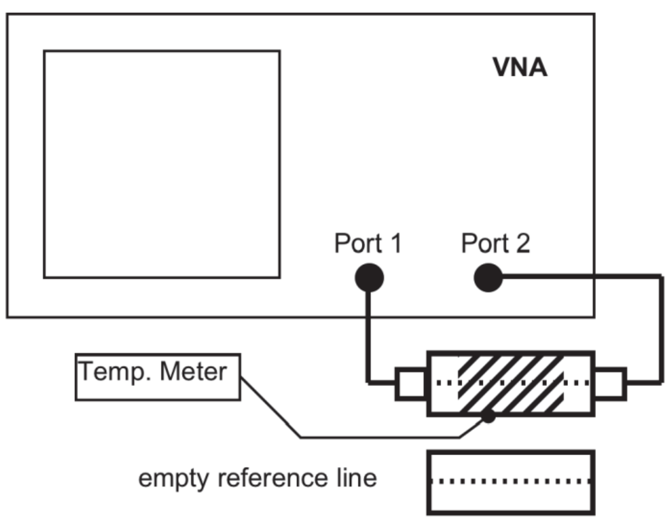

Figure 4.3.1-1 TEM Transmission Line Dielectric Measurement Method Setup

As shown in Figure 4.3.1-2 and Figure 4.3.1-3, the set-up can be implemented using either a cylindrical (coaxial) or a planar (strip-line) geometry, as long as the empty cell is of 50 ohm impedance. The same equations apply for both. The strip-line implementation described by Toropainen has been widely used for liquids measurements. Different lengths of the sensor can be selected for optimum measurements depending upon the lossiness of the materials. A line of between 80-160 mm is suitable for measurement of hand materials.

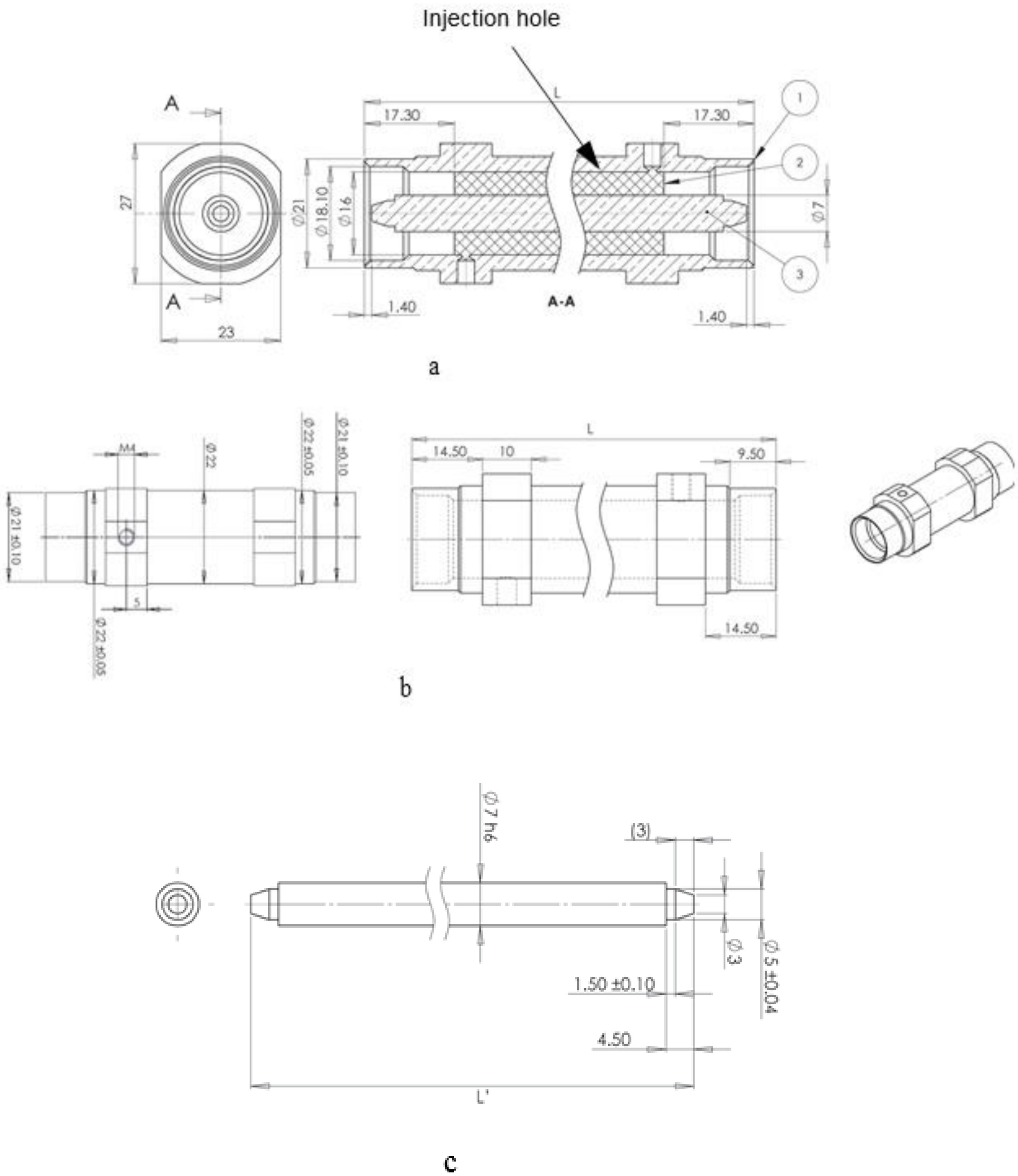

Figure 4.3.1-2 Geometry of the Sample Holder (Dielectric Test Cell, Dimensions In mm)

① is the outer conductor of the coaxial line

② is the injected sample material

③ is the inner conductor of the coaxial line

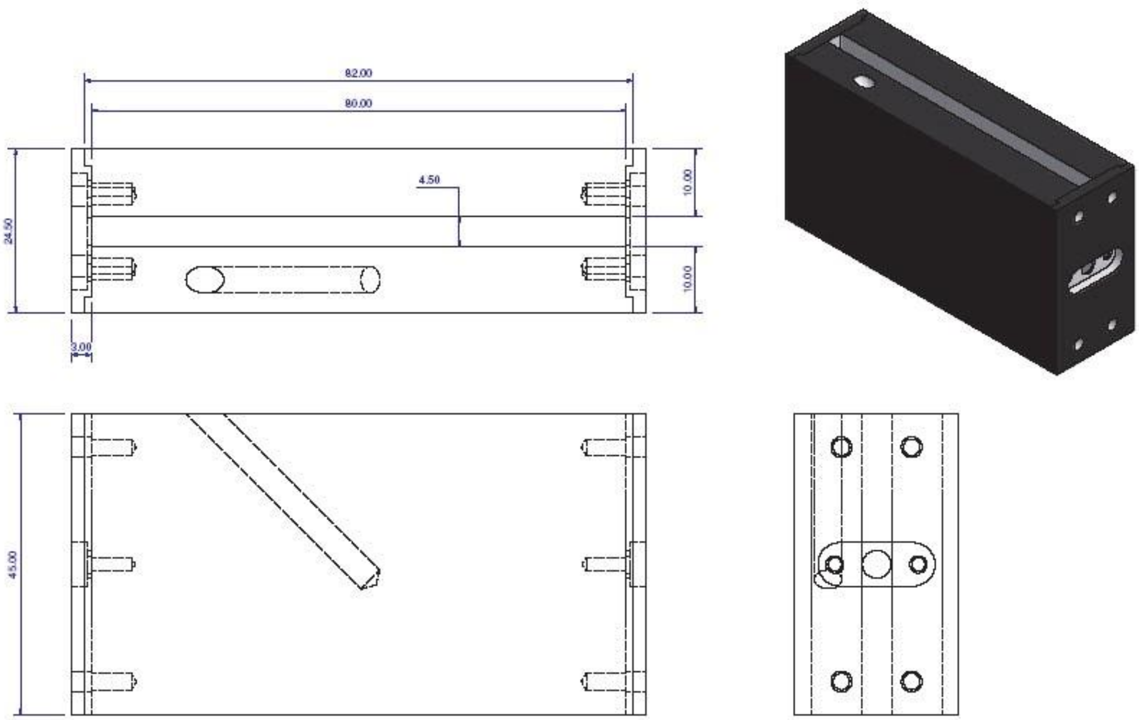

Figure 4.3.1-3 Construction Diagram of Strip-Line TEM Sensor (All Dimensions in mm)

The solution to the equations in section 4.3.2 is not unique and it is possible to obtain the wrong solution if a narrow measurement frequency range is used with materials of unknown composition. Use of a wide frequency range for measurement ensures selection of the appropriate solution.

Neither the strip-line sensor, nor the coaxial implementation proposed in Figure 4.3.1-2 and Figure 4.3.1-3 are particularly convenient for solids material measurements if the cell has to be dismantled to remove the solid sample after use.

The cross section of the sample and the holder is constant. The dimensions are optimized for required frequency range to minimize the effects of higher order modes, have a sufficiently large sample and allow usage of industrially available connectors. The sample length is selected for not exceeding the dynamic range of the analyzer at the highest frequency (100 mm are equivalent to 60 dB attenuation at 3 GHz). The sample to be measured is injected into the cell in vacuumed condition to avoid air bubbles and air gaps. The process of filling and consecutive hardening is equivalent to the production process of the hand phantom. In case of shrinking of the material during the hardening process, the length difference has to be considered in the evaluation. Gaps in the radial direction must be avoided.

4.3.2 Measurement Procedure

1. Configure and calibrate the network analyzer such that the reference planes coincide with the sample holder ports.
2. Record the magnitude and phase of S_{21}^{0} of the empty reference sample holder at the desired frequencies.
3. Connect the holder with the sample material mounted and repeat the measurement to obtain the transmission coefficient with the sample S_{21}^{S}

Calculate the complex permittivity of the sample from the magnitude and phase of S_{21}^{S}/S_{21}^{0} by a solution of the equations.

$$\frac{S_{21}^{S}}{S_{21}^{0}} = \frac{\left(1-\Gamma^{2}\right)\exp[-j(k-\ k_{0})d]}{1-\Gamma^{2}\exp(-j2kd)}$$

$$\Gamma = \frac{1-\sqrt{\varepsilon_{r}}}{1+\sqrt{\varepsilon_{r}}}$$

$$k = \frac{2\pi f}{c_{0}}\sqrt{\varepsilon_{r}}\,, k_{0} = \frac{2\pi f}{c_{0}}$$

where:

Γ is the reflection coefficient at either end of the TEM line (air/material interface);

k is the wave number in the sample;

k_0 is the free-space wave number;

d is the length of the sample in the TEM line;

f is the frequency;

c_0 is the free-space speed of light;

Equation 4.2-1 is the complex relative permittivity of the sample.

The measurement accuracy can be increased by considering the influence of the triple pass wave in the well-known length of the sample.

Appendix A Revision History

Date	Version	Description
February 2022	4.0.0	Initial release of document The following content from Version 3.9.3 of the SISO OTA Test Plan was incorporated: Section 2 • Appendix C: SAM Head and Hand Phantom • Appendix Q: Forearm Phantom Section 3 • Appendix U: Phantom Material Selection Based on Test Frequency Section 4 • Appendix H: Tissue Equivalent Dielectric Property Measurement The following content was added: Section 2 • Chest phantom (Informative)
December 2022	5.0.0	Section 2 • Section 2.5: added ankle phantom (Informative) Section 3 • Added ankle phantom
March 2023	6.0.0	Section 2 • Section 2.2.5: removed old phantom frequency range applicability Section 3 • Added new phantom frequency range applicability
April 2024	7.0.0	No changes this release.
September 2024	8.0.0	Section 2 • Sections 2.4 and 2.5: remove (informative) from the header • Sections 2.3.4, 2.4.4 and 2.5.4: add the word “Dimensions” in the header