

RF-DC Differences of Micropotentiometers

De-Xiang Huang, Gregorio Rebuldele, and Jerry D. Harper

Abstract—Various sources for the rf-dc differences of micropotentiometers (micropots) are analyzed and calculated. The results are shown to agree well with experimental values. A new design is introduced that reduces the rf-dc differences of the micropots significantly. Observations show good stability over a long period. This makes the micropot suitable as a primary rf and audio standard in the microvolt and millivolt ranges.

Index Terms—Annular resistor, micropotentiometer, thermoelement, transmission line.

I. INTRODUCTION

SIGNIFICANT progress has been made in the last decade to extend the frequency range of the rf micropot down to 10 Hz [1]–[3], and up to 1.2 GHz [4]. The accuracy of rf millivolt measurements have also been improved. Since micropots are used as primary standards for low voltages, it is necessary to investigate all possible sources of error when determining the rf-dc differences. Equations for calculating the various error sources of the rf-dc differences of micropots will be described. A new design is then developed and the rf-dc differences of the micropots are reduced significantly. Further improvements are under consideration. Determinations of measurement errors and necessary precautions to take when performing the measurements in order to achieve the highest accuracy will be given.

Fig. 1 shows a diagram of the rf micropot assembly. When excited with an external rf source, it is designed to provide a precisely determined voltage V_{rf} at its output terminal. The input current I_h flows through the heater of a UHF-type thermoelement (TE) to a disk resistor R_o and the voltage drop across R_o is a low-impedance source of rf voltage. The output voltage is nominally the product of the heater current I_h and the resistance of the disk resistor R_o .

II. RF-DC DIFFERENCES OF A MICROPOTENTIOMETER

The micropot is usually characterized by its rf-dc difference d which is defined by

$$d = \frac{V_{rf}}{V_{dc}} - 1 \quad (1)$$

where V_{rf} is the rf output voltage of the micropot and V_{dc} is the average of the positive and negative dc voltage outputs for the same emf output of the thermoelement. The design

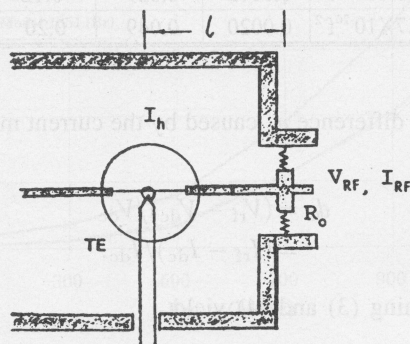


Fig. 1. Diagram of an rf micropotentiometer.

considerations and characteristics of the micropot which affect its rf-dc differences are discussed below.

A. Current Errors Caused by Transmission Line Effect

A vacuum TE is usually used to measure the rf current through the micropot. Any standing wave which exists will cause errors in measuring the rf currents. The current I_{hrf} at the center of TE is less than the current I_{rf} at the disk resistor.

According to the transmission line equation

$$I_{hrf} = V_{rf} \sinh(ZY)^{0.5} / (Z/Y)^{0.5} + I_{rf} \cosh(ZY)^{0.5} \quad (2)$$

where:

- V_{rf} Phasor output voltage of micropot.
- I_{rf} Phasor current at the center of disk resistor.
- I_{hrf} Phasor current at the center of heater of TE.
- I_{dc} DC current through the heater of TE.
- l Distance from the center of heater to the center of disk resistor in cm (see Fig. 1).
- L Distributed inductance of heater and lead per unit length, in henries.
- R Distributed resistance of heater and lead per unit length in ohms.
- C Distributed capacitance of heater and lead to the shield per unit length in farads.
- Z $R + j\omega L$
- Y $j\omega C$.

If the annular disk resistor R_o is a thin-film resistor constructed using state-of-the-art techniques, the distributed parameters can be neglected. Thus $V_{rf} = I_{rf}R_o$,

$$I_{hrf} = I_{rf} [R_o(Y/Z)^{0.5} \sinh(ZY)^{0.5} + \cosh(ZY)^{0.5}] \quad (3)$$

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TABLE I
ESTIMATED RF-DC DIFFERENCES CAUSED BY CURRENT
TRANSMISSION LINE EFFECT AND GROUND IMPEDANCE

Estimated equivalent length (CM)	d_c	RF-DC Difference (%)			
		10 MHz	50 MHz	100 MHz	500 MHz
2.3	$11.6 \times 10^{-20} f^2$	0.0012	0.029	0.12	2.90
3.0	$19.7 \times 10^{-20} f^2$	0.0020	0.049	0.20	4.93

and the rf-dc difference d_c caused by the current measurement is simply

$$d_c = (V_{rf} - V_{dc})/V_{dc} = (I_{rf} - I_{dc})/I_{dc}. \quad (4)$$

Then combining (3) and (4) yield

$$d_c = \{1/[R_o(Y/Z)^{0.5} \sinh(ZY)^{0.5} + \cosh(ZY)^{0.5}]\} - 1. \quad (5)$$

Generally, R_o ranges from 1 m Ω to 22 Ω , and the characteristic impedance $(Z/Y)^{0.5}$ is about 200 Ω , thus $R_o(Y/Z)^{0.5} \ll 1$:

$$d_c = [1/\cosh(ZY)^{0.5}] - 1$$

Since $\omega CR \ll 1$, and if $\omega L/R \ll 1$:

$$d_c = (\omega^2 LC - C^2 R^2/6)/2 = \omega^2 LC/2$$

For a coaxial line, $L/l = 2 \times 10^{-7} \ln(b/a)$ in H/m, $C/l = 1/1.8 \times 10^{10} \ln(b/a)$ in F/m, a is the outer diameter of the inner conductor, b is the inner diameter of the outer conductor. Then

$$d_c = 2.19 \times 10^{-20} l^2 f^2 \quad (6)$$

where f is the frequency in Hz. In order to reduce the inductance of the thermoelement, it is necessary to reduce both the size of the housing, and the length l as much as practical. An experiment has shown that reducing the length by about 2 mm in a commercial unit reduces the rf-dc difference by 1.5% at 900 MHz.

The thermoelement in the micropot might sometimes be replaced due to failure. The rf-dc differences are usually not appreciably affected if the replacement is the same type of TE and inserted at the same location.

B. Ground Impedance

Ground impedance such as rf resistance and equivalent inductance in the housing, which are present at high frequencies, increases the equivalent length l resulting in differences between the calculated rf-dc differences according to (6) and measurement results. Furthermore, the rf-dc differences will be different for various micropot housing materials. The calculated rf-dc differences for a typical micropot caused by the current transmission line effect and ground impedance according to (6) are shown in Table I.

C. Skin Effect of the Heater and Its Inner Leads

Due to skin effect at high frequencies, the rf resistances of the heater and its inner leads are larger than their dc resistances. Many commercial vacuum TE's are made with copper-coated magnetic leads, so the skin effect is larger than for nonmagnetic leads. There is also a skin effect in platinum leads. Therefore, the rf current is less than the dc value for the same emf output causing negative rf-dc differences. The larger the current range, the larger the diameter of the heater, the smaller the heater resistance, and the larger the skin effect. The rf-dc differences of micropots caused only by the skin effect in the TE, d_s , is derived as follows

For the same emf output, $I_{dc}^2 R_{hdc} = I_{hrf}^2 R_{hrf}$.

Then

$$d_s = I_{rf}/I_{dc} - 1 = (R_{hdc}/R_{hrf})^{0.5} - 1.$$

Let

$$\Delta = R_{hrf}/R_{hdc} - 1.$$

At frequencies greater than 1 MHz, Δ is proportional to the square root of the frequency. Using Taylor series expansion

$$d_s = -\Delta/2 = Af^{0.5} \quad (7)$$

where:

- R_{hdc} DC resistance of heater and its internal leads.
- R_{hrf} RF resistance of heater and its internal leads.
- A Coefficient determined by individual TE.

The rf-dc differences caused by the skin effect of the TE are proportional to the square root of frequency at frequencies greater than 1 MHz. They are larger when the current rating of TE is larger and may become the major error source around 10 MHz. This error can compensate for the current error caused by the transmission line effect.

D. Errors of Annular Resistor

The rf-dc difference caused by inductance of the output resistor R_o is

$$d_L = \frac{|Z|}{R_o} - 1 = \frac{(\omega L)^2}{2R_o^2}.$$

The inductance of a well made annular resistor is extremely small, thus the rf-dc difference is very small.

When the thickness of the resistance film is much smaller than its skin depth, the skin effect of a well made annular resistor can generally be neglected. However, the rf-dc differences may be very large if the annulus is damaged (e.g., poor electrical contact, ceramic substrate broken) when the micropot is connected to a nonstandard N-type male connector. When the resistance value is very small, say, several milliohms for the microvolt ranges, the thickness of the resistance film is relatively large and is comparable to its skin depth. The film annulus can be considered as a section of coaxial line with a solid conductor as the propagation medium. By using the same method which Selby [5] used, the transfer impedance Z_m

TABLE II
UNCERTAINTIES OF RF-DC DIFFERENCES OF μ POTS AT NIST

F (MHz)	Voltage Level (mV)	Uncertainty (%)
30	200	0.36
	20	0.40
	2	0.43
	0.2	0.46
100 - 400	200 - 0.2	0.85
500 - 700	200 - 0.2	1.1
800 - 1000	200 - 0.2	1.2

which is defined as the output voltage of an annular resistor versus the input current of the same resistor, is

$$Z_m = \frac{R_o(1+j)t/\delta}{\text{Sinh}[(1+j)t/\delta]}$$

where R_o is the dc resistance of annular resistor, t is the thickness of the film, and δ is the skin depth.

The rf-dc difference d_R caused by the annulus is

$$d_R = (Z_m/R_o) - 1. \quad (8)$$

Then, using Taylor series expansion

$$d_R = (1/|1+jt^2/3\delta^2 - t^4/30\delta^4 - jt^6/630\delta^6 + \dots|) - 1. \quad (9)$$

The calculated rf-dc differences caused by the annulus are negative and large. This is why the rf-dc differences of microvolt range micropots are usually negative. For a 1 milliohm gold film resistor, t is $3.2 \mu\text{m}$, the rf-dc difference from (9) at 1 GHz is -5.5% . This is smaller than the measured value because there is a similar effect in the caps of the resistor.

E. Transmission Line Effect of the Output Connector

At frequencies above a few megahertz, the distance between reference planes of standard and test device is not negligible compared to the wavelength. When the impedance of the interconnections and the input impedance of the test device are not matched, the rf voltage will usually rise from the center of the annular film resistor to the reference plane of the test device and continue to rise to the input load of the test device. Although the transmission lines effect can be calculated [4]–[6], the measurements of the load impedance and the total length of the actual transmission line are difficult to obtain practically. When the input impedance of the test device is much higher than the characteristic impedance of the interconnection line, the calculation formula is simply the following [6]

$$d_T = 2.19 \times 10^{-20} l_T^2 f^2 \quad (10)$$

where l_T is the distance between the annular film resistor and the front face of the input load of the test device (not the reference plane of test device). When performing high-frequency voltage calibrations, all interconnecting devices, adapters, and leads between the micropot and instrument under test should be as short as possible in order to reduce transmission line errors.

10 mA 22 Ohm

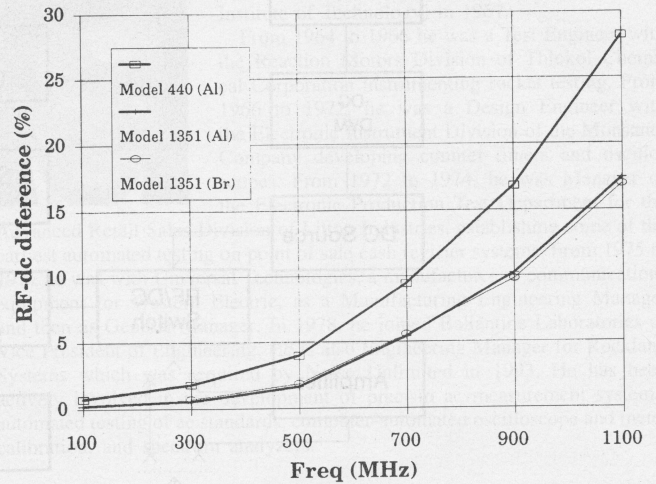


Fig. 2. The rf-dc differences of Model 440 micropot and Model 1351⁴ micropot with new design (AL: Aluminum, BR: Brass).

F. Empirical Equation for rf-dc Difference

From the above analysis, we can obtain an empirical equation for the rf-dc difference of a micropot.

$$\begin{aligned} d &= d_o + d_c + d_s + d_R + d_T \\ &= d_o + Af^{0.5} + Bf + Cf^2 + Df^3 \end{aligned} \quad (11)$$

where d_o is the ac-dc difference at audio frequency, which can be measured directly, A is related to the skin effect of the thermoelement, B , C , and D are related to the skin effect of the annular resistor, C is also related to the distributed inductance and capacitance of the thermoelement and annular resistor. A , B , C , and D can be derived by a nonlinear fit from the rf-dc differences of the micropot to be measured. The calculated rf-dc differences from (11) agree with the measurement data.

G. The Improvements in the New Design

Based on the theory described above, a new commercial micropot housing has been designed and constructed to reduce the error of rf current measurements. The rf-dc differences of micropots with new housings are reduced significantly as shown in Fig. 2.

III. MEASUREMENT METHOD AND RESULTS

A. Calibration Method and Uncertainties

The primary standard micropots are calibrated against a bolometer at NIST, Boulder. The bolometer is connected at the output of the micropot. The rf output voltage of the micropot is derived from the power and impedance measurements for the bolometer.

⁴Certain commercial equipment, instruments, or materials are identified in this paper in order to adequately specify the experimental procedure. In no case does such identification imply recommendation or endorsement by National Institute of Standards and Technology, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

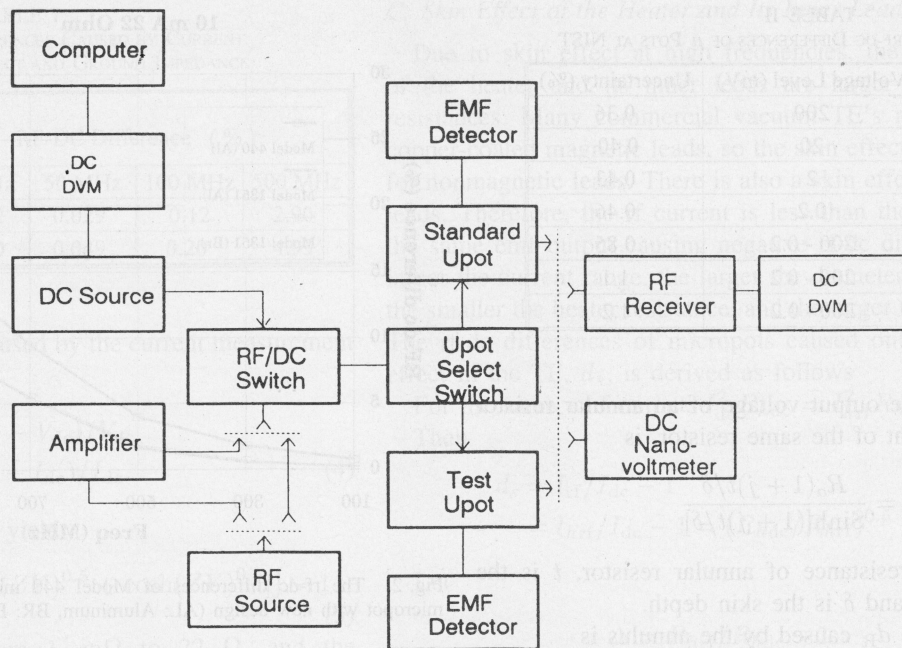


Fig. 3. The block diagram of a micropot measurement system.

TABLE III
EXPERIMENTAL DATA SHOWING THE STABILITY OF A RF μ POT

F(MHz)	RF-DC Difference (%)														Uncertn (%)	
100	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3
500	3	3	4	4	4	5	5	4	4	5	3	5	5	4	5	5
900	13	13	14	14	14	14	14	14	13	15	14	14	15	14	15	5
Year	64	65	66	67	68	69	70	72	73	74	75	76	77	80	83	

The calibration of a micropot may also be performed by comparison with a calibrated micropot [7] or an rf thermal voltage converter. In both the later cases, a transfer or comparison device such as an rf receiver is used to transfer the rf output voltage of the standard to the micropot under test. The block diagram of a typical measurement system is shown in Fig. 3. Table II lists the uncertainty ranges for special micropot calibrations at NIST, Boulder.

A nonlinear fitting method using (11) was used to treat the measurement data and derive the predicted rf-dc differences. Eight micropots were studied from 100 MHz to 1 GHz; the differences between fitted and test results varied from 0.03% to 0.6% depending on the individual micropot. This method has been used for extending the frequency up to 1.2 GHz.

B. Lifetime Stability

Experimental results show that micropots are stable rf voltage standards over a very long period of time. The data in Table III indicate that changes in the rf-dc difference of a Ballantine micropot (10 mA, 22 Ω) over a 20 year period are generally smaller than the measurement uncertainties. This micropot was calibrated relative to the standards at NIST, Boulder.

C. Precautions

Since rf micropots have frequency responses which extend to 1.2 GHz, they should not be used in areas where the

interference from high field strengths may be a problem; otherwise, additional shielding will be necessary. The loading effect should also be considered [2], [8].

D. Equation for Calculating Larger rf-dc Differences

The rf-dc differences of micropots and thermal voltage converters at several hundred MHz are generally several percent or more, test instruments may also have errors of several percent or more. In order to achieve the best accuracy, it is necessary to use the equation

$$d_t = d_s + \Delta + d_s \Delta \quad (12)$$

where d_s and d_t are the ac-dc differences of reference standard and test devices, and Δ is the difference measured between two devices. The second-order error $d_s \Delta$, which is generally neglected at low frequencies, may reach several tenths of one percent to several percent at high frequencies.

IV. CONCLUSION

Formulas for calculating the rf-dc differences of micropots for five major error sources are presented and analyzed. The rf-dc differences of micropots are determined by their geometry and materials. They can be reduced by proper designs of the housing and annular resistor. Micropots maintain their stability over several decades and are very suitable as primary standards in the microvolt and millivolt ranges from 10 Hz to 1.2 GHz.

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Gregorio Rebuldela, photograph and biography not available at the time of publication.



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