Metrology Measurement Capabilities

Federal Manufacturing & Technologies

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METROLOGY MEASUREMENT CAPABILITIES

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OPTICAL AND RADIATION

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Honeywell Federal Manufacturing & Technologies
Metrology Calibration Capabilities

INTRODUCTION

This document contains descriptions of Federal Manufacturing & Technologies (FM&T) Metrology capabilities, traceability flow charts, and the measurement uncertainty of each measurement capability.

Metrology provides NIST traceable precision measurements or equipment calibration for a wide variety of parameters, ranges, and state-of-the-art uncertainties. Metrology laboratories conform to the requirements of the Department of Energy Development and Production Manual Chapter 8.4, ANSI/ISO/IEC ANSI/ISO/IEC 17025:2000, and ANSI/NCSL Z540-1 (equivalent to ISO Guide 25).

FM&T Metrology laboratories are accredited by NVLAP for the parameters, ranges, and uncertainties listed in the specific scope of accreditation under NVLAP Lab code 200108-0. See the Internet at http://ts.nist.gov/ts/htdocs/210/214/scopes/2001080.pdf. These parameters are summarized in the table at the bottom of this introduction.

The Honeywell Federal Manufacturing & Technologies (FM&T) Metrology Department has developed measurement technology and calibration capability in four major fields of measurement:

Mechanical;

Environmental, Gas, Liquid;

Electrical (DC, AC, RF/Microwave); and

Optical and Radiation.

Metrology Engineering provides the expertise to develop measurement capabilities for virtually any type of measurement in the fields listed above.

A strong audit function has been developed to provide a means to evaluate the calibration programs of our suppliers and internal calibration organizations. Evaluation includes measurement audits and technical surveys.

Measurement and Calibration Capabilities

*NVLAP Accredited in these parameters

Dimensional
- Length *
- Coordinate Measuring Machines *
- Coordinate Measurement *
- Angle Measurement *
- Gage Blocks *
- Glass Scales *
- Internal/External Diameters *
- Roundness *
- Spherical Diameter *
- Flatness Measurement *
- Thread Wires *
- Surface Finish Measurement

Angle, Roughness, and Flatness
- Angle *
- Surface Roughness
- Optical Surface Flatness *
- Surface Plate Flatness *

Mass, Force and Torque
- Mass *
- Force *
- Torque

Vibration, Acceleration, Shock, Sound Level
- Vibration *
- Shock *
- Sound Level

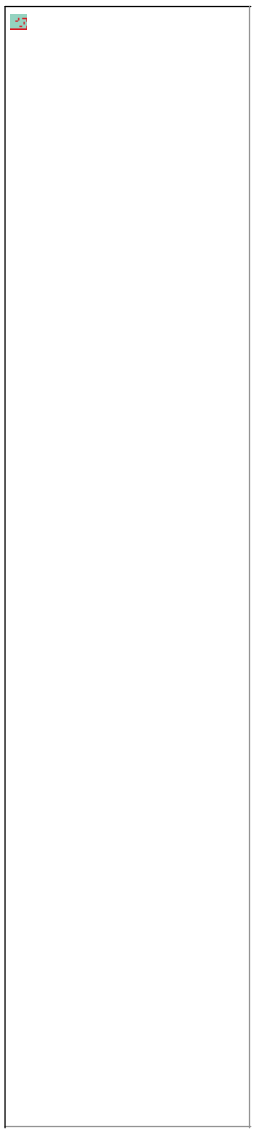
Environmental, Gas, Liquid
- Temperature *
- Fixed Point Temperature *
- Humidity
- Pressure *
- Gas Flow *
- Leak Rate *
- Viscosity

Electrical AC/DC
- AC/DC Voltage *
- AC/DC Current
- AC/DC Resistance *
- Capacitance, Inductance *
- Frequency, Time of Day *
- DC Magnetic Field Density

Electrical RF/Microwave
- Attenuation *
- RF Power *
- RF Reflection Coefficient *
- Network Analyzers

Laboratory Glassware Volume
- Burets
- Volumetric Pipets
- Measuring Pipets
- Volumetric Flasks
- Graduated Cylinders

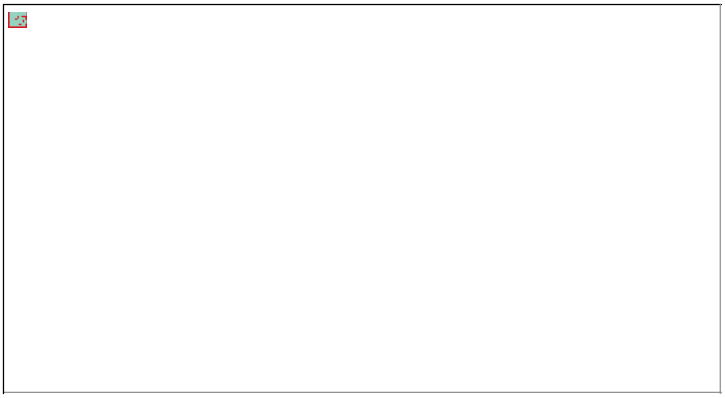
Optical Radiometric, Photometric
- Optical Transmittance
- Optical Spectral Response
- Laser Average Power
- Laser Peak Power
- LED Power
- Ultraviolet Irradiance
- Illuminance
- Monochrometers
- X-Ray Film Density
- Luminous Intensity
- HeNe Laser Frequency, Wavelength *



DIMENSIONAL

Length and Coordinate Measurement

Three-dimensional coordinate standards are measured interferometrically using a helium-neon laser light source. Laser interferometers are mounted on each axis of a three-dimensional coordinate measuring machine. Corrections are made for wavelength variation due to air density by an on-line computer. Uncertainties are listed in the accompanying table. Many length-measuring systems are calibrated using the laser interferometer.



Shelton CMM With CMM Calibration Artifact

Gage Block Measurement

Gage blocks are compared to blocks certified by the Primary Standards Laboratory (PSL) using a gage block comparator.

Roundness Measurement

Roundness measurements are made using a roundness machine with an air-bearing spindle. Spindle error and high accuracy roundness measurements are made using a reversal technique that separates spindle error from roundness error.

Flatness Measurement

Flatness of small surfaces is measured directly using an optical flat or an optical interferometer. Reference optical flats are calibrated using the three-flat method and a polychromatic fringe viewer.

Surface plate flatness is measured using an autocollimator and two mirrors. The flatness of the surface plate is determined using both the Moody method and a three-dimensional least squares technique.

Angle Measurement

Small angles are measured using an autocollimator. The autocollimator is calibrated using a small-angle generator consisting of a pivot arm of known length and a set of certified gage

blocks.

Large angles are measured using an autocollimator, a rotary table, an optical polygon, and angle gage blocks.

Surface Finish Measurement

Surface finish standards are measured using a profile-type surface finish analyzer. The surface finish analyzer is calibrated using a lever arm calibrator and roughness standards calibrated by NIST.

CMM With Video Edge Detection System

Dimensional Measurement Capability

Type	*Range*	*Measuring Uncertainty (?) k=2*
Gage Blocks	To 4 in.	2.5 min. + 0.44 ppm
	> 4 to 20 in.	5.4 min. + 0.49 ppm
Coordinate Measurement *	Axial	10 min + 0.5 ppm
	Planar **	75 min. + 1 ppm
	Spatial ***	75 min. + 12 ppm
1-D Ball Plates	To 48 in.	20 min + 1.0 ppm.
2-D Ball Plates	36 in. by 36 in.	20 min + 1.0 ppm.
Step Gages	To 24 in.	20 min + 1.0 ppm.
Internal Diameters	0.04 to 1 in. 1 to 2 in. 2 to 14 in.	9 min. 10 min. Determined by Test.
Single Axis Glass Line Scales	0 to 2 in. > 2 to 12 in.	18 min. 32 min.
Spherical Diameter	0 to 1 in. 1 to 2 in.	12 min. 13 min.
Cylindrical Plug Gages	0 to 1 in.	7.3 min.
Squares	To 24 in. by 36 in.	30 min.
Straight Edges	To 48 in.	5 min.
Roundness	To 18-in. diameter	3 min.
Thread Wires	All standard pitches	8 min.

* Maximum range of length-coordinate measurement is x = 48 in., y = 36 in., and z = 12 in.

** Certain artifacts, such as ball plates, can be designed in such a way to allow the use of a single-axis calibration technique. The technique requires the balls to be located in an orderly array with one ball located in the center. Artifacts of this design can be certified to
±(20 min + 1.0 ppm).

*** 18 in. by 12 in. by 12 in. volume.

Dimensional Calibration Traceability

Dimensional Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
D1	Standard Gage Blocks	Do All	To 4 in.	1.6 µin. + 0.6 ppm
		Pratt & Whitney	5 to 20 in.	6 µin. + 0.5 ppm
D2	Gage Block Comparators	Link	0 to 2 in.	3 µin.
		Federal	0 to 4 in.	3 µin.
		Pratt & Whitney	0 to 20 in.	3 µin.
D3	Transfer Standard Gage Blocks	Do All	To 4 in.	2.5 µin. + 0.4 ppm
		Pratt & Whitney	5 to 20 in.	5.4 µin. + 0.5 ppm
D4	Lever Arm Calibrator	FM&T Metrology	0 to 0.0002 in	0.25 µin. + 0.5% of travel
		Mitutoyo	0 to 0.05 in.	10 µin. + 0.1% of travel
D5	Measuring Machine	Pratt & Whitney	0 to 14 in.	3 µin. + 2 ppm
D6	Standard Gaging Balls	AA Industries	1/16 to 1 in. (1/32-in. increments)	6 µin.
D7	Interference Microscope	Zeiss	0 to 0.01 in.	1 µin.
D8	Laser Interferometer	Hewlett-Packard	NA	0.05 ppm
D9	Measuring Machine	Pratt & Whitney	1 in.	10 µin.
D10	Measuring Machine	FM&T Metrology	0 to 2 in.	8 µin.
D11	Standard Plug Gages	Lincoln	0.050 to 1 in.	4.6 µin.
D12	Coordinate Measuring Machine	SIP/FM&T Metrology	0 to 16 in	Included in Line Scale Process
D13	Roundness Measuring Machine	Bendix A & M	18-in. diameter	3 µin.
D14 *	Coordinate Measuring Machine	Shelton	x axis	10 µin. + 0.5 ppm
			y axis	10 µin. + 0.5 ppm
			z axis	30 µin. + 0.5 ppm
			x-y plane**	71 µin. + 0.6 ppm

* Maximum range: x = 48 in., y = 36 in., z = 12 in.

** Certain artifacts, such as ball plates, can be designed in such a way to allow the use of a single-axis calibration technique. This requires the balls to be located in an orderly array with one ball located in the center. Artifacts of this design can be certified to ±(20 µin + 1.0 ppm.).

Angle, Roughness, and Flatness Measurement Capability

Type	*Range*	*Measuring Uncertainty (?) (k=2)*
Angle (Polygon/Index Table)	0 to 360°	0.6 arc second
Angle Blocks	To 45?	1.1 arc second
Autocollimators	0 to 600 arc seconds	0.3 arc second + 0.25%
Surface Roughness	0.024 in. (Peak-to-Peak)	0.4 + 1.2% of Reading (in min. Ra)
Optical Surface Flatness	To 12-in. diameter	1.2 min. (Three Flat Method) 2 min. (Interferometer) 4 min. (Direct Comparison)
Surface Plate Flatness	Up to 8 ft Diagonal	30 min. + 2 min./ft^2

Angle, Roughness, Flatness Traceability

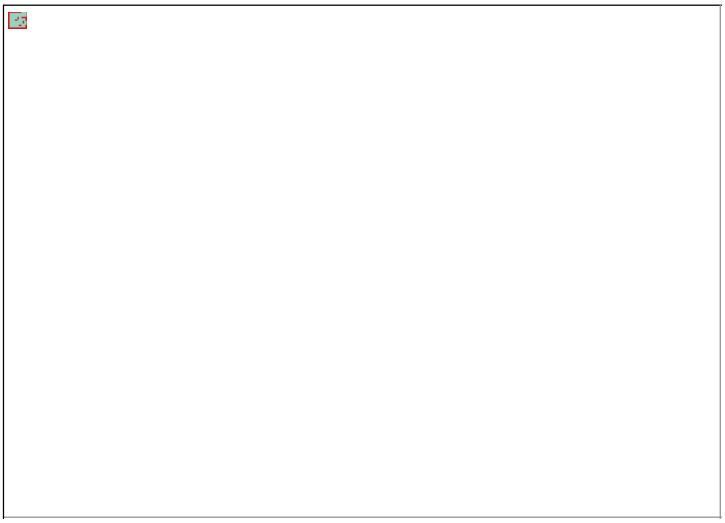
Angle, Roughness, and Flatness Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (?) (k=2)*
ARF1	Standard Angle Gage Blocks	Webber	1 arc second to 45? (16 blocks)	0.7 arc second
ARF2	Small Angle Generator	Matrix	10 arc minutes	0.1 arc second
ARF3	Autocollimator	Davidson	10 arc seconds	0.15 arc second
		Nikon	20 arc minutes	0.3 arc second + 0.25% of measured angle
		Hilger Watts	10 arc minutes	0.5 arc second = 0.25% of measured angle
ARF4	Comparison Autocollimator	Davidson	120 arc seconds	0.3 arc second + 0.5% of measured angle
ARF5	Surface Analyzer	Federal/Metrex	0.024 in. (peak to peak)	(0.4 +1.2% of reading) min. R_a
ARF6	Surface Roughness Standard	NIST	120 min. R_a 39.5 min. R_a 12.7 min. R_a	1.7 min. R_a 0.59 min. R_a 0.31 min. R_a
ARF7	Lever-Arm Calibrator	FM&T Metrology	0 to 0.0002 in.	0.2 min. +0.5% of travel
ARF8	Interference Microscope	Zeiss	0 to 0.01 in.	1 min.
ARF9	Plano Interferometer	Davidson	2 3/4-in. diameter	2 min.
ARF10	Standard Optical Flats (set of 3)	Do All	12-in. diameter	Flat within 4 min.
ARF11	Polychromatic Interference Fringe Viewer	Strang	NA	1 min.

MASS, FORCE, AND TORQUE AND VOLUMETRIC

Mass Measurement

Mass measurements are made by comparison to master weights or by direct weighing using eleven precision balances. The master weights are calibrated through the NIST Mass Measurement Assurance Program. Metrology also has the capability to perform extremely precise weighing on 1-2-3-5 decade progressions over the range from 1 mg to 5 kg.



Force Measurement

Force transducers up to 2400-lbf capacity are measured using weight sets or dead weight testers, which are certified in force units in our Mass lab. Larger force devices are measured by comparison to NIST-calibrated proving rings using a universal force tester.

Proving Ring Calibration

Dead Weight Force Calibration

Torque Measurement

Torque transducers are measured using weights, which are certified in force units in our Mass lab and lever arms of known length. The lever arms are calibrated on a coordinate measuring machine using a helium-neon laser as a standard.

Type	*Range*	*Measuring Uncertainty (±) (k=2)*

Laboratory Glassware Volume

Laboratory glassware volume is measured by the gravimetric method using precision balances and distilled water.

Laboratory Glassware Volumetric Measurement Capability

Type	*Range*	*Measuring Uncertainty (±) (k=2)*
Laboratory Glassware Volume		
Burets		
Volumetric Pipets	10 to 100 mL	NIST or ASTM Class A, B
Measuring Pipets	0.5 to 100 mL	NIST or ASTM Class A, B
Volumetric Flasks	1 to 30 mL	NIST or ASTM Class A, B
	1 to 5000 mL	NIST Class A, B
Graduated Cylinders	5 to 2000 mL	ASTM Class A, B
	5 to 2000 mL	NIST or ASTM Class A, B

Mass, Force, and Torque Traceability

Mass, Force, and Torque Standards

Code	Description	Manufacturer	Range	Uncertainty (?) (k=2)
MF1	Mass Standards	Troemner, Rice Lake	1 mg to 100 g	0.00027 to 0.018 mg
		Troemner	200 g to 20000 g	0.024 to 20 mg
		Troemner	1 lb to 50 lb	2 ppm
MF2	Proving Rings	Morehouse	3000 to 100,000 lbf	0.015 to 0.017% of range
			300,000 lbf	0.03% of range
MF3	Reference Load Cell	BLH	500,000 lbf	500 lbf
MF4	Transfer Load Cells	Various	0 to 240,000 lbf	0.05% F.S. + 0.1% load
MF5	Balances	Mettler Toledo	0 to 6.1 g	Comparison
	(uncertainties listed are for direct weighing)	Mettler Toledo	0 to 22 g	5 ppm + 0.01 mg
		Mettler Toledo	0 to 111 g	Comparision
		Mettler Toledo	0 to 205 g	3 ppm + 0.1 mg
		Mettler Toledo	0 to 1109 g	Comparison
		Mettler Toledo	0 to 2300 g	5 ppm
		Mettler Toledo	0 to 10100 g	1 ppm + 5 mg
		Mettler Toledo	0 to 52000 g	7 ppm + 40 mg
		Mettler	0 to 1000 g	3 ppm + 0.5 mg
		Mettler	0 to 5000 g	3 ppm + 11 mg
		Mettler	0 to 60 kg	2 g
MF6	Dead Weight Calibrating Machine	Morehouse (modified)	5 to 300 lbf	0.01% of reading
	Dead Weight Calibrating Machine	FM&T Metrology	50 to 2400 lbf	0.01% of reading
MF7	Torque Standard	FM&T Metrology	0 to 700 lbf-ft	0.125 to 0.2% of reading
MF9	Transfer Torque Standard	Norbar	0 to 700 lbf-ft	0.15% of range + 0.75% of reading

Vibration

Standard accelerometers are calibrated at NIST and certified for the transfer of its sensitivity to the Vibration Systems transfer standard accelerometer. The vibration system transfers the sensitivity to other accelerometers. Sensitivity can be determined at ambient temperature or over the range of –70 to +125°C. A control standard is measured on the vibration system to verify that the system is functioning properly.

Vibration Calibration System with Environmental Capability

Mechanical Shock

The shock standard accelerometer and accelerometers calibrated for shock levels above 10,000 g's are calibrated using a velocity change shock pulse generator. The area of the shock pulse and the time of flight through a known distance are captured to calculate the sensitivity using the velocity change method. Accelerometers calibrated for shock less than 10,000 g's are calibrated in a back-to-back configuration on a hammer-activated shock pulse generator by comparison to the shock standard accelerometer.

Sound Level

Calibration of sound level is made by comparison of a sound level meter to a standard pistonphone that is calibrated at NIST.

Velocity Change Shock Pulse Generator

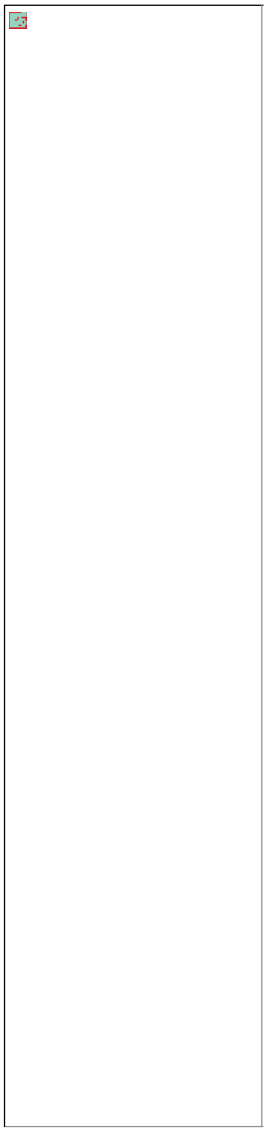
Vibration, Acceleration, Shock, Sound Level Measurement Capability

Type	*Range*	*Measuring Uncertainty (?) (k=2)*
Vibration	0.3 to 75 g at 10 Hz to 10 kHz at ambient temperature	1.8 to 2.5%
	10 g at 100 Hz to 10 kHz at -65 to +125°C	1.8 to 4.0%
Shock	100 to 25,000 g at 0.05 to 10 ms	2.5 to 3.0%
	>25,000 g <0.2 ms	Capability
Sound Level	94 to 124 dB at 250 Hz	0.5 dB

Vibration, Shock, Sound Level Traceability

Vibration, Acceleration, and Shock Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (?) (k=2)*
SVA1	Vibration Accelerometer Reference	Endevco	0.3 to 10 g 10 Hz to 10 kHz	1 to 2%
SVA2	Vibration Accelerometer Transfer Standard	Unholtz Dickie	0.3 to 10 g 10 Hz to 10 kHz	1.8 to 2.5%
SVA3	Vibration System	FM&T	0.3 to 75 g 10 Hz to 10 kHz	Used only with other calibrated measuring standards
SVA4	Shock Accelerometer Standard	Endevco	10 to 10,000 g	3%
SVA5	Back to Back Shock System	FM&T Metrology	100 to 10,000 g	Used only with other calibrated measuring standards
SVA6	Velocity Change Shock System	FM&T Metrology	500 to >25,000 g	2.5 to 3.0%
SVA7	Time Interval Counter	Stanford Research Systems	100 msec to 10 sec	0.05% of reading
SVA8	Coordinate Measuring Machine	Brown & Sharp	0 to 0.5 in.	±0.0003 in. from nominal
SVA9	Standard Pistonphone	B and K	124 dB at 250 Hz	0.25 dB
SVA10	Capacitance Meter	Data Precision	to 1 mF	0.1% of reading + 1 digit
SVA11	Temperature Indicators	Keithley	-65?C to +125?C	1?C



TEMPERATURE, HUMIDITY

Temperature

Temperature measurements in Metrology are based both on the International Temperature Scale of 1990 (ITS-90) and the International Practical Temperature Scale of 1968 (IPTS-68). IPTS-68 capabilities will be maintained as long as older equipment is used. There are three primary standards at FM&T for temperature calibration: fixed point cells, the standard platinum resistance thermometer (SPRT), and the platinum/10% rhodium versus platinum thermocouple (type S).

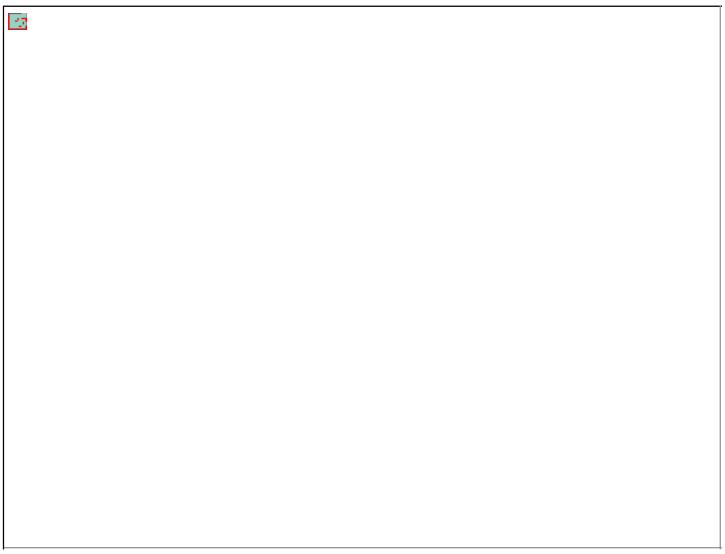
SPRT Calibration Using a Fixed Point Temperature Cell

The SPRT covers the range from -180 to 500°C and is certified to an accuracy of ±(0.01 to 0.05°C). The type S thermocouple covers the range from 0 to 1450°C and is certified to an accuracy of ±(0.5°C or 0.2% of reading), whichever is greater.

Temperature environments for calibrations are created with two stirred baths, a horizontal tube furnace, and fixed point temperature cells. The first stirred bath contains Fluorinert and covers the range from -100 to +140°F. The second bath contains silicon oil and covers the range from 70 to 500°F. Both baths are used to calibrate thermocouples, SPRTs, thermistors, liquid-in-glass thermometers, and some solid state sensors. The horizontal tube furnace covers the range from 73 to 2700°F and is used to calibrate different types of thermocouples in air. Fixed-point temperature cells make possible very accurate single point temperature measurements for SPRTs and thermocouples. These cells are (temperatures in ITS-90 scale) Mercury (-38.8344°C), Water (0.01°C), Gallium (29.7646°C), Indium (156.5985°C), Tin (231.928°C), and Zinc (419.527°C).

Humidity

Humidity calibrations are performed with two instruments. The first is a frost point generator capable of generating frost points from -75°C to 0°C ±0.5°C. The second is a two-pressure system that can generate humidity from 5% to 95% RH ±0.5% RH.



Humidity Calibration Using the Two-Pressure Method

The dew/frost point temperature and the ambient air temperature of the moist air are measured to determine absolute and relative humidity. Air flow through the test chamber can be varied from 0 to 140 slpm.

Temperature, Humidity Measurement Capability

Type	*Range*	*Measuring Uncertainty (?) (k=2)*
Temperature	-183?C to +420?C 420?C to 1093?C	0.005?C to 0.02?C 0.4% of reading
Fixed Point	-38.8344?C 0.01?C 29.7646?C 156.5985?C 231.928?C 419.527?C	0.001?C 0.0005?C 0.0005?C 0.001?C 0.002?C 0.002?C
Humidity	-75?C to 0.0?C 5% RH to 95% RH	0.5?C 0.5% RH

Temperature, Humidity Calibration Traceability

Temperature, Humidity Standards

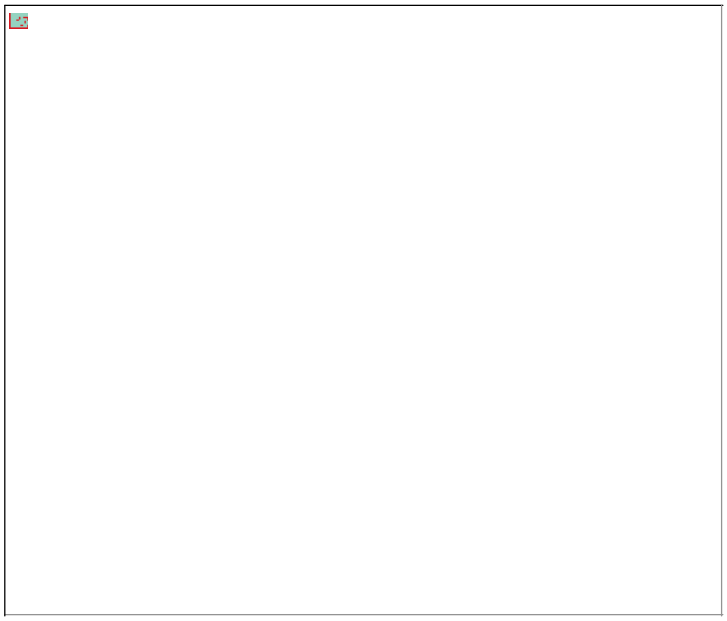
Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (?) (k=2)*
TH1	Standard Platinum Resistance Thermometer	Leeds & Northrup	-186 to 0?C -40 to 420?C	0.02?C 0.005?C
TH2	Platinum - Platinum 10% Rhodium Thermocouple	Leeds & Northrup	0 to 1450?C	0.5?C or 0.2% of reading (whichever is greater)
TH3	Fixed Temperature Points			
	Mercury	Isotech	-38.8344?C	0.001?C
	TP Water	Jarrett	0.01?C	0.0005?C
	Gallium	Isotech	29.7646?C	0.0005?C
	Indium	Hart Scientific	156.5985?C	0.001?C
	Tin	Isotech	231.928?C	0.002?C
	Zinc	Hart Scientific	419.527?C	0.002?
TH4	Frost Point Generator	Thunder Scientific	-70 to 0?C	0.5?C
	Two-Pressure Generator	Thunder Scientific	5 to 95% RH	0.5% RH
TH7	Resistance Ratio Bridge	ASL	0 to 1.2	5 ppm
TH8	DVM	Keithley	0 to 1000 Vdc	0.015% of reading + 4 digits

GAS, LIQUID

Pressure

Pressure gages are calibrated using dead-weight piston gages. The effective area of the 0 to 500 psi reference is determined by NIST. The effective area of the 0 to 15,000 psi reference is determined by PSL. The effective area of the 0 to 100,000 psi reference is determined at FM&T with NIST traceable standards. True mass for each reference is determined using the NIST Mass MAP program.

30,000 psig Gas Pressure Calibration



Pressure Calibration Using Controlled Clearance Dead-Weight Piston Gage

Vacuum

Vacuum calibrations at or below 10^{-3} mmHg are performed using a molecular drag gage, sometimes called a spinning rotor gage (SRG). The SRG is calibrated by NIST. Orfice ratioing is used to achieve calibrations below 5×10^{-6} Torr with an SRG.

Vacuum calibrations above $5x10^{-3}$ mmHg are performed using either a capacitance manometer or digital Quartz manometer, depending upon the range of the gage. The manometers are calibrated using a PSL-certified dead weight piston gage.

Vacuum Gage Calibration

Air Velocity

Air velocity meters are calibrated using a certified wind tunnel. The wind tunnel is calibrated using NIST-certified hot wire anemometer and pitot tube.

Air Velocity Calibration

Gas Leaks

Gas leak devices are calibrated by making direct comparisons to PSL-certified leaks on a mass spectrometer or using the pressure, volume, temperature (PVT) technique. All measurement parameters of the PVT technique are certified and NIST traceable. A precision gas analyzer is used to evaluate the composition of the leak gas.

Standard Leak Calibration

Gas Flow

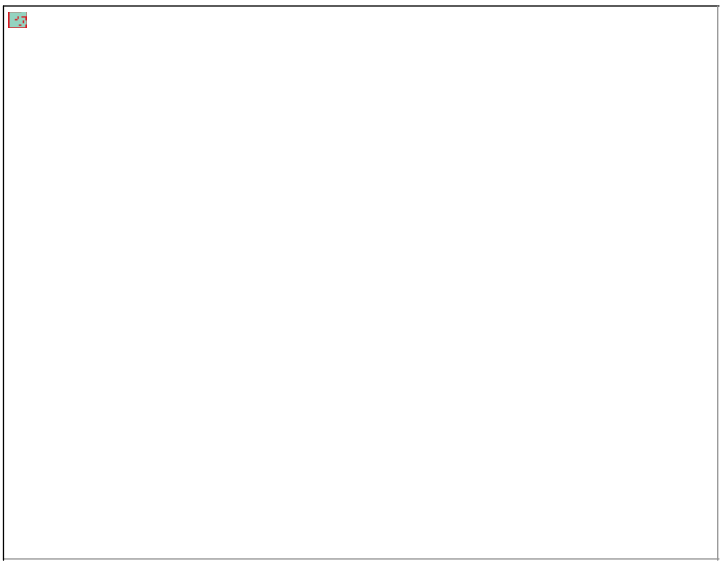
Gas flowmeters are calibrated by direct comparisons to PSL-certified flow meters or volumetric displacement devices. Volume, time, pressure, and temperature measurements are combined to obtain a value of flow. All measurement parameters are certified and NIST traceable.

Viscosity

Viscometers are calibrated using standard viscosity oils obtained from the Cannon Instrument Company, an approved CCL source.

Gas, Liquid Measurement Capability

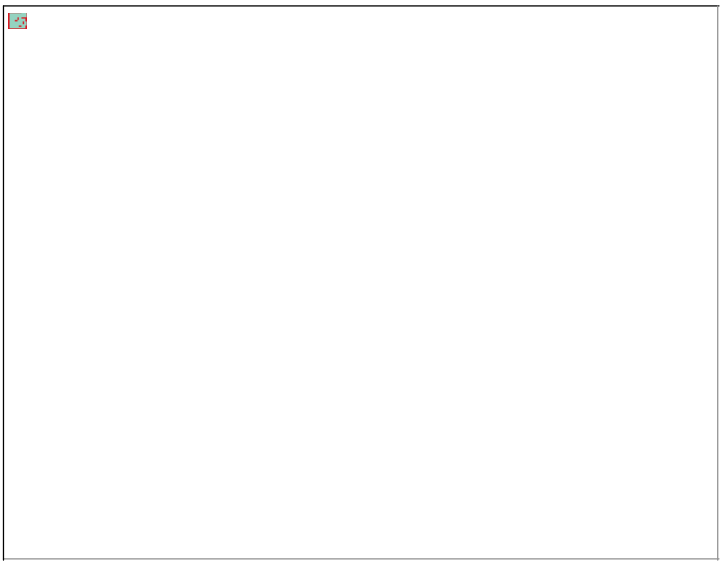
Type	*Range*	*Uncertainty (?) (k=2)*
Pressure	Absolute 10^{-8} to 10^{-4} Torr 10^{-3} to 0.05 Torr 1 to 10 Torr 10 to 1100 Torr 0 to 30 psia Gage 0.5 to 1800 psig 600 to 15,000 psig 15,000 to 100,000 psig	 10% (0.0003 + 0.005 x reading) Torr (0.0005 + 0.003 x reading) Torr (0.03 + 0.0002 x reading) Torr (0.01 + 0.0002 x reading) psi 0.025% 0.05% 0.05%
Air Velocity	30 to 250 sfpm 251 to 1500 sfpm 1501 to 9500	4.5 sfpm + 1% of Reading 6.0 + 1% of Reading 30 sfpm + 2% of Reading
Gas Flow	1 to 100,000 sccm 50 to 1800 slpm	1% 2%
Leak Rate	1×10^{-1} to 5×10^{-9} standard cm^3/s STP 10^{-10} standard cm^3/s STP	5 to 15% 25%
Viscosity	0.3 to 5,300,000 mPa·s	2.5 to 5%



Pressure Calibration Calibration Traceability

Pressure Standards

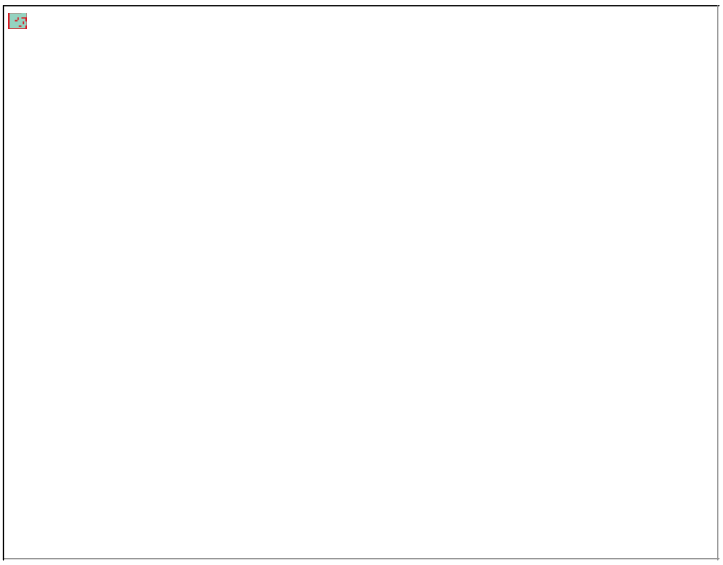
Code	Description	Manufacturer	Range	Uncertainty (?) (k=2)
P1	Piston Gage	CEC	0.2 to 600 psi	0.015%
			0 to 30 PSID	0.15%
		DH Instruments	20 to 1800 psi	0.015%
P2	Piston Gages	Ruska	30 to 15,000 psig	0.03%
P3	Molecular Drag Gage	MKS	10^{-8} Torr	8%
			10^{-7} Torr	8%
			10^{-6} Torr	8%
			10^{-5} Torr	4%
			10^{-4} Torr	3%
			10^{-3} Torr	3%
			10^{-2} Torr	3%
P4	Digital Quartz	Paroscientific	0.1 to 1100 Torr	(0.02 + 0.0001 x Reading) Torr
				(0.004 + 0.0001 x Reading) psi
P5	Capacitance Manometer (Differential)	MKS	10^{-3} to 0.05 Torr	0.0005 Torr
			0.05 to 1 Torr	0.001 Torr or 0.0075 x Reading whichever is greater
			1 to 1000 Torr	(0.01 + 0.00015 x Reading) Torr
P6	Controlled-Clearance DWPG	Harwood	5000 to 100,000 psi	0.03% of Reading
P7	Capacitance Manometer (Absolute)	MKS	10^{-3} to 0.1 Torr	(0.5 + 0.0025 ÷ Reading)%
			0.01 to 10 Torr	(0.4 + 0.03 ÷ Reading)%
P8	Orifice (Pressure Ratio)	MKS	100:1	3%
			1000:1	3%



Air Velocity Calibration Traceability

Air Velocity Standards

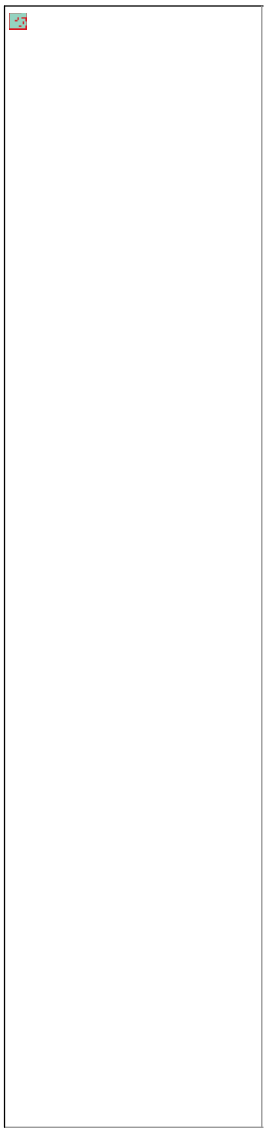
Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (?) (k=2)*
AV1	Pitot Tube		1000 to 9500 sfpm	$(1 + 2375081.6/\text{Reading}^2)\%$
AV2	Hot Wire Anemometer	TSI	30 to 100 sfpm 101 to 1000 sfpm	$(2 + 1453.7724/\text{Reading}^2)$ sfpm $(7.436 + 440.86/\text{Reading}^2)$ sfpm
AV3	Differential Pressure Sensor	MKS	0 to 10 Torr 0 to 100 Torr	0.004 x Reading 0.2%
AV4	Barometer	Paroscientific		0.3 mmHg
AV5	Thermometer	Yellow Springs		0.1°C
AV6	Humidity Sensor	FM&T		5%



Gas Leak, Flow Rate, Viscosity Calibration Traceability

Gas Leak, Flow Rate, Viscosity Standards

Code	Description	Manufacturer	Range	Uncertainty (?) (k=2)
FLV1	Leak Standard	Veeco/VIC/VTI	1×10^{-7} to 1×10^{-6} cm^3/s STP 1×10^{-9} to 9.9×10^{-8} cm^3/s STP 2×10^{-10} to 9.9×10^{-10} cm^3/s STP	2 to 4% 2 to 5.5% 7 to 10%
FLV2	Leak Detector	Vacuum Technology, Inc.	1×10^{-6} to 1×10^{-9} cm^3/s STP 1×10^{-9} to 2×10^{-10} cm^3/s STP	2% 2%
FLV3	Laminar Flowmeter	National Instrument Laboratories	1 to 500 slpm	1 to 2%
FLV4	Piston Column	George Porter	Volume 400 cm^3	0.3 cm^3
FLV5	Floating Piston Column	FM&T Metrology	1 to 100,000 SCCM	0.25%
FLV6	Timer	Standard Electric	0 to 999 seconds	0.1% + 1 count
FLV7	Variable Area Flowmeter	Fisher & Porter	8 to 23 sfpm	0.3 sfpm
FLV8	Standard Viscosity Oils	Cannon Instrument	0.3 to 5,300,000 mPa·s	0.58 to 0.83%
FLV9	Leak Calibrator (Rate of pressure rise)	VTI	0.1 to 1×10^{-7} cm^3/s STP	3 to 5%
FLV10	Volume	Whitey	25 to 1100 cm^3	0.1%
FLV11	Sonic Nozzle	Flow Dyne	0.2 to 1800 slpm	1%



ELECTRICAL

DC Electrical Measurement

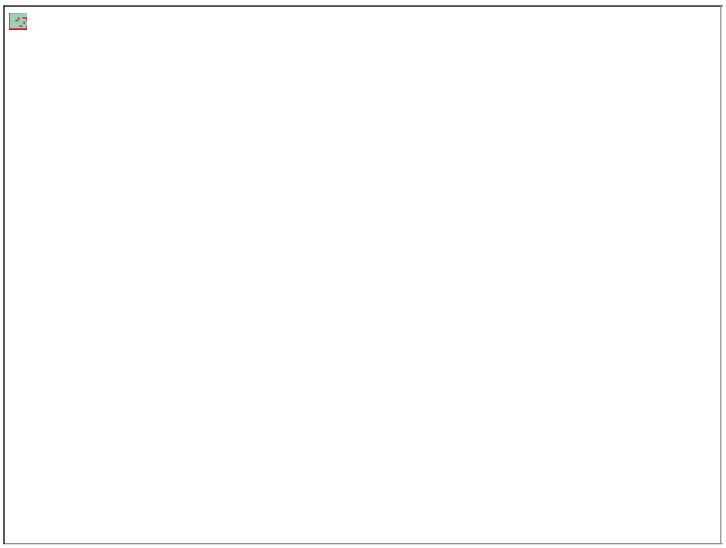
DC Voltage

The basic reference for DC voltage measurements consists of two groups of zener voltage references. Both groups are re-certified by intercomparison tests with a Josephson array voltage standard from the Primary Standards Laboratory. A precision potentiometer is used for voltage measurements to 10 volts. The potentiometer and a precision divider are used for measurements up to 1500 volts. High voltage dividers calibrated by the Primary Standards Laboratory or by NIST are used for measurements up to 150 kilovolts.

DC Voltage Inter-comparison

DC Current

Measurements of current up to 2 amperes are made using resistance and voltage standards. Shunts calibrated by the Primary Standards Laboratory are used for current measurements from 2 amperes to 300 amperes.



Automated Digital Multimeter Calibration

Electrical DC Measurement Capability

Type	*Range*	*Measuring Uncertainty (?) (k=2)*
DC Voltage	0 to 10 V 10 to 1500 V 1.5 kV to 10 kV >10 kV to 150 kV	(0.75 ppm + 0.0375 mV) 2.5 ppm 0.02% 0.028%
DC Current	10^{-10} A 10^{-9} A 10^{-8} A 10^{-7} to 10^{-6} A 10^{-5} to 0.3 A >0.3 to 15 A >15 to 100 A >100 to 500 A	0.1% 0.1% 0.04% 0.04% 0.004% 0.005% 0.007% 0.008%
DC Resistance	10^{-4} to 10^{-1} W 10^{0} to 10^{3} W 10^{3} to 10^{7} W 10^{7} to 10^{8} W 10^{8} to 10^{10} W 10^{10} to 10^{13} W	0.6 ppm 0.34 ppm 0.56 ppm 1.52 ppm 0.2% 0.05%
DC Magnetic Flux Density	Transverse Probe: 20 to 10,000 Gauss Axial Probe: 50 to 2000 Gauss	 2% to 4% 2% to 4%

DC Current, Voltage, and Ratio Traceability

DC Current and Voltage Standards

Code	Description	Manufacturer	Range	Uncertainty (?) (k=2)
DC1	Zener Voltage References	Fluke	1.018 V and 10 V nominal	0.33 ppm
DC2	Voltage Dividers	Julie	10 to 100 kV	0.013% (Calibrated by NIST)
		Fluke	1 to 10 kV	0.033% (Calibrated by Metrology)
DC3	Precision Potentiometer	Measurements International	0 to 10 V	(0.25 ppm + 0.0375 mV)
DC4	Precision Shunt Boxes	Leeds & Northrup	0.015 to 15 A	33 ppm
DC5	Precision DC Current Supply	FM&T Metrology	1.5 mA to 15 A (7 ranges)	(0.02% or 1 nA), whichever is greater
DC6	Precision DC Voltage Source	Fluke	0 to 220 mV	8 ppm + 3 ppm of range
			>0.22 to 220 V	8 ppm + 0.5 ppm of range
			>220 to 1100 V	9 ppm + 0.5 ppm of range
DC7	Ratio Divider	Guildline	1:1 to 10,000:1	2 ppm
DC8	Shunt Standards	Leeds & Northrup	0 to 15 A	0.0033%
		Guildline	0 to 100 A	0.0066%
			0 to 300 A	0.0066%
			0 to 500 A	0.0066%
DC9	Precision Digital Multimeter	Hewlett-Packard	0.1 to 100 V	25 ppm (Ratio)
			0.1 to 1000 V	11 ppm to 25 ppm (DC Voltage)

DC Resistance

The reference for resistance measurements is a Thomas 1 ohm and a 10 kohm standard resistor that are certified by the Sandia Primary Standards Laboratory. These resistors in conjunction with an automated resistance system are used to measure resistance from 0.001 ohm to 100 megohm. From 100 megohm to 10 teraohm, resistance measurements are accomplished using a high resistance meter.

Automated Resistance Measuring System

DC Resistance Traceability

DC Resistance and Ratio Standards

Code	Description	Manufacturer	Range	Uncertainty (?) (k=2)
RES1	Master Resistors	Leeds & Northrup ESI	1 W 10 kW	0.333 ppm 0.25 ppm
RES3	High Resistance Meter	Keithley	10^6 to 10^{13} W	0.125% to 1.025%
RES4	Standard Resistors	Leeds & Northrup, Julie, Guildline	0.001 W to 100 MW	5 ppm to 25 ppm
RES5	Automated Resistance System	Measurements International	0.0001 W to 100 MW	0.1 ppm to 30 ppm (Ratio)
RES6	High Resistance Measuring System	Mid-Eastern	10^3 to 10^{13} W	0.13%
RES7	High Voltage Resistance Standard	Spellman	2000 x 10^6 W	0.02%
RES8	Multifunction Calibrator	Fluke	1 W to 100 MW	15 ppm to 100 ppm
RES9	High Precision DMM	Hewlett-Packard	10 W to 100 MW	25 ppm to 500 ppm

AC Electrical Measurement

AC Voltage

AC voltage sources are calibrated using an Alternating Voltage Measurement Standard, which is calibrated by a DC voltage standard and standard thermal voltage converters certified for AC-DC difference by the Primary Standards Laboratory.

Test thermal voltage converter devices can be calibrated for AC-DC difference by direct comparison of their response to the response of the standard thermal voltage converter devices.

AC Current

AC current sources are calibrated using known DC current and standard current shunts, which are certified by the Primary Standards Laboratory. Current levels lower than 10 mA are calibrated using standard AC resistors. The shunts are terminated with a standard thermal voltage converter certified for AC-DC difference by the Primary Standards Laboratory. The voltage across the AC resistor, which is directly proportional to the current through the resistor, is measured with an AC voltmeter.

AC Ratio

Decade voltage ratio transformers are calibrated by connecting a standard ratio transformer, certified by the Primary Standards Laboratory, and a test transformer to the same input signal and comparing their output signals.

Capacitance and Inductance

Calibration of capacitors and inductors is made by direct comparison of the unknown to a standard capacitor or standard inductor calibrated by the Primary Standards Laboratory. Depending on accuracy and frequency, the comparison is made on a transformer ratio arm bridge (for capacitance only) or on one of three different LCR meters.

The measurement uncertainties vary with value and frequency. Capacitance uncertainties range upward from ±0.02%. Inductance uncertainties range upward from ±0.03%.

Frequency and Time

The GPS receiver was calibrated by the Primary Standards Laboratory and tested against their primary frequency standard using NIST's Frequency Measurement and Analysis System. The frequency standards are used to calibrate counters, sources, and time interval. A digital clock is synchronized with the time information transmitted by the WWVB signal at NIST.

Computer-Controlled Counter Calibration

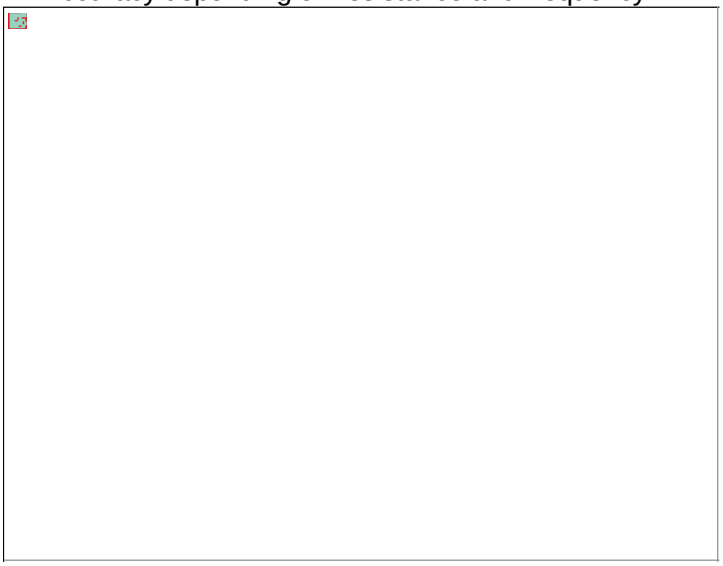
AC Measurement Capability

Type	Range	Frequency	Measuring Uncertainty (?) (k=2)
AC Voltage *	2.2 to 70 mV 2.2 to 70 mV 70 to 700 mV 70 to 700 mV 700 mV to 70 V 700 mV to 70 V 70 V to 220 V 220 V to 1000 V 1 to 30 kV	10 Hz to 100 kHz 100 kHz to 1 MHz 10 Hz to 100 kHz 100 kHz to 1 MHz 10 Hz to 300 kHz 300 kHz to 1 MHz 10 Hz to 500 kHz 10 Hz to 100 kHz 60 Hz	<0.12% + 2.5 mV <0.35% + 8 mV <0.03% + 2.5 mV <0.11% + 8 mV <200 ppm <1200 ppm <500 ppm <800 ppm 0.066%
AC Current	10 mA to 20 A	10 Hz to 50 kHz	0.05 to 0.07%
Capacitance	0.001 pF to 1 mF 1 to 10 mF 10 to 100 mF 1.0 to 1000 pF	1 kHz 1 kHz 1 kHz 1 MHz	(0.01% + 0.00005 pF) 0.02% 0.5% 0.1 to 0.2%
Inductance **	0.05 to 2 mH 2 to 100 mH 100 mH to 10 H	10 kHz to 1 MHz 10 kHz to MHz 1 kHz	0.7% to 12% 0.7% to 3% 0.04% to 0.4%
AC Resistance ***	1 to 20 kO 0.1 to 100 kO	50 kHz DC to 1 MHz	0.05% 0.07%
Frequency	1 Hz to 18 GHz		1 part in 10^9
Time of Day			0.5 ms

* Accuracy depending on range and frequency

** Accuracy depending on inductance and frequency

*** Accuracy depending on resistance and frequency



AC Current, Voltage, and Ratio Traceability

AC Current, Voltage, and Ratio Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (?) (k=2)*
ACV1	Thermal Converters	Holt	0.5 V to 1000 V (10 Hz to 1 MHz)	25 ppm to 110 ppm
		Ballantine	1 V (10 Hz to 100 MHz)	0.02 to 1.2%
ACV2	High Voltage Divider	Julie	20 to 100 kV	0.066%
ACV3	Inductive Ratio Divider	ESI	Ratio only, 0.1 ppm resolution (50 Hz to 10 kHz)	1 to 150 ppm
ACV4	AC-DC Transfer Standard	Fluke 5790A	2.2 to 70 mV (10 Hz to 100 kHz)	<0.12% + 2.5 mV
			2.2 to 70 mV (100 kHz to 1 MHz)	<0.35% + 8 mV
			70 to 700 mV (10 Hz to 100 kHz)	<0.03% + 2.5 mV
			70 to 700 mV (100 kHz to 1 MHz)	<0.11% + 8 mV
			700 mV to 70 V (10 Hz to 300 kHz)	<200 ppm
			700 mV to 70 V (300 kHz to 1 MHz)	<1200 ppm
			70 V to 220 V (10 Hz to 500 kHz)	<500 ppm
			220 V to 1000 V (10 Hz to 100 kHz)	<800 ppm
			1 to 30 kV (60 Hz)	0.066%
ACV5	Shunts	Holt	10 mA to 20 A (10 Hz to 50 kHz)	0.05 to 0.07%
ACV6	Digital Multimeter	Hewlett Packard	100 mV range	15 ppm + 10 ppm of range
			1 to 100 V ranges	10 ppm +1 ppm of range
			1000 V range	20 ppm +1 ppm of range
ACV7	Calibrated DC Voltage Source	Fluke	10 to 1000 V three ranges	<15 ppm
ACV8	AC Calibrator	Fluke	1 mV to 100 mV (10 Hz to 30 kHz)	0.02% of setting + 0.005% FS + 10 mV
			1 V to 100 V (10 Hz to 50 kHz)	0.02% of setting + 0.005% FS +10 mV
			1 mV to 100 mV (30 kHz to 100 kHz)	0.06% of setting + 0.006% FS +10 mV
			1 V to 10 V (50 kHz to 100 kHz)	0.06% of setting + 0.006% FS +10 mV
			1000 V range (50 Hz to 1 kHz)	0.06% of setting + 0.006% FS +10 mV
			1 mV to 100 mV (100 kHz to 1 MHz)	0.6% of setting + 0.1% FS
			1 V to 10 V (100 kHz to 1 MHz)	0.4% of setting + 0.1% FS
			100 V range (50 kHz to 100 kHz)	0.1% of setting
			Wideband output	
			10 to 30 Hz	0.3%
			>30 Hz to 1 MHz	0.25%
			>1 MHz to 20 MHz	0.75%
			>20 MHz to 30 MHz	1.0%
			to 2 A	0.07% of setting + 0.01% of range

Inductance, Capacitance, and AC Resistance Traceability

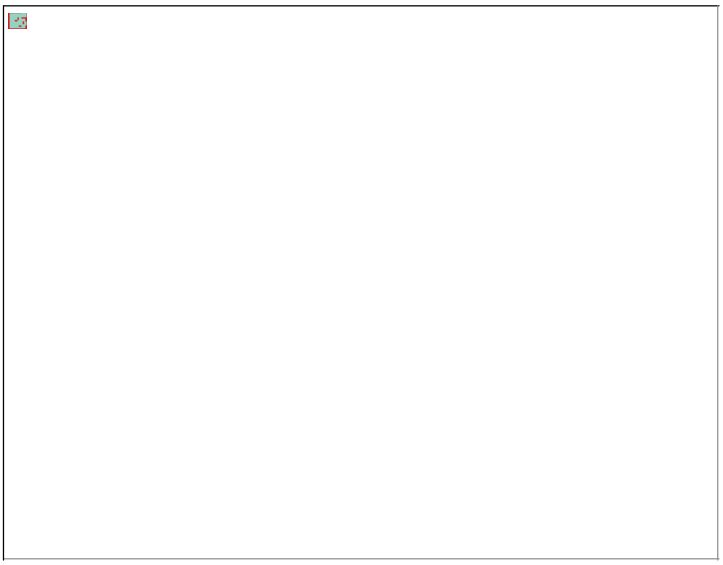
Inductance, Capacitance, and AC Resistance Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (?) (k=2)*
ACZ1	Standard Inductors	General Radio, FM&T Metrology, Hewlett-Packard, Boonton	50 mH to 10 H	0.03 to 0.3% *
			50 nH to 100 mH	0.3 to 10% *
ACZ2	Standard Capacitors	General Radio	1000 pF, fixed	0.003% at 1 kHz
ACZ3	Standard Resistors	Leeds & Northrup	1 to 20 kW	0.015%
		Hewlett-Packard	0.1 to 100 kW	0.05% ***
ACZ4	LCR Meter	Hewlett-Packard	100 mH to 5H	0.15 to 0.3% (direct measurement)
			0.05 mH to 10 mH	0.1 to 10% (comparison to standard inductors)
ACZ6	Capacitance Bridge	General Radio	0.001 pF to 1 mF	0.01% + 0.00005 pF
			1 mF to 10 mF	0.02% (at 1 kHz)
		Hewlett-Packard	0.1 to 1000 pF	0.1% at 1 kHz 0.2% at 1 MHz
ACZ7	Reference Capacitors	Boonton Electric General Radio FM&T Metrology	1 to 1000 pF	0.02% to 0.11% **
			0.1 to 1000 pF	0.1 to 0.15% **
			0.001 to 1 mF	0.02% at 1 kHz
			1 to 10 mF in 1 mF increments	0.1% at 1 kHz
			10 to 100 mF in 10 mF increments	0.1% at 1 kHz

* Uncertainty depending on inductance value and frequency

** Uncertainty depending on capacitance value and frequency

*** Uncertainty depending on resistance value and frequency



Frequency and Time Traceability

Frequency and Time Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (±) (k=2)*
FT1	WWVB Receiver	Kinemetrics	60 kHz	Used with Digital Clock
FT3	Counter	Various	to 46 GHz	Used with GPS
FT4	Digital Clock	Truetime	24 hours	0.5 s
FT5	GPS Receiver	Hewlett Packard	10 MHz, 1 pps	5 parts in 10^{12}
FT6	Distribution Amplifier	Hewlett Packard	0.1 MHz to 10 MHz	Used with GPS
FT7	Synthesizer	Various	to 50 GHz	Used with GPS

RF/MICROWAVE MEASUREMENTS

Air Lines

Air line impedance standards are calibrated using dimensional measurement techniques. The inner and outer conductors' diameters are measured using air gages, and the lengths are measured using a length measurement system by comparison to gage blocks of similar lengths. The dimensional measurements are used to calculate the impedance and electrical length.

Attenuators and Terminations

Standard attenuators and terminations are calibrated by NIST and certified for calibrating Attenuation and Network Analyzer systems and to transfer their values by comparison to other attenuators and terminations.

Attenuator Calibration Using an Automatic Network Analyzer

Network Analyzers and Attenuation Systems

Network analyzers and attenuation systems are calibrated over their operating range by air lines and NIST-calibrated terminations and attenuators. They are used to calibrate single and multi-port devices for s-parameter measurements.

Noise Source

Standard noise sources are calibrated for excess noise ratio (ENR) across a frequency range at the Primary Standards Laboratory (PSL). They are used to transfer the ENR values by comparison to other noise sources.

Thermistor Mounts

Standard thermistor mounts are calibrated by PSL and certified for calibrating a Power Meter/Sensor Calibration system and transferring the calibration factor values by comparison to other thermistor mounts.

Probe Station

The probe station is used to measure chip devices and wafer components. NIST reference materials are available for comparisons. The probes are 100 µm to 3000 µm widths, GS, SG, and Ground Signal Ground with cal substrates.

Probe Station

Power System

The power system is calibrated by transferring the calibration factors from PSL calibrated thermistor mounts to the systems reference sensor. The power system is used to calibrate power meters, sensors, and thermistor mounts.

Power Meter Calibration

Electrical Radio Frequency/Microwave Measurement Capability

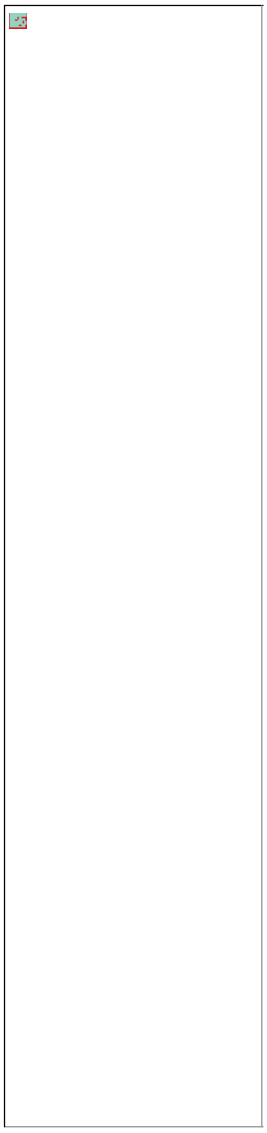
Type	*Range*	*Frequency*	*Measuring Uncertainty (±) (k=2)*
Air Lines (Air-Dielectric)	Impedance Electrical Length (3 to 30 cm)	50 MHz to 26.5 GHz 50 MHz to 26.5 GHz	0.028 Ω to 0.20 Ω 0.0019 cm to 0.03 cm
Scattering Parameters[1]			
|G|	$\|S_{ii}\|$, 0 to 1	300 kHz to 26.5 GHz	0.001 to 0.035
	$\|S_{ii}\|$, 0 to 1	> 26.5 GHz to 50 GHz	Capability
G Phase	$Arg(S_{ii})$, -180° to 180°	300 kHz to 26.5 GHz	0.35° to 180°
	$Arg(S_{ii})$, -180° to 180°	> 26.5 GHz to 50 GHz	Capability
Attenuation	$\|S_{ij}\|$, 0 dB to 70 dB	300 kHz to 26.5 GHz	0.01 dB to 1.1 dB
	$\|S_{ij}\|$, 0 dB to 70 dB	> 26.5 GHz to 50 GHz	Capability
Transmission Phase	$Arg(S_{ij})$, 0 dB to 70 dB	300 kHz to 50 GHz	Capability
Thermistor Mounts[1]	Calibration Factor (0.9 to 1.0)	1 MHz to 18 GHz	0.5% to 5%
CW Power Meter Systems[1]	10 µW to 100 mW 10 µW to 100 mW 1 nW to 10 µW 100 mW to 5 W	100 kHz to 4.2 GHz >4.2 GHz to 18 GHz 10 MHz to 18 GHz 10 MHz to 1.0 GHz	2.4% to 4.2% 3.0% to 10 % 2.5% to 10 % 5% + Additional Unc.
Peak Power Meter Systems[1]	10 µW to 100 mW	1 GHz to 2 GHz	5%
Group Delay[1]	1 ns to 1200 ns	50 MHz to 2.0 GHz	0.005 ns to 0.5 ns
Noise Sources[1]	ENR ~ 15 dB	60 MHz to 3.55 GHz	0.1 dB to 0.35
Chip Devices/Wafer Components	Various Measurements	dc to 50 GHz	Capability

[1] Referenced to 50Ω + j0Ω.

Radio Frequency and Microwave Traceability

Radio Frequency and Microwave Standards

Code	Description	Manufacturer	Range	Uncertainty (k=2)
MW1	Air Lines	General Radio	3.5 mm, 7 mm, 14 mm, and N	|Z| ± 0.028W to 0.20W
		Maury Microwave	50 MHz to 26.5 GHz	E.L. ± 0.0019 cm to 0.03 cm
MW2	Attenuators	Hewlett Packard	10 dB, 300 kHz to 26.5 GHz	± 0.008 dB to 0.042 dB
MW3	Terminations	General Radio Wiltron	300 kHz to 100 MHz	|G| ± 0.0008 to 0.003 f ± 0.2° to 180°
MW4	GPS Receiver	Hewlett Packard	10 MHz	± 0.000 005 ppm
MW5	Network Analyzers	Hewlett Packard	300 kHz to 26.5 GHz	|G| ± 0.001 to 0.035
			|G|, 0 to 1; f, -180° to 180°	f ± 0.35° to 180°
			Attenuation: 0 to 70 dB	
MW6	Noise Source	Hewlett Packard	60 MHz to 3.55 GHz	± 0.1 to 0.35 dB
MW7	Thermistor Mounts	Hewlett Packard	1 MHz to 18 GHz	± 0.3% to 1.5%
MW8	Probe Station		dc to 50 GHz	Used with other calibrated measuring standards.
MW9	Power System	FM&T Metrology	1 MHz to 18 GHz	± 1.0% to 4%



OPTICAL AND RADIATION

Optical Radiometric Measurement

Radiometry is the measurement of radiation in the optical spectrum, which includes ultraviolet, visible, and infrared light. The main radiometric reference standards at FM&T are heat-flow calorimeters and wavelength standards, which include Helium-Neon (HeNe) lasers and Mercury spectral lamps. The Primary Standards Laboratory calibrates the heat flow calorimeters. The HeNe laser wavelength standard is calibrated by NIST because of its low uncertainty. The mercury spectral lamps do not require calibration because of their physical characteristics. Measurements performed include noncoherent measurement in the ultraviolet and visible regions of the optical spectrum and coherent measurements, which consist of HeNe, Nd:YAG, and CO_2

lasers. Power levels of these measurements range from fractions of a microwatt to levels in excess of 1000 watts over wavelengths of 365 nm to 10.6 mm. Most of the radiometric calibration activity at FM&T is calibrating Nd:YAG and CO_2 laser power sensors and meters in CW mode.

Optical Photometric Measurement

Photometry is the measurement of visible light intensity and energy as it affects the human eye. The main photometric reference standards at FM&T are standard photometers, calibrated by NIST. Standard photometers output current and are used with a digital picoammeter to measure illuminance in units of footcandles or lux. When used in conjunction with an optical bench, luminous intensity, in units of candela, can be measured.

Radiation Measurement

Radiation measurements are made using standards of alpha-particle emission rate from plutonium 239 and lead-probe neutron detectors. Alpha sources and lead probes are calibrated by the PSL. Accuracy of these standards ranges from ±3% to ±10%.

Photodiode Detector Calibration

Optical Radiometric Measurement Capability

Type	*Range*	*Measuring Uncertainty (?) (k=2)*
Optical Transmittance	l = 235 to 1100 nm	1.5%
Optical Spectral Response	235 to 400 nm 400 to 900 nm	5% 1.5%
Laser Average Power	l = 488 nm to 1.064 mm 1 mW to 1 mW 1 mW to 10 W l = 10.6 mm 1 mW to 10 W 10 to 1000 W	 1.5% 1.0% 3% 6%
LED Power	l = 570 to 910 nm 10 mW to 10 mW (CW)	 5%
Ultraviolet Irradiance	l = 254 nm and 365 nm 0.1 to 10 mW/cm^2	 3%

X-Ray Film Density	0 to 4 Optical Density Units	(0.03 density units + 1% of reading)

Optical Traceability (Radiometric)

Optical Radiometric Measurement Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (?) (k=2)*
OR2	Calorimeter	Scientech	1 mW to 10 W 365 nm to 1100 nm 10.6 mm	 1.0% 3%
OR3	Digital Nanovoltmeter	Keithley	2mV to 200 V	(0.015% of reading + 10 digits) to (0.01% of reading + 2 digits)
OR4	Mercury Spectral Lamp	Oriel	237.8 to 1092.2 nm	0.1 nm
OR5	Monochromator	Various	235 to 1092.2 nm	1.0 nm
OR6	Photodiode Trap Detector	FM&T	400 to 900 nm 1mW to 2 mW	1.5%
OR7	HeNe Laser	Hewlett Packard	632.991 nm	0.015 ppm
OR8	Photographic Step Tablet	NIST	0 to 4 density units	0.006 density units

Nd:YAG Laser Power Meter Calibration

Optical Photometric Measurement Capability

Type	*Range*	*Measuring Uncertainty (?) (k=2)*
Illuminance	1 to 500 foot-candle	1.5%
Luminous Intensity	100 to 750 candela	2.0%

Optical Traceability (Photometric)

Optical Photometric Measurement Standards

Code	*Description*	*Manufacturer*	*Range*	*Uncertainty (?) (k=2)*
OP2	Standard Photometer	Graseby	0.1 to 2000 foot-candles	1.5%
OP3	Digital Picoammeter	Keithley	200 nA to 20 mA	(0.4% of reading + 4 digits) to (0.1% of reading + 1 digit
OP4	Optical Bench	Ealing	0 to 200 cm	0.1 cm