Using Commercial Source Measure Units for Traceable RF Power Measurements

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***Abstract*—As a National Metrology Institute (NMI), the National Institute of Standards and Technology (NIST) maintains traceable measurement capabilities for a variety of quantities, including microwave power. At NMIs and calibration laboratories, traceable microwave power measurements often rely on the principle of dc substitution. This approach involves a power meter that provides dc power to a sensor under test. Typically, dc substitution power meters are implemented by analog electronics, making them difficult to maintain. Here, we explore programmable source measure units as an alternative implementation of the power meter. We offer a preliminary uncertainty analysis and describe a method to reduce measurement uncertainty due to the accuracy of the measurement equipment.**

***Index Terms*—Microwave measurement, Power measurement, Calibration, Measurement Uncertainty.**

I. INTRODUCTION

Providing traceable measurements is a core part of NIST's mission. Traceable measurements can be related to a reference through an unbroken chain of calibrations, each contributing to measurement uncertainty through rigorous uncertainty analysis. From a technical perspective, there are two requirements for traceability: a clear relationship between the measurement result and the references it depends on, and a reliable uncertainty model.

In the case of microwave power measurements, NIST realizes traceability through the principle of dc substitution [1], which allows RF power measurements to be traceable to dc current and voltage. This approach has the advantage that dc measurements can be easily traced to primary standards with a high degree of accuracy. Sensors used in dc substitution measurements contain a temperature-sensitive resistor that can be heated by both RF and dc power. A power meter consists of a feedback loop that maintains the resistor at a specified resistance by varying the applied dc power. The RF power absorbed by a sensor is then determined by

$$P_{\mathrm{sub}} = \eta P_{\mathrm{RF}}, \quad (1)$$

$$P_{\mathrm{sub}} = V_{\mathrm{off}} I_{\mathrm{off}} - V_{\mathrm{on}} I_{\mathrm{on}}, \quad (2)$$

where I and V are the dc current and voltage supplied to the resistor, the subscripts "on" and "off" indicate whether the continuous wave RF source was turned on or turned off before the sensor is allowed to settle, and P_{RF} is RF power absorbed by the sensor. The frequency dependent effective efficiency, η, is defined by (1), and is measured in a microcalorimeter [2].

NIST uses several sensor designs in dc substitution measurements. In the 2.4 mm connector type, NIST uses sensors based on platinum thin films with a positive temperature coefficient of resistance and an operating resistance of about 1 kΩ. In Type N and several types of rectangular waveguide, NIST uses thermistors with a negative temperature coefficient of resistance. These sensors have operating resistance of either 100 Ω or 200 Ω, depending on the model.

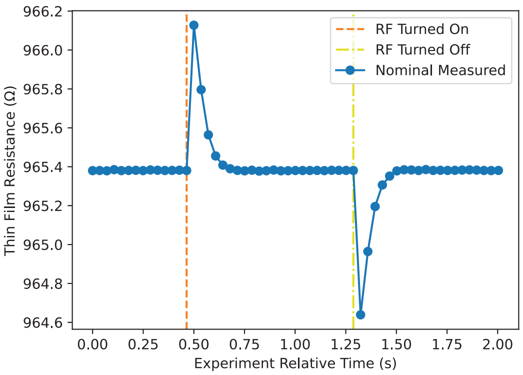
For several decades, NIST has relied on the Type IV power meter, an analog meter developed in 1976 [3]. There are two different types of Type IV power meters corresponding to sensors with positive or negative coefficients of resistance. While these power meters have facilitated precision measurements for several decades, they are inconvenient to maintain because testing and repairing these complex analog devices requires a significant amount of specialized knowledge. This challenge motivated us to try using a commercial instrument that requires only basic computer programming skills to operate.

Here, we describe a dc substitution power meter using a commercial source measure unit (SMU) with a programmable embedded microcontroller. Besides the ease of maintenance, we see other advantages to this approach. Because the SMU can execute user-defined programs, its behavior can be easily modified. One immediate use of this flexibility is testing resistance states for the thermistor sensors other than the specified 200 Ω and 100 Ω, which may be helpful in microcalorimeter evaluation. Another advantage is the SMU records both current and voltage timeseries, which are convenient for uncertainty evaluation. Because the SMU can execute programs independently, it can operate in parallel to a computer that coordinates measurements between the SMU and other instruments.

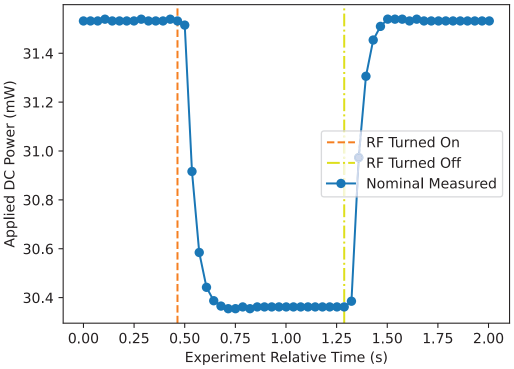
We programmed the SMU's embedded controller to update applied dc voltage, for thin film sensors, or current, for thermistor sensors, using a proportional–integral–derivative (PID) controller. This paper focuses on thin film sensors only.

Figure 1 illustrates the dc substitution measurement process using time series data acquired by an SMU. The SMU supplied dc power to a thin film sensor and was configured to maintain the thin film's resistance at 965.4 Ω. When RF power was applied, the RF termination inside the sensor absorbed power, which heated the thin film, causing its resistance to increase. The SMU then reduced applied dc power to return the resistance to the set point. The applied RF power at the sensor's reference plane is then equal to the difference in power between the off and on state, divided by the frequency dependent effective efficiency as described by (1) and (2).

To evaluate the SMU uncertainty, we considered both random and systematic deviations of the measured value. In this paper, we focus on the systematic measurement un-



(a) Time series of measured dc resistance of sensor.



(b) Time series of applied dc power to sensor.

Fig. 1: Example of an SMU performing a dc substitution measurement at 50 GHz for the 2.4 mm connector type. A time series of measured dc resistance of the thin film is plotted in (a) and a time series of applied dc power to control the resistance is plotted in (b). The thin film inside sensor is held at 965.4 Ω by the feedback loop. The dc power adjusts to maintain a constant resistance during the on/off cycle.

certainty model, which describes our ability to verify that our voltage and current readings are actually expressed in Volts and Amperes as defined by the SI units. In the Microwave Calorimetry calibration service, we typically use the manufacturer's accuracy specifications which are verified by the Sources and Detectors Group at NIST [4], who have the capability to measure voltage and resistance in a way that is traceable to primary standards. When we performed a preliminary uncertainty analysis of the SMU-based power meter, we found the systematic uncertainties of the SMU readings as defined by the manufacturer were potentially large on the scale of precision microwave power measurements. This observation lead us to implement a calibration method to reduce the measurement uncertainty.

In this paper, we present a method of calibrating an SMU by comparison to a reference digital multi meter (DMM) that has better accuracy specifications than the SMU. This procedure requires just the reference DMM and a variable resistor, and only takes about 10 minutes. We also evaluate the impact on uncertainty in RF power measurements, and show that the calibration significantly reduces the systematic uncertainty.

II. SETUP AND MODEL

Figure 2 illustrates how we connect a reference DMM to the SMU during our calibration procedure. There are two separate configurations, depending on whether the DMM acts as either a voltmeter or an ammeter. In either case, the DMM and SMU are simultaneously measuring either the voltage or the current supplied by the SMU to a variable resistor. Using a single DMM decreases the number of traceable instruments needed to be maintained. The resistor does not need to be well-characterized because its only purpose is to allow for a range of combinations of voltage and current.

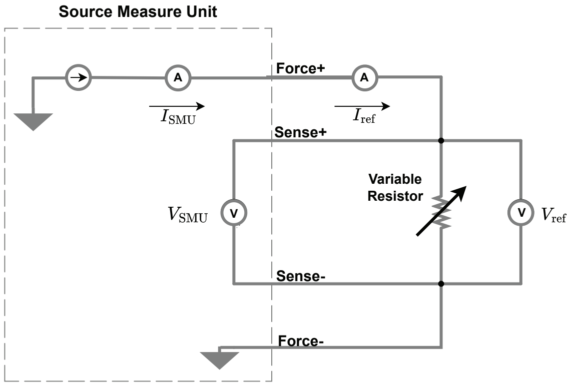


Fig. 2: Circuit diagram of experimental setup. A single traceable digital multimeter is used to measure I_{ref} and V_{ref}.

Our approach to calibrating the SMU is based on a linear model. We assume that the current and voltage measured by the reference DMM, I_{ref} and V_{ref}, and the values indicated by the SMU, I_{SMU} and V_{SMU}, are related by:

$$V_{\mathrm{ref}} = (1 + v_m)\, V_{\mathrm{SMU}} + v_0, \tag{3}$$

$$I_{\mathrm{ref}} = (1 + i_m)\, I_{\mathrm{SMU}} + i_0. \tag{4}$$

The quantities v_m and i_m represent scale errors, and the quantities v_0 and i_0 represent offset errors. To determine v_m and v_0, we apply a series of voltages with the SMU at a series of resistance settings of the variable resistor. For each combination of resistance and voltage, we measure V_{ref} and V_{SMU} simultaneously. Then, we compute the coefficients by least squares regression. The measurement procedure for i_m and i_0 is the same, except that we measure current instead of voltage. The voltage and resistance settings are drawn from a narrow operating region defined by (5) through (8). This region accounts for typical operating regimes of the sensors, SMU, and DMM; it contains all possible future measurements that might be made on any given sensor.

$$1\,\mathrm{V} \leq \quad V \quad \leq 7\,\mathrm{V}, \tag{5}$$

$$I \quad \leq 10\,\mathrm{mA}, \tag{6}$$

$$150\,\Omega \leq \quad R \quad \leq 1000\,\Omega, \tag{7}$$

$$P \quad \leq 40\,\mathrm{mW}. \tag{8}$$

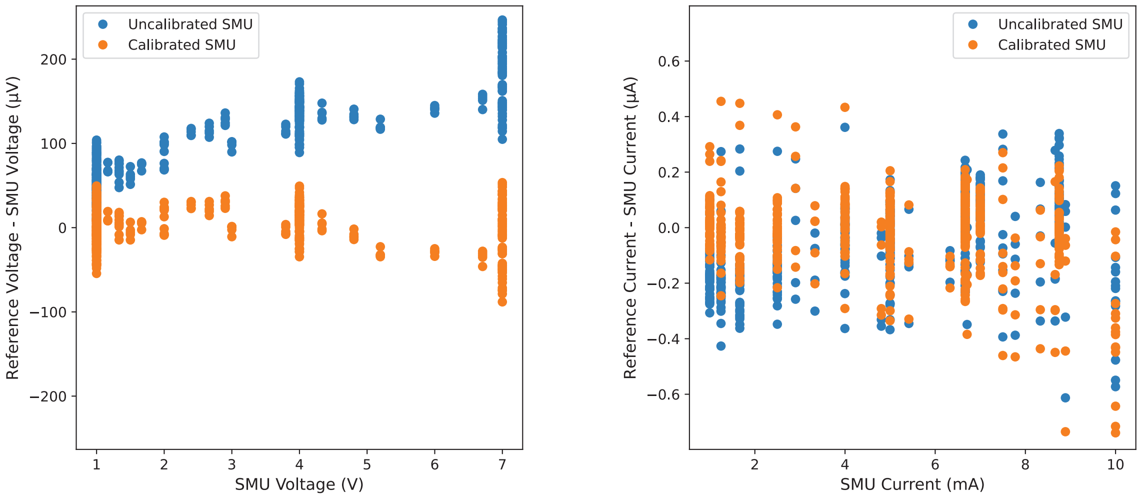


Fig. 3: Differences in voltage (left) and current (right) between readings on the reference DMM and the SMU (calibrated and uncalibrated). Voltage and current measurements are from 10 calibrations performed over a 2 month period and corrected using the long term calibration model shown in Figure 4. The model generally corrects readings on the SMU to behave more like the reference DMM.

To evaluate our calibration model, (3) and (4), we plotted the differences between the voltage and current as reported by the reference DMM and the SMU with and without the calibration applied (Figure 3). We see that by applying the calibration, we reduce the difference between the reference DMM and SMU readings across the operating range.

While Figure 3 demonstrates that the calibration model describes some of the difference between the DMM and the SMU, we still need to assess the uncertainty of the calibration procedure. Our analysis includes both random variability and the accuracy of the DMM. We modeled the accuracy of the DMM by the manufacturers specifications, which were verified by the Sources and Detectors Group at NIST. We assessed the random variation in two ways. First, to assess the short-term repeatability, we repeated each voltage and current measurement involved in the calibration 5 times. We also assessed the length of time that the calibration remains valid by performing repeated calibrations over a period of two months (10 calibrations in total). In each case, we arrived at an estimate of the random measurement deviations by calculating the covariance matrix of the repeated measurements. We then combined these uncertainty estimates with the accuracy specifications of the DMM to yield two uncertainty estimates: a long-term estimate, and a short-term estimate.

Figure 4 shows the results of this uncertainty analysis. The blue error bars show the short-term uncertainty estimate and the orange region shows the long-term uncertainty estimate. The short-term estimate is significantly smaller for v_0 and v_m, and comparable for i_0 and i_m. At several instances during the measurement campaign, we performed several calibrations within a day, and found that they typically differ by less than the short term uncertainty. Calibrations repeated on a single day were not included in the long term repeatability estimate. So, our uncertainty analysis appears to justify reduced measurement uncertainty, compared to the long term, if we perform measurements on the same day as the calibration. Finally, we notice that in the long term, we see correlations between the slope and offset deviations for both current and voltage over time. We include these correlations in our uncertainty analysis.

III. UNCERTAINTY ANALYSIS

To assess the influence of the calibration on RF power measurements, we evaluated the measurement uncertainty of a hypothetical measurement using three uncertainty models. The first treats the SMU manufacturer specified accuracy as a fully independent uncertainty mechanism for each measurement. The second treats the SMU manufacturer specified accuracy as perfectly correlated for every voltage or current measurement. The manufacturer's uncertainty models do not provide information about correlations between measurements, but these correlations impact the uncertainty estimate substantially. The third model follows the long term calibration and correction procedure described in this paper. In all cases, we calculated the SMU readings and their associated measurement uncertainties according to the model, and propagated these uncertainties to P_{sub} using linear propagation of uncertainties as described by [5]. In these calculations, the platinum thin film was described by typical parameters values: the sensor was held at a resistance of 965.4 Ω and required 31.55 mW of applied dc power to achieve this resistance in the RF off state.

We find the calibration reduces the systematic k = 1 uncertainty of the dc substituted power (at a nominal 1 mW) from about 16.8 μW to about 0.039 μW (Figure 5(b)), or from 1.68 % to 0.004 %. For comparison, the historical variability

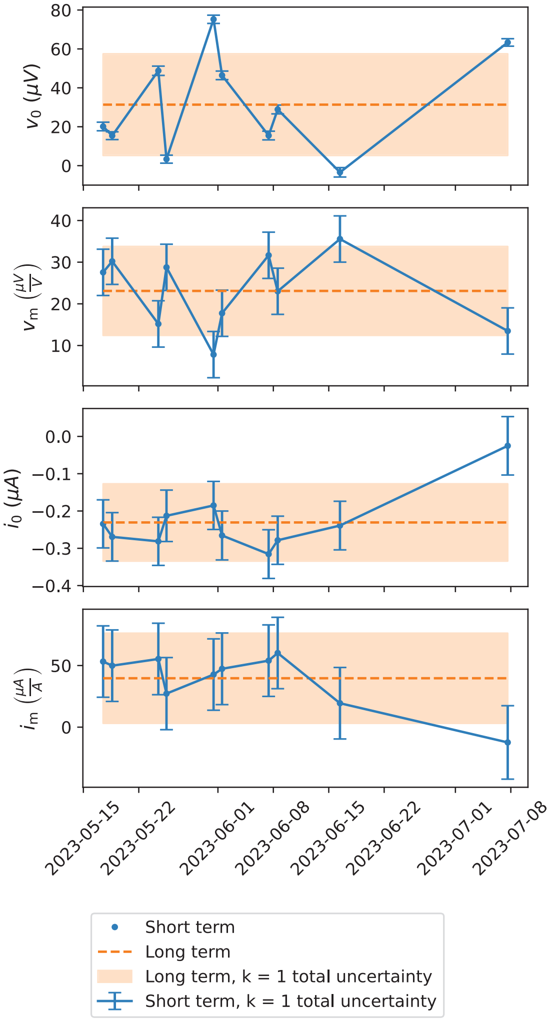
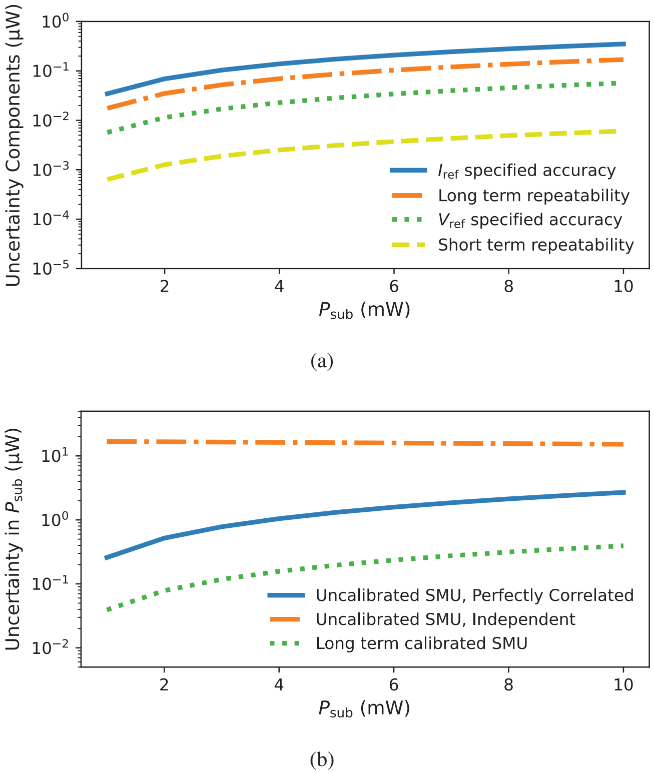


Fig. 4: Calibrations repeated over a 2 month period. Correlations between offset and slope coefficients are apparent. Blue error bars are k = 1 total uncertainty of the short term model (a single calibration) including short term repeatability and accuracy specifications of the reference DMM. The orange region is the k = 1 total uncertainty over the 2 month period including long term repeatability, short term repeatability, and accuracy specifications of the reference DMM. Points for the short term model are expected to occasionally be outside k = 1 uncertainty bounds.

of η in the 2.4 mm microcalorimeter is between 0.1 % and 1 % depending on frequency. A full uncertainty analysis will also consider the repeatability of the dc substitution measurement. From our experience so far, the repeatability of these measurements with thin-film sensors is surprisingly difficult to quantify because P_{sub} drifts with ambient temperature over a range of timescales. We hope to address this question in the future.

IV. CONCLUSION

In this paper, we described an implementation of a dc substitution RF power meter based on a programmable SMU. In evaluating the measurement uncertainty of this power meter, we found that the manufacturer's accuracy specifications were a large contribution to the overall uncertainty. We demonstrated that we could improve the measurement accuracy by a factor of about 400 by comparing the SMU readings to a reference DMM. With calibration, the SMU's systematic accuracy is no longer a concern for dc substitution measurements.



(a)

(b)

Fig. 5: Systematic uncertainties (k=1) in P_{sub} power for a simulated measurement. Figure (a) represents uncertainty mechanisms contributing to the uncertainty of P_{sub}. Based on the time since the last calibration, we could use either the short term or long term estimate of repeatability. Plot (b) compares total systematic uncertainties between manufacturer specified accuracy models and the calibration model of the SMU, with the long term repeatability model.

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