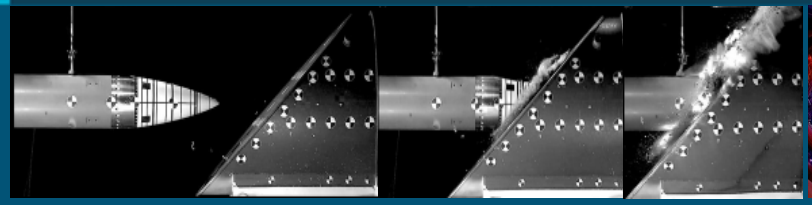
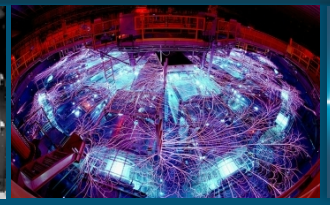
SAND2021-9871C

Sandia National Laboratories

A New Automated Calibration System for 5790 Alternating Current Measurement Standards





PRESENTED BY

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U.S. DEPARTMENT OF ENERGY | NNSA

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5790 AC Measurement Standard

What is it and how is one currently calibrated?

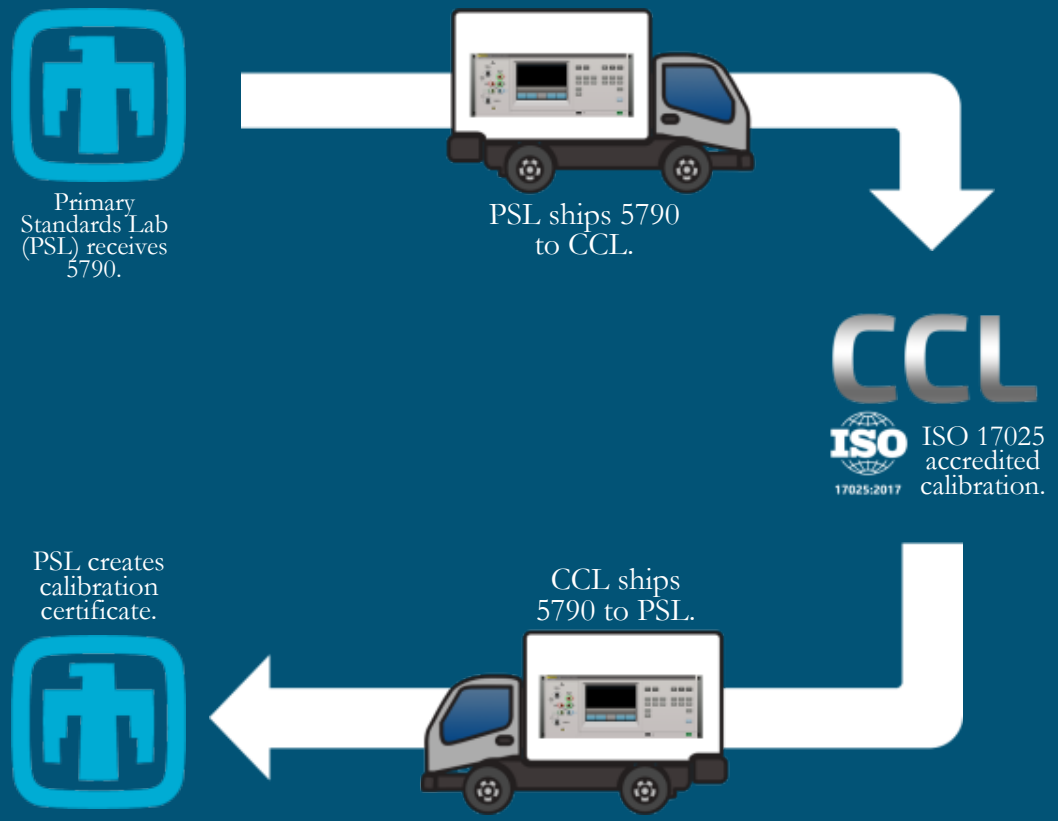
5790 AC Measurement Standard

- Designed to provide the accuracy of a thermal transfer standard in a digital multimeter package.
- Can verify Alternating Current (AC) voltage, AC current with shunts, and high-frequency AC for various models of calibrators.
- Voltage range covers 600 µV through 1000 V.
- Frequency range covers 10 Hz through 1 MHz. High-frequency options extend range through 30 MHz or 50 MHz.

*Certain commercial equipment, instruments, software, or materials are identified in this presentation in order to adequately describe the experimental procedure. Such identification does not imply recommendation or endorsement by the authors, Sandia National Laboratories, nor does it imply that the materials or equipment identified are the only or best available for the purpose.

Former Calibration Process

The former process for calibrating 5790s involved shipping each unit to an approved Commercial Calibration Laboratory (CCL).



Expensive equipment was shipped annually.

Minimum calibration time of 1 month.

Costs up to $10,685 per calibration.

No physical control of asset.

Motivations

Why do we now calibrate 5790’s at the PSL?

Improve Calibration Process

Eliminate possibility of equipment damage when shipping asset to and from CCL.

Reduce the calibration and adjustment time.

Reduce the calibration cost.

Maintain physical control.

Support convergence.

Ensure Proper Guardbanding

To determine the adequacy of a calibration process relative to manufacturer's specification or limit, a Test Uncertainty Ratio (TUR) can be used, which is defined as:

$$\text{TUR} = \frac{\text{Limit}}{\text{Measurement Uncertainty } (k = 2)}$$

If the TUR is 4:1 or greater, the calibration process is adequate. However, if the TUR is between 1.5:1 and 4:1, the specifications must be adjusted (PSL-PRO-001-03-C).

$$\text{Adjusted Limit} = \sqrt{1 - \frac{1}{\text{TUR}^2}} \times \text{Limit}$$

This adjustment process is called "Guardbanding", and it provides essentially the same constant consumer risk (false accept) for TURs from 1.5:1 to 4:1 (approximately 0.6%).

Guardbanding increases producer risk (false reject) from 2% at a TUR of 4:1, to approximately 8% at a TUR of 2:1.

Design Philosophy

What approach was used in system design?

Calibration Complexity

The calibration and adjustment of a 5790 AC Measurement Standard is complex and consists of the following:

- 9 instruments
- 14 functional tests
- 22 unique calculations
- 30 connection configurations
- >1000 measurement and adjustment points

Manual calibration and adjustment would take dozens of hours at a minimum to complete.

Lab personnel would require extensive training to learn the calibration and adjustment process.

Numerous manual calculations could introduce error into the calibration and adjustment.

Automation and Software Control

Used a software-driven system with nearly total automation and minimum user interaction. This system design approach includes the following attributes:

- Complete instrument Input-Output (I/O)
- Flexibility to enter and exit any of the 14 tests at any time.
- Software-controlled calculations including time-of-test uncertainties and TURs.
- Step-by-step diagrams for calibration setup and teardown
- Ability to retest individual points and collect raw data

Calibration will still take dozens of hours to complete. However, personnel interaction is reduced to less than 1 hour.

Minimum training for lab personnel.

Once submitted through Software Quality Assurance (SQA), calculations can be trusted every time.

System Overview

Equipment and accessories

Major Measurement System 1202

Tri-Color Indicator Light

Normal Operation

Needs Attention

High Voltage

Main Test Bench

Desktop computer for software control

System Footprint

Instrument Rack

5790A

5790B

792A and Power Pack

732C DC Standard

752A Reference Divider

2182 Nanovoltmeter

53220A Freq. Counter

8508 Reference Multimeter

5730A Calibrator & 5725 Amplifier

Traceability

5790 calibration requires traceability for the following parameters:

- Frequency
- Direct Current (DC) Voltage
- AC Voltage
- High-Frequency AC Voltage

Second SI Unit

All calibration traceability comes from the second!

s

NIST FREQUENCY MEASUREMENT & ANALYSIS SERVICE

NIST FMAS

Hz = 1/s

5071A Cesium Frequency Standard

10MHz

53220A Frequency Counter

Frequency

10MHz

The PJVS provides a quantum-accurate DC voltage with accuracy of parts 10^{10}!

Programmable Josephson Voltage Standard (PJVS)

Volt

DC Voltage

732C DC Voltage Standard

DC Voltage

DC Voltage

792 AC/DC Transfer Standard

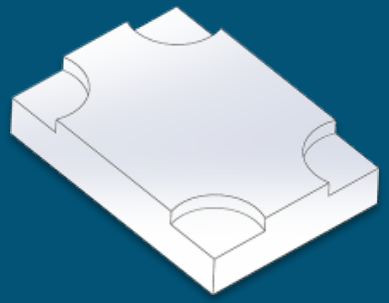
AC Voltage

High-Frequency Voltage

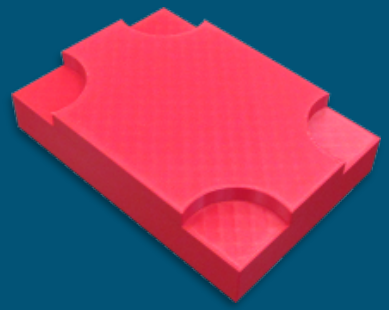
Thermal Voltage Converters (TVC)

Design and Fabrication

The following items were constructed to complete the 5790 calibrations:



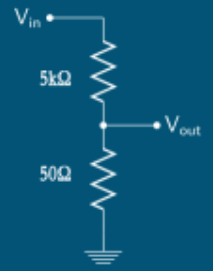
3D Modeled 792 Stand



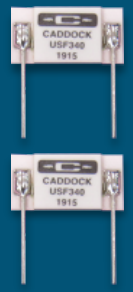
3D Printed 792 Stand

A cable was constructed to connect the 2182A Nanovoltmeter to the EL1100 TVC.

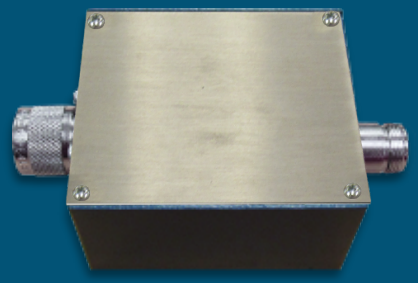
For the 20mV through 2mV ranges, a 100:1 voltage divider was needed.



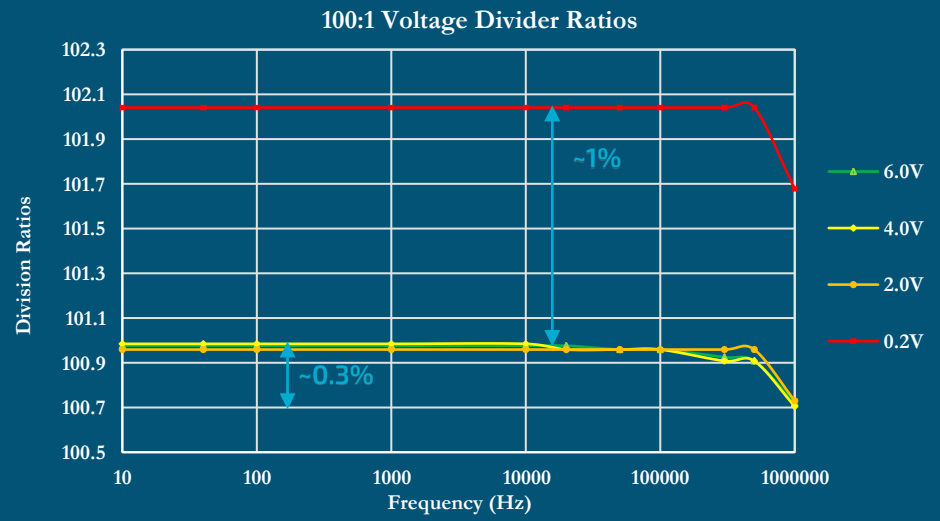
100:1 Voltage Divider



Caddock USF340 5kΩ and 50Ω pair ±0.01%



Assembled Divider for 2V-6V



Software Overview

Software Design

Software Features

Software was constructed in LabVIEW and consists of ~300 Virtual Instruments (VIs).

Instrument configuration checks calibration dates, controls I/O, and loads current standard uncertainties.

Detailed connection diagrams for every step of the calibration.

Animated user prompts to effectively communicate calibration steps and progress.

Real-Time Instrument User Interfaces

Every instrument has a real-time user interface to reflect the current status and measurement readings. This allows for continuous situational awareness regardless of instrument placement relative to lab personnel.

User Interface

Actual Instrument

Customizable User Experience (UX)

The user interface can be tabbed through to see the different measurement parameters and results. The current measurement information is also displayed real time.

The user interface will only show the current instruments being used. These instruments can be hidden or displayed based on monitor size and user preference. This allows for a minimal or robust program display.

Automation

Added Tri-Color indicator lights for visual and audible indications of system status and safety signaling.

Normal Operation | Action Needed | High Voltage

Implementing SunJEM 2011B Automatic Range Switch for the 792A. Eliminates 50% of user interaction.

Uncertainty and TUR Calculations

The software performs all calculations required in the calibration. It also calculates time-of-test uncertainties and determines the TUR. Finally, if a TUR is <4:1, the software will guardband the specification.

Standard uncertainty

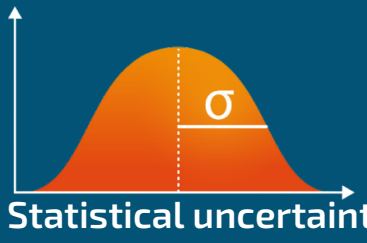
u_{b1}

Standard uncertainty

u_{b2}

Standard uncertainty

u_{b3}



Statistical uncertainty

u_{a1}

Time-of-Test Uncertainty

$$U_c = \sqrt{u_{b1}^2 + u_{b2}^2 + u_{b3}^2 + u_{a1}^2} \times 2.58$$

U_c = expanded uncertainty

u_b = standard uncertainties

u_a = statistical uncertainty

k(coverage factor)=2.58

Coverage factor is 2.58 rather than 2 due to manufacturer's specifications using k=2.58.

U_c

$$TUR = \frac{limit}{U_c}$$

Results

System Analysis and Calibration Reports

Process Improvements

Eliminated possibility of damage during shipping to and from CCL.

Reduced calibration and adjustment time from a minimum of 1 month to 3 days for main input and 1 week for high-frequency calibrations.

Expense	Cost
Equipment Purchases	$87,769
Burdened Labor	$123,683
Estimated Total System Cost	$211,452

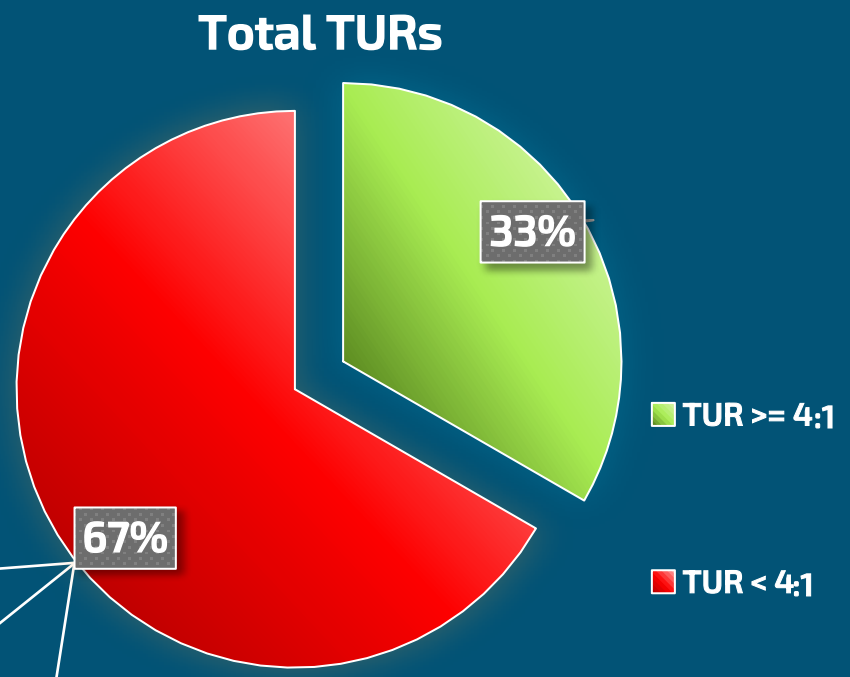
Model	Quantity	Cost
5790A	2	$7,215
5790A/3	8	$10,685
5790B	1	$7,215
5790B/3	2	$10,685
5790B/5	3	$10,500
Total Annual CCL Cost		$159,995

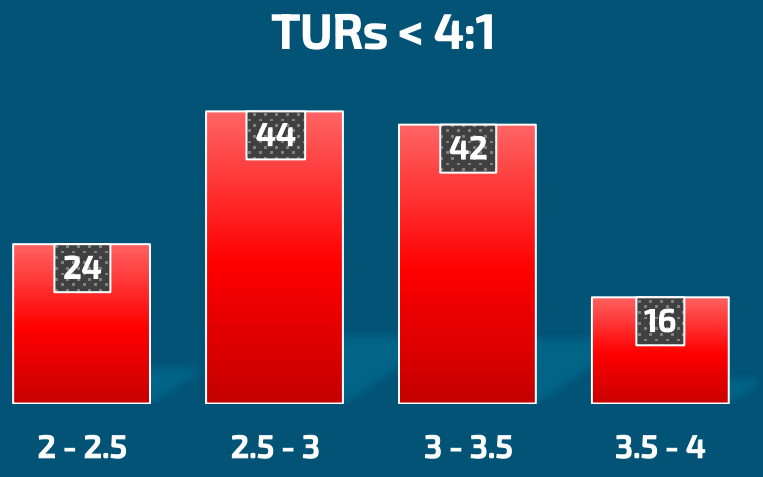
Maintain physical control throughout calibration process.

Calibration supports convergence.

Test Uncertainty Ratios

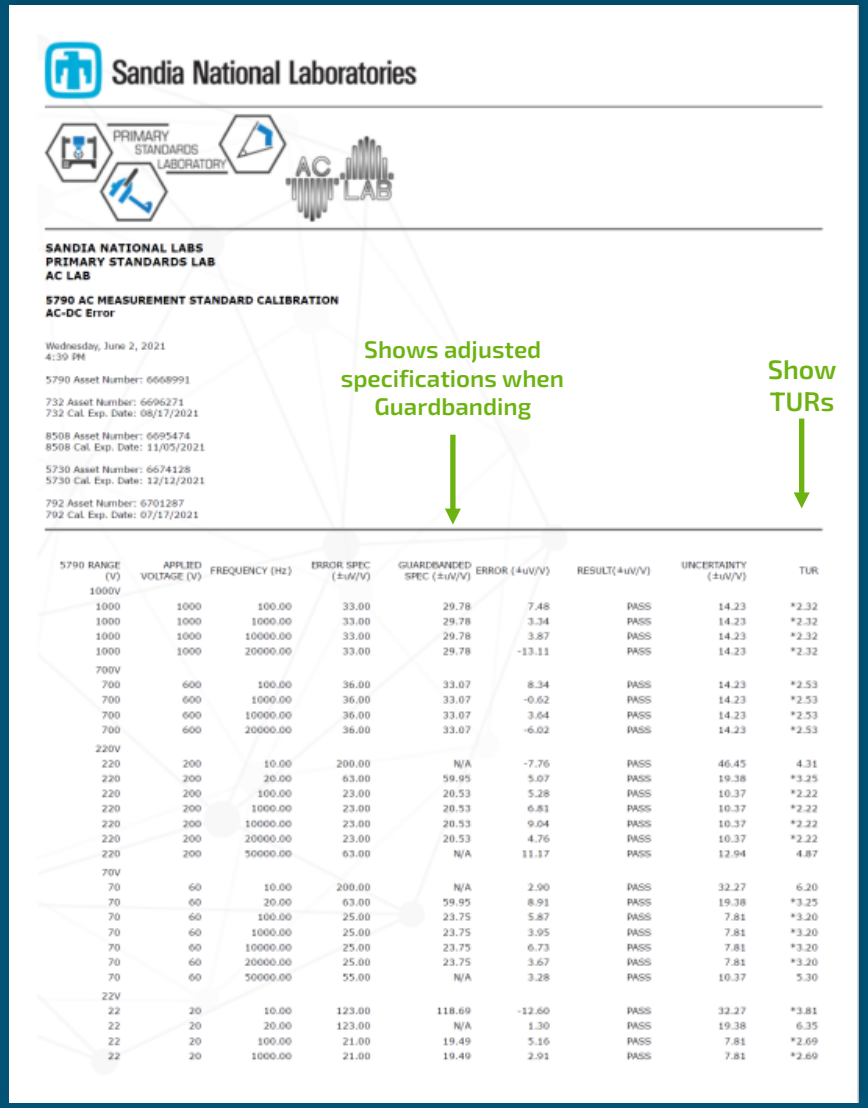
- 189 calibration points for main input calibration
- 63 points had a TUR >= 4:1
- 126 points had a TUR < 4:1





- 126 points guardbanded to provide adequate constant consumer risk (false accept of ~0.6%)
- No calibration points had a TUR < 2:1

Calibration Report



Sandia National Laboratories

PRIMARY STANDARDS LABORATORY

AC LAB

SANDIA NATIONAL LABS
PRIMARY STANDARDS LAB
AC LAB

5790 AC MEASUREMENT STANDARD CALIBRATION
AC-DC Error

Wednesday, June 2, 2021
4:39 PM

5790 Asset Number: 6668991

732 Asset Number: 6696271
732 Cal. Exp. Date: 08/17/2021

8508 Asset Number: 6695474
8508 Cal. Exp. Date: 11/05/2021

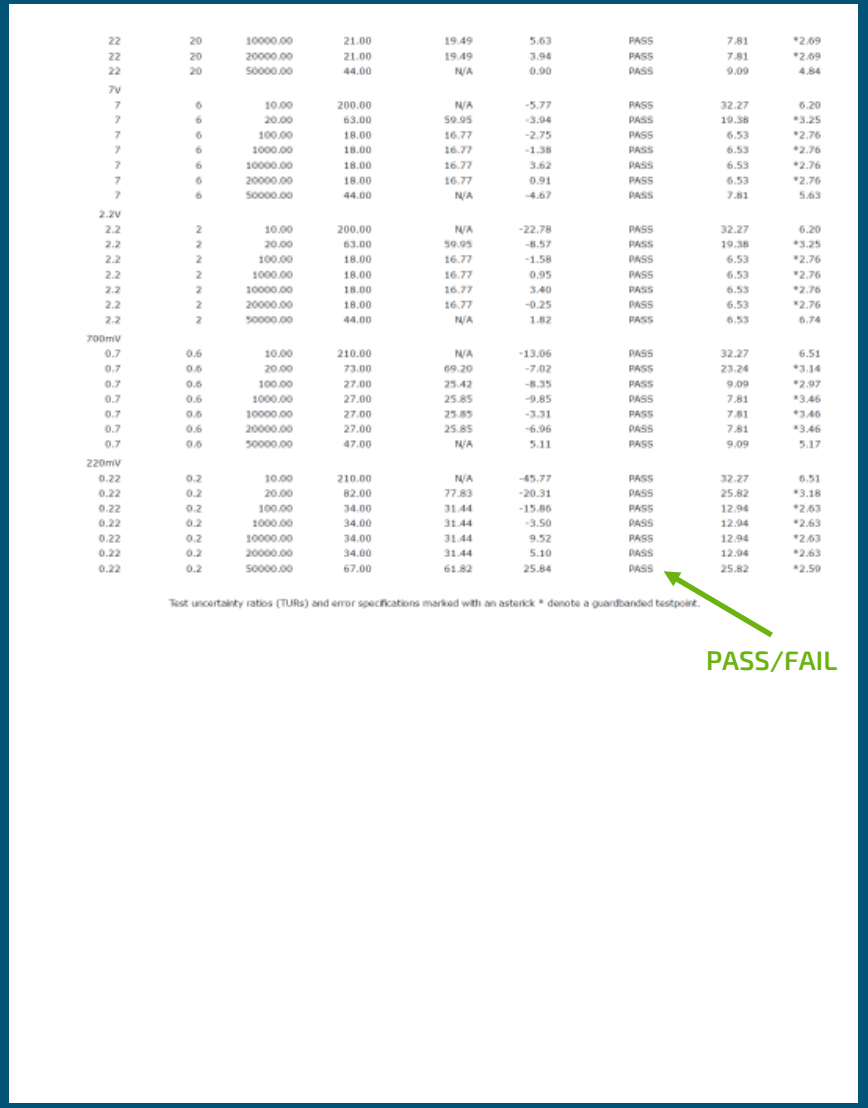
5730 Asset Number: 6674128
5730 Cal. Exp. Date: 12/12/2021

792 Asset Number: 6701287
792 Cal. Exp. Date: 07/17/2021

Shows adjusted specifications when Guardbanding

Show TURs

5790 RANGE (V)	APPLIED VOLTAGE (V)	FREQUENCY (Hz)	ERROR SPEC (±uV/V)	GUARDBANDED SPEC (±uV/V)	ERROR (±uV/V)	RESULT(±uV/V)	UNCERTAINTY (±uV/V)	TUR
1000V								
1000	1000	100.00	33.00	29.78	7.48	PASS	14.23	*2.32
1000	1000	1000.00	33.00	29.78	3.34	PASS	14.23	*2.32
1000	1000	10000.00	33.00	29.78	3.87	PASS	14.23	*2.32
1000	1000	20000.00	33.00	29.78	-13.11	PASS	14.23	*2.32
700V								
700	600	100.00	36.00	33.07	8.34	PASS	14.23	*2.53
700	600	1000.00	36.00	33.07	-0.62	PASS	14.23	*2.53
700	600	10000.00	36.00	33.07	3.64	PASS	14.23	*2.53
700	600	20000.00	36.00	33.07	-6.02	PASS	14.23	*2.53
220V								
220	200	10.00	200.00	N/A	-7.76	PASS	46.45	4.31
220	200	20.00	63.00	59.95	5.07	PASS	19.38	*3.25
220	200	100.00	23.00	20.53	5.28	PASS	10.37	*2.22
220	200	1000.00	23.00	20.53	6.81	PASS	10.37	*2.22
220	200	10000.00	23.00	20.53	9.04	PASS	10.37	*2.22
220	200	20000.00	23.00	20.53	4.76	PASS	10.37	*2.22
220	200	50000.00	63.00	N/A	11.17	PASS	12.94	4.87
70V								
70	60	10.00	200.00	N/A	2.90	PASS	32.27	6.20
70	60	20.00	63.00	59.95	8.91	PASS	19.38	*3.25
70	60	100.00	25.00	23.75	5.87	PASS	7.81	*3.20
70	60	1000.00	25.00	23.75	3.95	PASS	7.81	*3.20
70	60	10000.00	25.00	23.75	6.73	PASS	7.81	*3.20
70	60	20000.00	25.00	23.75	3.67	PASS	7.81	*3.20
70	60	50000.00	55.00	N/A	3.28	PASS	10.37	5.30
22V								
22	20	10.00	123.00	118.69	-12.60	PASS	32.27	*3.81
22	20	20.00	123.00	N/A	1.30	PASS	19.38	6.35
22	20	100.00	21.00	19.49	5.16	PASS	7.81	*2.69
22	20	1000.00	21.00	19.49	2.91	PASS	7.81	*2.69



22	20	10000.00	21.00	19.49	5.63	PASS	7.81	*2.69
22	20	20000.00	21.00	19.49	3.94	PASS	7.81	*2.69
22	20	50000.00	44.00	N/A	0.90	PASS	9.09	4.84
7V								
7	6	10.00	200.00	N/A	-5.77	PASS	32.27	6.20
7	6	20.00	63.00	59.95	-3.94	PASS	19.38	*3.25
7	6	100.00	18.00	16.77	-2.75	PASS	6.53	*2.76
7	6	1000.00	18.00	16.77	-1.38	PASS	6.53	*2.76
7	6	10000.00	18.00	16.77	3.62	PASS	6.53	*2.76
7	6	20000.00	18.00	16.77	0.91	PASS	6.53	*2.76
7	6	50000.00	44.00	N/A	-4.67	PASS	7.81	5.63
2.2V								
2.2	2	10.00	200.00	N/A	-22.78	PASS	32.27	6.20
2.2	2	20.00	63.00	59.95	-8.57	PASS	19.38	*3.25
2.2	2	100.00	18.00	16.77	-1.58	PASS	6.53	*2.76
2.2	2	1000.00	18.00	16.77	0.95	PASS	6.53	*2.76
2.2	2	10000.00	18.00	16.77	3.40	PASS	6.53	*2.76
2.2	2	20000.00	18.00	16.77	-0.25	PASS	6.53	*2.76
2.2	2	50000.00	44.00	N/A	1.82	PASS	6.53	6.74
700mV								
0.7	0.6	10.00	210.00	N/A	-13.06	PASS	32.27	6.51
0.7	0.6	20.00	73.00	69.20	-7.02	PASS	23.24	*3.14
0.7	0.6	100.00	27.00	25.42	-8.35	PASS	9.09	*2.97
0.7	0.6	1000.00	27.00	25.85	-9.85	PASS	7.81	*3.46
0.7	0.6	10000.00	27.00	25.85	-3.31	PASS	7.81	*3.46
0.7	0.6	20000.00	27.00	25.85	-6.96	PASS	7.81	*3.46
0.7	0.6	50000.00	47.00	N/A	5.11	PASS	9.09	5.17
220mV								
0.22	0.2	10.00	210.00	N/A	-45.77	PASS	32.27	6.51
0.22	0.2	20.00	82.00	77.83	-20.31	PASS	25.82	*3.18
0.22	0.2	100.00	34.00	31.44	-15.86	PASS	12.94	*2.63
0.22	0.2	1000.00	34.00	31.44	-3.50	PASS	12.94	*2.63
0.22	0.2	10000.00	34.00	31.44	9.52	PASS	12.94	*2.63
0.22	0.2	20000.00	34.00	31.44	5.10	PASS	12.94	*2.63
0.22	0.2	50000.00	67.00	61.82	25.84	PASS	25.82	*2.59

Test uncertainty ratios (TURs) and error specifications marked with an asterick * denote a guardbanded testpoint.

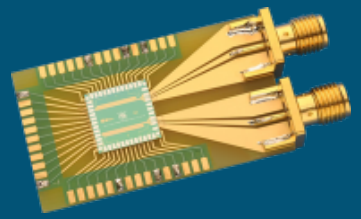
PASS/FAIL

Provide customer with easy to read calibration report.

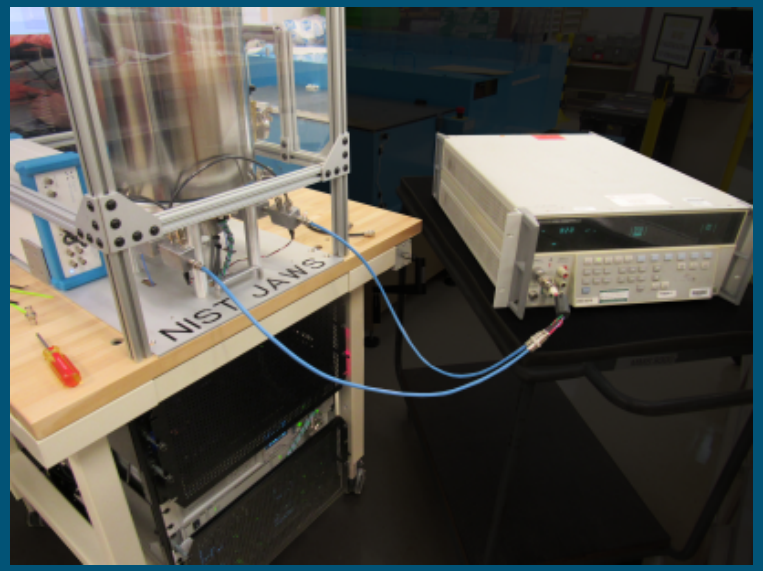
Future Work

System Analysis and Improvements

Future Work



Use the Josephson Arbitrary Waveform Synthesizer (JAWS) to achieve lower uncertainties for millivolt ranges up to 20kHz.



Primary Standards Lab's
NIST JAWS System

Continue analyzing results of high-frequency calibrations.

Acknowledgements

Thank you to the following individuals and organizations!

- Meaghan Carpenter
- Roger Burton
- Brian Liddle
- Convergence Team
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Questions