

# Measuring the Electric Field of Flat Surfaces with Electrostatic Fieldmeters

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**OVERVIEW:** This article investigates the most common causes of errors in measurements performed with electrostatic fieldmeters and presents methods and arrangements which minimize or eliminate those errors.

The charged flat surface represents a very common object of electrostatic measurements, for instance:

- In investigation of electrostatic hazards in industries such as plastics, textiles, graphic arts, film and paper converting and electronics.
- In various static decay tests.
- In calibration of electrostatic fieldmeters.

Measurements of electrostatic fields are made with the help of various types of noncontact electrostatic fieldmeters, with two better known: electrometer type instruments and chopper stabilized or “field mill” type instruments.

The simplified block diagram of an electrostatic fieldmeter is shown in Figure 1.  $C_1$  is the capacitance between the charged surface and the sensing electrode.  $C_1$  is maintained constant in electrometer type fieldmeters.  $C_2$  is the capacitance to ground of the sensing electrode and is constant.

The charge density  $\sigma$  developed on the sensing electrode is proportional to the electrical field intensity  $E$  at the electrode's surface

$$\sigma = \epsilon_0 E \quad (1)$$

The voltage  $V_2$  developed on the sensing electrode will be

$$V_2 = \frac{\epsilon_0 E A}{C_2} \quad (2)$$

where  $A$  is the area of the sensing electrode,  $\epsilon_0$  is the permittivity of free space ( $8.855 \times 10^{-12}$  farad/meter).

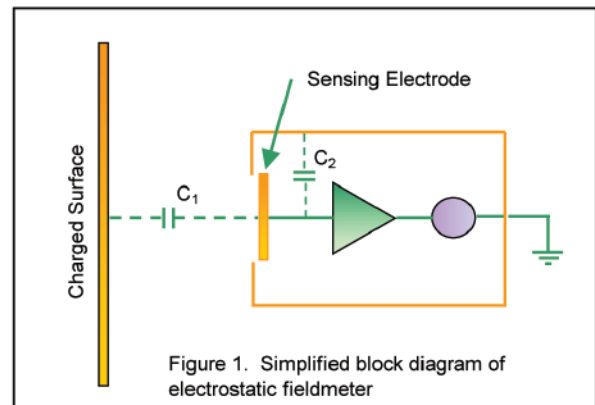


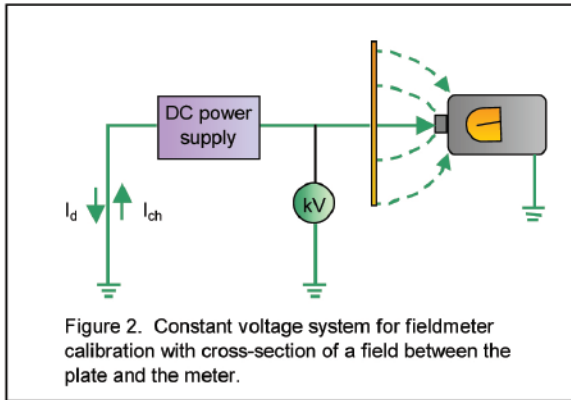
Figure 1. Simplified block diagram of electrostatic fieldmeter

The values of electrode area  $A$  and capacitance  $C_2$  are constant for a given fieldmeter. The single variable in formula (2) is the electrical field intensity  $E$ . That is why the instruments are called fieldmeters even though some of them are calibrated in terms of volts. A large charged plate in free space produces a uniform electrical field. However, the introduction of an electrostatic fieldmeter into that field disturbs its uniformity. Therefore, most electrostatic measurements are performed in nonuniform electrical fields, and instruments are calibrated under similar nonuniform field conditions. This can be seen in Figure 2 where a constant voltage system is used for fieldmeter calibration. The charge on the plate can be calculated as:

$$Q_{pl} = C_{pl} V_{pl} \quad (3)$$

As the meter is brought into the field of the plate, the system's capacitance will change. Unless charge  $Q_{pl}$  is changed proportionally, the plate potential  $V_{pl}$  will also change. This does not happen in the constant voltage system where the power supply will replenish the charge with current  $I_{ch}$ . When the meter is removed, current of opposite direction  $I_d$  will remove the excess charge from the plate, thereby maintaining constant voltage.

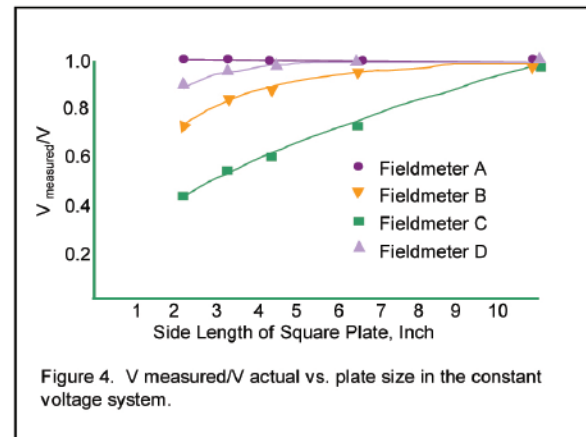
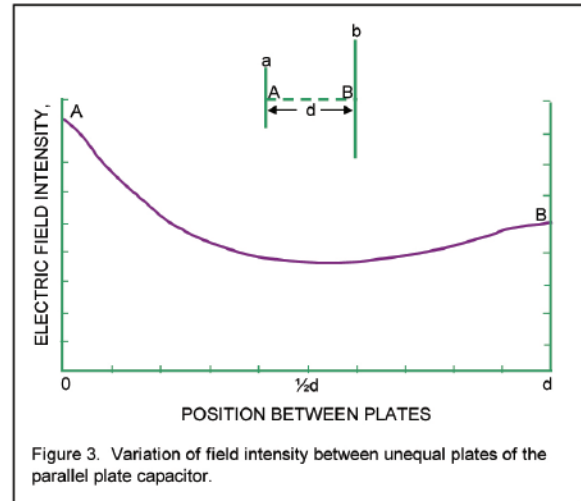




In the nonuniform electrical field between meter and plate, the charge induced on the electrode is proportional to its intensity at the electrode's surface, but the field intensity is not uniform in direction and magnitude.

The field intensity which determines the voltage  $V_2$  on the electrode, and therefore the meter readings, depends on the distance to the source of the field and the configuration of the system. The front surface of the probe and the charged plate could be looked at as a parallel plate capacitor with unequal plates.

The field intensity curve plotted for the space between two unequal plates along the centerline is shown in Figure 3. The intensity of the field is greatest near the small plate (a) and decreases along the centerline AB toward the large plate b. A minimum occurs just beyond the mid point and the value of the intensity then rises more slowly as b is approached, reaching a value at the large plate considerably lower than that at A. It should be noted that even if potential difference and distance between the plates is maintained constant, as soon as size of either plate changes, the values of field intensity at the surface of both plates will change and the whole field intensity variation curve will be different. To verify this, four different fieldmeters were tested, three commercially available meters A, B, C and an experimental model D. In the first experiment the effect of plate size on the fieldmeter's accuracy was studied. Five plates of different sizes were used in the constant voltage system configuration. Measurements were taken with each fieldmeter following the procedures given in their respective instruction manuals. The results of the experiment are shown in Figure 4.

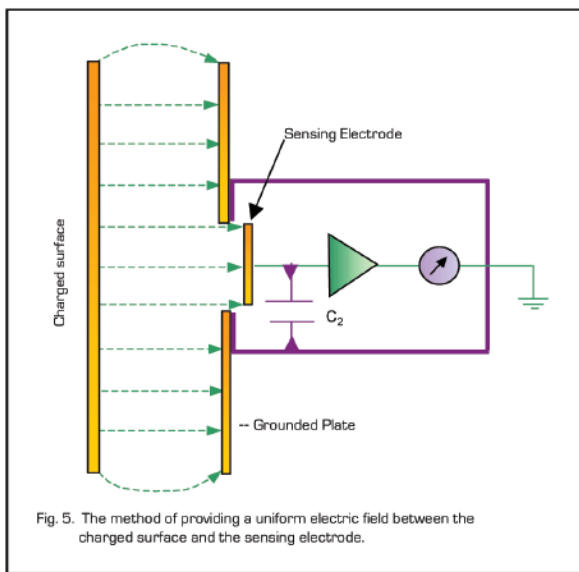


The experiment proved that as the size of the plate was decreased, the field intensity at the sensing electrode went down. Significant errors resulted since most meters are calibrated with large plates. As shown in Figure 4, the best accuracy over the range of plate sizes was displayed by the fieldmeters A and D, where error did not exceed 10 percent. At the same time, fieldmeter C produced an error exceeding 50 percent. Two factors contributed to the higher accuracy of fieldmeters A and D: a calibration distance of one inch, as compared to 2" and 3 1/2" for the other two meters, and properly designed sensing elements. The combination of these two factors helps maintain a constant field intensity at the sensing element

over a wide range of plate sizes. At close calibrating distances, the meter's accuracy is relatively independent of plate size. As the distance increases, accuracy decreases, becoming more dependent on plate size.

The fieldmeter can be a very accurate instrument if a uniform field is always provided between a measured object and a meter.

There are examples of setups for electrostatic measurements where the probe of a fieldmeter is mounted within a grounded metal plate with an opening for the sensing electrode through which it senses the field produced by the charged plate (Figure 5.)  $\sigma = \epsilon_0$



This is usually done to provide a uniform field for measurement. However, it should be realized that the field in the space between the meter and the plate has been altered as compared to that of its original calibration. Measurements were taken with the sensing probes of fieldmeters A through D mounted in a 6" x 6" grounded metal plate. Errors of up to 30 percent were encountered in these readings since the field intensity decreased at the sensing element as compared to the original arrangement. Therefore, a good rule is to check the calibration of the meter when the test arrangement involves grounded surfaces near the meter's probe.

Once the uniform field for measurements is provided and the fieldmeter is calibrated for that arrangement, the following relationship will determine its operation. In the case of two parallel plates whose spacing is small compared with the lateral dimensions, the electric field in the region between the plates is uniform in direction and magnitude. The field intensity depends only on charge source potential  $V_1$  and the distance  $d$  between the plates

$$E = \frac{V_1}{d} \quad (4)$$

or from (1)

$$\sigma = \frac{\epsilon_0 V_1}{d} \quad (5)$$

The capacitance per unit area ( $C_1'$ ) of the parallel plates is the charge per unit area divided by the potential difference or

$$C_1' = \frac{\sigma}{V_1} \quad (6)$$

Multiplying (6) by the area of the sensing electrode ( $A$ ) gives for the charge source to sensing electrode capacitance,

$$C_1' = \frac{\sigma A}{V_1} \quad (7)$$

Hence

$$V_1 = \frac{\sigma A}{C_1} \quad (8)$$

The voltage ( $V_2$ ) could be determined as

$$V_2 = \frac{\sigma A}{C_2} \quad (9)$$

and from (8) and (9) we have

$$V_2 = V_1 \frac{C_1}{C_2} \quad (10)$$

In a uniform field, this relationship will always be correct, providing a good vehicle for measurement at any distance. A meter could be calibrated in units for field intensity, since in (10)  $C_2$  is always constant and  $C_1$  is a reciprocal function of the distance.

$$V_2 = V_1 \frac{\epsilon_0 A}{D C_2} \quad (11)$$

The last experiment of the series involved a study of the relationship between distance and fieldmeter accuracy.

As shown, the fieldmeter reading is always proportional to the field intensity at the sensing probe surface. From (11) we can also write

$$V_2 = \frac{V_1 \epsilon_0' A}{D_{cal} C_2} \quad (12)$$

Where  $d_{cal}$  is the distance at which the meter was calibrated.

Now if the measurement is taken at a distance other than  $d_{cal}$  then we have

$$V_2 = \frac{V_1 \epsilon_0 A}{D_m C_2} \quad (13)$$

where  $d_m$  is the plate to probe distance. Therefore:

$$\frac{V_2}{V_1} = \frac{d_m}{d_{cal}} \quad (14)$$

Substituting (12) into (14) and solving for the source potential ( $V_1$ ), we have the true value of the plate potential measured at a distance other than  $d_{cal}$  in a uniform electric field calculated as

$$V_1 = V_2 \frac{d_{cal} C_2}{\epsilon_0 A} = \frac{d_m}{d_{cal}} \quad (15)$$

The term  $(d_{cal} C_2 / \epsilon_0 A)$  is the fieldmeter calibration factor which, when multiplied by  $V_2$  is the uncalibrated fieldmeter reading. Multiplying by the ratio  $d_m/d_{cal}$  effectively recalibrates the meter for the new distance,  $d_m$ .

The accuracy of measurements taken in a uniform field was checked on the setup of Figure 6. The fieldmeters B and C were calibrated in that arrangement and readings of a plate charged to +5,000 volts were taken at distances from 1 to 6 inches. The measured plate potential was calculated per formula (15) and plotted in Figure 7 along with the results of measurements taken in a similar test in a nonuniform field condition.

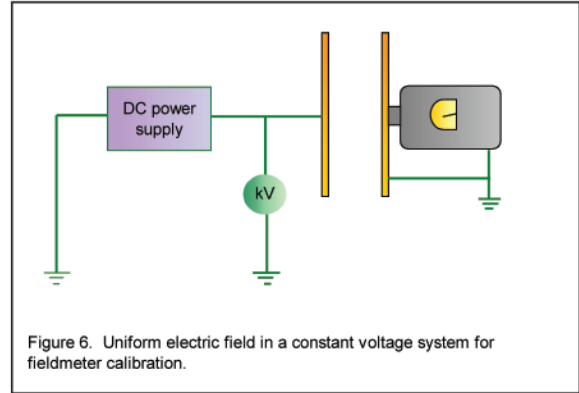


Figure 6. Uniform electric field in a constant voltage system for fieldmeter calibration.

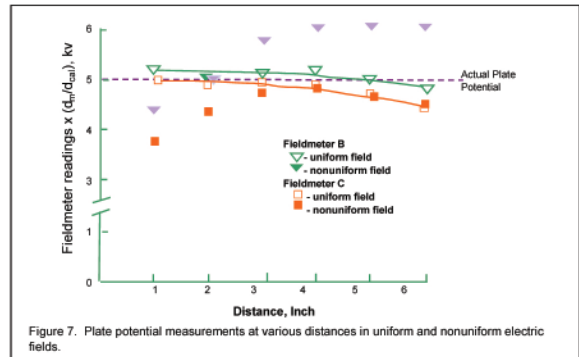


Figure 7. Plate potential measurements at various distances in uniform and nonuniform electric fields.

The results obtained in a nonuniform field show significant errors of measurements at distances other than specified by the manufacturers of the instruments, while results obtained in a uniform field show very good accuracy over a wide range of distances.

The obtained results show that it is absolutely essential to have curves of the correction factor for various possible uses of the electrostatic meter, such as measurements at distances other than specified, and measurements where the field configuration differs from that of standard calibration.

The other very common use of the electrostatic meter is for measurements in constant charge systems. A constant charge system is usually encountered when a very good insulator becomes electrostatically charged. The charge on the surface of the material can be considered constant over a short period of time, depending on ambient conditions.

Unlike the case with the constant voltage system, the influence of a meter brought into the constant charge system is more of a concern. That influence amounts to a change of the object's capacitance to ground  $C_0$  by the value of its capacitance to the ground fieldmeter  $C_m$ . The quantitative value of this influence depends on the ratio of the capacitance of the object to ground before and after the introduction of the meter. Therefore, it would be very useful to have a chart of the meter's capacitance to plates of various sizes so that the meter's influence could be compensated for. Besides the influence of the meter, there are still the same factors of the measurements of nonuniform electrical fields to consider. The best solution is to determine surface charge density, which is proportional to the field intensity.

$$E = \frac{\sigma}{\epsilon_0}$$

To obtain error-free measurements, especially where charged dielectric surfaces are measured, the meter should be installed within a grounded metal plate with an opening for the meter's aperture and calibrated at a specific distance. This will provide an almost uniform

electrical field so that the observed electrical potential will be proportional to the charge density.

$$E = \frac{V_m}{d}$$

where  $V_m$  = obtained reading  
 $d$  = distance to the object, and therefore

$$\sigma = \frac{V_m \epsilon_0}{d}$$

The obtained value of charge density is used to calculate the charge on the object and its potential to ground. Good understanding of the physics of electrostatic measurement will help avoid errors. The necessary steps are summarized in the flowchart (Figure 8)

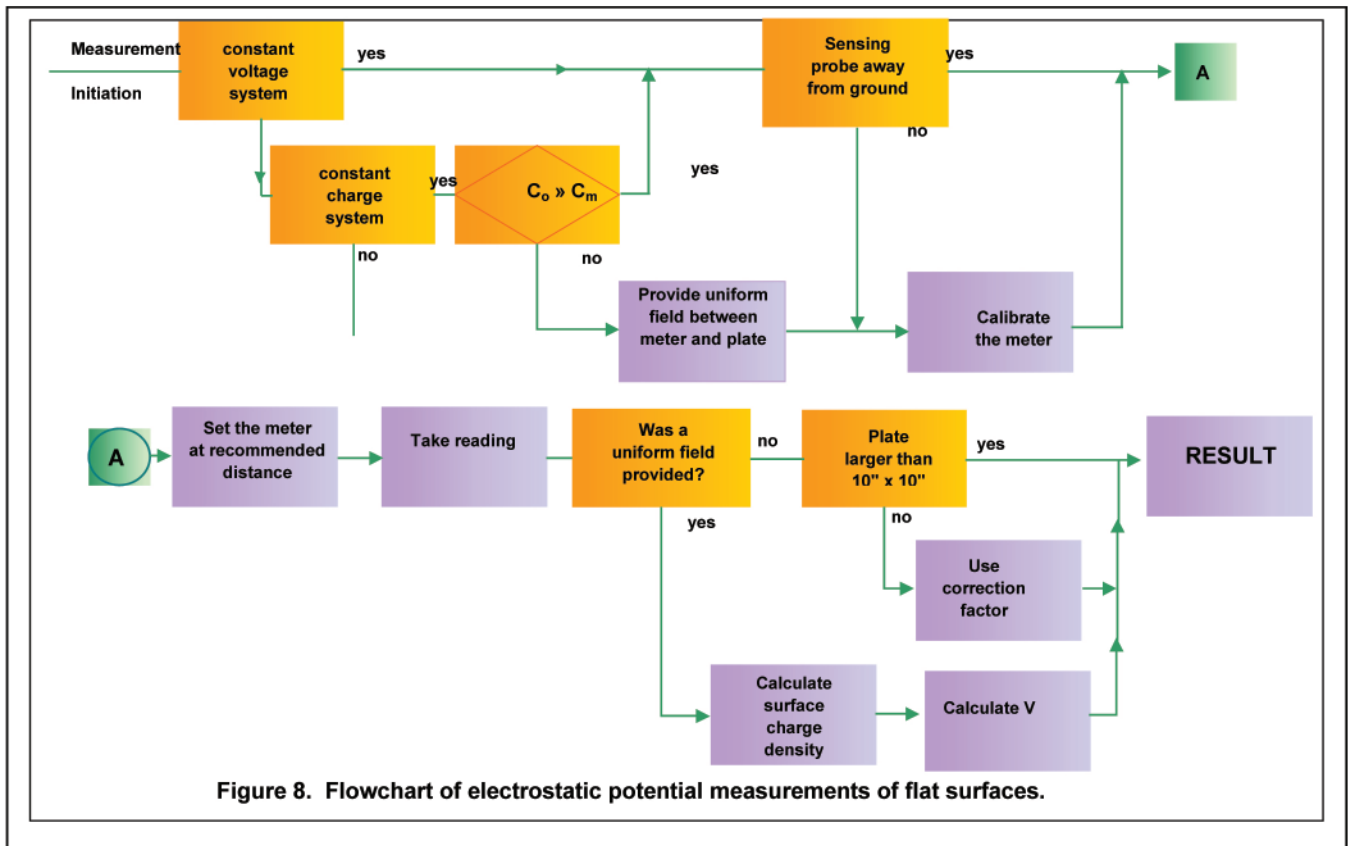
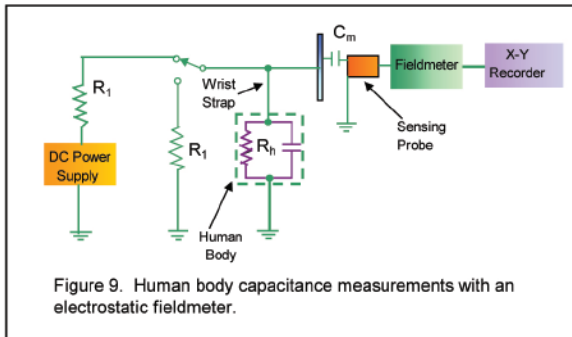


Figure 8. Flowchart of electrostatic potential measurements of flat surfaces.

The experience we have gathered in electrostatic measurement has been used in some unusual experiments. One of them was human body capacitance measurement. Figure 9 illustrates the test method used to determine the capacitance of a human body.



The person under test was connected via a wriststrap to a metal plate, the potential of which was monitored by a fieldmeter. The human body in Figure 9 is shown as an equivalent circuit. The contact resistance between a wriststrap and human skin was neglected in calculations because of a low value; also, the safety resistor was removed from the wriststrap. To provide accurate results, all efforts were made to have  $R_h \rightarrow \infty$  by maintaining low relative humidity and completely isolating the person from ground. The person was charged to a known potential and then the charge stored in the body and decayed through the resistor  $R_1$ . The decay curve was recorded and then processed to determine the time constant  $\tau$  of the decay. The value of  $C_h$  then could be calculated from

$$C_h = \tau \left( \frac{1}{R_1} + \frac{1}{R_h} \right) \cdot C_m$$

Where  $\tau$  is the decay time constant.

## CONCLUSIONS

1. The accuracy of measurements made with electrostatic fieldmeters depends on the conditions under which measurements are taken.
2. Specified distance must be maintained to insure accurate measurements, otherwise a correction factor must be used.
3. The fieldmeter's sensing head can be modified to provide a uniform electric field between the surface and the meter. The actual potential of the surface can then be easily calculated from the readings obtained at distances other than specified.
4. The size of the surface being measured may affect the accuracy of the readings. Correction curves must be used to compensate for possible error.
5. The capacitance of the sensing head alters total capacitance of the constant charge system. The indirect measurement of charge density is recommended in this case.

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