

High Resolution Measurements of Surface Charge Densities on Insulator Surfaces

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Abstract

The uses and limitations of the electrostatic probe for the measurement of charge densities on insulating surfaces are discussed. A development of the technique is described in which two important limitations have together been overcome:

- (i) The effects on the probe signal of charges on all points of the surface have been taken into account by means of a matrix inversion procedure.
- (ii) A robotic control system has been developed which enables the probe to follow and scan a wide range of axi-symmetric insulator profiles.

The degree of resolution achieved enables the probe system to display and measure charge densities in individual streamer channels of a corona discharge on a PTFE surface. An example is given and comparison made with a dust figure of the same event.

1. Introduction

In high voltage engineering, an insulator surface is intrinsically the weakest part of a solid-gas insulation system. Knowledge of the insulating properties of solid insulator surfaces and the influence of their profile is thus very important. A major factor influencing the dielectric strength is the charge deposited on the surface of the solid insulation. This may arise as the result of pre-discharges, or of charge migration either along the surface from the electrodes or from within the bulk material.

A number of accounts have been given of the effect of a surface charge in reducing the flashover voltage of an insulator specimen. For example in [1] measured accumulation has been identified

with migration from bulk epoxy resin when there was a significant component of field normal to the surface. Very recently, Darveniza et al. [2] have demonstrated that deposited charge can change the flashover characteristics of practical polymeric insulators under standard test conditions.

The need to elucidate the effects of surface charging has led to the development of the scanning electrostatic probe described in this paper. Here, the primary requirement has been to study the surface corona discharges which precede breakdown. Since such discharges contain much detail, a high degree of resolution was desirable, leading to the choice of a small diameter electrostatic probe. Such probes have long been used and the theory of the capacitive probe was first discussed critically by D.K.Davies in 1967 [3]. Many researchers have employed high-resolution techniques without calibration [3] [4] [5]; they have been justified in this because their measurements used thin insulating samples on a grounded back plane. In this way, each voltage measurement was converted directly to a charge density measurement. However Al-Bawy et al [6] used the same without calibration for thick specimens. Their probe resolution had inadequate voltage resolution between neighbouring surface elements, so that charge distributions were inaccurate. Takuma et al [7], in a recent review concluded that a multi-point calibration technique, aided by numerical field calculations, as used in the technique described here, is the only way to obtain accurate charge density measurements for thick insulating specimens.

Rerup et al (8) [9] used Pedersen's λ -function [10] but did not use a 3D field solver to find the probe's response function. This leads to inaccuracies described in a discussion paper [11]. Other researchers [12] had problems with inaccurate calculation of the probe response function by neglecting the effect of the presence of the probe itself in their calculations. Ootera and Nakanishi [13] developed a scanning system for GIS cone spacers, but achieved poor spatial resolution because of the size of their probe and discretisation of their surface.

The system described in the present paper addresses the problems of the λ -function and probe geometry in a refinement designated as the ϕ -function. It is versatile and capable of mapping deposited charge densities with high resolution over a wide range of insulator profiles.

2. Surface Charge Density Measurement Theory

2.1. Electrostatic Probe

The electrostatic probe principle [3] is used, where charge on the surface induces a voltage on the centre conductor of a coaxial probe positioned above the surface. The outer conductor is grounded and the voltage induced on the centre conductor is measured via a very high input impedance ($>10^{15}\Omega$) op-amp. Basic construction is shown in Figure 1(a), the probe dimensions used in the present work are shown in Figure 1(b).

A multi-point measuring technique is employed, in which the insulator surface is divided up into a large number of surface elements. The probe voltage is recorded above each surface element, and from these probe measurements the surface charge density on each surface element can be calculated, using the method described later in the paper.

2.2. Surface Charge Density Calculation from Probe Voltage

2.2.1 Thin Insulators

For thin insulator specimens above a grounded back plane the circuit shown in Figure 2(b) can be solved, using the capacitances defined by Figure 2(a).

$$\sigma = V_{\text{out}} \left(\frac{C_{\text{sg}} (C_{\text{pg}} + C_{\text{sp}}) + C_{\text{pg}} C_{\text{sp}}}{AC_{\text{sp}}} \right) \quad (1)$$

where A is the effective area of the insulator surface and V_{out} is the measured voltage across C_{pg} .

Assuming that the probe is shielded from other nearby charges, and all capacitances and element area remain constant, then the probe voltage is linearly related to the element surface charge

density. This is a one to one mapping of each probe voltage measurement to each surface charge density element. Many previous investigators have employed this technique [3][4][5][6].

2.2.2 Thick Insulators

When the insulator specimen is much thicker and no longer against a grounded back plane two problems arise:

1. The shielding effect of the outer grounded conductor of the probe to nearby charges is reduced. The probe's selectivity is effectively reduced so that its response to neighbouring charges on the surface must also be taken into account.
2. It is no longer possible to assume that all capacitances, such as C_{sg2} and C_{sg3} (Figure 2c), remain constant as the probe moves over the surface taking measurements at various distances from the ground planes. This varies the constant of proportionality between probe voltage and surface charge density, though the basic equivalent circuit remains the same.

In recent years techniques have evolved to model the probe response to distant charges [8][9]. The technique described in this paper is an adaptation of Pedersen's λ -function [10], which relates the Poissonian charge q induced on the probe to the surface charge density (σ) on a surface element:

$$q = \lambda\sigma \quad (2)$$

The technique employed here relates the contribution v to the total probe voltage V directly to the surface charge density σ on a surface element: $v = \phi\sigma$, where ϕ is the constant of proportionality measured in $VC^{-1}m^2$. Each element has a different associated ϕ -value depending on its distance from the probe. The total probe voltage V is the sum of the contributions from all the elements of surface charge:

$$V = \Sigma v = \Sigma \phi\sigma \quad (3)$$

For the probe in one particular position the ϕ -values for all the elements on the surface make up the probe response function.

The technique employed here also deals with the second problem of varying capacitances by calculating a different response function for each voltage measurement position.

2.3 The Φ -Matrix Technique

The surface area is divided into elements as shown in Figure 3. The elements do not have to be square and there does not have to be an equal number of horizontal and vertical divisions. The probe voltage in position (i,j) is given by:

$$V_{ij} = \sum_{n_y}^{y=1} \left[\sum_{n_x}^{x=1} \phi_{ij}(xy) \sigma_{xy} \right] \quad (4)$$

where, $\phi_{ij}(xy)$ is the value of the probe's response function to charge at position (x,y) for the probe at position (i,j) and, σ_{xy} is the surface charge density on the surface element at position (x,y). This is a first order function of the $n_x n_y$ surface charge densities.

There are $n_x n_y$ probe voltage measurements in total and each of these voltages is a function of $n_x n_y$ surface charge densities. The problem is reduced to the solution of $n_x n_y$ simultaneous equations, which is solved using the matrix inversion technique.

The measured probe voltages and the unknown charge densities are grouped to two vectors \bar{V} and $\bar{\sigma}$. They are related by the matrix equation:

$$\bar{V} = \bar{\sigma} \Phi \quad (5)$$

where, Φ is a matrix containing all the ϕ -function values that are coefficients of the simultaneous equations. Hence the unknown charge densities can be found from:

$$\bar{\sigma} = \bar{V} \Phi^{-1} \quad (6)$$

2.4. Implementation of the Φ -Matrix Technique

2.4.1 Calculation of the ϕ -functions

The probe's response functions are found using a 3-D electrostatic field solver. The probe and insulator arrangement is fully modelled and key ϕ -values are found by moving a unit charge around elements on the surface. The proximity of the probe to the ground plane is then varied and the next set of key ϕ -values calculated. The complete set of ϕ -functions is produced by interpolating these key values.

Figure 4a shows an example of a ϕ -function. The 2-dimensional probe response function is shown as two separate functions ϕ_x and ϕ_y , which when placed at right angles and radially interpolated produce the full 2-dimensional ϕ -function. The probe's reduced response to distant charges in the y direction shown in Figure 4(b) illustrates the probe's increased selectivity when it is near the ground plane.

Figure 5(a) shows how the insulator material permittivity will affect the shape of the ϕ -functions. The importance of maintaining a constant distance between the insulator and the probe is illustrated by Figure 5(b). This places particular demands on the tolerances of the scanning apparatus.

2.4.2 Resolution

The spatial resolution of the probe is related to the shape of the ϕ -function. The smaller the width of the ϕ -function the higher the resolution obtainable. In addition to the response noted in Figure 4(a), it is clear that the shape of the ϕ -function is related to the dimensions of the probe and the probe-surface separation (Figure 5(b)). These must be considered in determining the resolution.

The spatial resolution of the scanning system is determined by the size of elements which divide the surface, Figure 3. In principle, the surface elements could be infinitely small for any probe geometry, but that would require a perfect measurement system with zero inaccuracy. Errors in measurement are greatly amplified during the solution of the simultaneous equations for calculating the charge distribution; this is because of the large number of multiplications in the solution

procedure. If the element size is too small for the ϕ -function of a particular probe geometry, there is poor differentiation between elements. Differences in probe voltages above neighbouring elements are then very small, so that any inaccuracies in the measurement system become critical. Thus, the element size should be chosen to provide good probe voltage differentiation between neighbouring elements for a given probe ϕ -function.

For the probe geometry used in this work (Figure 1(b)) an element size of 1mm^2 was chosen because it fitted in the area bounded by the outer grounded shielding conductor and provided satisfactory element probe voltage differentiation for the accuracy of the scanning system.

2.4.3 Solution of the Simultaneous Equations

The Solver software that implements the surface charge density calculation needs to know the exact shape of the ϕ -function for every probe position on the surface. It obtains these values by quadratic interpolation of key values from a text file. This is an essential feature of the solver software because it allows the investigator full control over what is effectively a four dimensional function. The effect of ground plane proximity and insulator shape can thus be fully implemented into the solution procedure.

The matrix is inverted in Matlab running under UNIX on a Fujitsu AP3000. The solution of the charge distributions is automated using script files; files generated by the scanning system are read in, the required Φ -matrix is automatically generated and the charge distributions are solved and saved, all without any user intervention.

The solution time increases with the resolution of the surface. As the number of surface divisions increases so does the size of the matrix required to solve the charge distribution. The amount of computer memory required increases as n^4 where n is the 1-dimensional division of the surface (i.e. a surface is divided into $n \times n$ elements). For example a surface scanned to a 100×100 resolution requires a $10,000 \times 10,000$ Φ -matrix which needs 800MB of RAM and takes just under 24 hours to

solve. The amount of RAM required increases very quickly with resolution; for a 150×150 surface division 4GB of RAM is required.

3. Surface Charge Density Measurement Implementation

3.1 The Scanning Apparatus

The probe is positioned by the adjustable scanning platform shown in Figure 6 using 4-stepper motors. A computer controls the whole scanning system using specially written software. The contour of the test object can be entered into the computer manually or the system can measure the shape of the test object automatically using a spring-loaded sensor. The computer then calculates the probe positions in order to scan the surface. The probe must be kept perpendicular to, and at a constant distance from, the surface. The surface is divided up into measurement points at which the probe voltage is recorded.

The surface is scanned in layers by rotating the test object. After each rotation the probe moves to the start position of the next layer until the whole surface has been scanned.

As the probe moves over the surface the probe voltage is measured at each point and stored in a file on the computer. All the settings for the scanning system are also stored in the same file; this allows the user to recall measurement parameters at a later date. The software has the facility to display graphically the scanned in voltage measurements and monitor each layer as it is scanned in. The scanning system has been developed as a versatile, easy to use piece of equipment with many useful facilities to help the user.

3.2 Calibration Technique

It is not possible to construct a calibration test object with a specific surface charge density. However it is possible to use a conducting surface set at a specific voltage as shown in Figure 7.

The test object consists of a cylindrical insulating former upon which a copper foil is glued, a strip about 10mm wide was isolated by removing two thin strips of foil about 2mm wide. The isolated copper strip can be set at a potential,

This arrangement does not allow a direct calibration of charge density to probe voltage but does allow the accuracy of the modelling technique used to find the ϕ -functions to be assessed. The test piece is modelled using the same finite element modelling techniques and the relationship between surface potential and probe voltage is found.

Figure 8 shows the probe output voltage as it is scanned across the test piece with different voltages on the copper strip. The distance between the probe and the surface is 1mm. The edges of the copper strip are not perfectly smooth which alters the probe-surface separation very slightly, causing the small distortions in probe output voltage.

The probe voltage calculated by modelling is only 1% more than the average of the actual measured values shown in Figure 9. This puts great confidence in the modelling procedure and in the overall accuracy of the scanning system.

4. Example Surface Charge Density Measurements

A 100mm high, 40mm diameter cylindrical PTFE insulator specimen was placed in a rod plane gap and a +35kVp 1.2/50 μ s impulse voltage was applied to the rod. A single burst of streamers was produced as detected by current and photomultiplier measurements. The surface was first scanned by the probe and a dust figure subsequently obtained using photocopier toner that adheres to positive charge.

Figure 10(a) shows the probe voltage distribution obtained. The scanned cylindrical insulator surface is displayed unrolled, with the rod electrode at the top in the middle and the plane electrode running along the bottom. Figure 10(b) shows the calculated surface charge distribution. Individual streamer paths can be resolved. The surface charge density is greatest at the streamer tips where they stopped propagating. Figure 10(c) shows the dust figure obtained. When the charged and non-charged regions of the calculated distribution (Figure 10(b)) are separated as shown in Figure 10(d) the close relation between the calculated charge distribution and the measured dust figure can be seen (Figure 10(e)).

The scanning system can detect charge densities in the range of 0.1 to about $50\mu\text{Cm}^{-2}$ on 1mm^2 elements of the surface. The total measured charge on the insulator surface is in the order of a few nano-coulombs of positive and negative charge. The net charge on the surface is often close to zero, after a series of repeated tests. This emphasises the inadequacy of low-resolution measurements of surface charge density that would simply show that there is very little charge on the surface. Very localised regions of charge density would be averaged out by low-resolution net surface charge measurements.

5. Discussion and Conclusions

The very close agreement between the measured and simulated probe voltages for the calibration test piece combined with the similarity between the measured surface charge density distributions and the corresponding dust figures, gives great confidence in the results obtained.

Prior to the development of the scanning system, dust figures were the only way of getting a detailed view of the charge distribution on the surface of a practical insulator. The dust figure still provides the best possible spatial resolution, but it has a number of drawbacks. It is not quantitative; it is very messy; it is final because once the dust figure has been obtained no further test voltages can be applied to the insulator specimen without first thoroughly cleaning it. The electrostatic

probe, combined with the scanning technique is, by comparison, quantitative, clean and avoids contact with the insulating surface.

A significant advance in the electrostatic probe technique has been the improvement in spatial resolution; previous researchers have been able to solve distributions with a restricted number of large surface elements [13]. A major factor in this advance has been the exponential increase in computing power in the late 20th.Century, which has permitted the design and implementation of the data-handling strategy used. As a result, the following attributes have been achieved:

- The probe response function has been obtained accurately in three dimensions.
- High spatial resolution, permitting identification and measurement of individual streamers in a corona discharge.
- There is no restriction to thin insulator specimens; the technique can be applied to specimens of any thickness.
- The scanning mechanism can be applied to contoured insulator geometries of practical significance.
- An accurate quantitative macroscopic view can be obtained of the overall surface charge distribution.
- The system is easy to use.

A further paper will describe the use of this system in investigating the deposition of charge on insulating surfaces by corona discharges.

6. Acknowledgements

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List Of Symbols

<i>Symbol</i>	<i>Variable</i>	<i>Units</i>
σ	Surface Charge Density.	Cm^{-2}
V	The Voltage induced on the electrostatic probe.	V
λ	The constant of proportionality between Surface Charge Density and Poissonian Induced Charge on the electrostatic probe sensor plate.	m^2
ϕ	Phi, The constant of proportionality between Surface Charge Density and contribution to the total voltage on the electrostatic sensor plate.	VC^{-1}m^2
v	The contribution to the total probe voltage from one element of surface charge.	V
σ_{xy}	The surface charge density on a surface element at position (x, y).	Cm^{-2}
$\phi_{ij}(xy)$	The probe's response function to charge at position (x,y) for the probe at position (i,j).	VC^{-1}m^2
n_x	The number of surface elements in the x-axis direction.	None
n_y	The number of surface elements in the y-axis direction.	None
\vec{V}	A vector containing all the probe voltage measurements.	V
$\vec{\sigma}$	A vector containing all the surface charge densities.	Cm^{-2}
Φ	A matrix containing every ϕ function for the entire surface.	VC^{-1}m^2

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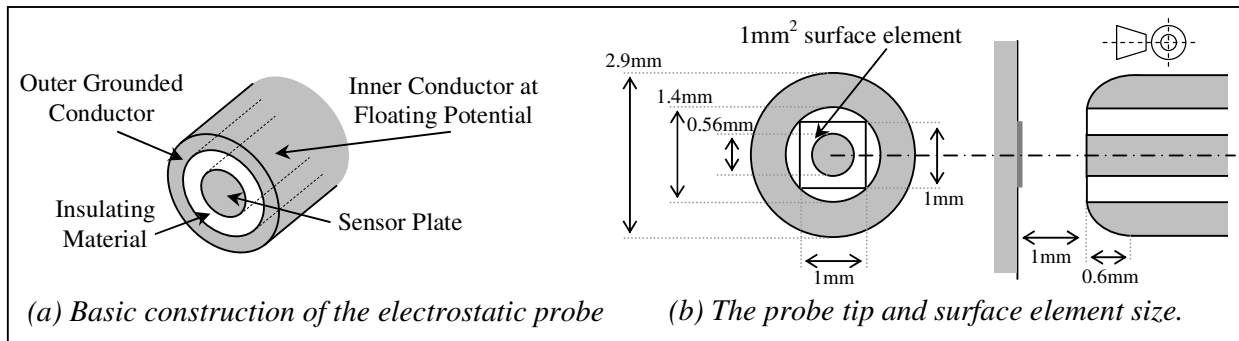


Figure 1: The Electrostatic Probe.

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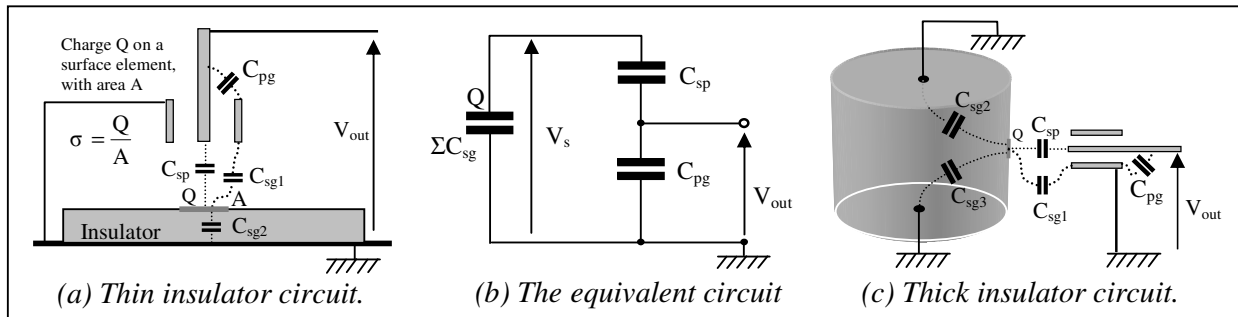


Figure 2: Simple explanation of probe operation for thin and thick insulator specimens in terms of circuit capacitances.

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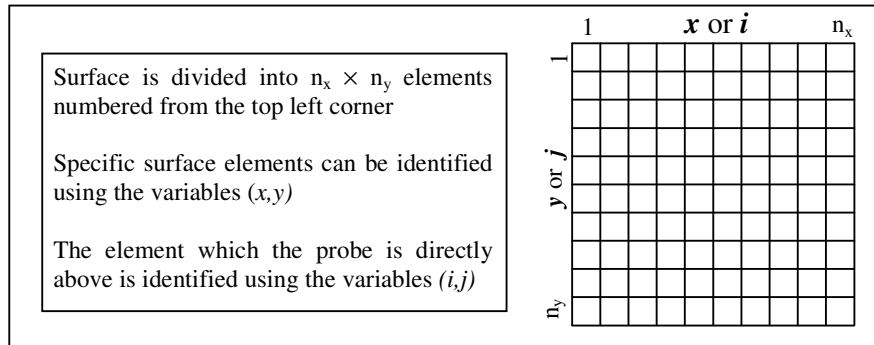


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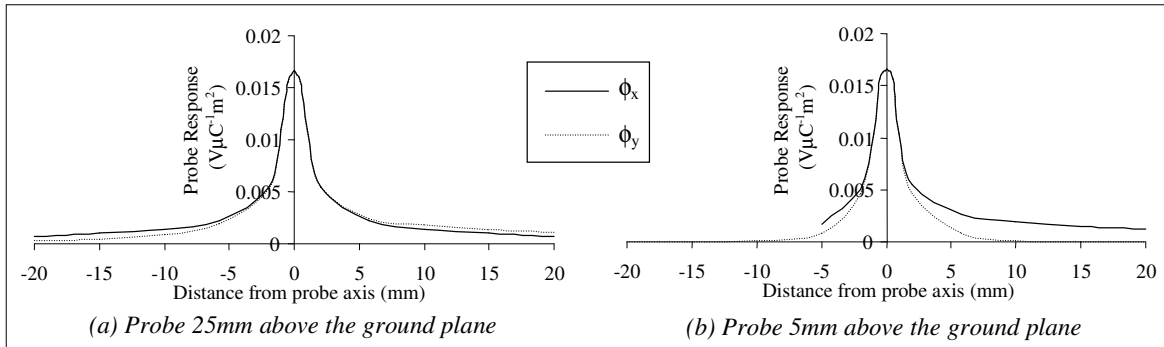


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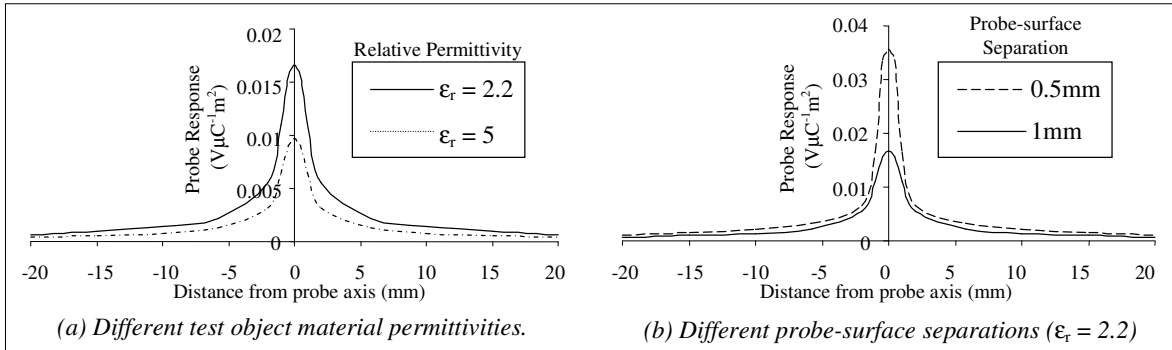


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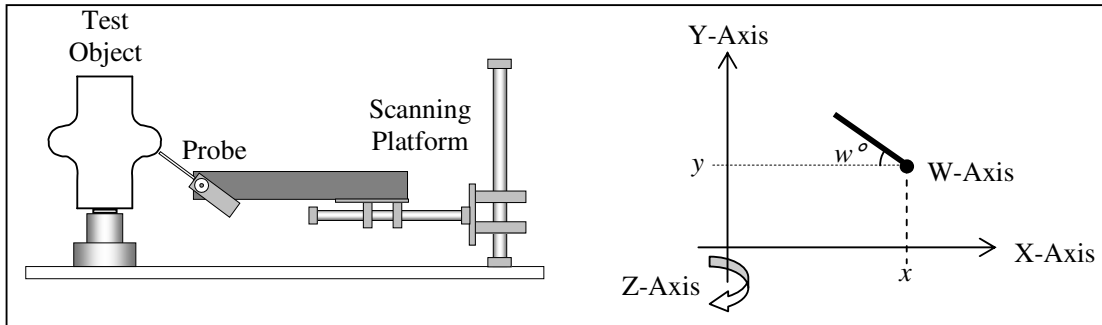


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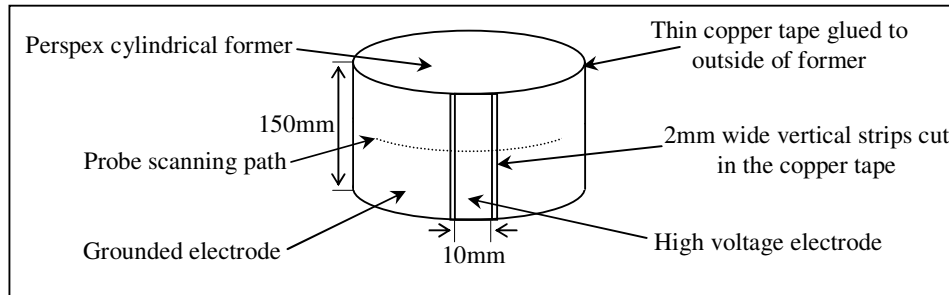


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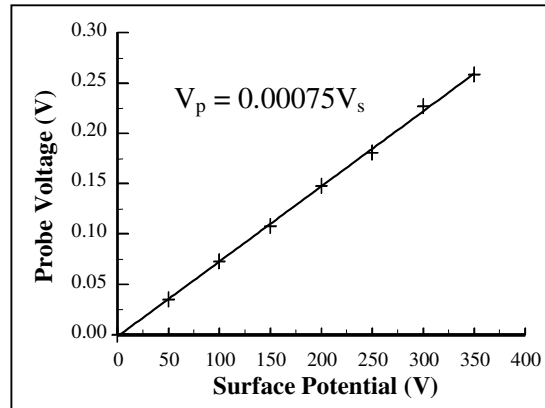
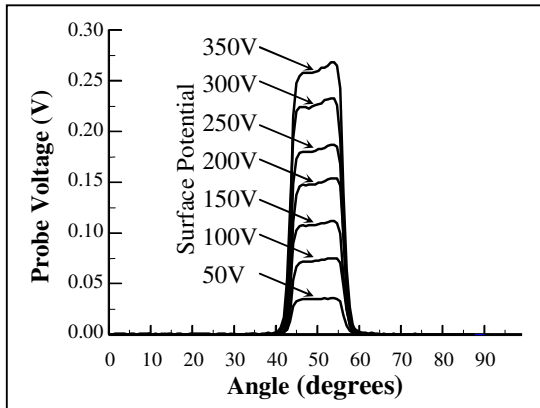


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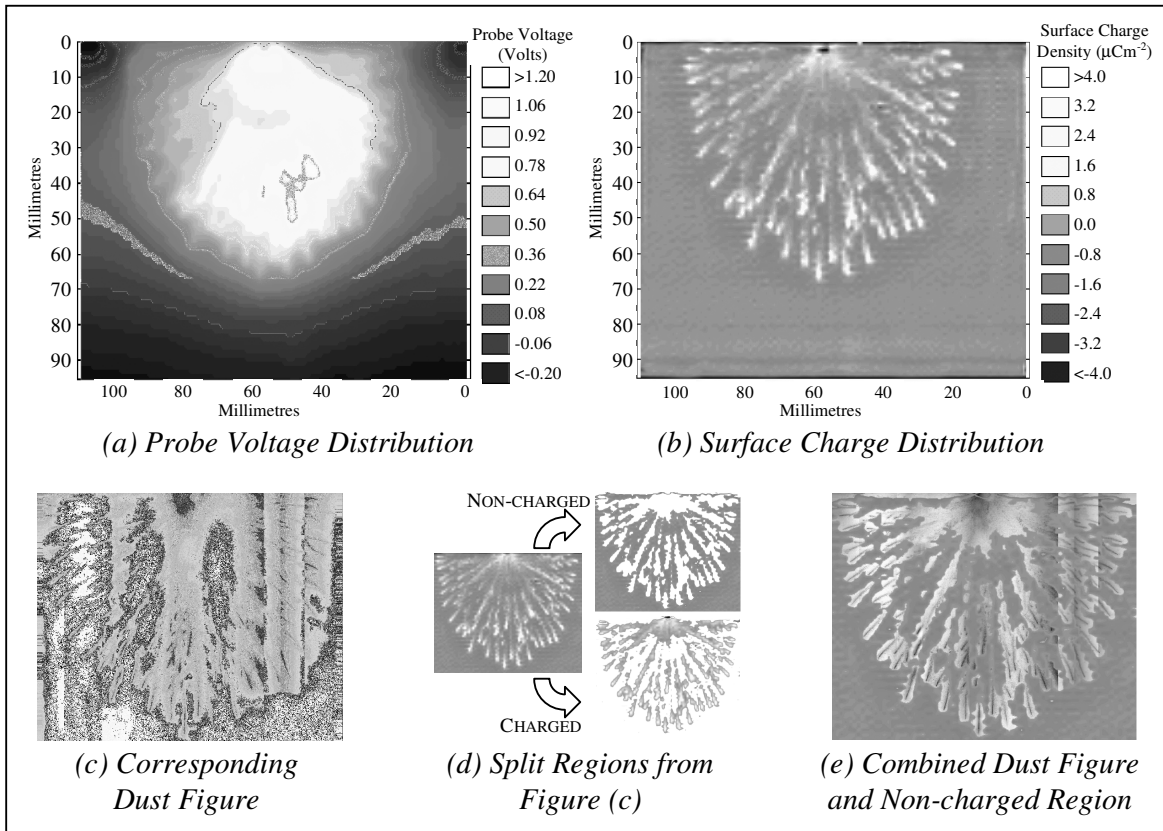


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