Technical Note 9-84

HUMAN ENGINEERING LABORATORY GROUNDING ANALYSIS - PROJECT HELGA

Bernhard Keiser

June 1984

U. S. ARMY HUMAN ENGINEERING LABORATORY
Aberdeen Proving Ground, Maryland

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: Technical Note 9-84
2. GOVT ACCESSION NO.: AD-A145 728
3. RECIPIENT'S CATALOG NUMBER:
4. TITLE (and Subtitle): HUMAN ENGINEERING LABORATORY GROUNDING ANALYSIS - PROJECT HELGA
5. TYPE OF REPORT & PERIOD COVERED: Final
6. PERFORMING ORG. REPORT NUMBER:
7. AUTHOR(s): Bernhard Keiser
8. CONTRACT OR GRANT NUMBER(s): ~~DAAD05-83-M-C795~~
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Keiser Engineering Incorporated, 2046 Carrhill Road, Vienna, VA 22180
10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Human Engineering Laboratory, Aberdeen Proving Ground, MD 21005
12. REPORT DATE: June 1984
13. NUMBER OF PAGES: 32
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):
15. SECURITY CLASS. (of this report): Unclassified
15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:
16. DISTRIBUTION STATEMENT (of this Report):

Approved for public release;
distribution is unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):
18. SUPPLEMENTARY NOTES:
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

- Earth Grounding
- Ground Resistivity
- Grounding Techniques
- Electrical Protection
- Grounding Rods
- Grounding Screens
- Earth Ground Measurements

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Techniques for grounding mobile (relocatable) tactical army systems are described. Alternative methods for grounding tactical military structures are discussed and a diamond mesh grounding screen is recommended for investigation.

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PREFACE

This report documents a study performed for the US Army Human Engineering Laboratory (USAHEL) by Keiser Engineering, Incorporated, under Purchase Order No. DAAD05-83-M-6795. The contracting officer's Technical Representative for this contract was Mr. Russell M. Phelps, Team Leader of the Communications-Electronics Team, Close Combat Directorate. Mr. Walter N. McJilton, Communications-Electronics Team, coordinated, reviewed, and technically edited the report.

CONTENTS

HUMAN ENGINEERING LABORATORY GROUNDING ANALYSIS - PROJECT HELGA

INTRODUCTION

The Need for Earth Grounding

The earth grounding of mobile tactical electronic systems is necessary to protect these systems and their operating personnel from the hazards of electrical shock. These hazards may arise not only through the use of electrical generating equipment, but also from lightning and electromagnetic pulses (EMP).

Grounding during thunderstorms provides a low impedance path from the lightning stroke through the air terminal (lightning rod) and down-conductor to earth ground. Mobile systems must be grounded with a lower impedance than that of the power supply ground so that lightning surges travel through the mobile system or lightning down-conductor rather than through the power wiring. Mobile systems must also comply with the grounding procedures described in the National Electrical Code[1].

Existing Approach

The present approach to the earth grounding of mobile tactical electronic systems involves the use of 6-foot long vertical ground rods which are driven into the earth with a sledge hammer.

Installation time under optimum conditions ranges from 1.68 to 3.55 minutes. Attempts are made to reuse each ground rod at least once, which means that the rod must be pulled from the earth using either a vehicle jack or a slip hammer. Removal time ranges from 2.98 to 3.40 minutes. The installation/removal times given here and later in this report were derived from video tapes made on 5 and 21 April 1983 at Ft. Hood, Texas, during operational test and evaluation of the AN/TYC-39 system.

OBJECTIVES OF PROJECT HELGA

The objective of this report is to discuss the current techniques for grounding mobile tactical shelters, to describe alternate methods of earth grounding, and to suggest methods for testing new grounding equipment and procedures.

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[1] National Fire Protection Association, National Electrical Code 1981, Boston, MA: Author, 1980.

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Grounding techniques currently used for mobile tactical electronic systems are described in Grounding Techniques, Document TC 11-6[2], developed by the US Army Signal School, Fort Gordon, GA. This document is evaluated in the Section titled "Evaluation of Grounding Techniques, TC#11-6." The requirements to be fulfilled by a grounding system are outlined in the Section on Requirements/Criteria. The section titled "Methods of Grounding" describes the various available grounding techniques and the Section titled "Horizontal Grid and Wire Grounds" describes a particularly promising technique, the horizontal grid ground. The section titled "Chemical Enhancement describes the use of chemicals as they improve the performance of grid and rod grounds. Ground resistance measurement methods are outlined on pages 25 and 26 with the objective being a go-no go measurement method suitable for quickly checking field installations. Grounding considerations for various terrain types are presented under the heading "Alternatives for Special Environments." Conclusions and recommendations for further work toward an improved earth grounding method, including preparation and field test, complete the report.

EVALUATION OF GROUNDING TECHNIQUES, TC 11-6

Document TC 11-6 is a training circular which presents various grounding techniques to the user. This circular is written so it can be understood by field personnel having limited backgrounds. While presenting much useful information, it has certain failings which are discussed below.

Connections

The connection of the down-conductor to the ground rod is described in TC 11-6, but no mention is made of possible metal dissimilarities. First, the underground connection to the ground rod itself must be limited to copper on copper. If a noncopper down-conductor must be used, a bimetallic junction such as the "Bug" [Ideal Manufacturing Co., Cat. No. 87-681] must be used. This bimetallic junction should be made no closer to the surface of the earth than 1 foot.

Wrap Method

The wrap method of fastening a down-conductor to a ground rod is described TC 11-6. While the words are satisfactory, the sketch is misleading because it implies that the down-conductor may be attached to the ground rod in a downward direction. Lightning currents do not like direction changes. Direction changes are inductive. The preferred drawing is shown in Figure 1. A statement should be added to the effect that, as drawn, the down-conductor itself is never to be wrapped around the rod, but only brought in parallel and bound tightly to it.

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[2] Department of the Army. Grounding techniques, Training Circular 11-6. 30 September 1976. Publication.

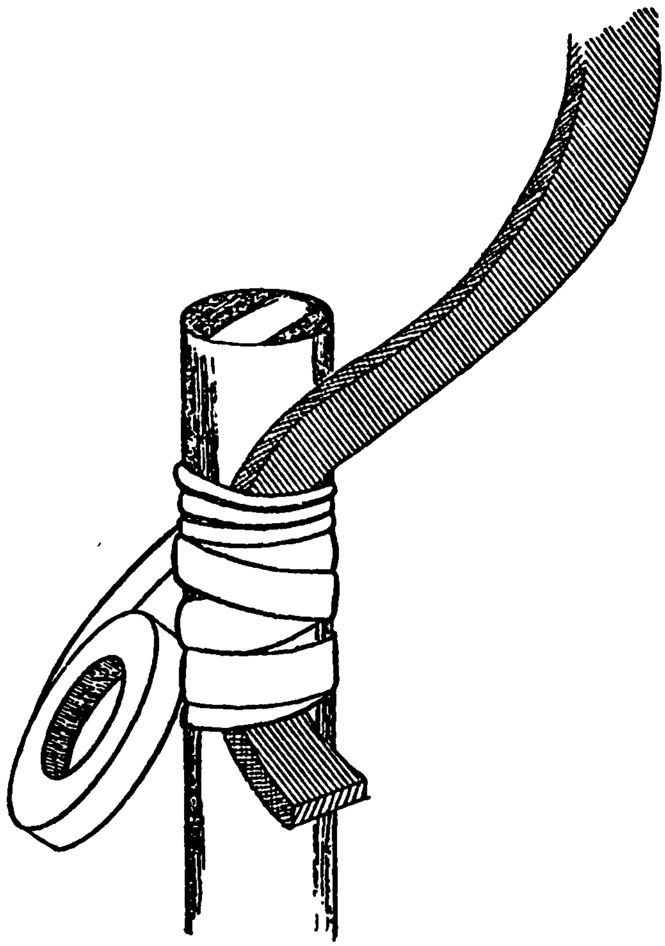

Figure 1. Correct use of the wrap method.

Removal

The difficulty encountered in the removal of rod grounds is also mentioned in TC 11-6. A grounding approach using a horizontal wire grid which allows for easy removal is described as well as a test for grounding adequacy. The test involves measuring the ac voltage between "equipment bare metal" and the "ground strap". A reading of 5 volts or less is said to indicate "adequate grounding." This description is very misleading. The measurement described in the circular provides no indication about the resistance of the earth ground which presumably is used. The measured voltage does indicate the flow of current through a ground lead's contact resistance with bare metal, but the number of volts read will depend on the magnitude of this current which, in turn, will depend on the magnitude of the supply voltage and the impedance of the ground lead. A reading of 5 volts seems high under any circumstances. The presence of even 1 volt ac could indicate a poor ground under such circumstances.

The test for grounding adequacy must be done before power is applied to equipment. In fact, a ground's adequacy must not depend on the presence of any specific powered equipment.

The section on measurement methods, of this report, describes a "go-no go" method for measuring the resistance of an earth ground. This method does not depend upon specific connections of equipment to the ground. The test described is to be done before ac power is applied.

REQUIREMENTS/CRITERIA

What is an acceptable resistance for an earth ground? What are the electrical characteristics of the soil in which the ground is to be made? What are the criteria for installation and removal time for the ground? Can installation and removal be done safely? What hardware must be carried so that grounding can be achieved in various soil types?

Before discussing various earth grounding types and focusing on one for development, the foregoing questions must be explored so that criteria can be established for the selection of the preferred grounding techniques.

Earth Resistivity Versus Soil Type and Conditions

The various formulas for ground resistance all show the resistance to be directly proportional to the resistivity of the surrounding earth. This resistivity decreases with increasing temperature, as shown in Table 1 of reference 3 and also decreases with increasing moisture content, as shown in Table 2 of reference 4.

[3] Towne, H. M. Lightning arrester grounds, Parts I, II and III, General Electric Review, Vol. 35 and p. 173, 215 and 280 (March, April and May 1932).
[4] P.J. Higgs, An investigation of earthing resistances, IEEE Journal 1930, Vol. 68, p. 736.

A ground measured in the late spring when the soil is warm and moist will exhibit a lower resistance than one measured during a cool and dry part of the year. Fortunately, the resistance is at or near its lowest during the usual peaks of thunderstorm activity. However, low ground resistance also is important with respect to power safety. Accordingly, special chemical treatment (see page 24) may be needed to keep the resistance low during times when the earth is dry and cold.

In computations made later in this report, the soil resistivity is assumed to be 200 ohm-meters or 20,000 ohm-cm. If the moisture content is below 10% or the temperature below freezing, chemical treatment can be used to achieve a resistivity of 20,000 ohm-cm or less.

TABLE 1

Effect of Temperature on Soil Resistivity
(Sandy Loam with 15.2% Moisture)

Temperature, deg. F	Resistivity, ohm-cm
68	7,200
50	9,900
32 (water) 13,800	13,800
32 (ice)	30,000
23	79,000
14	330,000

TABLE 2

Effect of Moisture Content on Soil Resistivity (50 deg. F)

Moisture Content (percent by weight)	Resistivity (ohm-cm)	
	Top Soil	Sandy Loam
0	$>10^6$	$>10^6$
2.5	250,000	150.000
5	165,000	43,000
10	53,000	18,000
15	19,000	10,500
20	12,000	6,300
30	6,400	4,200

Ground Resistance

Various ground resistance target values have been specified in military and commercial documents. For example, the Defense Communications Agency (DCA)[5] calls for a 5 ohm ground, whereas MIL-STD-188-124[6] calls for a 10 ohm ground. On the other hand, Underwriters' Laboratories[7] points out that "low resistance is, of course, desirable but not essential," and states further that "the resistance of a proper ground connection may be on the order of up to 50 ohms, and two such ground connections on a small rectangular building have been found by experience to be sufficient." The National Electrical Code, 1981, states in Paragraph 250-84 that "a single electrode...which does not have a resistance to ground of 25 ohms or less shall be augmented by one additional electrode..." The same type of statement is made by the National Electrical Safety Code[8] (Section 96) about the suitability of a 25 ohm ground.

In view of these facts, as well as the writer's own experience, two electrodes providing a parallel combination of 25 ohms is taken as a criterion in this report.

FACTORS OF ANALYSIS

Time to Install

The time to install the 6-foot ground rod presently used for mobile tactical electronic systems ranges from 1.68 to 3.55 minutes under optimum conditions based upon tests at Ft. Hood, TX. Therefore, a 2.6 minute installation time is taken as the criterion for a new grounding method.

Time to Remove

The time to remove the 6-foot ground rod in present use ranges from 2.98 to 3.40 minutes under optimum conditions. Therefore, a 3.2 minute removal time is taken as the criterion for a new grounding method.

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[5] Defense Communications Agency. Methods and procedures, DCS interim guidance on grounding, bonding and shielding (DCA Notice 310-70-1). Washington, DC: Author, 24 September 1976.

[6] Department of Defense. Military standard, grounding, bonding and shielding for common long haul/tactical communication systems, general requirements (MIL-STD-188-124). Washington, DC: Author, 24 February 1977.

[7] Underwriters' Laboratories. Installation Requirements, Master labeled lightning protection systems," (Document UL96A). Eighth Edition, June 1963.

[8] American National Standards Institute. National electrical safety code. Institute of Electrical and Electronics Engineers, New York, NY; 1981.

Life Cycle Cost

Life cycle cost information is not available for the present ground rod approach. However, a basis for comparison might be the fact that a 6-foot copper ground rod sells for approximately $7.00 each and is used twice. A ground system that is reusable many times could initially be correspondingly more costly. However, the cost of ancillary equipment needed for installation purposes, if not otherwise needed, must also be considered.

Weight

A 6-foot copper ground rod weighs 4.6 pounds. The weight criterion is that the ground system material should be light enough to be carried easily by one man. For this purpose, a criterion of 10 pounds is selected.

Safety

The ground must be installable in a safe manner. Concerns exist about the safety of using a sledge hammer to install the rod-type ground. Accordingly, the recommended system must not involve such unsafe procedures.

Effectiveness

The resistance of a single, 0.5 inch diameter, 6.0 foot ground rod in earth of 20,000 ohm-cm resistivity is 105 ohms. Lower observed resistance values result from earth resistivity values lower than 20,000 ohm-cm. Accordingly, the use of a 25 ohm resistance criterion in soil of 20,000 ohm-cm resistivity will provide a more effective ground than the type currently in use. For a given soil type, the resistance will be only 24% as great as that of the rod ground.

Hardware Types

The selected ground approaches must allow good grounds to be achieved in a variety of soil types, terrain conditions and climates. This must be done with the use of the fewest types of ground material and installation devices.

METHODS OF GROUNDING

This section describes and evaluates the numerous available grounding techniques. Since the purpose of any ground system is to provide the lowest possible impedance to ground, approaches like coiled wire are excluded because they would be ineffective against lightning.

Vertical and Slanted Grounds

The vertical rod ground provides a resistance of

$$R = \left(\frac{\rho}{2 \pi L} \right) \left(\ell n \left[\frac{4L}{a} \right] - 1 \right) \quad \text{ohms} \tag{1}$$

where ρ = soil resistivity, ohm-cm
L = rod length, cm
a = rod radius, cm

The foregoing equation applies to the following ground types:

Standard 6-foot ground driven in with a sledge hammer

Six-foot ground with a slip-ring device

Ground rod assembled in segments with a slip ring end

Six-foot ground with an electromechanical assist device

Equation (1) also applies to short (e.g., 18 inch) rod grounds using chemical additives and to reservoir grounds containing charcoal or other special materials. The additives lower the soil resistivity.

Rod grounds are straightforward in their design and easy (but not safe) to install. The hardware is readily available and extensions can be used to reach the water table in many areas if rock layers are not present beneath the surface. However, the removal of rod grounds presents difficulties, especially if extensions are used or the rods are 8 or more feet long.

A disadvantage of all vertical rods and, to a lesser extent, slanted rods is their high impulse impedance. This means that for the first fraction of a microsecond of a pulse the rod will exhibit a relatively high impedance (e.g., several hundred ohms) because its full length is not effective. This results from the fact that the skin effect (the tendency of alternating current to concentrate on the surface of a conductor) prevents the current from entering any significant depth of earth at first. Thus, only the part of the rod very close to the surface is effective initially. In other words, the initial portion of the current transient corresponds to very high frequency components which flow only at the surface of the earth and the topmost part of the rod.

Vertical and slanted rods are not useful where large rock formations exist near the surface of the earth. In addition, in the presence of high fault currents caused by electrical shorts in on-board power equipment or during a direct lightning strike, a significant step voltage may exist on the surface of the earth. This step voltage will be directed radially with respect to the rod. The high surface voltage results from the fact that current from the rod spreads radially throughout the earth.

Horizontal Grid Grounds

Horizontal grid grounds at the surface of the earth provide a resistance[9] of

$$R = (\rho/\pi L)\ (\ell\eta\ [2L/a] + K_1\ L\ /\sqrt{A} - K_2)\ \text{ohms} \qquad (2)$$

where A = area of grid, m^2

L = total wire length in grid, cm

k_1 = constant (defined on page 16)

k_2 = constant (defined on page 16)

Horizontal grid grounds keep the surface potential gradient to a minimum since the conductors are either on the surface or just under it. They can be installed in flat grassy areas by removing the grass with a sod cutter. The presence of rock formations beneath the surface does not prevent the installation of a horizontal grid ground although the resistance may fluctuate as the soil dries.

Horizontal Wire Grounds

For a half-buried straight conductor (axis in the plane of the earth's surface), the earth resistance[9] is

$$R = (\rho/\pi L)[\ell\eta((L/a)[1+\sqrt{1+(a/L)^2}]) + (a/L) - \sqrt{1+(a/L)^2}\,] \qquad (3)$$

$$= (\rho/\pi L)[\ell\eta(2L/a)-1]\ \text{for}\ L>>a \qquad (4)$$

If the conductor is buried at depth d, the resistance is obtained by assuming two conductors a distance 2d apart in a medium of infinite extent in all directions. Then the resistance is

$$R \simeq (\rho/\pi L)\ (\ell\eta\ [2L\ \sqrt{2ad}]\ -1) \qquad (5)$$

Thus a wire buried at depth, d, has the same resistance as one at the surface whose radius is $\sqrt{2ad}$. Figure 2[10] shows that for a #10 wire in 100 ohm meter earth, the desired 25 ohm resistance for 200 ohm-meter earth would require a #10 bare wire 25 meters (82 feet) long on the surface or 15.4 meters (51 feet) long if buried 1 foot. These values were derived by doubling the scales in Figure 4.1 to change from 100 ohm-meters to 200 ohm-meters.

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[9] White, D. R. J. EMI control methods and techniques. Vol. III of the Handbook series on Electromagnetic Interference and Compatibility, Don White Consultants, Inc., 1973.

[10] Sunde, E. D. Earth conduction effects in transmission systems, New York, NY: D. Van Nostrand Co., Inc.: 1949.

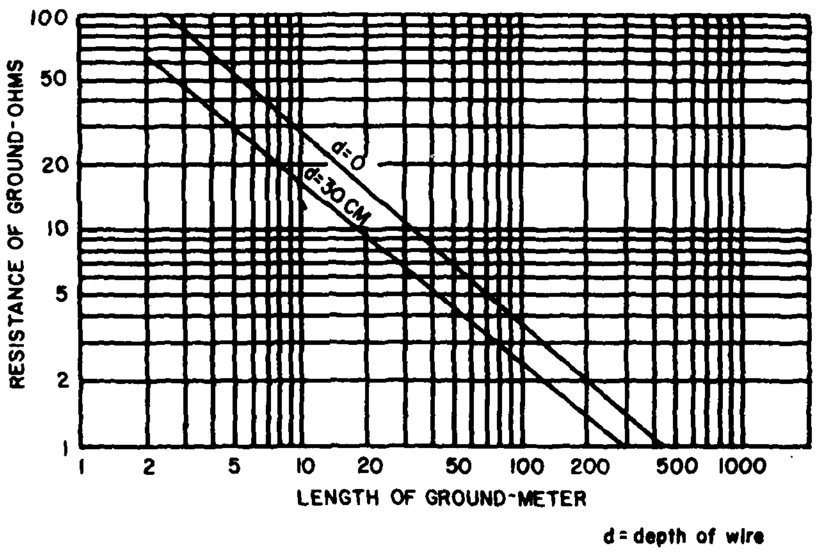

Figure 2. Resistance of horizontal #10 wire in 100 ohm meter earth.

(Permission to use granted by Wadsworth Publishing Company. From E. D. Sunde "Earth Conduction Effects in Transmission Systems")

Flat Tape

Plate metal tape provides a lower resistance than a round wire for the same amount of copper[11]. The equivalent radius of a thin tape of width a_o is

$$a = a_o / e^{3/2} \simeq 0.22\ a_o \qquad (6)$$

A grid made of flat tape thus would be lighter in weight than that of ordinary hardware cloth, whose conductors are round, for a given resistance. However, the advantage over round conductors is rather small since conductor radius enters into Equation 6 only on a logarithmic basis. Other aspects of the flat tape ground are the same as those of the horizontal grid ground.

Plates

Plates can achieve a low resistance contact in a limited area, but are difficult to install. For maximum effectiveness there should be no air pockets under the plate, so the soil must be made very flat and moist enough so that good contact is obtained.

For a flat circular disc of radius, a, at the surface of the earth[12], the resistance is

$$R = \rho / 4a \text{ ohms} \qquad (7)$$

For a rectangular plate of area A at the surface of the earth[13], the resistance is

$$R = (K_1 / \pi \sqrt{A}) \quad \text{ohms} \qquad (8)$$

Computations show plate grounds to be quite effective in terms of low resistance, but if they are thick enough for durability, their weight may be a problem. Iron or steel plates should be at least 1/4 inch thick and nonferrous metals should be at least 0.06 inches thick[14].

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[11] Sunde, E. D. Op. Cit.
[12] Sunde, E. D., Op. Cit.
[13] White, D. R. J., Op. Cit.
[14] Denny, H. W. et.al.. Grounding, bonding, and shielding practices and procedures for electronic equipments and facilities, (Department of Transportation Report No. FAA-RD-75-215). Vol I Fundamental Considerations, Georgia Institute of Technology. 1 December 1975, Pp 1-18.

Horizontal Radial Wires

Horizontal wires have many of the advantages of the horizontal grid ground. They are especially useful where rock formations prevent the use of other ground types. Often the horizontal radial wire is used as a radio frequency counterpoise or ground plane.

For the grounding of mobile tactical electronic systems,however, the radial wire ground would be more time consuming and complicated to install than the horizontal grid ground and not offer commensurate returns in terms lower resistance or material weight. Its use is not recommended except for special terrain conditions (see page 27).

Incidental Electrodes

Such items as utility pipes, building foundations and buried tanks can offer excellent grounds where available. However, such grounding means cannot be expected to be generally available for field applications. Instruction manuals should alert field personnel to their possibilities, but other grounding means will be necessary in many cases because of the absence of suitable incidental electrodes.

COMPARISON OF GROUNDING METHODS

Vertical grounds have been used for many years for mobile tactical electronic systems. However, the installation process presents safety hazards. They exhibit a high impulse impedance, a special problem in the presence of EMP, and under lightning or power fault conditions, dangerous step voltages can exist in their vicinity. Other problems are the difficulty encountered in removing them from the ground and using them where large rock formations are near the surface.

Incidental electrodes provide excellent grounds where they are available. However, their presence cannot be expected at the typical field site.

The horizontal grounds do not exhibit the problems of the vertical grounds. In terms of effectiveness (low resistance and light weight), the horizontal grid ground and horizontal wire, in spite of some disadvantages, are felt to be preferable to the other types.

The horizontal wire must be straight, or nearly so, to achieve the resistance shown by equations (3), (4) and (5) and Figure 2. If a straight stretch of ground of adequate length (e.g., 82 feet) is not available, field personnel might be tempted to fold the wire back on itself, to coil or loop it, or in other ways to place it so its resistance is higher than desired. They must be instructed not to do this. In addition, continuous contact with the earth along its entire length is required to achieve the indicated resistance. Given an adequate length of soil, however, the horizontal wire probably could be trenched in to a depth of a few inches and thus achieve the desired effectiveness.

Where adequate linear distance is not available, the horizontal grid must be used.

The flat tape is similar in many respects to the straight horizontal wire. Its configuration might render it less likely to be installed improperly, but it still requires a relatively long straight stretch of land.

Plates must be in complete contact with the earth, at least on one side, to provide the resistance expected of them. Compared with horizontal grid grounds they are far heavier per unit area, and thus do not offer a light weight solution to the grounding problem.

Horizontal radial wires, per total wire length, do not provide as low a resistance as the straight horizontal wire. Moreover, they require that a relatively large surface area be prepared for their installation. For this reason, other techniques such as the horizontal wire and the horizontal grid ground are felt to be preferable.

In conclusion, the various horizontal ground types are ranked in the following order (the best first) with respect to their applicability to mobile tactical electronic systems:

Horizontal straight wire
Horizontal grid
Flat tape
Horizontal radial wires
Plates

Horizontal Grid and Wire Grounds

The horizontal grid ground consists of a coarse mesh of conductors covering an area A of earth. This type of ground may be either laid on the surface or buried at any depth. Because of the desirability of easy and quick removal, the grounds in this report are assumed to be laid on the surface. The horizontal wire is a single straight wire, to which connection is made at one point. This point can be anywhere along the wire, but preferably is near the center.

Equation (2) describes the resistance of a horizontal grid ground at the surface of the earth. It is repeated here as equation 9, and for practical applications is expressed in mixed metric/English units rather than metric:

$$R = (1.045\ \rho/L)(\ln[24L/a] + k_1 L/\sqrt{A} - k_2) \text{ ohms} \qquad (9)$$

where ρ = earth resistivity in ohm-meters

- LL = length of grid, feet
- W = width of grid, feet
- A = LLW = area of grid, feet^2
- L = total wire length in grid, feet
- a = wire radius, inches
- k_1 = constant defined in Table 3
- k_2 = 5.40+0.15(LL/W), LL > W

TABLE 3

Values of Constant K_1

Length/Width of Grid	K_1
1.0	1.37
1.5	1.34
2.0	1.31
2.5	1.28
3.0	1.26
3.5	1.24
4.0	1.22
4.5	1.20
5.0	1.18
5.5	1.16
6.0	1.14
6.5	1.13
7.0	1.12
7.5	1.11
8.0	1.10
8.5	1.09
9.0	1.08
9.5	1.07
10.0	1.06

For the horizontal wire the resistance is described by the equation for a wire on the surface and by the equation for a buried wire. They are repeated here as equations 10 and 11, expressed in mixed units rather than metric:

$$R = (1.045\,\rho/L)(\ln[24L/a]-1) \qquad (10)$$

$$R = (1.045\,\rho/L)(\ln[24L/\sqrt{2ad}]-1) \qquad (11)$$

where ρ = earth resistivity in ohm-meters

L = wire length in feet
a = wire radius in inches
d = wire depth in inches

INSTALLATION

To achieve the resistance indicated by equation (9), the wires of the grid must be in continuous contact with the earth along their full length. Figure 3 illustrates the contact problem in terms of a theoretical continuous contact (a) and a likely contact (b). A similar problem exists for the wire, tape, plate, and other horizontal grounds.

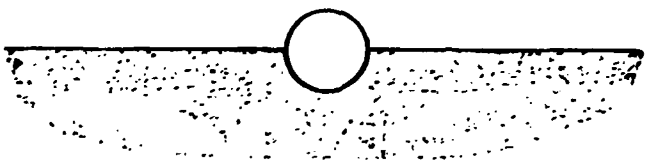

Figure 3a. Theoretical continuous contact.

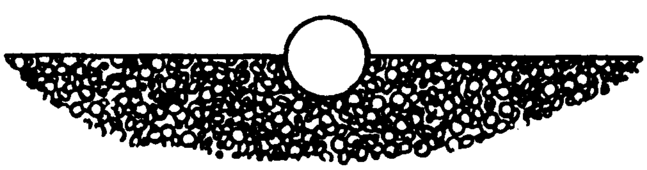

Figure 3b. Likely contact.

Figure 3. The earth contact problem for a horizontal ground.

Several approaches are recommended toward the solution of this problem. First, a tool to remove sod or other poorly conducting surface material is desirable. The sod cutter will serve this purpose for the horizontal grid, but is heavy and expensive. Sod cutters made by the Ryan Manufacturing Company have the characteristics shown in Table 4 . These machines are hand-guided. Their size is similar to that of a large roto-tiller. In areas of environmental concern, the sod can be rolled up and kept moist so it can be replaced when the ground system is removed.

TABLE 4

Sod Cutting Machines

Type	Motor (Hp)	Width (In)	Weight (lb)	Cost
Heavy Duty	12	18	446	$3,612
Heavy Duty	12	12	391	$3,426
Junior	7	18	338	$2,249
Junior	7	12	294	$2,122

After the earth has been suitably exposed, it should be sufficiently moistened to make it pasty in order to provide maximum contact with the grid wires. After the grid has been put into place, it should be covered with sand bags to provide good continuous contact. Removed sod could be placed over the grid but if the installation is to be in place for more than a few days, the sod might be difficult to remove by hand, and use of the sod cutter could damage the grid.

Since it is possible that a portion of the grid surfaces will not have a good earth contact, some over-design is desirable. The extent needed can be determined best by field testing (~~see conclusions~~).

The desired copper grid may have to be fabricated specially, but galvanized hardware cloth made of #16 wire is available at the following prices for a 1/2 inch mesh size in 100 foot rolls:

24" width	$0.72/foot
36" width	$1.05/foot
48" width	$1.40/foot

A 36" width of 1/2 inch mesh of #19 wire costs $0.92/foot in 100 foot rolls.

The time required to perform the above tasks for a 3' x 21' grid (see Results of Computations) is expected to be in excess of the 2.6 minute installation criterion. However, the removal time may be within the 3.2 minute cirterion.

By comparison, the horizontal wire gound, where it can be used, could be installed using a cable trenching machine like those used by telephone and cable television installers. Such an installation may be simpler than that of the grid. One product is the "Ditch Witch," manufactured by the Charles Machine Works, Inc., P. O. Box 66, Perry, OK. This device plows, lays the wire, and back fills in a single pass. The installation time will depend on the hardness of the soil, but the 2.6 minute criterion is expected to be attainable in many cases.

The "Ditch Witch" Model V-252 is sold through dealerships for $10,000; the feed blade an additional $250. The V-252 weighs about 1300 lbs., has a 25 hp Onan gasoline engine, and is a "walk beside" unit. It runs at 2.84 mph when not under load and at approximately 2 mph for a 5 inch burial depth in soft to medium earth. It is 42" high, 36" wide, has a 1" or greater clearance above ground, and a 16" maximum burial depth.

At 2 mph, the time to bury a 100 foot horizontal wire is 34 seconds. The "Ditch Witch" can also bury a 1" ribbon copper tape by using a properly fabricated blade with suitable width and depth.

Results of Computations

The equations of the sections titled "Methods of Grounding" and "Horizontal Grid and Wire Grounds" have been used to compute the resistance of various grounds to determine what wire sizes and areas provide sufficiently low resistance along with light weight. The results are shown in Table 5.

TABLE 5

Results of Computations

Type	Size	Weight (lb.	Resistance (Ohms)
Diamond Mesh, each mat with 35 sq. ft. of weights	Two 8.2'x6.0' mats, each of 1/4'' braid spaced 3"	7.9	25.0
Circular Plate, 20 ga.	6' diameterx0.036"	47.0	50.0
Tape on Surface	66' long x 1" wide	-	24.9
Tape on Surface	50' long x 6" wide	-	24.3
6' x 21' Grid	6" x 6" #13 wire	7.9	25.8
3' x 21' Grid	12 x 12" #2 wire	30.1	34.7
3' x 21' Grid	1" x 1" #13 wire	30.1	30.4
3' x 21' Grid	12" x 12" #13 wire	2.4	36.5
3' x 21' Grid	1" x 1" #16 wire	14.1	30.4
3' x 25' Grid	1/2" x 1/2" #19 wire	14.0	26.8
3' x 27' Grid	1/2" x 1/2" #19 wire	15.2	25.5
3' x 30' Grid	1/2" x 1/2" #19 wire	16.8	23.8
Wire on Surface	82' of #10 wire	2.6	24.3
Wire 1' Deep	51' of #10 wire	1.6	24.6

The recommended ground is two diamond meshes of flat, metallic braided tape, as illustrated in Figure 4 and installed as shown in Figure 5. The diamond mesh is chosen over a square grid mesh because it is easier to roll on a dowel for storage purposes. Values of the dimensions a and b are shown in Table 6 along with the resistance in ohms achieved by mats held down only by the tires of the trucks and their trailers. As expected, the 1/2 inch braid with 1 inch spacing provides the lowest resistance, 51.5 ohms for the large truck with trailer. If a trailer is not used, the trailer mat must be mounted under the front wheels for the same results to be achieved.

As can be seen from Table 6, the use of 1/2-inch braid to make 1-inch mesh mats results in a cost of $1160.97 based upon a cost of $842 per 1,000 feet of braid. The use of 1/4-inch braid rather than 1/2-inch braid results in a significant cost reduction ($200 per 1000 feet of braid).

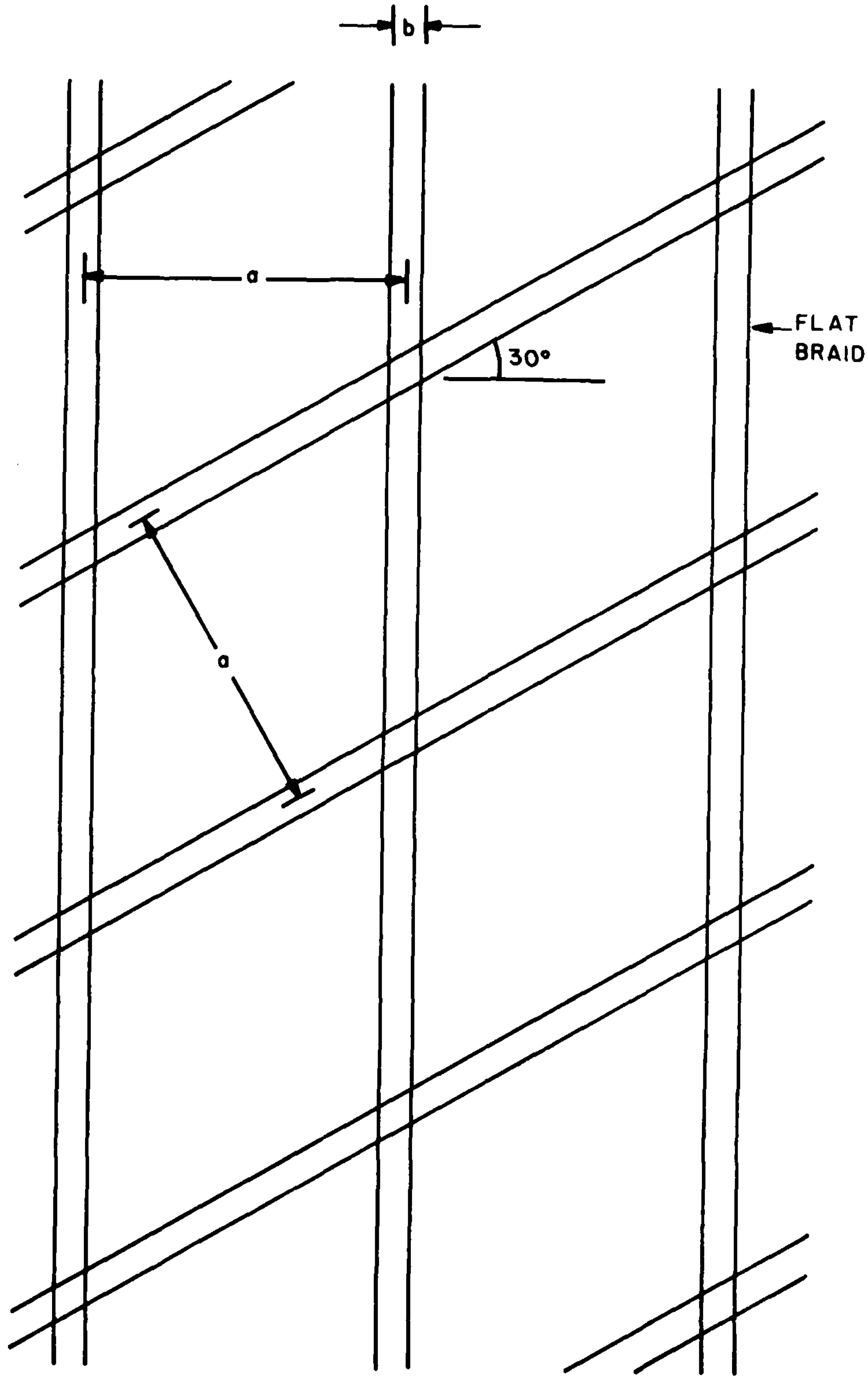

Figure 4. Recommended ground mesh configuration.

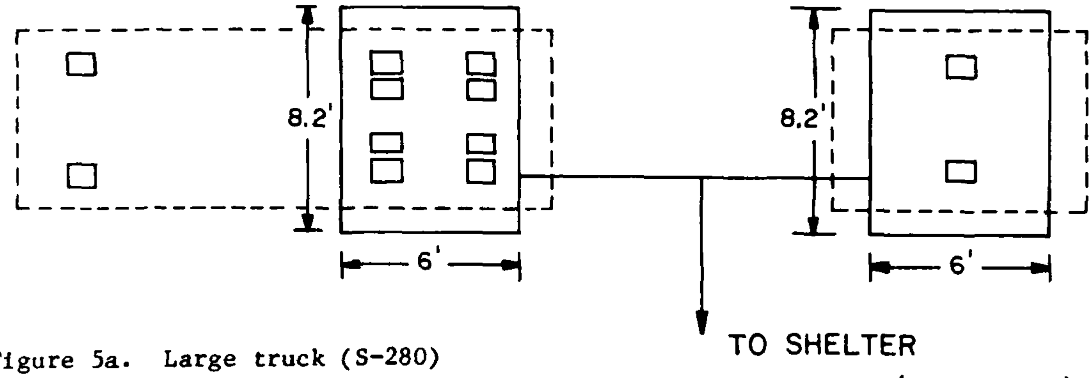

Figure 5a. Large truck (S-280) with trailer.

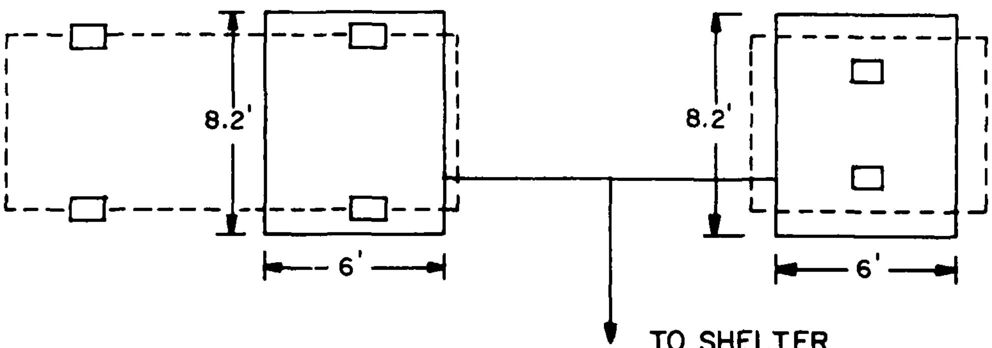

Figure 5b. Small truck (pickup) with trailer.

Figure 5. Installation of diamond neshes under trucks.

By going to 2- and 3-inch spacings of 1/4-inch braid, the cost can be reduced even further. The largest spacing recommended is 3-inches since for larger spacings, the resistance begins to depend critically on exactly how the truck wheels are placed on the mesh. A 3-inch spacing always assures at least two braids in each direction under each tire. In addition, larger braid spacings may produce a mat that is more difficult to roll, even with the diamond configuration.

For the 3-inch spacing (1/4-inch braid), the 8.2 x 6.0 foot mat costs $91.88. The desired 25.0 ohm resistance can be achieved by pressing a total of 34.95 square feet of each mat into the ground in addition to its being held down by the two rear wheels of the small truck. The number of pounds needed depends on the hardness of the surface of the earth. Wetting is advisable for hard, dry surfaces.

TABLE 6

Values of Resistance and Costs of Diamond Mesh

	a = 1" b = 1/2"	a = 1" b = 1/4"	a = 2" b = 1/4"	a = 3" b = 1/4"
Large Truck with Trailer	51.5 ohms	52.4 ohms	55.6 ohms	61.9 ohms
Large Truck Only (one mat)	72.0 ohms	73.2 ohms	77.8 ohms	88.2 ohms
Small Truck with Trailer	123.3 ohms	126.8 ohms	132.2 ohms	139.9 ohms
Small Truck Only (one mat)	255.8 ohms	263.2 ohms	276.6 ohms	288.9 ohms
Cost of one 8.2' x 6.0' Mat	$1,160.97	$275.77	$137.81	$91.88

a and b are defined as shown in Figure 4.

DISCUSSION OF RESULTS

The criteria on pages 6 through 8 call for the attainment of a 25 ohm ground in 200 ohm-meter soil in 2.6 minutes with a removal time of 3.2 minutes. Weight is to be less than 10 pounds and material cost per usage should not exceed $3.50.

The horizontal diamond mesh may well meet the resistance, weight, and installation time criteria, but a pair must be usable 53 times to meet the $3.50 per usage criterion. The time required to lay and retrieve the mats may well be within the 2.6 minute and 3.2 minute removal criteria but this remains to be proven in actual tests.

Chemical Enhancement

If the resistance of an installed ground is found to be higher than expected, the resistance can be reduced by chemically treating the soil. Table 6 shows the effect of adding sodium chloride (NaCl) to red clay having 30% moisture by weight[15].

TABLE 7

Effect of Sodium Chloride on Earth Resistivity

% Salt in Moisture	Resistivity (ohm-cm)
0	4000
1	900
2	450
3	250
4	150
5	100

While sodium chloride is low in cost and readily available, consideration should be given to other chemicals. For general effectiveness and anticorrosion qualities, the main usable chemical aids[16] are:

(1) Magnesium sulphate
(2) Copper sulphate
(3) Calcium chloride
(4) Sodium chloride
(5) Potassium nitrate

[15] White, D. R. J., Op. Cit.
[16] Department of the Army, Grounding, bonding and shielding design, practices (MIL-STD-1857 (EL)), Washington, DC: Author, 30 June 1976.

Chemical treatment usually is used where the earth resistivity is relatively high. Thus the resistivity of the treated earth around the ground conductors may become very low compared with that of the surrounding earth. As a result, the effect of chemical enhancement is to increase the radius of the ground conductors[17]. While chemicals have a tendency to be absorbed by the surrounding earth, they generally remain effective for several months to a year, probably well beyond the time of stay of the mobile facilities.

If the the surface layer is of high resistivity, but lower layers are of low resistivity, the chemicals may provide a low resistance path to the lower layer of low resistivity. This could occur either for a vertical rod or for a plate of limited dimensions.

Chemical salts are used most frequently to improve the performance of vertical rod grounds. Results can be achieved by adding the salts within a relatively confined volume. This is not true for the horizontal grounds, which would require salting along a line or over an entire area. For horizontal wire or long grid grounds, the achievement of sufficiently low resistance may be done more effectively by extending the length of the horizontal ground.

MEASUREMENT METHODS

The ground-resistance measuring method must provide a go-no go check for either a horizontal or vertical rod grounding system. The recommended method is known as the "fall of potential" technique. Figure 6 illustrates the technique. The method uses a device which is either battery operated or uses a hand-crank generator. It has three terminals, one of which is connected to the ground to be measured. For a long horizontal ground, however, this distance must be increased to 5 to 10 times the length of the ground system. The second probe is placed between the first probe and the ground to be measured. A fixed location 62% of the distance from the ground to the first probe may be used if buried conductors are known not to be in the vicinity. Otherwise, the second probe must be placed at several distances (e.g., 40%, 50%, 60%, 70%, 80%) between the ground and the first probe.

The instrument used to make the measurements obtains the ratio of the voltage observed between ground and the second probe to current drawn by the first probe. If a residual current flows without the application of voltage, stray currents are present in the earth. In this event, the measurement must be taken in other directions from the ground and the results averaged.

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[17] Sunde, E. D., Op. Cit.

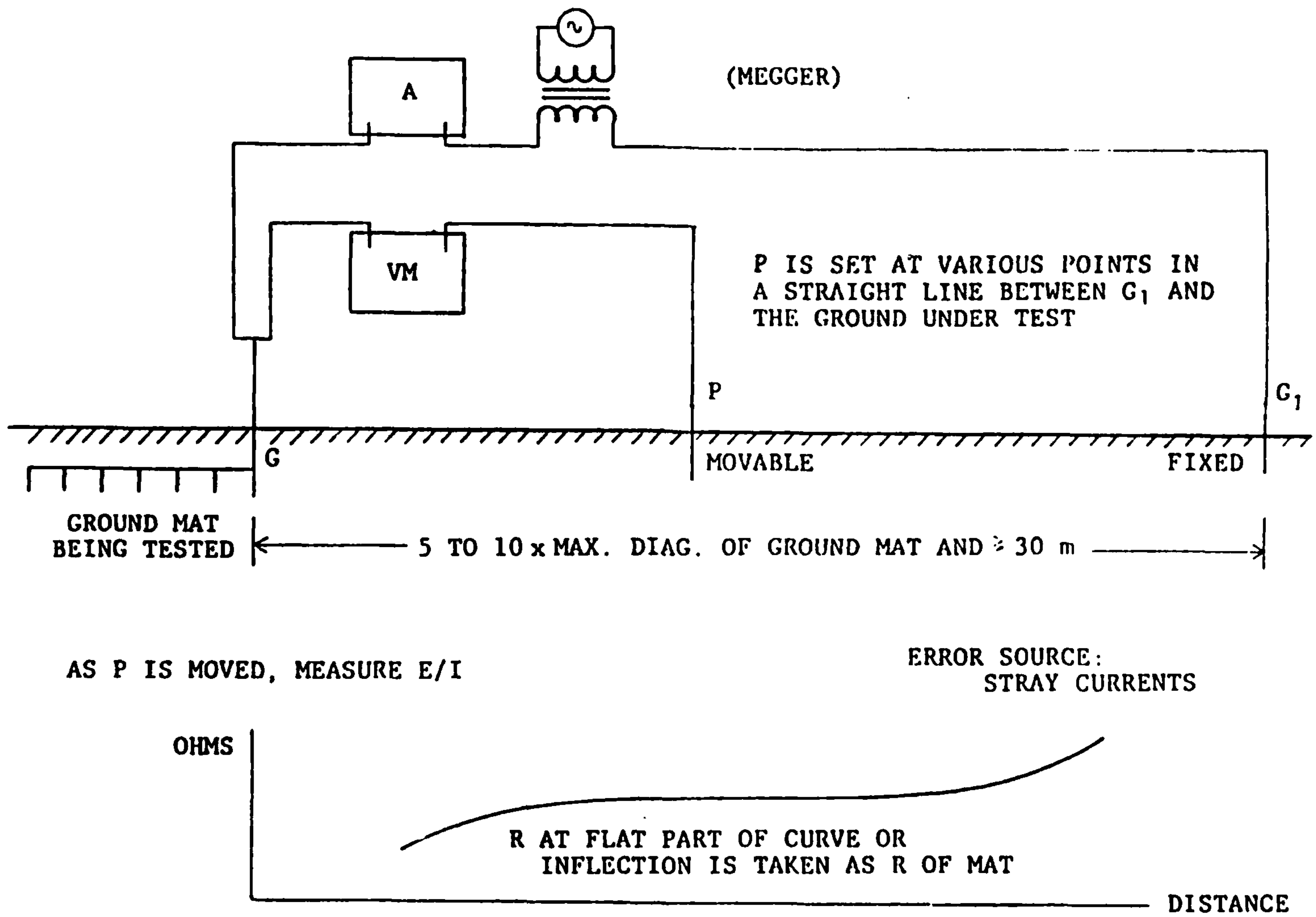


Figure 6. Fall of potential ground resistance measuring technique.

The instruments used to make the foregoing measurements go under trade names such as "earth megger," "earth tester," and "vibra ground." The desired resistance can be set by decade dials, whereupon a lower resistance ("go") is indicated by instrument meter deflection to the left, while a higher resistance ("no go") is indicated by a meter deflection to the right. The probes are made for ready removal from the earth, and rubber-covered flexible wires are provided for connection to the probes.

ALTERNATIVES FOR SPECIAL ENVIRONMENTS

The horizontal grid ground is expected to be applicable to about 70% of the situations which may be encountered by mobile tactical electronic systems. This section discusses special conditions which may be encountered the other 30% of the time.

Desert (Sandy Surface)

The horizontal grid should work well in a desert area. Chemical enhancement may be found helpful, however. The proximity of an oasis or under ground stream at which a vertical rod could be located would be very useful.

Mountains (Rocky Surface)

In mountainous areas no surface soil may be present. In this case grid mats must be used. If soil is present, salting will be helpful. Any nearby stream bed also will be useful. A horizontal wire can be placed in the stream bed.

Arctic (Frozen Surface)

The horizontal wire should be placed in a narrow trench[18] in the snow as deeply as possible. Additional wires in several directions may be used to form a radial ground if the length of the trench must be limited. Salting should be done around the wire. Any nearby metal buildings or underground pipes should be used as well.

Tropical (Moist Surface)

In tropical regions a large horizontal extent may be difficult to obtain. A vertical rod may be quite effective and not too difficult to remove. Corrosion is a major problem in tropical areas, even over relatively short periods of time. For this reason solid copper rather than plated wires, grids, and rods are preferred. (Plated steel rods are needed

[18] MIL-STD-1857(EL), paragraph 3.2.7.2

for harder surfaces, however.) Bimetallic junctions become extremely important wherever dissimilar metals join. The Ideal "bug" (Cat. No. 7-681), the Thompson #744 or #745 bimetallic clamp, or a similar device should be used with a corrosion resistant conductive compound, and the entire junction then should be taped or otherwise protected from moisture.

CONCLUSIONS

The horizontal grid is the recommended approach for 70% of the grounding requirements for mobile tactical electronic systems with alternatives for limited lateral space being the horizontal wire ground and, for extremely limited space, the vertical rod. Chemical enhancement may be found useful on those installations which are confined to very limited space.

The recommended resistance measurement technique is the fall-of-potential method. Commercially-made portable equipment based on this method is readily available.

Table 8 shows how the various grounding techniques rate relative to the criteria discussed in this report. Those numerical values which were not calculated for Table 5 are the writer's estimates.

TABLE 8

Evaluation of Grounding Techniques

Technique	Resistance (Ohms)	Install Time (Min.)	Remove Time (Min.)	Cost	Weight (Lbs.)	Safety
(Criteria)	(25)	2.6	3.2	($3.50 use)	(10)	(Excellent)
Vertical Rod	100	2.6	3.2	$3.50/ use	4.6	Fair
Horizontal Grid	25	2.6	3.2	Material reusable	7.9	Excellent
Horizontal Wire	25	4.0	3.0	[a]Material reusable	2.6	Excellent
Flat Tape	25	10.0	3.0	[a]Material reusable	2.0	Excellent
Plates	50	5.0	1.0	Material reusable	47.0	Good
Horizontal Radial	25	12.0	3.0	Material reusable	4.0	Excellent
Incidental Electrodes	5	-	-	-		Excellent

[a]Ditch Witch, however, costs $10,250

RECOMMENDATIONS

Fabrication and field tests are the next steps in the achievement of improved grounding techniques for mobile tactical electronic systems.

The diamond mesh of metallic braid is to be fabricated and then tested by unrolling it in a flat area and driving a truck (S-280 or pick-up) over it as in Figure 5. Resistance should be measured as described. The use of sand bags or other heavy flat loads (spread over at least 70% of the mat area) then should produce the desired reduction in resistance.

The resistivity of the flat area should be checked in advance using the four-electrode method of earth resistivity testing[19]. Computations in this analysis report have assumed 200 ohm-meters earth resistivity.

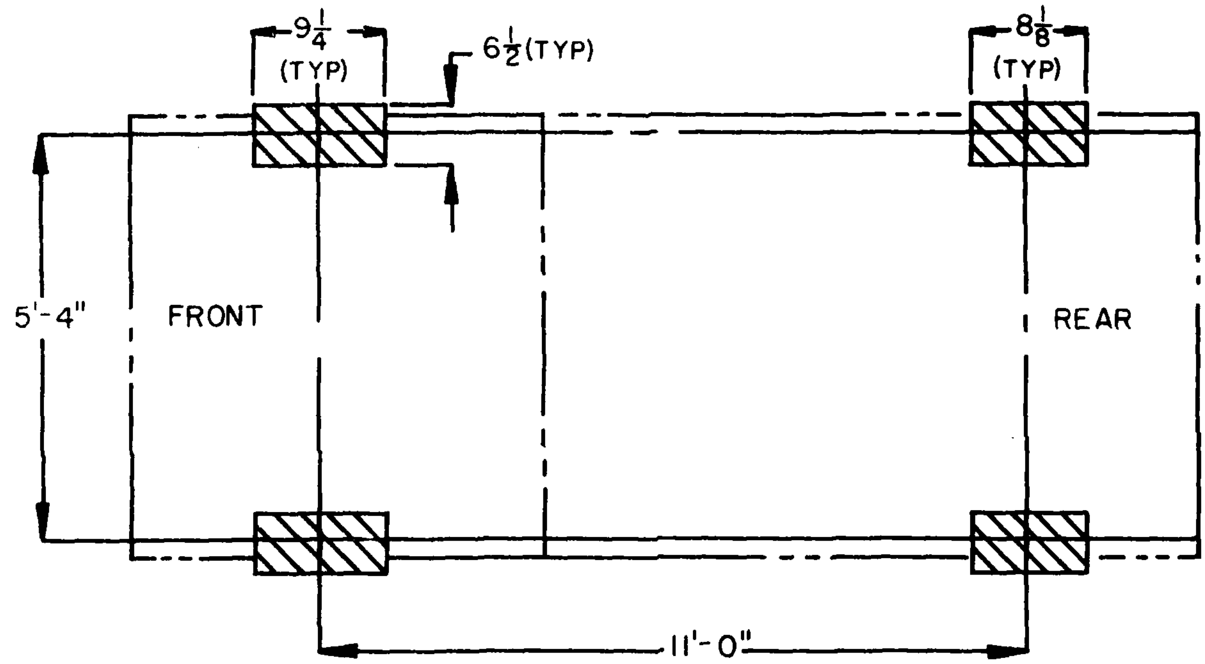
Field tests will show how the ground resistance, as actually measured, compares with theoretical expectations. Differences may be related to actual earth resistivity and how well the earth contacts the newly installed metal. A degree of over design, thus, may be required to compensate for less than perfect contact.

The effectiveness of chemical enhancement of the horizontal conductor grounding techniques also should be checked since the use of chemicals usually has been confined to the vertical rod grounds.

[19] Sunde, E. D., Op. Cit.

APPENDIX

VEHICLE TIREPRINTS



PICK UP TRUCK, (8'-BED)

(NOT TO SCALE)