NIST Antenna Gain and Polarization Calibration Service Reinstatement

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***Abstract*—After a five-year renovation of the National Institute of Standards and Technology (NIST) Boulder, CO, antenna measurement facility, the Antenna On-Axis Gain and Polarization Measurements Service SKU63100S was reinstated with the Bureau International des Poids et Mesures (BIPM). In addition to an overhaul of the antenna facility, the process of reinstatement involved a comprehensive measurement campaign of multiple international check-standard antennas over multiple frequency bands spanning 8 GHz to 110 GHz. Through the measurement campaign, equivalency with 16 National Metrology Institutes (NMIs) and continuity to several decades of antenna gain values was demonstrated. The renovation process, which included implementing new robotic antenna measurement systems, control software, and data processing tools is discussed. Equivalency results and uncertainties are presented and compared to check-standard historical values.**

I. INTRODUCTION

The on-axis gain and polarization antenna calibration service at the National Institute of Standards and Technology has been reinstated and reopened for calibrations at frequencies from roughly 1 GHz to 500 GHz. For over 4 decades NIST has provided traceable measurements of on-axis antenna gain and polarization using the generalized three-antenna gain extrapolation method described in [1]-[5]. The original NIST antenna calibration facilities that had be used for many decades underwent renovation starting in 2015 and were completed in late 2019. Upon completion of the facilities, an assessment of the antenna service Quality System ensuring ISO 17025 compliance was completed as well as a detailed measurement campaign to re-instate the calibration service internationally with the Bureau International des Poids et Mesures (BIPM). The measurement campaign demonstrated equivalency to 16 other national metrology institutes (NMIs) as well as previous results obtained by NIST (historically known as the National Bureau of Standards (NBS)) through a comparison of several historical antenna check standards spanning a frequency range of 8 GHz to 110 GHz and dating as far back as 1978.

II. ANTENNA SERVICE OVERVIEW

The on-axis gain and polarization antenna calibration service SKU63100S uses two different antenna measurement systems to provide calibrations over a wide frequency range from roughly 1 GHz to 500 GHz. The dual-robotic arm-based Large Antenna Positioning System (LAPS) [6],[7] covers a frequency range of roughly 1 GHz to 50 GHz while the hybrid-robotic Configurable Robotic Millimeter-wave Antenna (CROMMA) [6]-[9] system is optimized for higher frequencies and covers a range of roughly 50 GHz to 500 GHz. Customers can request calibrations through the NIST online store front at https://shop.nist.gov and navigate to the antenna calibration service either by entering ”63100S” or key phrases such as ”antenna-gain and polarization” or just ”antenna” in the search bar on the store front or, navigate the menus in the following order: $\boxed{\text{Calibrations}}$ → $\boxed{\text{Electromagnetic}}$ → $\boxed{\text{Antenna Parameters}}$ → $\boxed{\text{Antenna-Gain and Polarization}}$. For help and general inquiries customers can contact the NIST Calibrations Services by phone at 1-(866)-647-8746 (1-(866)-NIST-Shop) or e-mail at calibrations@nist.gov.

III. RENOVATION OVERVIEW

The renovation of the decades old NIST antenna facilities implements modern anechoic chamber construction and new robot-based antenna range designs which had been under development by the Antenna Metrology Project at NIST, Boulder, CO since 2010. The renovated facility is shown in Figures 1 and 2 soon after installation and with a full absorber treatment respectively. The old NIST antenna facility is shown in Figure 3. At one end it used an ad-hoc antenna positioning system made of stacked rotary and linear motion stages arranged in a roll-over-azimuth configuration and, at the other end, a fixed rotary antenna mount on a vertical slide. These positioners provided up to 7 degrees of freedom for antenna alignment and scanning. In contrast the LAPS system achieves 13 degrees of freedom and CROMMA 12 degrees of freedom through the use of serial robotic arms and parallel kinematic hexapod platforms discussed further below. As a result both LAPS and CROMMA are multi-purpose systems and are capable of executing many kinds of measurements geometries [7]-[11].

A. Anechoic Chamber

The renovated anechoic chamber dimensions are 6.5 m wide by 15 m long by 5.5 m high using modern construction of metal walls with 18 inch radio frequency (RF) absorber throughout the floor and interior surfaces where as the old anechoic chamber was constructed of wooden walls with 12

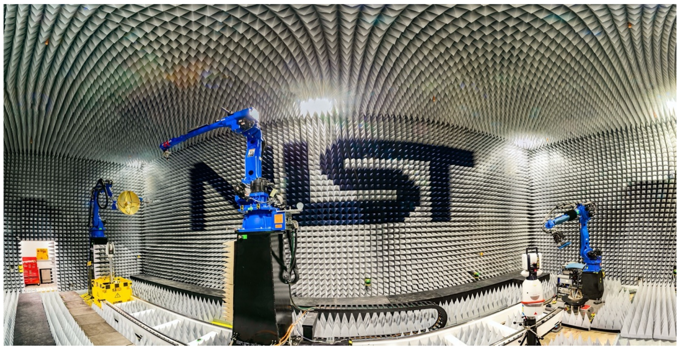

Fig. 1. Renovation after installation new chamber and multi-robotic antenna range at NIST, Boulder, CO.

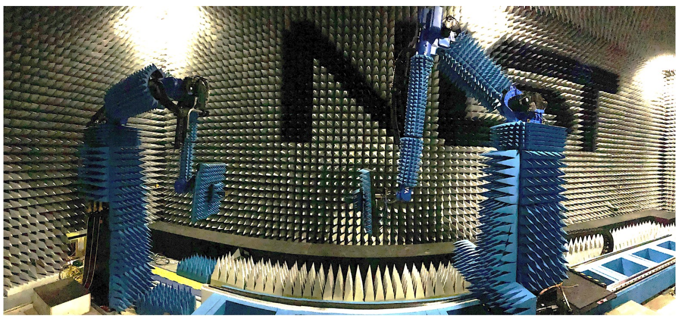

Fig. 2. LAPS dual-robotic antenna range with absorber installed. NIST, Boulder, CO.

inch absorber. The chamber sits on a specialized foundation with pylons extending nearly 60 feet to bedrock which is isolated from the main building foundation and which provides structural stability and vibration isolation. Laser tracker measurements show less than ± 15-μm drift of the floor and robot floor-anchored pedestals over a 72-hour period. Thermal stability is around ± 1.5 °C. The chamber including all inside equipment and exterior control stations are supported by an uninterruptible back-up electrical system providing filtered electrical supplies to mitigate any unforeseen power fluctuations or outages allowing time for controlled system power down. A Very Early Smoke Detection Apparatus (VESDA) and clean agent suppression system protects against fires. In compliance with ANSI/RIA R15.06 / ANSI B11.0 / ANSI B11.19 - "Industrial Robots And Machinery Safety Package" [12], personnel and equipment inside the chamber are safeguarded by four safety laser scanners which constantly monitor for the presence of personnel and equipment relative to robot motion cells. The laser scanners are integrated with all motion equipment providing automatic engineering controls which assures autonomous operation of the LAPS and CROMMA can only be enabled when no person is present or equipment is obstructing robot motion. Shown in Figure 4 is a diagram of the chamber with LAPS and CROMMA systems highlighted by the blue and red ovals respectively.

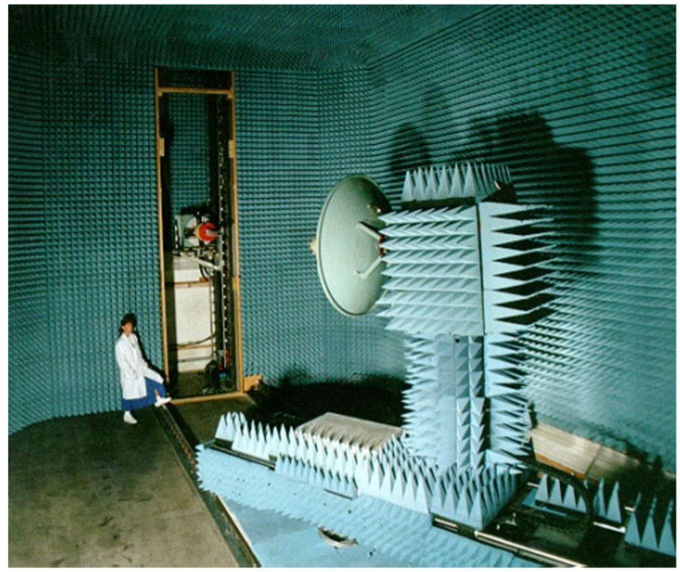

Fig. 3. Original antenna range at NIST, Boulder, CO.

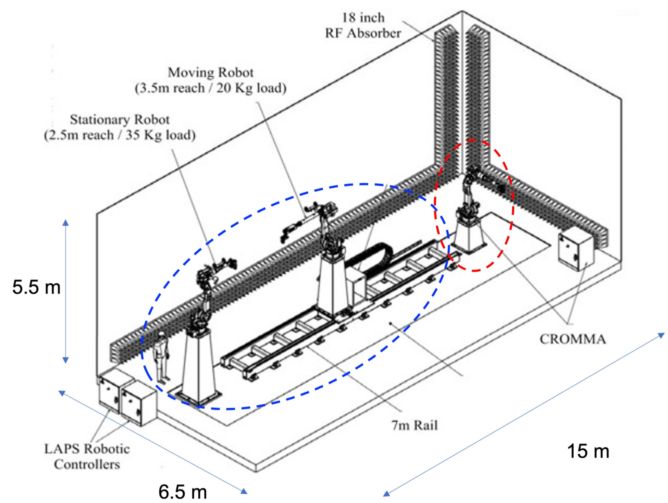

Fig. 4. Diagram of multi-robotic antenna range at NIST, Boulder, CO. The LAPS system is highlighted by the blue oval and the CROMMA is highlighted by the red oval.

B. Measurement System

The LAPS uses high-payload dual six-axis robotic arms and a 7 m long precision linear rail capable of multi-purpose scanning, for a multitude of measurement geometries, include those used in traditional gain extrapolation, polarization, and near-field measurements. At the time of installation the LAPS system was a first-of-its-kind dual-robot-on-rails antenna range design and has been used in other facilities that have recently come on-line [13],[14]. Shown in Figures 1,2,4 the LAPS consists of one six-axis arm robot mounted on the linear rail and a second stationary robot. The robot on rails has a payload capacity of 20 kg and stationary robot has 35 kg payload, both have nominal accuracy of 70 μm. The 4-port vector network analyzer (VNA) based RF system which can be integrated with other components (i.e., waveguides, amplifiers, mixers, attenuators, etc.) supports operation up to 50 GHz. Laser tracker alignment using precision spherical mounted reflectors and 6 degree of freedom targets allow antennas to be precisely and accurately setup for measurement. The use of a coordinate metrology space [15] further enhances antenna alignment workflow. Furthermore antenna poses are stored as variable in the robot controller for streamlined workflows.

The CROMMA is a hybrid-robotic antenna range design [8],[9],[16],[17]. A hybrid of a serial 6-axis arm and parallel 6-axis Stewart-Gough platform (a.k.a hexapod) [18],[19] it's design is optimized for high positional accuracy for millimeter-wave applications over the frequency range of 50 GHz-to-500 GHz. As opposed to LAPS, the CROMMA uses external laser tracker feedback to continuously correct for position of antennas during measurement to an accuracy of 20 μm. As a full discussion of the CROMMA's design is outside the scope of this paper the reader is encouraged to see [9] for more details. The 4-port VNA RF system is augmented with mm-wave frequency extenders to achieve full 2-port measurements from 50 GHz-to-500 GHz.

The robot-based platform of LAPS and CROMMA allows for automation through interfacing to the robot controller via a software development kit where the robots underlying kinematics can be fully exercised and exploited to enhance the precision and accuracy for antenna metrology and optimize measurement plans and workflow. Control software developed by NIST is used to automate measurements and tie to together measurement planing in a coordinate metrology space, robot motion, RF system triggering, and data acquisition.

Data processing software has also been updated where legacy FORTRAN based codes have been replaced by fresh Python based codes. These codes implement the full orders-of-scattering theory developed by David Kerns, Paul Wacker, and Allen Newell [2]-[4] for gain extrapolation measurements, with enhancements for dealing directly with bi-direction S-parameter [20] measurements, to address local-oscillator drift for improved accuracy when frequency extenders are used.

IV. Measurements and Metrological Equivalency

Three sets of antenna check standards that were part of previous intercomparisions [21]-[23] in the WR-90, WR-62 and WR-10 bands were measured with the new NIST facility to establish metrological equivalency to 16 other NMIs dating back to 1978. Table 1 shows the specifications for these antennas. A glossary for each NMI acronym is given in Figures 5. Gain and polarization measurements were performed with the new NIST antenna facility using the three antenna extrapolation method as discussed in [1]-[5]. Figures 6 through 8 show exemplary extrapolation data curves for each pair of check standard antennas at the center frequencies, 10 GHz, 15 GHz, and 95 GHz for each waveguide band along with the fit residuals. The X and Y-axis of these curves are scaled by the distance in the usual way for extrapolation measurements with the $||scaled\ signal||$ values on the Y-axis corresponding to $d|S_{ab}|$ in units of meters and $||scaled\ separation\ distance||$ values on the X-axis in units of $d/(D^2/\lambda)$ where, d is the distance between the two antennas, D is the dimensions of the antenna aperture and λ is the operating wavelength.

Results comparing the measurements obtained with the new NIST antenna facility to historical values are show in Table 2 and 3 below. In Table 2, check standard historical values are listed in the "Gain Reported (dB)" column, and the measured gain obtained with the new NIST facility shown in the "Gain (dB) Measured" column. The values listed in both of these columns are in the form $Gain \pm u$, with "u" being the $k = 2$ expanded uncertainty. Polarization parameters of axial ratio (A.R.), tilt, and sense are reported and compared with historical check standard values in Table 3 in the form $parameter \pm u$ again with u being the $k = 2$ expanded uncertainty. Table 4 gives the uncertainty analysis break down. Equivalency is established by the fact that the measurements made with the new facility agree with the reported historical values to within the uncertainties.

Table 1. Antenna Check Standard Specifications

Serial Number	Frequency Band	Gain (nominal)	Lab Equivalency	Year Organized
SN1	WR-90 (X-Band), 8.2 GHz-12.4 GHz	22 dB	FTZ, TUD, CNET, CSIRO, NPL, VSL, NIST	1978
SN2	WR-90 (X-Band), 8.2 GHz-12.4 GHz	22 dB	FTZ, TUD, CNET, CSIRO, NPL, VSL, NIST	1978
SN3935	WR-62 (Ku-Band), 12.4 GHz-18 GHz	23 dB	NMIA, NIM, CMI, LNE, NMIJ, VNIIFTRI, KRISS, SP, METAS, TUBITAK-UME, NPL, NIST	2008
SN3936	WR-62 (Ku-Band), 12.4 GHz-18 GHz	23dB	NMIA, NIM, CMI, LNE, NMIJ, VNIIFTRI, KRISS, SP, METAS, TUBITAK-UME, NPL, NIST	2008
SN022	WR-10 (W-Band) 75 GHz- 110 GHz	24 dB	KRISS, NPL, NIST	2010
SN025	WR-10 (W-Band) 75 GHz- 110 GHz	24 dB	KRISS, NPL, NIST	2010

NMIA - National Measurement Institute of Australia - Australia
CSIRO – Commonwealth Scientific and Industrial Organization – Australia
NIM – National Institute of Measurements - China
CMI – Czech Metrology Institute – Czech Republic
TUD - Technical University of Denmark – Denmark
LNE – Laboratoire national de metrologie et d'essais - France
CNET - Centre National d'Etudes des Telecommunications – France
FTZ - Fenmeldetechnischen Zentralamt – Germany
NMIJ – National Metrology Institute of Japan – Japan
KRISS – Korea Research Institute of Standards and Science – Korea
VNIIFTRI – Russian Scientific Research Institute of Physico-Technical Measurements - Russia
SP – Technical Research Institute of Sweden – Sweden
METAS – Federal Institute of Metrology – Switzerland
TÜBİTAK-UME – The Scientific and Technological Research Council of Turkey – Turkey
NPL – National Physical Laboratory – United Kingdom
NIST – National Institute of Standards and Technology – United States

Fig. 5. National Metrology Institute acronym glossary.

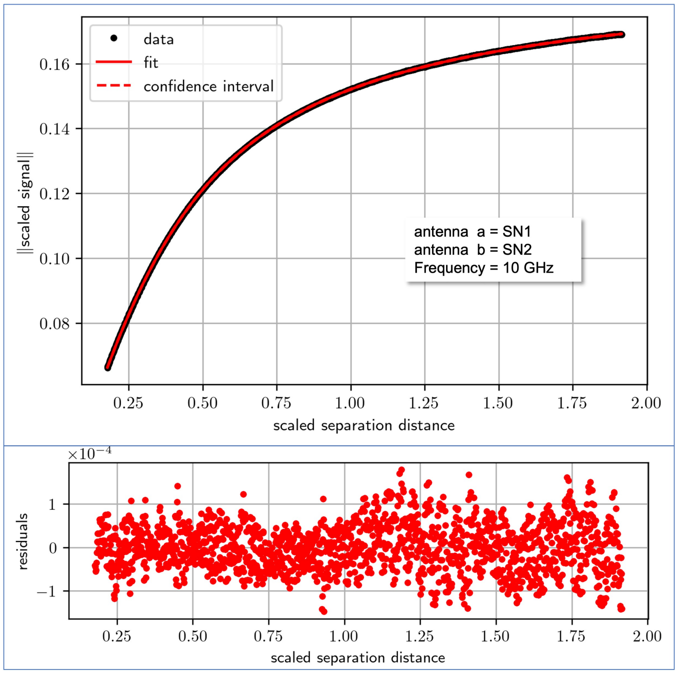

Fig. 6. Extrapolation measurement data and curve fit with residuals at 10 GHz.

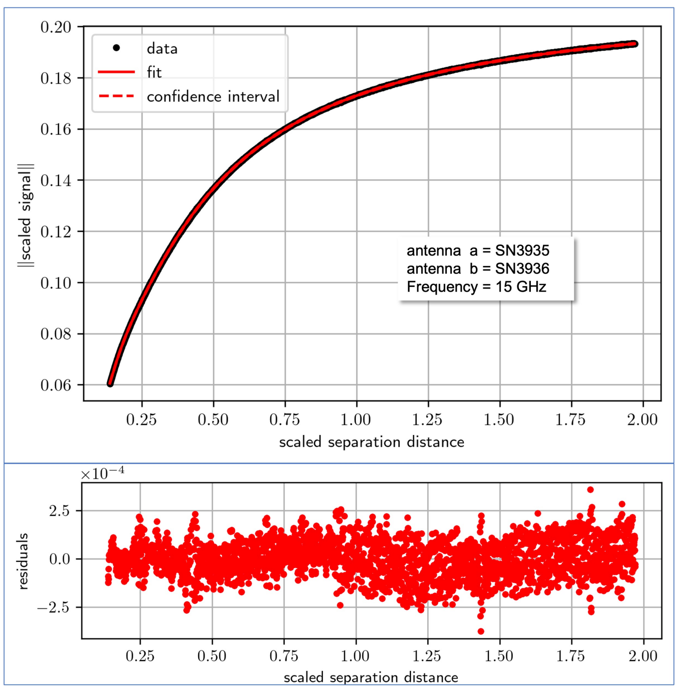

Fig. 7. Extrapolation measurement data and curve fit with residuals at 15 GHz.

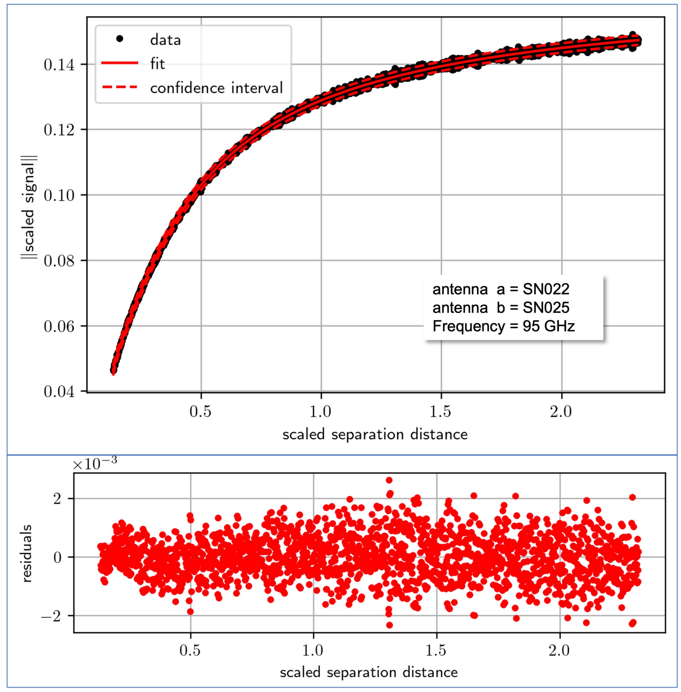

Fig. 8. Extrapolation measurement data and curve fit with residuals at 95 GHz.

Table 2. Antenna Gain Equivalency Values

Antenna Serial No.	Frequency (GHz)	Gain Reported (dB)	Gain Measured (dB)
SN1	8	21.39 ± 0.06	21.33 ± 0.07
SN1	10	22.17 ± 0.06	22.16 ± 0.07
SN1	12	22.61 ± 0.06	22.68 ± 0.07
SN2	8	21.37 ± 0.06	21.31 ± 0.07
SN2	10	22.18 ± 0.06	22.19 ± 0.07
SN2	12	22.58 ± 0.06	22.62 ± 0.07
SN3935	12.4	23.63 ± 0 .1	23.57 ± 0.07
SN3935	15	24.44 ± 0.05	24.41 ± 0.07
SN3935	18	24.86 ± 0.06	24.87 ± 0.07
SN3936	12.4	23.63 ± 0.1	23.56 ± 0.07
SN3936	15	24.45 ± 0.08	24.39 ±0.07
SN3936	18	24.85 ± 0.06	24.86 ± 0.07
SN022	75	22.58 ± 0.1	22.64 ± 0.1
SN022	95	23.46 ± 0.1	23.43 ± 0.1
SN022	110	23.55 ± 0.1	23.50 ± 0.1
SN025	75	22.54 ± 0.1	22.59 ± 0.1
SN025	95	23.42 ± 0.1	23.44 ± 0.1
SN025	110	23.58 ± 0.1	23.63 ± 0.1

V. Conclusion

An overview of the reinstatement of the NIST antenna gain and polarization calibration service (SKU63100S) has been given above. The process of reinstatement which included a major 5 year renovation and modernization of NIST's decades old original antenna range and, a measurement campaign of several historical antenna check standards is described. Metrological equivalency to 16 NMIs through this measurement campaign has been established with the NIST antenna service once again recognized internationally through the BIPM. Customers interested in traceable antenna gain and polarization calibrations through the NIST On-axis Gain and Polarization Service SKU63100 can go to www.shop.nist.gov to request a

Table 3. Antenna Polarization Equivalency Values

Antenna Serial No.	SN1			SN2		
Laboratory	A.R. (dB)	Tilt (degrees)	Sense	A.R. (dB)	Tilt (degrees)	Sense
Frequency 8.0 GHz						
NIST (1980)	60 ±2	90.3 ±0.5	Right	60±2	91.5 ±0.5	Right
NIST(1982)	52 ±2	90.7 ±0.5	Right	51±2	90.5 ±0.5	Right
NIST(1992)	52 ±2	90.9 ±0.25	Right	69±2	90.8 ±0.25	Right
NIST (2022)	60 ±2	91.2 ±0.5	Right	70±2	90.9 ±0.5	Right
Frequency 10.0 GHz						
NIST (1980)	43 ±2	90.4 ±0.5	Right	44 ±2	91.4 ±0.5	Right
NIST(1982)	44 ±2	90.7 ±0.5	Right	45 ±2	90.9 ±0.5	Right
NIST(1992)	44 ±2	90.8 ±0.25	Right	45 ±2	90.8 ±0.25	Right
NIST (2022)	44 ±2	91.4 ±0.5	Right	44 ±2	90.9 ±0.5	Right
TUD	44 ±2	90.9 ±.03	Right	45.3±2	90.8 ±0.03	Right
VSL	47 ± --	--	--	--	--	--
Frequency 12.0 GHz						
NIST (1980)	42±2	90.6 ±0.5	Right	47 ±2	90.8 ±0.5	Right
NIST(1982)	42±2	90.9 ±0.5	Right	47 ±2	90.6 ±0.5	Right
NIST(1992)	42±2	90.7 ±0.25	Right	44 ±2	90.8 ±0.25	Right
NIST (2022)	42±2	91.1 ±0.5	Right	44 ±2	90.7 ±05	Right
TUD	41.8±2	90.8 ±0.03	Right	46.4 ±2	90.7 ±0.03	Right

Table 4. Uncertainty Analysis

Gain Uncertainty Analysis for WR62 & WR90 Antennas: SN1, SN2, SN3935, SN3936		
Sources of Uncertainty for Gain	Probability Distribution	Standard Uncertainty (dB)
Receiver Nonlinearity	Rectangular	0.01
Impedance Mismatch	Rectangular	0.01
Antenna Alignment	Rectangular	0.01
Data Curve Fit	Rectangular	0.02
Connector Repeatability	Normal	0.01
Residual Multipath	Rectangular	0.02
Random Uncertainties	Normal	0.01
Expanded Uncertainty	Normal (k=2)	0.07

Gain Uncertainty Analysis for WR10 Antennas: SN022, SN025		
Sources of Uncertainty for Gain	Probability Distribution	Standard Uncertainty (dB)
Receiver Nonlinearity	Rectangular	0.01
Impedance Mismatch	Rectangular	0.01
Antenna Alignment	Rectangular	0.04
Data Curve Fit	Rectangular	0.02
Connector Repeatability	Normal	0.01
Residual Multipath	Rectangular	0.02
Random Uncertainties	Normal	0.01
Expanded Uncertainty	Normal (k=2)	0.1

Polarization A.R. and Tilt Uncertainty Analysis for WR90 Antennas: SN1 & SN2			
Sources of Uncertainty for Polarization (WR90)	Probability Distribution	Standard Uncertainty	
		Axial Ratio (A.R.) (dB)	Tilt Angle (deg)
Antenna Alignment	Rectangular	1	0.1
Residual Multipath	Rectangular	1	0.15
Data Curve Fit Max and Min Angle	Rectangular	1.5	0.2
Expanded Uncertainty	Normal (k=2)	2.0	0.5

calibration or contact the NIST Calibrations Services by phone at 1-(866)-647-8746 (1-(866)-NIST-Shop) or e-mail at calibrations@nist.gov.

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