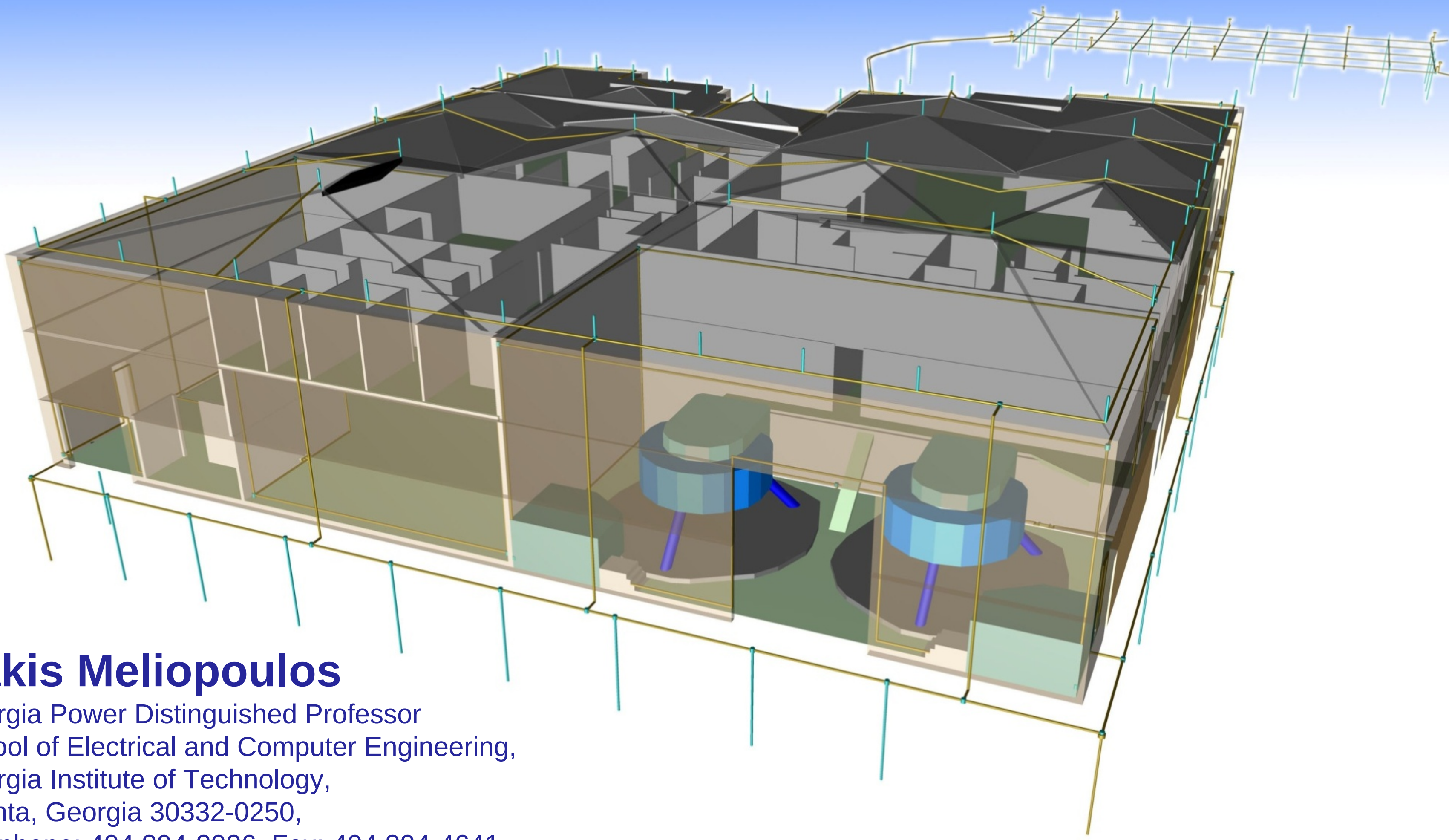
Testing and Evaluation of Grounding Systems: The Revision of the IEEE Std 81



Sakis Meliopoulos
Georgia Power Distinguished Professor
School of Electrical and Computer Engineering,
Georgia Institute of Technology,
Atlanta, Georgia 30332-0250,
Telephone: 404 894-2926, Fax: 404 894-4641
Email: sakis.m@gatech.edu or sakis@comcast.net

Grounding and Bonding is Fundamental for a Safe and Reliable Power System

Lightning and Surge Protection

Stabilize Circuit Potential and Assist in Proper Operation of:

- Communications
- Relaying
- Computers & Sensitive Electronic Equipment

Low Fault Circuit Path Impedance

Safety, Safety, Safety

Improve Quality of Power Service

Grounding, Bonding and Power Quality

"Recent studies indicate that as much as 80% of all failures of sensitive electronic equipment attributed to poor power quality may result from inadequate electrical grounding or wiring on the customer's premises or from interactions with other loads within the premises."

Wiring and Grounding for Power Quality
EPRI CU-2026, March 1990

"However, many power quality problems that occur within customer facilities are related to wiring and grounding practices. Up to 80% of all power quality problems reported by customers are related to wiring and grounding problems within a facility."

Power Quality Assessment Procedure
EPRI CU-7529, December 1991

Over the Years Grounding Design Procedures Have Been Developed as Well as Appropriate Standards, Most Notable:

•ANSI/IEEE Std 80-2000, IEEE Guide for Safety in AC Substation Grounding.

•IEEE Std 487-2007, Recommended Practice for the Protection of Wire-Line Communication Facilities Serving Electric Supply Locations.

•IEEE Std 998-1996, IEEE Guide for Direct Lightning Stroke Shielding of Substations.

•IEEE Std 1410-2004, IEEE Guide for Improving the Lightning Performance of Electric Power Overhead Distribution Lines.

•IEEE Std 1243-1997, IEEE Guide for Improving the Lightning Performance of Transmission Lines.

•National Electrical Code.

•National Electrical Safety Code.

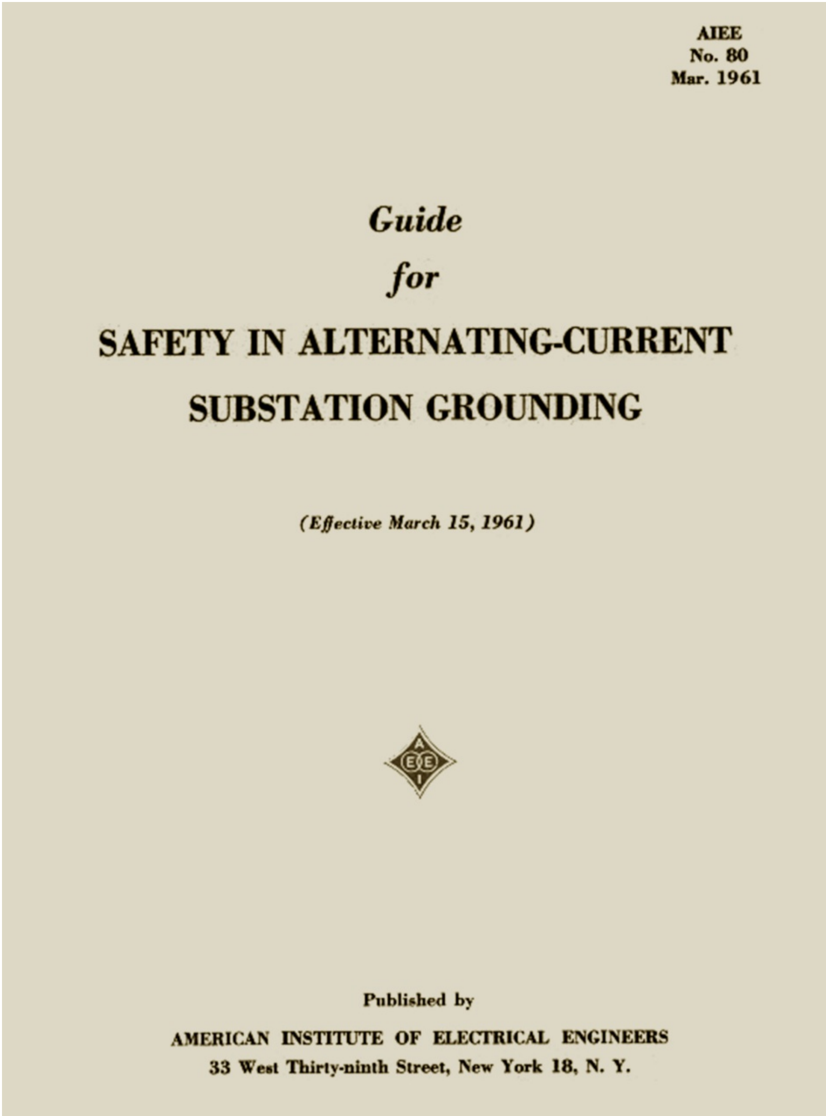
•FIPS 94 and Derivatives.

For the Purpose of Verifying Designs, Testing Procedures have Been also Developed. Most Notable:

•ANSI/IEEE Std 81-1983, IEEE Guide for Measuring Earth Resistivity, Ground Impedance and Earth Surface Potentials of a Ground System.

•ANSI/IEEE Std 81.2-1991, IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems.

The History of IEEE Std 80


AIEE
No. 80
Mar. 1961

Guide

for

SAFETY IN ALTERNATING-CURRENT

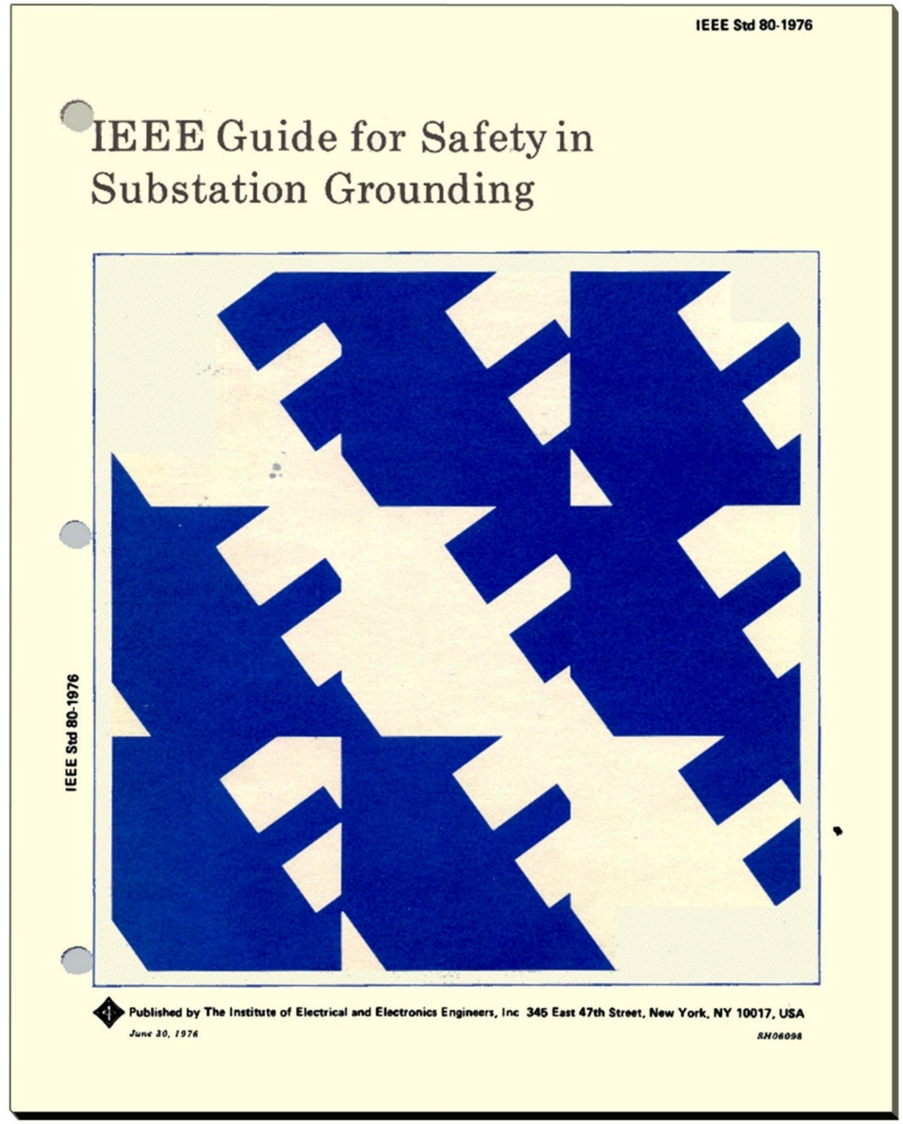
SUBSTATION GROUNDING

(Effective March 15, 1961)

Published by

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

33 West Thirty-ninth Street, New York 18, N. Y.


IEEE Std 80-1976

IEEE Guide for Safety in
Substation Grounding

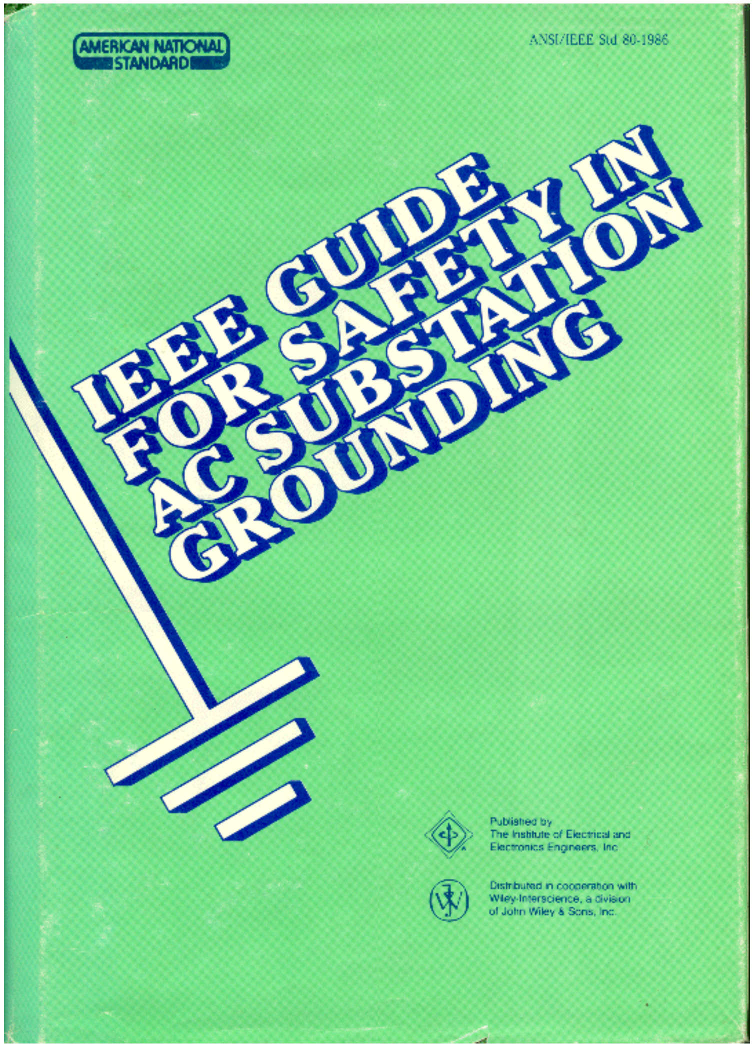
IEEE Std 80-1976

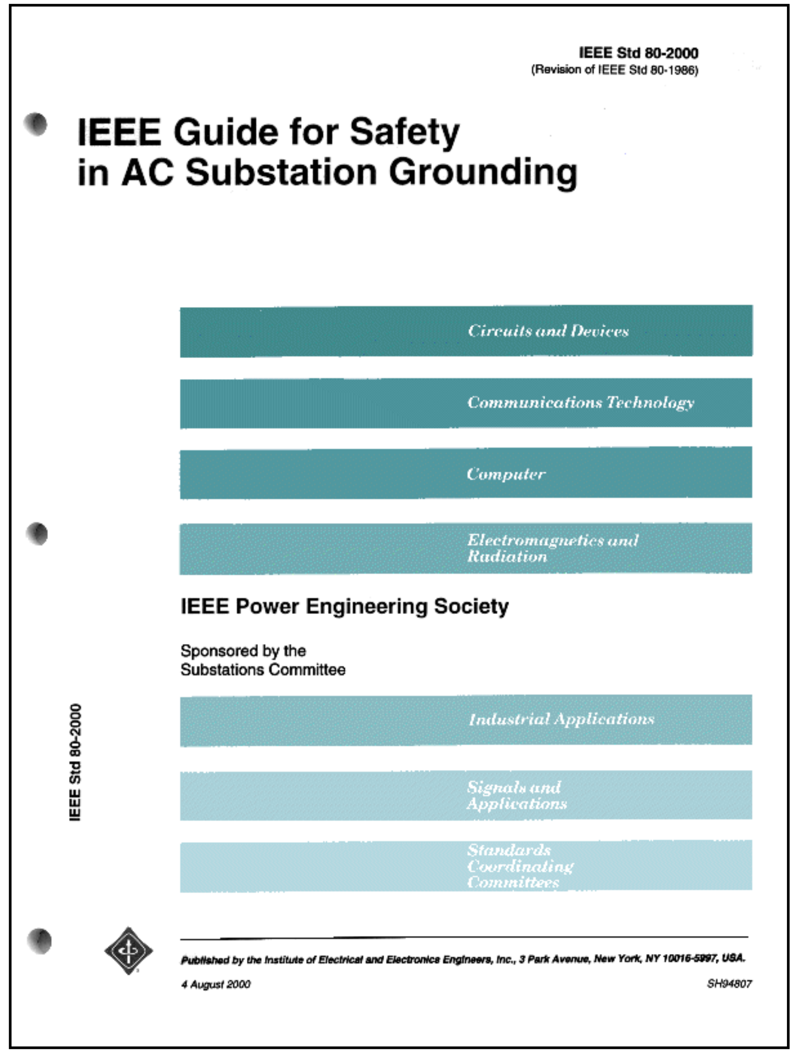
Published by The Institute of Electrical and Electronics Engineers, Inc 345 East 47th Street, New York, NY 10017, USA

June 30, 1976

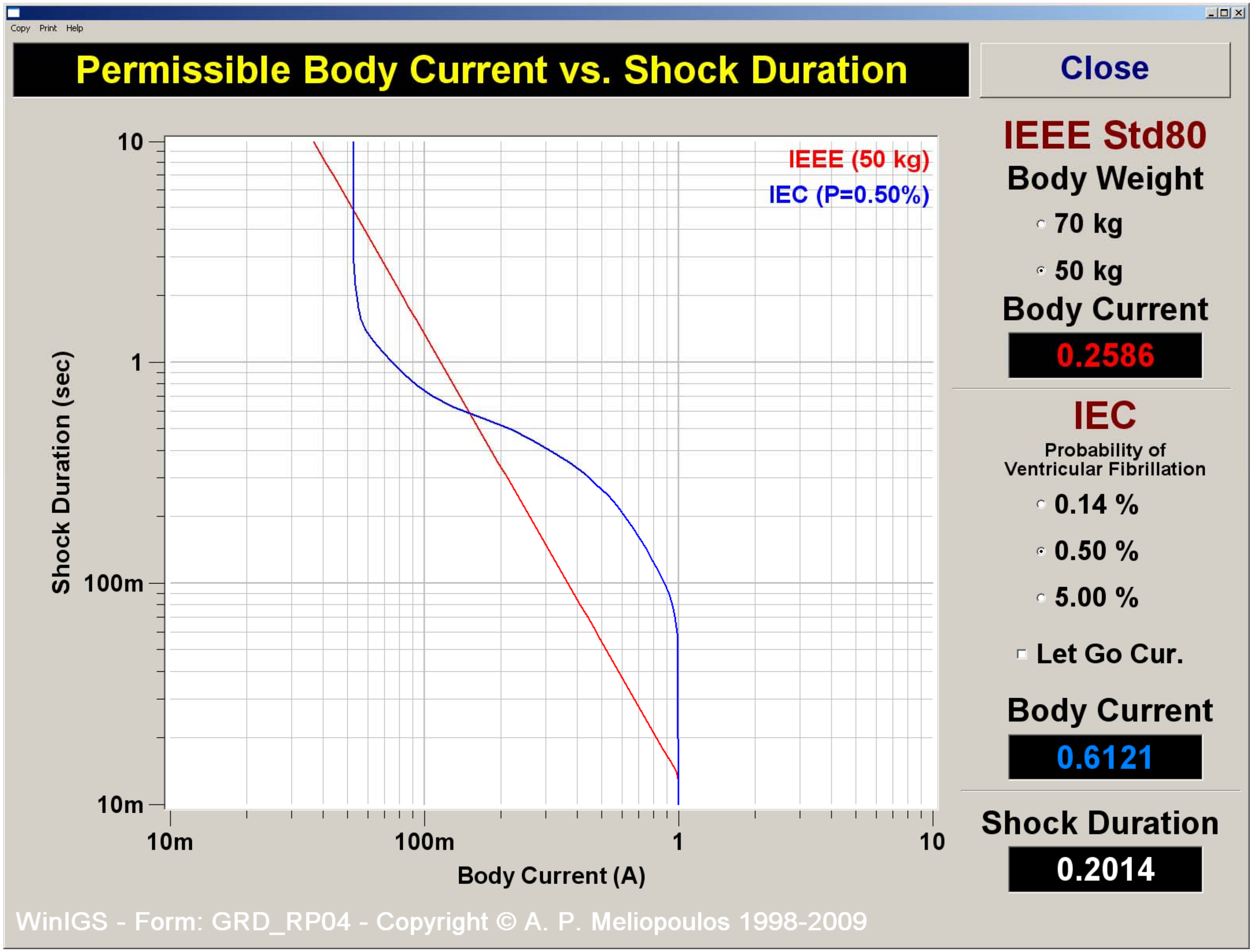
SH06098

The History of IEEE Std 80

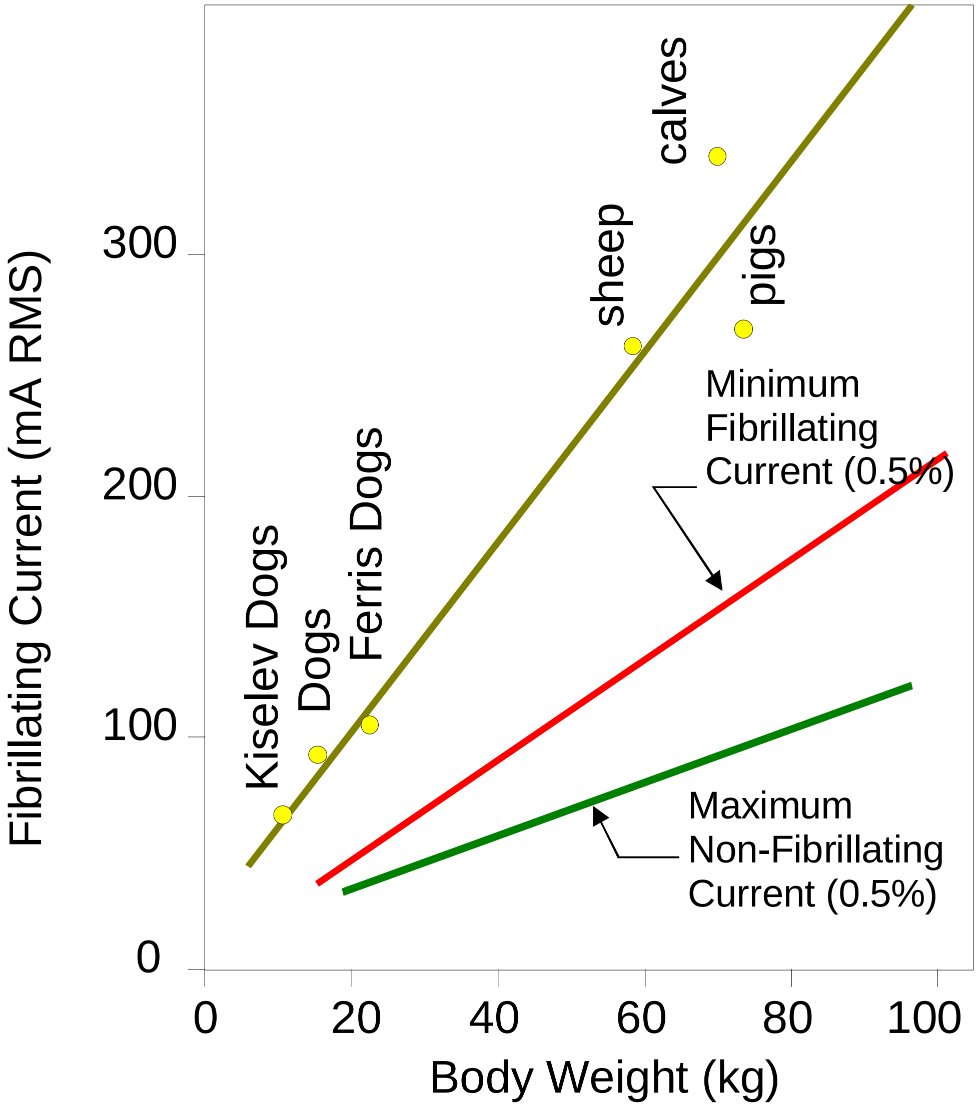




Basis of Standards: IEEE 80 & IEC



IEEE Std 80, 1986 Edition



Value of Constant k for Effective RMS Values of I_B:

$$k = I_b \sqrt{t_s}$$

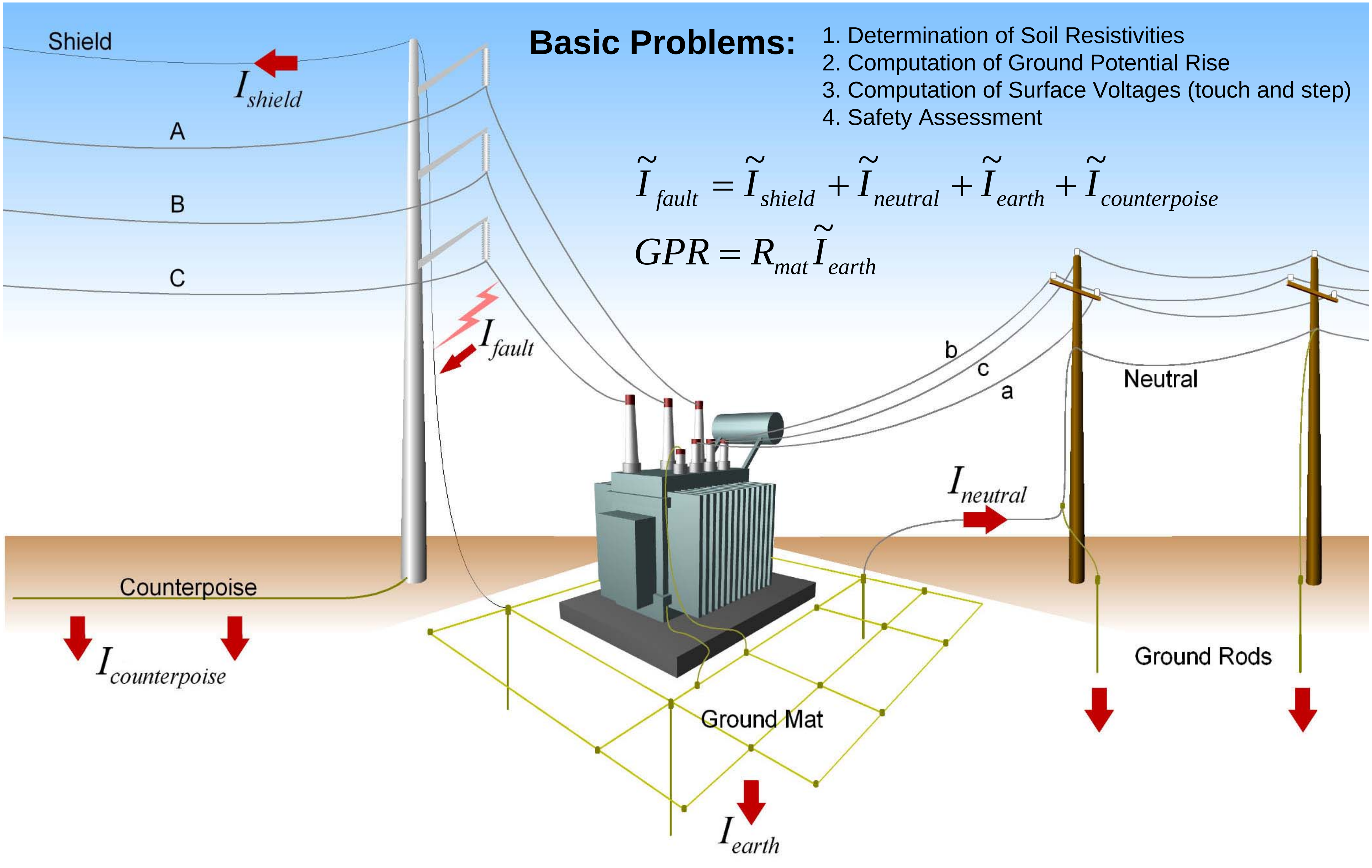
$k_{50} = 0.116$ (Non-Fibrillating, 0.5%)

$k_{50} = 0.185$ (Fibrillating, 0.5%)

$k_{70} = 0.157$ (Non-Fibrillating, 0.5%)

$k_{70} = 0.263$ (Fibrillating, 0.5%)

Earth Current, Ground Potential Rise, Touch & Step



Basic Problems:

1. Determination of Soil Resistivities
2. Computation of Ground Potential Rise
3. Computation of Surface Voltages (touch and step)
4. Safety Assessment

$$\tilde{I}_{fault} = \tilde{I}_{shield} + \tilde{I}_{neutral} + \tilde{I}_{earth} + \tilde{I}_{counterpoise}$$

$$GPR = R_{mat}\tilde{I}_{earth}$$

Verification - Measurements

Key Fact:

Target Values Must be Determined in Design Phase

The History of the IEEE Std 81

First Edition:
IEEE Std 81 – 1962

Revision:
ANSI/IEEE Std 81-1983
IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System

To Address Issues Related to Large Grounding Systems or Systems in Congested Areas:
IEEE Std 81.2-1991
IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems

All of Above Standards were sponsored by:

Power System Instrumentation and Measurement Committee
Of the
IEEE Power Engineering Society

In the period 2003-2004, I served as the Chair of the Substations Committee of the IEEE Power Engineering Society. I initiated and succeeded in transferring sponsorship of the standard to the Substations Committee with the plan to combine the two standards into one single standard. The unified standard has been developed in committee (working group E6, Chaired by Dennis DeCosta) and we expect to ballot it within the next 12 months.

ANSI/IEEE Std 81-1983
IEEE Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System

1. Purpose
2. Scope
3. Objectives of Tests
4. Definitions.
5. Safety Precautions While Making Ground Tests
6. General Considerations of the Problems Related to Measurements
    - 6.1 Complexities
    - 6.2 Test Electrodes
    - 6.3 Stray Direct Currents
    - 6.4 Stray Alternating Currents
    - 6.5 Reactive Component of Impedance of a Large Grounding System 6.6 Coupling Between Test Leads
    - 6.7 Buried Metallic Objects
7. Earth Resistivity
8. Ground Impedance
    - 8.1 General
    - 8.2 Methods of Measuring Ground Impedance
    - 8.3 Testing the Integrity of the Ground Grid
    - 8.4 Instrumentation
9. Earth Potential
    - 9.1 Equipotential Lines
    - 9.2 Potential Contour Surveys
    - 9.3 Step and Touch Voltages
10. Transient Impedance
11. Model Tests
12. Instrumentation
13. Practical Aspects of Measurements

Annex A Nonuniform Soils
Annex B Determination of an Earth Model
Annex C Theory of the Fall of Potential Method
Annex D Bibliography

IEEE Std 81.2-1991
IEEE Guide for Measurement of Impedance and Safety Characteristics of Large, Extended or Interconnected Grounding Systems

It was developed to address the special problems and issues associated with testing large interconnected grounding systems

1. Purpose
2. Scope
3. References
4. Safety Practices
5. Factors Effecting Grounding System Measurements
6. Preliminary Planning and Procedures
7. Earth-Return Mutual Effects When Measuring Grounding-System Impedance
    - 7.1 Introduction
    - 7.2 Measurement Error Due to Earth Mutual Resistances
    - 7.3 Measurement Error Due to AC Mutual Coupling
    - 7.4 Mutual Coupling to Potential Lead From Extended Ground Conductors
8. Measurement of Low-Impedance Grounding Systems by Test-Current Injection
    - 8.1 Introduction
    - 8.2 Signal Generator and Power Amplifier Source
    - 8.3 Portable Power-Generator Source
    - 8.4 Power System Low-Voltage Source
9. Measurement of Low-Impedance Grounding Systems by Power System Staged Faults
10. Current Distribution in Extended Grounding Systems
    - 10.1 Introduction
    - 10.2 Test Considerations
    - 10.3 Analysis of Current Distribution in a Grounding System
    - 10.4 Induced Current in the Angled Overhead Ground Wire
    - 10.5 Current Distribution During a Staged Fault Test
11. Transfer Impedances to Communication or Control Cables
12. Step, Touch, and Voltage-Profile Measurements
13. Instrumentation Components
    - 13.5 Fast Fourier Transform Analyzer
    - 13.6 Sine Wave Network Analyzer
    - 13.7 Staged Fault
    - 13.11 Low-Power Random Noise Source
    - 13.14 Pulse Generator
    - 13.15 Current Transformer (CT)
    - 13.16 Resistive Shunt
    - 13.17 Inductive Current Pickup
    - 13.18 Hall-Effect Probe
14. Instrument Performance Parameters
15. Bibliography

Present Revision
IEEE Std 81-XXXX
Guide for Measuring Earth Resistivity, Ground Impedance, and Earth Surface Potentials of a Ground System

1. Overview
    - 1.1 Purpose
    - 1.2 Scope
2. References
3. Definitions
4. Test Objectives
5. Safety Precautions While Making Ground Tests
    - 5.1 Station Ground Tests
    - 5.2 Special Considerations
6. General Considerations on the Problems Related to Measurement
7. Earth Resistivity
    - 7.1 General
    - 7.2 Methods of Measuring Earth Resistivity
    - 7.3 Interpretation of Measurements
    - 7.4 Guidance on performing field measurements
8. Ground Impedance
9. Testing Local Potential Differences
10. Integrity of Grounding Systems
11. Current Splits
12. Transient Impedance of Grounding System
13. Other

ANNEX A (INFORMATIVE) SURFACE MATERIAL RESISTIVITY

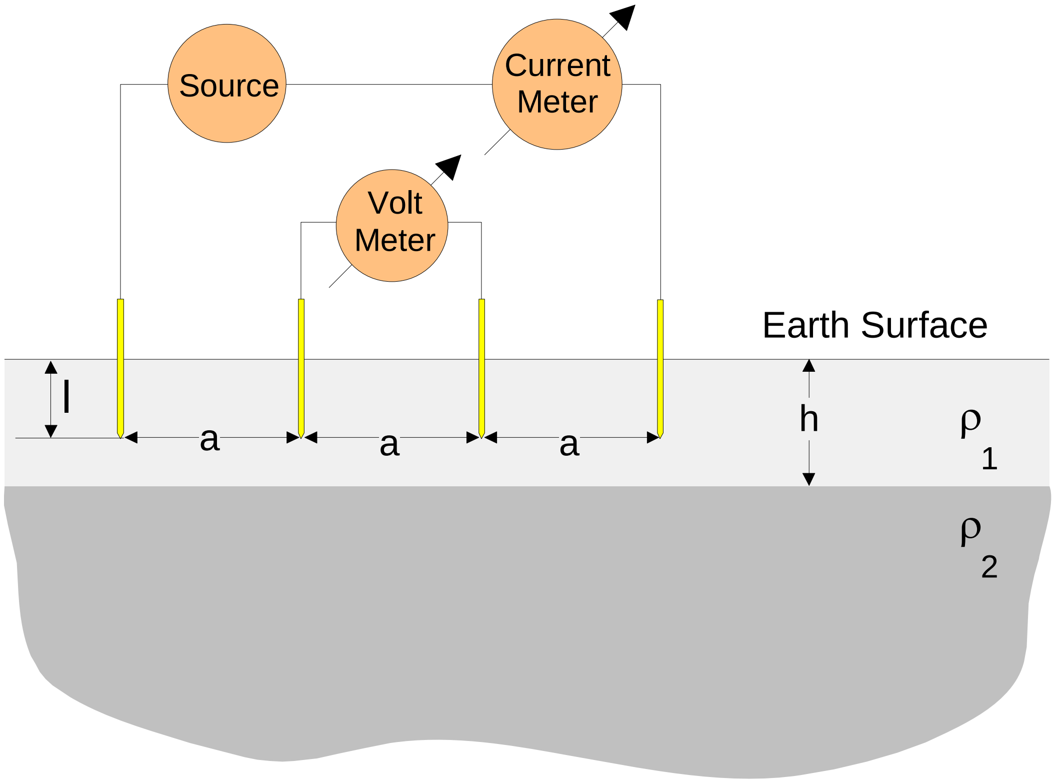
ANNEX B - INSTRUMENTATION

- B.1. Megohm Meter
- B.2. Clamp-On Ground Tester
- B.3. Smart Ground Meter
- B.4. Transient Impedance Meter

Grounding System Measurements

- Ground Impedance Measurement Methods
  - The 2-Point Method
  - The 3-Point Method
  - The Fall of Potential Method
  - The 62% Rule
  - The Ratio Method
  - The Tag Slope Method
  - The Intersecting Curve Method
  - Staged Fault Tests
  - Driving Point Impedance
  - The SGM Method
- Continuity/Integrity Testing
- Soil Resistivity Measurements
- Touch and Step Voltages
- Other Tests (Tower/Pole Ground, Transfer V.)

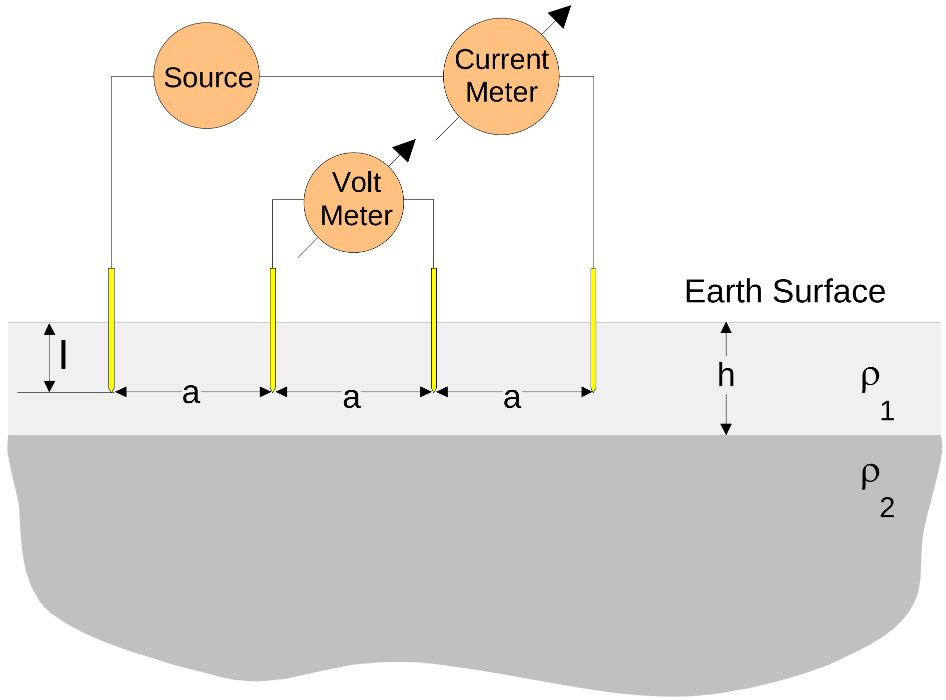
Four Point – Wenner Method



$$R = \frac{V}{I}$$

$$\rho = \frac{4\pi a R}{1 + \frac{2a}{\sqrt{a^2 + 4\ell^2}} - \frac{a}{\sqrt{a^2 + \ell^2}}} \cong 2\pi a R$$

Limitations of the Wenner Method



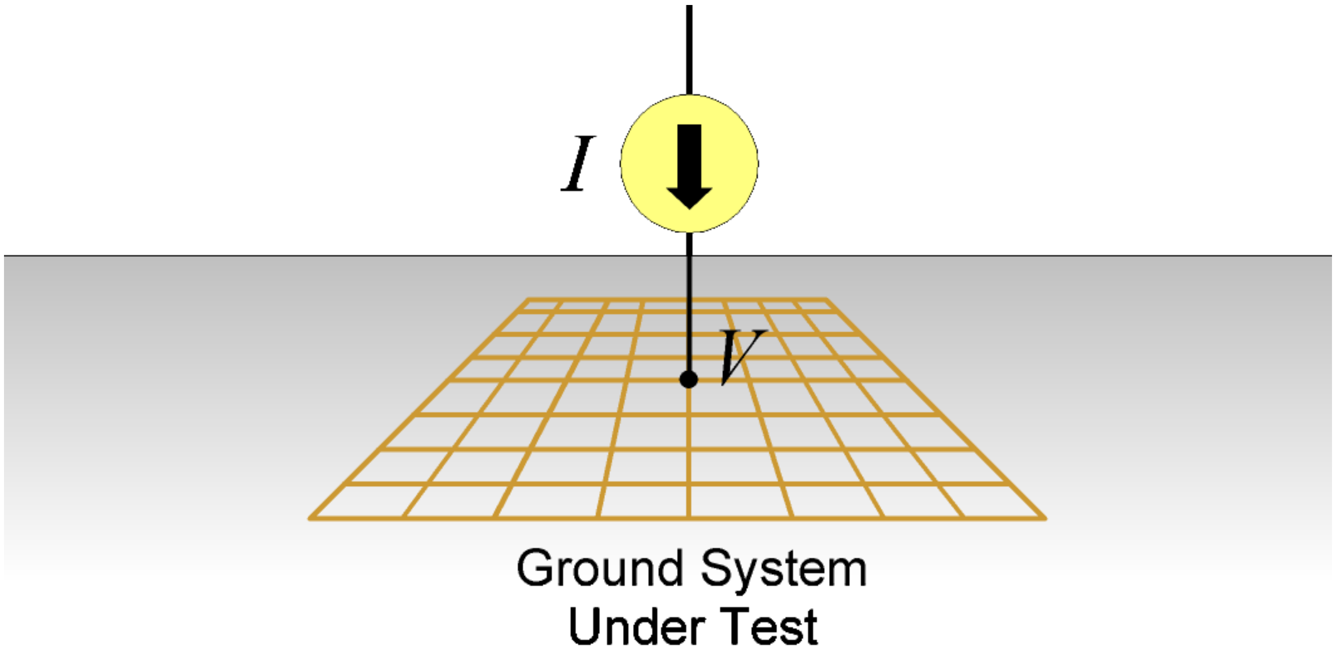
$$V_m = RI - r_e aI - jx_e aI$$

$$\frac{V_m}{I} = \frac{\rho}{2\pi a} - r_e a - jx_e a$$

Example: Soil of 10 Ohm.meter, separation 300 feet, measurements at 150 Hz. Compute error

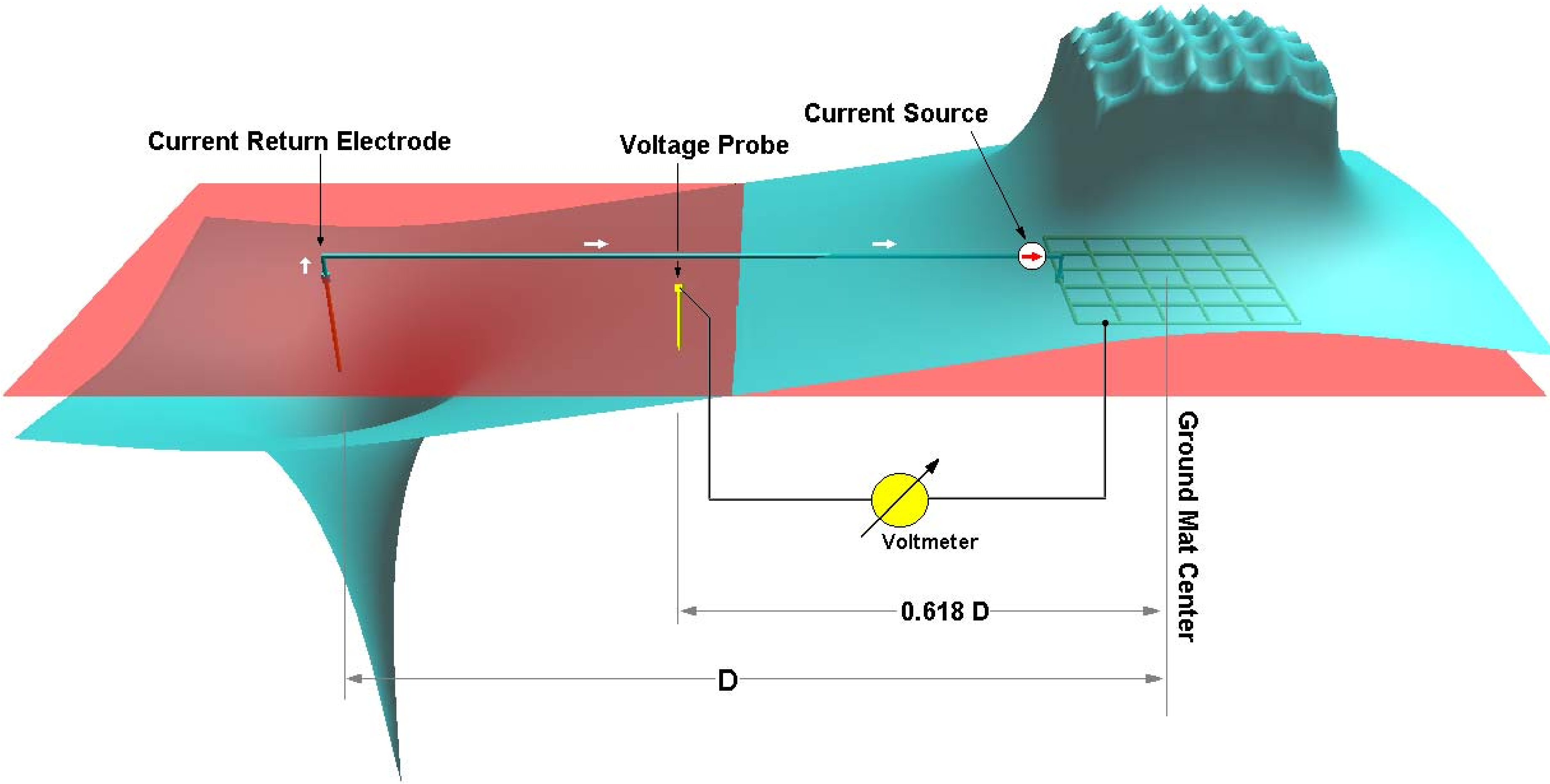
Basic Principles

Basic Arrangement

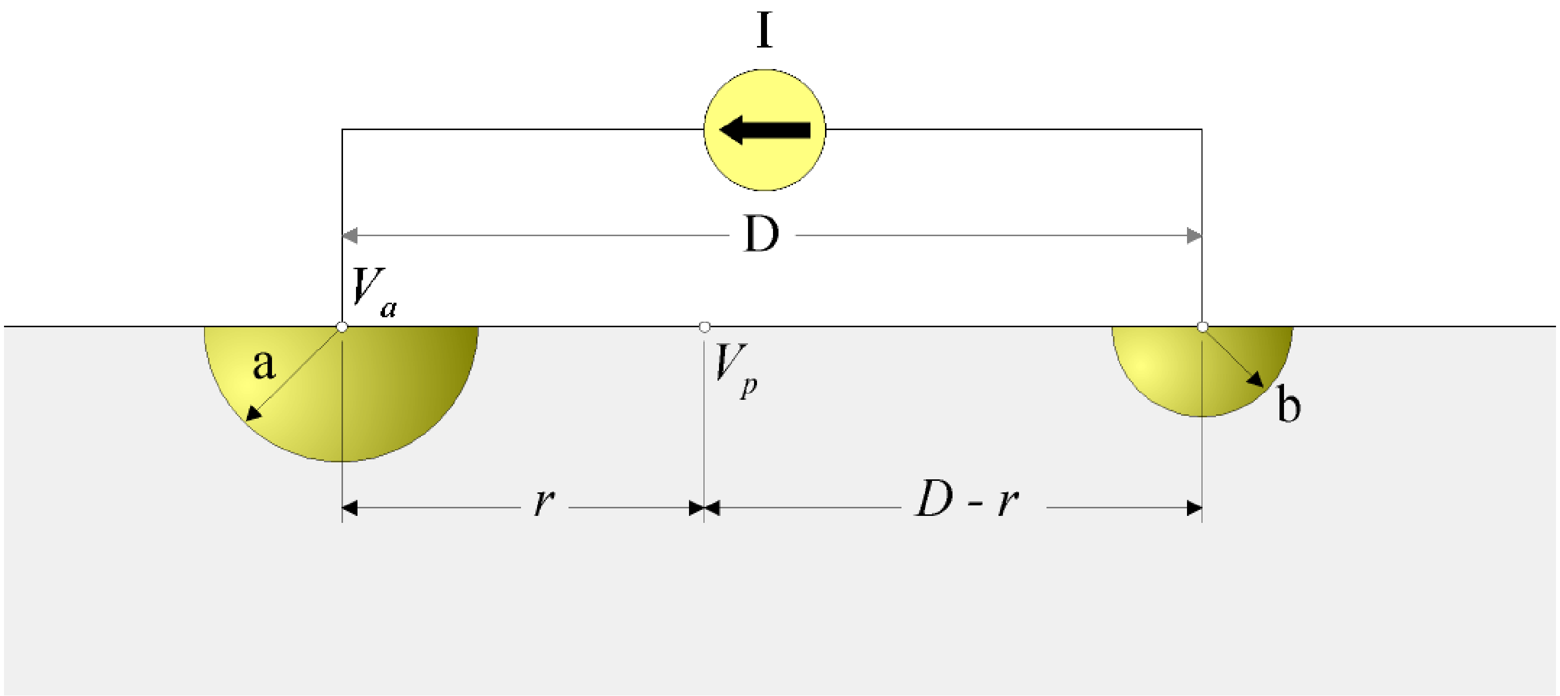


$$R_g = \frac{V}{I}$$

The Fall of Potential Method
The "62%" Rule



Optimal Voltage Probe Location – The 62% Rule



$$V_a = \frac{I\rho}{2\pi}\left(\frac{1}{a} - \frac{1}{D}\right) \qquad V_p = \frac{I\rho}{2\pi}\left(\frac{1}{r} - \frac{1}{D-r}\right)$$

$$R_a = \frac{V_a - V_p}{I} = \frac{\rho}{2\pi}\left(\frac{1}{a} - \frac{1}{D} - \frac{1}{r} + \frac{1}{D-r}\right)$$

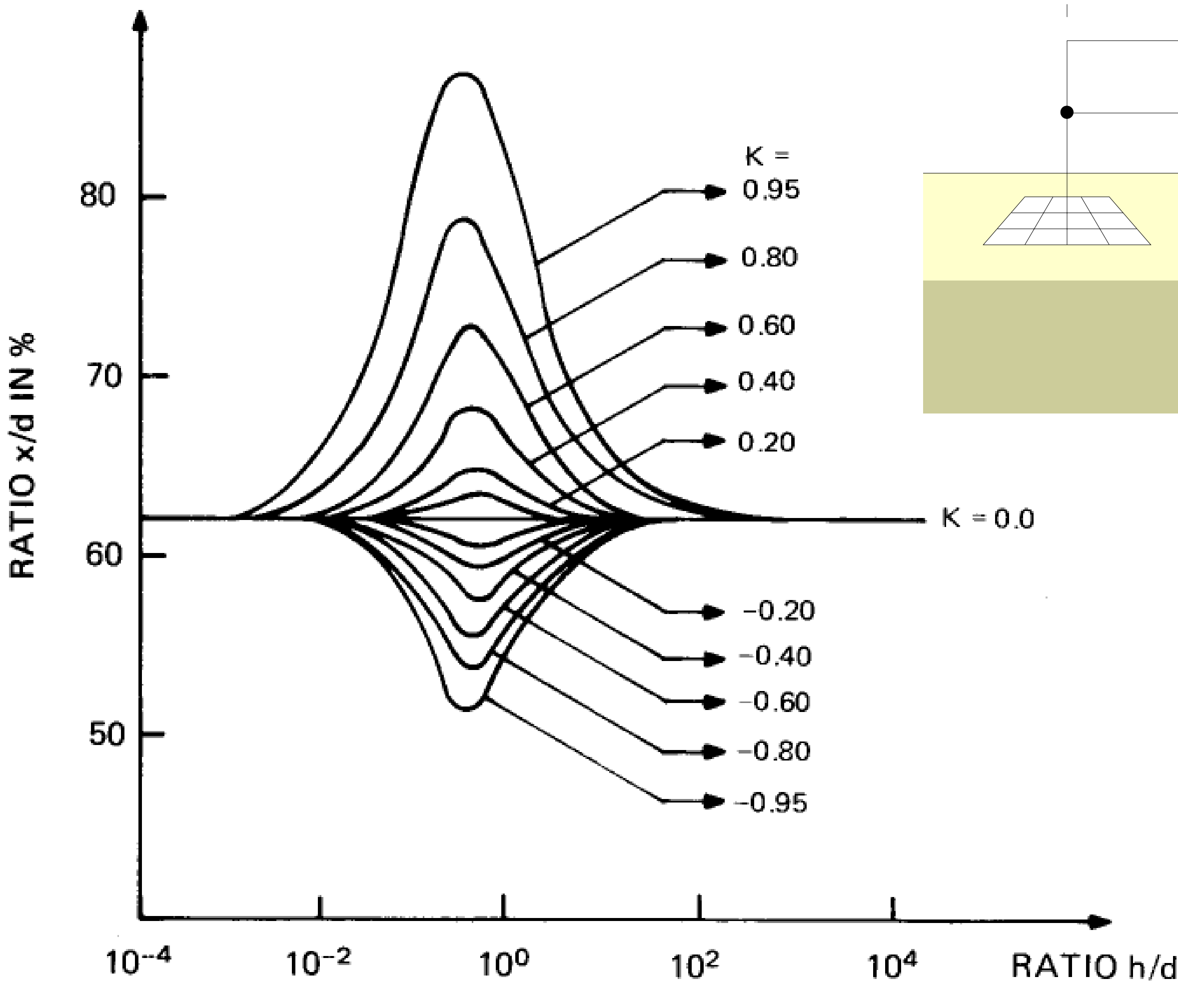
Optimal Voltage Probe Location – The 62% Rule

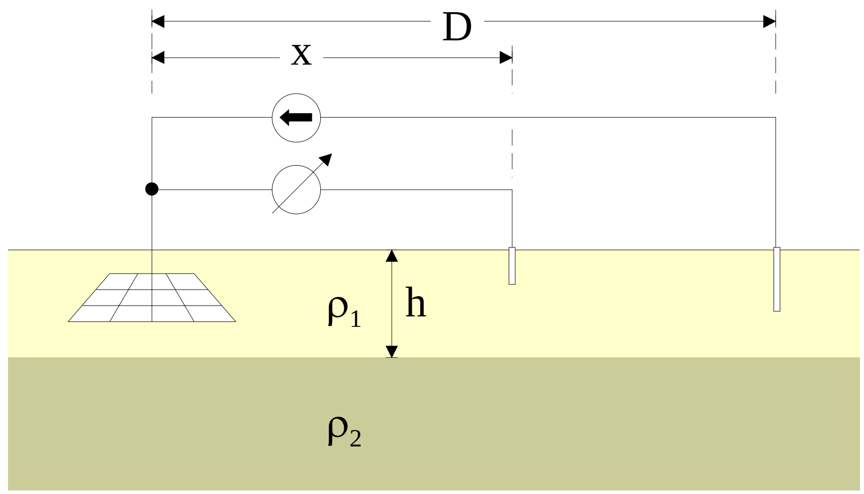
Compare
$$\begin{cases} R_g = \dfrac{V_a}{I} = \dfrac{\rho}{2\pi a} \\[2ex] R_a = \dfrac{V_a - V_p}{I} = \dfrac{\rho}{2\pi}\left(\dfrac{1}{a} - \dfrac{1}{D} - \dfrac{1}{r} + \dfrac{1}{D-r}\right) \end{cases}$$

$R_a = R_g$ requires that: $$\frac{1}{D} + \frac{1}{r} - \frac{1}{D-r} = 0$$

Solving for r/D yields: $$\frac{r}{D} = \frac{-1 \pm \sqrt{5}}{2} = 0.618034$$

The Fall of Potential Method – 62% Rule and Two Layer Soil

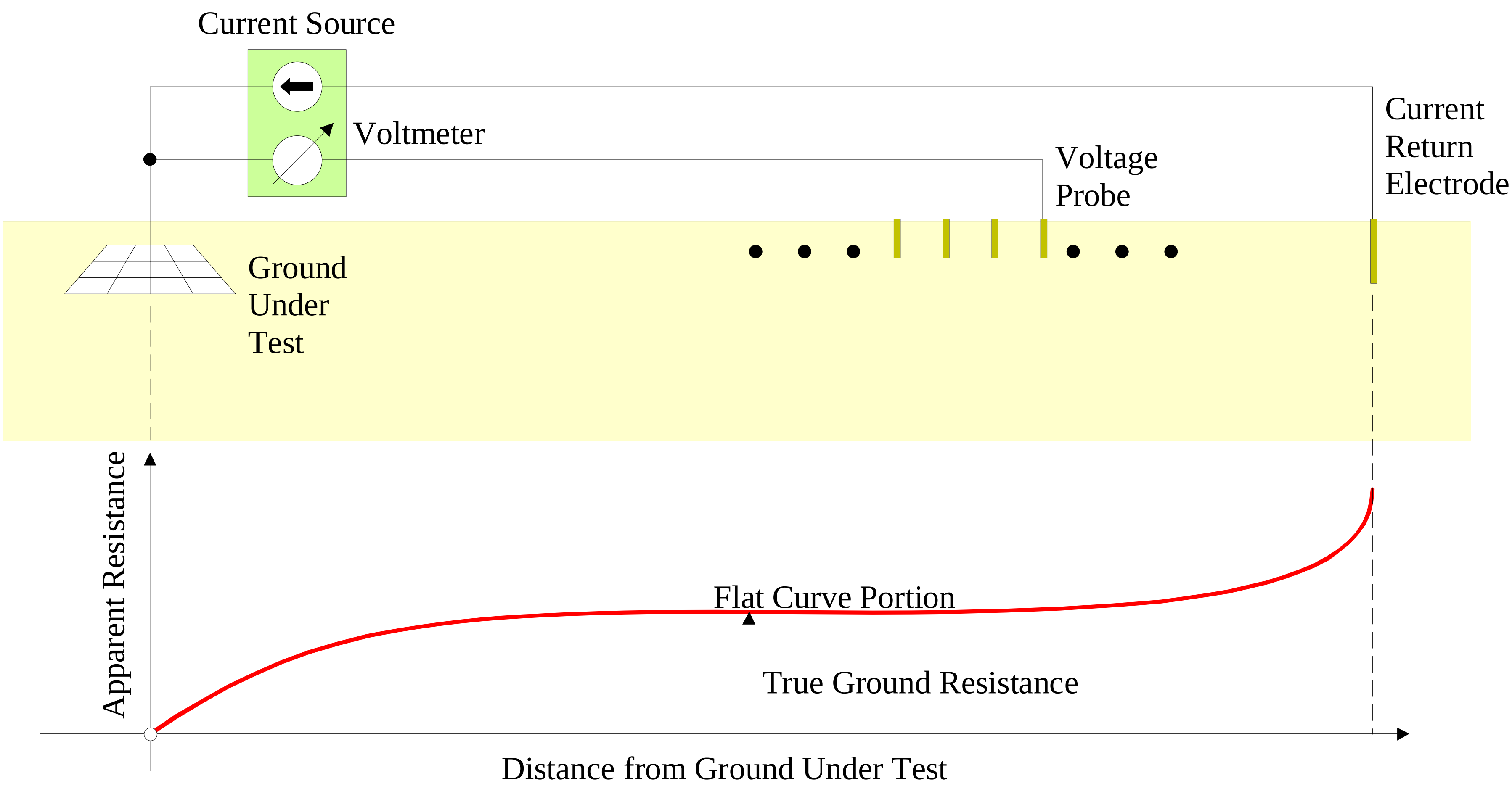




$$K = \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

Ground Impedance Measurements

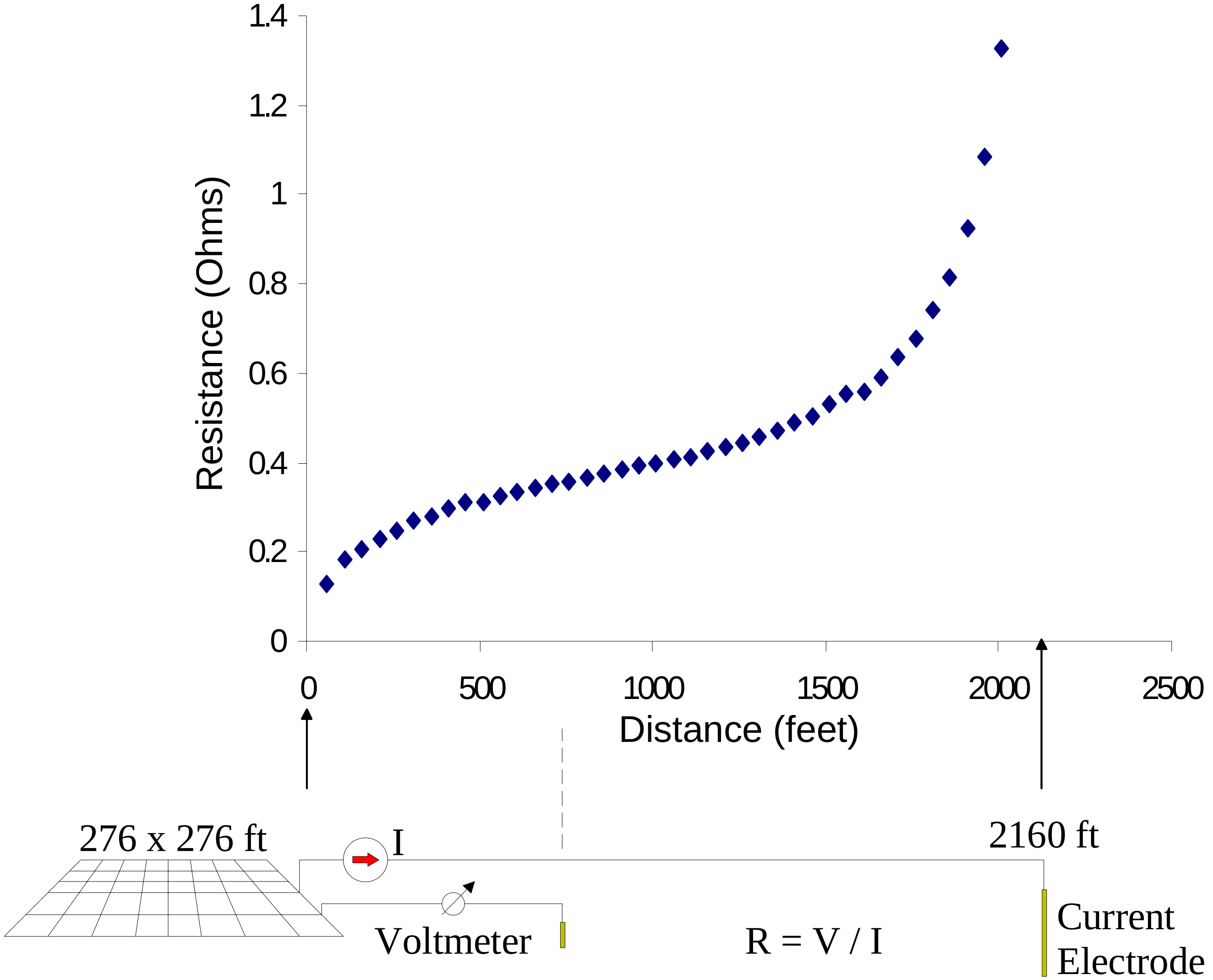
The Fall of Potential Method – Measurement Process THEORY



The Fall of Potential Method

Earth Voltage Distribution - Actual Measurements

Contributor: American Electric Power



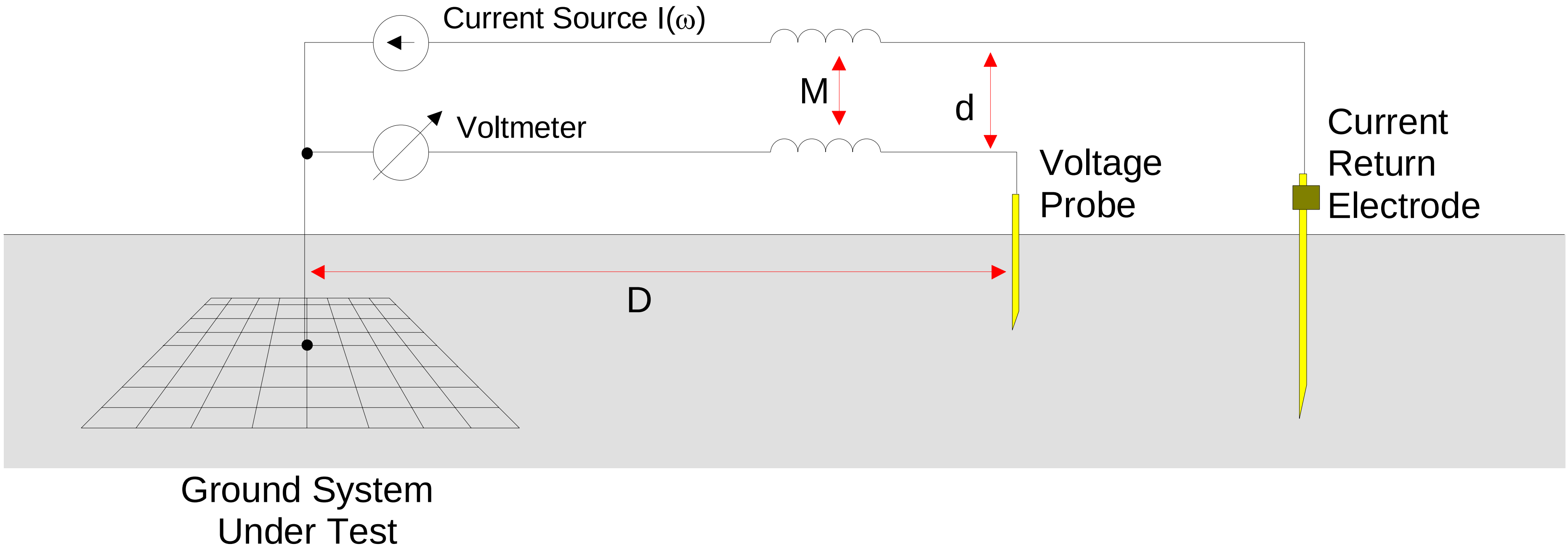
The Fall of Potential Method

Factors Affecting Ground Impedance Measurement

- Difficulty reaching true remote earth reference voltage
- Effect of Auxiliary Electrode Location (Earth Current Return)
- Size and location of voltage probes
- Interaction Between Instrumentation Wires
- Interference from Overhead Lines and their Grounding
- Background 60 Hz Voltage and Harmonics
- Ground Impedance Magnitude

Fall of Potential Method Errors

Interaction between Instrumentation Wires



$$M = l\frac{\mu_0}{2\pi}\ln\left(\frac{D_e}{d}\right)$$

where

$$D_e = 2160\sqrt{\rho / f}$$

(d,De in feet)

The Fall of Potential Method

Interaction between Instrumentation Wires

Induced Voltage Computation Example:

Length	500.00	feet
Current	1.00	Amperes
Rho	100.00	Ohm-meters
Frequency	90.00	Hz
d	10.00	feet
D_e	2276.84	feet
M	0.0001437	Henries
Voltage	**0.081**	**Volts**

Ground Mat Voltage: $$V = RI(\omega)$$

Induced Voltage on Lead: $$V_{md} = j\omega MI(\omega)$$

Measured Voltage: $$V_m = V + V_{ind}$$

Measured Impedance: $$Z_m = \frac{V_m}{I(\omega)}$$

Measurement Error: $$\frac{Z_m - R}{R} \times 100\%$$

The Fall of Potential Method

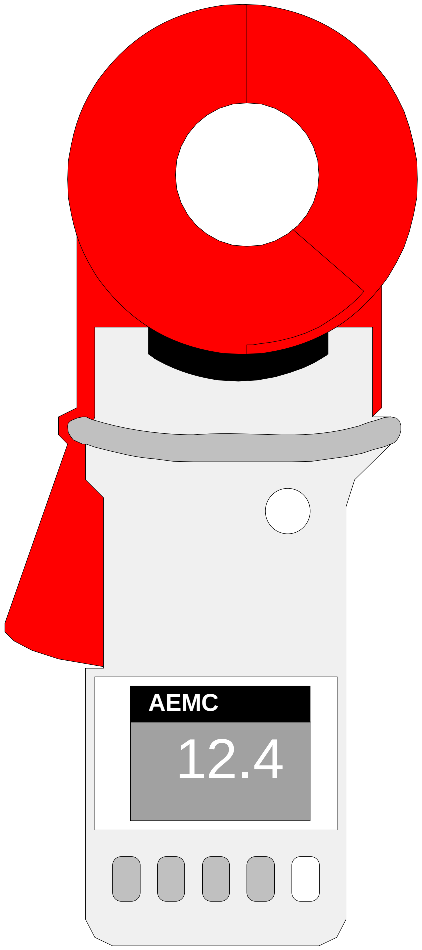
Interaction between Instrumentation Wires

Induced Voltage Computation Example:

Length	500.00	feet
Current	1.00	Amperes
Rho	100.00	Ohm-meters
Frequency	90.00	Hz
d	10.00	feet
D_e	2276.84	feet
M	0.0001437	Henries
Voltage	**0.081**	**Volts**

R	Magn. Error	Phase Error
10.0	0.006%	0.65 Deg
1.0	0.6%	6.49 Deg
0.1	51%	48.68 Deg

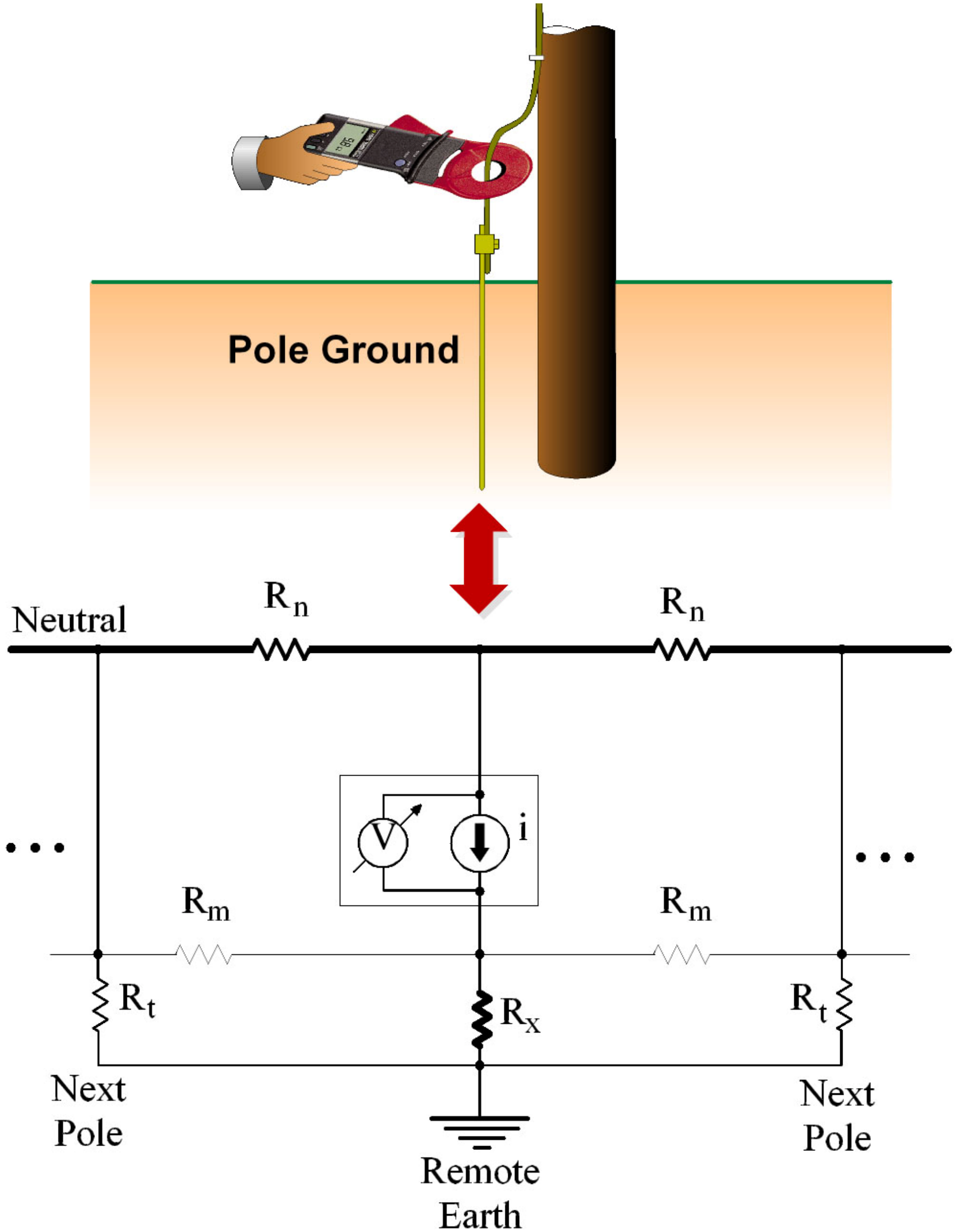
Driving Point Impedance Meters: Hand-Held Meters
Easy to Use But Limited Applications



AEMC

LEM GEO MODEL 15 - Ground Resistance Tester
Measurement Range: 0.025 ohms to 1500 ohms at 1.667 kHz

Hand-Held Meters



The Smart Ground Multimeter (SGM) Method: Model Based Measurement Instrument

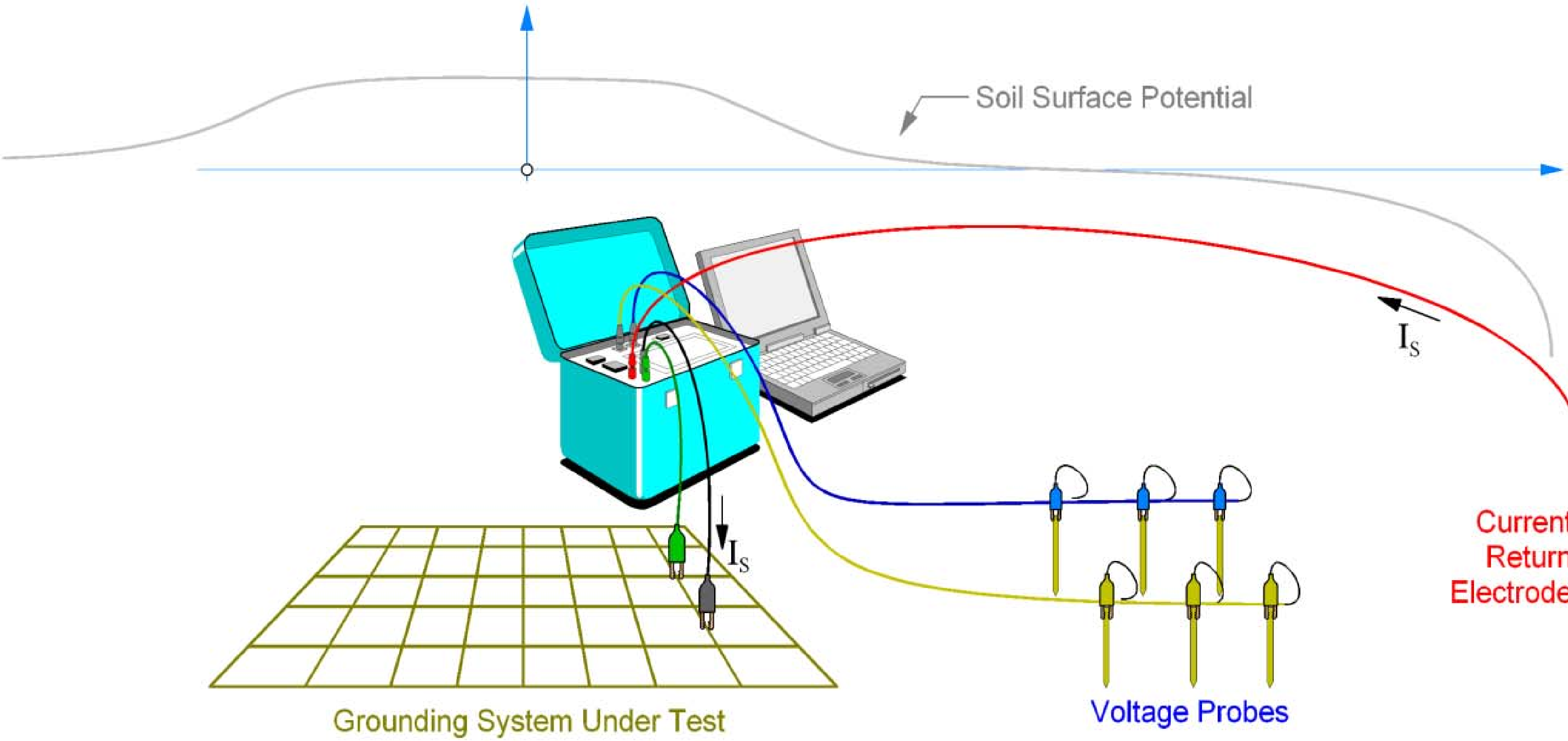
Presently Available Functions

User Selected 250V or 500V Internal Switchable Source

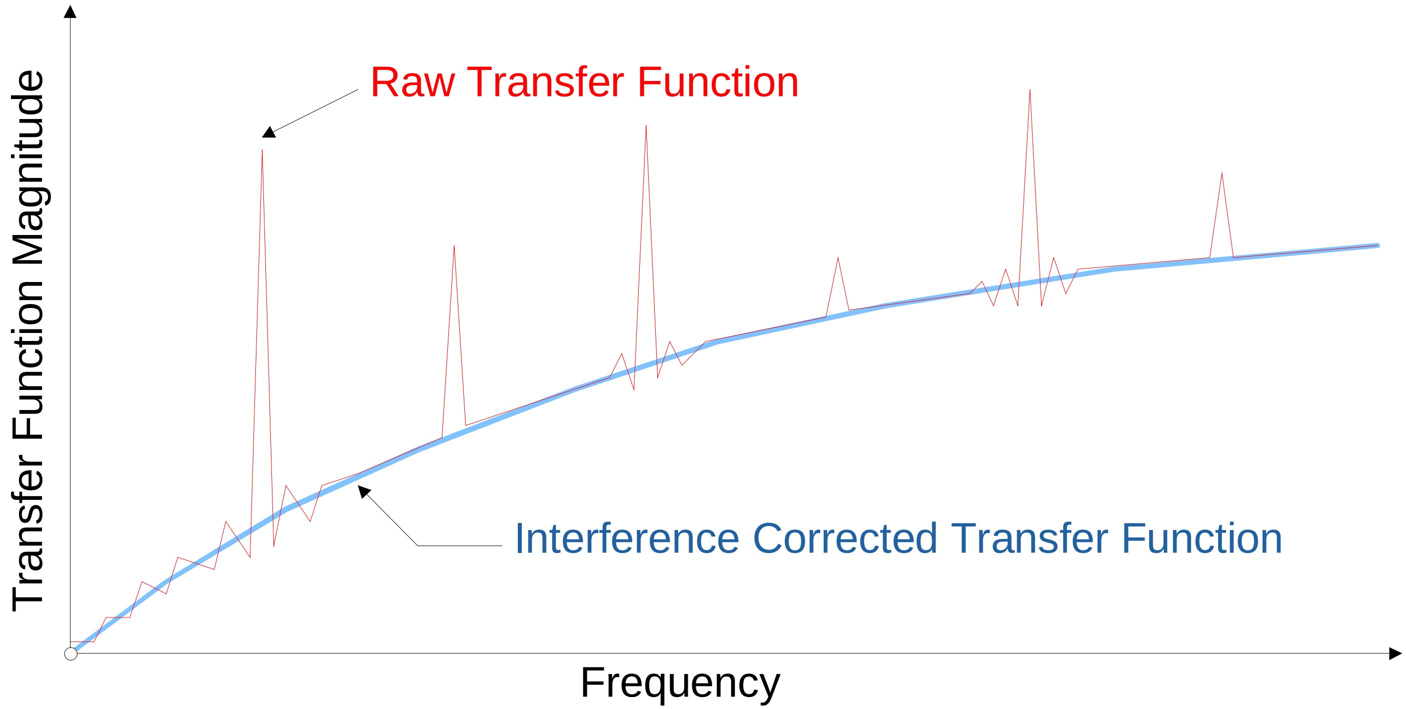
1. Ground (System) Impedance Meter
2. Touch Voltage Meter
3. Step Voltage Meter
4. Tower Ground Resistance Meter
5. Soil Resistivity Meter
6. Ground Mat Impedance
7. Transfer Voltage Meter
8. Low Impedance/Continuity Meter
9. Fall of Potential Method
10. Oscilloscopic Function
11. Pole Ground

Smart Ground Multimeter
Ground Impedance Function

Illustration of Probe Placement and SGM Connections



60 Hz and Harmonic Interference Correction

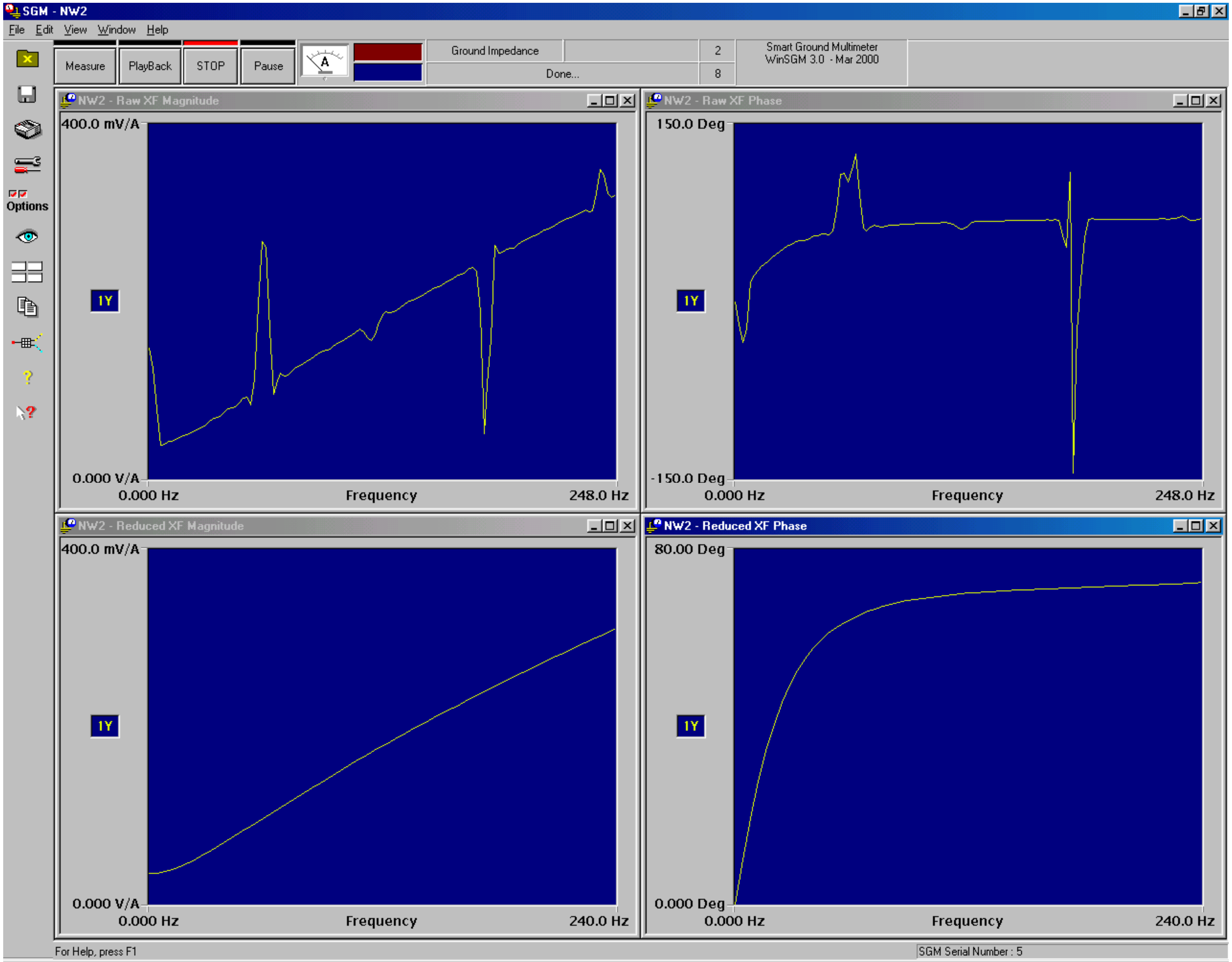


Correction Method: Based on quadratic rational transfer function fitting

Minimize: $$\sum_k W_k \left(\hat{H}(j\omega_k) - H(j\omega_k)\right)^2$$

where: $$\hat{H}(s) = a_0 + a_1 s + a_2 s^2$$ or $$\hat{H}(s) = \frac{a_0 + a_1 s + a_2 s^2}{b_0 + b_1 s + b_2 s^2}$$

60 Hz and Harmonic Interference Example



Grounding System Audit: Objectives

- Verify Design Values
- Verify Safety and Ground Potential Rise
- Verify Construction or Determine Ground Integrity
- Verify Lightning Performance
- Investigate Possible Points of Danger
- Evaluate Possible Ground Enhancements (Cost/Benefit Analysis)

Grounding System Audit: Procedure

Part 1: Testing

- Create a Facility Model (per drawings)
- Ground System Impedance Measurement
- Facility Ground Resistance Measurement
- Soil Resistivity Measurement
- Point-to-Point Ground Measurements
- Transfer Potential Measurement (as needed)
- Oscilloscopic View of GPR

Grounding System Audit: Procedure

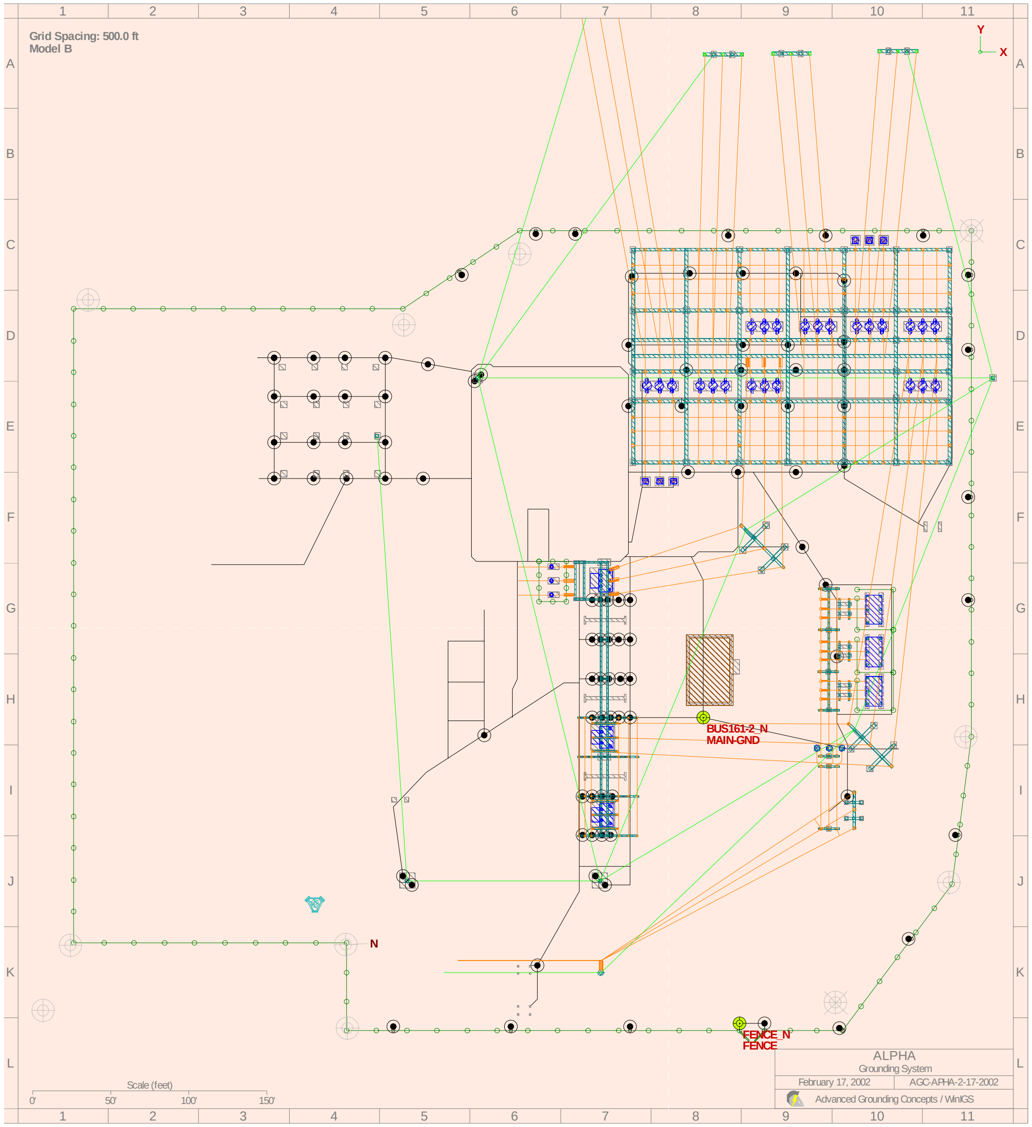
Part 2: Model Validation and Analysis

- Ground Model Validation (Compare Model to Measurements)
- Ground Conductor Size Adequacy Assessment
- Safety Assessment (IEEE Std 80 or IEC)
- Lightning Shielding Analysis and Risk Evaluation
- Evaluation of Remedial Measures (as needed)

Grounding System Audit – Testing
Detailed Grounding Model

Detailed Grounding Model (3D)

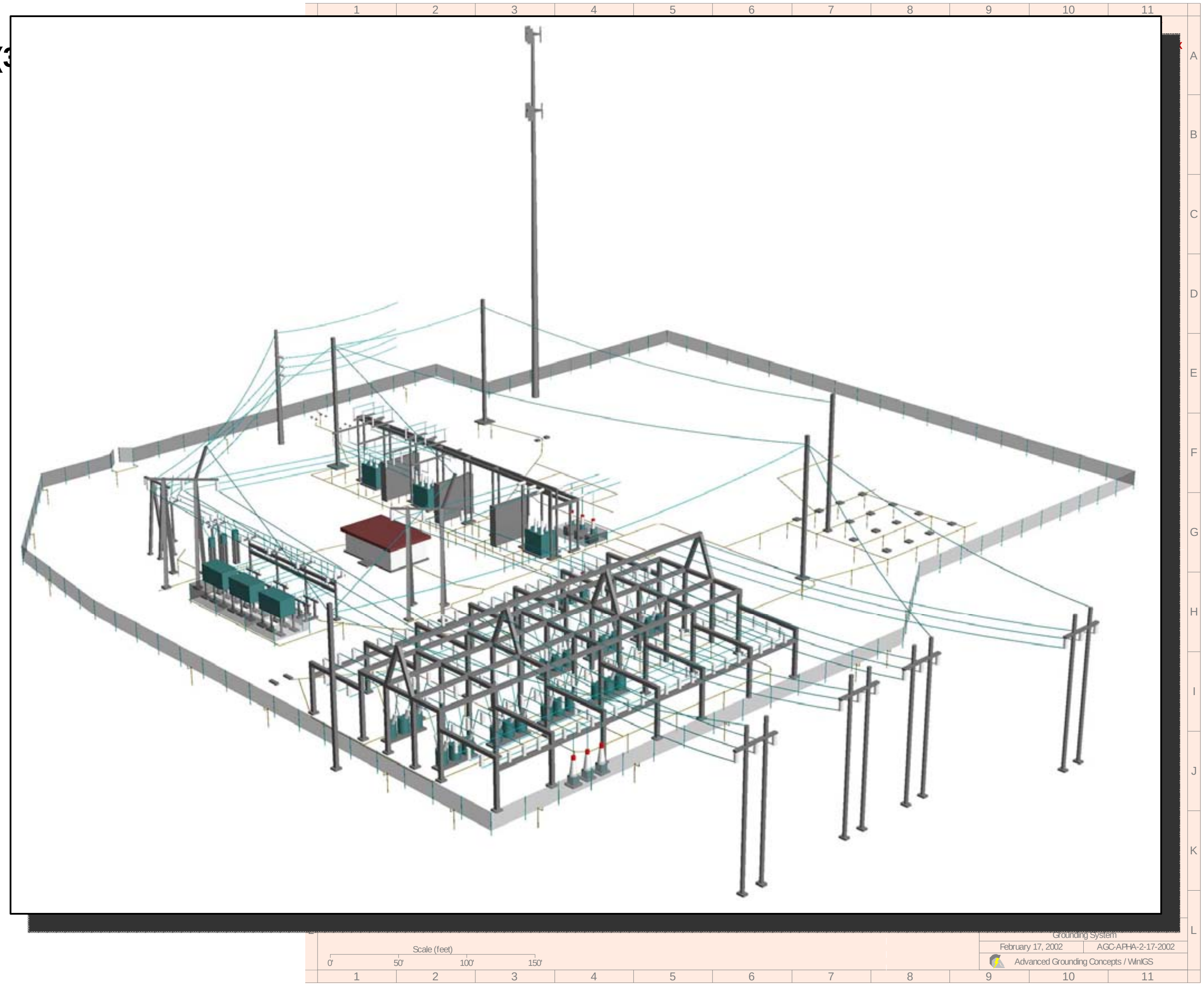
- •CAD Drawings
- •Top Views
- •Elevations
- •Photographs
- •On-Site Inspection



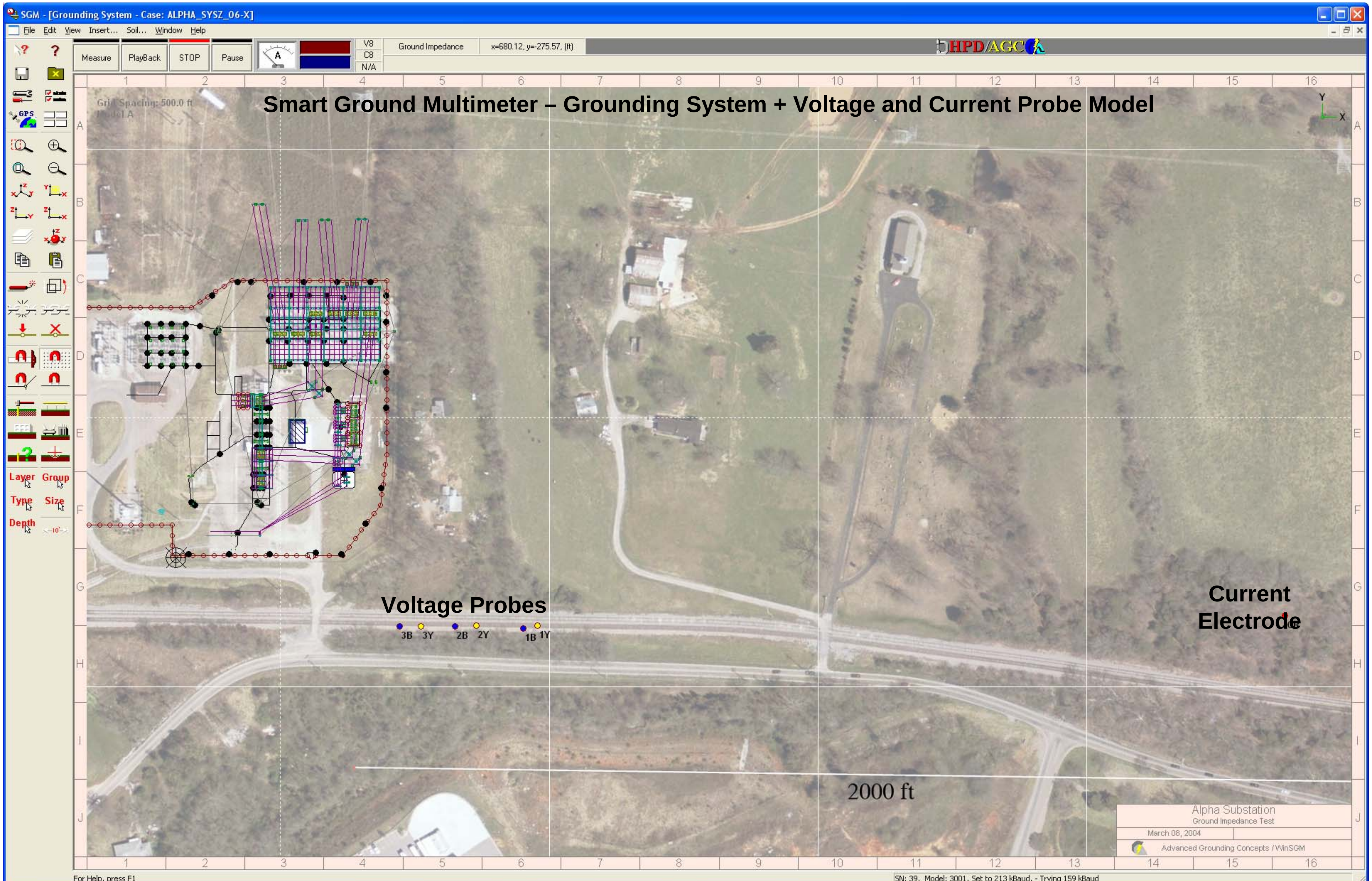
Grounding System Audit – Testing
Detailed Grounding Model

Detailed Grounding Model (3

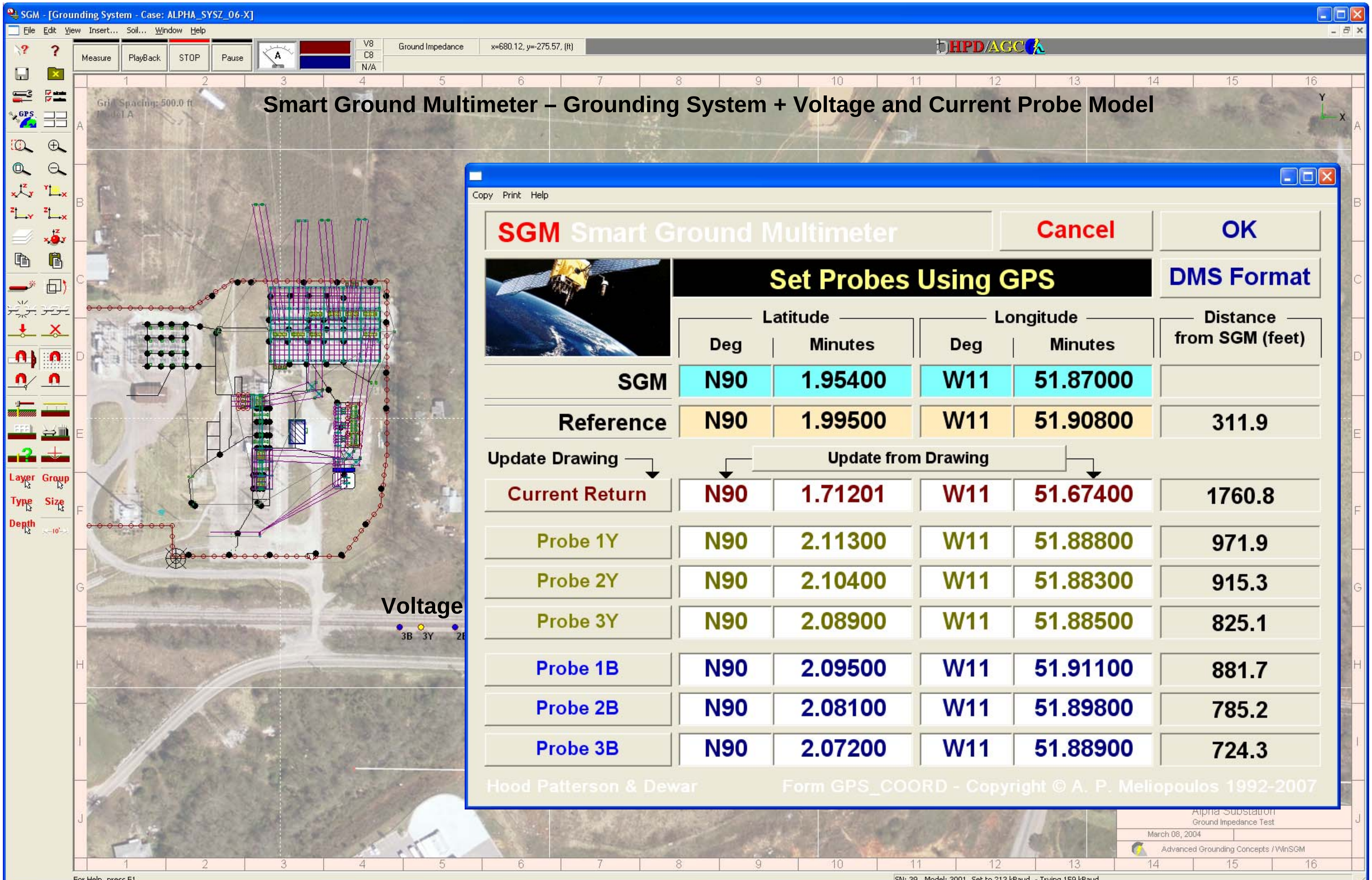
- CAD Drawings
- Top Views
- Elevations
- Photographs
- On-Site Inspection



Ground System Impedance Measurement



Ground System Impedance Measurement



	Latitude		Longitude		Distance from SGM (feet)
	Deg	Minutes	Deg	Minutes	
SGM	N90	1.95400	W11	51.87000	
Reference	N90	1.99500	W11	51.90800	311.9
Current Return	N90	1.71201	W11	51.67400	1760.8
Probe 1Y	N90	2.11300	W11	51.88800	971.9
Probe 2Y	N90	2.10400	W11	51.88300	915.3
Probe 3Y	N90	2.08900	W11	51.88500	825.1
Probe 1B	N90	2.09500	W11	51.91100	881.7
Probe 2B	N90	2.08100	W11	51.89800	785.2
Probe 3B	N90	2.07200	W11	51.88900	724.3

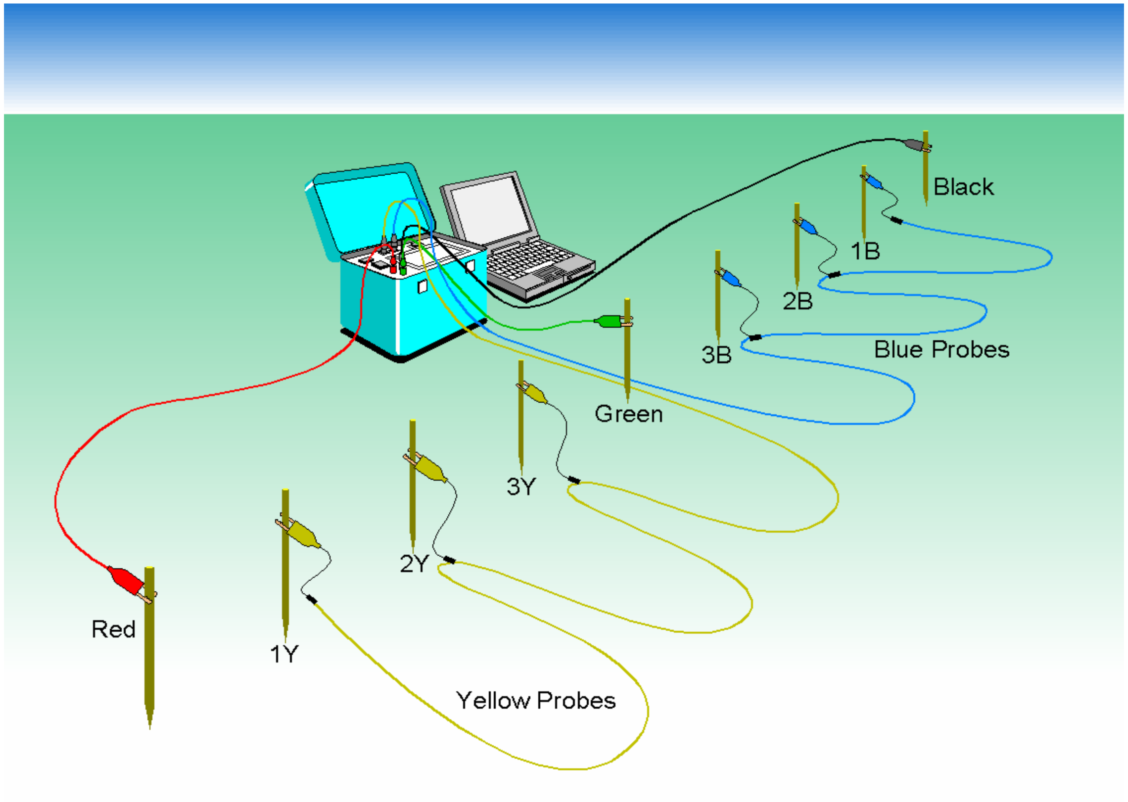
Grounding System Audit – Testing Soil Resistivity Measurement

Smart Ground Multimeter

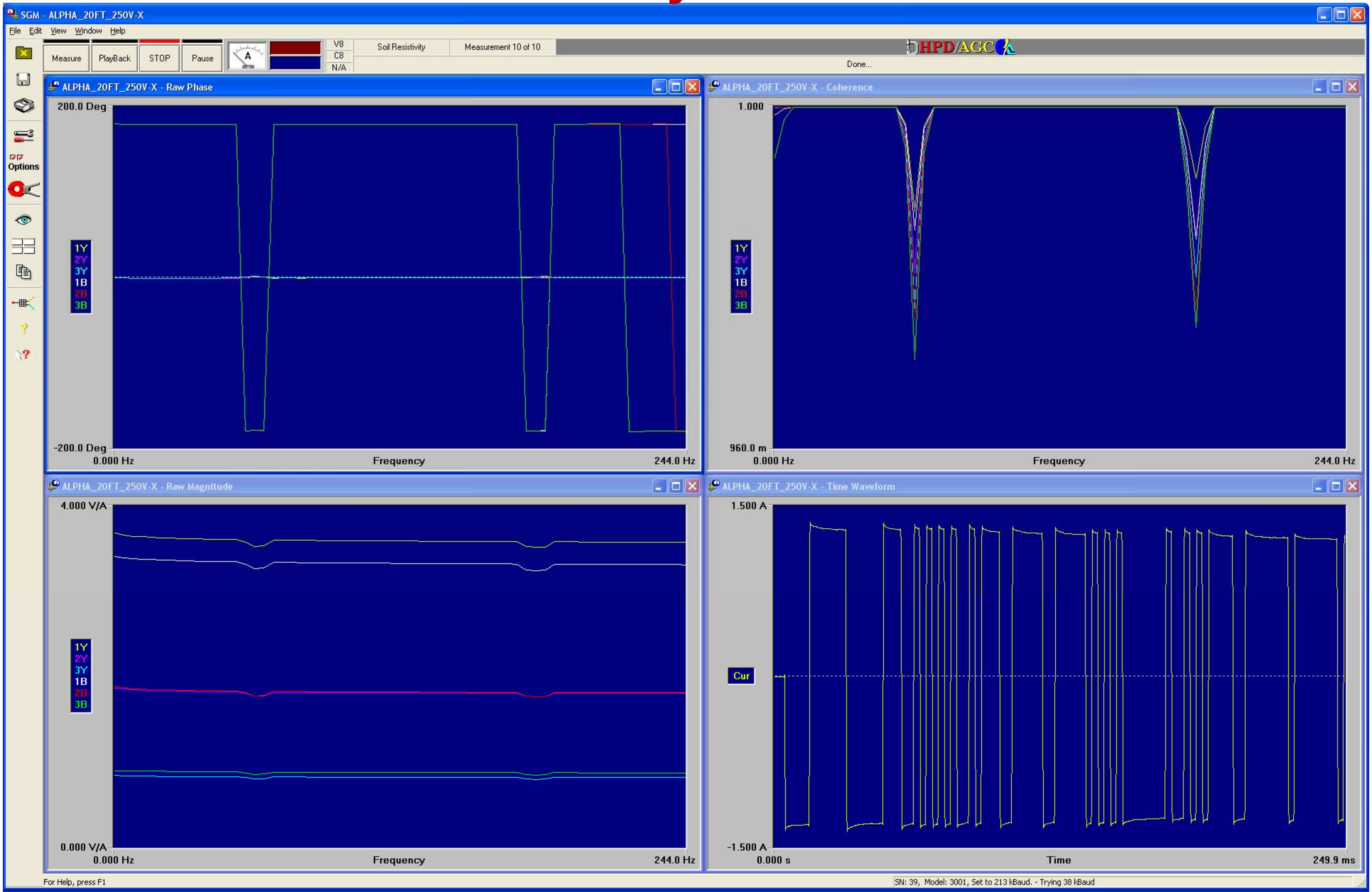
•Based on extension of the four pin method

•Measures ground potential differences between six voltage

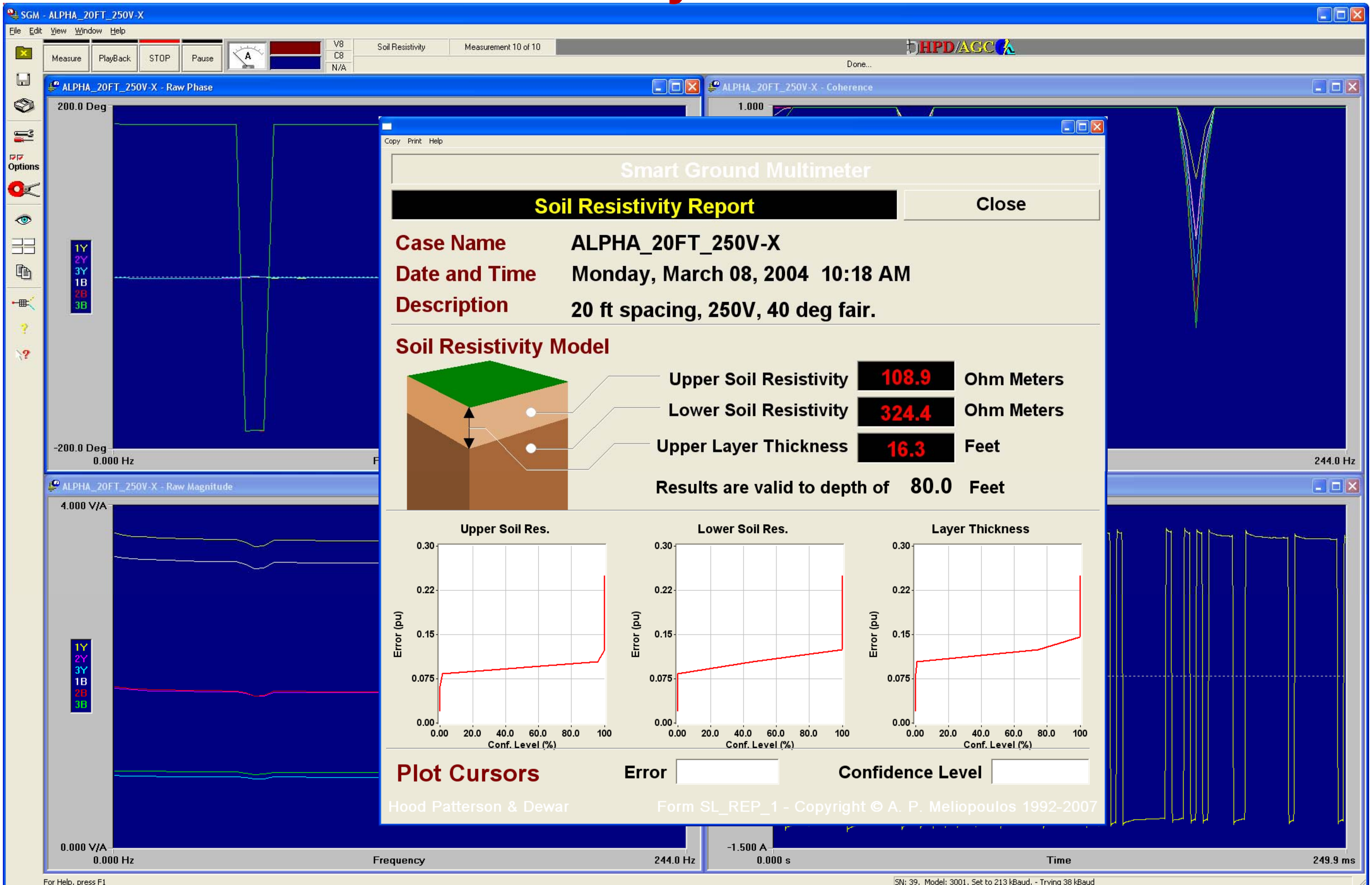
- Uses estimation based analysis to fit the measurements to the measurement system model
- Provides Measurement Interpretation (Two Layer Model)



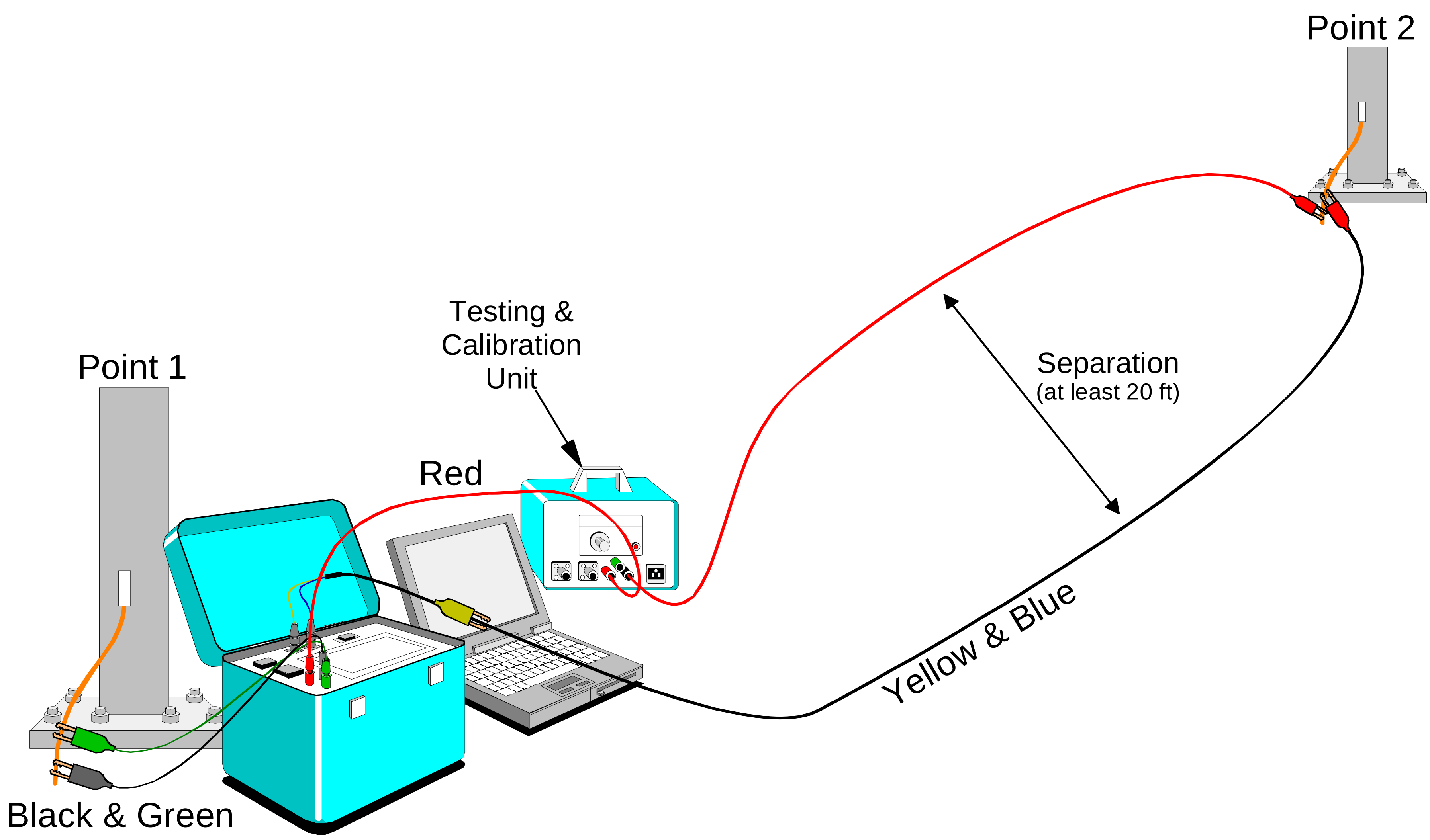
Soil Resistivity Measurement



Soil Resistivity Measurement



Grounding System Audit – Testing Point-to-Point Ground Measurements



Grounding System Audit – Testing Point-to-Point Ground Measurements

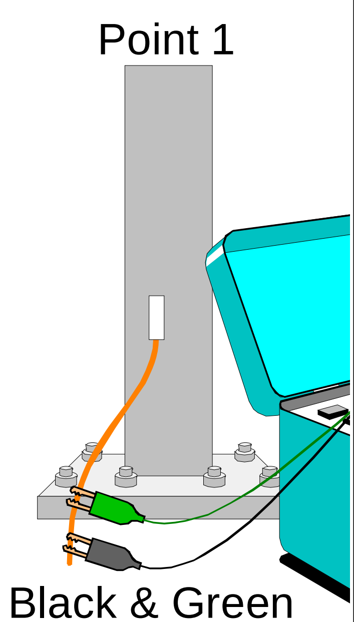


Fig #	Test Point Locations	Computed Resistance (mΩ)	Measured Resistance (mΩ)	Measured Reactance (mΩ)
D3	13 kV transformer to fence gate ground (points K01-K02)	**1315**	**433.2**	**437.1**
D4	13 kV transformer to fence pig-tail ground	**1315**	**437.2**	**442.0**
D5	13 kV transformer to TVA XFRM 2 (points K01-K03)	8.41	6.535	15.09
D6	Control House to Fence - Southeast Corner (points K04-K05)	**1166.4**	**1619.2**	**1620.0**
D7	Control House to Nixon Line PT - Phase C (points K04-K06)	6.77	8.704	15.18
D10	Control House to 161 kV Breaker #988 (points K04-K07)	7.29	8.196	15.28
D13	Control House to Breaker #968 (points K04-K08)	6.31	8.279	15.31
D17	Control House to Breaker #934 (points K04-K10)	7.71	8.209	14.08
D20	Control House to 161 kV Instrument PT - Phase B (points K04-K11)	6.87	8.475	14.50
D22	Control House to Breaker #954 (points K04-K09)	5.98	8.587	15.79
D26	Control House to Capacitor Bank Fence (points K04-K15)	**5.70**	**117.9**	**130.6**
D29	Control House to Capacitor Bank Sectionalizer Switch 2 Ground (points K04-K16)	9.48	12.99	33.36
D30	Control House to Capacitor Bank Sectionalizer Switch 3 Ground (points K04-K17)	12.21	13.21	34.51