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USE OF AN ELECTROLYTIC TANK IN STUDY OF SURFACE ELECTRIC FIELD DISTRIBUTIONS

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USE OF AN ELECTROLYTIC TANK IN STUDY OF SURFACE ELECTRIC FIELD DISTRIBUTIONS

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OCT 12 1951

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DEPARTMENT OF THE NAVY OFFICE OF NAVAL RESEARCH

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ABSTRACT

Previous two-dimensional electrical field experiments, involving glass disks covered on one side with a transparent conductive coating, disclosed that commercially available glass samples had a distinct nonuniform resistivity across the face of individual pieces. Using an electrolytic tank of analogous electrical characteristics with twenty-four peripheral electrodes connected to a suitable source, it was determined that probe voltage would, with negligible error, be proportional to probe coordinates within a working circle whose normalized diameter is 0.8. Either rectangular or polar coordinates can be used, but the resistive glass coating must be sufficiently uniform for such an operation.

An important application of the transparent, electrically conductive disk is the rapid, multiple designation of the coordinates of a target seen on a search-radar PPI indicator to a fire-control radar. Such a system is under development at this Laboratory.

PROBLEM STATUS

This is a final report on one phase of the problem; work on other phases continues.

AUTHORIZATION

NRL Problem R07-25R
RDB NR 507-250

Manuscript submitted for publication July 10, 1951.

USE OF AN ELECTROLYTIC TANK IN STUDY OF SURFACE ELECTRIC FIELD DISTRIBUTIONS

INTRODUCTION

An electrolytic tank was used in developing two systems in which electric fields are induced across conducting surfaces of finite dimensions. In both systems a probe voltage is interpreted in terms of probe position. A shallow, 12-1/2-inch-diameter tank served as the electrical equivalent of a plate-glass disk covered on one side with a transparent, conductive material. Because early samples of commercially available glass showed a distinct nonuniform resistivity across the face of individual pieces, the tank was used to represent an ideal surface.

Rectangular coordinates were used in one system and polar coordinates in the other, both systems requiring suitable voltages at points on the periphery of the disk to secure the desired voltage distribution across the conductive surface. Because only a limited number of peripheral points could be used, the resulting voltage distribution approximated the ideal form. In these investigations the number of points was increased until the desired approximation to the ideal voltage distribution was achieved across a major portion of the disk, this portion being known as the "working circle."

The distribution of voltage across a uniform surface could have been determined from purely theoretical considerations once the boundary conditions were assumed. However, it was concluded that this approach would be expensive and time-consuming, and accurate results could be secured more economically with an electrolytic tank, a useful tool for solving field problems, widely discussed in the literature. The ease by which the results of this investigation were secured amply justify the use of the tank in the present problem.

TANK TECHNIQUES

An electrolytic tank (Figure 1) was designed so that the short-copper electrodes could be easily rearranged. The electrolyte, mixed to approximate the resistivity of the disk, was composed of equal parts of water and a copper sulfate saturated solution mixed to a depth of 3/8 inch. The probe was a short length of No. 26 gauge copper wire vertically mounted with its end resting on the tank bottom, and probe position was read from rectangular coordinate paper placed beneath the transparent bottom of the tank.

Tank leveling was accomplished by placing the probe at the physical center of the tank and then adjusting the leveling screws until this point was also the electrical center. A bridge circuit (Figure 2) was used so that the null reading of a galvanometer would indicate a level condition. The tank was leveled about the X-axis by turning screw A (Figure 1) until the bridge circuit was balanced; the two electrodes were then placed on the X-axis and screw B was adjusted for a new balance. These two operations were repeated in sequence until no further adjustment was necessary. Because of the

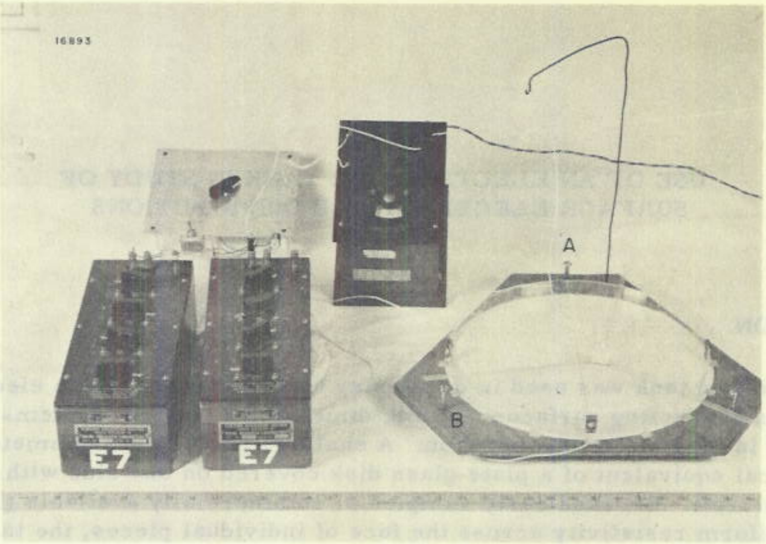

Figure 1 - Electrolytic tank setup for leveling

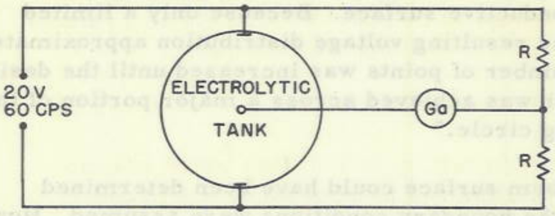

Figure 2 - Tank leveling circuit

bridge-type circuit used, the leveling procedure was independent of minor variations in supply voltage.

A similar bridge circuit was used in all voltage measurements. When a null was indicated, the probe position represented one point on the mid-equipotential line, which was traced by moving the probe so as to preserve the bridge balance. A change in ratio of the two bridge-arm resistors permitted tracing other equipotential lines. A check on the levelness of the tank disclosed the mid-equipotential line straight and normal to an orientation line through the two leveling electrodes. Plots of two symmetrically chosen equipotential lines were found symmetrical to the tank center as well as to the mid-equipotential line.

The null-indicating instrument, Leeds and Northrup ac galvanometer No. 2370-C, rated at 1.0 μa/mm, proved so sensitive that the limiting factor was the accuracy to which the probe position could be read from the graph paper beneath the 1/4-inch-thick tank bottom; accuracies to 1/40 inch or better were recorded.

X-Y POTENTIAL DISTRIBUTION

Two voltage orientations and one switching operation were required to secure the two rectangular coordinate voltages; however, it was sufficient to investigate only one coordinate reading, known as the Y-coordinate.

Consider the voltage at point C (Figure 3) on the periphery as measured with respect to the voltage along the X-axis. It can be shown that if the voltage at every peripheral point can be written

$$V_c = V_m \sin \theta , \qquad (1)$$

where V_m is the voltage at $\theta = \pi/2$, then the normalized voltage at any point within the circle can be written

$$V_y/V_m = y/r, \tag{2}$$

where r is the radius of the circle and y is the Y-coordinate of that point. Observe that the greatest voltage across the circle is $E = 2V_m$. Equation (2) expresses the desired relationship between probe voltage and probe position.

If the boundary voltage is not continuous but is applied at discrete points on the periphery with an amplitude determined by Equation (1), then the right-hand side of Equation (2) must be augmented by an error term to give the following expression for the probe voltage:

$$V_y/V_m = y/r + e(x,y), \tag{3}$$

the error term being a function of both coordinates.

In practice, point electrodes are not possible, and the voltage is applied to an arc on the periphery or to a small area within the circle. However, the general form of Equation (3) still holds.

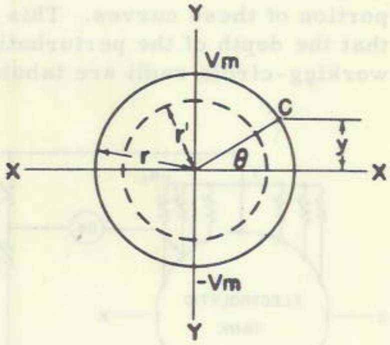

Figure 3 - Tank coordinate system

One would expect that as the number of electrodes is increased the error term would become negligible within a working circle of radius r′. A tolerable error of

$$e(x,y) \leq 0.01 \tag{4}$$

was selected as the criterion for experimental determination of r′. This value of error was considered to be roughly that for which an operator can place a hand-held probe at a desired point within the circle.

Where the error term can be neglected, Equation (3) is rearranged to give

$$y = r\,V_y/V_m. \tag{5}$$

Thus, the probe voltage, V_y, can be interpreted in terms of probe position, y, with some error.

If the glass disk is placed over the PPI indicator of a radar set, a desirable working-circle radius is expressed by the ratio

$$r'/r = 0.8. \tag{6}$$

A circuit (Figure 4) was set up to determine the number of electrodes necessary to meet the foregoing requirements. Owing to circuit symmetry, no current flowed at the X-axis electrodes, and these were left blank. Electrodes were spaced uniformly and made an integral multiple of four. They were regulated to the proper potentials by adjusting series resistors R_s to secure a bridge balance. For example, the electrode at the 45° point had a normalized voltage of $V_c/V_m = \sin 45^0 = 0.7071$. Resistor R_2 was set at 707.1 ohms and R_1 at 292.9 ohms so that $R_2/R_1 + R_2 = 0.7071$, and so that $(R_1 + R_2) = R = 1000$ ohms. This value of R was large enough to avoid excessive bleeder currents and low enough to avoid the effects of distributed capacity.

The foregoing procedure is complicated because the adjustment of any series resistor will change the voltage at all electrodes to some extent. With this circuit the sequence of adjusting the series resistors must be repeated several times to secure proper electrode voltages.

Equipotential plots for 12, 20, and 24 electrodes (Figures 5, 6, and 7) indicate electrode sizes and positions. Only semicircular plots are shown, as the lines are essentially symmetrical to the X-axis. Normalized voltage variations along the Y-axis are graphed (Figure 8) to aid the selection of the working-circle radius, which is based on the linear portion of these curves. This procedure is justified because the equipotential plots show that the depth of the perturbation region is fairly constant around the circle. Normalized working-circle radii are tabulated, 4n being the number of electrodes.

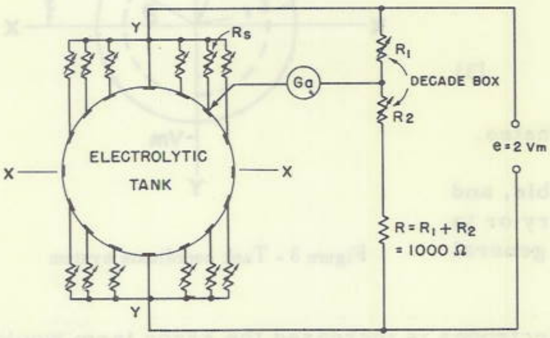

Figure 4 - Experimental circuit, X-Y coordinates

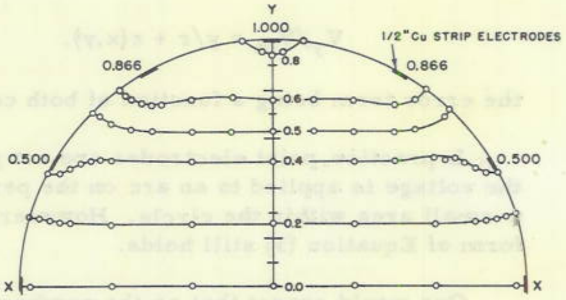

Figure 5 - Equipotential lines for 12 electrodes

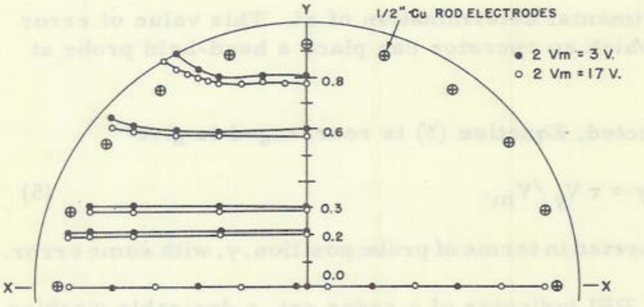

Figure 6 - Equipotential lines for 20 electrodes

4n	r'/r
12	0.72
20	0.77
24	0.83

From these conservative values it is evident that 24 electrodes will be sufficient to secure the desired working circle. The validity of the foregoing tabulation will be discussed after a presentation of data for the rho-theta coordinate system.

RHO-THETA POTENTIAL DISTRIBUTION

A polyphase electric field was set up in the tank by connecting a 12-phase voltage source to electrodes spaced uniformly on the tank periphery. These phases were secured from a 3-phase, 60-cycle source by the circuit shown in Figure 9a. Unity-ratio isolation transformers were used so that the "wye" bank of transformers could be supplied by a solid neutral to reduce the third-harmonic content to equal that of the "delta" bank. Since the same type of transformer (Thordarson No. T-21F08 Filament Transformer) was used in the "delta" bank, the three Variacs were included so that the secondary voltages of this

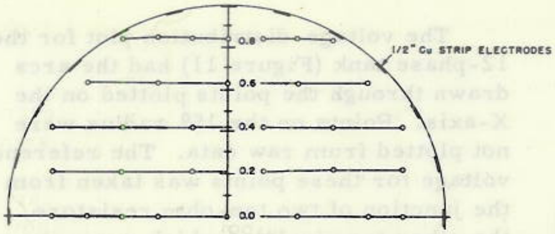

Figure 7 - Equipotential lines for 24 electrodes

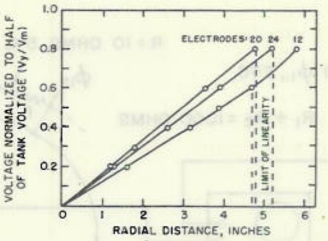

Figure 8 - Composite graph of voltage distribution on Y-axis

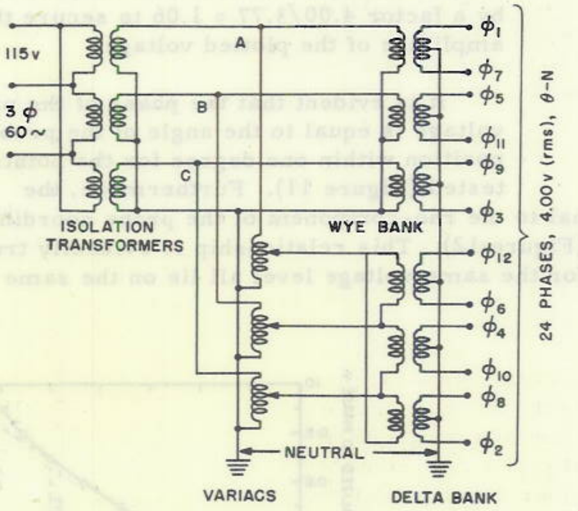

Figure 9a - Twelve phases from 3-phase source—wiring diagram

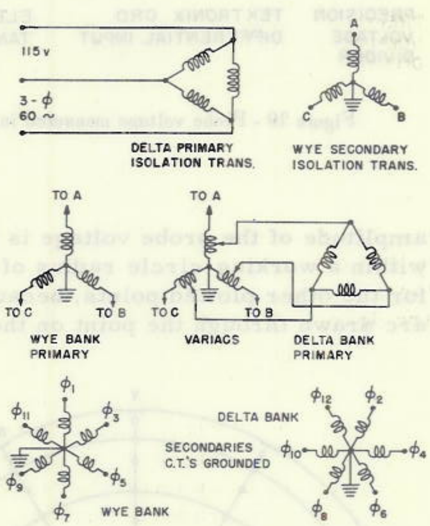

Figure 9b - Twelve phases from 3-phase source-coils drawn to represent phase relationships

bank could be adjusted to match those of the "wye" bank. Center taps of the six secondary windings were connected together to form the neutral connection for the twelve phases with all voltages being measured with respect to this neutral and the probe voltages normalized to the phase voltage: V_p/V_ϕ.

A Tektronix Cathode-Ray Oscilloscope Model 512 was used as the null indicator because, through the differential inputs (Figure 10), it was sensitive to both amplitude and phase of the probe voltage. The trace represented the difference between the two inputs, one being connected to a reference voltage of known amplitude and phase and the other connected to the probe, which was then moved until the oscilloscope trace indicated minimum amplitude. Normalized probe voltage was then $V_p/V_\phi = R_1/(R_1 + R_2)$, and the phase was determined by the phase of the reference point.

The small residual trace observed when the probe was in the null position was attributable to the presence of a third harmonic with an amplitude less than one percent of the phase-voltage amplitude. This null indicator was so sensitive that on repeated trials the plotted points lay within 1/40 inch of each other.

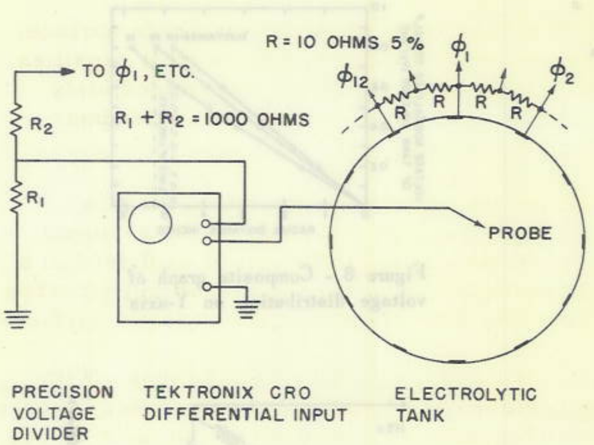

Figure 10 - Probe voltage measured in polar form

The voltage-distribution plot for the 12-phase tank (Figure 11) had the arcs drawn through the points plotted on the X-axis. Points on the 15° radius were not plotted from raw data. The reference voltage for these points was taken from the junction of two ten-ohm resistors, the other terminals of which were connected to the proper phases at the transformer bank. The amplitude of this reference voltage was 3.77 volts compared to 4.00 volts for each phase. Thus, it was necessary to multiply the observed amplitude by a factor 4.00/3.77 = 1.06 to secure the amplitude of the plotted voltage.

It is evident that the phase of the probe voltage is equal to the angle of the probe position within one degree for the points tested (Figure 11). Furthermore, the amplitude of the probe voltage is proportional to the rho-component of the probe coordinates within a working-circle radius of 5 inches (Figure 12). This relationship is evidently true for the other plotted points, because those for the same voltage level all lie on the same arc drawn through the point on the X-axis.

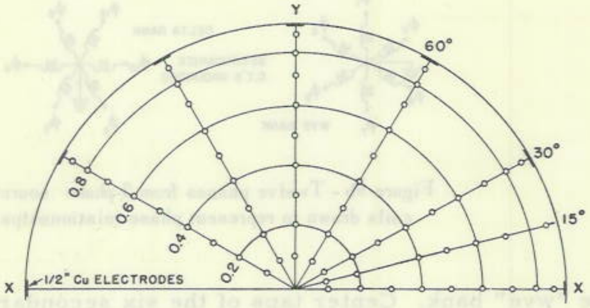

Figure 11 - Voltage distribution in 12-phase tank

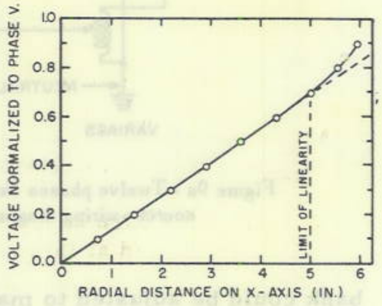

Figure 12 - Radial distribution of voltage for a single phase

VALIDITY OF DATA

In all experiments with the electrolytic tank it was observed that a comparatively high potential gradient existed at or near the electrode. Hansen and Lundstrom[1] call this the "electrode effect," which is evident from the plot of equipotential lines for 12 electrodes (Figure 5). Here the 0.5 equipotential line[2] meets the periphery about midway between the two electrodes, the normalized voltages of which are 0.500 and 0.866. The 0.4 line meets the periphery quite close to the 0.500 electrode.

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[1] Hansen, W. W., and Lundstrom, O. C., "Experimental Determination of Impedance Functions by the Use of an Electrolytic Tank," IRE Proc. Vol 33, No. 8, pp. 528-534, August 1945

[2] These figures refer to normalized voltages.

The electrode effect may be caused by minute bubbling at the electrode surface; bubbles of macroscopic proportions were observed at much higher current densities. Under such conditions two potential distributions were observed, one immediately upon applying the voltage, the other after equilibrium was reached with attendant bubbling.

Equipotential lines shifted slightly as the applied voltage was changed; this effect is shown in Figure 6 where equipotential lines are plotted for a plate-supply voltage, e, of both 3 and 17 volts. The upward shift of the lines can be explained in a qualitative manner by the supposition that at the lower voltage less bubbling occurred at the electrode surfaces and hence the potential gradient was lower at those surfaces.

A frequency effect was also observed during preliminary investigations. With the tank treated as a two-terminal circuit element and with copper electrodes immersed in a saturated copper sulfate solution, the impedance varied from 635 ohms at 25 cps to 583 ohms at 400 cps. Calculations were based on the assumption that the impedance was purely resistive; applied voltages were less than 0.1 volt.

Final choice of a frequency of 60 cps was determined by the availability of a sensitive galvanometer designed for this frequency. Accordingly, the influence of this variable on the equipotential plots was not investigated.

The neglect of frequency, strength of the electrolyte, and other parameters in these investigations were based on the assumption that any effects attributable to variations in these parameters would, if anything, lead to pessimistic rather than optimistic results. Subsequent experiments with electrically conducting glass disks produced results which bear out this assumption.

Few data were found in the literature to aid in setting up an electrolytic-tank experiment. The most instructive information was discovered at a late date in a report issued by the Sperry Gyroscope Company,[3] which described a tank, operating at one kc, using a dilute solution of potassium chloride and rhodium-plated copper electrodes. The report stated that the equivalent ionic conductances of the K^+ and the Cl^- ions were approximately equal and that polarization sheaths on the electrodes were minimized at this frequency. Both rhodium and platinum are highly inactive chemically and electrically, but rhodium is said to form a more satisfactorily plated surface.

Adoption of these specifications in future tank experiments might lead to results which more nearly represent the theoretical relationships and which can be more accurately reproduced.

APPLICATIONS OF CONDUCTIVE DISK

An electrically conductive disk would be useful for fast, remote designation of the coordinates of any point beneath the transparent glass overlay. Thus, a tactical map or the screen of a cro tube might be placed beneath the glass disk. An operator would place his probe on the disk directly over the selected point on the map. Depending upon the coordinate system used, the X-Y or rho-theta components of the probe voltage will be displayed at the receiving end of a wire or radio link.

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[3] First Quarterly Report on Investigation of Metallic Delay Lenses, Sperry Gyroscope Co., Report No. 5224-1151, (Uncl.), July 15, 1949

Such a system is sufficiently flexible to have many applications and modifications. For instance, the Systems Utilization Branch of Radio Division II at NRL is developing an application of the conductive disk in which the glass overlay is placed over the Model VK Plan-Position-Indicator. Each time the probe is placed over a target pip, the range and bearing of that target are indicated by two dials driven by a servo system connected to the probe. Thus, the PPI operator can, in a matter of seconds, designate any target to one or more remote fire-control radars, permitting them to acquire and track a target.

Another circuit has been planned to use rectangular coordinates. A switching operation will be necessary because the two coordinate voltages must be read separately. These two voltages might be transmitted alternately on a time-sharing basis, or they might be held in a capacitor store between sampling periods to secure a continuous transmission of the two coordinate voltages over separate lines. If the sampling frequency is sufficiently high, the outputs will be two step functions and will closely approximate the coordinate voltages of a continuously moving probe.

The rectangular coordinate overlay might be used with a shipboard radar system to secure remote designation of any target position selected by the PPI operator. The electrical axes of the conductive disk are readily shifted to accomodate off-centering of the PPI display. Thus, the two probe voltages would then represent the coordinates of the target with respect to the ship regardless of off-centering.

If the designation were made to some other ship in the task force, the PPI operator could shift the electrical axes to the position of the other ship as seen on the PPI display. The operator would place his probe on the glass over the pip representing the other ship and then adjust two knobs for zero probe output. The two probe voltages would then represent the coordinates of the target with respect to any desired ship in the force.

When desirable; the two coordinate voltages could control the position of the cro electron beam. If a translucent map were placed directly over the face of the cro, the electron beam would illuminate a point on the map. Now, if a similar map were placed under the conductive disk, the probe operator could instantaneously designate any point on the remote map by placing the probe over the corresponding point on the map under the disk. Furthermore, if the cro screen is of the long-persistence type, changes on the sender's map could be "drawn" with the probe and reproduced on the cro to be traced by the receiving operator.

This brief discussion should suggest other applications of a transparent, electrically conductive disk for which probe voltages can be interpreted in terms of probe coordinates.

CONCLUSIONS

An electrically conductive disk with 24 peripheral electrodes connected to suitable voltages will have a potential distribution across its surface so that the probe voltage will be proportional to probe coordinate. Using this number of electrodes, satisfactory accuracy can be achieved within a circle whose normalized diameter is 0.8.

Were only 12 electrodes used in the rho-theta application, there would be no safety factor because the working circle would have a diameter of just 0.8 (Figure 12). Power supply considerations lead to the selection of 24 electrodes as the next feasible number. Since 24 electrodes are also recommended for the X-Y application, this choice permits the conductive glass disk to be interchangeable in the two systems. Obviously, interchangeability is advantageous.

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These conclusions are based on tests with an electrolytic tank of analogous electrical characteristics. Specifying the degree in uniformity required for the resistive disk coating is reserved for subsequent investigations.

By means of suitable circuits, either rectangular or polar coordinates can be used. A two-step switching cycle is necessary to read the two rectangular coordinate probe voltages because the plate-supply voltage must be connected to each of two transverse orientations. The two polar coordinates can be read simultaneously by connecting the probe to one circuit[4] sensitive to the probe-voltage amplitude and another circuit sensitive to the phase. The required 24 phases can be secured from the 12-phase supply by center-tapped resistors connected between adjacent phases. The proportionality constant, relating probe position to probe voltage, must be found by empirical means.

An important application of the transparent, electrically conductive disk is the rapid, multiple designation of the coordinates of a target seen on a search-radar PPI indicator to a fire-control radar. Such a system is under development at the Laboratory.

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[4] Such a circuit is described in a forthcoming report written by a member of the Systems Utilization Branch of Radio Division II. Letter report "Conducting Glass Polar Coordinate ~~Glass~~ Generator for Multiple Target Designation" NRL Problem No. 39R07-25, Letter Report C-3950-242A/51 mws, 11Sept. 1951, Robert W. Whiteley, Confidential.