Metrology Measurement Capabilities

Federal Manufacturing & Technologies

Leon M. Barnes

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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 in laboratories that conform to the requirements of the Department of Energy Development and Production Manual Chapter 8.4, 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 areas of measurement:

Mechanical;

Environmental, Gas, Liquid;

Electrical (D.C., A.C., RF/Microwave); and

Optical and Radiation.

Metrology Engineering provides the expertise to develop measurement capabilities for virtually any type of measurement which falls into the broad areas listed above. The engineering staff currently averages almost 16 years of measurement experience.

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

Measurement and Calibration Capabilities

*NVLAP Accredited in these parameters

**Applied for NVLAP Accreditation 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 **

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

Specific Gravity, Laboratory Glassware Volume

Specific Gravity

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

Fixed Point Temperature **

Humidity **

Pressure

Gas Flow **

Leak Rate **

Viscosity

LED Power

Ultraviolet Irradiance **

Illuminance **

Monochrometers **

X-Ray Film Density

Luminous Intensity **

HeNe Laser Frequency, Wavelength *

Mechanical

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.

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.

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. A control standard is measured on the vibration system to verify that the system is functioning properly.

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 shock pulses area and the time 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.

Mass Measurement

Mass measurements are made by comparison to master weights using seven 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

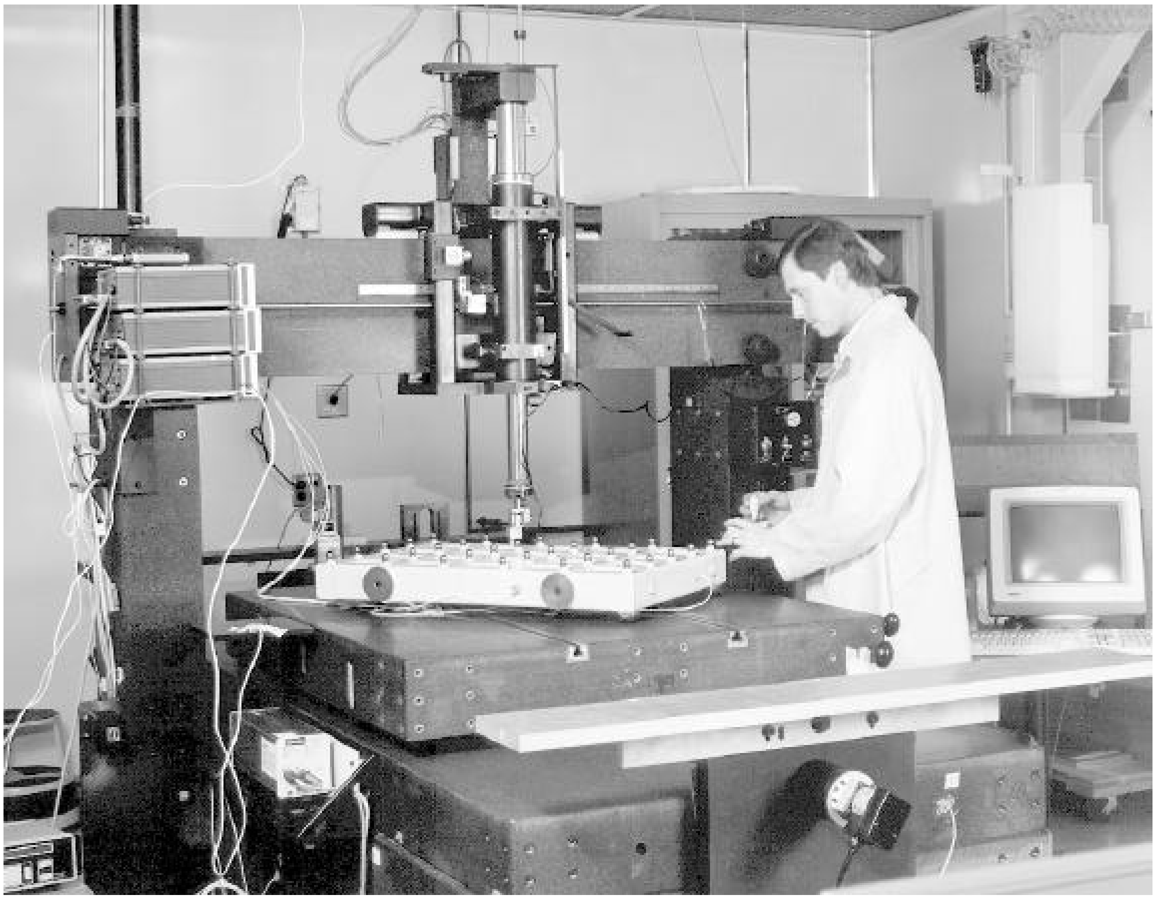
Force transducers up to 2400-lbf capacity are measured using weight sets or dead weight testers which are certified in force units in our Mass lab. Larger force devices are measured by comparison to NIST-calibrated proving rings using a universal force tester.

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.

Laboratory Glassware Volume

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



Shelton CMM With Two-Dimensional CMM Calibration Artifact

CMM With Video Edge Detection System

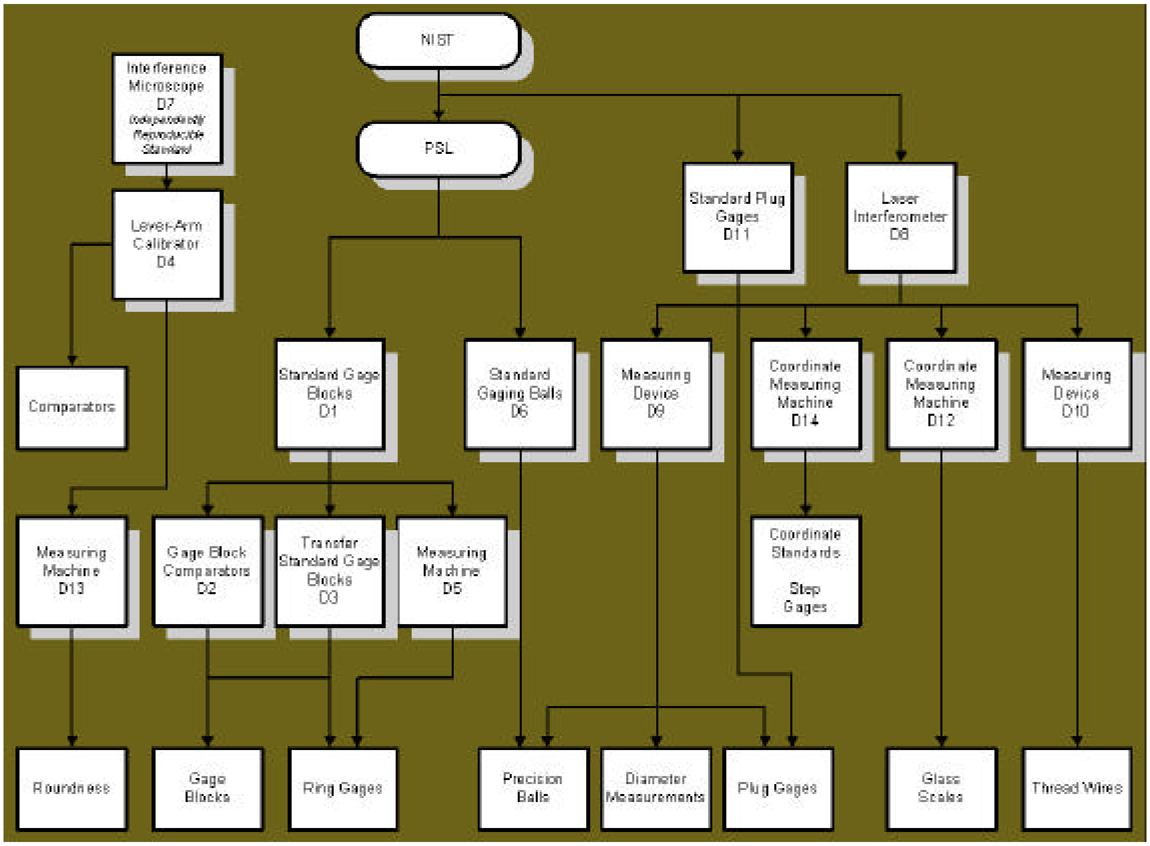
Dimensional Measurement Capability

Type	Range	Measuring Uncertainty (±) (k=2)
Gage Blocks	To 4 in.	2.5 µ in. + 0.7 ppm
	> 4 to 20 in.	6 µ in. + 0.5 ppm
Coordinate Measurement *	Axial	(10 µ in + 0.5 ppm)
	Planar **	(75 µ in. + 1 ppm)
	Spatial ***	(75 µ in. + 12 ppm)
1-D Ball Plates	To 48 in.	±(20 µ in + 1.2 ppm).
2-D Ball Plates	36 in. by 36 in.	±(22 µ in + 1.5 ppm).
Step Gages	To 24 in.	±(15 µ in + 1.0 ppm).
Internal Diameters	0.04 to 1 in.	9 µ in.
	1 to 2 in.	10 µ in.
	2 to 14 in.	Determined by Test.
Single Axis Glass Line Scales	0 to 2 in.	18 µ in.
	> 2 to 12 in.	32 µ in.
Spherical Diameter	0 to 1 in.	9 µ in.
Cylindrical Plug Gages	0 to 1 in.	6.5 µ in.
Squares	To 24 in. by 36 in.	30 µ in.
Straight Edges	To 48 in.	5 µ in.
Roundness	To 18-in. diameter	3 µ in.
Thread Wires	All standard pitches	8 µ in.

* 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
±(22 µ in + 1.5 ppm).

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



Mechanical Calibration Traceability (Dimensional)

Dimensional Standards

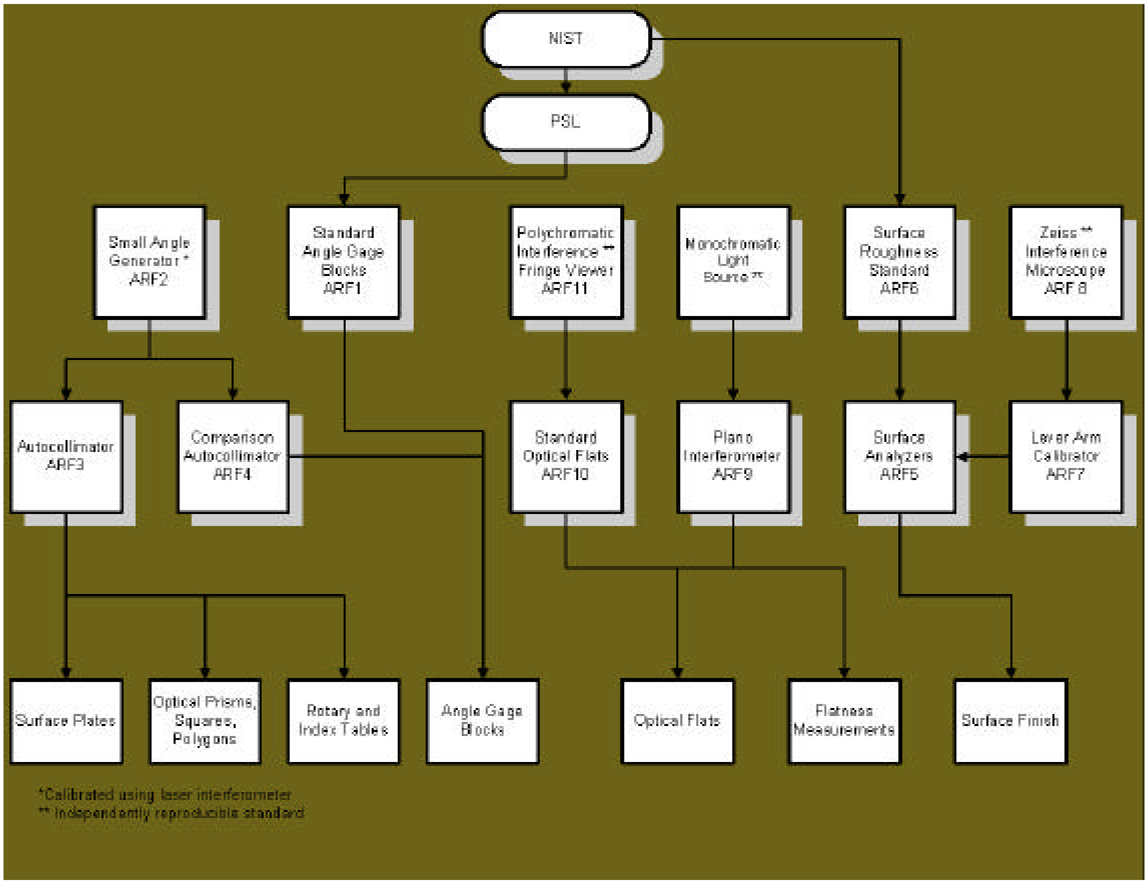
Code	Description	Manufacturer	Range	Uncertainty (±) (k=2)
D1	Standard Gage Blocks	Do All	To 4 in.	1.6 µ in. + 0.6 ppm
		Pratt & Whitney	5 to 20 in.	6 µ in. + 0.5 ppm
D2	Gage Block Comparators	Link Federal Pratt & Whitney	0 to 2 in. 0 to 4 in. 0 to 20 in.	3 µ in. 3 µ in. 3 µ in.
D3	Transfer Standard Gage Blocks	Do All	To 4 in.	2.5 µ in. + 0.7 ppm
		Pratt & Whitney	5 to 20 in.	5 µ in. + 0.3 ppm
D4	Lever Arm Calibrator	FM&T Metrology	0 to 0.0002 in	0.25 µ in. + 0.5% of travel
		Mitutoyo	0 to 0.05 in.	10 µ in. + 0.1% of travel
D5	Measuring Machine	Pratt & Whitney	0 to 14 in.	3 µ in. + 2 ppm
D6	Standard Gaging Balls	AA Industries	1/16 to 1 in. (1/32-in. increments)	6 µ in.
D7	Interference Microscope	Zeiss	0 to 0.01 in.	1 µ in.
D8	Laser Interferometer	Hewlett-Packard	NA	0.05 ppm
D9	Measuring Machine	Pratt & Whitney	1 in.	10 µ in.
D10	Measuring Machine	FM&T Metrology	0 to 2 in.	8 µ in.
D11	Standard Plug Gages	Lincoln	0.050 to 1 in.	4.6 µ in.
D12	Coordinate Measuring Machine	SIP/FM&T Metrology	0 to 12 in	Included in Line Scale Process
D13	Roundness Measuring Machine	Bendix A & M	18-in. diameter	3 µ in.
D14 *	Coordinate Measuring Machine	Shelton	x axis	(10 µ in. + 0.5 ppm)
			y axis	(12 µ in. + 0.3 ppm)
			z axis	(21 µ in. + 0.3 ppm)
			x-y plane**	(71 µ in. + 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 ± (22 μ in + 1.5 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 μ in. Ra)
Optical Surface Flatness	To 12-in. diameter	1.2 μ in. (Three Flat Method) 2 μ in. (Interferometer) 4 μ in. (Direct Comparison)
Surface Plate Flatness	Up to 8 ft Diagonal	30 μ in. + 2 μ in./ft^2



Mechanical Calibration Traceability (Angle, Roughness, Flatness)

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	0.4 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	0 to 0.008 in. R_a (10 ranges)	0.7 to 400 µ in. R_a
ARF6	Surface Roughness Standard	NIST	120 µ in. R_a	3.1 µ in. R_a
ARF7	Lever-Arm Calibrator	FM&T Metrology	0 to 0.0002 in.	0.2 µ in. +0.5% of travel
ARF8	Interference Microscope	Zeiss	0 to 0.01 in.	1 µ in.
ARF9	Plano Interferometer	Davidson	2 3/4-in. diameter	2 µ in.
ARF10	Standard Optical Flats (set of 3)	Do All	12-in. diameter	Flat within 4 µ in.
ARF11	Polychromatic Interference Fringe Viewer	Strang	NA	1 µ in.

Mass Calibration

Mass, Force, Torque, Specific Gravity, and Laboratory Glassware

Volumetric Measurement Capability

Type	Range	Measuring Uncertainty (±) (k=2)
Mass (Direct Weighing)	To 15 mg	0.020 mg
	15 to 30 mg	0.040 mg
	30 mg to 1 g	0.026 to 0.030 mg
	1 to 3 g	0.030 to 0.042 mg
	3 to 20 g	0.070 to 0.15 mg
	20 to 100 g	0.38 to 0.60 mg
	100 to 1000 g	0.69 to 3.8 mg
	1000 to 5000 g	9.6 to 20 mg
	5000 to 60000 g	2 g
Mass (Substitution Weighing)	1 to 100 mg	0.0025 to 0.0036 mg
	200 mg to 10 g	0.0041 to 0.032 mg
	20 to 50 g	0.055 to 0.15 mg
	100 to 5000 g	0.24 to 6.6 mg

	5 to 22 kg	45 to 65 mg
Mass (Calibration Design Using 1-2-3-5 Decade Progressions)	1 to 500 mg	0.00036 to 0.0015 mg
	1 to 5 g	0.0030 to 0.0052 mg
	10 to 50 g	0.0096 to 0.015 mg
	100 to 5000 g	0.028 to 0.81 mg
Mass (1 kg Design)	1 kg	0.11 ppm
Mass (Class Weights and Weight Sets)	1 mg to 20 kg	ANSI/ASTM Class 3, 4, 5, 6
		OIML Class F_2, M_1, M_2
	1 lb to 10 lb	ANSI/ASTM Class 3, 4, 5, 6
Force	0.0625 to 5 lbf	0.1% of reading
	5 to 300 lbf	0.01% of reading
	300 to 2400 lbf	0.01% of reading
	750 to 3000 lbf	0.45 lbf
	3000 to 5000 lbf	0.75 lbf
	5000 to 10000 lbf	1.6 lbf
	10000 to 20000 lbf	3.0 lbf
	20000 to 30000 lbf	5.0 lbf
	30000 to 60000 lbf	9.0 lbf
	60000 to 100000 lbf	15.0 lbf
	100000 to 300000 lbf	90 lbf
	300000 to 500000 lbf	500 lbf
Torque	1 to 160 ozf-in.	0.175% of reading
	1 to 5 lbf-ft	0.125% of reading
	5 to 50 lbf-ft	0.15% of reading
	50 to 700 lbf-ft	0.2% of reading
Specific Gravity	1.050 to 1.500	0.005
Laboratory Glassware Volume		
Burets	10 to 100 mL	NIST or ASTM Class A, B
Volumetric Pipets	0.5 to 100 mL	NIST or ASTM Class A, B
Measuring Pipets	1 to 30 mL	NIST or ASTM Class A, B
Volumetric Flasks	1 to 5000 mL	NIST Class A, B
	5 to 2000 mL	ASTM Class A, B
Graduated Cylinders	5 to 2000 mL	NIST or ASTM Class A, B

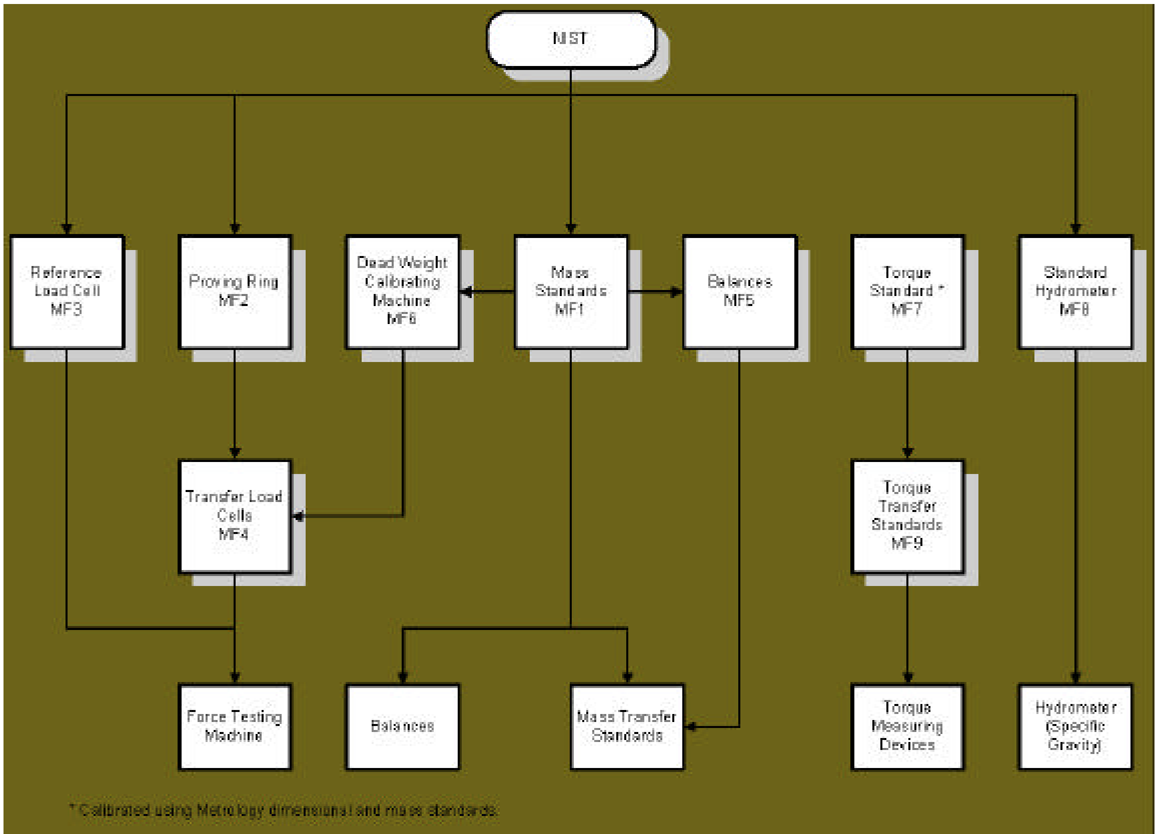


Figure 3A. Mechanical Calibration Traceability (Mass, Force, Torque, Specific Gravity

Mass, Force, Torque, and Specific Gravity Standards

Code

MF1

MF2

MF3

MF4

MF5

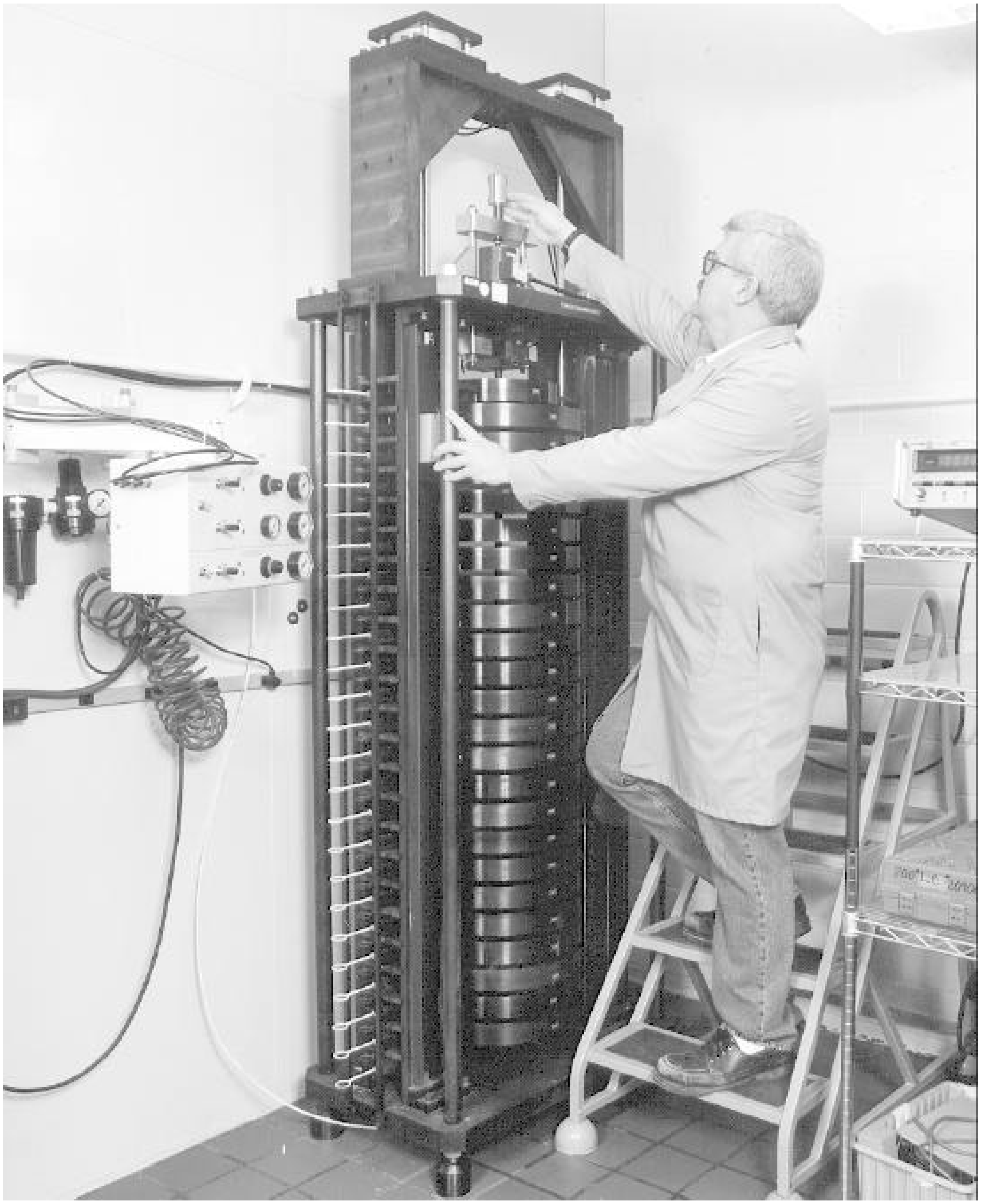
MF6

MF7

MF8

MF9

* Uncertainty listed is for direct weighing.



Dead Weight Force Calibration

Proving Ring Calibration

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 10,000 g at 0.1 to 10 ms	2.5 to 3.0%
	>10,000 g 0.1 to 10 ms	Capability
Sound Level	94 to 124 dB at 250 Hz	0.5 dB

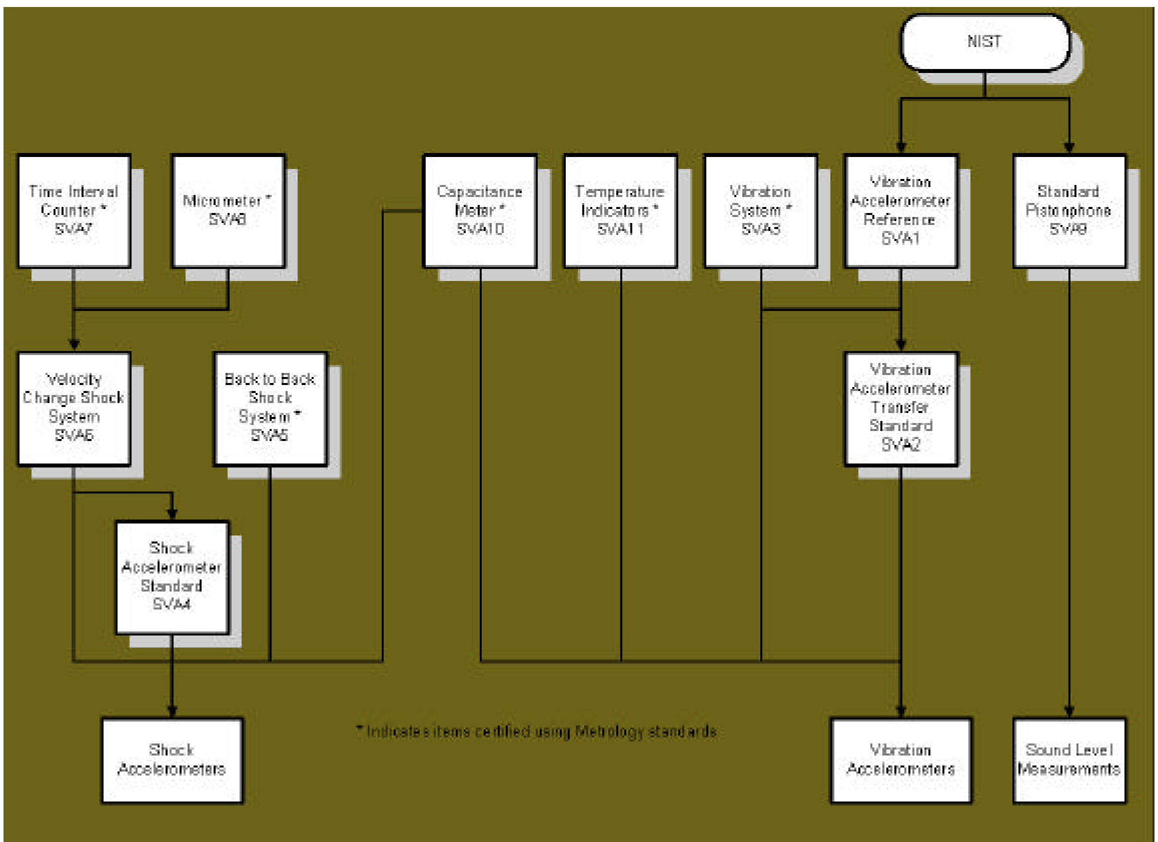


Figure 4A. Mechanical Calibration Traceability (Vibration, Shock, Sound Level)

Vibration, Acceleratio and Shock Standards

Code

SVA1

SVA2

SVA3

SVA4

SVA5

SVA6

SVA7

SVA8

SVA9

SVA10

SVA11

Accelerometer Vibration Calibration

ENVIRONMENTAL, GAS, LIQUID

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).

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.

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.

SPRT Calibration Using a Fixed Point Temperature Cell

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.

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.

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.

Vacuum calibrations above 10^{-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.

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.

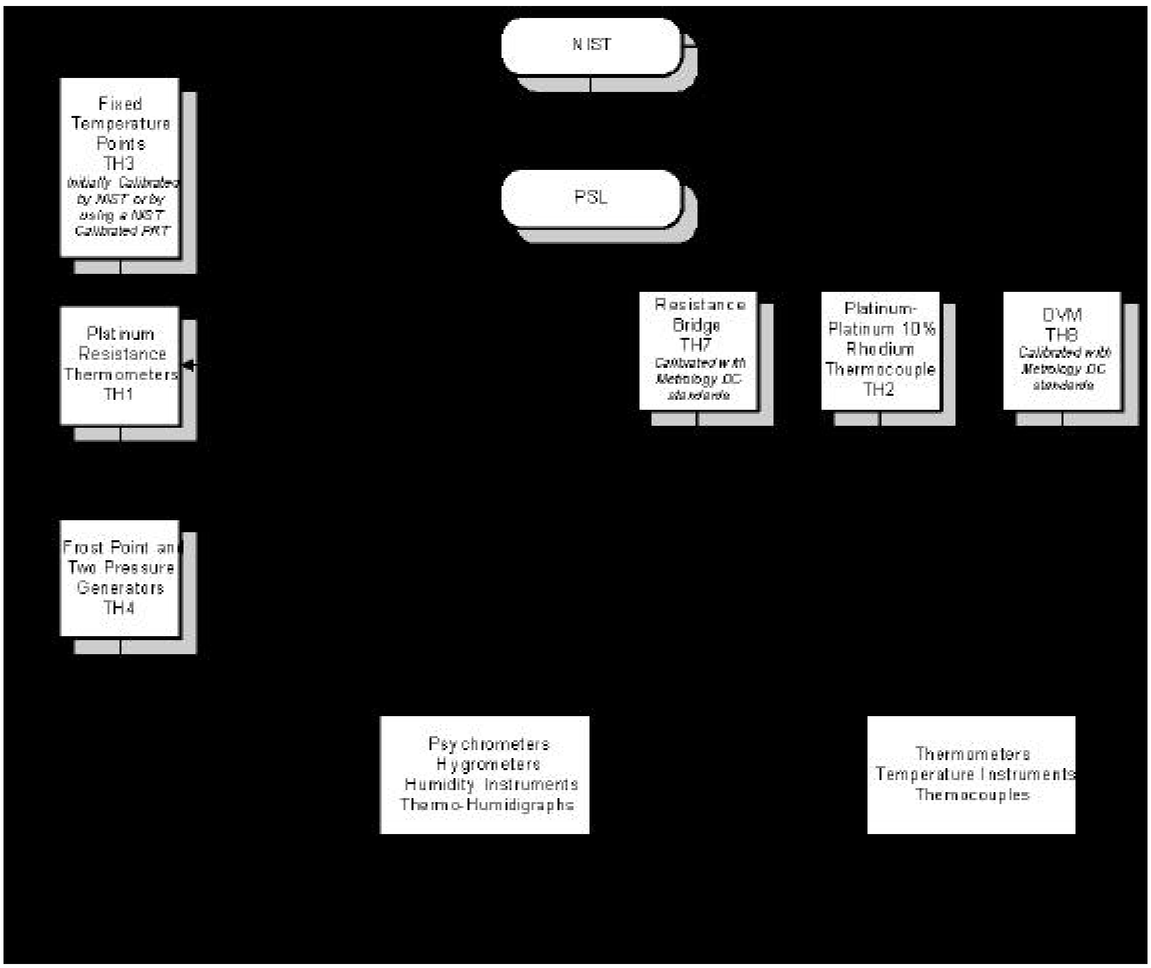
Viscosity

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

Humidity Calibration Using the Two-Pressure Method

Environmental Measurement Capability (Temperature, Humidity)

Type	Range	Measuring Uncertainty (±) (k=2)
Temperature	-183° C to +500° C	0.01° C to 0.05° C
	500° C to 1093° C	0.4% of reading
Fixed Point	-38.8344° C	0.005° C
	0.01° C	0.0005° C
	29.7646° C	0.0005° C
	156.5985° C	0.007° C
	231.928° C	0.008° C
	419.527° C	0.01° C
Humidity	-75° C to 0.0° C	0.5° C
	5% RH to 95% RH	0.5% RH



Environmer
Standards

Code

TH1

TH2

TH3

TH4

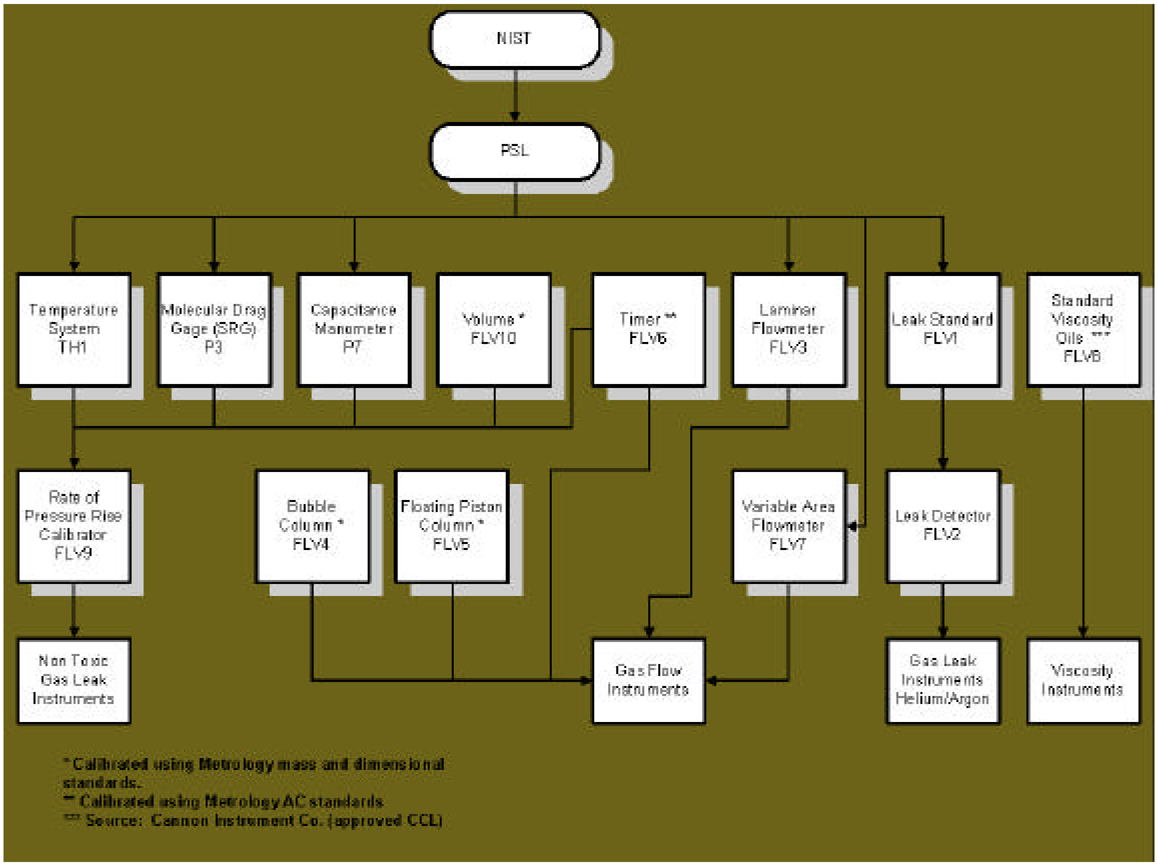
TH7

Pressure Calibration Using Controlled Clearance Dead Weight Piston Gage

Standard Leak Calibration System

Gas, Liquid Measurement Capability

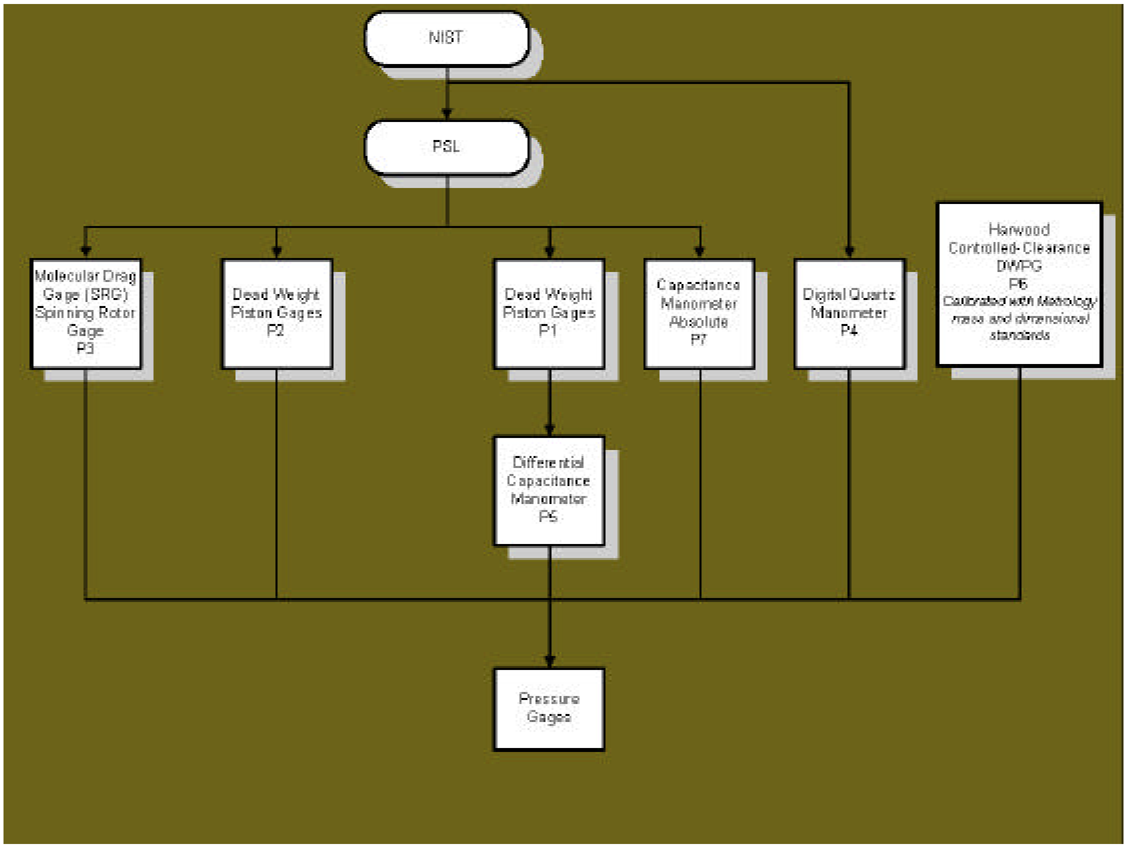
Type	Range	Measuring Uncertainty (±) (k=2)
Pressure	Absolute	
	10^{-6} to 10^{-4} torr	10%
	10^{-3} to 0.05 torr	(0.0003 + 0.005 x reading) torr
	1 to 10 torr	(0.0005 + 0.003 x reading) torr
	10 to 1100 torr	(0.03 + 0.0002 x reading) torr
	0 to 30 psia	(0.01 + 0.0002 x reading) psi
	Gage	
	0.5 to 1800 psig	0.025%
	600 to 15,000 psig	0.05%
	15,000 to 100,000 psig	0.05%
Gas Flow	1 to 100,000 sccm	1%
	50 to 1800 slpm	2%
Leak Rate	1×10^{-1} to 5×10^{-9} standard cm^3/s STP	5 to 15%
	10^{-10} standard cm^3/s STP	25%
Viscosity	0.3 to 5,300,000 mPa• s	2.5 to 5%



Environmental Calibration Traceability (Gas Leak and Flow Rates, Viscosity)

Gas Leak and Flow Rates, 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	4 to 8% 5 to 10% 9 to 15%
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	3% 3.5%
FLV3	Laminar Flowmeter	National Instrument Laboratories	1 to 500 SLPM	1 to 2%
		CME	180 to 1800 SLPM	18 SCFM
FLV4	Bubble Column	Matheson Scientific	Volume 50 cm^3	0.05 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 SCFM	0.3 SCFM
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%



Environmental Calibration Traceability (Pressure Calibration)

Pressure Standards

Code	Description	Manufacturer	Range	Uncertainty (±) (k=2)
P1	Piston Gage	CEC	0.2 to 600 psi	0.015%
		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^{-6} torr 10^{-5} torr 10^{-4} torr 10^{-3} torr 10^{-2} torr	8% 4% 3% 3% 3%
P4	Digital Quartz Manometer (Differential)	Paroscientific	0.1 to 1100 torr 0 to 30 psia	(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 0.05 to 1 torr 1 to 1000 torr	0.0005 torr 0.001 torr or 0.0075 x reading whichever is greater (0.01 + 0.0015 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 0.01 to 10 torr	(0.4 torr + 1.62 x reading + 0.002/reading)% (0.2 + 0.03/reading)%

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 voltage standard from the Primary Standards Laboratory. A precision potentiometer is used for voltage measurements to 1.5 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 100 kilovolts.

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.

DC Resistance

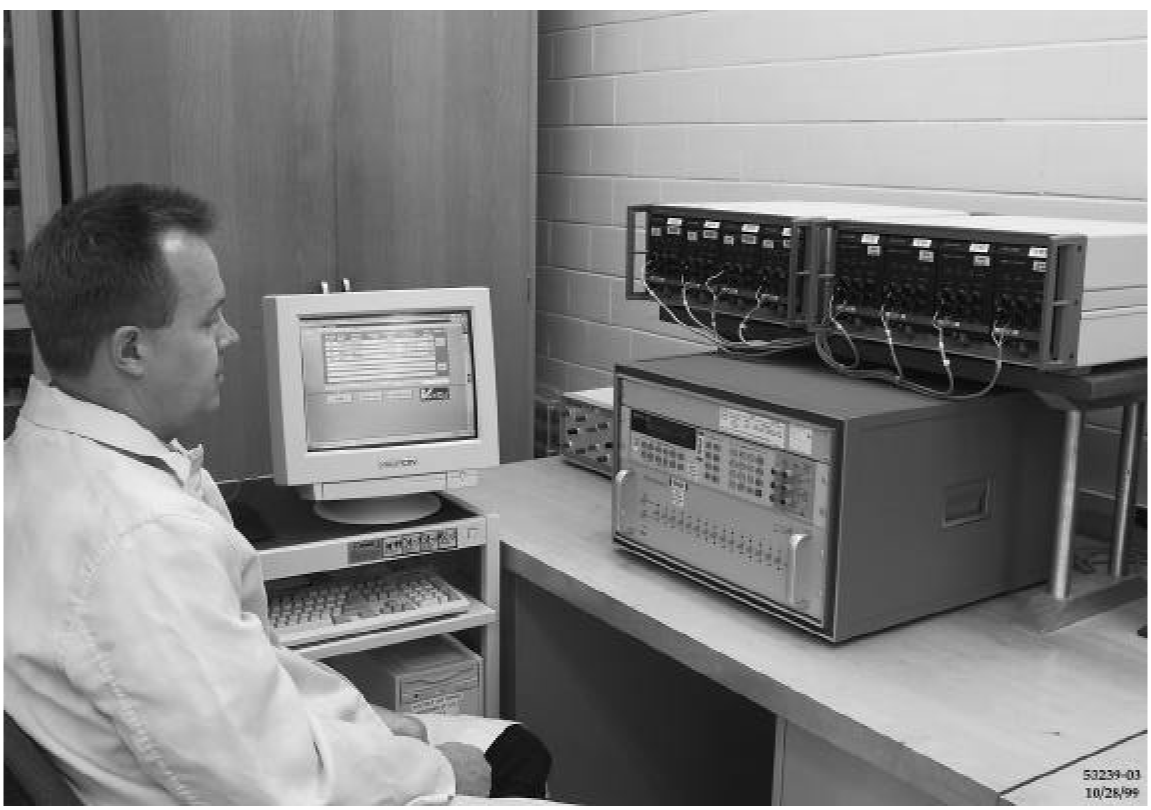
The reference for resistance measurements is two groups of standard resistors, ranging from 0.001 ohm to 100 megohms, which are certified by the Primary Standards Laboratory. These resistors, a double ratio set and a precision bridge, are used for resistance measurements to 100 megohms. Above 100 megohms and up to
10 teraohms, resistance measurements are accomplished using either a wheatstone bridge or a teraohmmeter.

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.



DC Voltage Inter-comparison

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.

Automated Digital Multimeter Calibration

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.

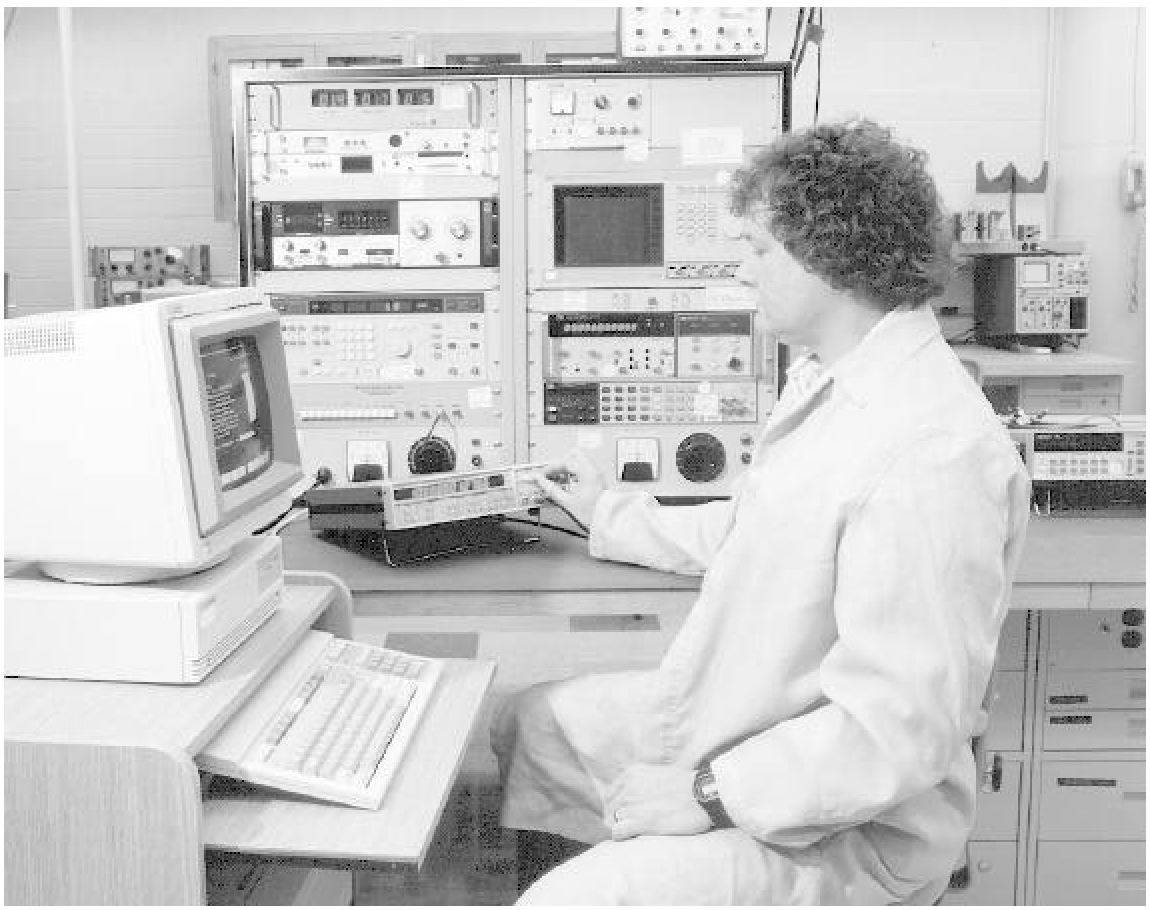
Capacitance and Inductance

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 output of a rubidium frequency standard is compared periodically with the WWVB frequency transmitted by NIST. 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

RF/MICROWAVE MEASUREMENTS

Air Lines

Air line impedance standards are calibrated using dimensional measurement techniques. The inner and outer conductor’s 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

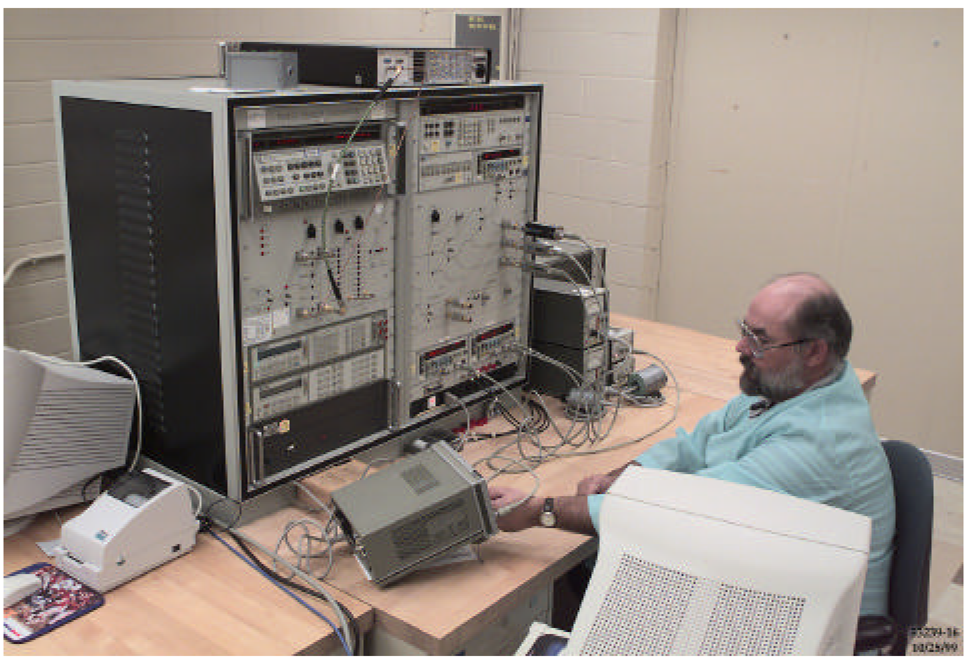
Standard thermistor mounts are calibrated by NIST and certified for calibrating a Power Meter/Sensor Calibration system and transferring the calibration factor values by comparison to other thermistor mounts.

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.

Power System

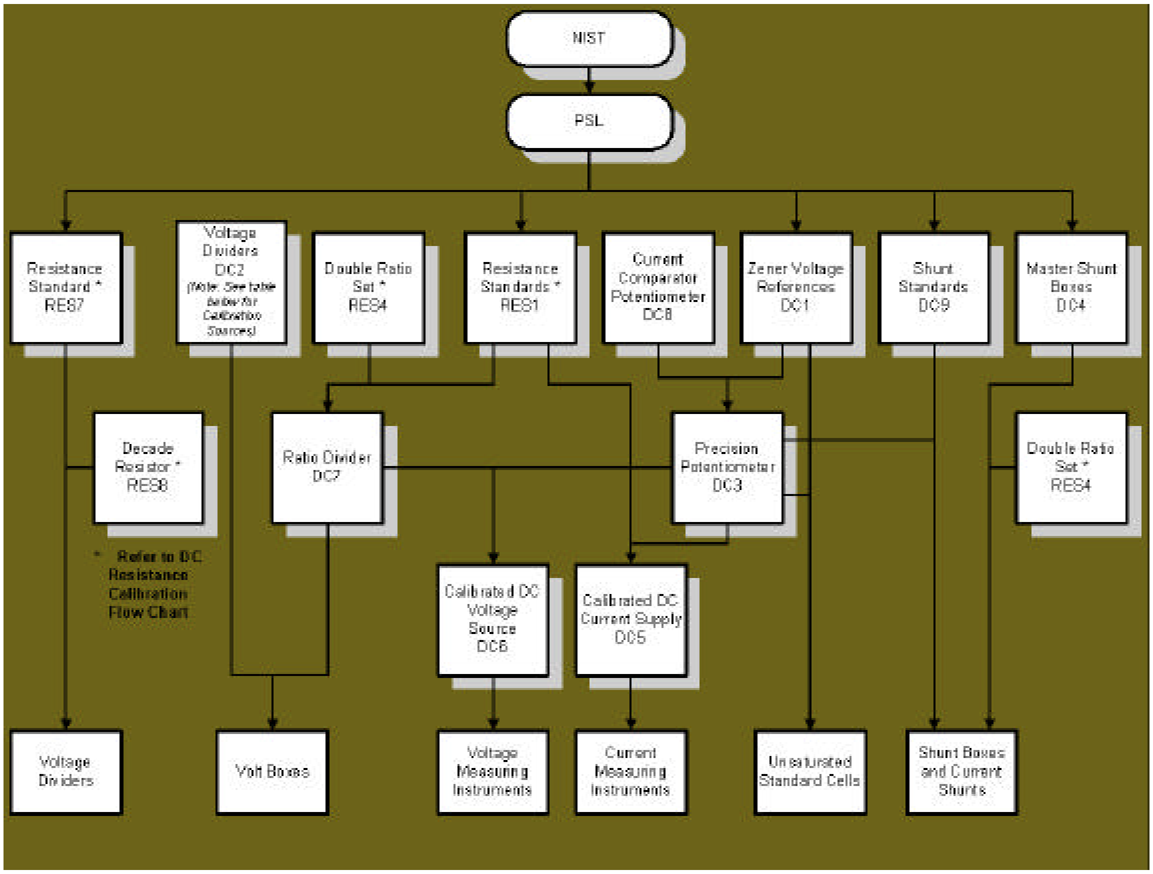
The power system is calibrated by transferring the calibration factors from NIST calibrated thermistor mounts to the systems reference sensor. The power system is used to calibrate power meters, sensors, and thermistor mounts.



Power Meter Calibration

Electrical Direct Current Measurement Capability

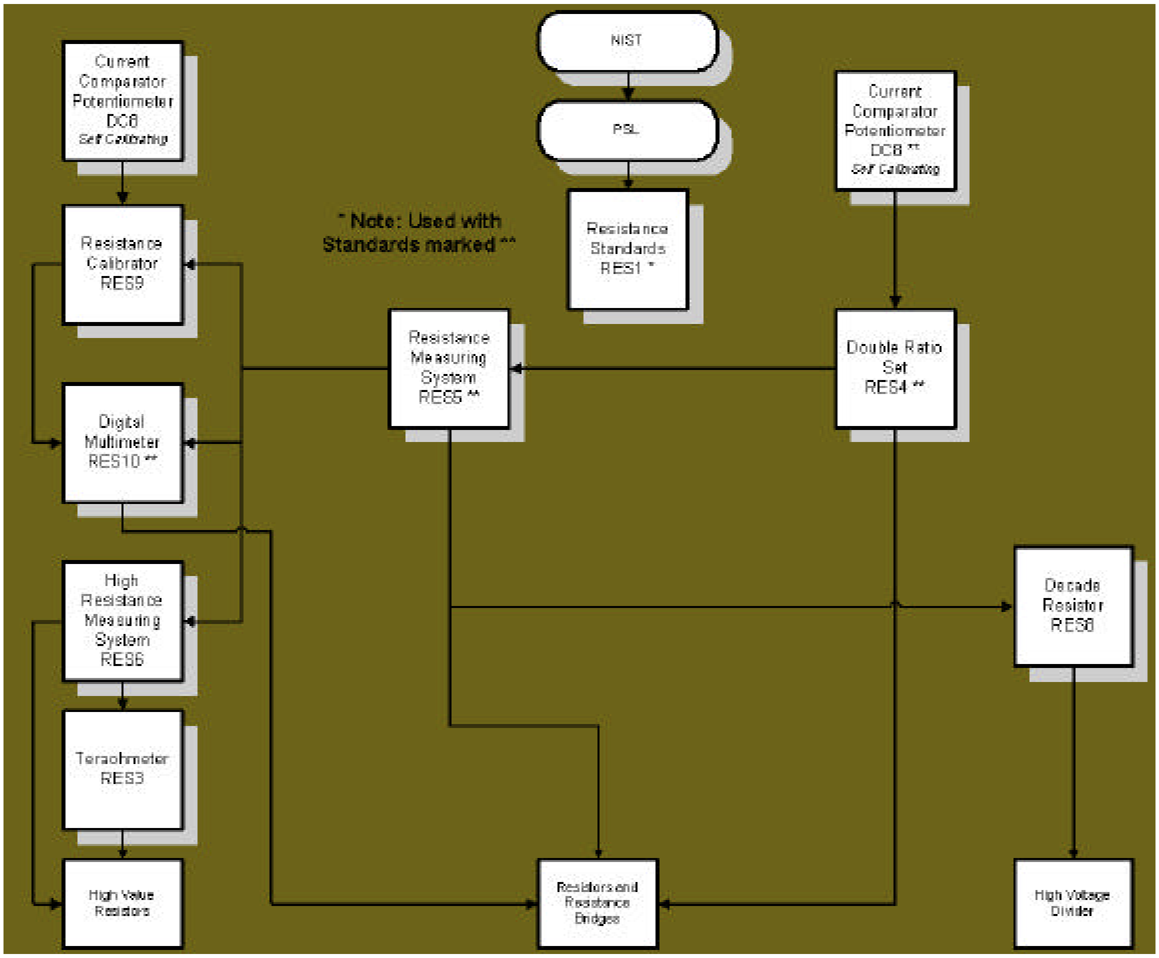
Type	Range	Measuring Uncertainty (±) (k=2)
DC Voltage	0 to 0.016 V	(15 ppm + 0.05 μ V)
	0.016 to 0.16 V	(10 ppm + 0.2 μ V)
	0.16 to 1.6 V	(5 ppm + 2 μ V)
	1.6 to 1500 V	10 ppm
	1.5 to 10 kV	0.04%
	>10 to 150 kV	0.075%
DC Current	10^{-9} A	0.5%
	10^{-8} A	0.4%
	10^{-7} to 10^{-6} A	0.2%
	10^{-5} to 0.3 A	0.005%
	> 0.3 to 15 A	0.007%
	>15 to 100 A	0.02%
	>100 to 300 A	0.03%
DC Resistance	10^{-4} to 10^{-1} Ω	0.007%
	10^{0} to 10^{7} Ω	0.005%
	10^{7} to 10^{8} Ω	0.01%
	10^{8} to 10^{10} Ω	0.2%
	10^{10} to 10^{12} Ω	0.5%
	10^{12} to 10^{13} Ω	1.0%
DC Magnetic Field Density	Transverse Probe: 20 to 10,000 Gauss	3% to 7.5%
	Axial Probe: 50 to 2000 Gauss	3 % to 7.5%



DC Current and Voltage 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	0.5 ppm
DC2	Voltage Dividers	Julie	10 to 100 kV	0.05% (Calibrated by NIST)
		Spellman	60 to 150 kV	0.03% (Calibrated by PSL)
		Fluke	1 to 10 kV	0.025% (Calibrated by Metrology)
DC3	Precision Potentiometer	Leeds & Northrup	0 to 1.6 V	(15 ppm + 0.05 μ V) to (5 ppm + 2 μ V)
DC4	Master Shunt Boxes	Leeds & Northrup	0.015 to 15 A	0.005%
DC5	Calibrated DC Current Supply	FM&T Metrology	1.5 μ A to 15 A (7 ranges)	(0.02% or 1 nA), whichever is greater
DC6	Calibrated DC Voltage Source	Fluke	0 to 999.999 mV	14 ppm + 1 μV
			1 to 11 V	10 ppm + 5 μV
			>11 to 22 V	10 ppm + 8 μV
			>22 to 275 V	10 ppm + 100 μV
			>275 to 1100 V	11 ppm + 400 μV
DC7	Ratio Divider	Guildline	1:1 to 10,000:1	4 ppm
DC8	Current Comparator Potentiometer	Guildline	0 to 0.02 V	(4 ppm + 0.01 μ V)
			0 to 0.2 V	(2 ppm + 0.02 μ V)
			0 to 2 V	(1 ppm + 0.1 μ V)
DC9	Shunt Standards	Leeds & Northrup Guildline	0 to 15 A	0.005%
			0 to 100 A	0.01%
			0 to 300 A	0.015%
			0 to 500 A	0.010%



DC Resistance and Ratio Traceability

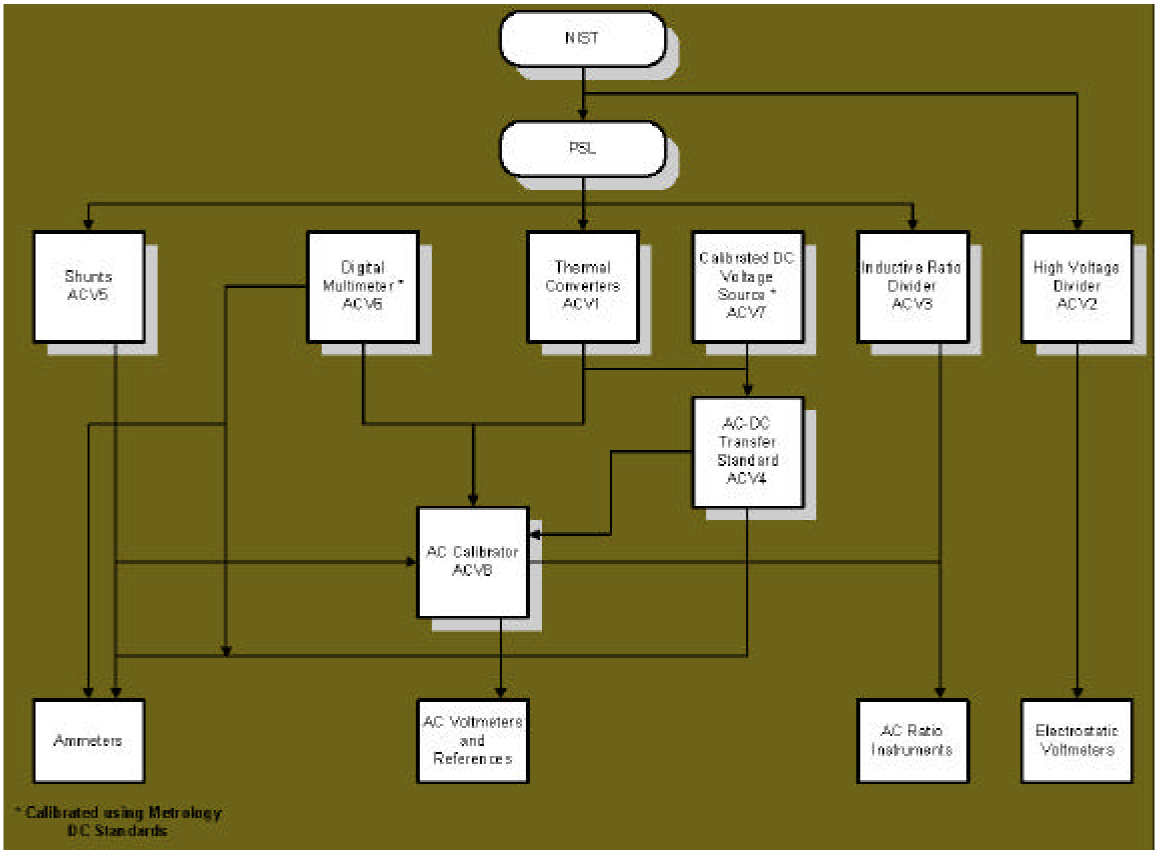
DC Resistance and Ratio Standards

Code	Description	Manufacturer	Range	Uncertainty (±) (k=2)
RES1	Resistance Standard	Leeds & Northrup, Julie, Guildline	0.001 Ω to 100 MΩ	0.002 to 0.01%
RES3	Teraohmmeter	Guildline	10^7 to 10^{13} Ω	0.05% to 0.5%
RES4	Double Ratio Set/Direct Reading Ratio Set	Leeds & Northrup	0.0001 Ω to 1 MΩ	0.002% (DRS) 0.0002% (DRRS)
RES5	Resistance Measuring System	ESI	0.001 Ω to 10 MΩ	(0.005% + M x 0.005 Ω)
			10 to 100 MΩ	(0.01% + M x 0.005 Ω) M = range multiplier
RES6	High-Resistance Measuring System	Mid-Eastern	10^8 to 10^{13} Ω	0.3% to 0.5%
RES7	High Voltage Resistance Standard	Spellman	2000 x 10^6 Ω	0.03%
RES8	Decade Resistor	Guildline	0 to 100 kΩ	(0.005% of setting + 0.004 Ω)
RES9	Resistance Calibrator	Fluke	1 Ω to 100 MΩ	0.005% to 0.02%
RES10	Digital Multimeter	Hewlett-Packard	10 Ω to 100 MΩ	(0.01% or 10 digits) whichever is greater (0.05% or 50 digits) whichever is greater

Electrical Alternating Current Measurement Capability

Type	Range	Frequency	Measuring Uncertainty (±) (k=2)
AC Voltage *	2.2 to 70 mV	10 Hz to 100 kHz	<0.12% + 2.5 µV
	2.2 to 70 mV	100 kHz to 1 MHz	<0.35% + 8 µV
	70 to 700 mV	10 Hz to 100 kHz	<10 ppm + 2.5 µV
	70 to 700 mV	100 kHz to 1 MHz	<0.10% + 8 µV
	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 70 kV	60 Hz	0.3%
AC Current	10 mA to 20 A	10 Hz to 50 kHz	0.05 to 0.07%
Capacitance	0.001 pF to 1 µ F	1 kHz	(0.01% + 0.00005 pF)
	1 to 10 µ F	1 kHz	0.02%
	10 to 100 µ F	1 kHz	0.5%
	1.0 to 1000 pF	1 MHz	0.1 to 0.2%
Inductance **	0.05 to 2 µ H	10 kHz to 1 MHz	0.7% to 12%
	2 to 100 µ H	10 kHz to MHz	0.7% to 3%
	100 µ H to 10 H	1 kHz	0.04% to 0.4%
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



AC Current, Voltage, and Ratio Traceability

AC Current, Voltage, and Ratio Standards

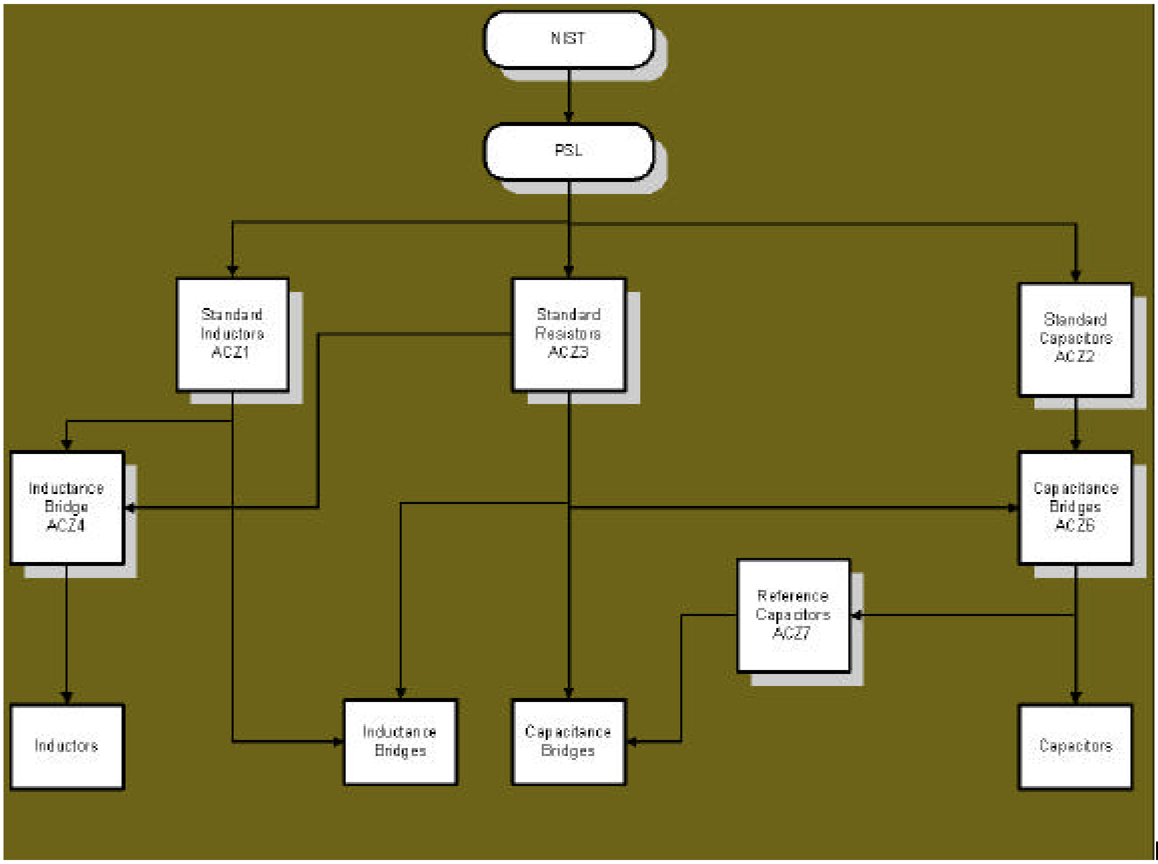
Code	Description	Manufacturer	Range	Uncertainty (±) (k=2)
ACV1	Thermal Converters	Holt	0.5 V to 1000 V (10 Hz to 1 MHz)	25 ppm to 110 ppm
		Ballantine		0.02 to 1.2%
			1 V (10 Hz to 100 MHz)	
		Fluke		0.1 to 1.2%
			1.0 to 10 V (10 Hz to 100 MHz)	
		Holt		25 ppm to 700 ppm
		Holt	2 mV to 200 mV (20 Hz to 1 MHz)	10 ppm to 325 ppm
			0.5 V (10 Hz to 1 MHz)	
ACV2	High Voltage Divider	Julie	20 to 100 kV	0.25%
ACV3	Inductive Ratio Divider	ESI	Ratio only, 0.1 ppm resolution (50 Hz to 10 kHz)	1 to 150 ppm
ACV4	AC-DC	Fluke 5790A	2.2 to 70 mV (10 Hz to 100	<0.12% + 2.5 µV

	Transfer Standard		kHz) 2.2 to 70 mV (100 kHz to 1 MHz) 70 to 700 mV (10 Hz to 100 kHz) 70 to 700 mV (100 kHz to 1 MHz) 700 mV to 70 V (10 Hz to 300 kHz) 700 mV to 70 V (300 kHz to 1 MHz) 70 V to 220 V (10 Hz to 500 kHz) 220 V to 1000 V (10 Hz to 100 kHz) 1 to 70 kV (60 Hz)	<0.5% + 8 μV <200 ppm + 2.5 μV <0.10% + 8 μV <200 ppm <1200 ppm <500 ppm <800 ppm 0.3%
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 1 to 100 V ranges 1000 V range	15 ppm + 10 ppm of range 10 ppm +1 ppm of range 20 ppm +1 ppm of range
ACV7	Calibrated DC Voltage Source	Fluke	10 to 1000 V three ranges	0.0025% or 1 μ V, whichever is greater
ACV8	AC Calibrator	Fluke	1 mV to 100 mV (10 Hz to 30 kHz)	(0.02% of setting + 0.005% FS + 10 μ V)

1 V to 100 V (10 Hz to 50 kHz)	(0.02% of setting + 0.005% FS +10 μ V)
	(0.06% of setting + 0.006% FS +10 μ V)
1 mV to 100 mV (30 kHz to 100 kHz)	(0.06% of setting + 0.006% FS +10 μ V)
1 V to 10 V (50 kHz to 100 kHz)	(0.06% of setting + 0.006% FS +10 μ V)
	(0.6% of setting + 0.1% FS)
1000 V range (50 Hz to 1 kHz)	(0.4% of setting + 0.1% FS)
1 mV to 100 mV (100 kHz to 1 MHz)	0.1% of setting
1 V to 10 V (100 kHz to 1 MHz)	0.3% 0.25% 0.75% 1.0%
100 V range (50 kHz to 100 kHz)	(0.07% of setting + 0.01% of range)

Wideband output
10 to 30 Hz
> 30 Hz to 1 MHz
> 1 MHz to 20 MHz
> 20 MHz to 30 MHz

0 - 2 A



Inductance and Capacitance Traceability

Inductance, Capacitance, and AC Resistance Standards

Code	Description	Manufacturer	Range	Uncertainty (±) (k=2)
ACZ1	Standard Inductors	General Radio, FM&T	50 µ H to 10 H	0.03 to 0.3% *
		Metrology, Hewlett-Packard,	50 nH to 100 µ H	0.3 to 10% *
		Boonton		
ACZ2	Standard Capacitors	General Radio	1000 pF, fixed	0.004% at 1 kHz
ACZ3	Standard Resistors	Leeds & Northrup	1 to 20K Ω	0.015%
ACZ4	Inductance Bridge	Hewlett-Packard	100 µ H to 5H	0.15 to 0.3% (direct measurement)
			0.05 µ H to 10 µ H	0.1 to 10% (comparison to standard inductors)
ACZ6	Capacitance Bridge	General Radio	0.001 pF to 1 µ F 1 µ F to 10 µ F	(0.01% + 0.00005 pF) 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	1 to 1000 pF	0.02% to 0.11% **
		General Radio FM&T	0.1 to 1000 pF	0.1 to 0.15% **
		Metrology	0.001 to 1 µ F	0.02% at 1 kHz
			1 to 10 µ F in 1 µ F increments	0.1% at 1 kHz
			10 to 100 µ F in 10 µ F increments	0.1% at 1 kHz

* Uncertainty depending on inductance value and frequency
** Uncertainty depending on capacitance value and frequency

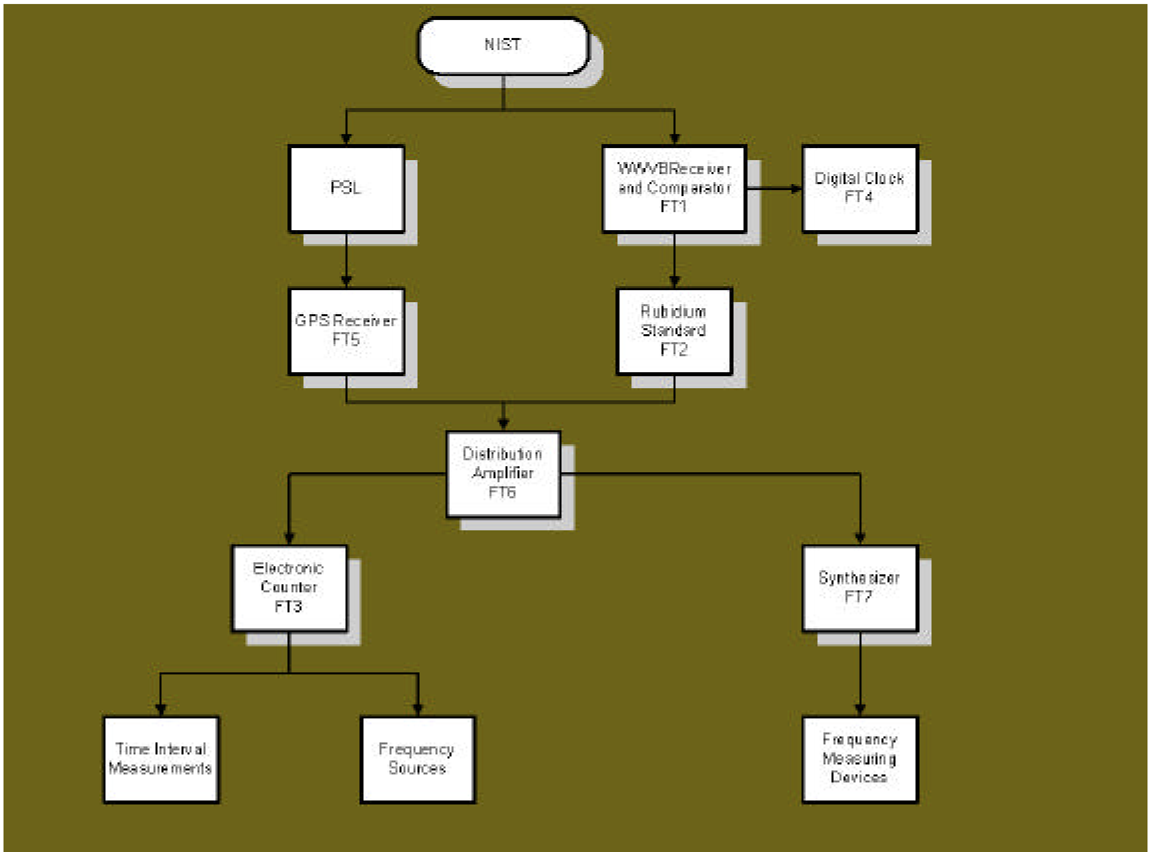


Figure 5C. Frequency and Time Traceability

Frequency and Time Standards

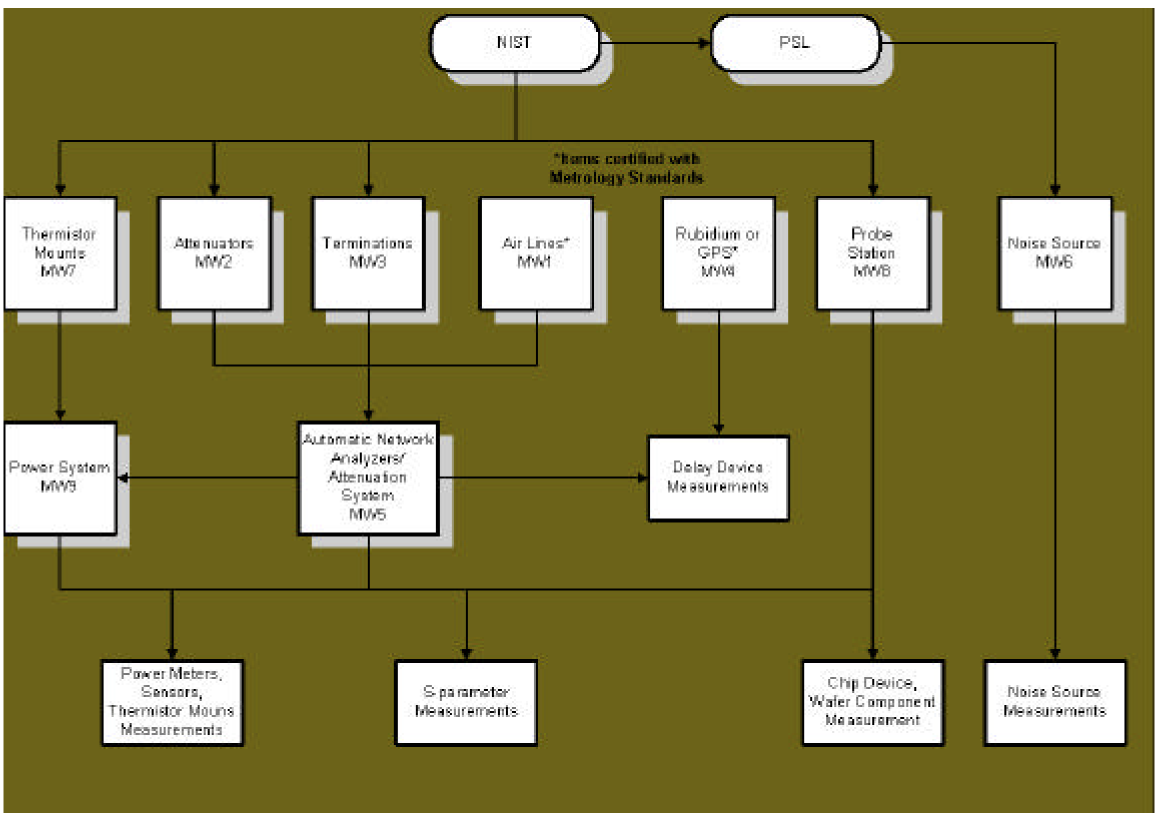
Code	Description	Manufacturer	Range	Uncertainty (±) (k=2)
FT1	WWVB Receiver and Comparator	Kinemetrics	60 kHz	Comparison Device
FT2	Rubidium Standard	Efratom	0.1 MHz to 10 MHz	1 part in 10^9
FT3	Counter	Various	>0 Hz to 46 GHz	Used with rubidium or GPS
FT4	Digital Clock	Truetime	24 hours	0.5 ms
FT5	GPS 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 Rubidium or GPS
FT7	Synthesizer	Various	>0 kHz to 50 GHz	Used with Rubidium or GPS

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]			
$\|\Gamma\|$	$\|S_{ii}\|$, 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
	$\|S_{ij}\|$, >70 dB to 100 dB	10 MHz to 8.5 GHz	0.25 dB to 2 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 5 W to 1000 W	100 kHz to 4.2 GHz >4.2 GHz to 18 GHz 10 MHz to 18 GHz 10 MHz to 1.0 GHz 10 MHz to 200 MHz	2.4% to 4.2% 3.0% to 10 % 2.5% to 10 % 5% + Additional Unc. 5% + Additional Unc.
Peak Power Meter	10 µW to 100 mW	1 GHz to 2 GHz	5%

Systems[1]			
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

1Referenced 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| ± 0.028Ω to 0.20Ω
		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	|Γ| ± 0.0008 to 0.003 ϕ ± 0.2° to 180°
MW4	Rubidium	Efratom	10 MHz	± 0.001 ppm
	GPS Receiver	Hewlett Packard	10 MHz	± 0.000005 ppm
MW5	Network Analyzers/	Hewlett Packard	300 kHz to 26.5 GHz	|Γ| ± 0.001 to 0.035
			|Γ|, 0 to 1; ϕ, -180° to 180°	f ± 0.35° to 180°
	Attenuation System	Weinschel Eng.	Attenuation, 0 dB to 100 dB	± 0.02 dB to 2 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	± 0.95% 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 heat flow calorimeters are calibrated by the Primary Standards Laboratory. 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 µm. 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.

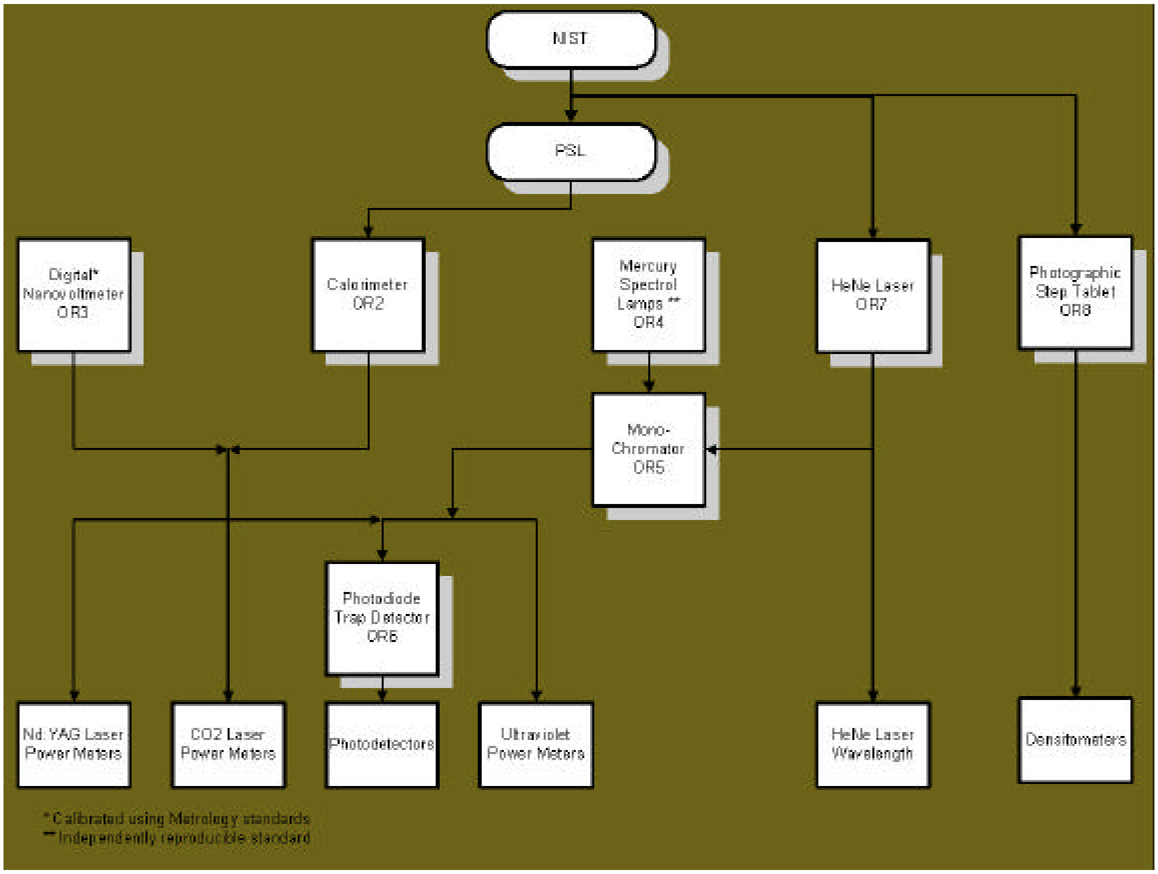
Radiation Measurement

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 µ m 1 µ W to 1 mW 1 mW to 10 W	 1.5% 1.0%
	l = 10.6 µ m 1 mW to 10 W 10 to 1000 W	 3% 6%
LED Power	l = 570 to 910 nm 10 µ W 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 (Radiometr

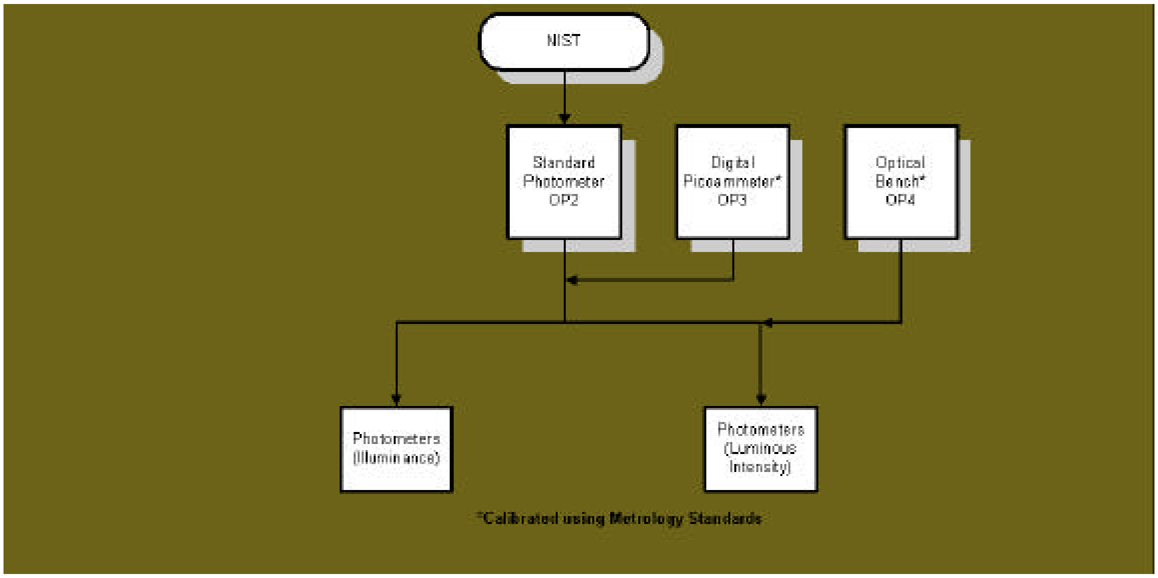
Optical Radiometri Measureme Standards

Code	De
OR2	Ca
OR3	Di Na
OR4	Me La
OR5	Mo
OR6	Ph De
OR7	He
OR8	Ph Ta

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 (Photometr

Optical Photometric Measureme Standards

Code	De
OP2	Sta Ph
OP3	Dig Pic
OP4	Op