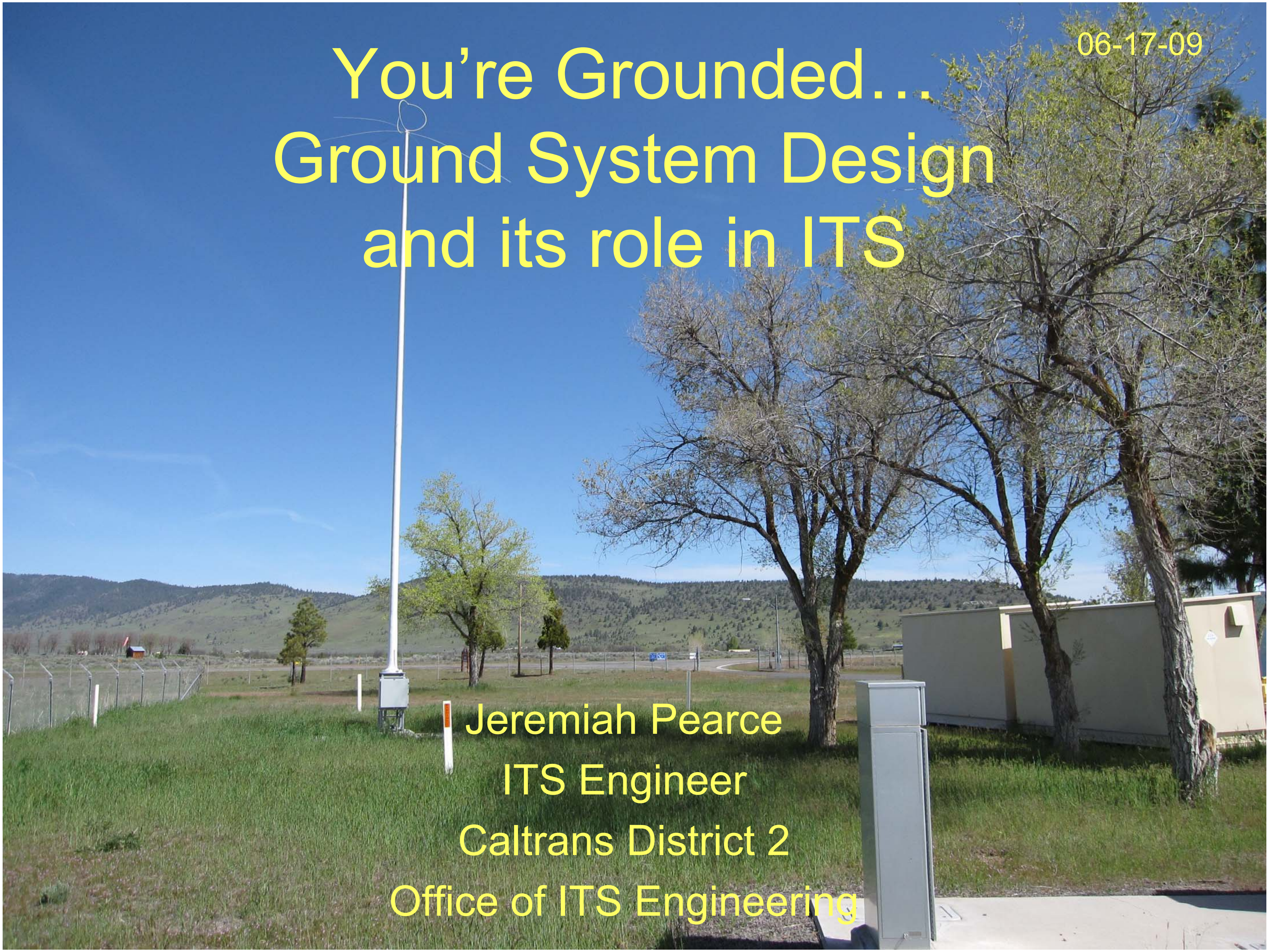
06-17-09
You’re Grounded…
Ground System Design
and its role in ITS
Jeremiah Pearce
ITS Engineer
Caltrans District 2
Office of ITS Engineering

Problem statement

Our grounding problems came from two different directions

1. Corning Highway Advisory Radio (HAR)

   Signal quality sounds poor, issues with ground during construction

2. Bass Mountain – Mountain top communication site

   Insufficient design, did not meet testing specification

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How is grounding applicable?
How does it work?
What can we do to fix it?

Why Ground?

Why Ground?

- Safety

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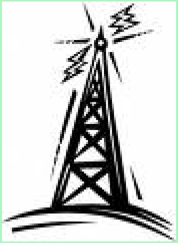
- Signal



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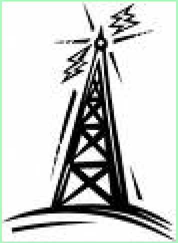

- Lightning Protection

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- Required for all industry by the National Fire Protection Association (NFPA) Article 70, also known as the National Electric Code (NEC)

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- Occupational Safety and Health Administration (OSHA) requires ground systems for occupational safety
- Good practice, can save lives

Signal Ground

- Highway Advisory Radio (HAR) systems

Lightning Protection

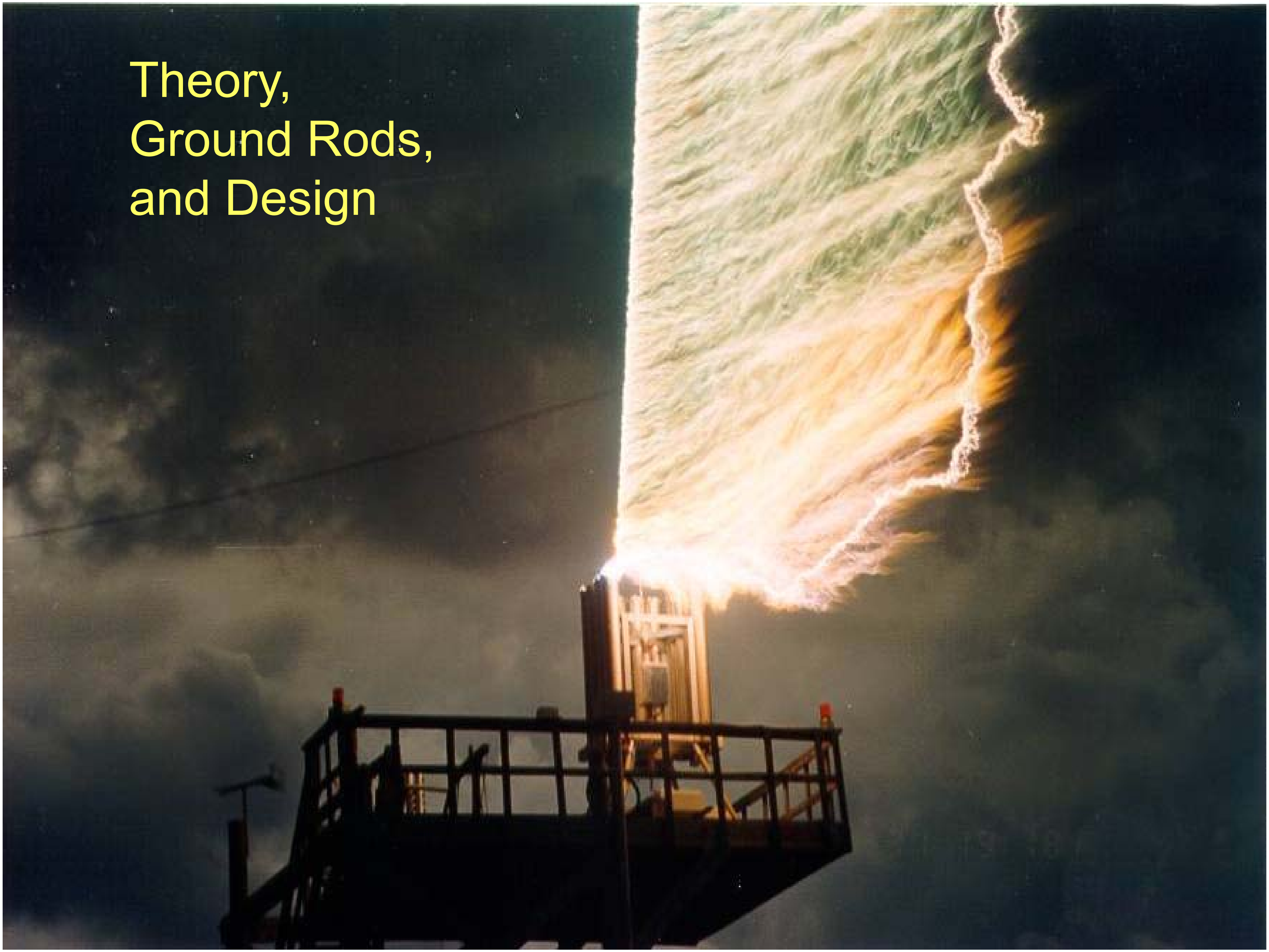
- Mountain top communication sites

Lightning Protection

- Mountain top communication sites
- RWIS towers

Lightning Protection

- Mountain top communication sites
- RWIS towers
- CCTV poles


Theory,
Ground Rods,
and Design

Ground Rod Theory

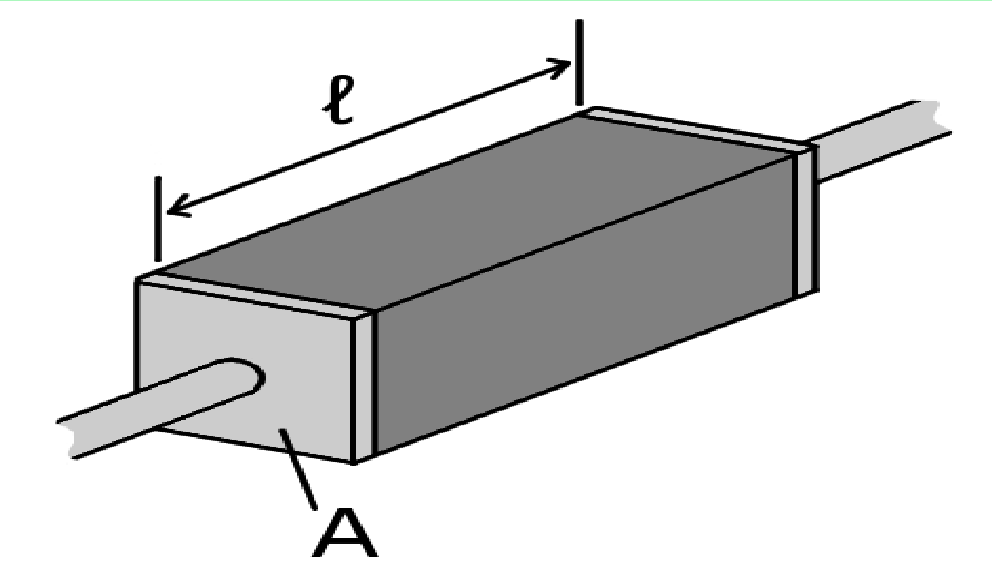
Resistance and Resistivity

Resistance, $R = \rho(L/A)$ (Ω)

ρ = Resistivity (Ω-m)

L = Length of conducting path (m)

A = Cross sectional area of conductor (m^2)



Ground Rod Theory

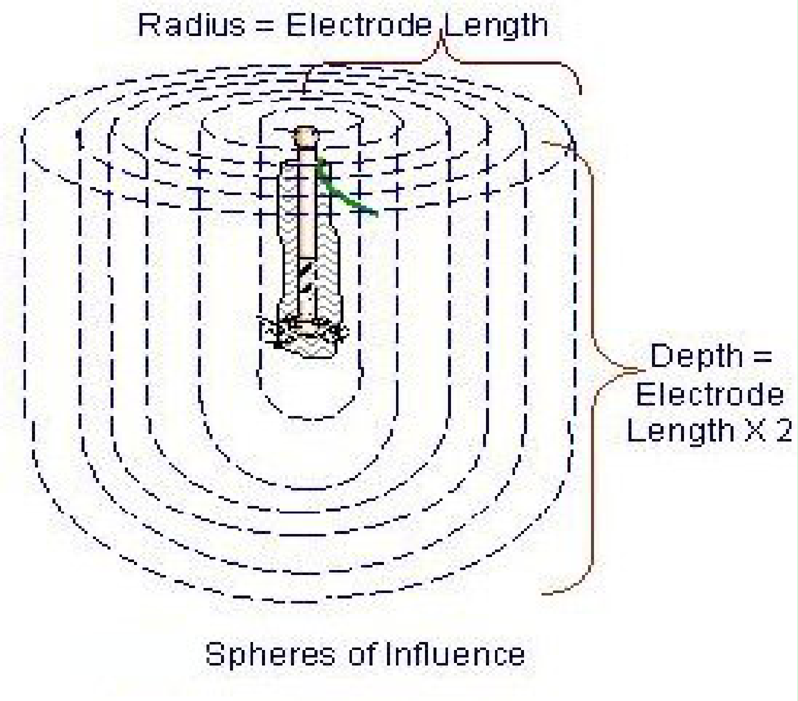
Accepted model – Concentric earth shells

Resistance of Earth, $R = \rho(L/A)$ (Ω)

ρ = Resistivity of soil (Ω-m)

L = Thickness of shell (m)

A = Surface area of shell (m^2)



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  $$R = (\rho/(2\pi L))\ \{(\ln 4L)-1\}/r\ (\Omega)$$

  L=electrode length (m)

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L=electrode length (m)

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- Multiple Rod systems much more complex geometry and require computer models and/or approximations

Soil Resistivity

- Important Consideration for ground system design

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Resistivity (approx), Ohm-centimeters			
SOIL	MINIMUM	AVERAGE	MAXIMUM
Ashes, cinders, brine, waste	590	2370	7000
Clay, shale, gumbo, loam	340	4060	16,300
Same, with varying proportions of sand and gravel	1020	15,800	135,000
Gravel, sand, stones with little clay or loam	59,000	94,000	458,000

Soil Resistivity

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- Several factors affect soil resistivity
  i. Soil type
  ii. Moisture content (and humidity)

Moisture content % by weight	Resistivity (Ohm-centimeters)	
	TOP SOIL	SANDY LOAM
0	$>10^9$	$>10^9$
2.5	250,000	150,000
5	165,000	43,000
10	53,000	18,500
15	19,000	10,500
20	12,000	6300
30	6400	4200

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  iii. pH of soil

THE EFFECT OF SALT* CONTENT ON THE RESISTIVITY OF SOIL (Sandy loam, Moisture content, 15% by weight, Temperature, 17°C)	
Added Salt (% By weight of moisture)	Resistivity (Ohm-centimeters)
0	10,700
0.1	1800
1.0	460
5	190
10	130
20	100

THE EFFECT OF TEMPERATURE ON THE RESISTIVITY OF SOIL CONTAINING SALT (Sandy loam, 20% moisture, Salt 5% of weight of moisture)	
Temperature C	Resistivity (Ohm-centimeters)
20	110
10	142
1.00	190
-5	312
-13	1440

Soil Resistivity

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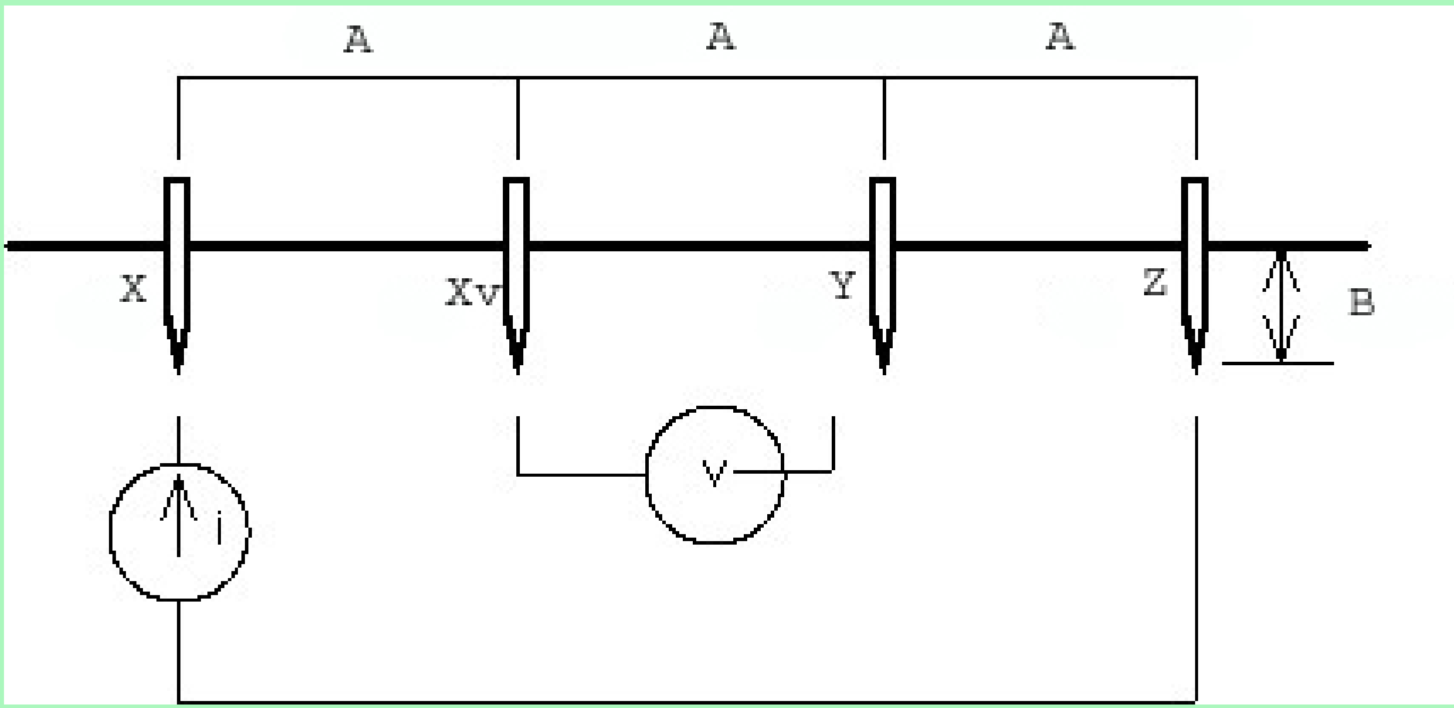
- Several factors affect soil resistivity
  i. Soil type
  ii. Moisture content
  iii. pH of soil
  iv. temperature

Temperature C	F	Resistivity (Ohm-centimeters)
20	68	7,200
10	50	9,900
0	32 (water)	13,800
0	32 (ice)	30,000
-5	23	79,000
-15	14	330,000

Measuring Resistivity

- Four-Point Wenner method



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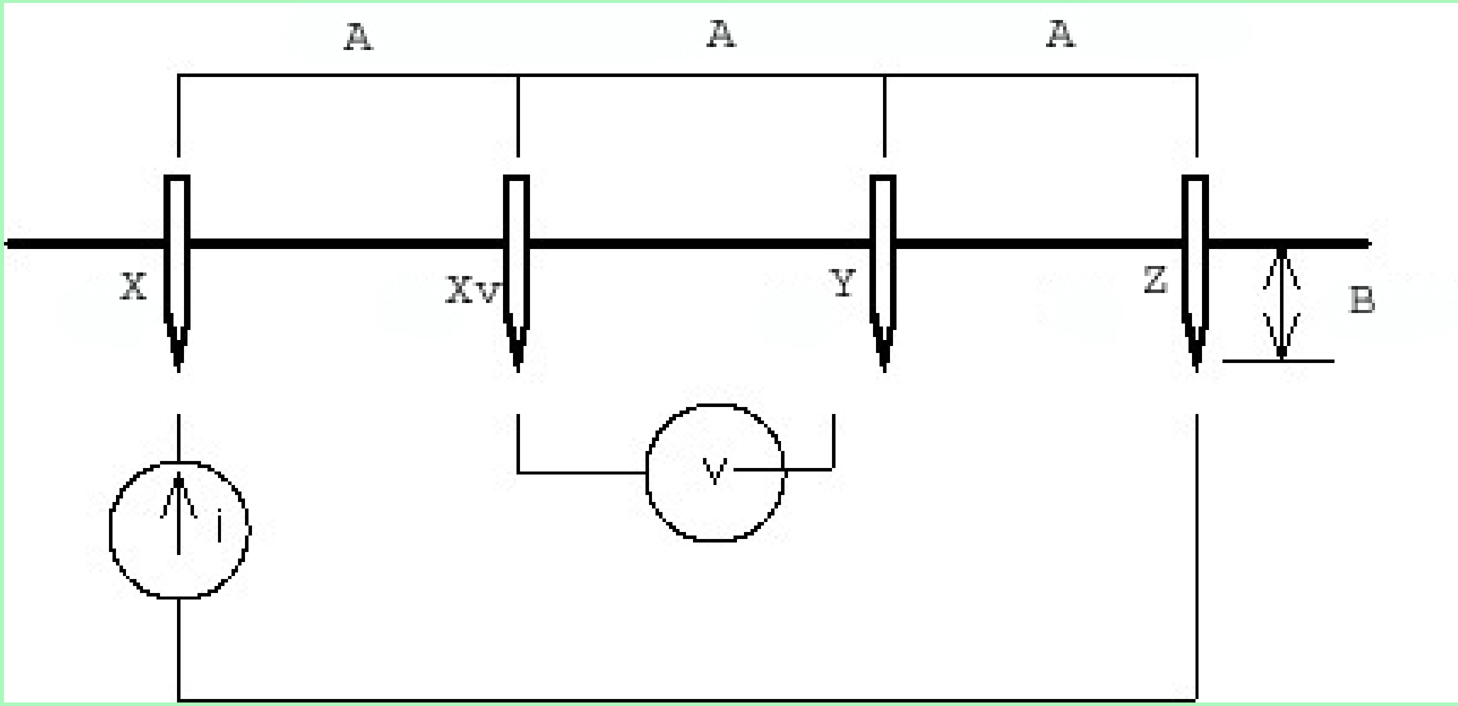

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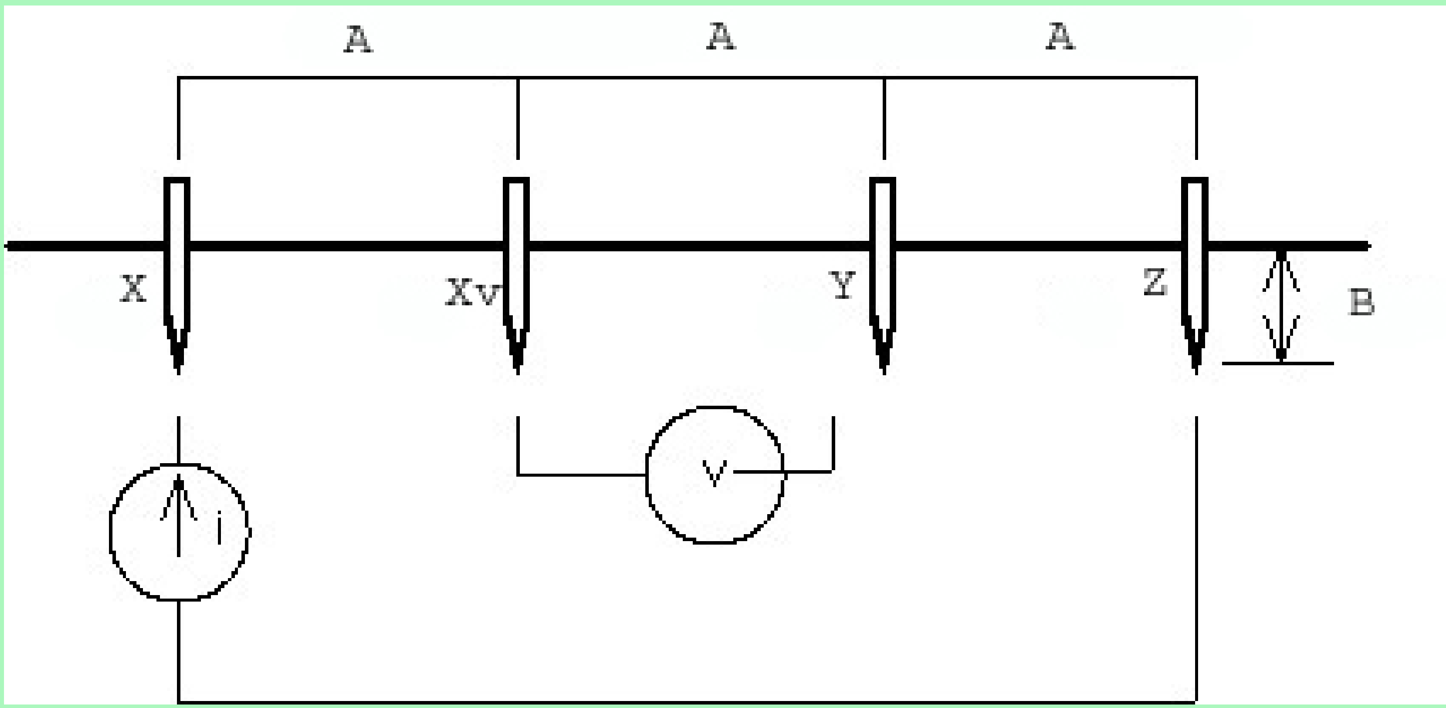
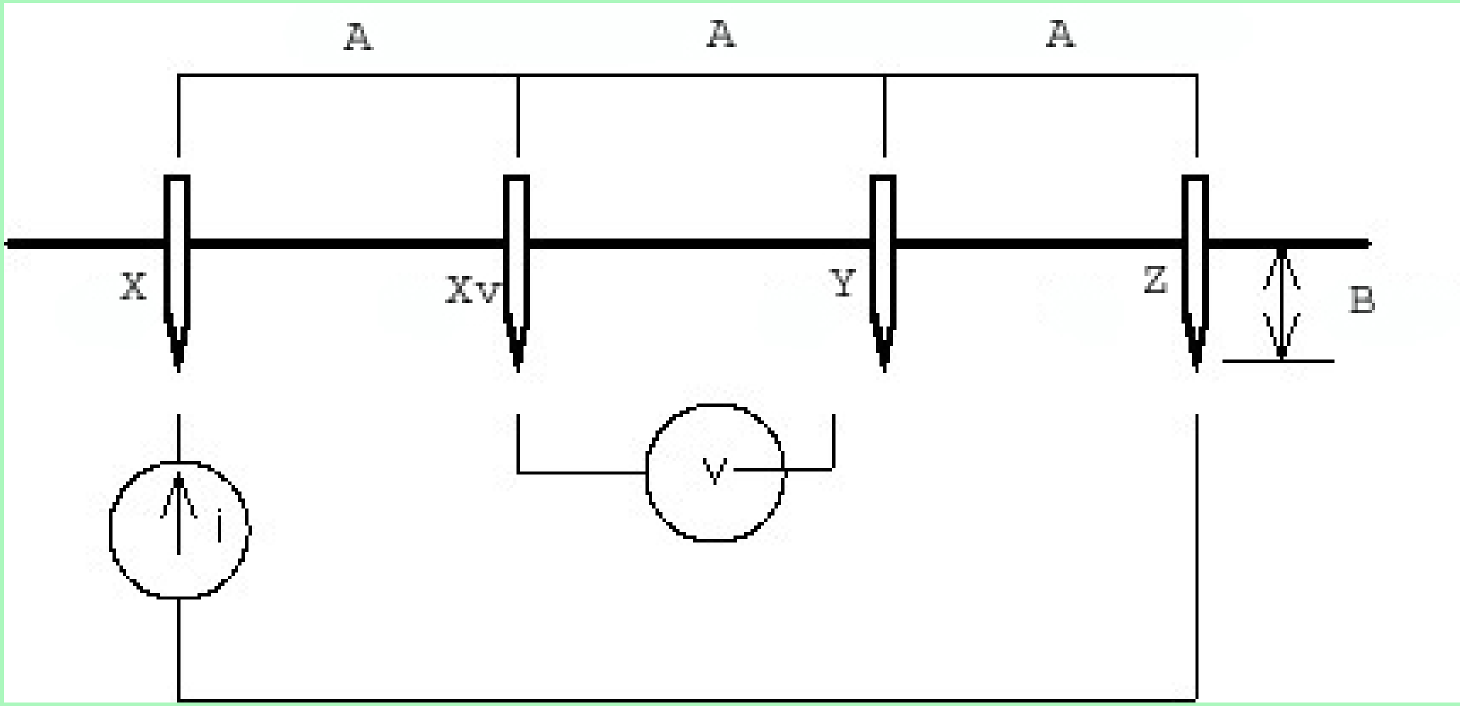
- Current passed between outermost electrodes
- Potential drop measured between inner electrodes



Measuring Resistivity

- Four-Point Wenner method
- Current passed between outermost electrodes
- Potential drop measured between inner electrodes
- Instrument calculates resistance



Measuring resistivity

- Convert to resistivity using the following formula

$$\rho = \frac{4\pi AR}{1 + \frac{2A}{\sqrt{A^2 + 4B^2}} - \frac{2A}{\sqrt{4A^2 + 4B^2}}}$$

where: A = distance between the electrodes in centimeters

B = electrode depth in centimeters

if A > 20B, the formula becomes:

$\rho = 2\pi AR$ (with A in cm) Ω-cm

$\rho = 191.5AR$ (with A in ft) Ω-cm


Resistivity Testing Setup
Redding HAR

Measuring Resistivity

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- Field measurements better indicator than soil sample

More on Resistivity

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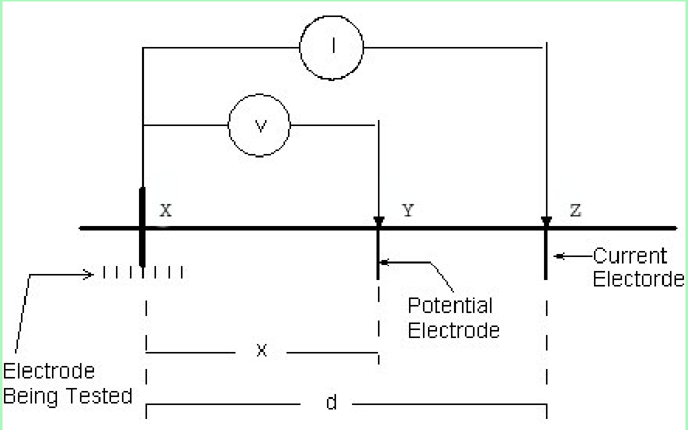
- Rods can lose more charge in top 5-10 feet of ground rod due to eddy currents

Measuring Resistance

- Three-Point fall-to-potential method



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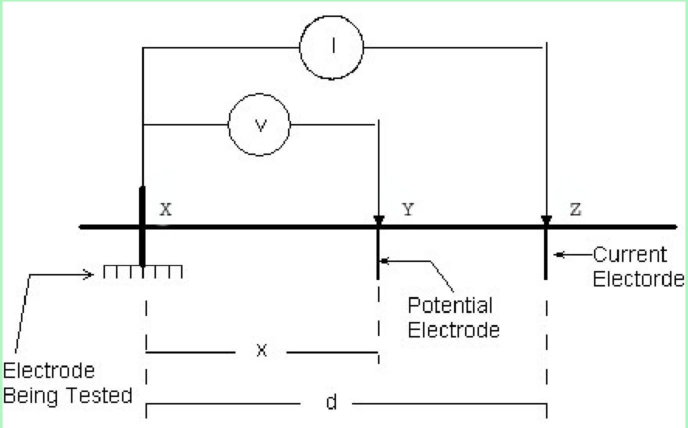

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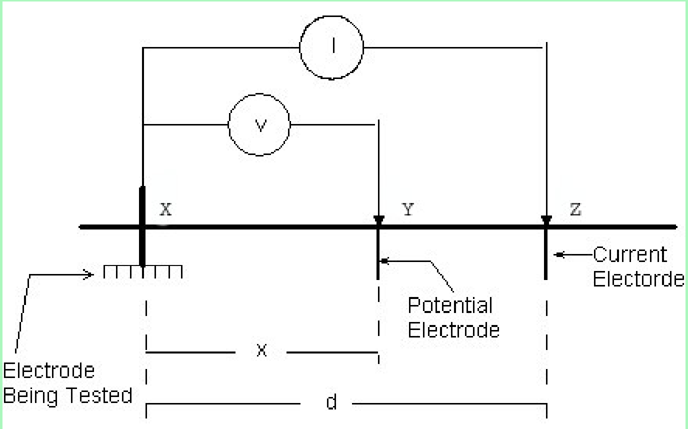

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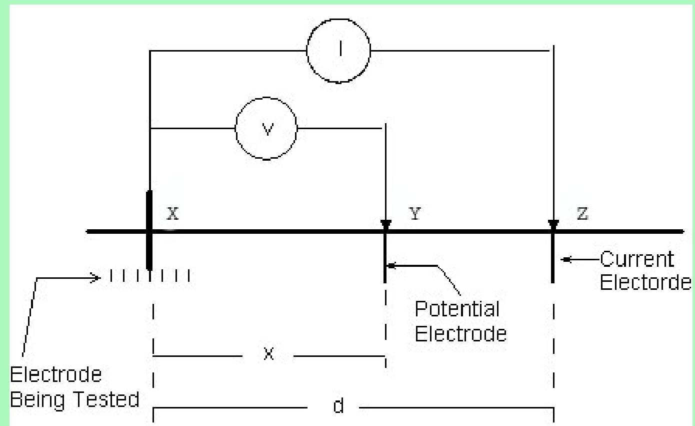

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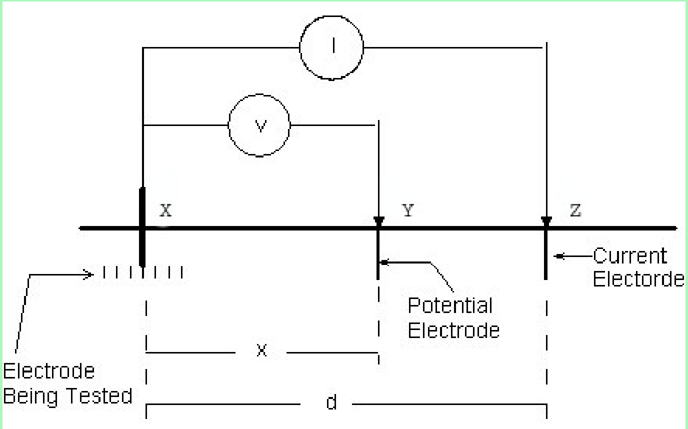

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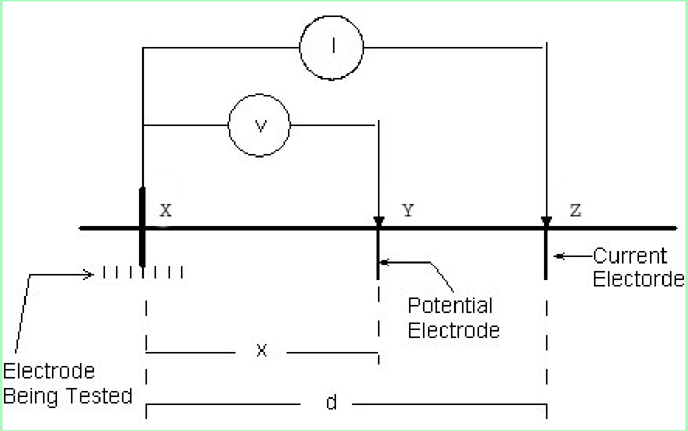
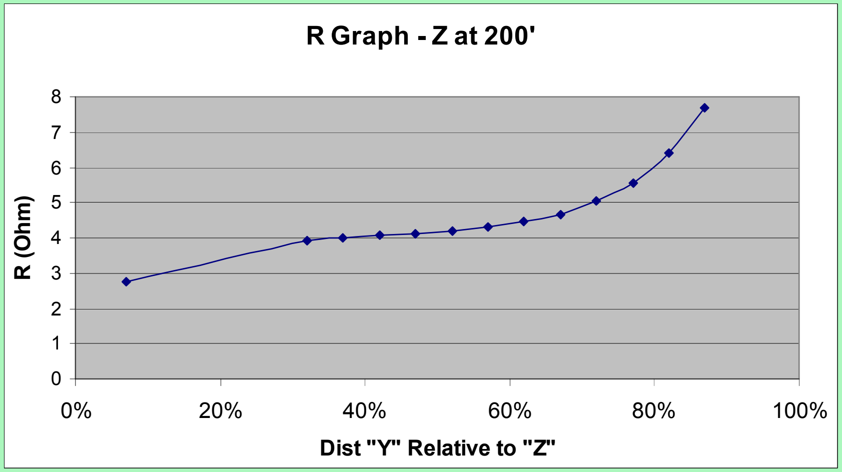
- Electrode y at 62% good indicator of ground resistance






Resistance test setup…
It can get messy

Measuring Resistance

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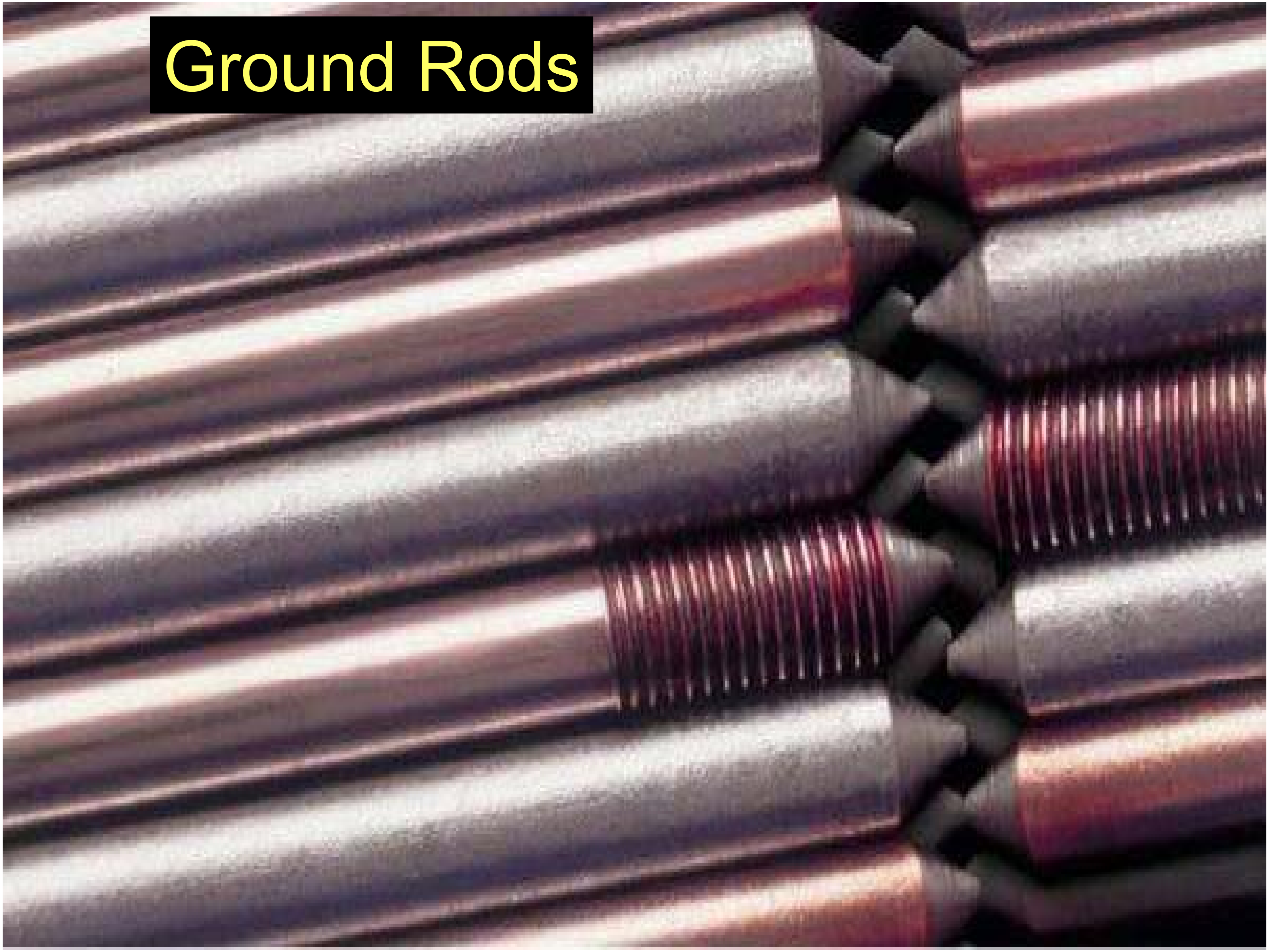
- Instrument can be touchy in highly resistive soil, troubleshooting guide can be useful

Ground Rods



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Electrolytic Ground Rods

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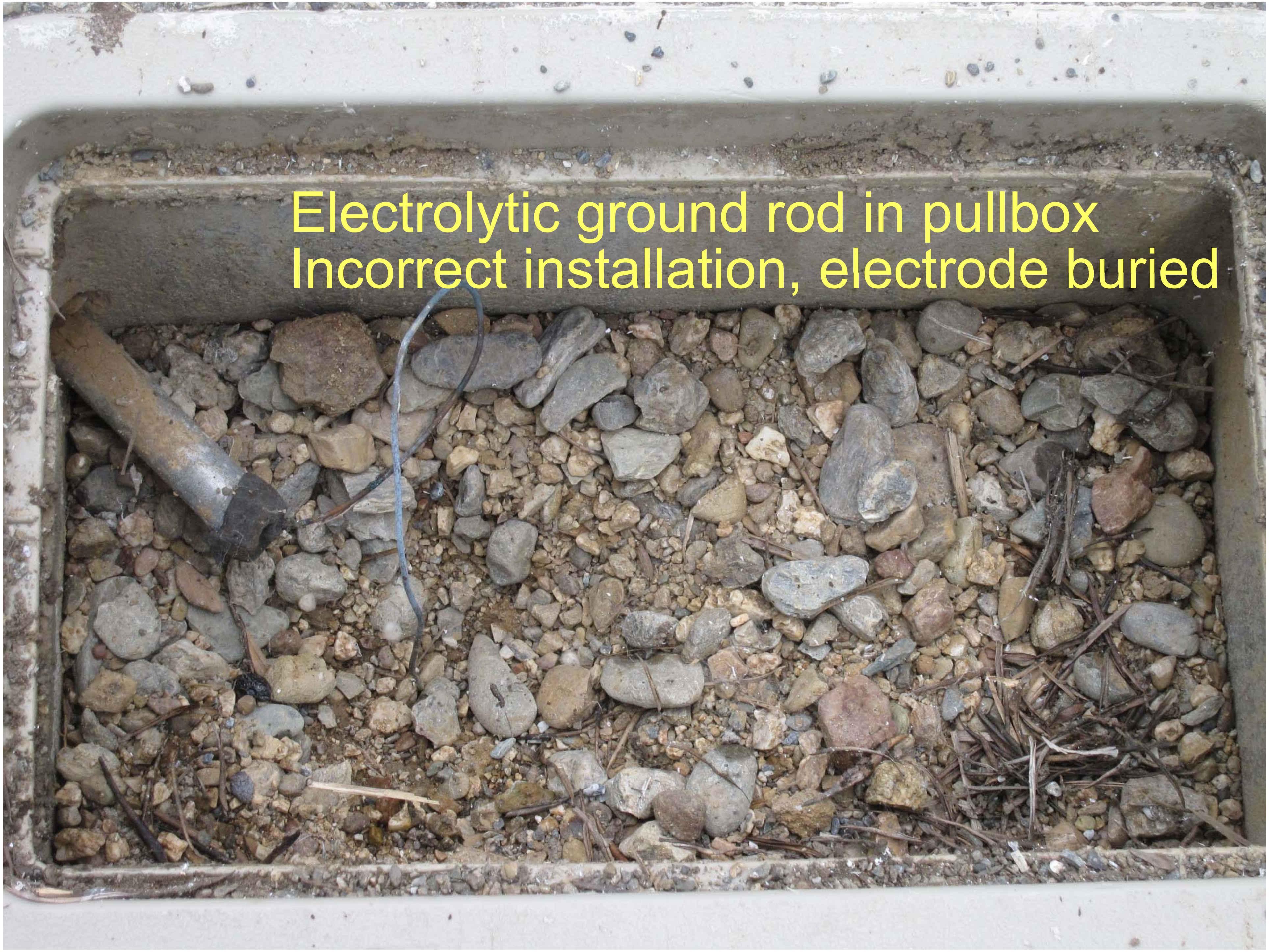
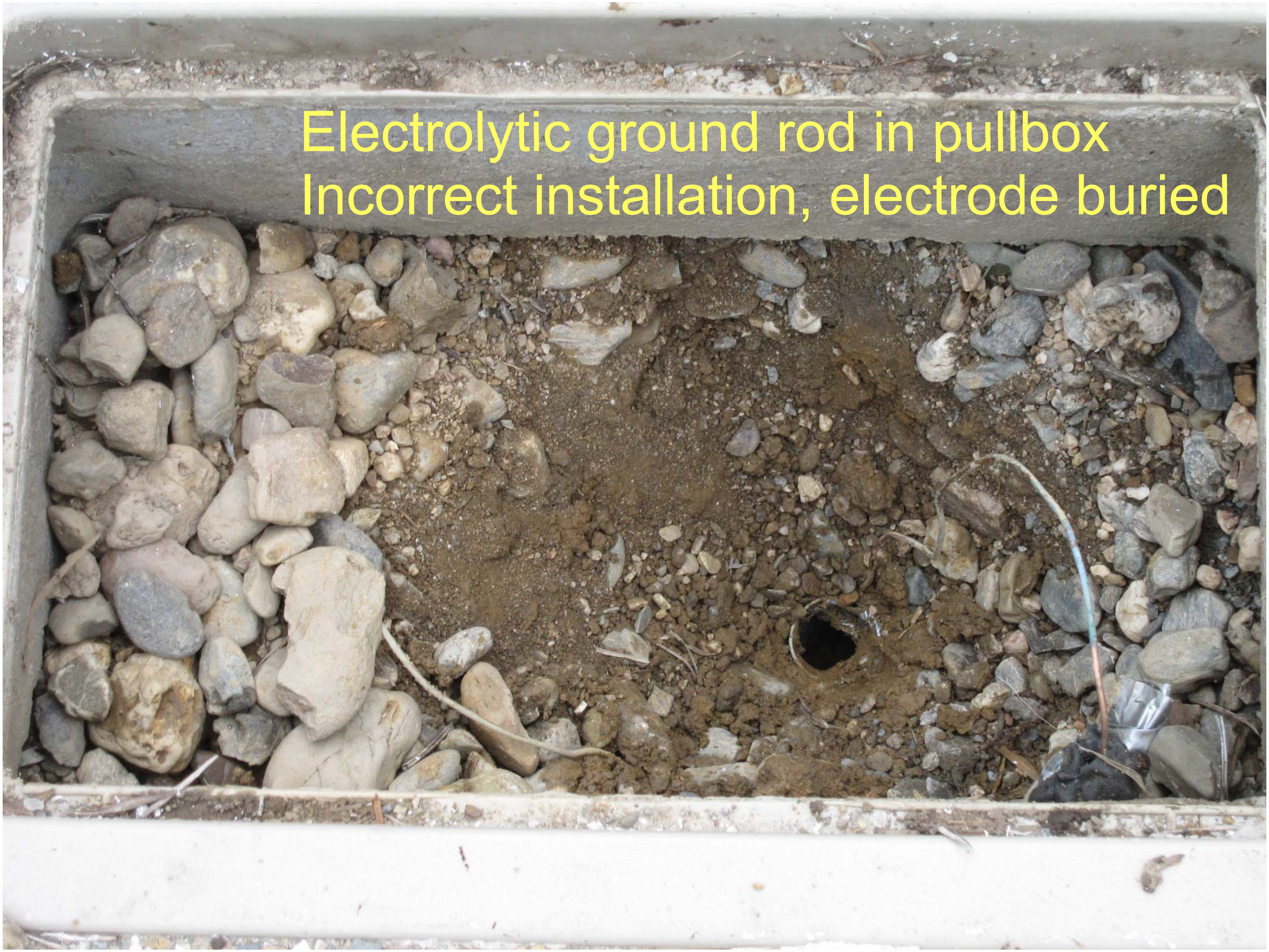
- Reduced soil resistivity by leeching electrolytes into the soil
- Vertical and horizontal installations available
- Vendors advertising maintenance free products patented since 1968
- More costly to install, but much more effective


Electrolytic ground rod in box


Electrolytic ground rod in pullbox
Incorrect installation, electrode buried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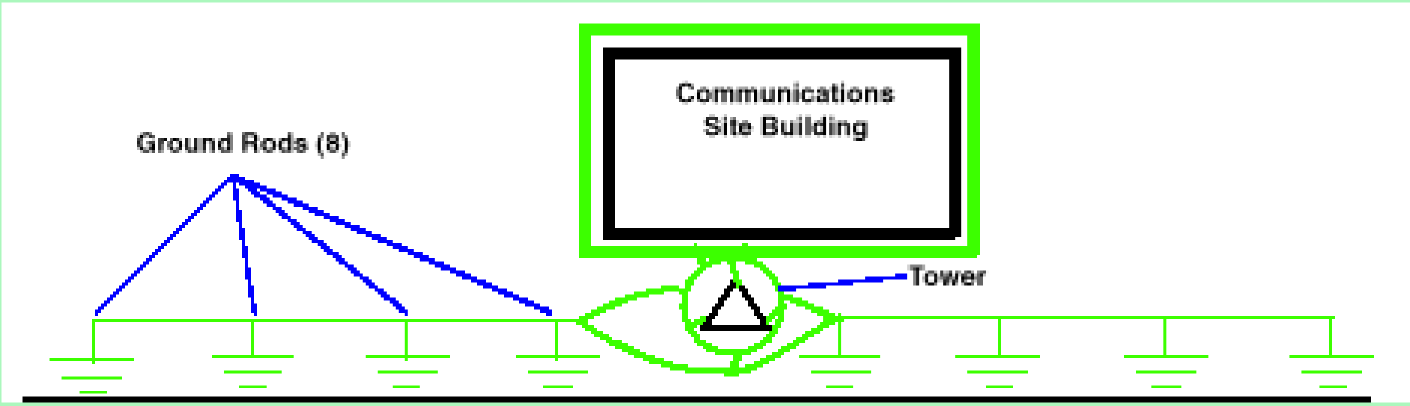
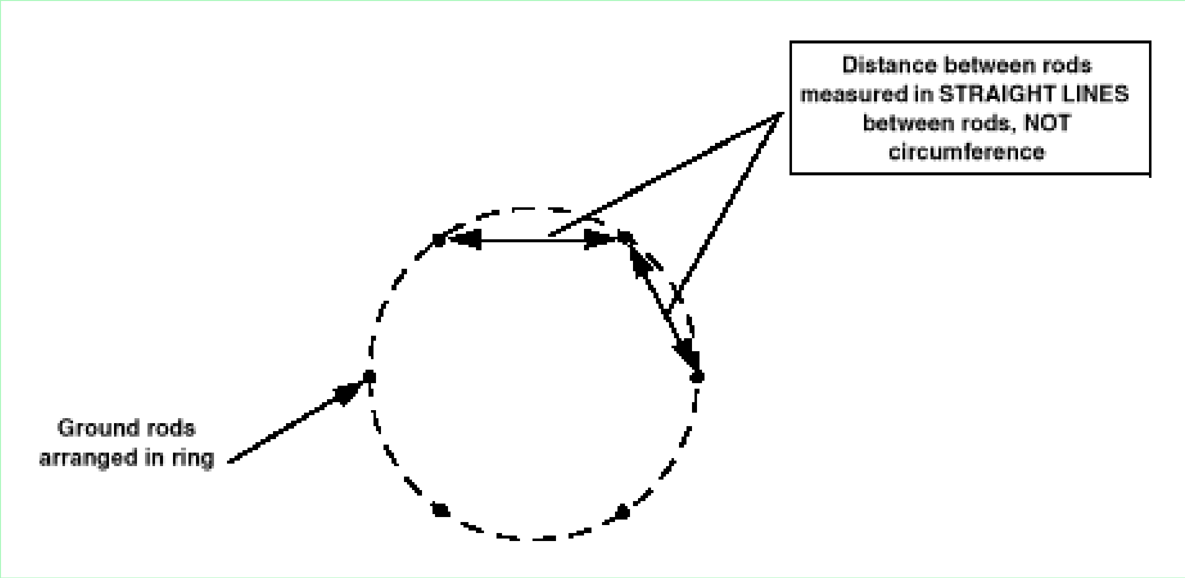
  i. Line



Ground Rod Systems

- Ground Rod Systems comprised of multiple ground rods
- Often necessary to reduce ground resistance
- Using copper/clad or electrolytic rods
- Several configurations
  i. Line
  ii. Ring



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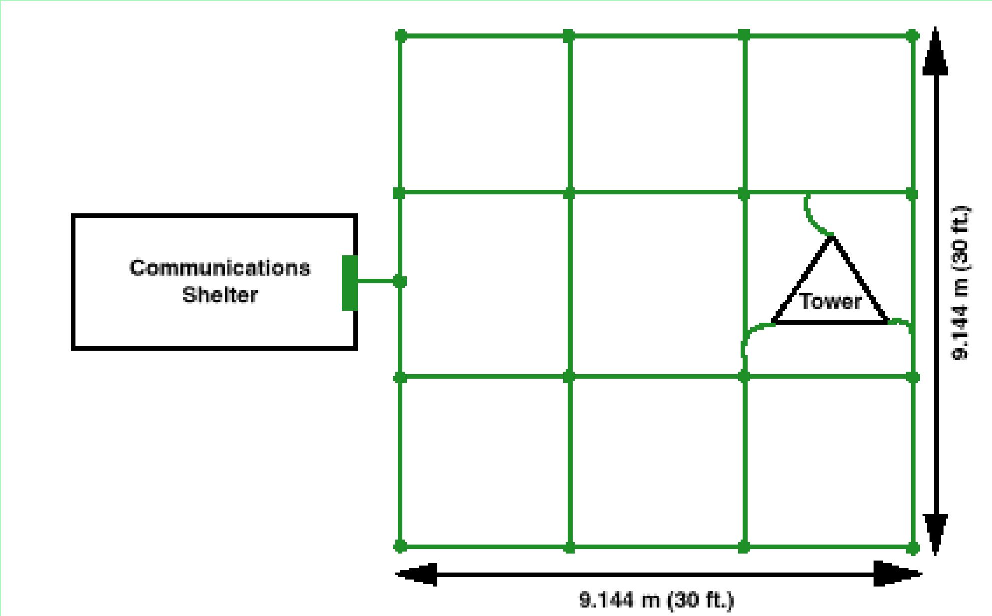

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    i. Line
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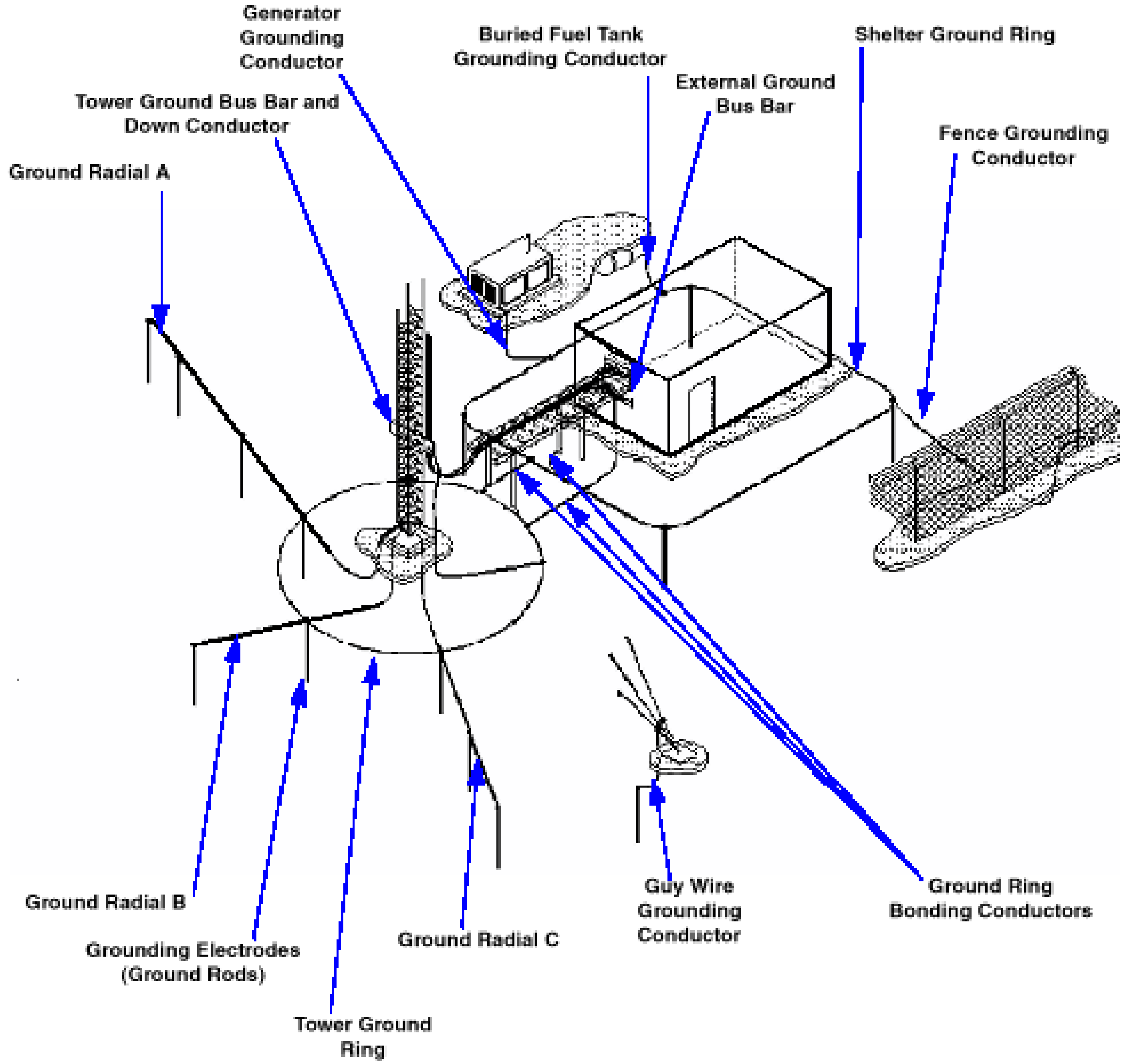
    iii. Grid
    iv. Complex


Generator Grounding Conductor
Buried Fuel Tank Grounding Conductor
Shelter Ground Ring
External Ground Bus Bar
Tower Ground Bus Bar and Down Conductor
Fence Grounding Conductor
Ground Radial A
Ground Radial B
Grounding Electrodes (Ground Rods)
Tower Ground Ring
Ground Radial C
Guy Wire Grounding Conductor
Ground Ring Bonding Conductors

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- Other grounding system options available depending upon application

Design Tools

- Nomograph’s
    i. Readily available
    ii. Effective

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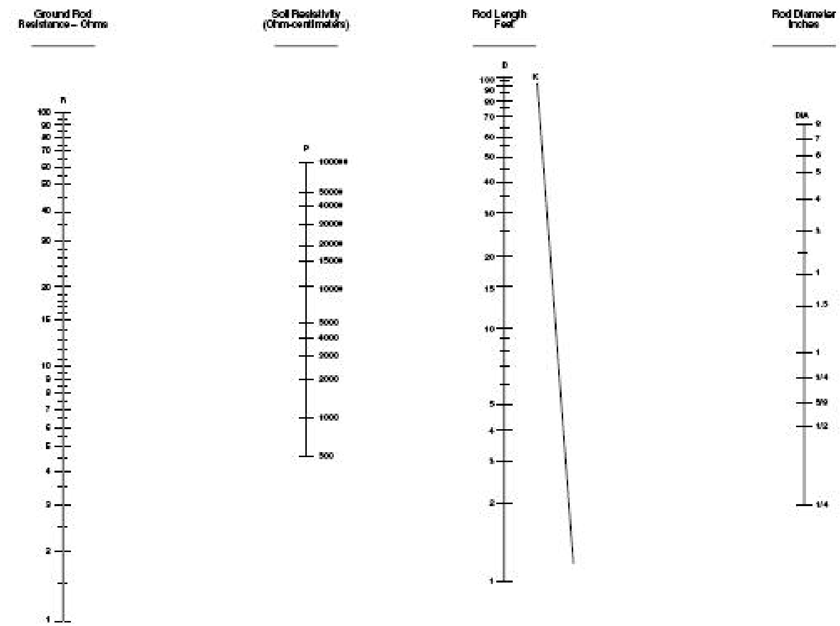
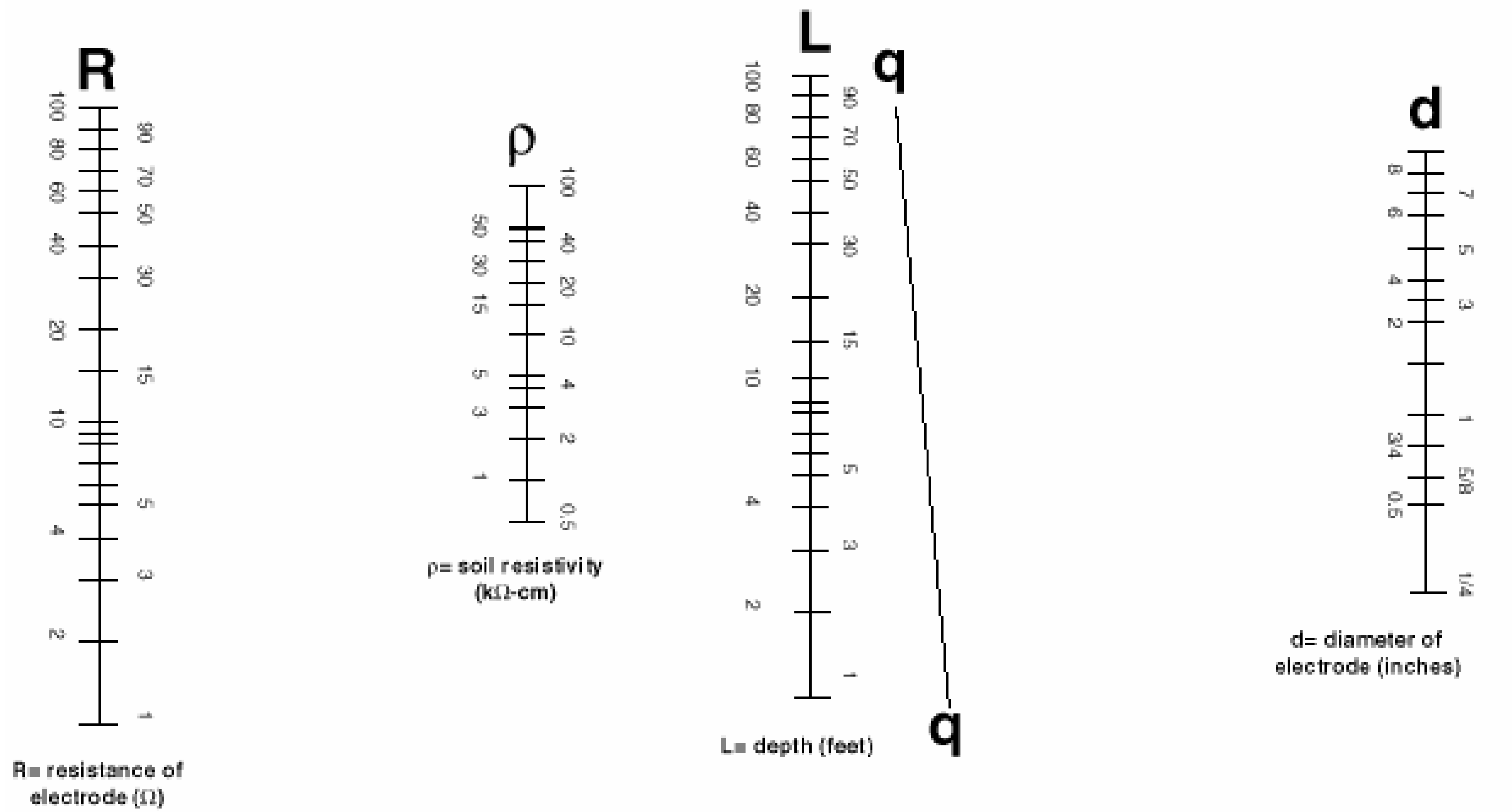
- On-line calculators
  i. Available on-line
  ii. Reliable?

Operator Name: ________________
Date: ________________
Site: ________________
City: ________________
State: ________________

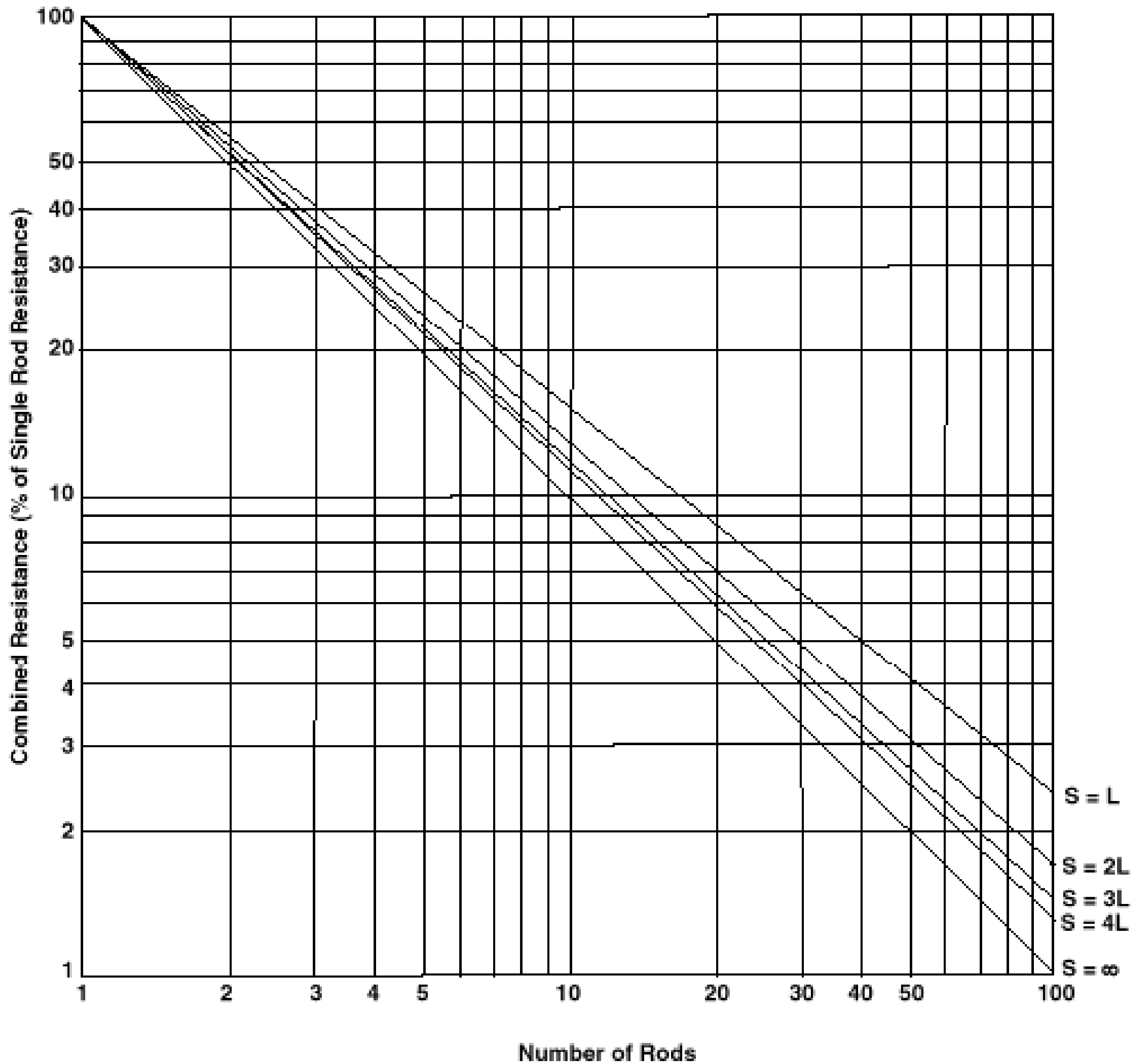
Grounding Nomograph



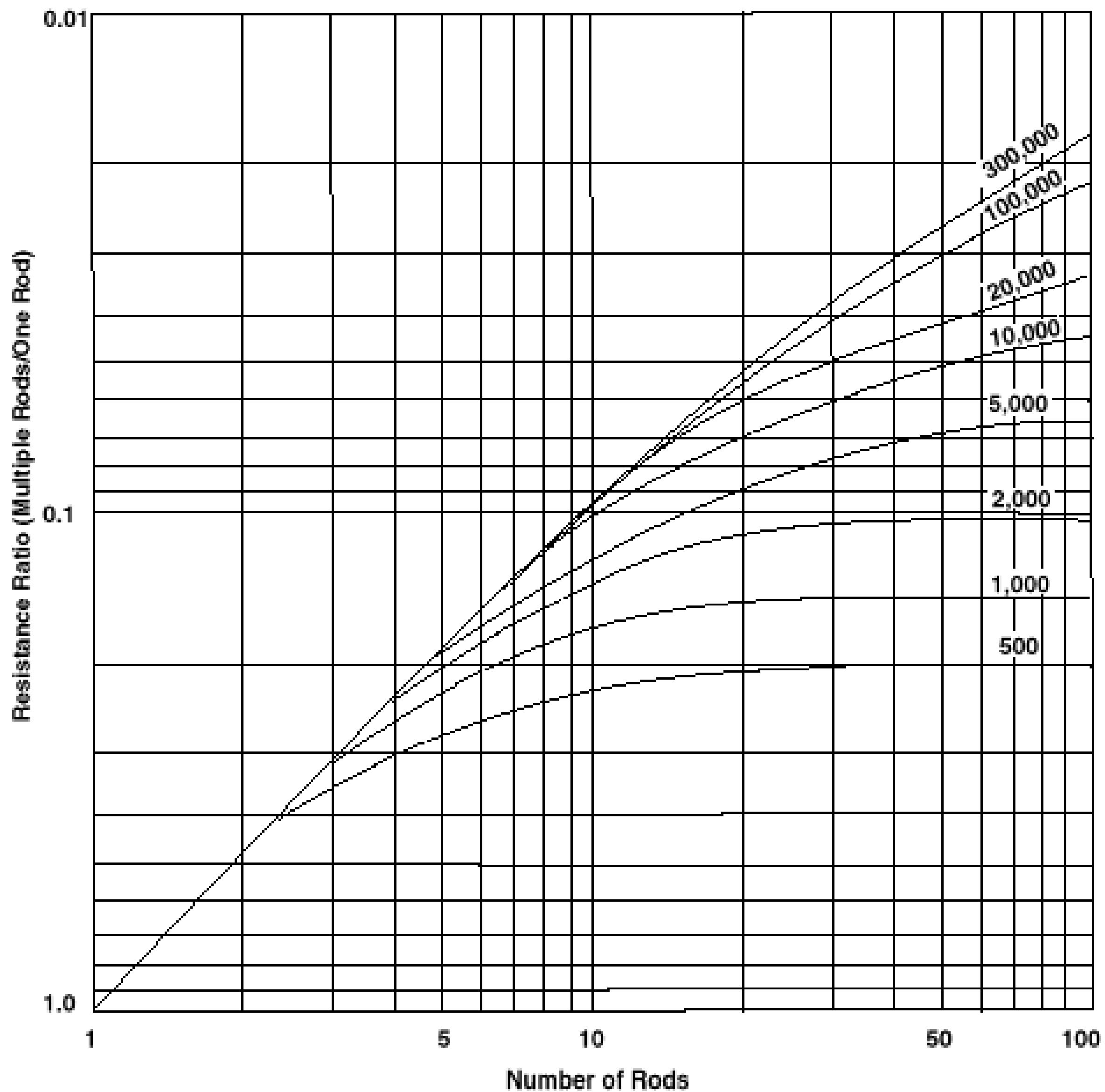
1. Select required resistance on R scale
2. Select apparent resistivity on P scale
3. Lay straightedge on R and P scale, and allow to intersect with K scale
4. Mark K scale point
5. Lay straightedge on K scale point and DIA scale, and allow to intersect with D scale
6. Point on D scale will be the rod depth required for resistance on R scale



Single Rod nomograph - Motorola R56



Line or Ring configuration nomograph – Motorola R56

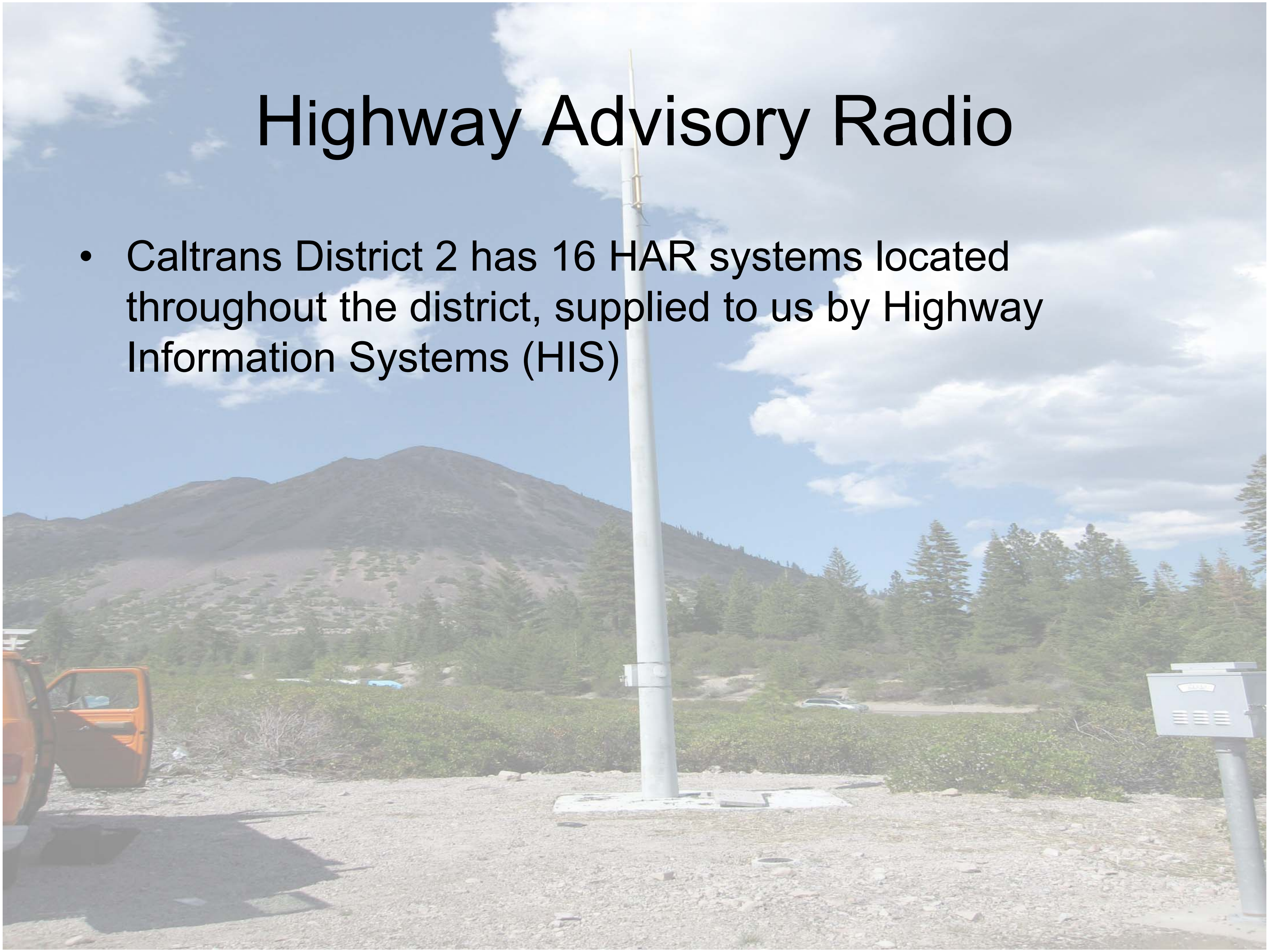


Grid configuration nomograph – Motorola R56


Application to ITS
Highway Advisory Radio

Highway Advisory Radio

- Caltrans District 2 has 16 HAR systems located throughout the district, supplied to us by Highway Information Systems (HIS)



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Highway Advisory Radio

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- Used frequently by TMC operators
- Travelers rely on HAR system for critical traveler information

HAR Issues

- An inherent lack of standardization

HAR Issues

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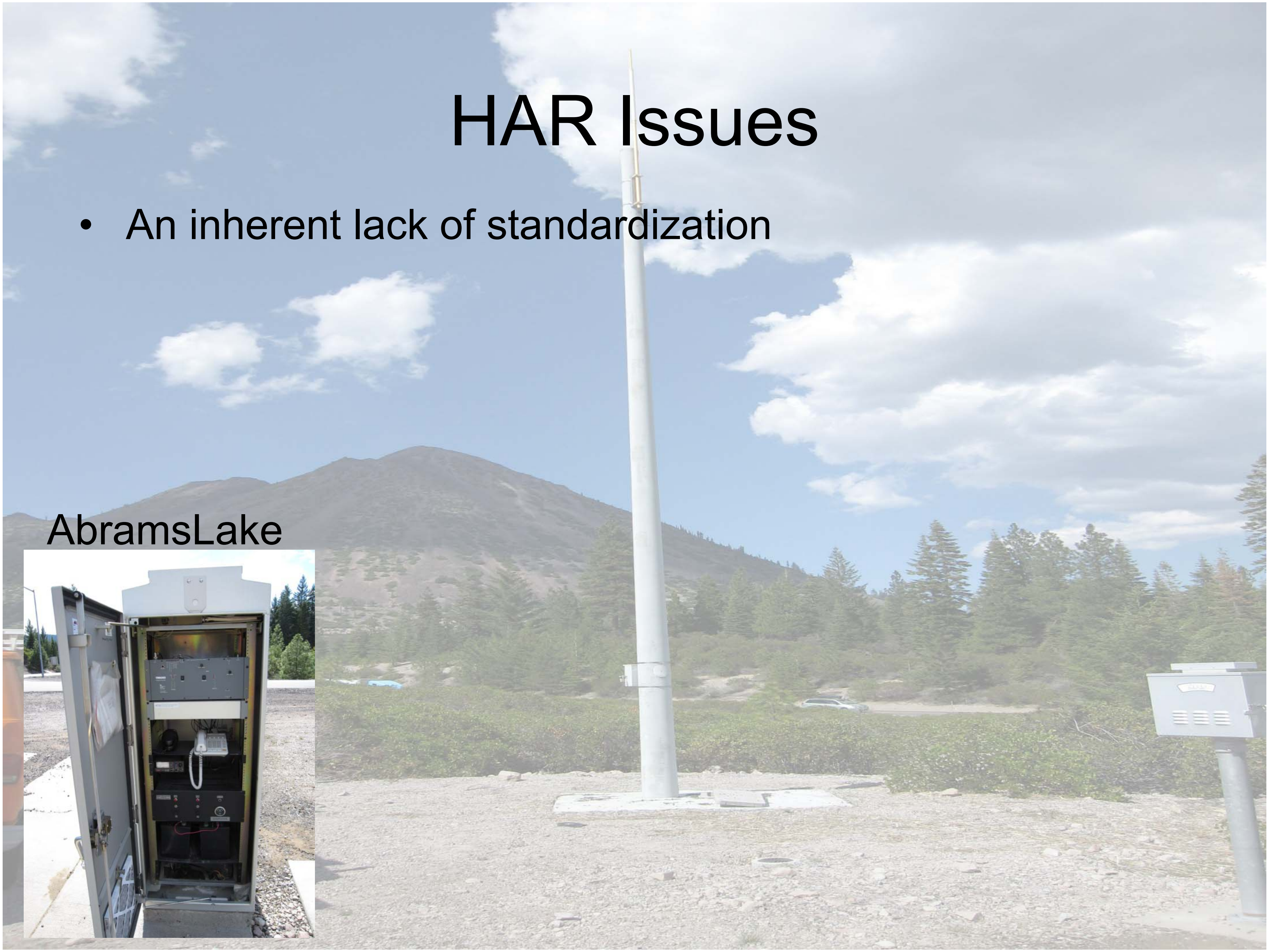

AbramsLake

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AbramsLake

Corning

HAR Issues

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- Differents sites installed by different contractors

AbramsLake

Corning

Weaverville

HAR Issues

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- Makes troubleshooting difficult

AbramsLake

Corning

Weaverville

WaltersRd

HAR Issues

- An inherent lack of standardization
- Multiple revisions in the field
- Differents sites installed by different contractors
- Makes troubleshooting difficult
- Some sites sound different from other sites

AbramsLake

Corning

Weaverville

WaltersRd

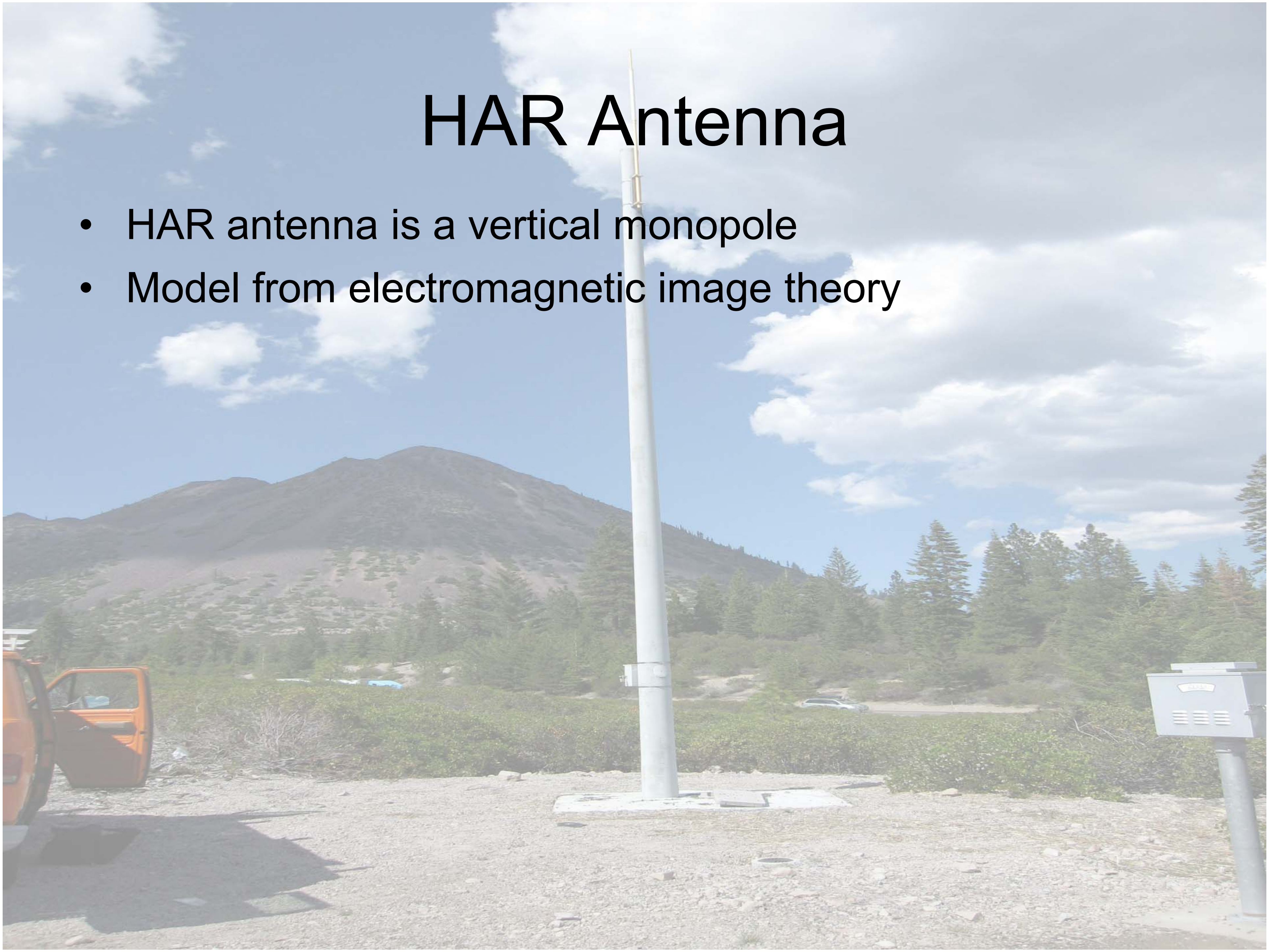
Why is the ground important?

HAR Antenna

- HAR antenna is a vertical monopole

HAR Antenna

- HAR antenna is a vertical monopole
- Model from electromagnetic image theory



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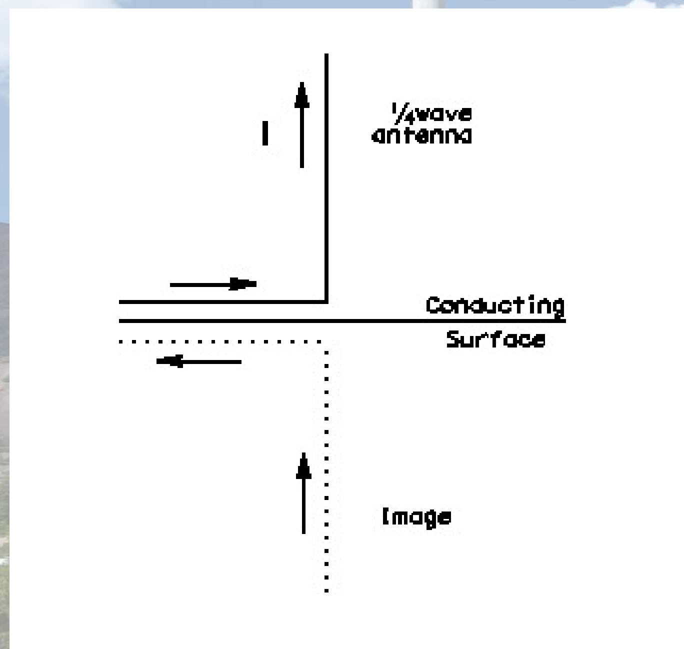

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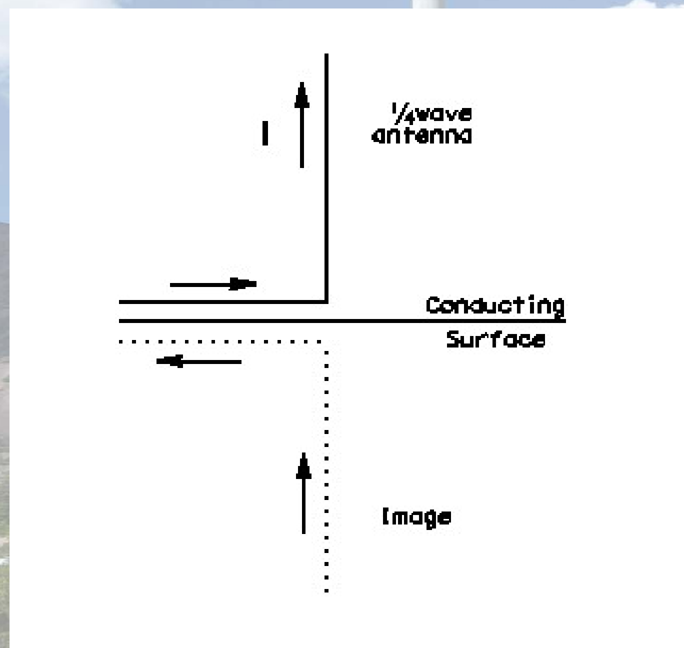

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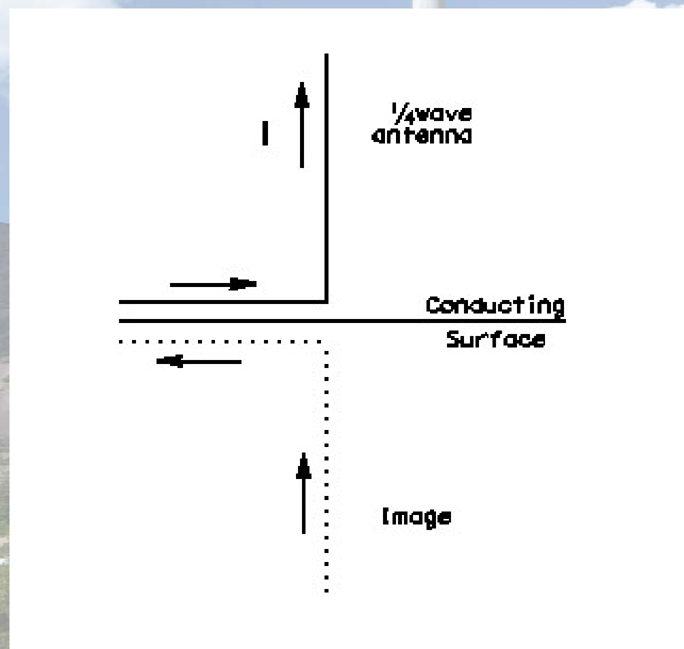

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HAR Antenna

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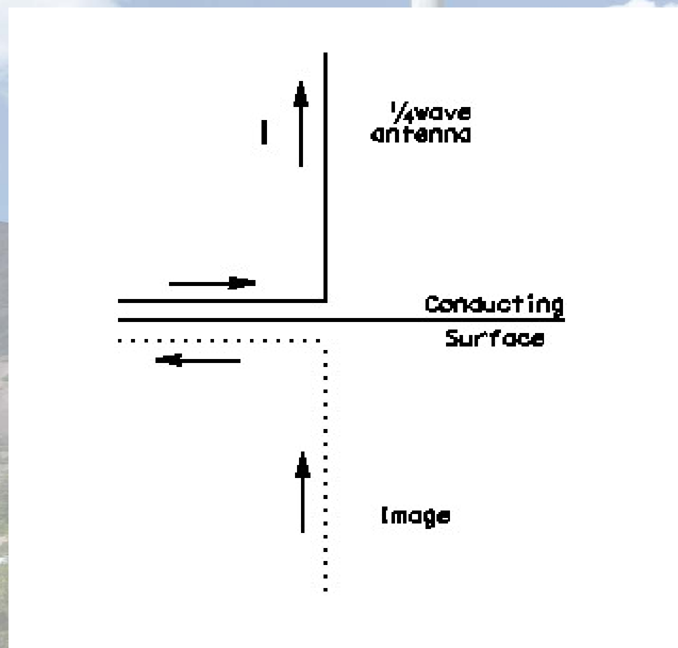

- Appears to be a half wave dipole
- In this case the conducting surface is the ground
- A better ground means better radiation efficiency

Surface Wave Propagation

- At low frequencies vertical monopoles may induce surface waves (ground waves)

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- The existence of surface waves still debated 100 years after being proposed by Sommerfield and Zenneck

Surface Wave Propagation

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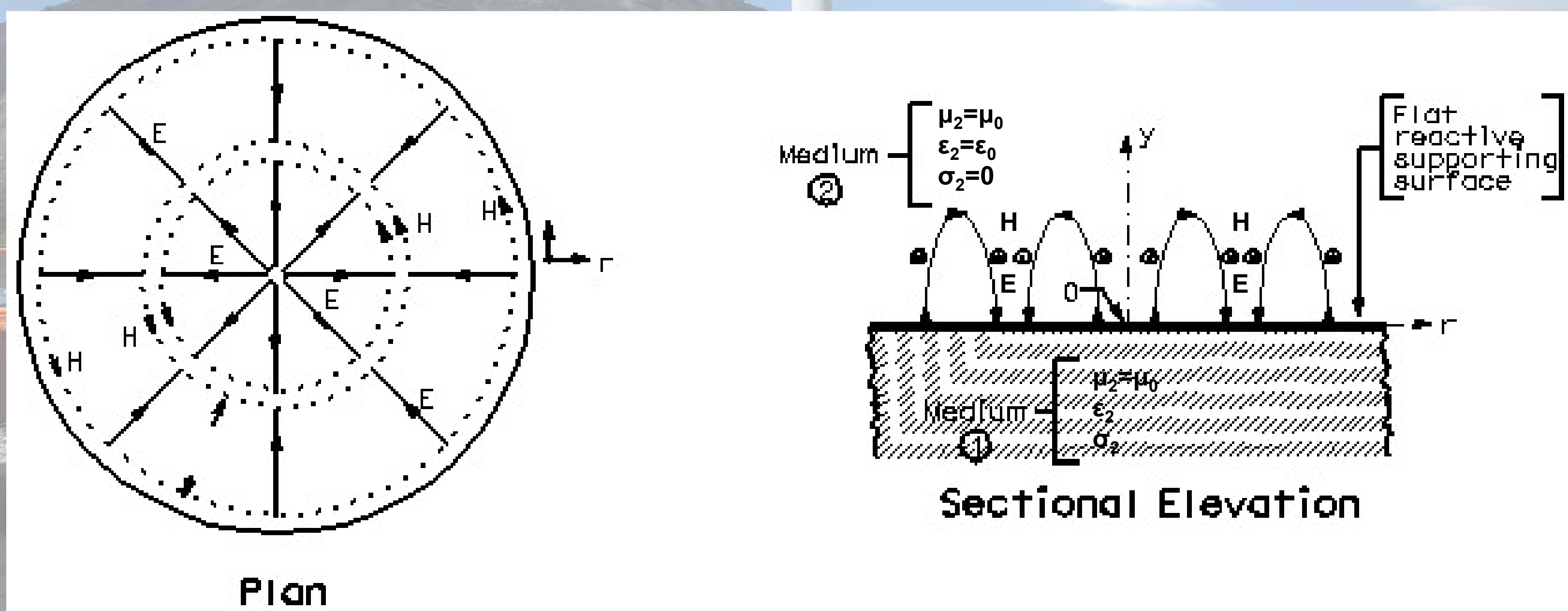
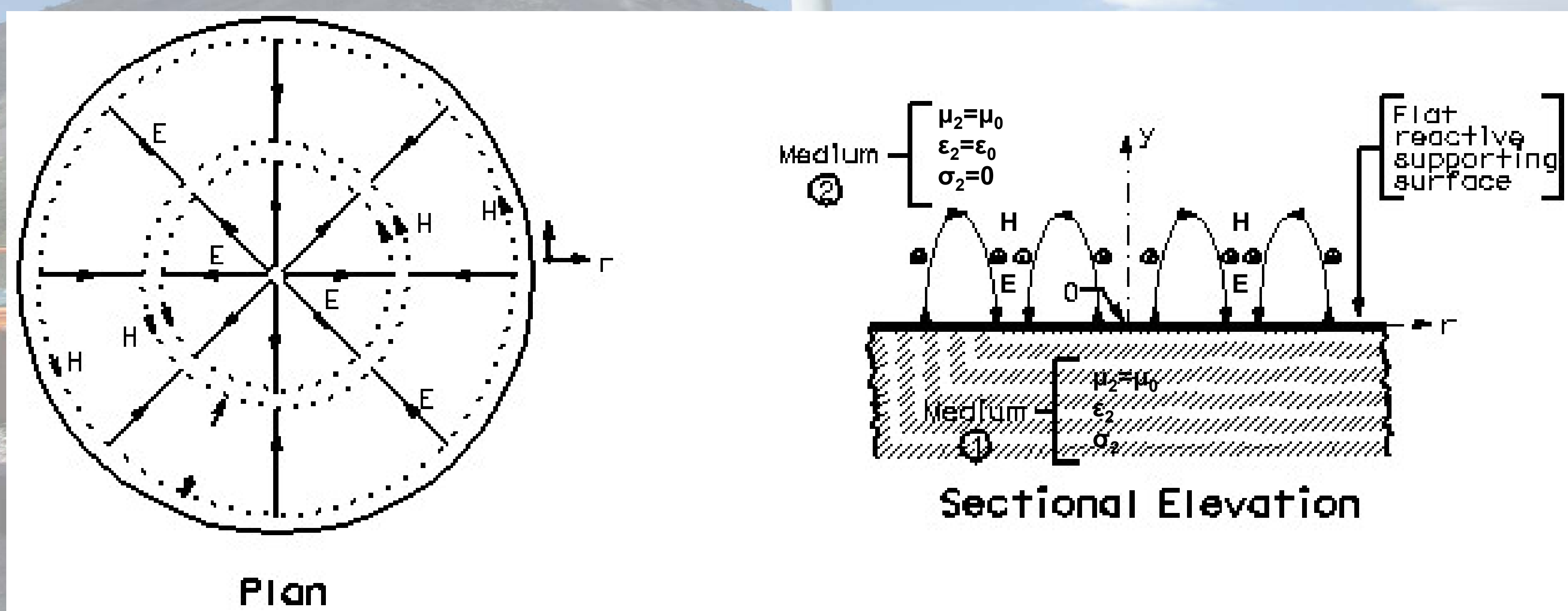
- The existence of surface waves still debated 100 years after being proposed by Sommerfield and Zenneck
- Surface wave model for vertical monopoles is a radial cylinder



Surface Wave Propagation

- Dipole model uses spherical shell, signal strength drops off at $1/r^2$



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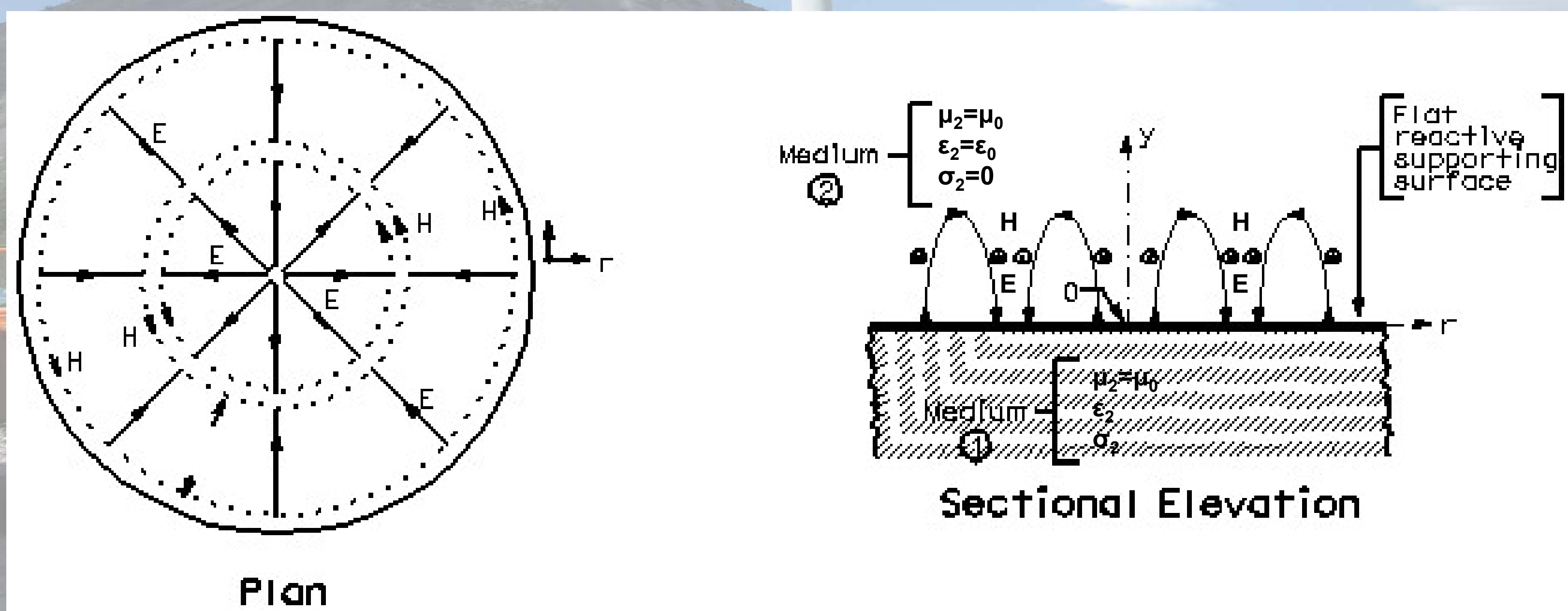
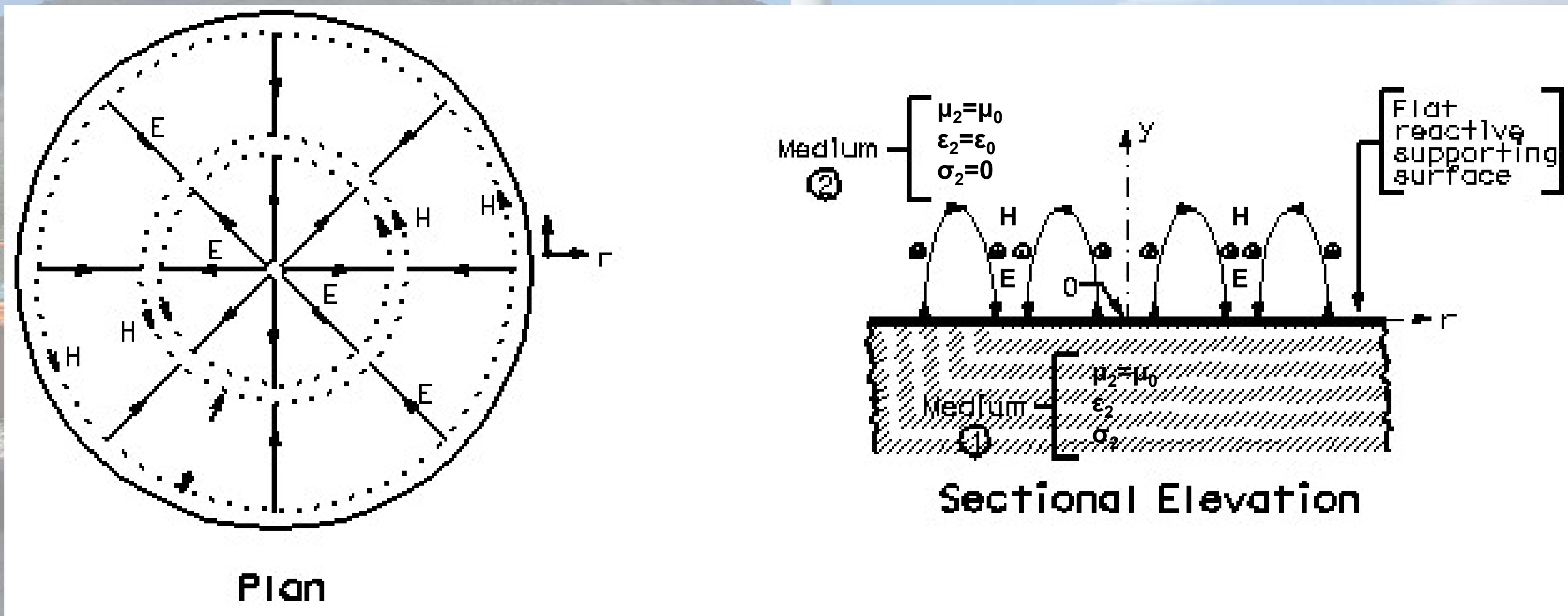


Surface Wave Propagation

- Dipole model uses spherical shell, signal strength drops off at $1/r^2$
- Cylindrical model implies a decay of $1/r$, math tells us $1/r^{1/2}$
- **This is important, if true we can increase our coverage area without deviating from FCC spec**



HAR Grounds

HAR Grounds

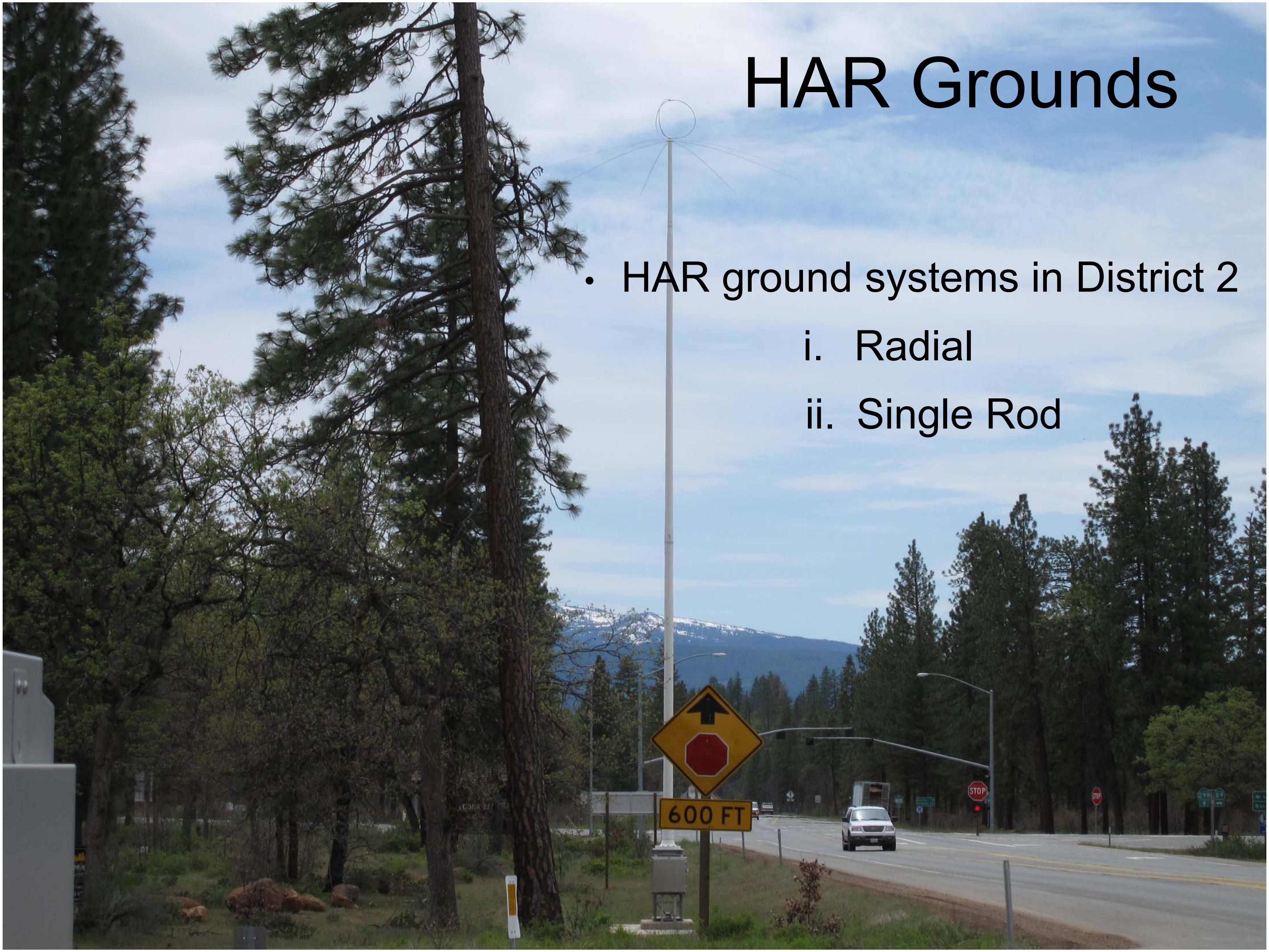
- HAR ground systems in District 2

HAR Grounds

- HAR ground systems in District 2
    i. Radial

HAR Grounds

- HAR ground systems in District 2
  i. Radial
  ii. Single Rod



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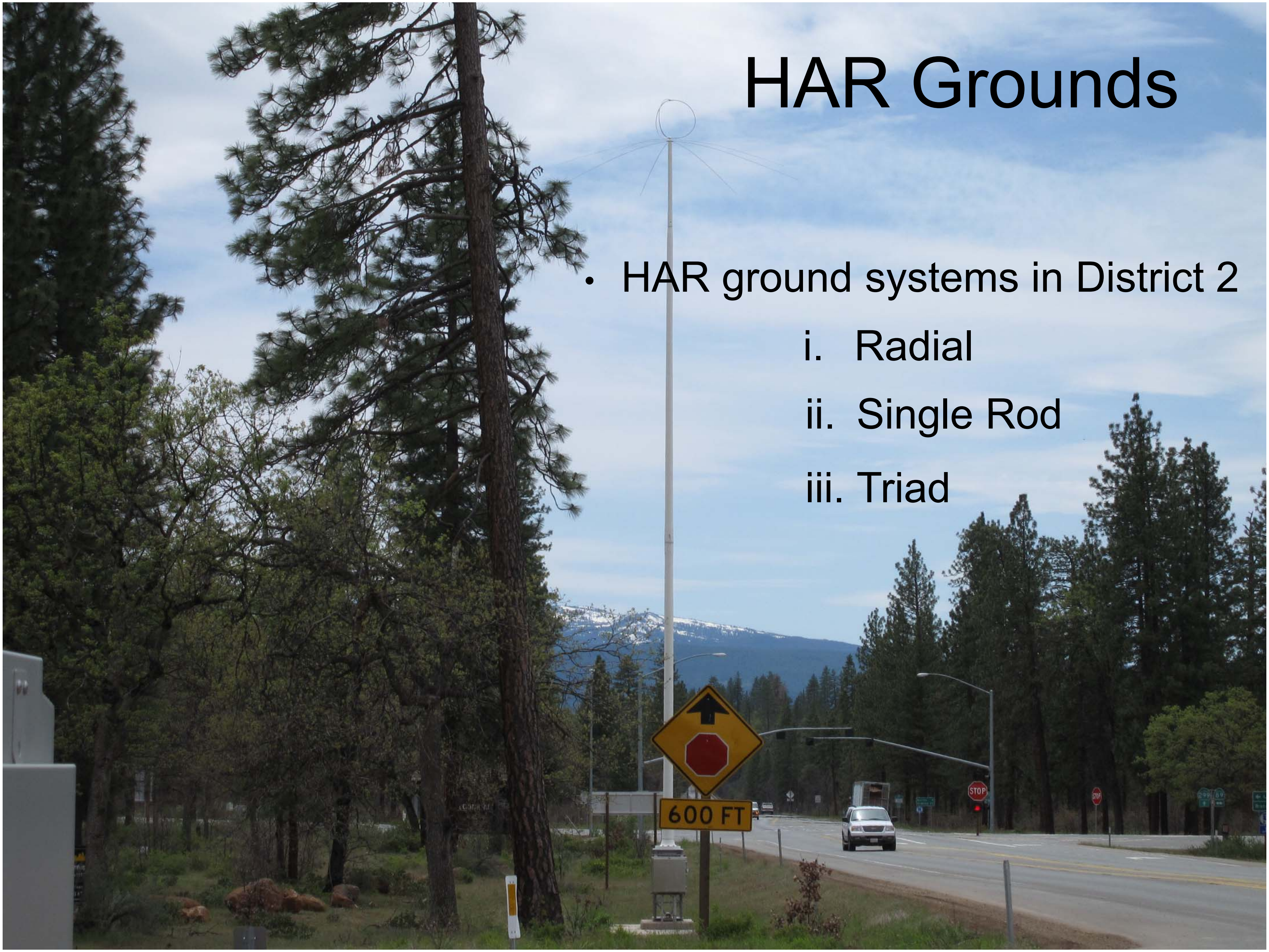
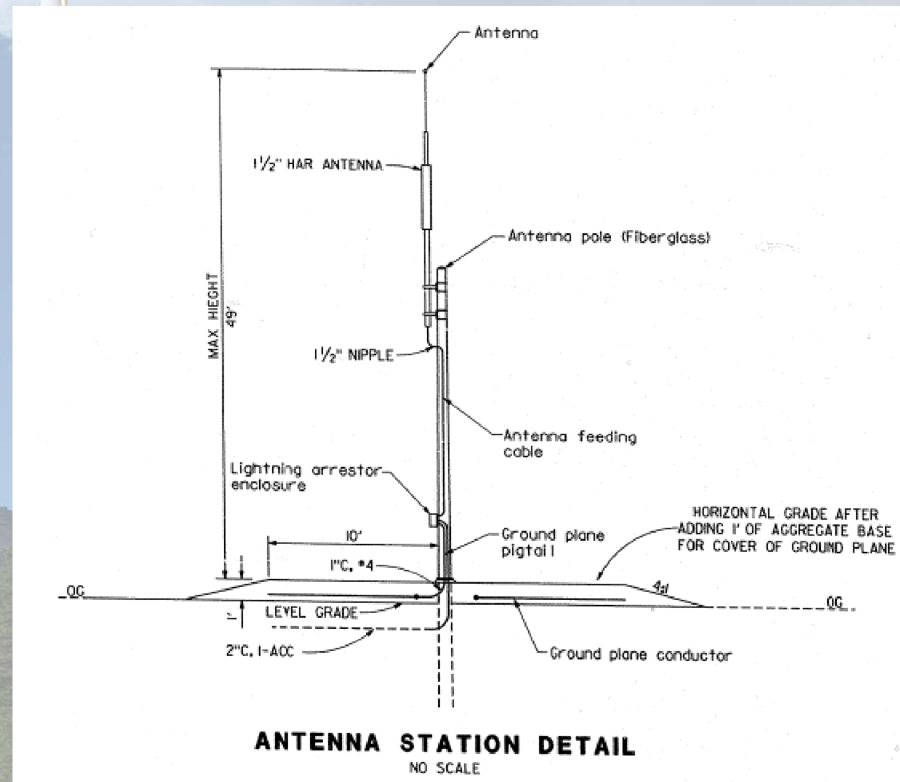
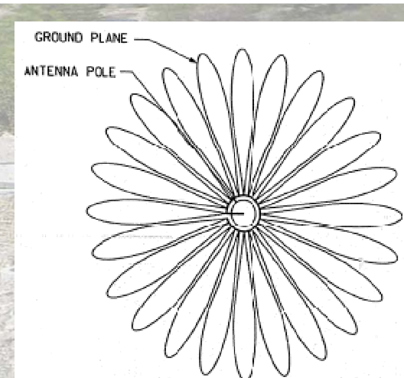


- HAR ground systems in District 2
  - i. Radial
  - ii. Single Rod
  - iii. Triad

Radial Ground

- Composed of #12 bare copper wire laid symmetrically around antenna, length of conductor varies from site to site, generally about 30 feet





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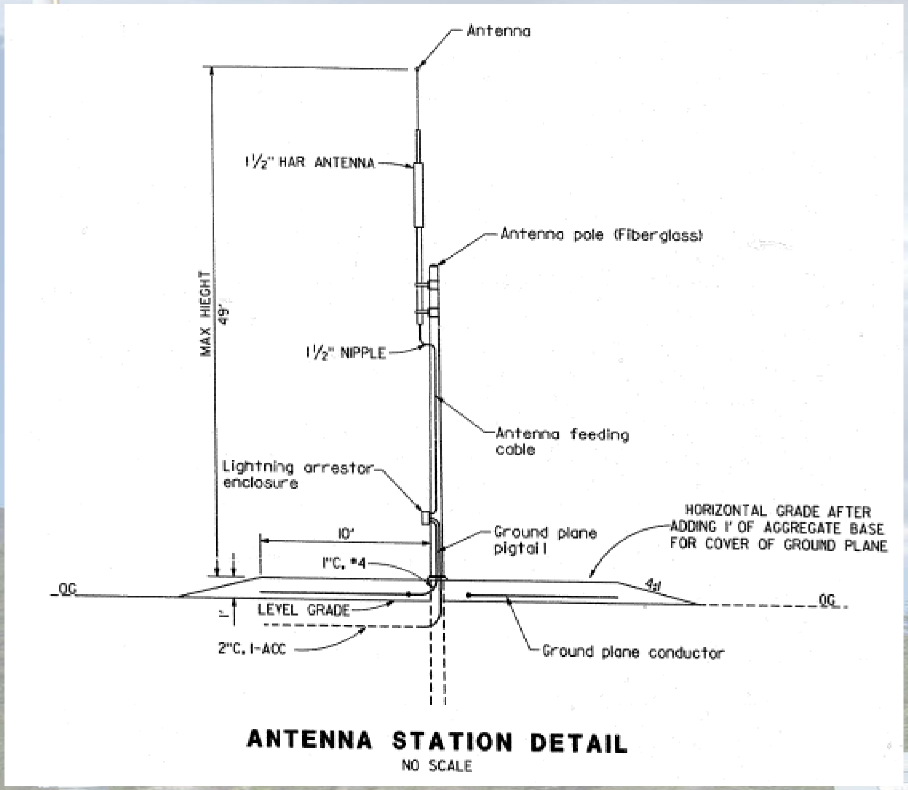
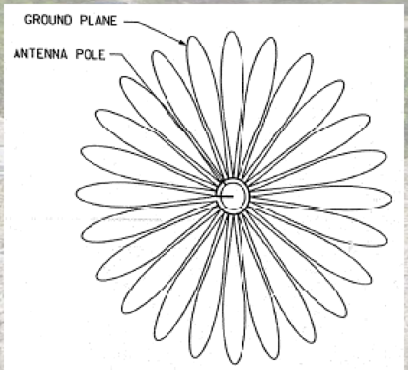
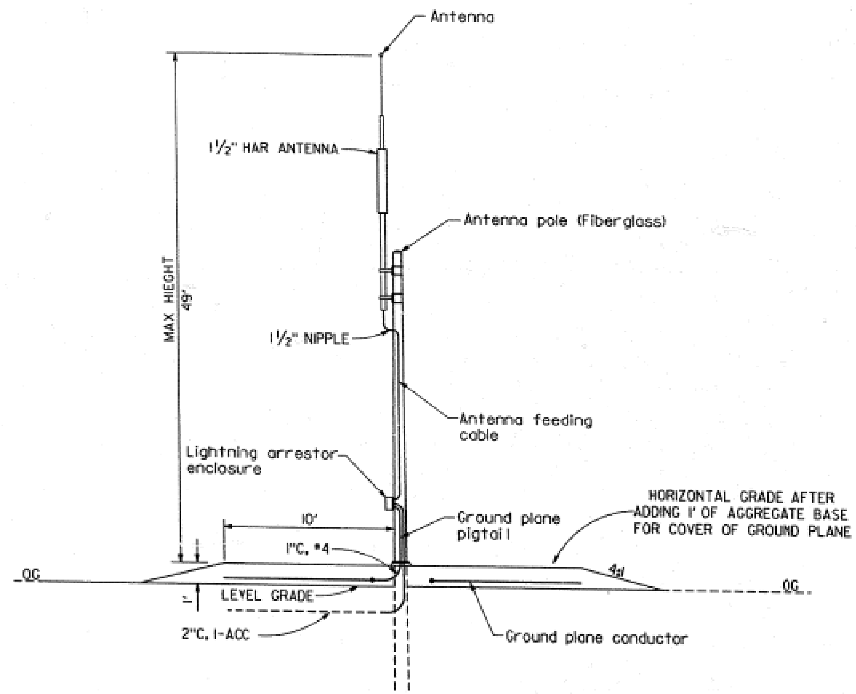
- Can be costly due to right-of-way issues



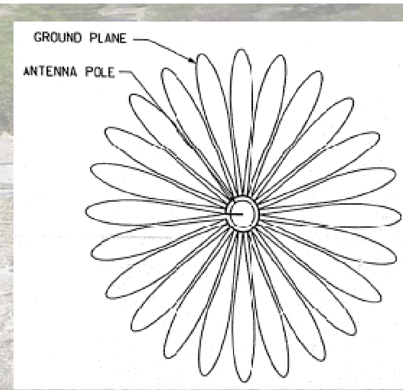


Radial Ground

- Composed of #12 bare copper wire laid symmetrically around antenna, length of conductor varies from site to site, generally about 30 feet
- Can be costly due to right-of-way issues
- Most HAR ground systems in the District are of the radial type

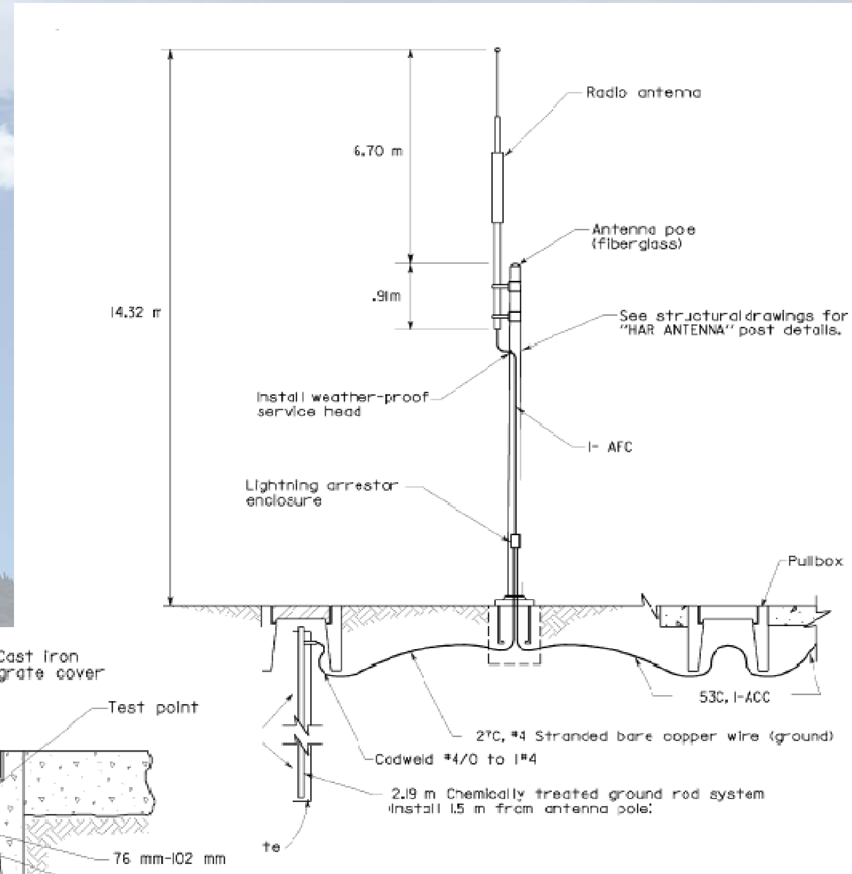


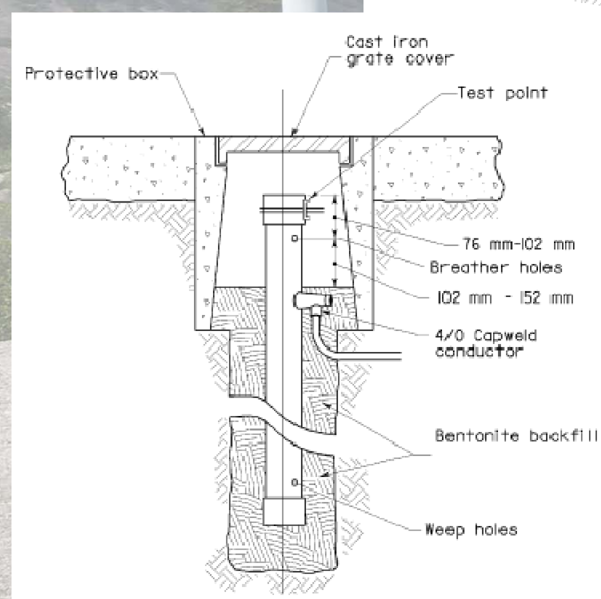
ANTENNA STATION DETAIL
NO SCALE



Single Rod Ground

- Composed of a single 40 foot electrolytic ground rod buried within 6 feet of the antenna





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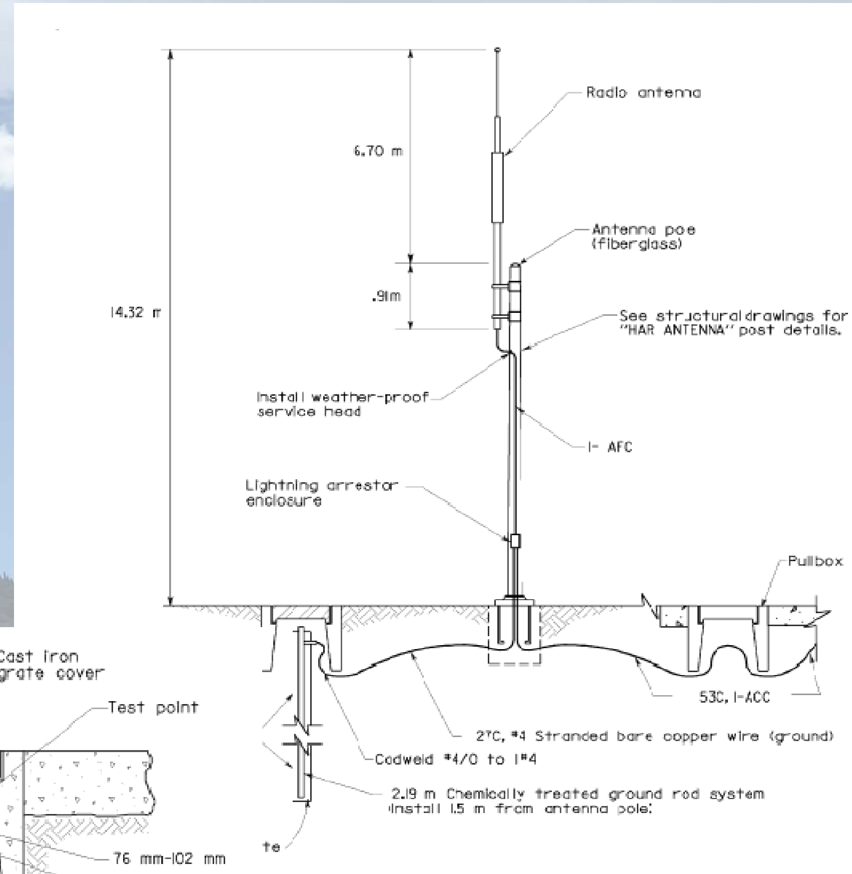
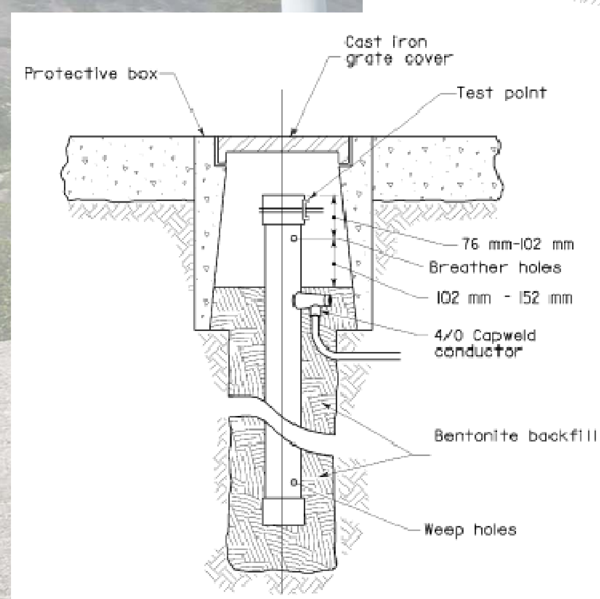
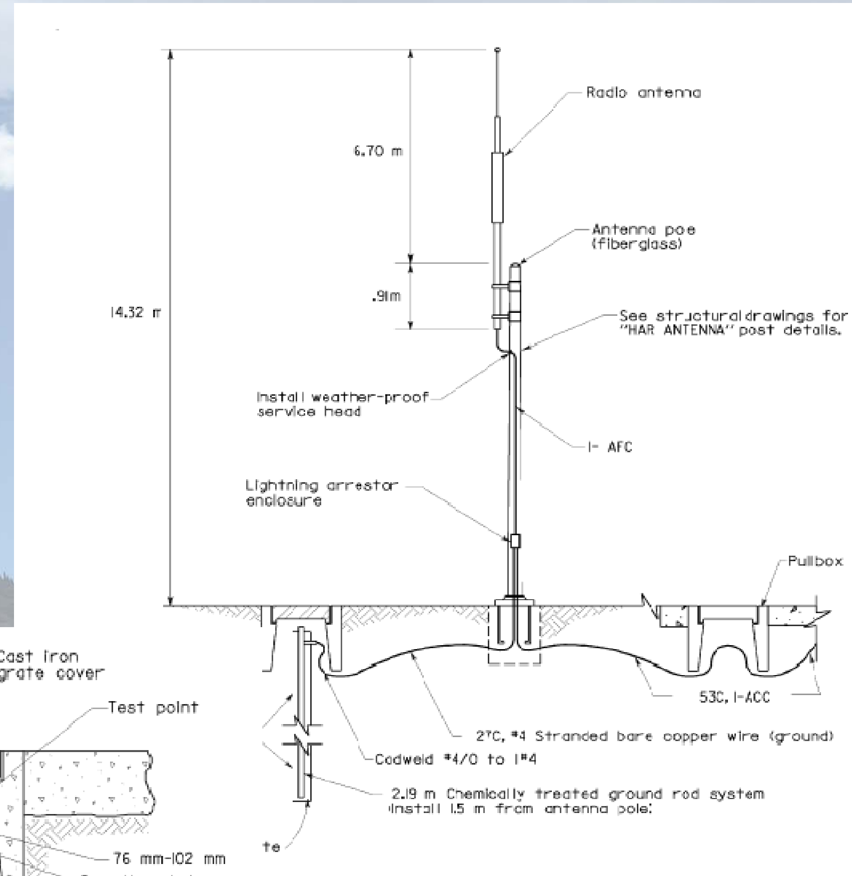
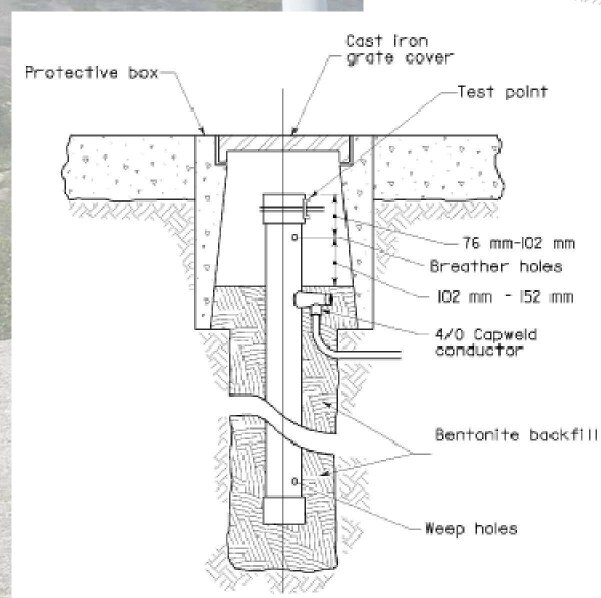




Single Rod Ground

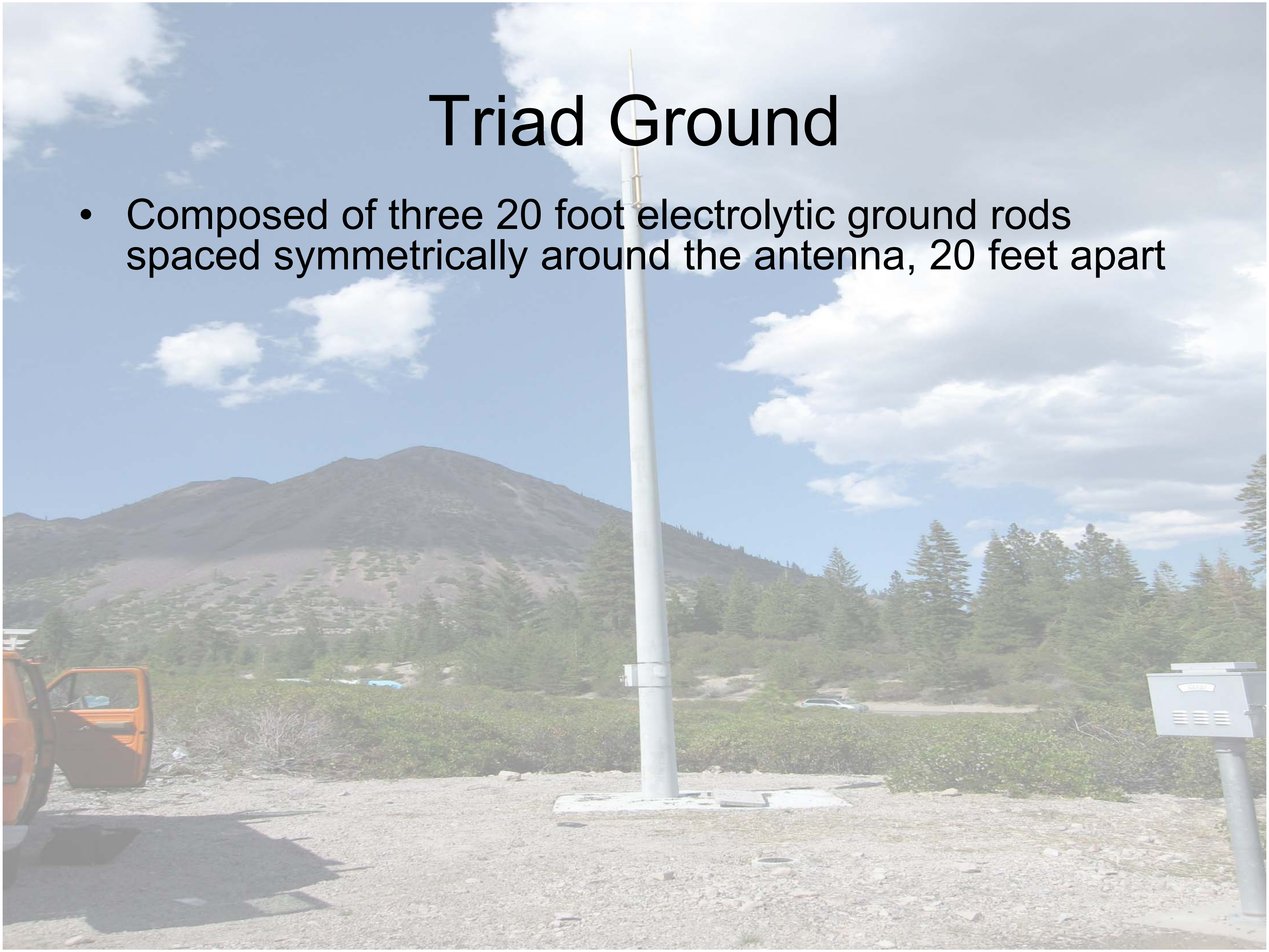
- Composed of a single 40 foot electrolytic ground rod buried within 6 feet of the antenna
- Can be costly to install
- Proposed as a solution to right-of-way issues





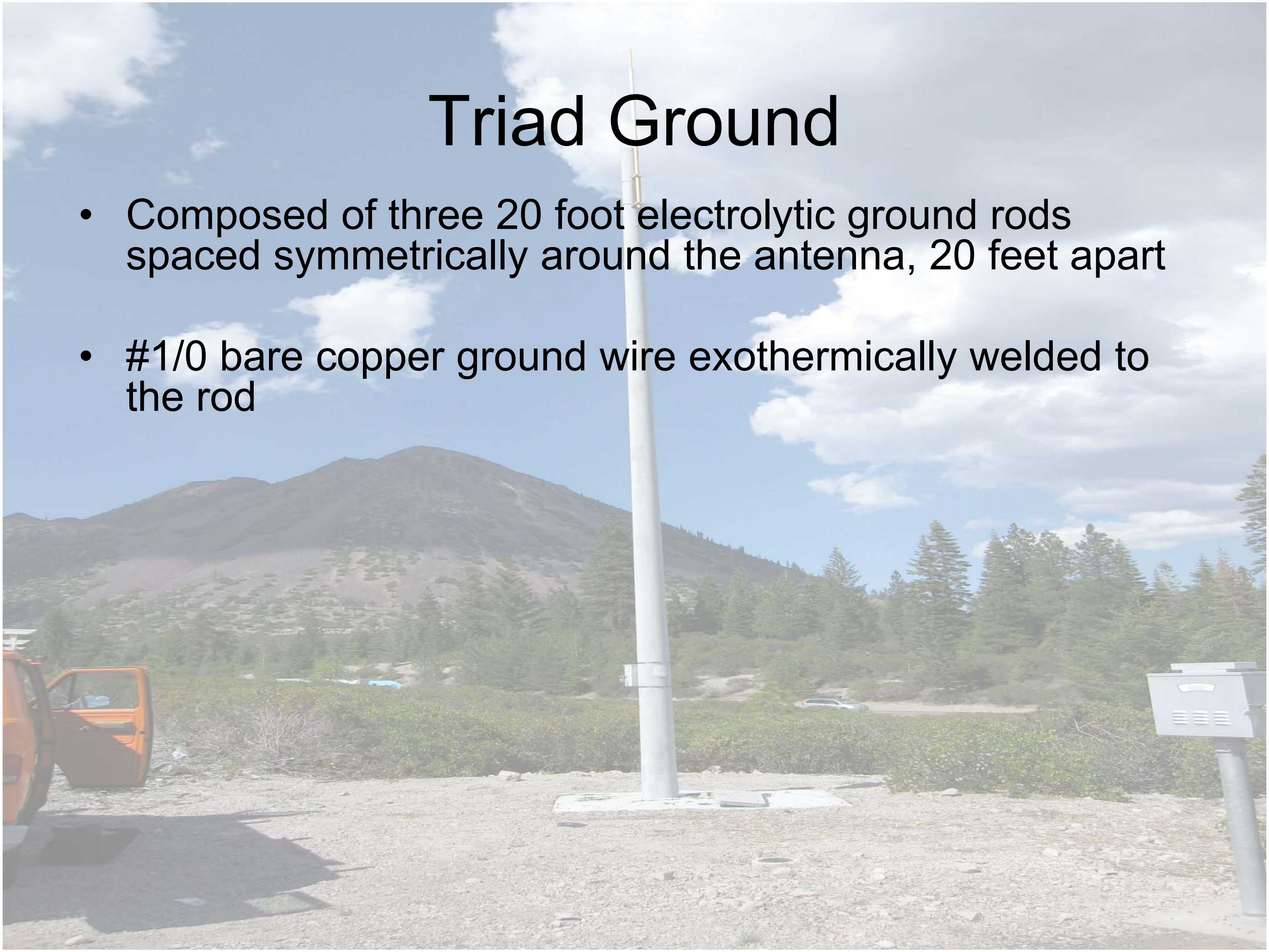
Triad Ground

- Composed of three 20 foot electrolytic ground rods spaced symmetrically around the antenna, 20 feet apart

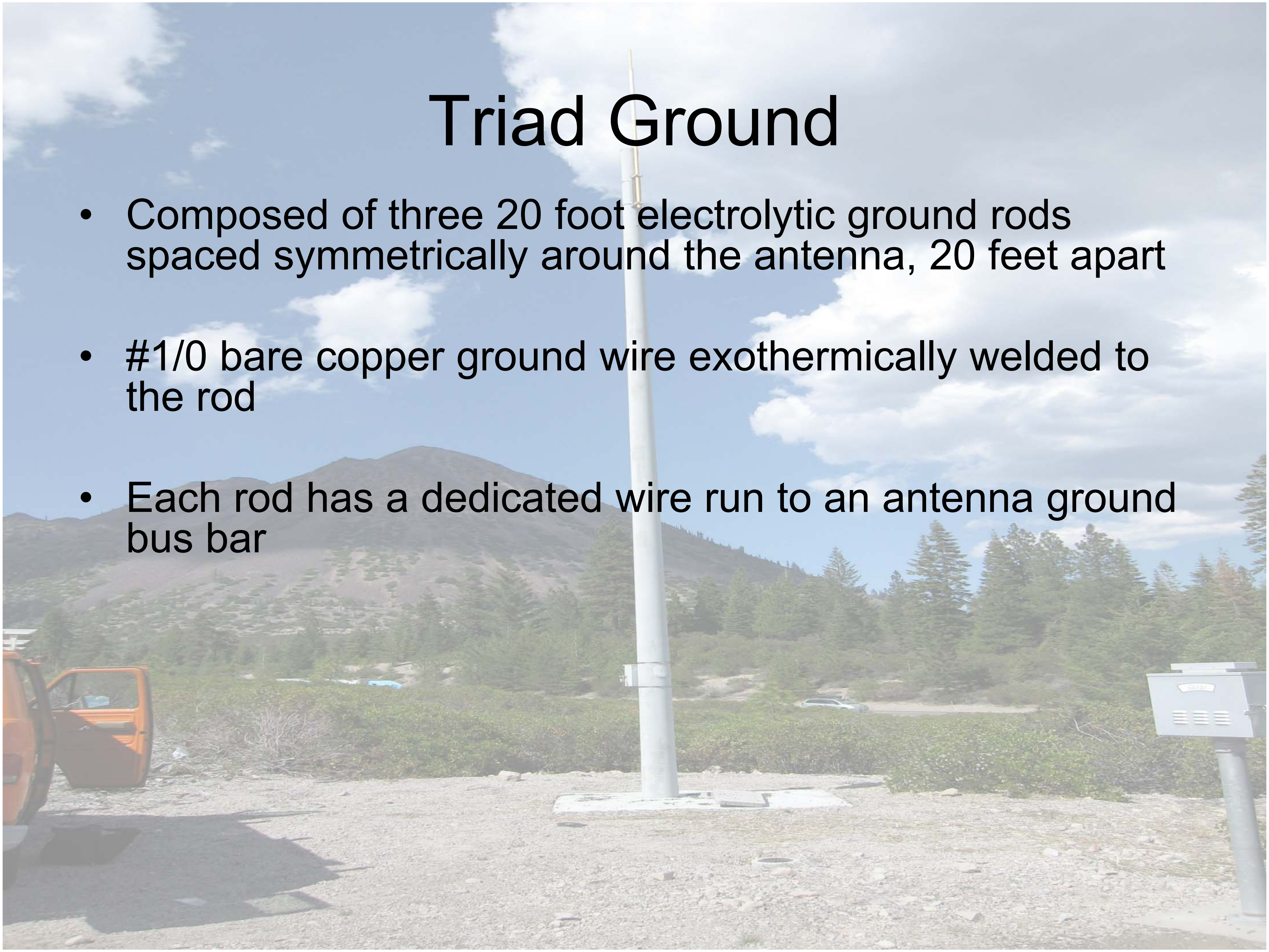


Triad Ground

- Composed of three 20 foot electrolytic ground rods spaced symmetrically around the antenna, 20 feet apart
- #1/0 bare copper ground wire exothermically welded to the rod



Triad Ground



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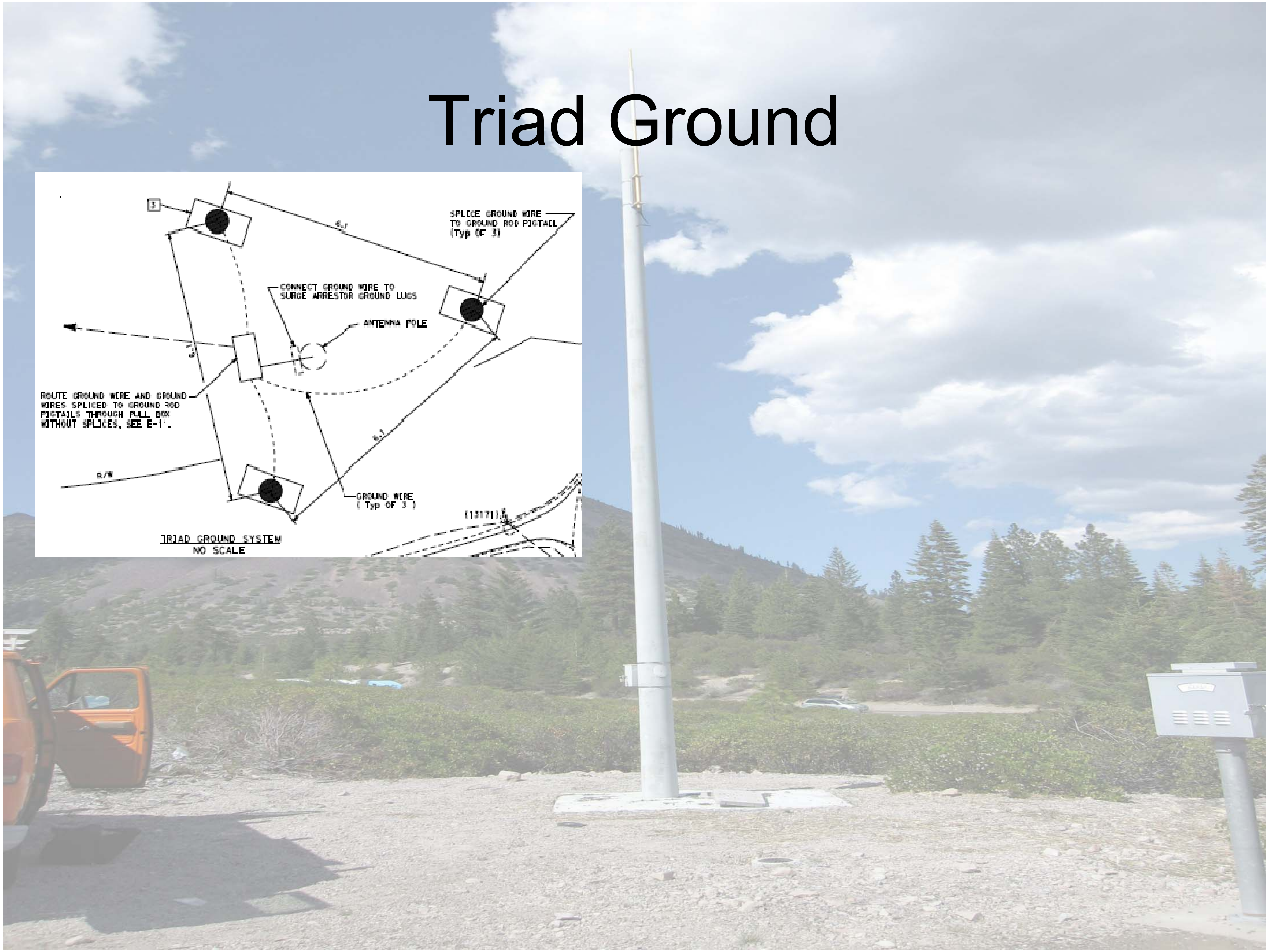
Triad Ground



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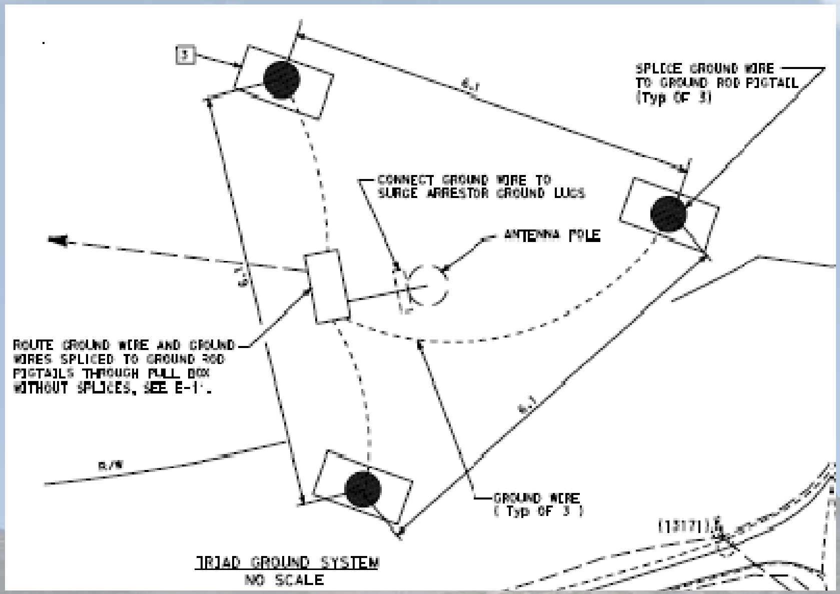

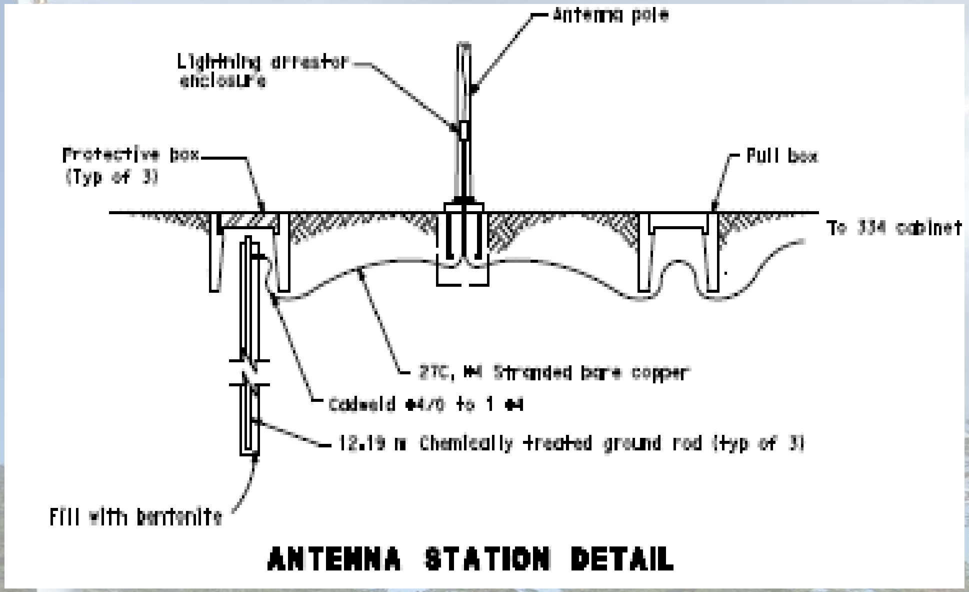

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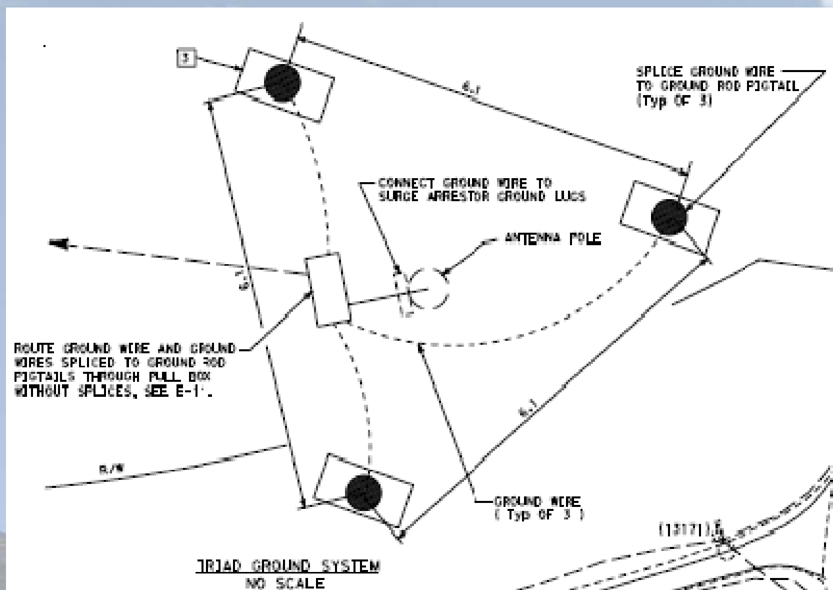
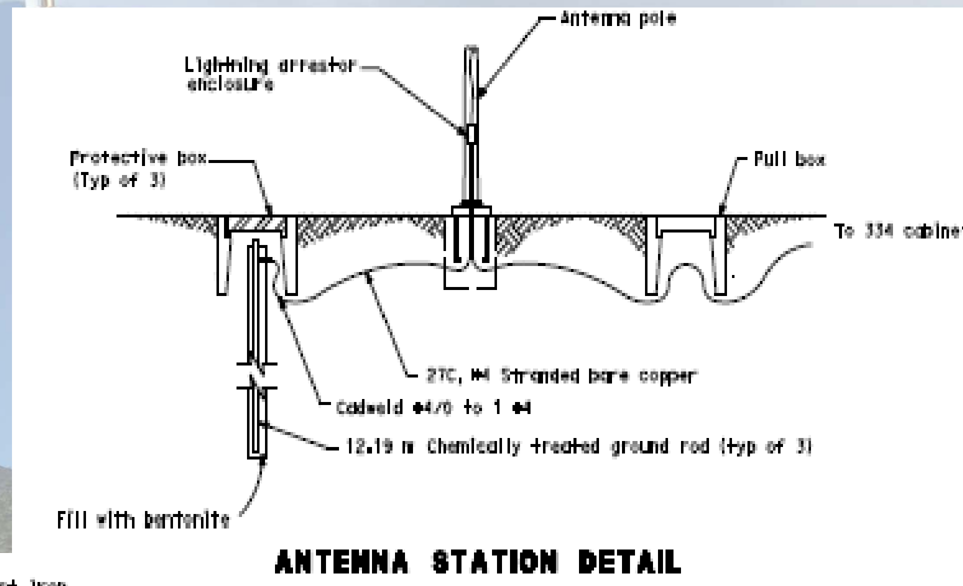
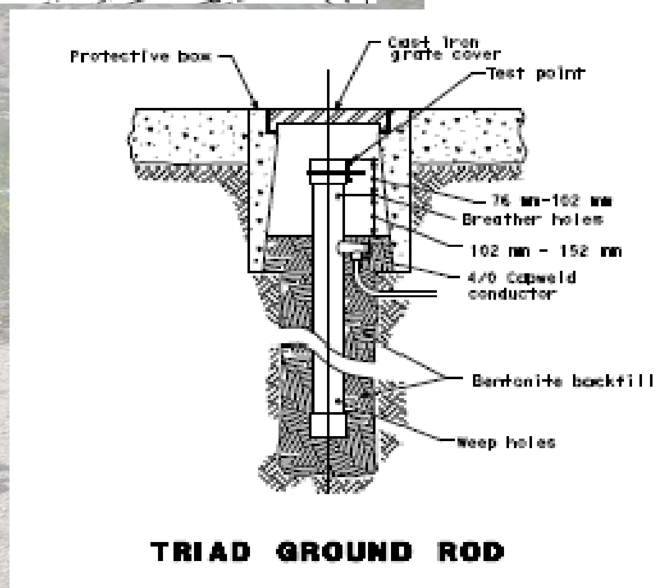


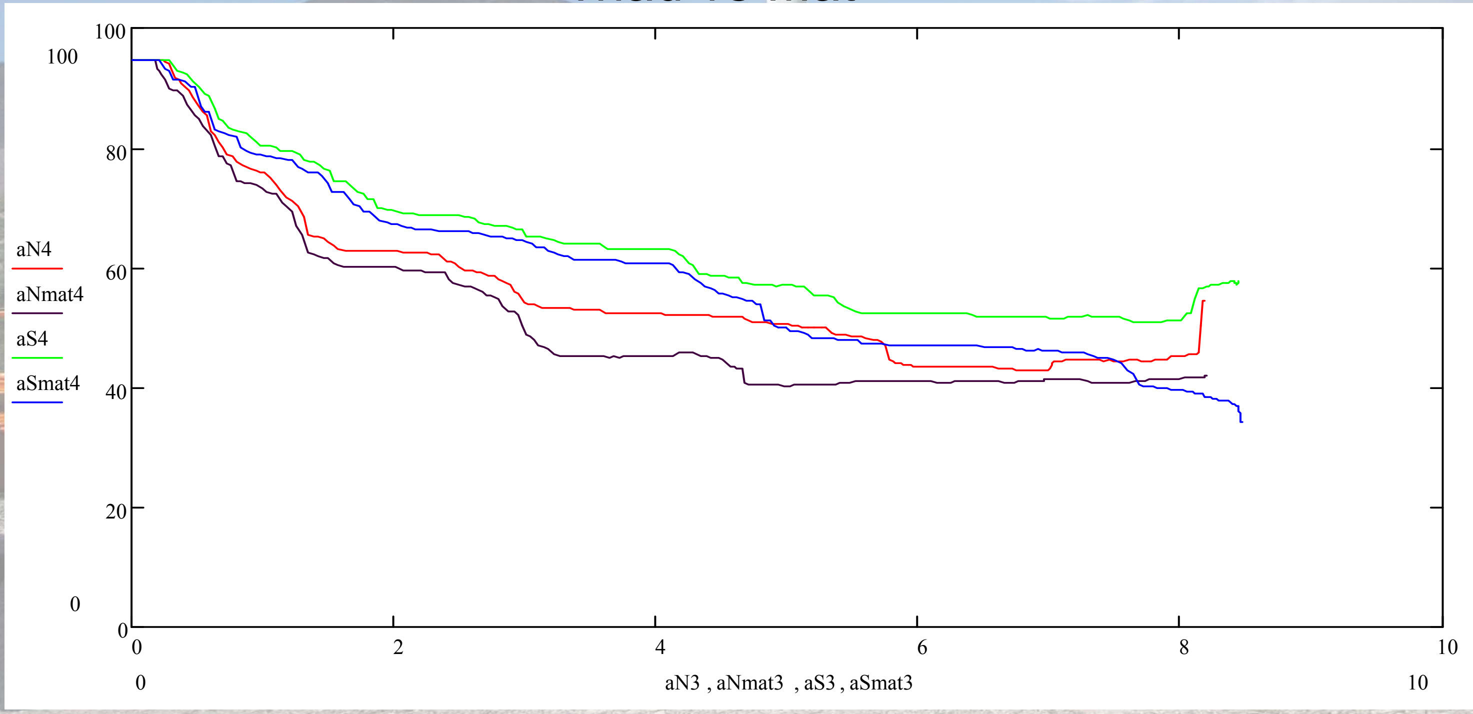




Further Study

- Currently under investigation in District 2 is the relationship between the ground system and surface wave propagation

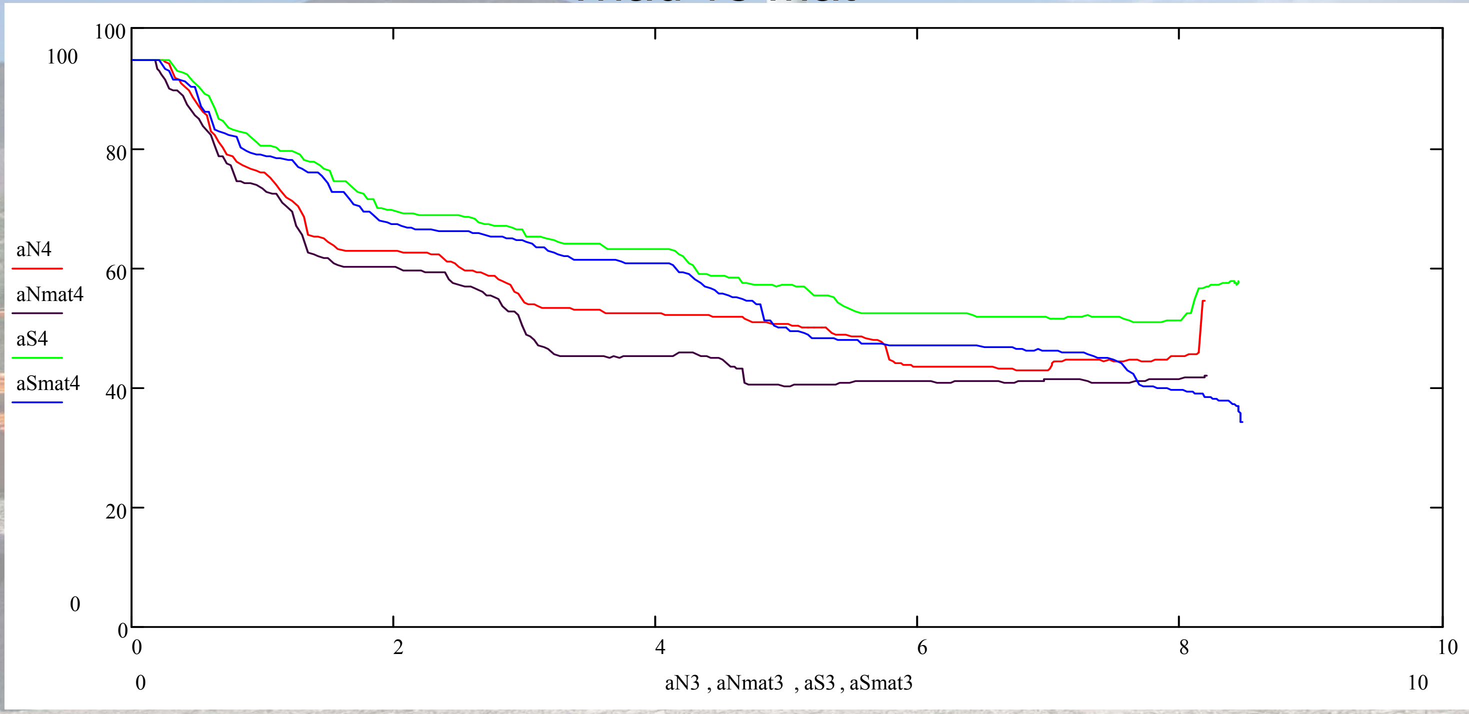
AbramsLakeHAR
Triad vs Mat



Further Study

- Whether surface waves play a roll at this time is unclear, but we do know, according to measured data, the ground system does affect signal strength, and the strength decays differently for different grounding systems

AbramsLakeHAR
Triad vs Mat




Applications to ITS
Mountain-Top Communication Sites

Mountain-Top Sites

- District 2 has three mountain-top sites and growing,

Hill900

Mountain-Top Sites

- District 2 has three mountain-top sites and growing,

Hill900

Bass Mountain

Mountain-Top Sites

- District 2 has three mountain-top sites and growing,

  Hill900

  Bass Mountain

  Sugarloaf

Mountain-Top Sites

- District 2 has three mountain-top sites and growing,

  Hill900

  Bass Mountain

  Sugarloaf

- The sites are used as data aggregation points for our point-to-point microwave network


Lightning Protection

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- Ground system important at Mountain-top sites

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- Protects sensitive equipment from transient voltages produced by lightning disturbances

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Lightning Protection

- Ground system important at Mountain-top sites
- Protects sensitive equipment from transient voltages produced by lightning disturbances
- Provides direct path to ground dissipating energy in the Earth
- Low ground resistance is the key
- Recommend 1-ohm ground resistance for high strike density areas

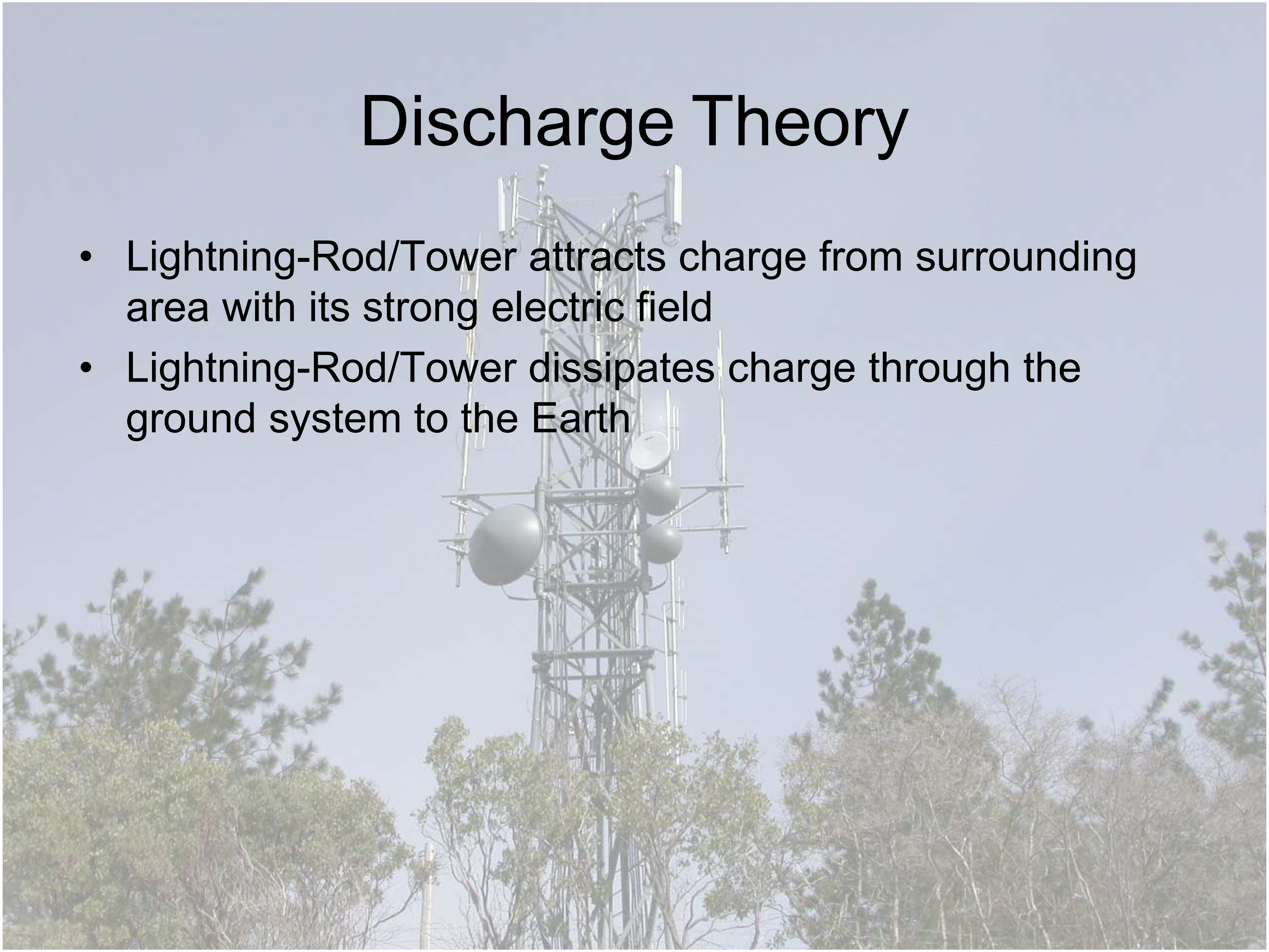
Lightning Damage can be costly


Prevention:
Lightning maybe…
Tornado No

Discharge Theory

- Lightning-Rod/Tower attracts charge from surrounding area with its strong electric field

Discharge Theory



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- Lowers potential for cloud-to-ground strike

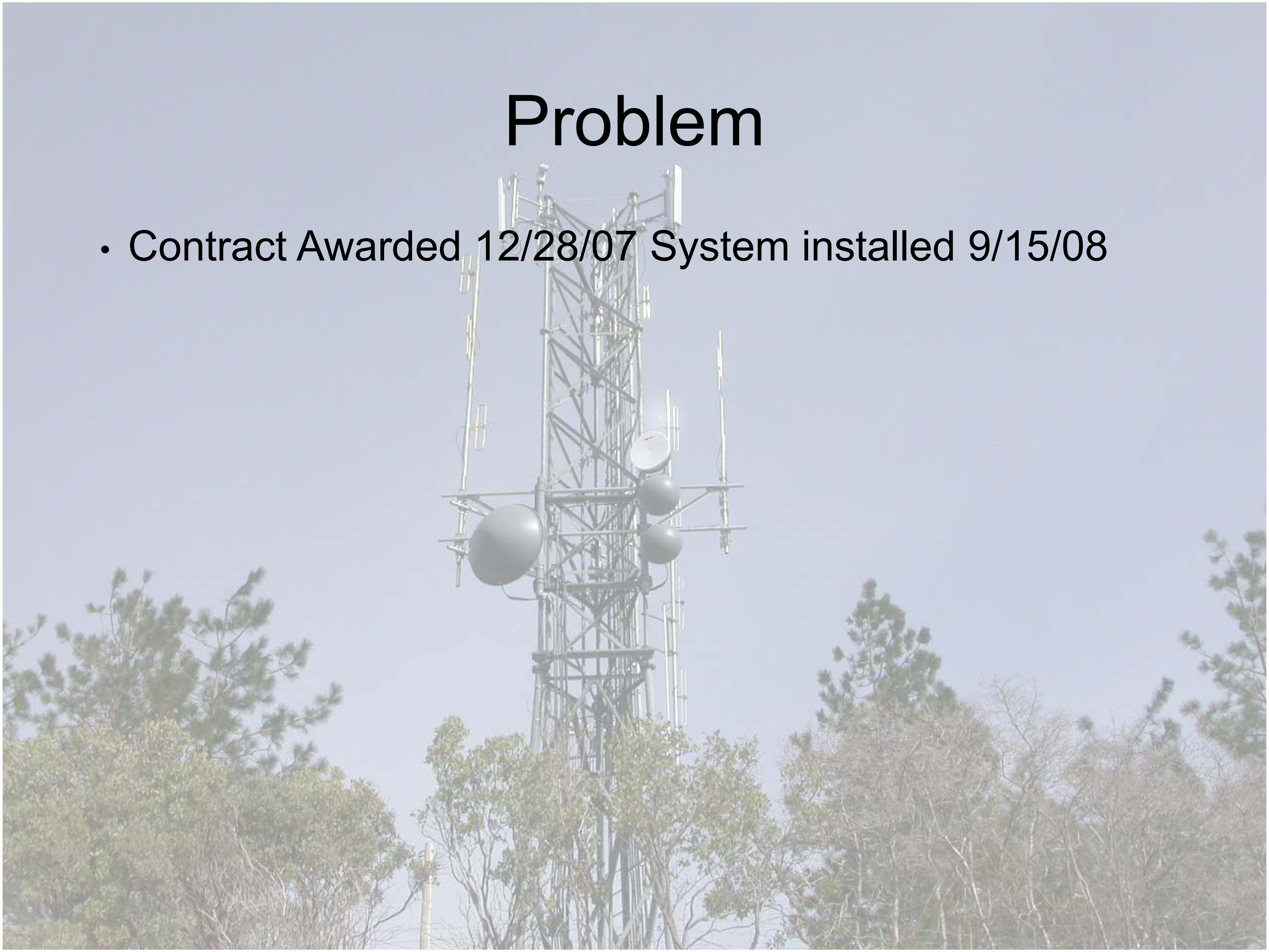
Discharge Theory

- Lightning-Rod/Tower attracts charge from surrounding area with its strong electric field
- Lightning-Rod/Tower dissipates charge through the ground system to the Earth
- Lowers potential for cloud-to-ground strike
- Tower now appears “electrically equal” to the area around it

Bass Mountain Ground

Problem

- Contract Awarded 12/28/07 System installed 9/15/08



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- Contract Awarded 12/28/07 System installed 9/15/08
- Tested by District 2 ITS Engineering 9/16/08, result 13 Ω

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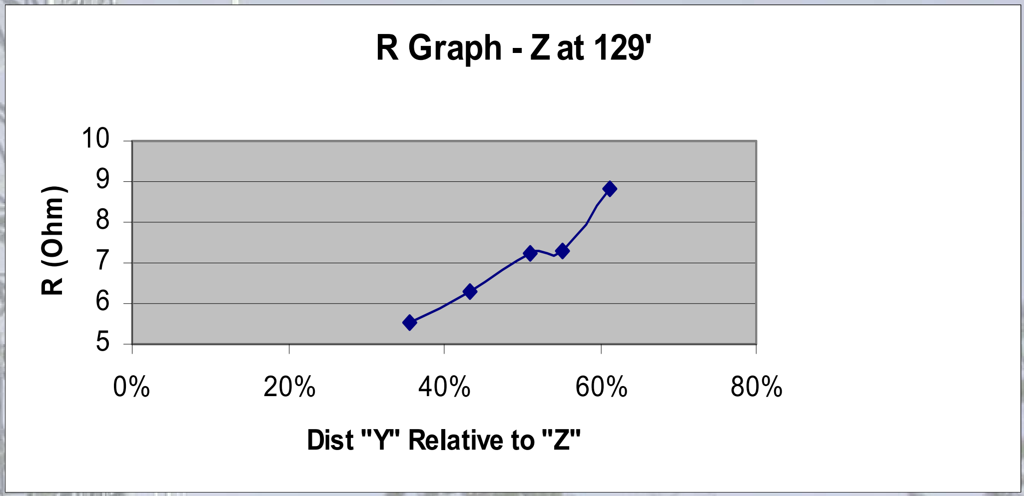
- Tested by District 2 ITS Engineering 9/16/08, result 13 Ω
- Tested by Contractor 10/03/08, result 7 Ω



Problem

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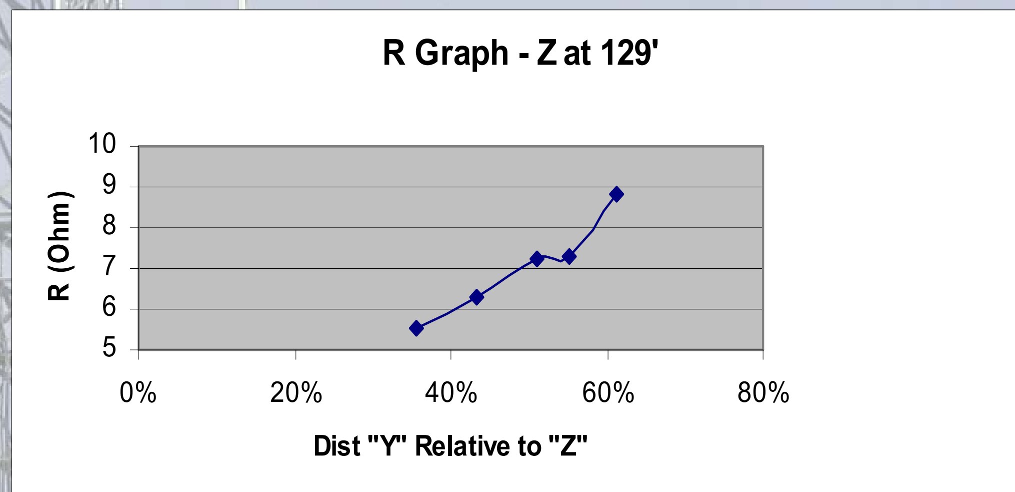
- Tested by Contractor 10/03/08, result 7 Ω
- Test performed in light rain and cooler weather



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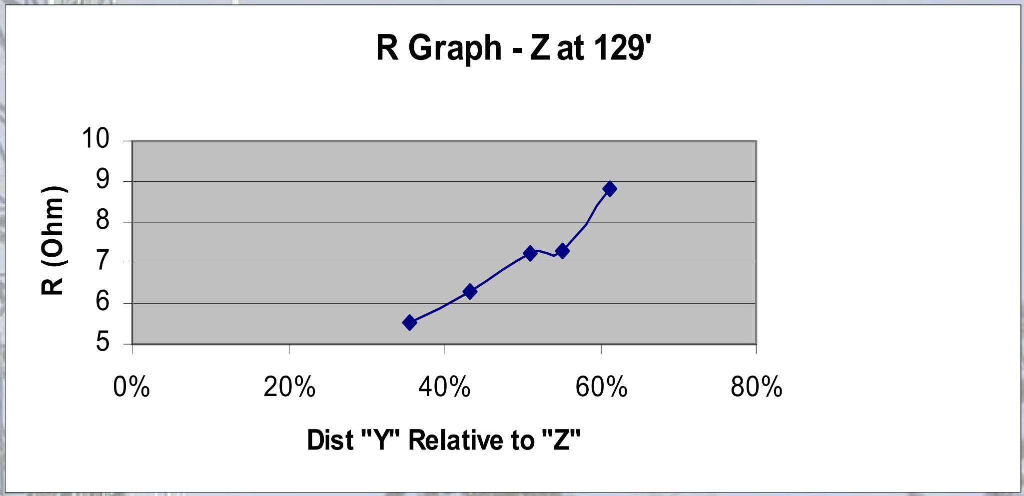
- Specification required a 1 Ω measurement to pass



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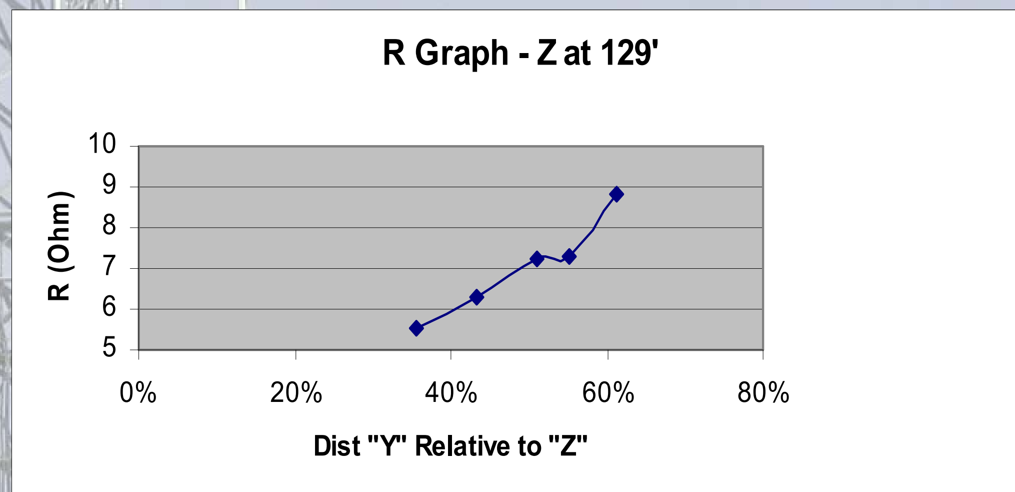


- Specification required a 1 Ω measurement to pass
- What happened?

What happened

- Ground system designed around a borrowed spec and not thoroughly researched

What happened

- Ground system designed around a borrowed spec and not thoroughly researched

- No soil resistivity measurement taken before design

What happened

- Ground system designed around a borrowed spec and not thoroughly researched
- No soil resistivity measurement taken before design
- Not built strictly to plan during construction

Solution

- Soil resistivity measured at site

Solution

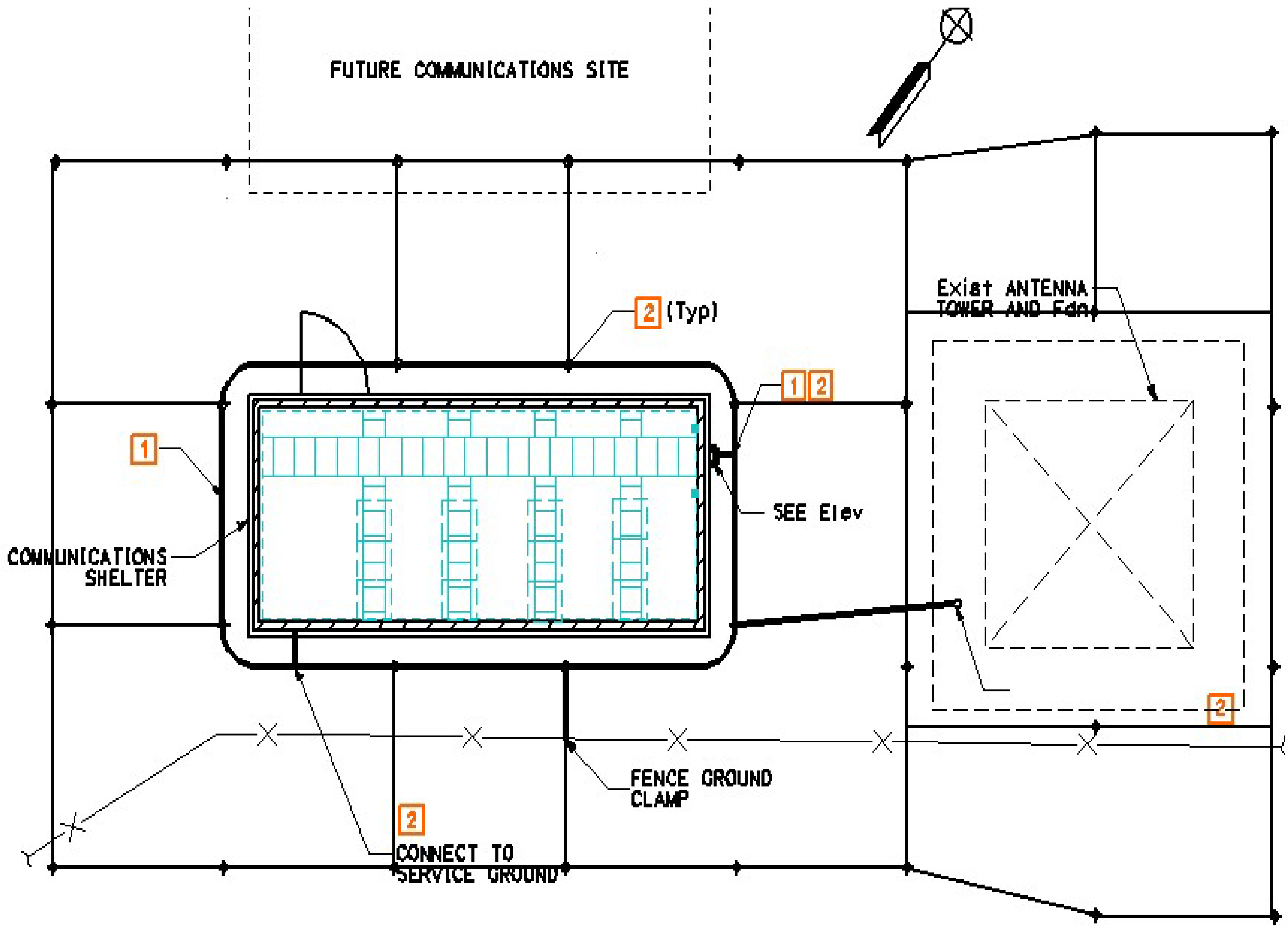
- Soil resistivity measured at site

  Result – 15 kΩ-cm

Solution

- Soil resistivity measured at site
- Several ground rod system configurations were looked at to build around existing configuration (impractical to remove existing system)

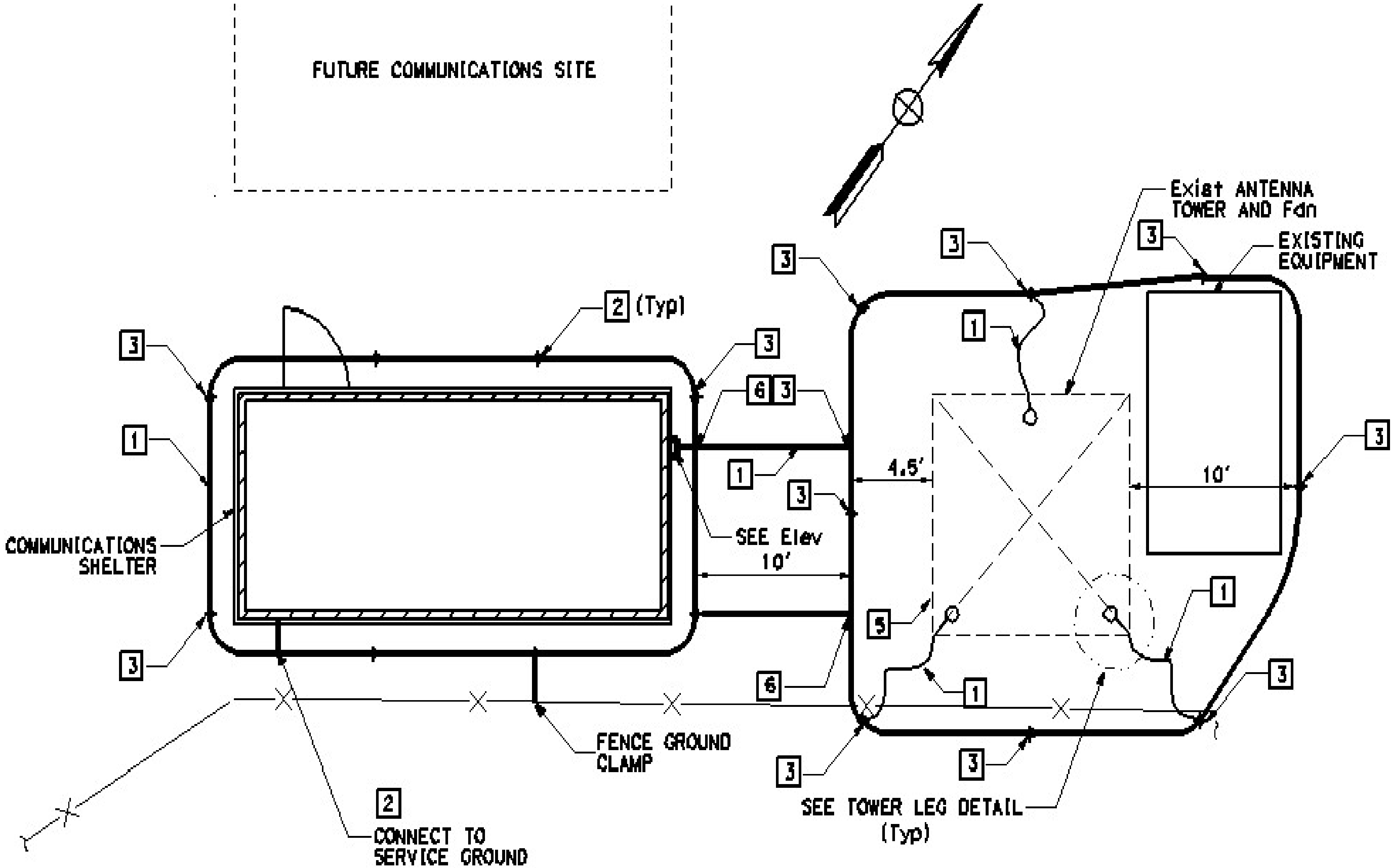
See next two slides for grid and complex configurations



PLAN

SCALE: 1" = 5'

EXTERIOR GROUNDING SYSTEM



PLAN
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EXTERIOR GROUNDING SYSTEM

Solution

- Soil resistivity measured at site
- Several ground rod system configurations were looked at to build around existing configuration (impractical to remove existing system)
- Theoretical ground system resistance calculated using nomograph's

See next three slides

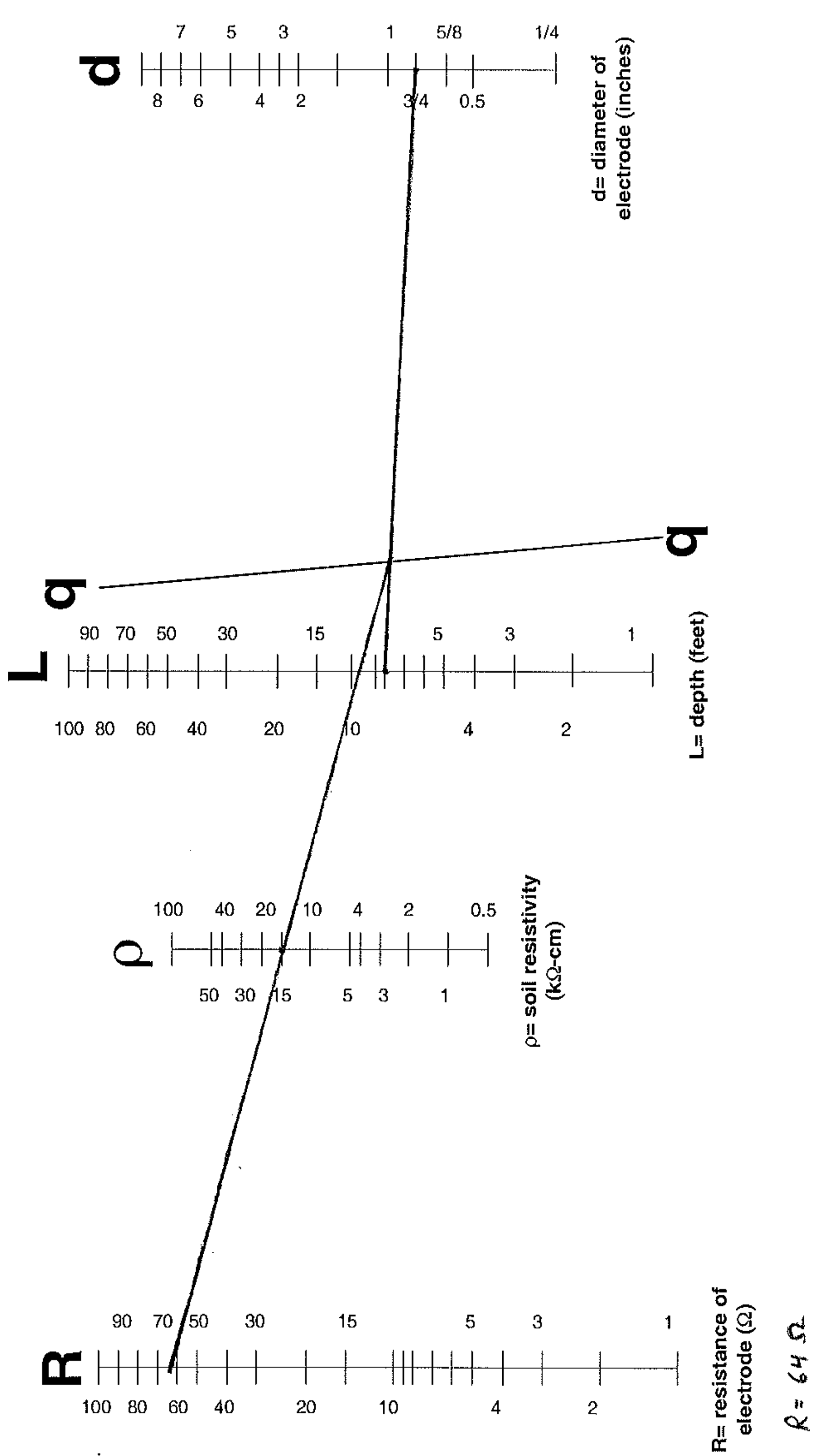


FIGURE 4-5 SOIL RESISTIVITY NOMOGRAPH

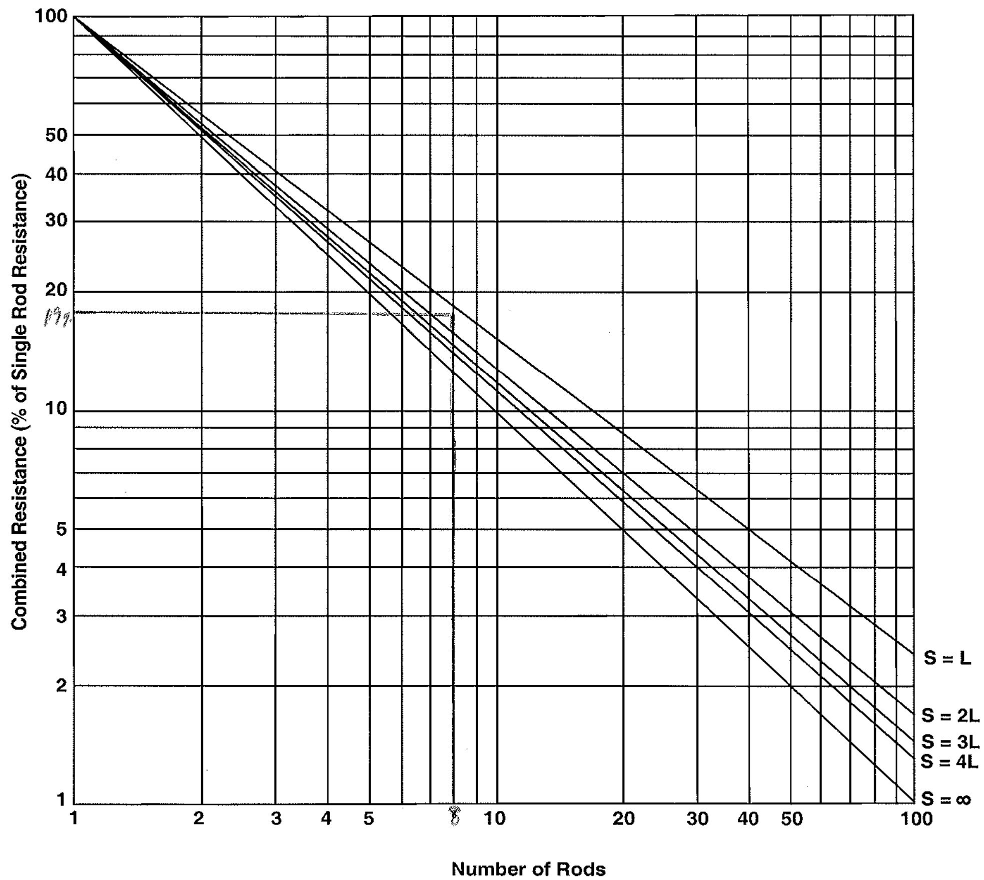


FIGURE 4-7 COMBINED RESISTANCE GRAPH (GROUND RODS ARRANGED IN LINE OR RING)

- Complex ground system calculation

- Subsystems modeled as a parallel resistance

- For Bass Mountain

$$1/R_{total} = 1/R_{building} + 1/R_{tower}$$

$$R_{total} = 8\ \Omega$$

Solution

- Soil resistivity measured at site
- Several ground rod system configurations were looked at to build around existing configuration (impractical to remove existing system)
- Theoretical ground system resistance calculated using nomograph's

Result – approximately 8 Ω

Solution

- Soil resistivity measured at site
- Several ground rod system configurations were looked at to build around existing configuration (impractical to remove existing system)
- Theoretical ground system resistance calculated using nomograph’s
- The most practical, cost effective configuration selected

Solution

- Soil resistivity measured at site
- Several ground rod system configurations were looked at to build around existing configuration (impractical to remove existing system)
- Theoretical ground system resistance calculated using nomograph's
- The most practical, cost effective configuration selected

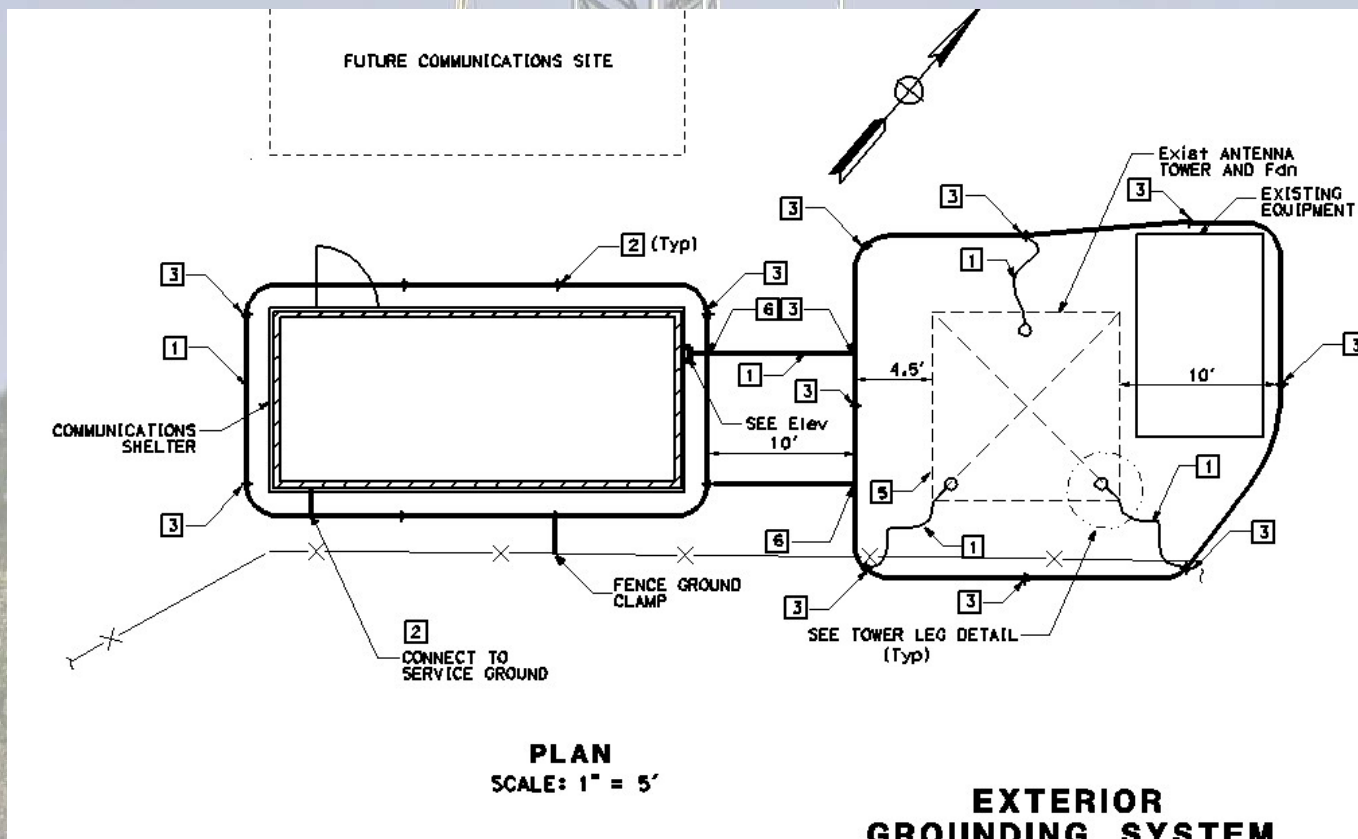
  Complex system selected (ring around tower)

Solution

- Soil resistivity measured at site
- Several ground rod system configurations were looked at to build around existing configuration (impractical to remove existing system)
- Theoretical ground system resistance calculated using nomograph’s
- The most practical, cost effective configuration selected
- Contract Change Order initiated

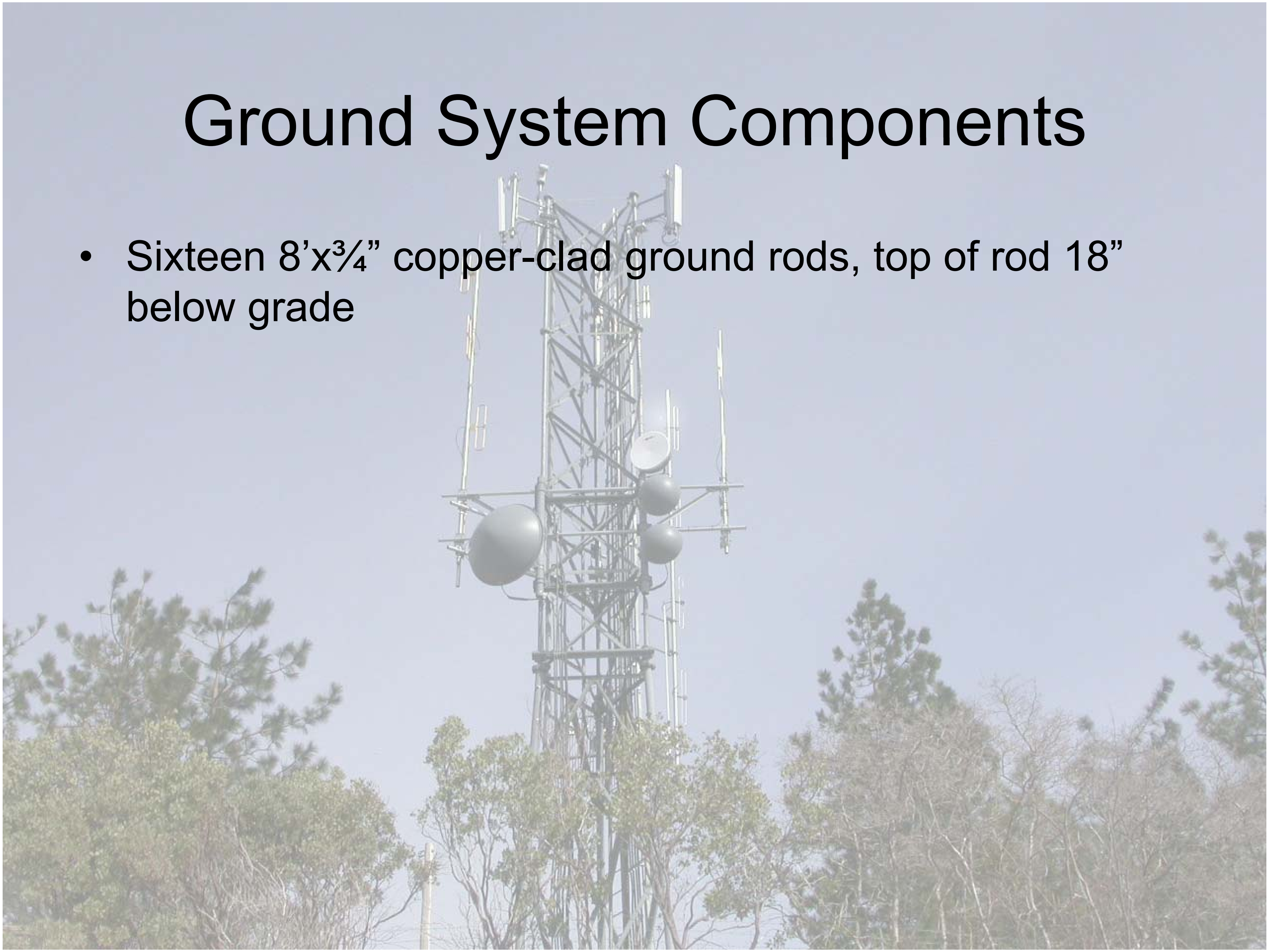
Bass Mountain Ground System

- Complex ground configuration – Eight-rod ring around tower, connected to building ground



Ground System Components

- Sixteen 8’x¾” copper-clad ground rods, top of rod 18” below grade



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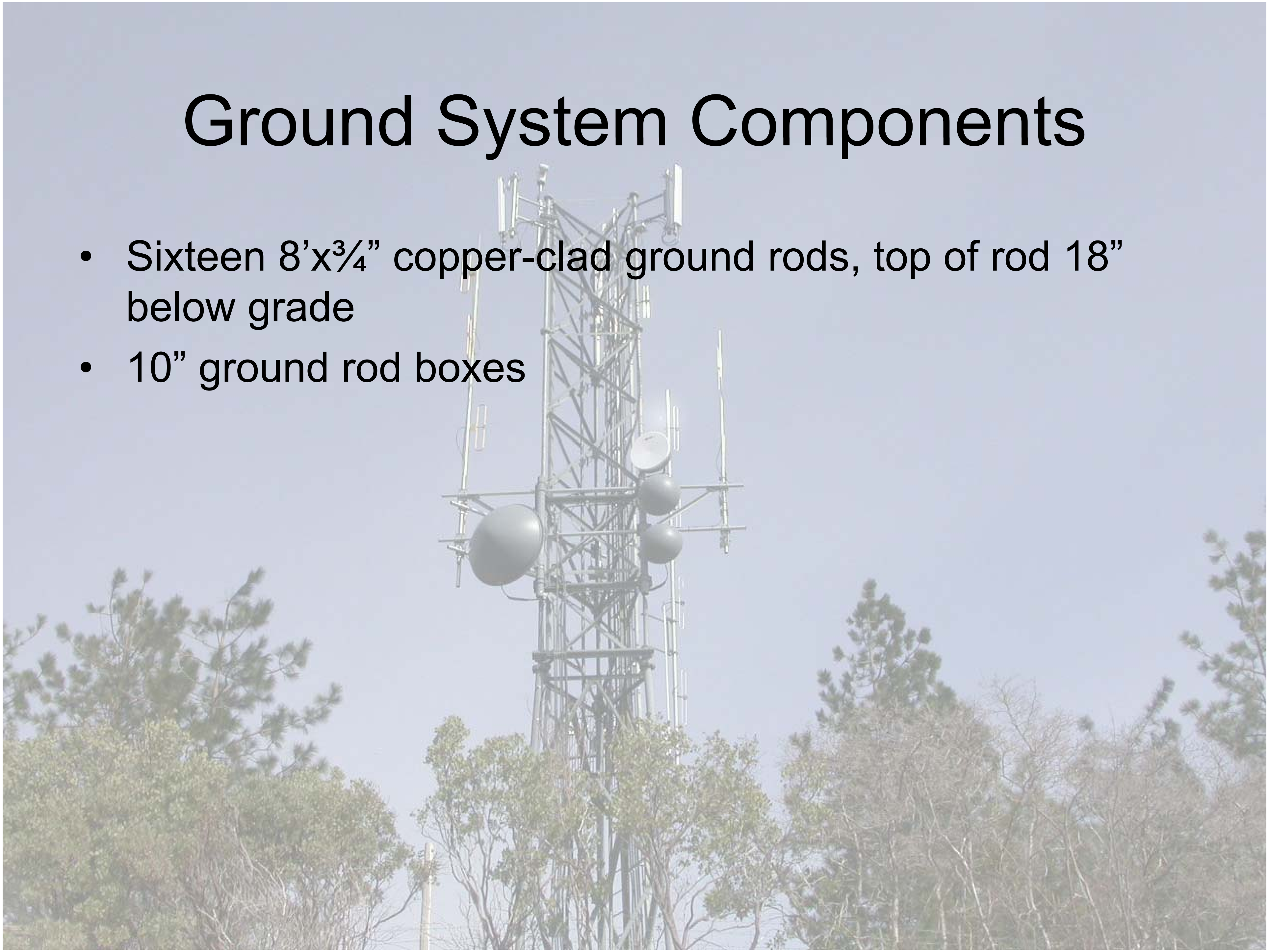
- 10” ground rod boxes



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- #1/0 bare copper ground wire, 18” below grade

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- Exothermic welds, important to know the layout and specify the molds

Ground System Components

- Sixteen 8’x¾” copper-clad ground rods, top of rod 18” below grade
- 10” ground rod boxes
- #1/0 bare copper ground wire, 18” below grade
- Exothermic welds, important to know the layout and specify the molds
- Exothermic weld lugs for a mechanical connection to tower

Ground System Components

- Sixteen 8’x¾” copper-clad ground rods, top of rod 18” below grade
- 10” ground rod boxes
- #1/0 bare copper ground wire, 18” below grade
- Exothermic welds, important to know the layout and specify the molds
- Exothermic weld lugs for a mechanical connection to tower
- Fence clamp

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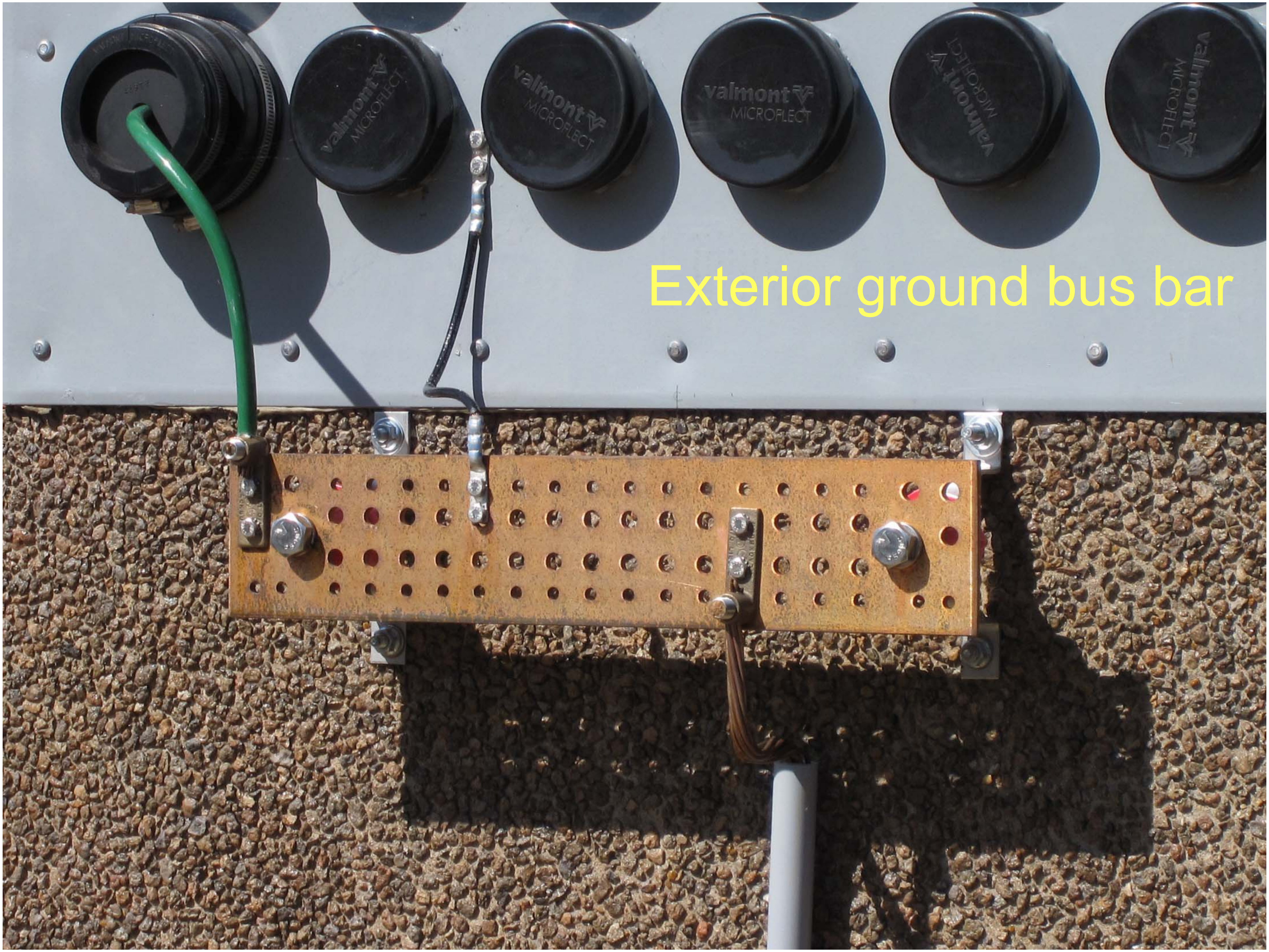
- Exterior ground bus bar


Bass Mountain cable entry


Exterior ground bus bar
valmont
MICROFLECT

Exothermic Weld in ground rod box

Ground System Components

- Interior ground bus bar

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- Rack ground connectors

Ground System Components

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- Tower ground bus bar

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- Rack ground connectors
- Tower ground bus bar
- Coaxial cable ground kits

Ground System Components

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- #1/0 bare copper ground connected to exterior ground bus bar
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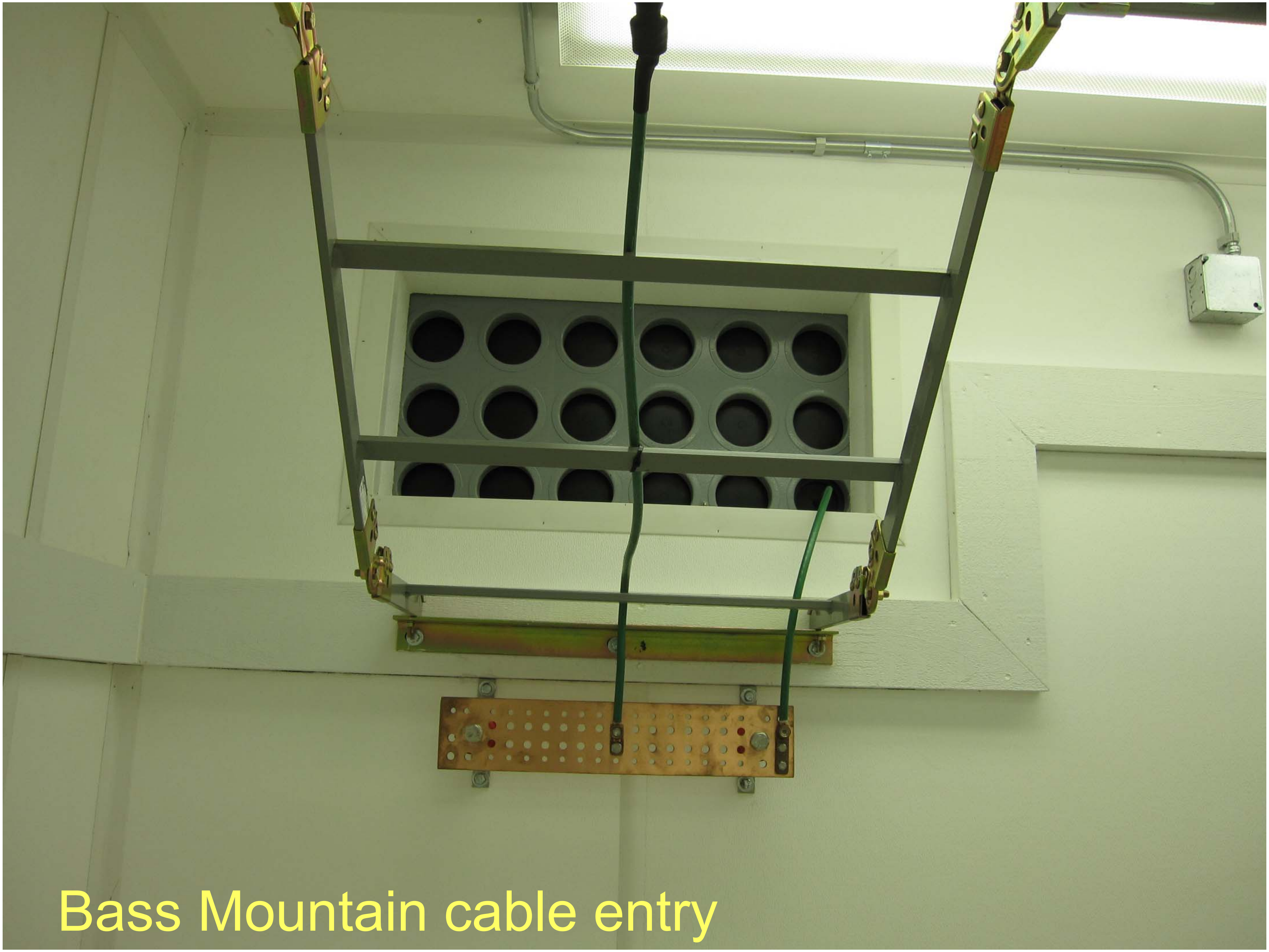
- Rack ground connectors
- Tower ground bus bar
- Coaxial cable ground kits
- Ice bridge ground connection

Ground System Components

- Interior ground bus bar
- #1/0 bare copper ground connected to exterior ground bus bar
- #1/0 insulated copper ground wire, run the length of the cable runway
- #8 insulated copper ground wire pigtailed above each rack location
- Rack ground connectors
- Tower ground bus bar
- Coaxial cable ground kits
- Ice bridge ground connection
- Service ground connection

Ground System Components

- Interior ground bus bar
- #1/0 bare copper ground connected to exterior ground bus bar
- #1/0 insulated copper ground wire, run the length of the cable runway
- #8 insulated copper ground wire pigtailed above each rack location
- Rack ground connectors
- Tower ground bus bar
- Coaxial cable ground kits
- Ice bridge ground connection
- Service ground connection
- Future generator ground connection



Bass Mountain cable entry


Interior ground bus bar

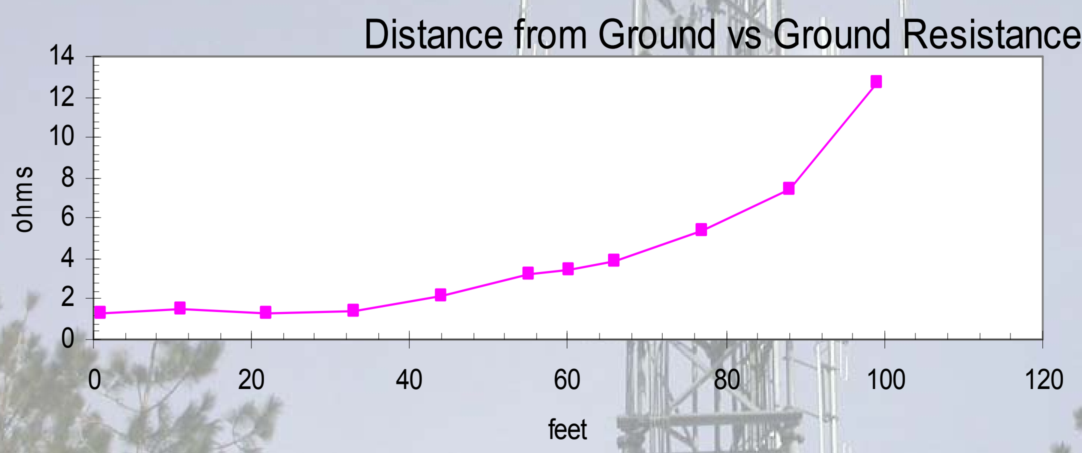

Ground bus bar on tower and coax ground kits

Additional Info

- Tower ground connection, many tower manufacturers don’t recommend exothermic welding on the tower base
- Minimize exothermic welds, each weld introduces resistance to the system
- Contractor used incorrect and/or unnecessary exothermic weld molds
- Everything metallic should be grounded at the site including guy wires, fence, generator, etc.
- Utility connection should be grounded

Ground Results

- Contractor test results after redesigned ground
  - Date 02-10-09
  - Weather light to moderate rain



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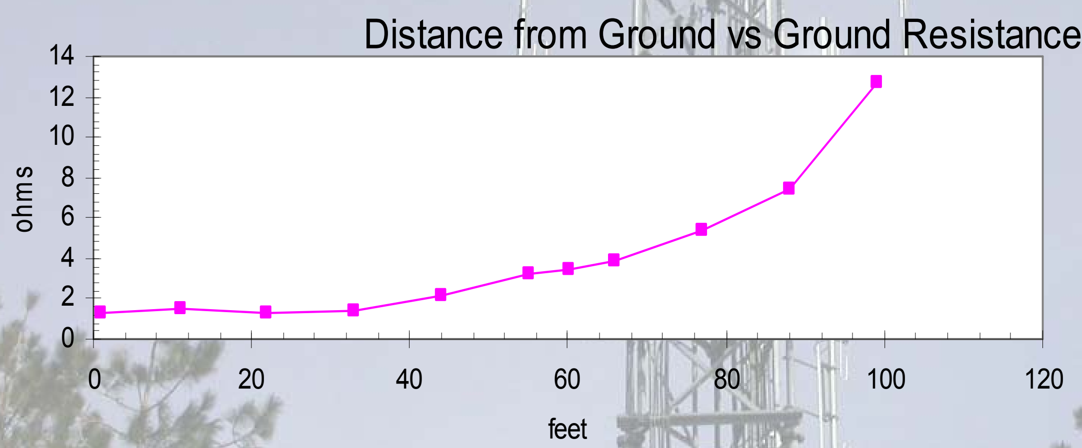

- Test not performed correctly

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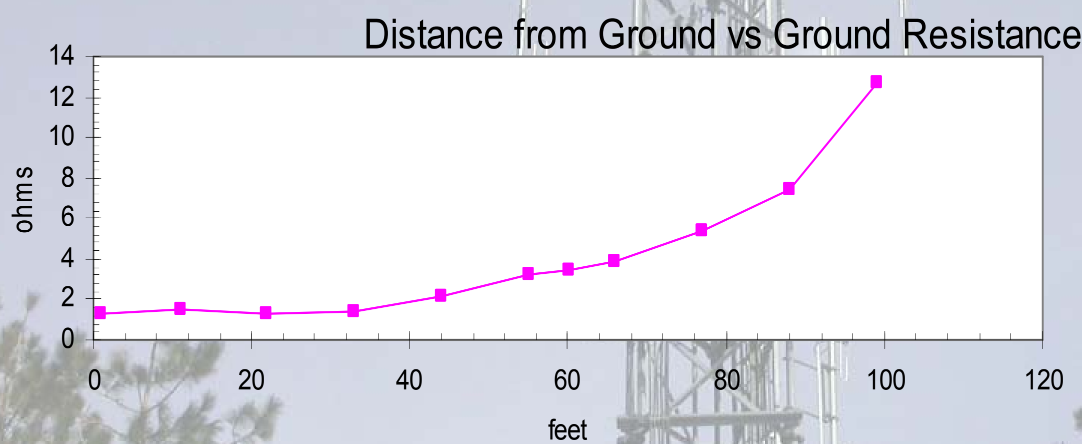

- Test not performed correctly
  - X-Z distance not large enough

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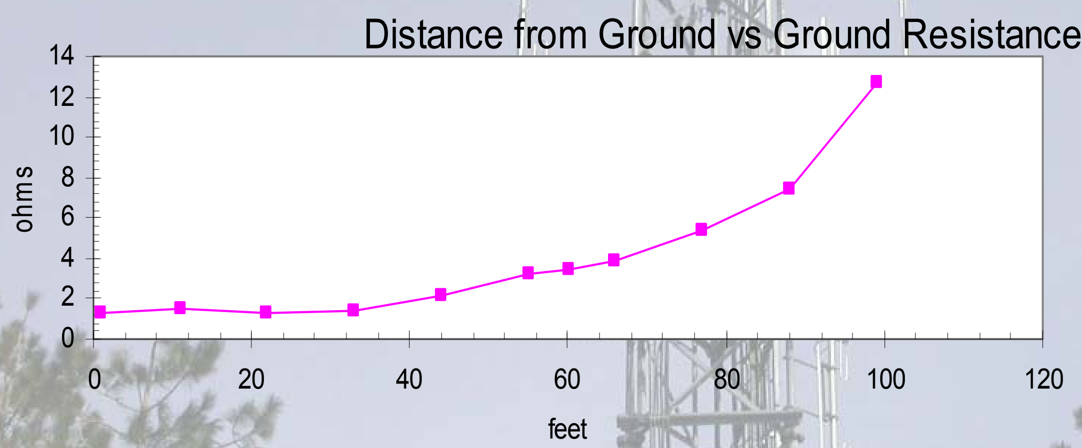
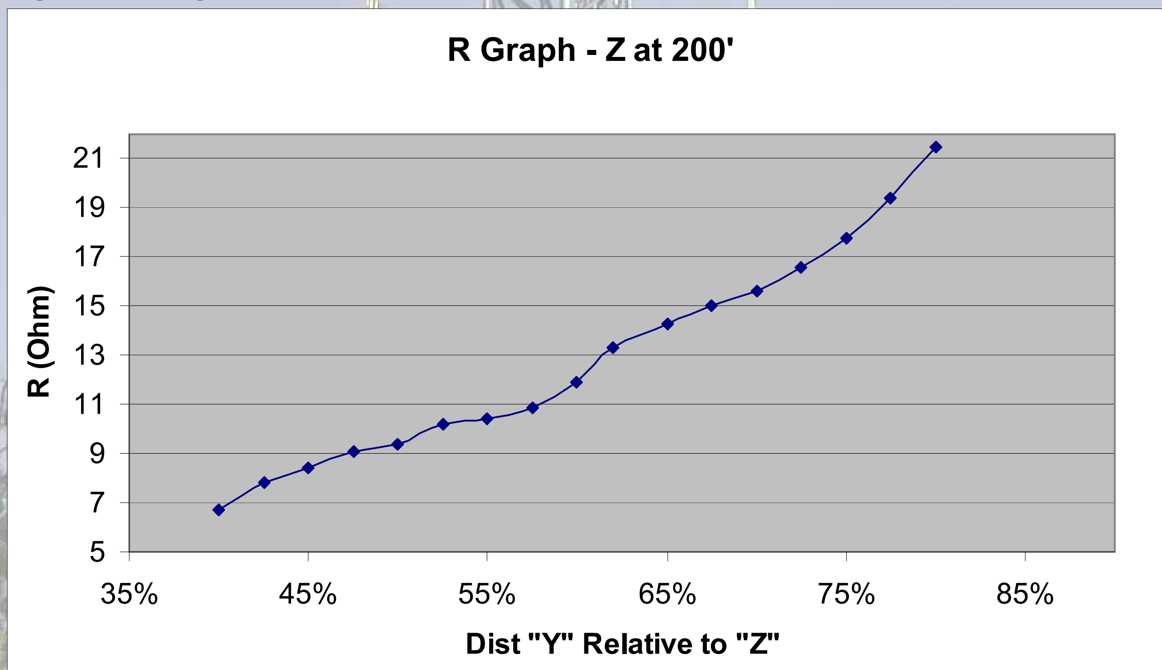


- Test not performed correctly
  - X-Z distance not large enough
  - X-Z ran parallel to building ground ring, should be perpendicular

Ground Results

- District 2 ITS Engineering test results after redesigned ground



- Effective ground resistance approximately 10 Ω

Lessons Learned

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  - Theoretical ground resistance value + margin of error

Lessons Learned

- Soil resistivity measurements are a key component to any ground system design
- Utilization of the proper design tools
- Good construction support
- Tighter specification on exothermic welds
- Tighter testing specification
  - Theoretical ground resistance value + margin of error
  - Where to test, and X – Z distance

Lessons Learned

- Soil resistivity measurements are a key component to any ground system design
- Utilization of the proper design tools
- Good construction support
- Tighter specification on exothermic welds
- Tighter testing specification
  - Theoretical ground resistance value + margin of error
  - Where to test, and X – Z distance
  - Test in dry conditions, if possible

Grounding Recap

- Obtaining soil resistivity measurements is the key to designing an effective ground system
- Design ground system for worse case
- Utilize design tools, nomograph's, software, etc
- For vertical antenna's, ground system very important
- For lightning protection, ground system important to protect sensitive equipment from lightning induced transients

Questions