# FACILITY GROUNDING

## BASIC GROUND PLANE

A good basic ground plane is the foundation for obtaining reliable interference-free equipment operation and to obtain all of the inherent shielding qualities of the facility. An ideal ground plane would be a zero-potential, zero-impedance system that could be used as a reference for all signals in the associated circuitry. This would allow all undesirable signals and ambient radiation to be transferred to it for elimination. Ideally, it should be able to absorb all signals and radiation while itself remaining stable. An ideal ground plane would provide equipment with a common potential reference point anywhere in the system, so that no voltage would exist between any two points in the ground plane. However, because of the physical properties and characteristics of grounding materials, no ground plane is ideal and some potential always exists between points.

A ground plane should either be constructed of low-impedance material such as copper, or be long, wide, and thick enough to provide a minimum of impedance between its extremities at all frequencies. The ground plane for a fixed location, plant, or facility should consist of a continuous sheet of expanded copper, or of rigid copper conductors 10 x 10 ft grid with open-center spacing, or less; it should also present the highest capacity possible to the earth. It should extend continuously under all equipment areas in the building, under the footings, and 6 ft or more beyond the building limits.

High-power transmitter plants may require ground radials extending from the ground plane 1/4 of a wavelength at the lowest operating frequency to permit adequate decay of ground currents. The dc resistance to earth must be kept low to prevent large changes in ground plane potential produced by conducted or induced currents caused by the operation of internal or external systems. Ground rods driven into the permanent water table and bonded to the ground plane will usually provide an earth connection of 2-1/2 ohms or less. In extreme cases, as in desert areas, where ground resistance is high and the permanent water table is deep, drilled wells may be required to provide a low-impedance dc path to ground. Equipment ground tie points may be provided by a conveniently located ground plate bonded to the ground plane by copper straps.

There are three fundamental grounding techniques and they can be used either separately or in combination (Figure 1). They are as follows:

1. Underlying floating ground system, in which the ground plane is completely isolated from all circuits.
2. Single-point ground system, in which a single physical point in the circuitry is designated as a ground reference point. (All ground connections are tied to this point.)
3. An underlying multipoint ground system, in which a ground plane (for example, an entire chassis), is used instead of individual return wires for each of the circuits.

A ground point is the location where a circuit, piece of equipment, or system is connected to the ground plane. The impedance of a ground connection is a function of such factors as the size of the conductor, the length of the leads, the wiring techniques, and the frequency of the implementing system. If the ground connection is improperly made, it may be inadequate for the satisfactory operation of the circuitry, or may in fact be more detrimental to the control of interference than no ground connection at all.

Grounding the high-frequency portion of the spectrum is difficult and complex, its complexity varying in direct proportion to the operating frequency. The following factors contribute to this:

1. Every wire has a defined conductance.
2. A current flowing through a wire induces flux around the wire.
3. As radio frequencies increase, inductive reactions cause circuit impedances to increase.
4. The resonant frequency of even small inductance acting with circuit components often falls within the operating frequency of the circuit.
5. As operational frequencies increase, skin effects become an important consideration.

A low-impedance ground connection requires the ground lead to be as large and short as possible, and to be securely bonded directly to ground plane. A typical ground lug connection and its equivalent circuit are shown in Figure 2. As the frequency increases, the inductance of the ground lead can become appreciable and, if the power of high-frequency interference currents is appreciable, the currents may be conducted through the ground pin and coupled into the external wiring.

## EARTH GROUNDING

To be effective, earth grounding must provide a low-impedance path at all frequencies to the soil immediately beneath the equipment. The local soil condition of the underground shelves will determine how elaborate the earth ground system installation must be. The ground resistance will be determined largely by chemical ingredients in the soil and the amount of moisture maintained in it. The Bureau of Standards summary in Table 1 (Reference 1) shows the wide variation in resistance for different types of soil.

If a soil of uniform resistivity is assumed, the greatest resistance is in the shell immediately surrounding the electrode buried beneath the ground, which has the smallest cross section of soil at right angles to the flow of current through it. Each succeeding shell of this electrode has a larger cross section and, therefore, lower resistance. At a distance of 8 to 10 ft from the rod, the area is so large that the resistance of successive shells is almost minute compared to that of the shell immediately surrounding the rod.

Resistance will vary inversely to the cross section, with the greatest variation occurring within a few feet of the rod. Where the conductive shell is small, the resistivity of the soil is an important factor in the effectiveness of the ground connection to earth. The moisture content of the soil causes a marked difference in its resistivity; the variation of only a few percent in the moisture content, especially below 20 percent, will change ground rod resistance to earth over a wide variety of soils, as illustrated in Figure 3. The normal moisture content of soil varies for different localities as a function of rainfall. On the average it is 10 percent during dry seasons and approximately 35 percent during wet seasons.

Soil resistivity will also vary as a function of temperature. This is an important factor in locales where winter is very severe and the earth freezes to a considerable depth below the surface. Any moisture in the soil experiencing temperatures below 32°F causes a tremendous increase in the temperature coefficient of resistance for the soil. This coefficient is negative and, as the temperature drops, the resistance of the soil increases, as shown in Figure 4. The ground rod should be driven below the frost line in the locales where temperature variation is relatively large. The upper soil, when frozen, shortens the effective length of the ground rod, which should therefore be long enough to reach the permanent moisture level of the soil. If it does not, large seasonal variations in resistance will occur and nominal resistance to the earth will remain high.

Soil seldom has a uniform resistivity throughout the different depths. The deeper the soil the more stable it is, while the surface soil exhibits large variations due to alternate wetting and drying out. Figure 5 shows a calculated effect of ground rod resistance to earth as a function of the depth of penetration. It is based on the assumption of a uniform soil at all depths. If the soil were of a homogeneous nature throughout and had the same resistivity at all depths, it would be possible to predict with reasonable accuracy the length of

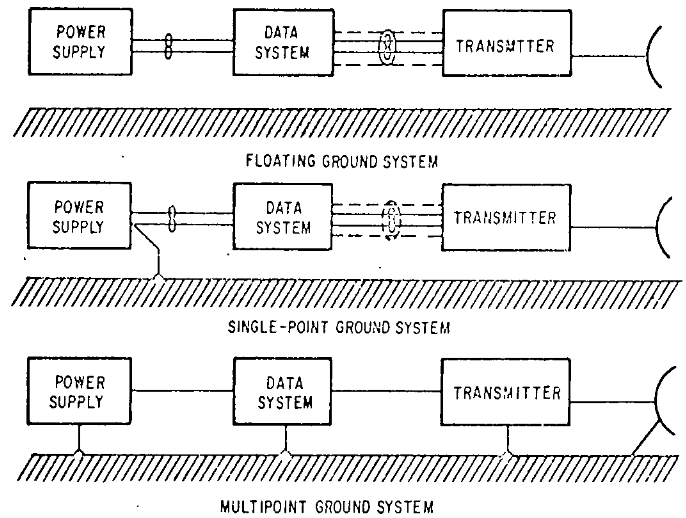


Figure 1. Ground Systems

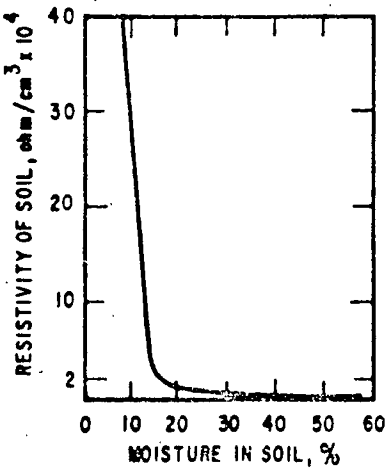


Figure 3. Variation of Soil Resistivity As a Function of Moisture Content

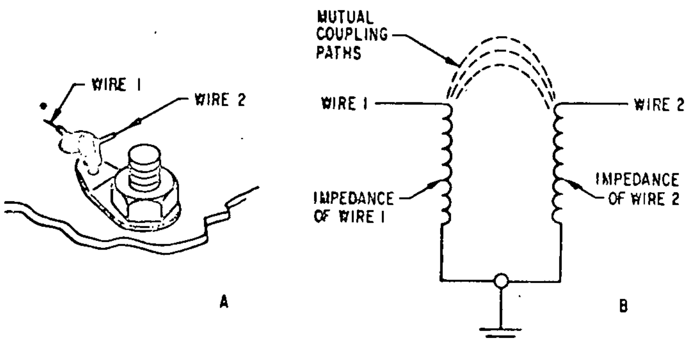


Figure 2. Ground Lug Connection and Equivalent Circuit

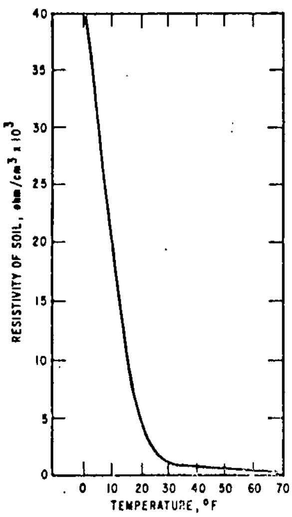


Figure 4. Variation of Soil Resistivity versus Temperature

Table 1. Resistance of Different Types of Soil (3-Stake Measurement Method)

| Soil | Resistance, Ohms | | |
|---|---|---|---|
| | Average | Minimum | Maximum |
| Fills and ground containing more or less refuse such as ashes, cinders, and brine waste. | 14 | 3.5 | 41 |
| Clay, shale, adobe, gumbo, loam, and slightly sandy loam with no stones or gravel. | 24 | 2.0 | 98 |
| Clay, adobe, gumbo, and loam mixed with varying proportions of sand, gravel, and stones. | 93 | 6.0 | 800 |
| Sand, stones, or gravel with little or no clay or loam. | 554 | 35.0 | 2700 |

the rod and the depth of penetration required to reach the desired resistance. The variation of rod-to-earth resistance with depth is computed from:

$$R = \frac{\rho}{2L}\left(\log \frac{41}{a-1}\right)$$

where

R = resistance (ohm)

a = radius of the rod (cm)

L = length (cm)

$\rho$ = resistivity of soil (ohm-cm)

Using larger-diameter rods results in but a small change in rod-to-ground resistance, which is primarily determined by the soil and its characteristics. As an example, see Figure 6 in which rods of 1/2" and 1" diameters are compared. The 1" rod, which has twice the diameter and four times the contact area and volume of the earth displaced, decreases the rod-to-earth resistance by about only 10 to 20 percent. The ground rod selected should have a large diameter and be strong enough for it to be driven to the required depth without being bent or otherwise damaged. Chemical treatment of soil surrounding the ground rod will in most cases reduce rod-to-earth resistance. Chemicals such as magnesium sulphate are particularly desirable being the least corrosive. Such treatment is not permanent because the chemicals are carried away by rainfall and natural drainage. These treatments should be made periodically, depending on the ferriferousness of the soil and the precipitation. This method of reducing rod-to-earth resistance is not too effective where deep grounding or multiple grounding is used.

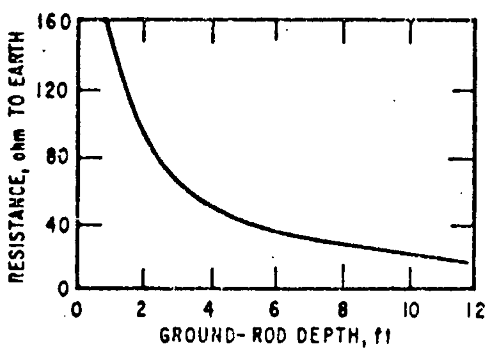


Figure 5. Ground Rod Depth versus Resistance

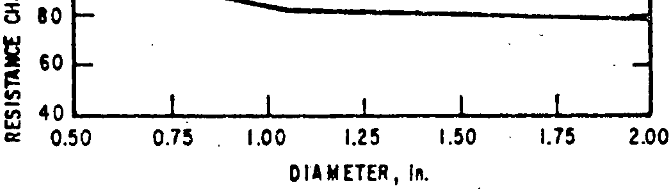


Figure 6. Ground-Rod Diameter versus Resistance Change

Multiple rods reduce the ground system resistance to earth providing there is sufficient spacing between them and a minimum intercept of magnetic fields from each. Figure 7 compares their percent of reduction of rod-to-earth resistance to that of a single rod.

Copper-clad rods are preferred because the primary conductor is made of high-purity, very conductive copper with a steel core for strength. High-purity copper does not readily combine with oxygen or other chemicals, except sulphate, to form a high-resistance surface barrier as does steel or aluminum. The copper-clad high-strength steel should have a minimum copper thickness of 0.024 in. at any point in the cylindrical surface. The copper cladding should be done by a molten wetting process so that the interlocking crystalline union is secured between the copper and steel. A standard counterpoise ground mat is designed for the sole purpose of dissipating into the earth the electrical energy from lightning strokes and power fault currents. The earth ground system used for effective grounding of electronic equipment that operates over a broad frequency spectrum has the more stringent requirement of rapidly and effectively conducting radio frequency currents for dissipation into the earth.

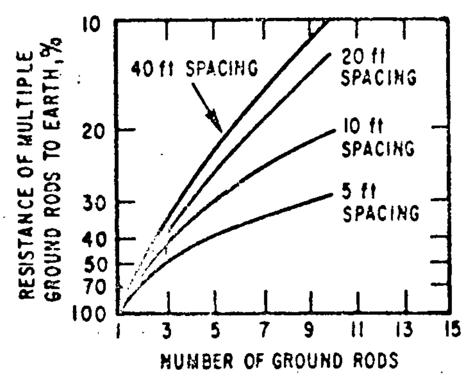


Figure 7. Comparative Resistance of Multiple Rods

## EARTH GROUND RESISTANCE MEASUREMENT TECHNIQUES

The most effective technique for measuring the resistance between a ground rod and the earth is by use of the Ground Resistance Megger instrument and the "fall-of-potential" test method. Other methods have been developed but most are subject to errors from polarization, electrolysis, or stray currents in the earth.

### METHODS OF MEASUREMENT

The three general methods for determining the resistance to ground of an electrode use two independent auxiliary ground electrodes in addition to the one under test. By suitable procedure, the resistance of the auxiliary electrodes is eliminated from the final values. In some cases, the procedure involves using one auxiliary electrode to introduce the current into the ground circuit, while the other is only a potential terminal carrying negligible current so the resistance drop at its earth contact is zero. In the other arrangement, equal currents are carried, thus making the auxiliary electrode drops the same (if it is assumed that the electrodes are identical).

**Three-Point Method.** In this method, the resistances of the electrode under test (X) and the auxiliary electrodes (A and B) are measured two at a time. The unknown resistance may be computed from the formula

$$X = \frac{(X + A) + (X + B) - (A + B)}{2}$$

To be accurate, it is important to use auxiliary electrodes with resistances of the same magnitude as the unknown. The series resistances may be measured either with a bridge or with a voltmeter and ammeter. Either alternating or direct current may be used as the source of test current.

**Fall-of-Potential Method.** This scheme involves the passing of a known current through the electrode and one of the auxiliary electrodes. The drop in potential between the former and the second auxiliary electrode, located between the two electrodes carrying the current, is then measured and the ratio of this voltage drop to the known current gives the desired resistance to ground. By using a voltage measuring device—a null instrument or one having a high impedance—the resistance of the auxiliary electrode connected to the voltage measuring device will have no appreciable effect on the accuracy of the measurement.

The determination of the resistance of the connection to earth by this method may be made with an ammeter and voltmeter with either alternating or direct current as the current source; or it may be made by self-contained instruments such as the "merger" ground tester, or "ground ohmer," which are based on this method and give direct readings of resistance.

**Ratio Method.** In this method, the series resistance of the electrode being tested and an auxiliary electrode is determined by means of a Wheatstone bridge. A slide-wire potentiometer is shunted across these two ground connections and the detector is connected between the sliding contact and the second auxiliary electrode. In this way, the ratio of the unknown resistance to the total resistance of the two electrodes in series is obtained, and the required value is determined by multiplying this ratio by the first series resistance measurement.

Measurements by this method may be made with a bridge and a calibrated slide-wire potentiometer for obtaining the ratio, or a commercial assembly of similar equipment (e.g., a "groundometer"), which gives direct readings in ohms.

## INSTRUMENTS USED IN MEASURING

**Bridge.** Either alternating or direct current may be used when measuring ground resistances by means of a bridge, although certain precautions should be used with this apparatus. In the ordinary direct-current bridge, the possible errors from stray currents and contact e.m.f.s. may be balanced out by taking a number of readings and frequently reversing the battery polarity. With an alternating-current bridge, a buzzer and dry cell battery usually form the source of audible frequency with a telephone receiver as the detector. While the accuracy of this bridge will not be affected by stray ground currents, the balance may be difficult to attain if stray alternating currents are present. When a buzzer is used, the length of the leads to the auxiliary electrodes should be reasonable to avoid errors that may be introduced because of the variable impedance of the leads at the various frequencies in the current from the buzzer.

**Voltmeter and Ammeter.** The use of the voltmeter and ammeter in the measurement of resistances to ground is subject to the same difficulties from stray currents as the bridge unless the test current is large enough to render these errors negligible. Two sets of readings taken with reversed polarity will aid in minimizing the effects of stray currents.

**Megger Ground Tester.** This instrument consists essentially of a current circuit and voltage circuit so coupled that a direct reading in ohms may be obtained. Current from a hand-driven, direct-current generator, after passing through the current measuring coil, is commutated into low-frequency alternating current and carried into the ground connection under test, with return by way of the current auxiliary. The potential circuit is connected between the ground under observation and the potential auxiliary. By virtue of another commutator, the potential drop is also reconverted into direct-current before being applied to the potential measuring coil. This cancels the effects of any stray direct currents. Stray alternating currents are also cancelled. Stray alternating currents will not affect the readings unless they are of the same frequency as that of the test current, which can be varied by changing the speed of the crank.

The megger ground tester should not be confused with the megger insulation tester, which, since it applies a direct-current testing potential to the resistance being measured is not suitable for testing ground connections.

**Ground Ohmer.** This instrument, like the megger, contains a hand-driven generator supplying alternating current to the ground connection being measured. The method used is to balance the potential drop across the ground connection in question against the drop across a known resistance that is carrying an equal current or a known multiple. The instrument offers direct reading and requires only one adjustment. At balance, the potential auxiliary draws no current so its resistance introduces no error. The effects of stray alternating currents may be limited by changing the generator speed until a positive reading is obtained. Stray direct currents of fairly steady character may be balanced out by adjusting the galvanometer to zero before starting the generator.

**Groundometer.** A battery and buzzer are used as the source of alternating current and a telephone receiver as the detector. After the ratio has been determined by means of a potentiometer, the circuit is converted into a Wheatstone bridge by throwing a key switch and the series resistance is balanced against the potentiometer setting. Although this instrument affords direct reading in ohms, it requires two adjustments and is subject to the same errors as the alternating current bridge.

## CONDUCTOR CHARACTERISTICS

If a conductor having high inductance and high ac resistance is used to interconnect the ground rods or to form ground planes, it may cause high transient potentials in the equipment, create personnel hazards, and damage the equipment. Skin effect is one of the main reasons for the high ac resistance in the conductors; the choice of conductors in a ground system is therefore critical. The skin effect is present at all frequencies, but becomes more noticeable as frequency increases and, thus, it must be considered in a design where higher frequencies such as those used by transmitters and ground stations can be expected.

The ratio of effective ac resistance at a specific frequency to the dc resistance of a conductor is termed "the resistance ratio," which increases with the frequency, and with the conductivity of the material and size of the conductor (because a higher frequency causes the extra inductance at the center of the conductor to have a higher reactance). Similarly, greater conductivity makes the reactance of the extra inductance more important in determining the distribution of current, while a greater cross section provides a large central region. It should be noted, however, that a larger conductor always has a smaller radio frequency resistance. Although the ac-to-dc resistance ratio is less favorable, the greater amount of conductor cross section more than compensates for it.

The effective ac resistance is found by using a hypothetical effect skin depth. This is defined as the depth where the current density is 1/e of the current density at the surface of the conductor, and the phase of the current lags the surface current by 1 radian for nonmagnetic material (e = natural log).

The skin depth and the resistance per square (of any size) in meter-kilogram-second (rationalized) units are

$$\delta = (\lambda/\pi\mu c)^{1/2} \text{ m} = \text{skin depth}$$

$$R = 1/\delta\,\sigma \text{ ohm} = \text{resistance}$$

where

$$c = \text{velocity of light} = 2.998 \times 10^8 \text{m/sec}$$

$$\mu = 4\pi \times 10^{-7}\,\mu_r = \text{henry/m}$$

$$\mu_{rad} = \text{relative permeability of conductor material}$$

$$1/\sigma = 1.724 \times 10^{-8}\,\rho/\rho_c = \text{ohm-meter}$$

where

$$\rho = \text{resistivity of conductor}$$

$$\rho_c = \text{resistivity of copper at } 20°\text{C} = 1.724 \times 10^{-6} \text{ ohm-cm}$$

## STRANDED CONDUCTORS

Figure 8 shows a plot of skin-depth effectiveness for copper vs frequency. The conductors consist of a number of strands close to and twisted about one another to keep the individual strands in position and to add flexibility to the conductor. The current flow through the conductor is assumed normally to be divided evenly among all the strands. This is not true at higher frequencies where the proximity of the strands to each other forces the desired current to the surface of the outer strands. causing skin effect. Each outer strand forms a helix due to the lay of the strands coupling. Coupling between turns is increased, thereby increasing the self-inductiveness of the conductor. The skin effect, in addition to the higher self-inductance of the stranded type, increases the ac resistance of the conductor. Stranded conductors are useful up to 1200 Hz, above which it is recommended that stranded conductive wire not be used.

## SOLID CONDUCTORS

Solid conductors exhibit lower self-inductance per unit length and also lower ac resistance than stranded conductors. For medium and low currents, a round cross section is the most effective to safely carry large currents. A considerable conductive cross-section area is required and solid wire more than 1/4" in diameter is commercially difficult to obtain. A flat conductor such as the common bus bar, which has a sufficient cross section to handle the required current, is therefore generally used.

There is a problem in using these bus bars, especially at higher frequencies; their sharp edges generate a radiation source of the given energy to be transductor becomes an efficient subantenna. If the edges are rounded so that the flat conductor assumes an elliptical shape, the subantenna is effectively reduced, but the ac resistance remains high. To alleviate most of these problems a tubular conductor is recommended. Over-all self-inductance is reduced by the absence of a conductor medium in the center. The larger radius of a given cross-section area or amount of conductive material by far outweighs the increased bulkiness of the conductor. For higher frequencies it will be found that the effective resistance per unit length of material per unit length will be less in a tubular conductor than in that of any other shape.

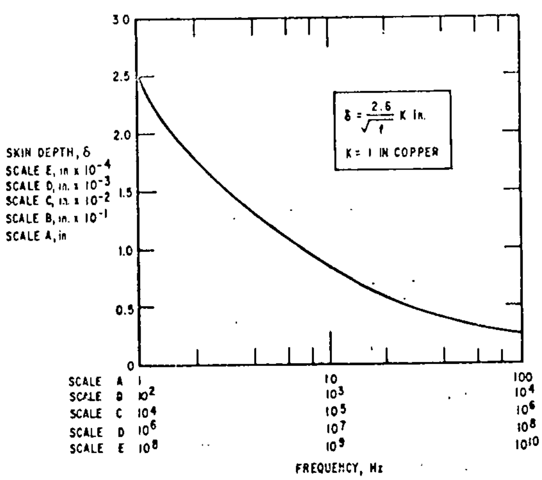


Figure 8. Skin Depth versus Frequency in Copper

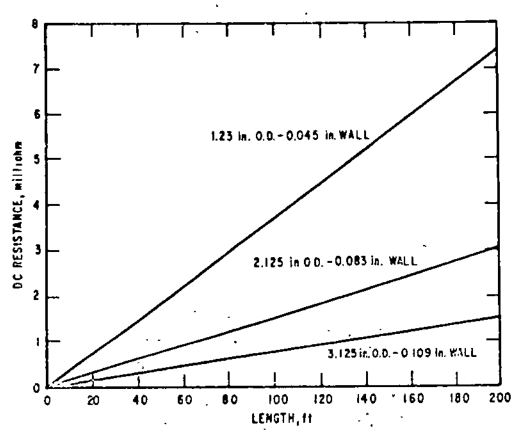


Figure 9. Direct Current Resistance versus Length for Various Sizes of Copper Tubing