

A REVIEW OF CURRENT ELECTROSTATIC MEASUREMENT TECHNIQUES
AND THEIR LIMITATIONS

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In electrostatic measurements, as in any other scientific measurements, there are two areas of limitations.

1. The limitation of the methods or instrumentation used to gather the data.
2. The researcher's understanding of the subject under investigation.

In this paper I will attempt to review some basic electrostatic principles in order to give the reader a necessary understanding to make accurate electrostatic measurements. Then I'll review the current state of the art in of electrostatic voltmeters and field-meters and their limitations.

It is well known that all matter is made up of positively and negatively charged electrical particles. Whenever there is an abundance of one polarity in a certain area, an electric field E is produced. An electric field is said to exist at a point if a force of electrical origin is exerted on a test charge at that point.

ELECTRIC FIELD:

$$E = \frac{F}{Q} \quad \frac{\text{NEWTONS}}{\text{COULOMB}} = \frac{V}{M} \quad \frac{\text{VOLTS}}{\text{METER}}$$

Please note that electric field is a vector quantity with force and direction for which the units are Newtons per coulomb or volts per meter. This is the definition of electric field.

When we move one coulomb of charge from one point to another in an electric field, we are doing work on that charge. The term we use for this is electric potential or voltage.

ELECTRIC POTENTIAL:

$$V_a - V_b = \int_a^b E \cdot ds$$

Again, a volt is the amount of work it takes to move one coulomb of charge a certain distance through an electrical field E.

This now leads us to capacitance. A capacitor is normally viewed as any two conductors

separated by an insulator but can be more generally defined as follows:

The capacitance C of a capacitor is the ratio of the magnitude of the charge Q on two bodies to the potential difference between the bodies.

CAPACITANCE:

$$C = \frac{Q}{V}$$

C in Farads, Q in coulombs, V in volts.

The energy stored in a capacitor is:

$$W \text{ (work)} = \frac{1}{2} CV^2$$

I feel these are the most important concepts to grasp in order to make scientific electrostatic measurements. I will give two examples to show how these laws are important in electrostatic measurement.

The first example I will use is where a continuous sheet ("web") of plastic or other non-conductor runs over rollers as in a usual processing situation. It is very common to have significant charge build-up in this type of situation. First let us assume that the "web" is uniformly "charged". The capacitance (C) of any small area of the web is proportional to its area (A) divided by the distance l the web is from any grounded object.

$$C = \epsilon \cdot \frac{A}{l}$$

If the web is in close contact with the rollers, l is very small and C is maximum. As the web moves off the roller into free space, l increases dramatically from almost 0, the thickness of the material to tens of centimeters. The capacitance C changes inversely proportional as noted above.

From this we can see that changes of capacitance in order of 100 to 1000 is not unusual.

The web being uniformly charged changes in potential or voltage proportionally to the capacitance of the web.

$$v = \frac{q}{c}$$

Variations can be seen in voltage measurements in factors of hundreds in this type of situation. Over the rollers voltage measurements would be very low at maybe 100 volts. Away from the roller voltages can exceed 10kV.

If a ground referenced fieldmeter is used in this situation, the capacitance of the field-meter probe can be significant and alter the voltage measurements. In general this is not a problem because we are most concerned with relative measurements and as long as the probe configuration is consistent in relation to the web, reproducible results can be obtained.

The second example is a variation of the first. Today we commonly hear of the need to keep the voltage levels on printed circuit boards below some set number because of the sensitivity of the components. Let's say we have a circuit board sitting 1.00 mm above a bench top and we measure 50 volts on that board. If we now lift that board to 10 cm without discharging the original charge the voltage will then rise to 5000 volts because the capacitance drop is inversely proportional to the distance of the printed circuit to the bench.

The point here is that the voltage isn't the whole story. If there is one equation that must always be kept in mind during electrostatic measurements, it is $Q=CV$.

THE ELECTROSTATIC FIELDMETER:

The ideal electrostatic fieldmeter would exhibit the following characteristics:

1. It would be very very small
2. It would be capable of orientation to determine the direction as well as the magnitude of the field.
3. It would be capable of assuming the potential in space of the point where field intensity measurements are desired.
4. It must telemeter data to ground as any interconnecting wire would grossly distort the field in the vicinity of the probe.

In general the ideal fieldmeter would have the capability of measuring the field without distorting that field in any way. Clearly such an instrument is quite impractical for everyday use.

The practical fieldmeter used today is a ground referenced measuring device in which readings are proportionally related to the distance from the probe to the surface or object under test.

This trait is one of the limiting factors of all fieldmeters and if accurate readings are to be obtained, the distance from the field-meter probe to the surface under test must be precisely known.

Another common characteristic of fieldmeters is the field of view of the probe. Figure 1 shows us a graph in which a square target or surface under test with side S is positioned one unit of distance away from the probe. We can see from this curve that for accuracy, the target size should be three to four times this distance from the probe to the surface under test. This dictates that the field-meter probe should be as close as possible to the test surface unless the need is to measure over a large area. Remember as spacing gets smaller, the variations in spacing becomes much more critical to the accuracy of the readings. For example: at 5.0 cm spacing a variation of 0.1 cm yields a change of 2%, at 1.0 cm spacing the same variation of 0.1 cm yields a change of 10%.

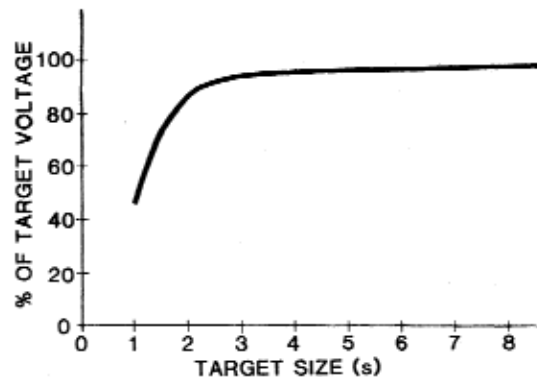


Figure 1

Range:

The range of sensitivity of electrostatic fieldmeters currently on the market is from 0.1 voltsper centimeter to 20K Volts per centimeter. The upper limit of fieldmeter measurement is usually dictated by the breakdown of air, which is around 20kV per centimeter.

Calibration:

Commercially available electrostatic fieldmeters, although responsive to electric field intensity, are often calibrated to read voltage when held at a fixed spacing with respect to a plane surface at constant voltage. The more sophisticated instruments are calibrated to read field intensity directly, usually in volts per centimeter or volts per meter.

A common calibration technique is to establish a uniform electric field by using two large parallel conductors separated by a smaller fixed known spacing across which is applied a known voltage. The electric field established in the center of the plates is then simply V/l .

One of these plates is grounded and a hole is provided in this plate just adequate to permit the fieldmeter probe to be held flush with the grounded surface. The fieldmeter probe is then subjected to the same electrostatic field as its surroundings and can be easily calibrated.

Probe-To-Surface geometry is very important and should always be taken into account when attempting to determine charge or voltage from a field intensity measurement.

A technique that is commonly promoted to obtain more accurate fieldmeter readings is to mount the probe looking through a grounded metal plate. This normalizes the meter's readings by reducing the electric field convergence on the probe thus creating a more uniform field condition at the probe. (For a more detailed study of fieldmeter theory and application, obtain a copy of Mark Blitshteyn's paper "Measuring The Electric Field Of Flat Surfaces With Electrostatic Fieldmeters".)

Types of Fieldmeters:

Fieldmeters are available in three basic variations. They are the electrometer type, the radioactive sensor type and the A.C. carrier type of fieldmeter.

The electrometer or the pocket size electrostatic locator type of fieldmeter will be reviewed first. This is basically a capacitively coupled D.C. amplifier with a shunt capacitor for calibration.

All amplifiers draw a finite amount of current, therefore this instrument's readings will drift over time at the rate of $dv/dt=I/C$ where I is the electrometer input current and C is the shunt capacitance. A more severe drift can also be caused by a minute ion imbalance if this type of field-meter is used in an ionized air environment. To counteract this problem the shunt capacitor must be periodically discharged in a zero field condition or a known field condition that may be used as a reference.

The main advantages of this type of fieldmeter are low cost, simplicity, small size and the ability to make extremely high speed measurements.

The disadvantages are the inability to monitor an area over an extended period of time, the need to periodically zero and, also because of its D.C. coupled circuitry, the inability to use these in an ionized air environment.

The second fieldmeter type utilizes a radioactive sensor. This sensor will ionize the air in its immediate vicinity. When this is exposed to an electric field, a current will flow that is proportional to the electric field. The current is then measured to obtain an electric field reading.

This is a very simple system and it is D.C. stable. Its drawbacks are the fears associated with radioactive materials, the possibility of

errors in readings due to dirt accumulation on the radioactive material affecting its ionization ability and the half-life of the radioactive material.

Fieldmeters utilizing an A.C. carrier type system are most common in high quality electric field monitoring systems. This A.C. signal is produced by modulating a capacitance pickup in an electric field. This is done normally by two means:

1. By a fieldmeter (see Fig. 2) which utilizes a rotor that chops the electric field and a stator which is the sensitive electrode in this system. This system is simple in design and principle. Its drawbacks are that they are usually rather large in size, and may have limited motor life. The speed of response for this instrument is limited by the chopping speed of the rotor.

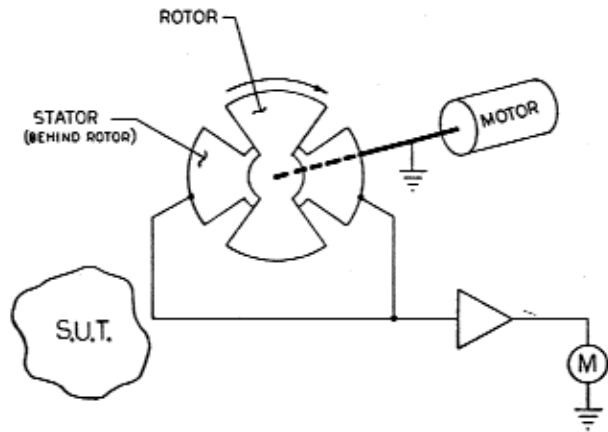
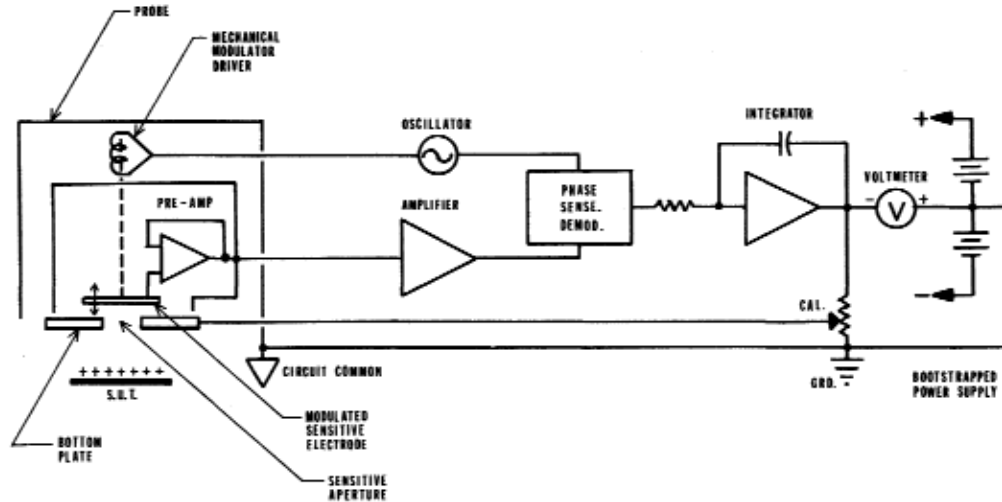


Figure 2

2. By vibrating capacitor fieldmeters which are probably the most commonly used for long term monitoring. These utilize an electrode which is vibrated perpendicularly to an electric field. For good reading stability the modulation amplitude must remain stable throughout the calibration period of the instrument. This is because the amplitude of the A.C. signal created is proportional to the modulation amplitude for any given electric field. This problem is commonly overcome by utilizing a null seeking feedback technique that minimizes any calibration variations due to modulation amplitude changes. (See Fig. 3.)



Simplified Block Diagram: ELECTROSTATIC FIELDMETER

Figure 3

These instruments can be made rather small with the probe size being one to two cubic inches. They are extremely reliable and require little power. The speed of response is typically around 0.5 seconds.

Minimizing Fieldmeter Drift -Purging:

Most fieldmeter probes must be kept clean to minimize drift (zero instability or offset). The drift can readily be understood by visualizing what happens when undesired charged dielectric material accumulates within the sensitive volume of the field-meter. The lines of force associated with this unwanted charge accumulation produces an additional uncontrolled electric field component which results in a zero offset in the instrument output.

An additional source of zero offset, although normally much less severe, results when the components of the fieldmeter probe are permitted to develop contact potential differences because of the adhesion of conductive materials on the electrodes. These effects can be minimized if the atmosphere within the fieldmeter is kept clear of particulate matter and is operated in a stable gaseous atmosphere. Usually this atmosphere is simply clean, filtered air which is fed to the sensitive volume to keep it continuously purged of foreign matter (solids, liquids, and gasses). If the explosion hazard is minimized by operating the entire system under inert gas, the probe can be similarly purged by the same filtered inert gas. Purging is a very important aspect which is commonly overlooked.

THE ELECTROSTATIC VOLTAGE FOLLOWER
OR VOLTMETER

Static Accuracy:

The electrostatic voltage follower is an electronic servo which functions to create a null in the DC electric field at its sensitive electrode. Zero electric field intensity necessitates that the sensitive electrode (probe) must be at the same potential as the surface it is sensing.

Modern circuitry permits even a modest system to function with a follow-up error of a small fraction of one percent at practical probe-to-surface spacings. Follow-up errors of less than 0.01% are routine for sophisticated circuitry.

Range:

The useable range of electrostatic voltmeters is from millivolts to tens of thousands of volts depending on what the system was designed for.

Spacing Sensitivity:

Theoretically, with sufficient gain, no change in indicated voltage should exist as an electrostatic voltage follower probe is moved away from a large uniformly charged surface-under-test.

In Figure 4, we see an accuracy vs. spacing measurement. This shows that voltmeters can indeed be used over a wide range of spacings with excellent results when viewing a large uniformly charged surface.

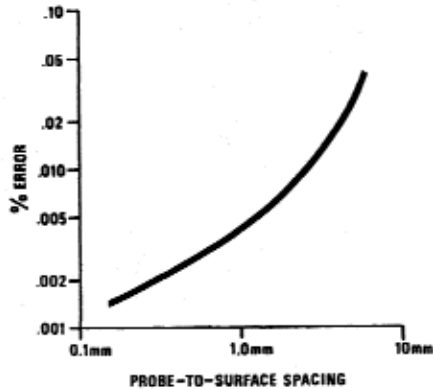


Figure 4

In the practical situation, any of the following can produce an error in the follow-up voltage:

1. Finite dimensions of surface-under-test.
2. Finite dimensions of probe in comparison with dimensions of the sensitive electrode or sensitive aperture.
3. Proximity of surfaces at voltages other than the unknown (typically at ground).

The above influences can be readily grasped if one realizes that as the probe is moved away from the surface-under-test, fringing fields due to influences other than the surface under test can influence the probe and thus produce a change in indication.

Adding a conductive shroud around the probe with the shroud electrically connected to the probe can very significantly reduce the influence of these fringing fields and, therefore, the probe-to-surface spacing errors.

Drift:

Although some drift may be attributable to instability of electronic circuitry, in a well designed system the major sources of drift are undesired charge accumulation and contact potential changes on the electrode of the probe.

1. Undesired Charge Accumulations:

This accumulation is generally some foreign undesired dielectric material such as dust or toner which accumulates on or in the vicinity of the probe. Care must be taken to minimize this accumulation. For stable, high sensitivity measurements, the probe should be purged with a clean, stable supply of air or other gas.

2. Contact Potential Changes:

The sensitive electrode of an electrostatic modulator is normally plated with some noble metal (typically gold) to create a stable, corrosion resistant surface.

Unfortunately, a change in the constituents of adsorbed gases on these sensitive electrodes can produce a contact potential difference of hundreds of millivolts. This can produce a very undesirable drift. If very low drift measurements are to be made, an extremely stable atmosphere surrounding the probe must be provided.

Using a selected probe and a purge kit to purge the probe with filtered room air has resulted in a drift rate in the laboratory in the order of one millivolt per hour.

Resolution:

In the field of electrophotography it is commonly desired to make high resolution measurements of charge patterns on photo-receptors. High resolution necessitates a small sensitive aperture in the probe. It is also essential that the probe-to-surface spacing be small compared to the aperture size or the benefits of the small aperture will be lost. Unfortunately, probe-to-surface spacing must at all times be adequate to prevent sparking* between the surface-under-test and the probe. This dictates, for a given surface voltage, a minimum spacing which in turn dictates a limit to resolution.

Figure 5 shows what probe-to-surface spacing is needed for 99% accuracy measurements of varying strip widths.

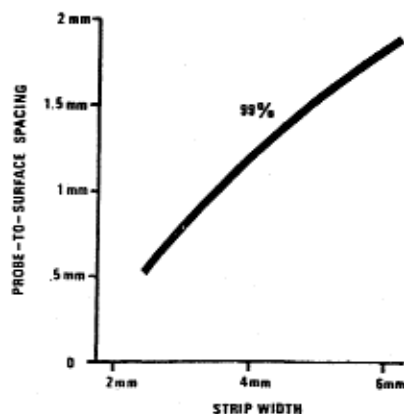


Figure 5

*Most instruments can normally withstand this sparking but it is destructive to the surface-under-test.

Speed of Response:

High resolution measurements can be very time consuming unless the system exhibits good speed-of-response.

Instruments currently available can exhibit 10% to 90% speeds-of-response in hundreds of microseconds.

Noise:

The laws of physics dictate that as more sensitive measurements are attempted the sensitivity is limited by noise. Therefore, high sensitivity, high resolution and high speed-of-response are not mutually exclusive.

Fortunately, in typical electrostatic measurements, noise is not too serious a problem as voltages are normally in the range of hundreds of volts.

It is possible to make non-contacting voltage measurements with a resolution of 100 microvolts. This can only be done by slowing the system down to the degree that its speed-of-response must be reckoned in seconds.

Types of Voltmeters:

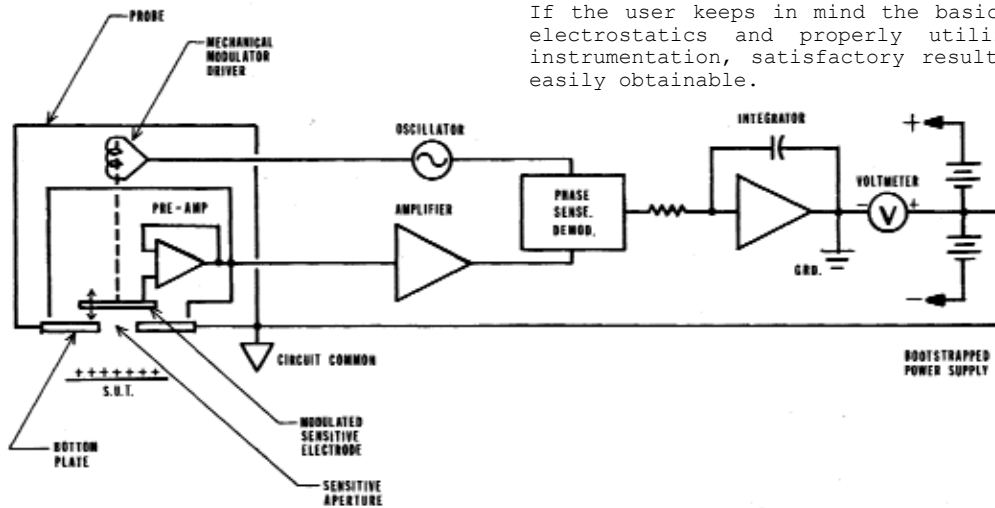
There are basically two types of electrostatic voltage follower voltmeters available today. There is the modulated capacitor sensor type which is by far the most common (See figure 6).

This utilizes either a vibrating capacitor or a tuning fork chopper type system for its sensor. This is a well proven system that was originally designed thirty years ago.

In the past few years a sensor using a weak radioactive source has been available. These are extremely simple and are capable of extremely high speed readings. The drawbacks are the usual fears associated with radioactive material, the need to keep radioactive elements clean because the element is so weak that any contamination can impair the system's function, and the ability of the radioactive material to damage or alter the material under test.

If accuracy better than 2% is needed and resolution of less than one inch is necessary, the electrostatic voltage follower or voltmeter should be used. If less accuracy and resolution is acceptable the electrostatic fieldmeter may be used.

If the user keeps in mind the basic physics of electrostatics and properly utilizes today's instrumentation, satisfactory results should be easily obtainable.



Simplified Block Diagram: ELECTROSTATIC VOLTAGE FOLLOWER

Figure 6

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