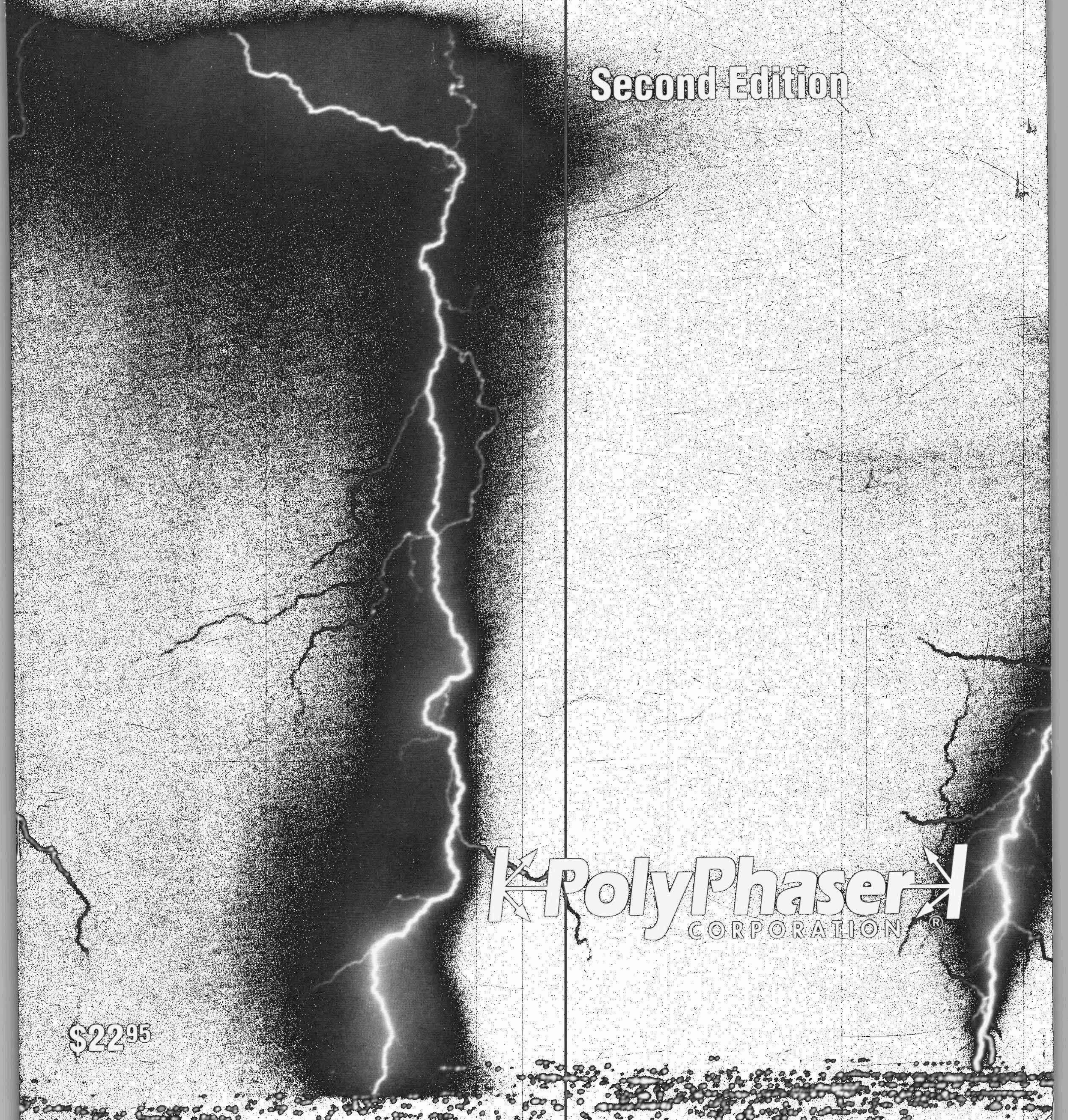
The "Grounds" for Lightning and EMP Protection

Second Edition



PolyPhaser CORPORATION ®

$22.95

The "Grounds" for Lightning and EMP Protection

SECOND EDITION

By Roger R. Block

Published by PolyPhaser Corporation

First Printing 1987

Second Edition, Revised 1993

Printed in the United States of America

INTRODUCTION

This book was written in a non-technical manner, with a minimum of formulas, so the maximum number of people could understand and install appropriate protection/ground system(s), to guard their communications equipment against all adverse pulses.

In 1983 this book started as a twelve page tutorial entitled "Impulse Suppression". It was enlarged to eighteen pages in 1984 and re-titled, "Lightning Protection for Radio Communications". In late 1985 and through most of 1986, a series of articles were published in trade journals. These articles were re-edited and additional unpublished material was incorporated to create, "The 'Grounds' for Lightning and EMP Protection". This second edition has new and re-edited material from our newsletter, "Striking News".

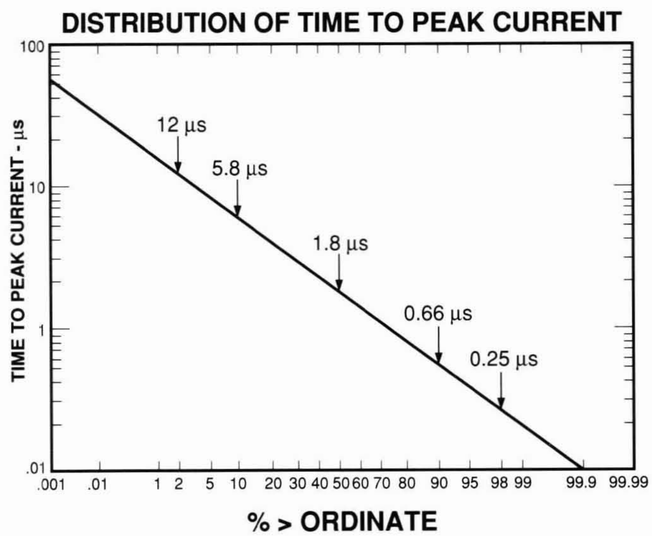
Many thanks to those who have devoted many hours to making this book possible: Gayle Block, Richard Dunning, Lorraine Grannis, J.J. Johnson, all of PolyPhaser Corporation and Arny Hass of Graphic Services.

Let us hope this book, as with our knowledge, will never have an end, for we are just beginning to learn and understand.

THE 'GROUNDS' FOR LIGHTNING AND EMP PROTECTION

chapter 1
Current Distribution

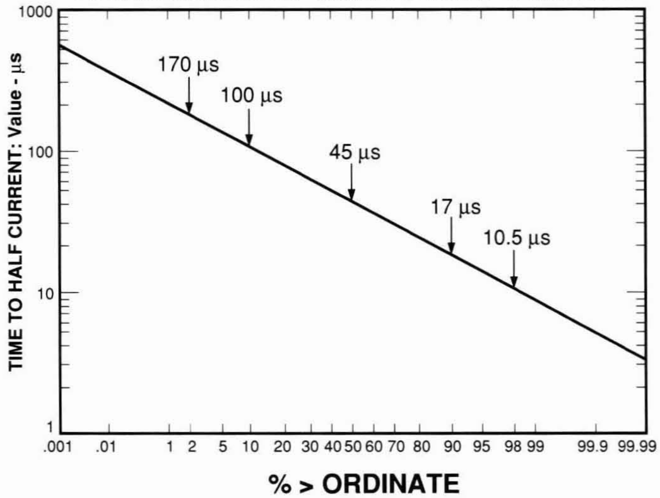
Much has been written on the techniques of Lightning Protection. Indeed, there is much to know about the art of proper grounding that encompasses the laws of physics and RF design. We hope you will follow these proven concepts which will protect your valuable equipment from even direct lightning hits. Whether your equipment is a radio site, pipe line, utility substation, telephone central office, tactical military, shipboard, or security installation, the same requirements apply for proper protection, installation and grounding.

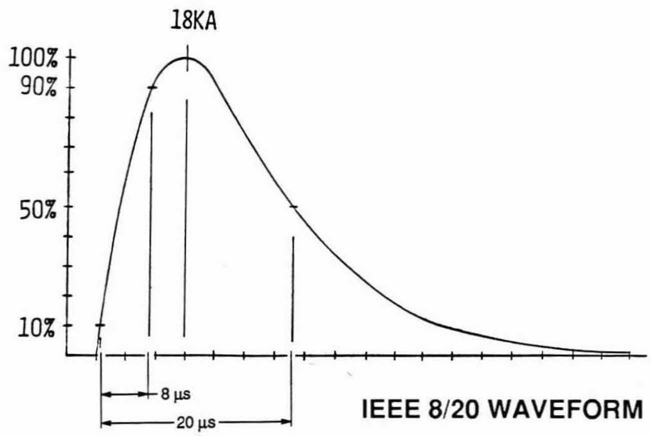


STROKES AND STRIKES

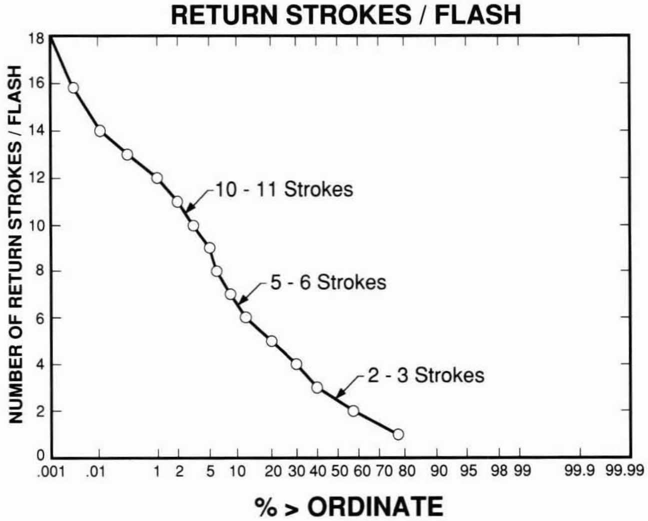
Lightning takes the form of a pulse which typically has about a 2µs rise and a 10 to 45µs decay to a 50% level. Presently, the IEEE Standard is an 8 by 20µs waveform. The peak current will average 18kA for the first impulse (stroke) and less (about half) for the second and third impulses. Three strokes is the average per lightning strike.

DISTRIBUTION OF TIME TO HALF CURRENT



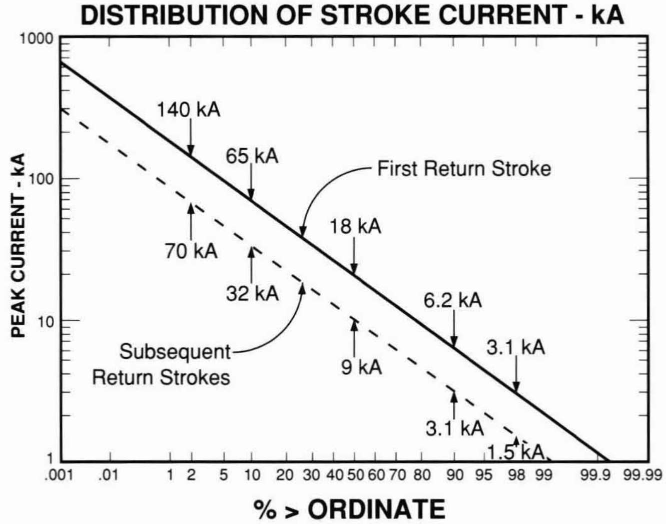


DISTRIBUTION OF THE NUMBER OF RETURN STROKES / FLASH



Once ionization occurs, the air becomes a conductive plasma reaching 60,000 degrees F and is luminous. This luminosity level is brighter than the surface of the sun! The resistance of a struck object is of small consequence, except for the power dissipation on that object ($I^2 \cdot R$). Fifty percent of all strikes will have a first strike of at least 18kA, ten percent will exceed a 65kA level and only one percent will have over 140kA. The largest strike ever recorded was almost 400kA.

DISTRIBUTION OF STROKE CURRENT - kA



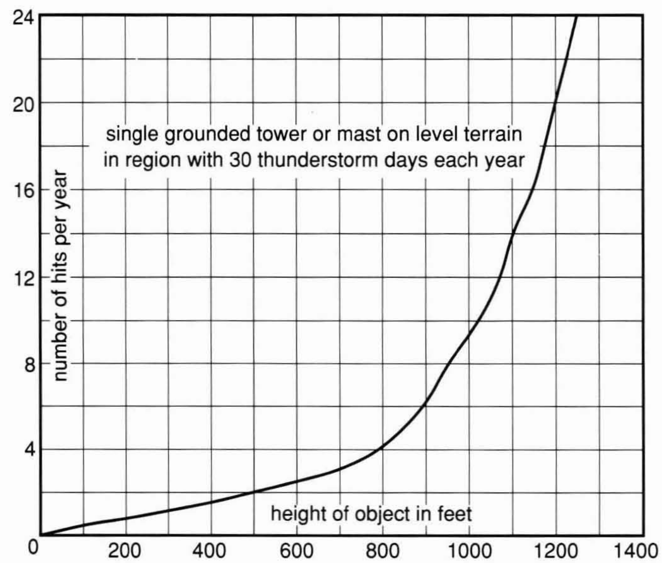


Chart shows strike susceptibility verses height based on Westinghouse data.

WHY THE DAMAGE AT TOWER SITES

Tower sites are struck by lightning more often than any other site. The reason is obvious; the tower is higher than the surrounding terrain and it's a conductor. Tower structures have a certain amount of resistance and inductance per foot. Most people think of resistance when talking about lightning. However, a tower with all of its weight has rather small joint resistance. A typical tower joint is less than .001 ohms. This may seem sizable when 18kA is traversing, but we will see that other larger voltages are present during a lightning strike.

Every conductor has inductance. The amount of tower inductance is dependent upon its geometric configuration. This width-to-height ratio and its height will determine the total inductance of a tower. A 150-foot tower, with 35-inch side widths, can have an inductance of about 40μH. This value of inductance can be approximated (W/H ≤ 1%) by treating the tower as a 1/4 wave antenna using:

$$\frac{468 \times 10^6}{2(\text{H in feet})} = f$$

$$\text{then inductance} \quad L = \frac{377}{2\pi f}$$

Inductance for either coaxial lines or single conductor grounding wire, can be estimated by using:

Length in Feet	Coax Diameter 1/2"	7/8"	1-1/4"	1-5/8"	2"	3"
100	51.0	48.0	45.7	44.2	43.0	40.4
150	81.0	76.0	72.3	70.0	68.0	64.3
200	111.0	104.0	100	97.0	94.2	89.2
300	174.0	164.0	157.3	152.5	148.7	141.2
500	306.0	289.0	277.8	270.0	263.4	251.0

Approximate Inductance In Microhenries
For Coaxial Lines

Length in Feet	Strap 6"	Strap 3"	Strap 1-1/2"	(0.46) 0000	(0.365) 00	(0.257) #2	(0.162) #6	(0.102) #10	(0.064) #14
5	1.07	1.28	1.49	1.68	1.75	1.86	2.0	2.14	2.28
10	2.56	2.98	3.39	3.78	3.922	4.13	4.4	4.7	4.98
15	4.21	4.83	5.46	6.04	6.25	6.57	7.0	7.42	7.85
20	5.96	6.8	7.63	8.4	8.7	9.1	9.7	10.25	10.81
25	7.78	8.83	9.88	10.85	11.2	11.7	12.44	13.15	13.85
30	9.67	10.93	12.19	13.35	13.78	14.4	15.26	16.11	16.96

Size & (Diameter)

Approximate Inductance In Microhenries
For Conductors

TO CALCULATE THE INDUCTANCE OF A WIRE USE:

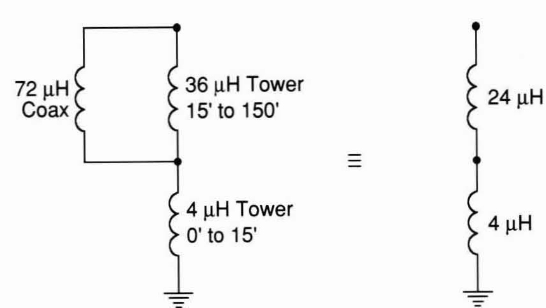
$$L(\text{in } \mu H) = 0.508\, s\, [2.303 \log_{10} (4\, s / d) - 0.75] \times 10^{-2}$$

TO CALCULATE THE INDUCTANCE OF STRAP USE:

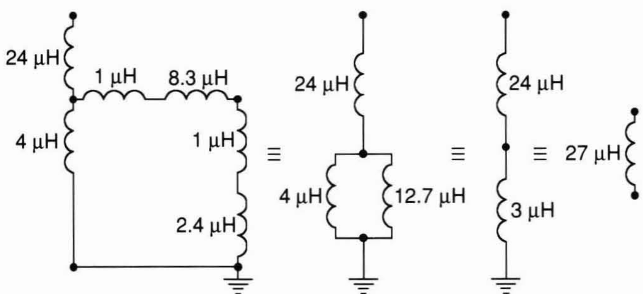
$$L(\text{in } \mu H) = 0.508\, s\, [2.303 \log_{10} (2\, s / (w + t)) + 0.5 + 0.2235\, (w + t) / s] \times 10^{-2}$$

Where s = length in inches
d = diameter in inches
w = width in inches
t = thickness in inches

Consider a 1/2-inch diameter coax running down 135-feet from the top of a 150-foot tower. It will have an inductance of about 72μH. If the coax shield is grounded at the top, as it should be, and at the 15-foot level of the tower (a location that we shall soon see is not optimal), then the total inductance of the tower would be:



If the coax line traverses 20-feet horizontally to the equipment hut and goes to a grounding kit plate having a 6-foot long, #6 ground wire, the total **shield** inductance for this path is 12.7µH. To account for each directional change - one for the coax bend at the tower and one for the ground plate, 1µH was added. This figure is used to facilitate calculations. The real value for a sharp bend is more in the order of 0.15µH and is dependent on the size and shape of the conductor.



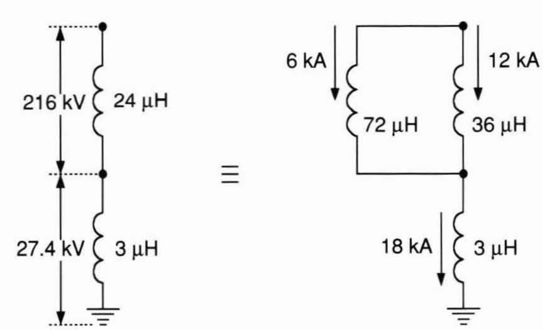
A perfect conducting ground system (with a non-inductive connection) is assumed. With a 2µs rise time, 18kA constant current strike hitting the tower, an L di/dt of 243kV will exist between the top of the tower and the bottom!

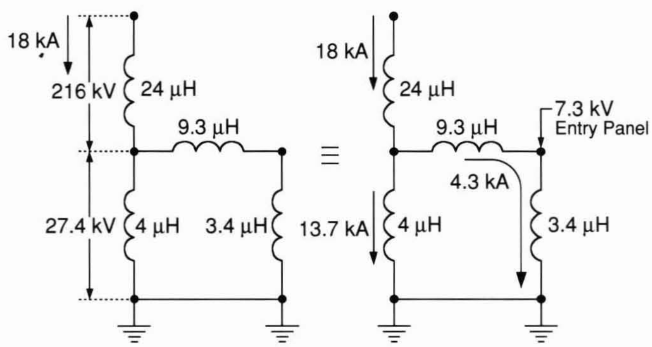
GROUNDED ANTENNAS: THE BEST WAY

For a long time antenna manufacturers have been utilizing shunt fed and dc grounded antennas as a means of providing some form of lightning protection to their customers. It has been proven that these antennas do work and should be used as a means of diverting a portion of the direct strike energy to the tower and its ground system. Unfortunately this protection is to help the antenna survive and **not** your equipment. A direct hit, or even a near hit, can ring an antenna whether it is grounded or not; after all, it is a tuned (resonant) circuit. However, only a grounded antenna can handle a direct hit. The ringing waveform will contain all resonances that are present in the antenna. This means both "on frequency" ringing and other frequencies will be present which will propagate down the transmission line towards your equipment. The "on frequency" energy will not be attenuated by a high Q duplex filter or a 1/4 wave grounded stub being used as a protector. In both instances, the energy will pass right through. Also, if we look at a typical dc grounded/shunt fed antenna at the top of our 150-foot tower example, both the center conductor and shield will be at the same 243kV potential above ground at the antenna feed. Although the grounded antenna will help prevent arc over of the transmission line, it will have a 6kA peak current traversing the coax. The same parallel tower segment will have 12kA. (Coaxial surge current propagation between the center conductor and shield is addressed later.) The shared strike current, between the tower and the coax, will contain mostly low frequency components. (A non-grounded antenna will arc over between center pin and shield, creating major high frequency components that will traverse the transmission line to your equipment.) The lack of high frequency components is due to both the grounding of the antenna and the inductance of the tower/coax which acts as a "filter". The antenna ringing, with much higher frequencies, will ride on top of these lower frequencies towards your equipment.

IT'S WRONG!

As we look at the junction point of the coax and tower, we see the tower will carry the major part of the surge. The ground plate will have 4.3kA delivered to it and be elevated to 7.3kV above system ground. Hardly a ground is it! This is only true for this configuration. Add another coax line or a grounded guy wire and it is completely different. (The purpose of this exercise is to show that the grounding of the coax at this elevated point on the tower is wrong. There is a better way of addressing this grounding.)





So far, we have taken a look at the current distribution on a self support tower for a typical strike. Now, let's see what happens to the coax line and the connected equipment.

If the coax line were left unterminated as it reaches the ground plate, the coax could arc over center conductor to shield, even if a grounded antenna was used on the tower. This is due to the difference in propagation between the shield and center conductor and the additive ringing voltage. It is important to eliminate or stop this energy from being delivered to your equipment. Since coax lines are rarely left unused, (especially connected to an antenna) these voltages will be converted to some current either via an arrestor, shunt fed cavity or by arcing over dc blocking capacitors inside the equipment.

DC ARRESTORS SHARE SURGE WITH EQUIPMENT

Lightning arrestors with dc continuity, such as a typical air gap, simple coaxial gas tube arrestors and 1/4 wave coaxial stubs, cannot divert this strike voltage without sharing some of it with the equipment. This "sharing" for dc continuity spark type arrestors, occurs during the time period between zero volts and when the threshold for turn-on has been achieved.

For 1/4 wave coaxial stubs, from 2GHz and down, the inductance of the stub will allow several hundreds of volts to be presented to the equipment (357Vp measured for a 900MHz 1/4 wave stub with a 40kA 8/20µs waveform). This is due to its inherent L di/dt inductive voltage drop, along with perhaps making the on frequency antenna ringing voltages greater, because of its own high Q ringing. All of this assumes your equipment has internal capacitive coupling to the center conductor of the coax line. If it doesn't, such as in the case of a shunt fed repeater duplexer, the lower frequency voltages are immediately converted to a current. In this case, these dc continuity type arrestors would be useless in stopping the surge current because the sparkover arrestor would never turn-on and the 1/4 wave stub will share surge current with the equipment.

SURGES DAMAGE DUPLEXERS AND ISOLATORS

Not all duplexers have shunt feeds, but those that do can handle some amount of the lower frequency lightning surge current if properly grounded. It depends on the length (frequency band), the size of the shunt fed loop and the stiffness of the loop. (It is really best to prevent the lightning energy from ever entering the equipment hut, let alone the equipment itself. Not doing so, is like letting the wolf into the hen house. It is tough to get the wolf out without losing a hen!) Tremendous magnetic fields can be generated in the duplexer which can bend the loop, detune the cavity and allow even stronger magnetic fields to exist in subsequent strikes. The strike can also weld the cavity input connectors together so the coax line can not be removed. The "on frequency" antenna ringing can create large voltages inside the cavities and cause internal arcing if an isolator is not used. If the first piece of equipment seen by the incoming low frequency coax surge is an isolator, with each strike, a gradual increase in insertion loss will occur due to the surge current's magnetic field orienting the ferrite material and changing the magnet's flux density.

THE BEST PROTECTOR

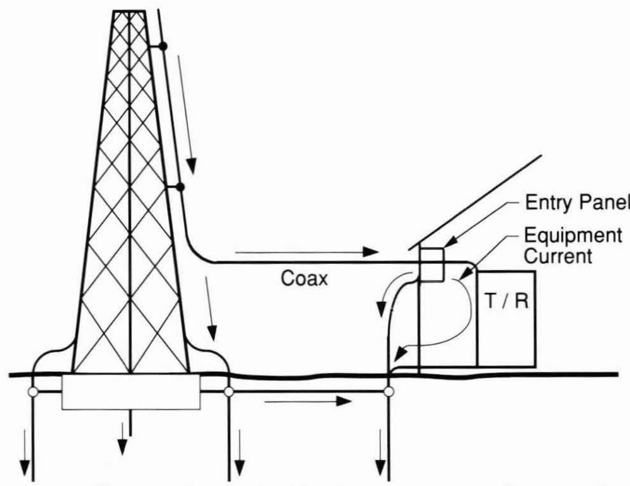
The most effective type of lightning arrestor has a special ultra-low loss, NP0, high voltage breakdown blocking cap. This internal cap will prevent the sharing of the low frequency surge current with the equipment and allow the "Impulse Suppressor" to fire as the voltage reaches the turn-on threshold. Such units are in the patented PolyPhaser Corporation's Impulse Suppressor Family. They go one step further by utilizing a fast, low-threshold, high current handling gas tube in lieu of the humidity/temperature sensitive air gap.

PolyPhaser has given considerable attention to the gas tube design to insure that when transmitting, the RF power will not keep alive the gas in the tube after a strike. Many other protectors, even those licensed by our patent, use a type of gas tube which will not extinguish properly. The transmit energy continues to excite the tube which becomes a broadband noise generator and will finally burn up unless the transmit power ceases. Still other arrestors use an internal grounding coil designed to drain any coax static voltage build up. (There would not be any, if a dc grounded antenna were used!) On a PolyPhaser protector, if a grounded antenna can't be used and voltage does build up, it will not get to your equipment. As the PolyPhaser protector reaches threshold for turn on, it will go into a momentary soft turn-on as the gas barely ionizes and bleeds the static charge to ground. This does not create noise since it will not get to the arc mode and lasts only a short time. The other brand protector uses a coil. The coil is in parallel with the gas tube and does not help filter higher frequency components like antenna ringing, etc. This type of design uses a simple gas tube and has the gas tube extinguishing problem. An additional problem of this design is the coil, which has added insertion losses, resonances and is wound on a ferrite torrodial core. When a hit occurs, the coil's magnetic field orients the domains of the ferrite core and degrades the inductance value of the coil. This causes further RF losses with each successive hit. (Over 90% of the strikes are of the same polarity so the effects of repeated hits are cumulative to the core.) PolyPhaser uses only air core coils where they are required. The coils carry a very small inductance and create a low L di/dt voltage drop.

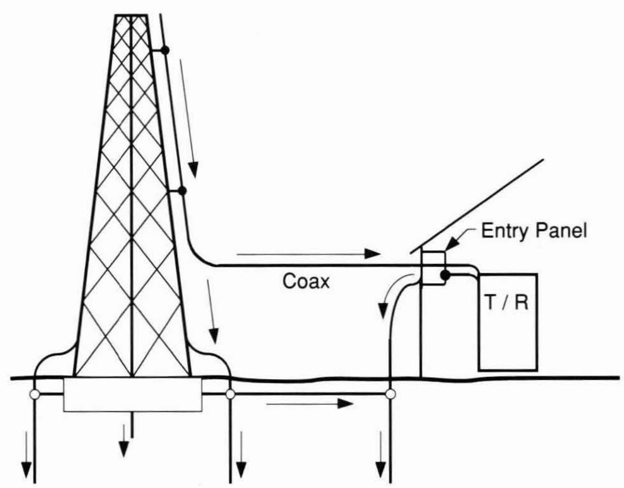
Additionally on some models, PolyPhaser's built-in bandpass filtering helps reject multi-resonances of the antenna from reaching the equipment. (Special antenna mounted protectors are now being tested to prevent the on frequency ringing of the antenna.)

SINGLE POINT GROUNDING

In order to have the coaxial protector work, the grounding must be implemented properly. As our example illustrates: the outside coax ground plate will rise to 7.3kV above the ground system, emphasizing the importance of a single point grounding concept. If the equipment has a separate path to ground, in addition to the ground plate (such as the safety ground of the power cord), then that parallel path will allow strike current to flow through the equipment chassis causing problems.



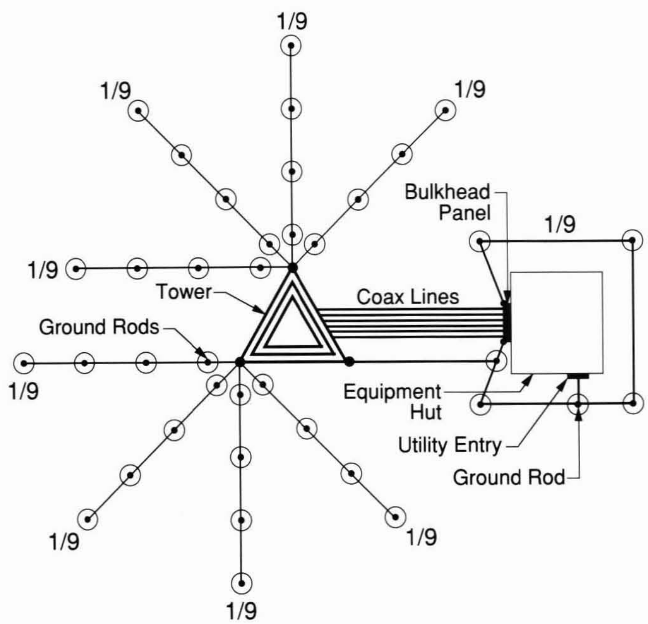
Grounding equipment at bottom creates a loop and surge current can traverse the equipment rack, hiccupping or destroying the equipment.



This shows proper grounding of the equipment. If coax cables enter the equipment high, ground high. If they enter low, ground low.

For small to average size equipment rooms, it is best to have the equipment's input/output (I/O) protector ground and equipment chassis tied together. The telephone line protectors, coax protectors, and power line protectors are then grounded either on a bulkhead panel or mounted together on a single point ground plate and tied to system ground. Equipment chassis ground would then be connected by a **single** low inductance strap to this ground point.

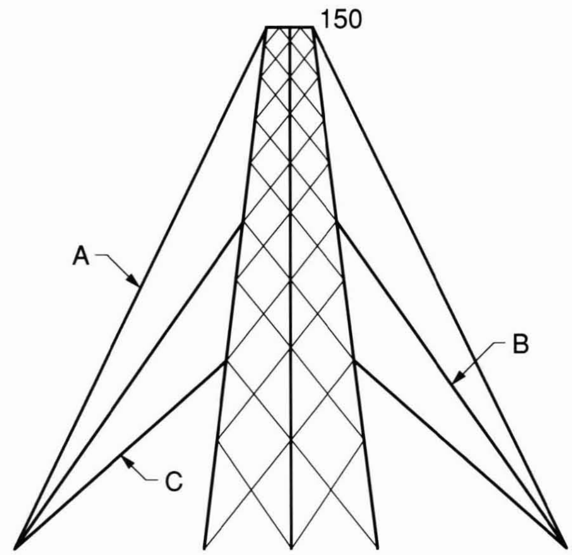
The exterior ground system consists of the tower leg grounds, utility ground and bulkhead equipment ground stakes. The radials are tied together with bare buried copper wire or copper strap.



LIGHTNING: CURRENT DISTRIBUTION GUYED TOWERS

So far, we have looked at a self support tower. We can conclude that without proper protection and grounding, our equipment will suffer damage. Now, let's look at the current distribution on a guyed tower. The guy wires and grounded guy anchor points perform an important role during a lightning strike.

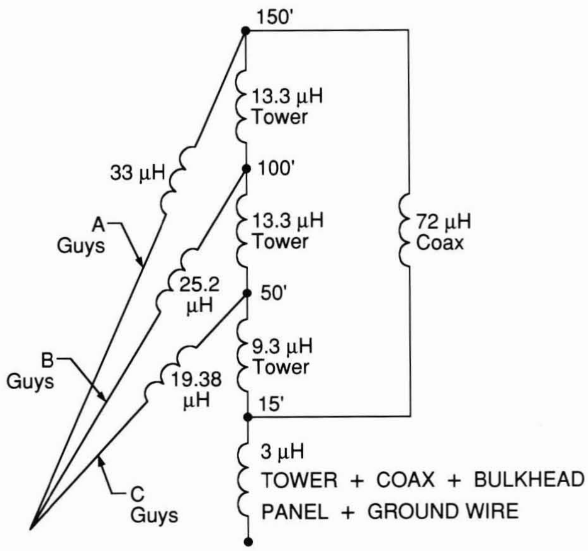
The same 150-foot tower, with 35-inch side widths, will be used as the example. The use of 1/2-inch diameter guy cable with no insulators would look like this:



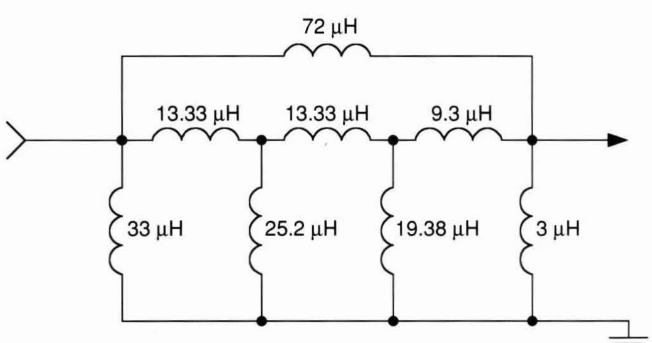
Example	Length In Feet	Inductance In μH	Inductance (μH) for 3 in Parallel
A	180.28	99.00	33.00
B	141.42	75.60	25.20
C	111.80	58.14	19.38

On a triangle base tower, where "A" is approximately 180-feet long or about 99μH each, there would be 3 "A's" in parallel or 33μH total inductance. This will significantly change some of our L di/dt values! Likewise, the lengths of "B" and "C" would be used to calculate their inductance contributions. The thing to remember is - "B" and "C" touch the main inductor (the tower) at different heights (inductances). These heights must be transformed into their appropriate values of inductance before the values of guy point inductances can be combined.

To keep it simple, our guy attach heights are at 150-feet, 100-feet and 50-feet. Our complete structure looks like this:



After re-drawing the tower circuit to:



Calculating this equals about 12μH top to bottom.

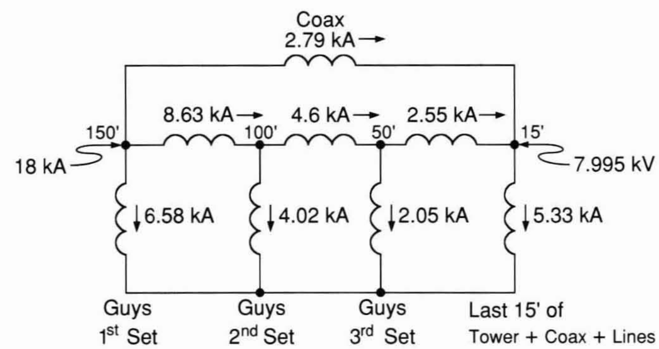
When the 18kA lightning strike occurs, it will have a voltage drop of

$$L\,di/dt = \frac{12\mu H \times 18{,}000}{2\mu s} = 108{,}000 \text{ Volts}$$

from tower top to bottom ground.

This is less than half of the voltage drop of the self support tower without guys.

The distribution of current on this set-up is a little more complicated. Using mesh current network analysis:



Average Coax Current is 2.79kA

The coax run to the ground plate would have only 1.26kA going to it and would be elevated to 2.14kV. Again, this is far less than the 4.3kA and 7.3kV of the self-support tower!

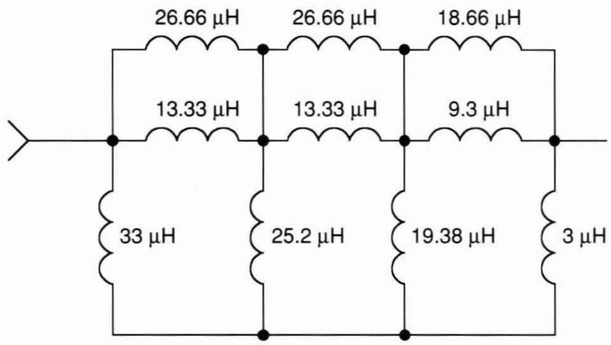
Before you pull down your self-support tower, remember, in our example we kept the same tower side width of 35-inches and just added guys. Obviously, a guyed tower would not be this wide, but we wanted to point out the improvement that the guys make by using the same size tower in our calculations.

All of the above is assuming the guys are without insulators and the anchors are grounded together with the tower leg grounds to form one ground system. If this is not done, the ground resistance/surge impedance at each guy anchor would determine the current distribution.

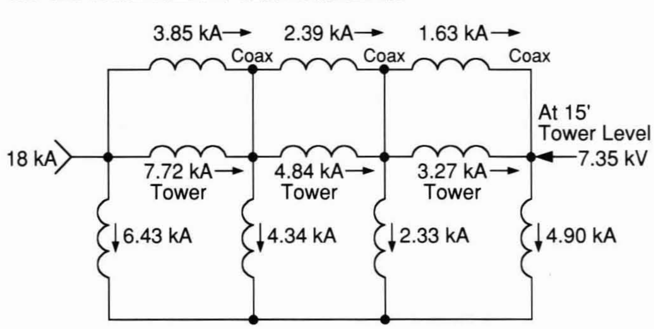
ADDITIONAL COAX TO TOWER GROUNDING - DOESN'T HELP MUCH

Now that we have the current distribution, let's see what happens if we ground the coax shield; not only to the bottom and top, but also ground the coax at the guy attachment points on the tower.

The new circuit would be:



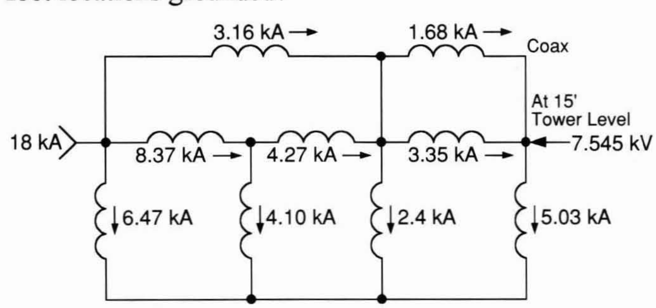
So the total current distribution is:



Average Proportional Coax Current is 2.733kA.

Any additional grounding of the coax, say to every tower section, would not provide any benefit for this size tower (150-feet and less). However, we will see later it is important to ground the coax lines more often when above this 150-feet level. The guy wire paths to ground give the reduction in current on the coax.

A comparison of the two examples shows that the grounding of the coax at each guy location will give a higher coax current between the 150-foot to 100-foot levels. Here it is increased 39% over the "bottom only" grounding situation. What if we didn't ground it at the 100-foot level, but kept the 150-foot, 50-foot and 15-foot locations grounded?



Average Proportional Current is 2.775kA.

Now the coax currents are somewhere in-between the levels of "grounding at each guy location" and "grounding at the 15-foot level only".

If we look at the average coax current, we have a maximum 2.79kA for the single ground at 15-feet and a minimum of 2.733kA for the multi-guy grounding. Note the voltage at the 15-foot level on each example. They do not vary more than about 8%. This is a very small reduction for the amount of effort and cost involved in the additional grounding installation.

OTHER FACTORS MUTUAL COUPLING

Another important factor that should be examined, is mutual coupling between the coax and the tower.

Mutual coupling is the name given to the linkage of the magnetic lines of flux between one conductor and another. In most cases, it is described using two non-ferrous (non-magnetic) conductors (copper - not steel). However, in our applications, we have one of each. The tower (steel) will cause the lines of flux to be concentrated in close proximity. We also need to take into account that each tower leg will share (divide) the current passing through the tower. A coax running down one leg would not have a very large coefficient of coupling of flux lines, even with the steel concentration. It is estimated that this coefficient is only about 0.166.

Using the formula:

$$M = k\sqrt{L_1 L_2}$$

where K is 0.166 and L_1 and L_2 are the tower and coax inductances, respectively.

In the self supporting tower where the tower had 40μH and the run of coax was about 72μH, M would be 8.9μH. This is a significant amount of additional inductance. At 18kA, our strike current and 2 microseconds rise time, this is an L di/dt of 80.2kV or a 33% increase!

In the guyed tower, the coefficient of coupling would be the same, but because there is less tower inductance and less current on the coax, the L di/dt is less dramatic. The grounding of the coax shield along the tower will segment proportionally, the amounts of mutual inductance. The mutual inductance will then add about 7% to all inductances and voltages we have calculated on all combinations of coax shield grounding.

PROPER GROUNDING VS DRIP LOOPS

After looking at some typical figures for current distribution for guyed and self-support towers, you can readily see the magnitude of the protection needs. One of the needs is to prevent as much current as possible from traversing the coax line and coming to the equipment location. Some may have heard of using drip loops or coiling the transmission line to add inductance to the line to choke off the surge currents from reaching the equipment. This seems like a good idea, but remember, there is a limit to the voltage this coil of line can handle before it breaks down. Also, the coil can, depending on its orientation, actually pickup **more** surge current than it reduces. The magnetic field from the tower can couple energy, like a transformer. Take heart - all the grounding techniques for the coax and the tying together of external grounds to form one ground system are true for either type tower and will help divert a lot of the current into the ground. In addition, a good coaxial surge suppressor is required which can eliminate the center to shield differential. PolyPhaser's protectors eliminate this differential and also stops the sharing of the center conductor current. However, the current which comes via the shield cannot be stopped completely. PolyPhaser's Isolated Equipment coaxial protectors can stop the coax shield currents as long as the instantaneous voltage difference between the equipment ground and the protector ground does not exceed 5kV. It won't be over 5kV if a single point ground is used, such as a PolyPhaser bulkhead panel or a single point ground panel.

THE REAL FIX!

It may be apparent to some, that in our example, we may be able to do something to the grounding of the coax shield to further alleviate the whole problem. We previously chose the coax exit/ground point on the tower (the shield grounding point) to be 15-feet above the ground system, to illustrate a point. The point is, this should **not** be done! This is what you will see most often in the field, even if it is incorrect. By having the coax continue down further on the tower to almost ground level and then ground the shield to the tower (just above the tower leg ground connection), the instantaneous voltage gradient on the coax shield would be almost zero. Therefore, theoretically, the coax shield current would also be almost nil. We must say "theoretically" because both the tower ground and the equipment ground must not only be interconnected (grounded) subterraneanly to have this be true, but they must also be large enough so that ground saturation will be minimal. Unfortunately, this does not mean you can eliminate the coax suppressor. Remember the antenna resonances/ringing voltage will still be present and just because we ground the coax line at the tower's grounding point doesn't mean that the differential voltage on the coax disappears. Likewise, don't think you can fix existing towers by running a copper conductor from the installed grounding kits to ground. It probably would not have anymore surface area than the tower and its inductance value would **not** be zero.

Remember! The more attention and effort you put into the outside grounding system, the less important the actual internal building grounding will become! (This is also true if you used the Isolated Equipment type PolyPhaser protector.)

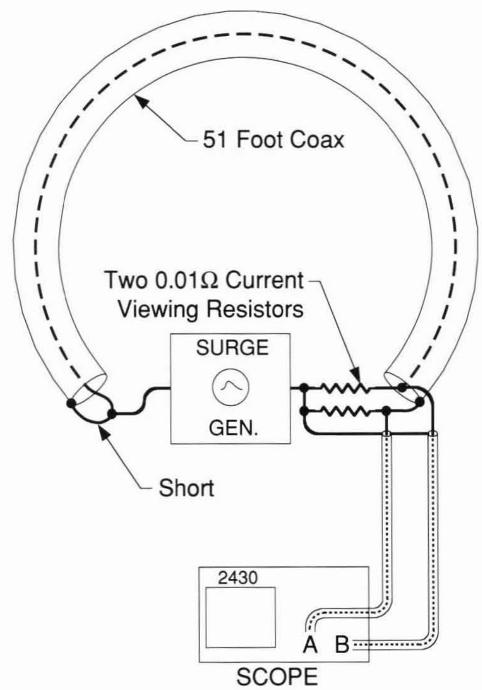
In the following chapters you will be shown, step by step, how to set up and measure a effective ground system and how to ground unique installations.

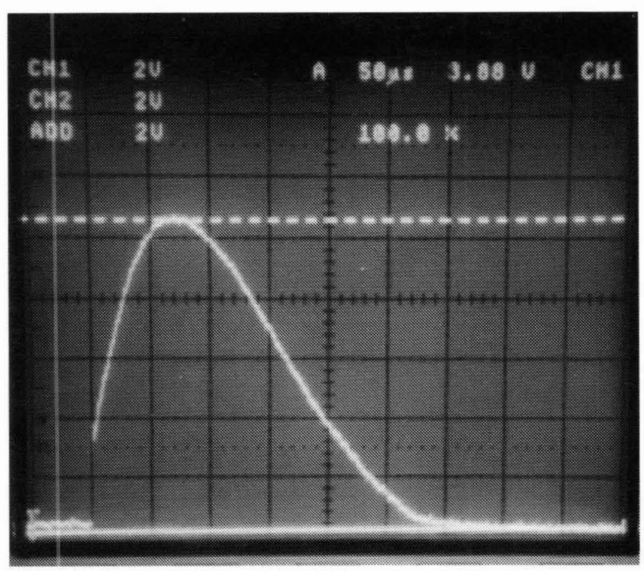
THE NEED FOR PROTECTION

Skin effect is a physical phenomenon that relates to the penetration depth into a conductor of a RF signal, according to its frequency. This effect is present in coax which keeps the RF signal inside and any coupled outside interference on the shield's outer surface. This begins to fall apart as the frequency is lowered and the penetration, which is a gradient, begins to mix the shield's outside interference energy with the desired inside signal. A ground loop, which imparts 60 Hz onto a desired signal, is due to dissimilar grounds causing ac current flow between points via the coax shield.

With lightning, the main frequency range is dc to about 1 MHz or so. This is in the range that affects the coax and is called transfer impedance. The thicker the shield material, the less the effect to these low frequency currents. (Also, the less the bending radius and the harder it is to work with.)

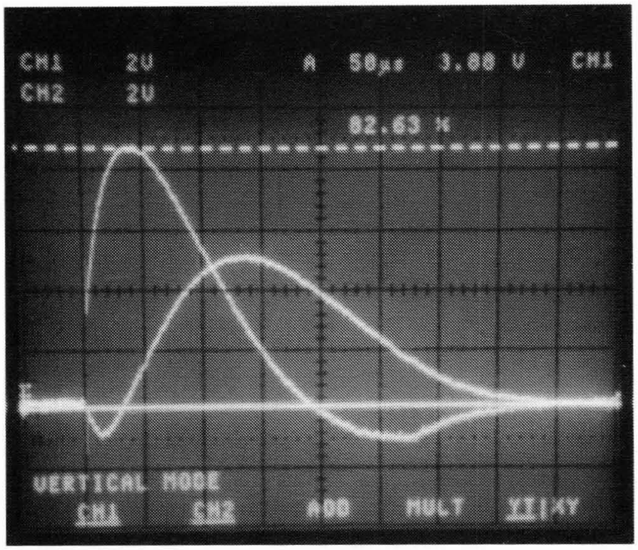
A test was performed on 51-feet of 1/2-inch hard line, where we shorted the center conductor to the shield on one end, simulating a shunt-fed antenna. 1050 amperes of current was pulsed to individual .01 ohm resistors at the far end. These current viewing resistors went to separate channels on a digital storage scope. The most obvious result was that the velocity factor of the shield caused the pulse to arrive first. The center conductor had more inductance, so the pulse was spread out in time. The energy (area under the curves) was exactly the same for both the shield and the center conductor. Since the pulses arrived at different times, a differential voltage occurred that must be equalized and prevented from reaching the equipment. This is precisely what the patented PolyPhaser products do to provide the ultimate protection.

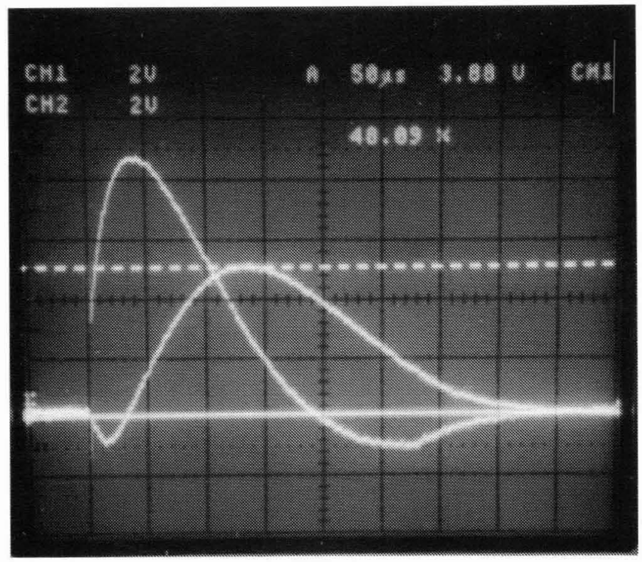




The above pulse was used on a 51-foot long 1/2-inch hard line. One end was shorted to simulate a shunt-fed antenna, while the other end went to separate .01 ohm current viewing resistors.

NOTE: This pulse is the algebraic summation and its peak 1050 Amps is referenced to 100%.





SHIELD
The voltage across each .01 resistor. Here the shield has 82.63% relative to the total pulse.

CENTER
Here the center conductor's peak is only 48.89% of the total. Note the area under both waveforms is nearly equal. Each has 50% of the total surge energy.

chapter 2
"Ufer" Grounds

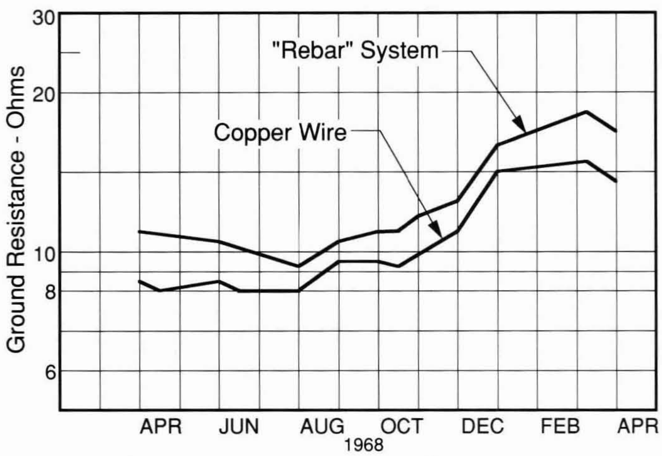
When building a new site, some radio installations do not take advantage of what is known as the **Ufer ground**. This grounding technique can significantly reduce the overall ground system impedance.

Mr. Ufer, for whom the technique is named, worked as a consultant for the US Army during World War II. The Army needed to ground bomb storage vaults in the area of Flagstaff, Arizona. Since an underground water system was not available and the annual rainfall was sparse, Mr. Ufer came up with the idea of using steel reinforcement rods embedded in concrete foundations as a ground. After much research and many tests, it was found that a ground wire, no smaller than a number 4AWG conductor, encased along the bottom of a concrete foundation footing in direct contact with earth, would give a low resistance ground. The length of the conductor's run inside the concrete is important. Typically a 20-foot run (10 feet in each direction) gives a 5-ohm ground in 1000-ohm-meter soil conditions.

UFER GROUND TESTS

One of the most important tests performed was under actual lightning conditions. The test was to see if the Ufer ground would turn the water inside the concrete into steam and blow the foundation apart. Results indicated that if the Ufer wire were long (20-feet minimum) and kept approximately 3-inches from the bottom and sides of the concrete, no such problems would occur. *(In my many years of experience, I have only seen one tower base with cracks that could be considered as lightning induced. Ufers should always be used to augment your grounding system and not to be the entire system. Radials or radials with ground rods should be used together with the Ufer. For those who are afraid to use the Ufer, think about this: The heating of the concrete is more likely if the current is high or concentrated in a given area. This is known as current density "J". The more surface area you have to spread out the current, the less the current density. Your tower's anchor bolts are in the concrete anyway. If your ground system is poor, the current density surrounding the bolts will be high and can blow apart your concrete. At least if you tie in your rebar, the area is increased and the current density is decreased. You will see later that the corrosion will be reduced as well.)*

The UFER technique can be used in building footers, concrete building floors, tower foundations and guy anchors.



Graph of Rebar Versus Copper Wire

A Ufer ground could be made by routing a solid wire (#4 gauge) in the concrete or by using the steel reinforcement bar (rebar). It stands to reason that the outer most sections of the rebar structure should be bonded together, not just tied. If tied, a poor connection could cause an arc. Because arc temperatures are very high and are very localized, they could cause deterioration of the concrete (cracking and carbonizing) in that area. This has **not** been the case. In fact, "...it has been found that these wire ties are surprisingly effective electrical connections. ...One might think that the ties would fail under fault conditions. However, it should be remembered that there are a large number of these junctions effectively in parallel, cinched tightly..." (IEEE Seminar Notes 1970.) The use of large amounts of copper cable coiled in the base of the tower has been shown to cause flaking of the concrete and could, over time, also cause corrosion of the rebar. This can occur due to the concrete's pH factor. The use of copper conductors, such as radials and ground rods, outside the concrete, has not shown these problems. Using a small amount of copper, (it works as a ratio of surface areas) such as for a radial pigtail (short run in the concrete) will not adversely affect the rebar during a typical 30 year tower life.

CHOOSING THE LENGTH

The minimum rebar length necessary to avoid concrete problems depends on the type of concrete (its water content, density, resistivity, etc.). It is also dependent on how much of the buried concrete's surface area is in contact with the ground, ground resistivity, ground water content, size and length of rod and probable size of lightning strike current. The last variable is a gamble! The 50% mean (occurrence) of lightning strikes is 18,000 amperes; however, **super** strikes can occur that approach 100,000 to 200,000 amperes.

Surge Current Capacity of Rebar in Concrete

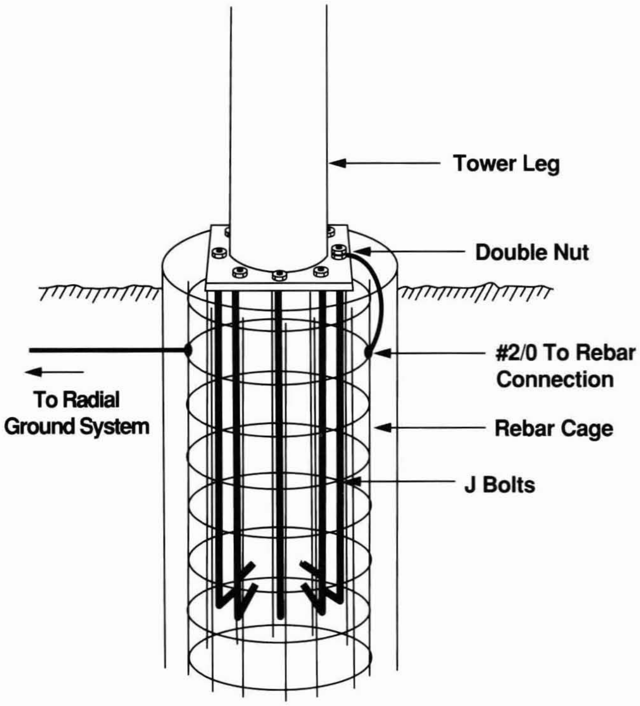
Conductor	Diameter In Inches	Surge Amps/Ft
Rebar	.375	3400
Rebar	.500	4500
Rebar	.625	5500
Rebar	.750	6400
Rebar	1.000	8150

The above shows how much lightning current may be conducted per foot of rebar for (dry mix) concrete. Take the total linear run of wire and multiply it by the corresponding amperes per foot, to find out how long the ground conductor must be to handle a given strike current. Only the outside most, three dimensional perimeter of the cage should be counted.

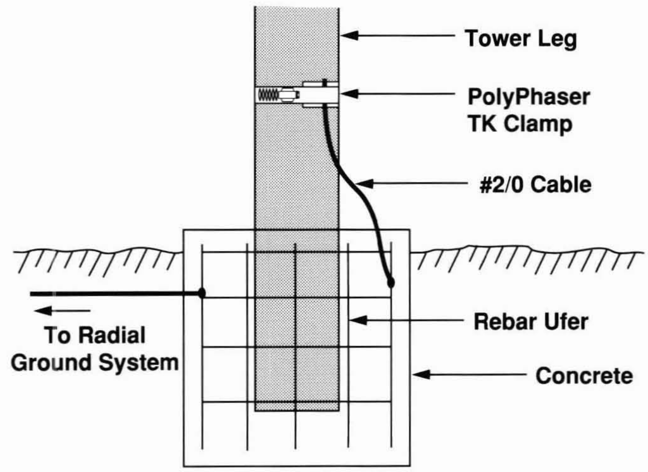
Protection to at least the 60,000-ampere level is desirable. This offers protection for 90% of all lightning strike (occurrences). Remember a Ufer is to be used together with a radial ground system!

HOW IT WORKS

How the Ufer ground works is easy to explain. Concrete retains moisture for 15 to 30 days after a rain, or snow melt. It absorbs moisture quickly, yet gives up moisture very slowly. Concrete's moisture retention, its minerals (lime and others) and inherent pH (a base, more than +7pH), means it has a ready supply of ions to conduct current. The concrete's large volume and great area of contact with the surrounding soil allows good charge transfer to the ground.



Drawing of tower base Rebar Assembly with #2/0 Stranded Copper Pigtails Used to Interconnect Tower Ufer Ground to Equipment Hut Ground, Ground Rods, Radials, etc.



Ufer Ground Detail of Tower Anchored into Concrete.

NEVER USE THE UFER ALONE

A radial system (with ground rods, if possible) should be used in conjunction with the tower Ufer ground. The best way to do this is to bond two pigtails to the rebar structure. One tail extends outward from the concrete **below** the earth's surface. This tail is to be used for a radial run. The other pigtail can be brought up, lugged and double nutted to a tower anchor bolt or bonded to the tower with a PolyPhaser TK series clamp. **For bigger towers additional S.S. hose clamps can be mated in series with the TK clamp.**

chapter 3
Grounding and Materials

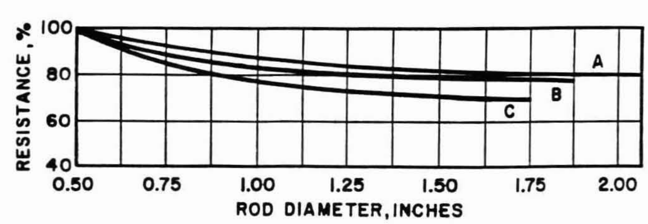
LOW INDUCTANCE GROUND RODS, THEIR CONNECTION AND CORROSION

Ground rods come in many sizes and lengths. Popular sizes are 1/2-inch, 5/8-inch, 3/4-inch and 1-inch. The 1/2-inch size comes in steel with stainless cladding, galvanized or copper cladding (all-stainless steel rods are also available) and can be purchased plain (unthreaded) or sectional (threaded). The threaded sizes are 1/2-inch or 9/16-inch rolled threads. It is important to buy all of the same type. Couplers look much like a brass pipe with internal threads and allow two threaded rods to be joined into each end of the coupler. Each can be used to couple 8-foot or 10-foot length rods together. So, a 40-foot ground rod is driven one 10-foot section at a time (four sections and three couplers).

DRIVING THE SECTIONS

Driven rods will out perform rods whose holes are augured or backfilled and not tamped down to the original density. This is due to the fact that the soil compactness is better around driven rods giving more "connection" to the rod. It will be necessary to purchase a PolyPhaser "pounding cap" (#FG 1900-0005) for hammering or a bolt that fits the coupler. By threading the coupler on to the top end of the rod and threading the bolt into the coupler provides a smash proof hammering point, saving the rod's threads. Always use protective goggles because the end cap, the bolt or the hammer head may chip when struck.

What type and size of ground rod should be used? Most seem to choose the copper clad 5/8-inch x 8 or 10-foot. The rod diameter should increase as the number of tandem rod sections and soil hardness/rockiness increases. The rod diameter has minimal effect on final ground impedance.



Three tests by different people (A, B & C.) Each took a 1/2-inch Ground Rod which was used as a reference and set to 100%. The Rod size was increased and different results are due to ground conductivity variations.

MATERIALS

Rods may be clad with copper to help prevent rust. It is not primarily for better conductivity, as many think. Of course, copper cladding is a good conductor, but the steel it covers is also an excellent conductor when compared to ground conductivity.

The thickness of the copper cladding is important when it comes to driving the rod and when the rod is placed in acidic soil. Penetrating rocky soil can scratch off the copper and rust will occur. Rust, an iron oxide, is not conductive when dry, but it is fairly conductive when wet. Depending on the water content, a less expensive (consumer-type) ground rod may be used. In acid ground conditions, such as in an evergreen area, the copper will be attacked. The thicker the copper cladding, the longer the rod will last. Industrial-quality ground rods are available from local electrical supply houses. Approximate cost is $11.00 to $15.00 a 10-foot length for 5/8-inch copper clad rod. Couplers are about $5.25 each. A swimming pool acid/base tab type tester can be used to determine the soil pH. By mixing in distilled water (50/50) and washing the mud off with distilled water, the tab color can be read. Remember, just because the ground system isn't visible, doesn't mean it will last forever! It will need to be checked or maintained on a regular basis.

ABOUT CORROSION

Corrosion is an electromechanical process which results in the degradation of a metal or alloy. Oxidation, pitting or crevicing, de-alloying, and hydrogen damage are but a few of the descriptions of corrosion. Most metals today are not perfectly pure and consequently when exposed to the environment will begin to exhibit some of the effects of corrosion.

Aluminum, such as that used in PolyPhaser's coaxial protectors, has an excellent corrosion resistance due to a 1 nano-meter thick barrier of oxide film which instantaneously forms on the metal. Even if abraded, it will re-form and protect the metal from any further corrosion. Any dulling, graying, or blackening which may subsequently appear is a result of pollutant accumulation.

Normally, corrosion is limited to mild surface roughening by shallow pitting with no general loss of metal. An aluminum roof after 30-years only had 0.076mm (0.0003 inch) average pitting depth. An electrical cable lost only 0.109mm (0.0043 inch) after 51-years of service near Hartford, Connecticut. Copper such as C110 used in our Bulkhead Panels has been utilized for roofing, flashing, gutters and down spouts. It is one of the most widely used metals for atmospheric exposure. Despite the formation of the green patina, copper has been used for centuries and has negligible rates of corrosion in unpolluted water and air. At high temperatures some copper alloys are better than stainless steel.

If you were to join copper to aluminum or copper to galvanized (hot dipped zinc) steel with no means of preventing moisture from bridging the joint, corrosion loss will occur over time. This is the accelerated corrosion (loss) of the least noble metal (anode) while protecting the more noble metal (cathode). Copper, in this example, is the more noble metal in both of these connections. See the Noble Metal Table, on the next page, for a ranking of commonly used metals.

Where the connection is with galvanized steel, the zinc coating will be reduced allowing the base steel to oxidize (rust), which in turn will increase the resistance of the connection and possibly over time compromise the integrity of the mechanical structure.

The aluminum will pit to the copper leaving less surface area for contact and the connection could become loose, noisy and even allow arcing.

These joint corrosion problems can be prevented by using a joint compound which can cover and prevent the bridging of moisture between the metals. The most popular compounds use either graphite or copper particles embedded in a grease. As the joint pressure is increased, the embedded particles dig into the metals and form a virgin junction of low resistivity void of air and its moisture.

The use of a joint compound has now been adopted as the recommended means for joining our coaxial protectors to our bulkhead panels for non-climate controlled installations. We have been supplying copper joint compound for our bulkhead panel ground strap connections. We have tested this compound with a "loose"

1 square-inch copper to copper joint and have found it to handle a 25,500 ampere 8/20 waveform surge with no flash over and no change in resistance (0.001 ohms). We have even wiggled the loose joint before and after the surge and experienced no change in its resistance.

The connection of a copper wire to a galvanized tower leg should be avoided even if joint compound is used. The primary problem here is the low surface area contact of the round wire with the (round) tower leg. Consider using two PolyPhaser TK series stainless steel clamps. The TK clamps will help increase the surface area of the connection, as well as provide the necessary isolation between the dissimilar metals. Don't forget to use joint compound on exposed applications of the TK clamps. For an even more effective connection, use copper strap in place of the wire with one TK series clamp.

Silver oxide is the only known conductive oxide. (This is one reason why PolyPhaser's N-type coax connectors are all silver with gold center pins.) Copper oxide is not conductive and the proper application of joint compound will prevent oxidation.

If copper clad ground rods are used, make sure the oxide layer is removed. PolyPhaser Corporation makes a Copper Cleaning Kit (CCK) that has all the necessary items (abrasive pad, joint compound, finger wipes and instructions) to make a good copper connection. Tinned wire should not be used together in the ground with copper ground rods. Tin, lead, zinc and aluminum are all more anodic than copper. They will be sacrificial and disappear into the soil. It is recommended that all components be made of the same external material.

Utilizing the above technique can make the difference between a site that stays on the air and one that requires a lot of maintenance after a short period of time.

LESS NOBLE ↑		MAGNESIUM	ALUMINUM	ZINC	IRON	CADMIUM	NICKEL	TIN	LEAD	COPPER	SILVER	PALLADIUM	GOLD
	MAGNESIUM	0.00	-0.71	-1.61	-1.93	-1.97	-2.12	-2.23	-2.24	-2.71	-3.17	-3.36	-3.87
	ALUMINUM	0.71	0.00	-0.90	-1.22	-1.26	-1.41	-1.52	-1.53	-2.00	-2.46	-2.65	-3.16
	ZINC	1.61	0.90	0.00	-0.32	-0.36	-0.51	-0.63	-0.64	-1.10	-1.56	-1.75	-2.26
	IRON	1.93	1.22	0.32	0.00	-0.04	-0.19	-0.30	-0.31	-0.78	-1.24	-1.43	-1.94
	CADMIUM	1.97	1.26	0.36	0.04	0.00	-0.15	-0.27	-0.28	-0.74	-1.20	-1.39	-1.90
	NICKEL	2.12	1.41	0.51	0.19	0.15	0.00	-0.11	-0.12	-0.59	-1.05	-1.24	-1.75
	TIN	2.23	1.52	0.63	0.30	0.27	0.11	0.00	-0.01	-0.47	-0.94	-1.12	-1.64
	LEAD	2.24	1.53	0.64	0.31	0.28	0.12	0.01	0.00	-0.46	-0.93	-1.11	-1.63
	COPPER	2.71	2.00	1.10	0.78	0.74	0.59	0.47	0.46	0.00	-0.46	-0.65	-1.16
	SILVER	3.17	2.46	1.56	1.24	1.20	1.05	0.94	0.93	0.46	0.00	-0.19	-0.70
	PALLADIUM	3.36	2.65	1.75	1.43	1.39	1.24	1.12	1.11	0.65	0.19	0.00	-0.51
	GOLD	3.87	3.16	2.26	1.94	1.90	1.75	1.64	1.63	1.16	0.70	0.51	0.00

← LESS NOBLE

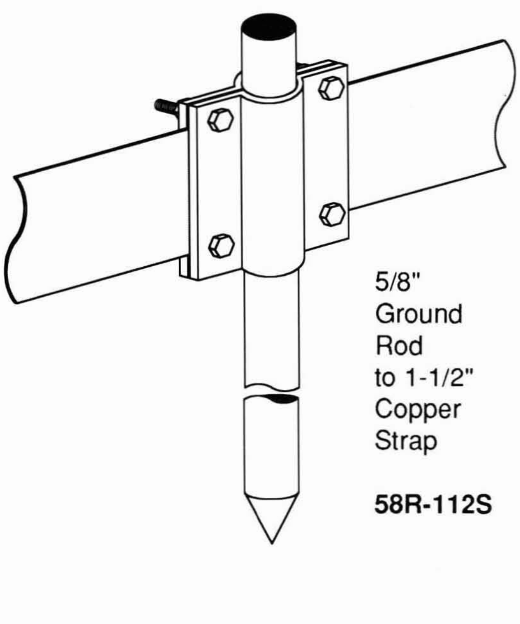
Noble Metal Table: Accelerated corrosion can occur between unprotected joints if the algebraic difference in atomic potential is greater than ± 0.3 volts.

UFER PLACEMENT

If a Ufer ground is used, be sure the first ground rod is at least 2-feet from the tower base. Placing ground rods some distance from each other gains the greatest benefit for the money and effort spent. With widely separated rods, care must be taken to interconnect them properly.

INTERCONNECTIONS

As the spacing between vertical ground rods is increased, the interconnect wire will be able to launch or leak current into the surrounding conductive earth. Therefore, it can be thought of as a horizontal ground "rod" connecting to vertical ground rods. In **highly conductive** soil, one should not be concerned about the inductance of such a straight wire because such a wire becomes like a leaky transmission line with very high losses. Therefore, wire size (skin effect) is of little importance, like that of rod diameter mentioned earlier, as long as it can handle the $I^2 \cdot R$ of the surge. For **highly conductive** soil, a #10-gauge (bare) is the smallest wire that should ever be used. This type of soil is **not** common and in areas where soil conductivity is poor, such as sandy soil, the buried interconnecting wire approximates the inductance of a wire suspended in air. This undesirable condition causes it to be highly inductive. The high inductance prevents strike current (which has a fast rise time) from being conducted by the wire. Ground rods connected in such a fashion are useless.



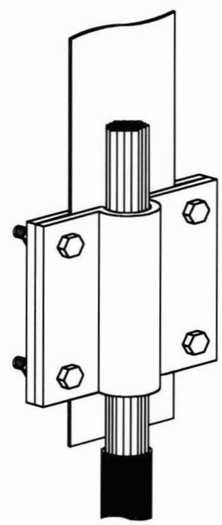
5/8"
Ground
Rod
to 1-1/2"
Copper
Strap

58R-112S

INTERCONNECTION MATERIALS

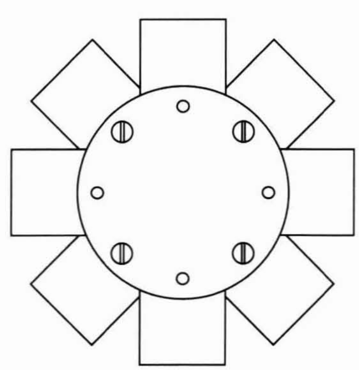
To connect ground rods together in low conductivity soil, solid copper strap should be used. The strap may be as thin as 0.016 inch. For 1-1/2-inch wide strap, the cross sectional area will equate to a #6 AWG wire. Greater thickness gains only a little advantage because high frequency currents (1 MHz) penetrate only to a depth of about 0.008 inch per surface, owing to "skin effect". The strap width should be about 1% of its length (e.g., 20-feet · 0.01 = 2.4-inches wide), providing a low inductance connection between rods.

Connecting the strap to the rod may be done using a PolyPhaser clamp. For 5/8-inch rods and 1-1/2-inch strap, the 58R-112S offers the best way to achieve a mechanically rigid, electrically superior, low-maintenance connection. The copper connection must be cleaned and a copper joint compound should be applied to prevent moisture. Clamps that bond straps together in the soil (MSC-3) and many other 1-1/2-inch strap to cable clamps (6AWG to 4/0) are available.



2/0 AWG
to 4/0 AWG
to 1-1/2"
Copper Strap

20C-112S



1-1/2" or 3"
Multi Copper
Strap

MSC-3

GROUND ROD DEPTH

The total depth each ground rod must be driven into the soil depends on local soil conductivity. Soil resistivities vary greatly depending on the content, quality and the distribution of both the water and natural salts in the soil. It is beneficial to reach the water table, but it is not necessary in all cases. In higher latitudes, rods should be long enough to penetrate below the maximum frost depth. In most cases, a total depth of 40-feet or less is necessary, with the average being 15-feet. Depth also depends on the number of rods and the distances between them.

KNOW WHAT YOU'RE DOING

Be aware of the rod's progress when striking it in place. Rods have been known to hit a rock in their travels and emerge out of the soil just a short distance away. In rocky soil, it is better to persevere in trying different locations than to dig a hole and repack the soil around the vertical ground rod. The repacked soil is less dense and will have a higher ground resistance. (Also, before the first rod is hammered in place, it should be measured as it is going in. This can tell a lot about the under layers of soil at the site, including when and if water or a highly conductive layer is reached. See Chapter 5 for more information.)

LIGHTNING, RF AND SAFETY GROUNDS

A single ground rod is never enough to ground a tower for lightning. Basically, there are three types of grounds.

One is a ground for RF, such as an antenna counterpoise. A ground plane takes the place of the other half of a normal dipole. A good RF ground plane could be elevated above ground (tuned) and thus can not be a good lightning ground. If such a ground plane is properly extended and placed in the soil, it will no longer be tuned. It can be an RF, noise and lightning sink. Therefore, we can say that not all RF grounds are good lightning grounds, but a good lightning ground is a good RF ground for low frequencies.

The second type of ground is the lightning ground. This ground must be able to sink vast amounts of current quickly. The typical frequency range of lightning energy at the bottom of a tower is from dc to the low VHF range (<100MHz). The ground system must be a broadband absorptive counterpoise over this frequency range.

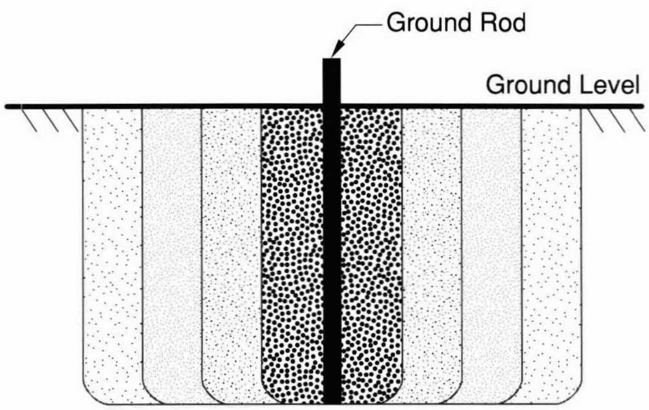
The third and final ground type is a power return or safety ground for ground faults. This is a low frequency (60Hz) ground and may be very inductive to lightning's fast rise time, yet still be okay for grounding 60Hz. The electrical safety ground is often not a good lightning ground for that reason. A low inductance connection to a Ufer is, however, both a good lightning ground and a safety ground. Under a ground fault condition, more energy will be conducted to ground than during a lightning strike, due to the longer time required to clear the fault. Lightning has an enormous peak energy, but the duration is very short. The Ufer has been proven to handle both without failure.

GROUND THEORY

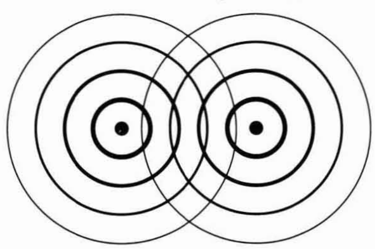
Theoretically, one rod with a 1-inch diameter driven in homogeneous 1,000-ohm per meter (ohm/meter) soil for one meter would only yield 765 ohms. Driving it two meters into the soil would give 437 ohms. Going to three meters, however, does not give as great a change (309 ohms). One would get faster ohmic reduction and easier installation by using three rods, each one meter long, giving 230 ohms compared to that of one rod three meters long. This assumes they are spaced "greater than the sum of their lengths apart". If the interconnecting wire is also buried below the surface, then the ground system may be less than 200 ohms. (Having one deep ground rod, 40-feet or more, even if it reaches the water table, will not act as a good dynamic ground because the top 5 to 10-feet will conduct most of the early current rise and will become somewhat saturated. This allows eddy currents to form in this top layer and cause inductance to impede the flow of current to any further depth.)

SATURATION

The statement that rods should have a separation, "greater than the sum of their lengths apart," originates from theory and the fact almost all ground rods will saturate the soil to which they connect. A ground rod connects to localized, irregularly sized, three-dimensional electrical clumps. Depending on the soil make-up (layering, etc.), the cylinder volume of earth that a ground rod can electrify can be visualized by this rule of thumb: The cylinder's radius and depth is equal to the rod depth. This is known as the sphere of influence of the rod. **Thus, the sum of the driven depths of two rods should be, theoretically, the closest that ground rods can be placed.** Anything closer will cause the soil (clumps) connected in common to saturate even faster.

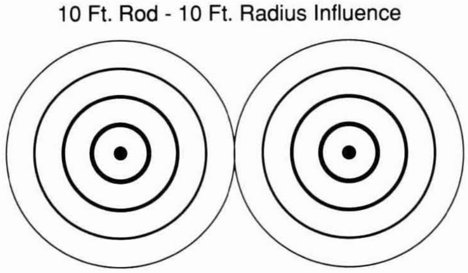


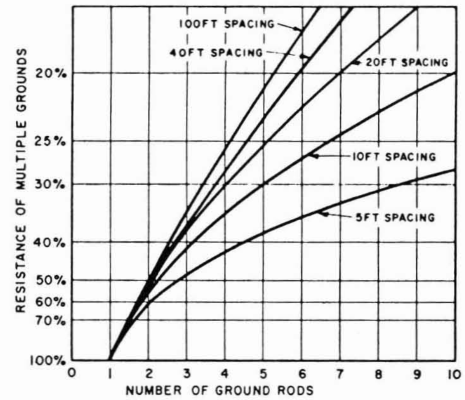
Incorrect Spacing



Correct Spacing

8Ft. Rod - 8Ft. Radius Influence
10 Ft. Rod - 10 Ft. Radius Influence





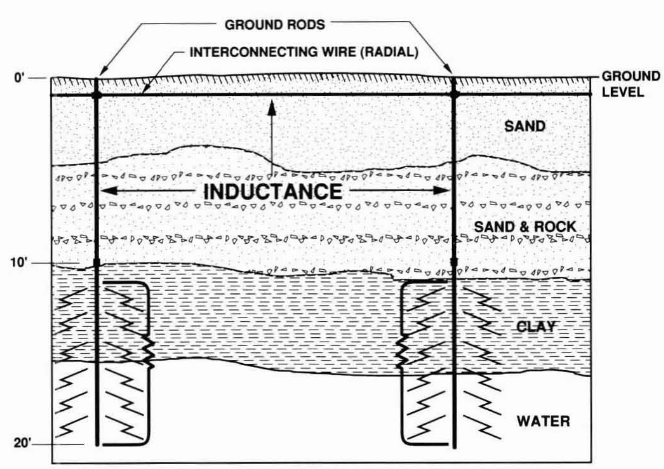
Theoretical resistance change for additionally spaced ground rods

EXAMPLE PROBLEM

Take for example a sandy area with a water table at the 10-foot level. The 10-foot ground rods are coupled and are to be driven to a total depth of 20-feet. A second rod is to be driven no closer than 20-feet to the first, but it should be 40-feet according to our rule! Our rule of thumb can be looked at two ways:

(1) Only 10-feet of each 20-foot rod is in conductive soil (the top 10-feet of each rod is in non-conductive dry sand), so 10-feet + 10-feet = 20-feet apart.

(2) Without taking the water table depth into consideration, 20-feet + 20-feet = 40-feet.



The answer: Following our rule of thumb, the #2 separation will not work! The interconnecting inductance will choke off the higher frequency components of the surge's rise time and create an L di/dt voltage drop. In other words, the surge will never reach the second ground rod. Following #1's spacing, the inductance will be less, but there are two other solutions to this real life problem. First, the interconnect inductance can be reduced by using copper strap. Second, by using chemical salts to increase soil conductivity around the rods and along the interconnect path, the inductance is also reduced. For the best performance, use both solutions together with #1's spacing.

RADIALS

The interconnecting of ground rods is fine for those locations where ground rods can be driven. Some locations are rocky enough that only the interconnecting lines can be run.

Horizontal radials, like those used on vertical broadcasting antennas, make an excellent RF and lightning ground system. Theoretically, four radials each twenty meters (m) long, of #10 gauge wire, just buried will yield 30 ohms in 1,000-ohm/meter (ohm/m) soil. Eight radials would give about 25 ohms. Eight radials each fifty meters (163-feet each or 1,300-feet total wire) on top of the ground or hardly buried could give about 13 ohms in 1K-ohm/m soil.. Theoretically, if we could drive rods, adding 2m long rods to this system, one on every radial (8 rods total), would calculate to below 10 ohms. If the rods were spaced every 10m on each radial (32 rods total), then the resistance would go to about 4 ohms. Remember this is theoretical and for 1,000-ohm/m soil, which is rather sandy or rocky. (We will see that a long radial run is not going to work as well as numerous shorter radials.)

ROCKS AND MOUNTAINS

If the soil is rocky enough that the radials are sometimes in air while spanning between rocks, the accumulated inductance along the runs will choke off the surge currents. In this situation, numerous slightly shorter lengths, along with using solid flat strap radial conductors, has been proven to work. The copper strap's sharp edge will concentrate the E fields that are present due to the existing L di/dt voltage drop and breakdown or arc onto the surface of the rock or soil. There is, however a law of diminishing returns for radials. As with sprinkler hoses, the amount of water, or in this case lightning energy, at the end of a 75-foot length radial is such that you may be wasting your time, effort and materials to go much further. It is recommended radials only have a 75-foot run (no shorter than 50-feet if possible) and then additional radials from the tower be used to further reduce the surge impedance/ground resistance. This way the greatest amount of energy is carried off from the tower and away from the equipment hut. The radials runs should be oriented away from the hut as much as possible. (More on this later when we talk about fences and grounding other objects in the hut and tower area.) The measured earth resistance of the radial system may be decreased. You will need to double what you have to not quite halve the resistance value.

On solid bare rock, straps will help spread out the charge on to the surface of the rock. Remember, 90% of the time a strike is an onslaught of electrons with like charge. They are repelled and want to spread out. In doing so, they lose energy due to the resistances involved. Since little conductivity is present on dry bare rock, there will be little spreading in the time frame of a strike. If rain occurs before the event, then the rock will be quite conductive and the charge can spread out, loosing energy in the process. The more it spreads, the more energy is lost as the charge density is reduced. The Ufer ground works the same, it spreads the charge to the outer most edges. The use of the Ufer ground technique at the tower base and at the guy anchors will help.

DOPING THE SOIL

Salts may be added to increase the conductivity of the soil, but it is a temporary solution that must be renewed every year to maintain the elevated conductivity. Chemical ground rods (PolyPhaser's PolyRod) can help capture the precipitation and direct it through the salts, creating a saline solution dispersed into the surrounding soil. The PolyRod can also be fed from a timed drip system, if domestic water is available. The ability to add on copper tubing makes it easy to design an entire ground system using multiple PolyRods. The copper tubing electrically interconnects the PolyRods and acts as a means to disperse the saline solution along its length. The surrounding soil is then made conductive, reducing the inductance of the copper tubing. (More on chemical doping in Chapter 13.)

OTHER MATERIALS

Grounding materials have appeared on the market claiming great things. They indicate that after applying, the resistance never changes. They also imply the earth resistance is invariant. No so! It is the material's resistance you put in place that will be the same over time, not the real earth resistance!

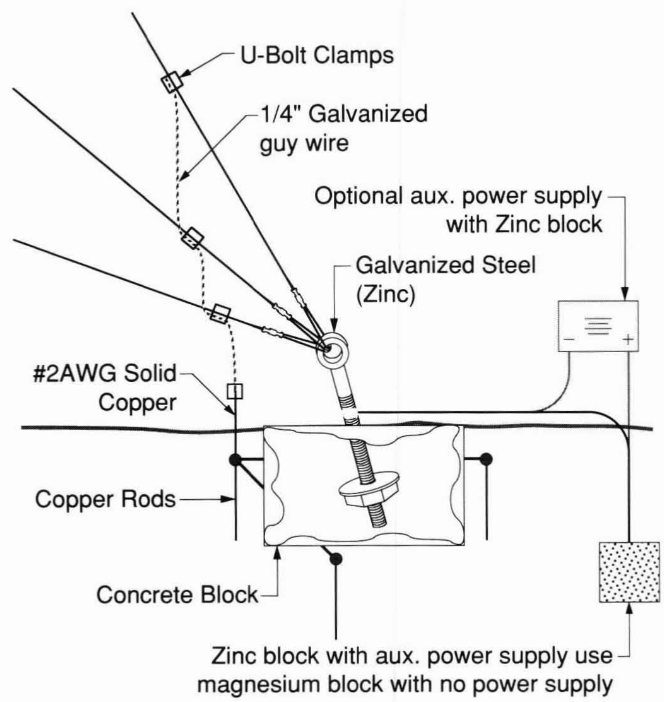
chapter 4
Guy Anchor Grounding

Guyed towers are better at handling lightning surge currents than self-supporting towers. This is only true if the anchors are grounded properly. Some of the strike current traverses the guy wires (instead of the tower) and may be safely conducted into the guy anchor ground(s). With some of the current conducted by the guy wires, less is available to saturate the ground at the tower base.

TURNBUCKLES

Turnbuckles should never be relied on as a path for lightning current. If the turnbuckles are provided with a safety loop of guy cable (as they should be), the loops may be damaged due to arcing where they come into contact with the guy wires and turnbuckles.

The following diagram shows the preferred method of grounding the guy wires - tying them together above the loops and turnbuckles.



Side view of a properly grounded guy anchor. Correctly dressed and installed, the ground wire prevents surge currents from welding turnbuckles and damaging the safety loop.

These connections should not be made with copper wire. The reason - when it rains, natural rain water has a pH of 5.5 to 6.0 which is acidic. Copper is only attacked by acids. Dripping water from the top copper wire will carry ions that react with the lower galvanized (zinc) guy wires. The reaction washes off the zinc coating, allowing rust to destroy the steel guy wire.

The best way to make the connection is with all galvanized materials. This includes the grounding wire or cable and clamps.

Just above the earth's surface, the galvanized wire is bonded to a copper conductor that penetrates below grade to a radial system which spreads out the strike energy into the ground.

How high this bonded connection should be placed above the soil, depends upon local snowfall or flood levels. Snow's electrical conductivity, although low, can still cause battery action from the copper through the surface water to the zinc by the solar heating of the wires. The joint should be positioned above the usual snow or flood level.

The lead is dressed straight down from the highest to the lowest guy or with a slight tilt toward the tower at the top. After bonding to a guy wire, it should be dressed downward from the lower side to the next guy wire. The most effective way to bond is to lightly wire brush the members, removing all oxides, and then apply a joint compound if a pressure clamp is to be used.

To ensure no arcing will occur through the turnbuckle, a connection from the anchor plate to the ground rod is recommended. Interconnect leads that are suspended in the air, must be dressed so the bending radius is not sharper than eight inches.

For guy anchors in typical soil conditions, use similar tower base radials, inter-spaced along their length with ground rods. The radials need not be much longer than 20-feet each because of the lower currents due to the high guy inductances. Two radials are the norm. If a wire/chain link fence is used, radial should bond to the fence post with a PolyPhaser TK style clamp and continue its run to 20-feet.

chapter 5
Ground Impedance

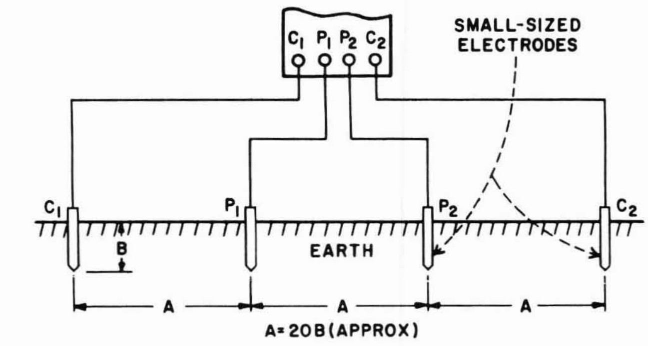
GROUND MEASUREMENTS

For towers, with or without guy anchors, we need to determine the type, number and length of the radials required for a good lightning ground system. To answer these questions, the soil conductivity must be known.

MEASURING YOUR SOIL

A simple method for determining soil resistivity is shown below. Four equally spaced electrodes are driven to a shallow depth; the penetration depth (b) is kept small in comparison to the inter-electrode spacing (a) where a ≥ 20(b). A known current is circulated between the two outer-electrodes while the potential is measured across the inner pair. If the electrode spacing (a) is in meters, use the formula:

$$\rho = 6.28a \frac{(v)}{I}$$



Four stake method of measuring soil resistivity.

This gives the soil resistivity in ohm-m. Generally, the electrode spacing (a) corresponds to the depth of soil seen by the test current. By varying the electrode spacing, a profile of resistivity versus depth can be obtained. Another way to obtain a profile of the soil is to measure a ground rod as you hammer it into the soil. Plot the measurements to see if any major changes occurred over what is expected from simple calculations.

MEASURING YOUR GROUND SYSTEM

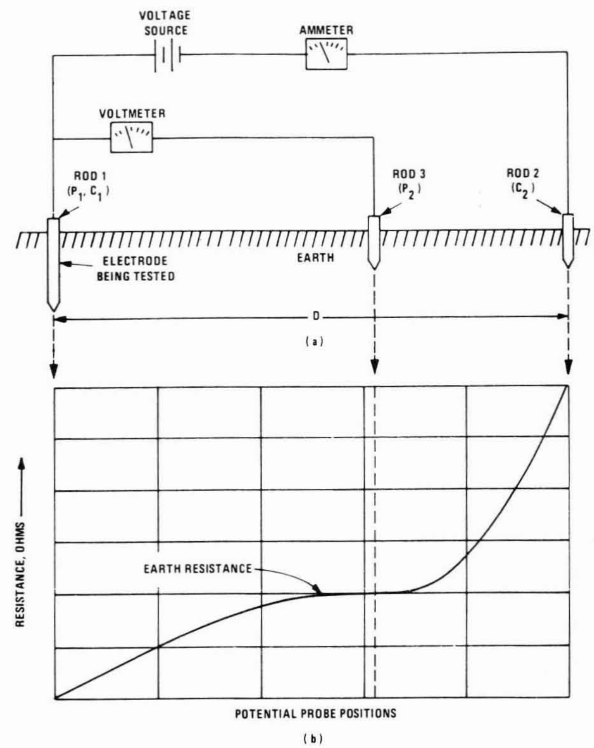
There is no substitute for an actual measurement of a ground system. Most measuring techniques are similar and therefore, they have similar faults. The techniques utilize equipment with steady state dc or low frequency ac waveforms. Neither comes close to simulating the dynamic surge conditions where inductive voltage drops are developed. Problems should not be incurred if good RF practices of low inductance are adhered to in the design and layout of the ground system. These measuring meters can be used at a site to get an idea of the subterranean makeup. If no other ground conductors are present, in or along a 100 foot path, a fall of potential (3 stake) measurement can be setup before a ground rod under test is inserted into the ground. (See the appendix for theoretical ground resistance formulas.)

Most sites have a ground, but it is an unknown. The ground system is considered an unknown because it has never been measured or if it was measured, it has probably changed. The resistivity varies through out the year because of seasonal moisture and temperature changes. (The more moisture and the higher the ground temperature, the lower the resistance.) A ground system is like any other piece of equipment and normal maintenance must be performed to keep it in operating condition. Unfortunately, it is out of sight and usually out of mind until a disaster strikes.

Ground systems composed of copper and zinc are quickly eaten away in acidic soils; yet are stable in the presence of alkaloids like concrete. Only aluminum is unaffected by acidic soils, but it is etched by alkaloids. As mentioned previously, a simple test can be performed using a pool/spa water strip pH tester.

In addition to pH level, a soil's conductivity is determined by its water and salt content. The more salts, the less water required to reach a specific conductivity. At least 16% water content, by weight, is required for a soil to be conductive. Gypsum can be added to the soil and is better than bentonite. Gypsum absorbs and retains water and it doesn't shrink/pull away when drying like bentonite. Also, adding 5% by weight, of epsom salts will further insure moisture retention and conductivity.

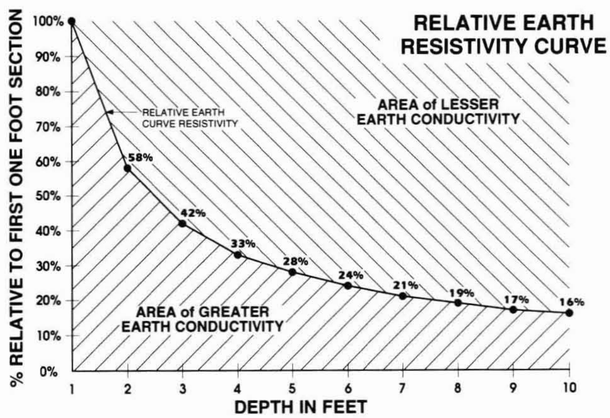
Like all partial conductors, the soil's resistance value is measured in ohm-m or ohm-cm. A site's soil resistivity can be measured, (shown on page 25) by equally spacing four stakes (four stake method) and infusing current into the two outer stakes (C_1 and C_2) while the two inner stakes (P_1 and P_2) measure the fall of potential (voltage). There are several companies that make earth resistance testers operating at low frequency (90Hz).



Three stake method for measuring a ground rod or system (fall-of-potential method).

The three stake method, also known as the Fall-of-Potential Method, is shown and is used to measure the resistance of a ground rod or system. This can be done on any four stake tester by tying P_1 and C_1 together. The initial spacing between electrodes P_1, C_1 and C_2 for a simple electrode would be approximately 100-feet, while for a ground system it would be approximately 1000-feet. The actual distance may be increased or decreased depending upon the size of the ground system being measured and the results of moving electrode P_2. The goal is to move electrode P_2 at discrete intervals along a line between electrodes P_1, C_1 and C_2 and record/plot the voltage measurement. It is necessary to locate the area of the curve where moving electrode P_2 has little or no affect on the measured voltage. The flattened area of the voltage curve is then converted using tables or formula supplied with the measuring instrument to the approximate ground system resistance.

Resign yourself to hammering in stakes to measure your ground system. The low frequencies used in most testers do not take into account any inductance which may exist in a ground system such as a rod penetrating a sandy layer, etc. The best way to determine the consistency of your underground soil layers is to perform a Fall-of-Potential measurement and log the readings for each foot that a ground rod is driven. Plotting it should approximate the Relative Earth Resistivity Curve shown here. Any large variation could mean water/clay or sand/gravel. With this knowledge, a better ground system can be designed for the RF properties of the lightning strike.



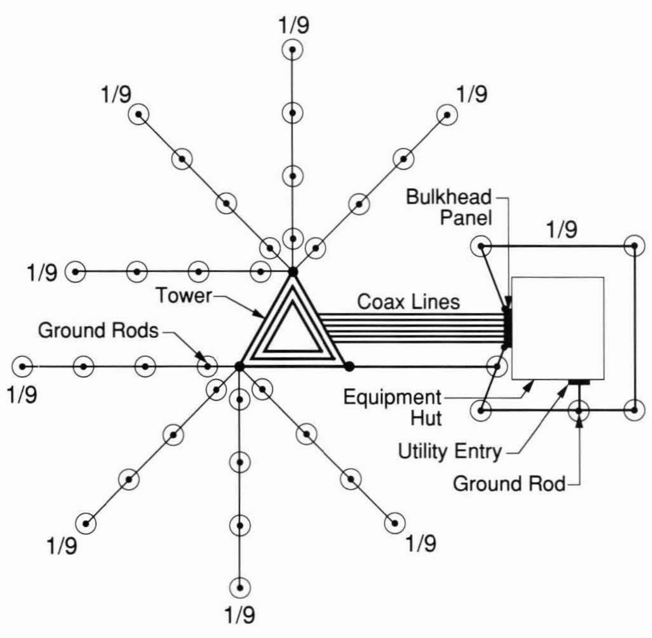
SURGE Z

In IEEE Transactions on Broadcasting, Volume BC-25, No.1, March 1979, it was established that radials, together with rods, show a lower dynamic surge impedance under real lightning conditions than the resistance measured at or near dc. This results from a lightning induced ground saturation causing localized arcing and creating a momentary low impedance path between ground masses. The effective area or size of the grounding system is thereby briefly increased. The arcing is due to the fact that any ground system, no matter how good, will momentarily elevate above the global earth potential. This saturation may be due to a slow propagation of the surge and is measured as the velocity factor and time constant of the ground system. (See Chapter 12.) Obviously the larger the impulse, the more arcing and the lower the dynamic impedance. It has been shown, that the lower the measured impedance using the dc or steady-state low frequency ac type instruments, the smaller the difference will be between the measured and the real dynamic impedance.

GROUND PROPAGATION

As in any medium, a dynamic pulse, like RF, will take time to propagate. This propagation time, together with resistive losses, will cause a differential step voltage to exist in time between any two ground rods that are of different radial distances from the strike. With a ground rod tied to the base of a struck tower, the impulse will ideally propagate its step voltage outwardly from this rod in ever-expanding circles, like a pebble thrown into a pond. If the equipment hut has a separate ground rod and the power company and/or telephone company grounds are separate still, the dynamic step voltage will cause currents to flow to equalize these separate ground voltages. If the coax cable is the only path linking the equipment chassis with the tower ground, the surge will destroy circuitry while getting through to the telephone and power grounds.

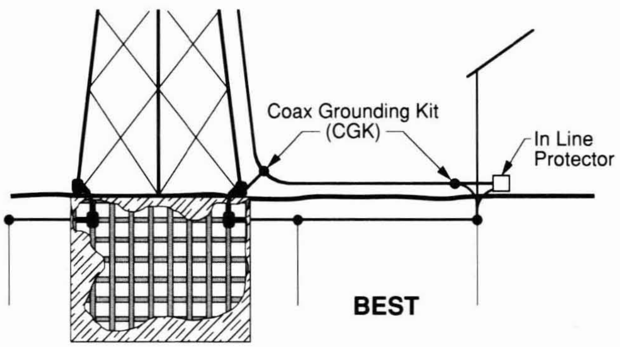
chapter 6
Putting it Together with Bulkhead Panels

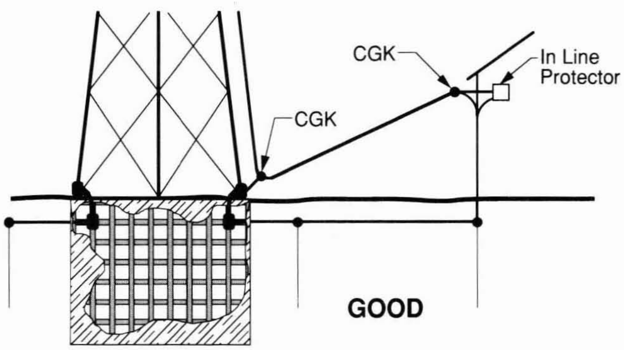


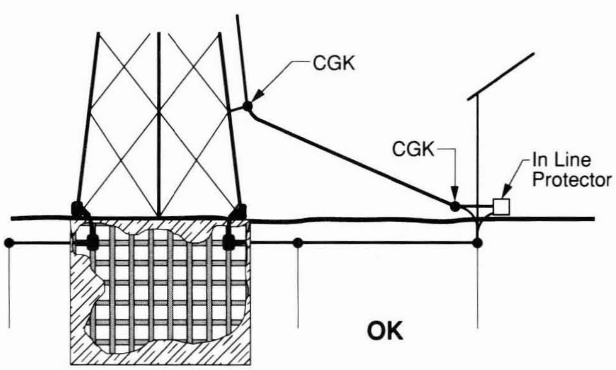
Correct tying of Ground Rods together to form one ground system.

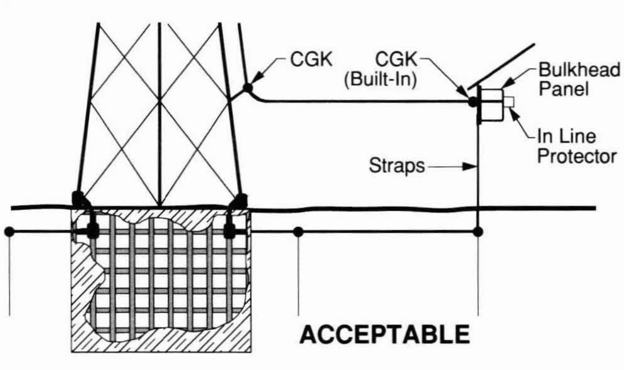
TYING IT ALL TOGETHER

To prevent the multiple ground disaster from occurring, one grounding system must be formed which interconnects all other grounds together. A lightning strike possesses a given amount of current and if there is a perimeter ground loop around the building, the division of current will be such that most of the lightning strike will be dispersed by the radials. This leaves a smaller amount remaining to be handled by the perimeter ground around the equipment building. We use a perimeter ring around the building because a loop will have a reduced amount of step voltage inside the loop. This is due to the repelling affect of like charge emanating from all points on the loop. This helps prevent current through concrete floors, protecting both equipment and personnel.









ADVANTAGES	DISADVANTAGES
Low L di/dt voltage	1) Coax must make tight bends. 2) Coax enters at floor level.
Low L di/dt at tower	1) Large L di/dt for in line protector unless large surface area grounding conductor is used for building CGK and protector. 2) Sloped line will intercept tower mag fields.
Low L di/dt at building	1) Coax must enter at floor level. 2) Sloped line will intercept tower mag fields.
1) Enters building high. 2) Does not intercept tower mag field.	Large straps cost more but are needed to reduce L di/dt voltage.

EQUIPMENT STRESS

Even with a "perfect" ground system, voltage stress during a lightning strike may still be experienced by the equipment if the coaxial cables are not brought to the base of the tower, before the outside shield is grounded or if a proper bulkhead panel is not installed with an isolated shield type protector (PolyPhaser's Isolated Equipment protector).

We have already seen the tower's inductance and the associated voltage drops. The tower connection at 15-feet above the earth may **appear** to be a good grounding point. An ohm meter might even show it to be a "good dc ground", but it is really a poor, even **dangerous** grounding location; dangerous to equipment and people.

For a 1 5/8-inch coax cable, it is virtually impossible to make as sharp a bend as is necessary to ground the shield at the tower base. Yet in the absence of other grounding methods, it is essential to ground the shield at this point to keep the shield voltage near zero.

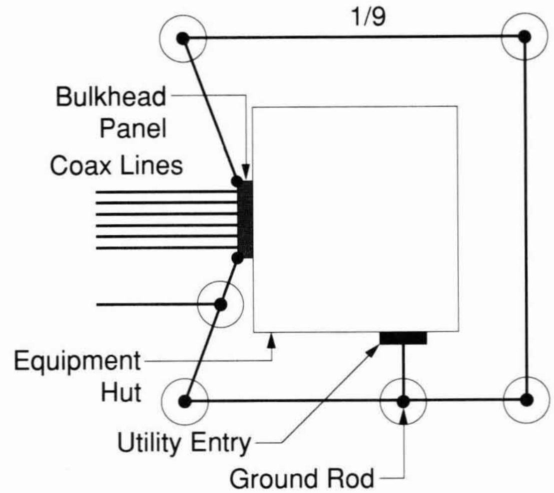
If the coax slopes downward from an elevated point on the tower so it enters the equipment hut at or very near ground level, another shield grounding kit should be incorporated.

If neither method is practical and the coax must enter the building significantly elevated above the earth, then a large surface area grounding **bulkhead panel** should be used to ensure a good, low inductance grounding route.

BULKHEAD PANEL

Bulkhead panels have been used for many years. The initial reason was to provide the equipment hut with a structurally strong entry point for one or more cables. The bulkhead panel was a rigid metal plate that covered a penetrating hole in the building's wall.

In installations where the coax lines must exit high on the tower, it is best to terminate coax lines at a bulkhead plate/coax protector and run a smaller more flexible line from the coaxial protector to the equipment. Grounding the bulkhead plate has, in the past, consisted of connecting a ground wire to this plate. A ground wire is very inductive - almost as inductive as 15-foot on the tower. A wire like this is ineffective, because of the inductance. A bulkhead plate grounded in this manner will not strip surge current from the coax shield.

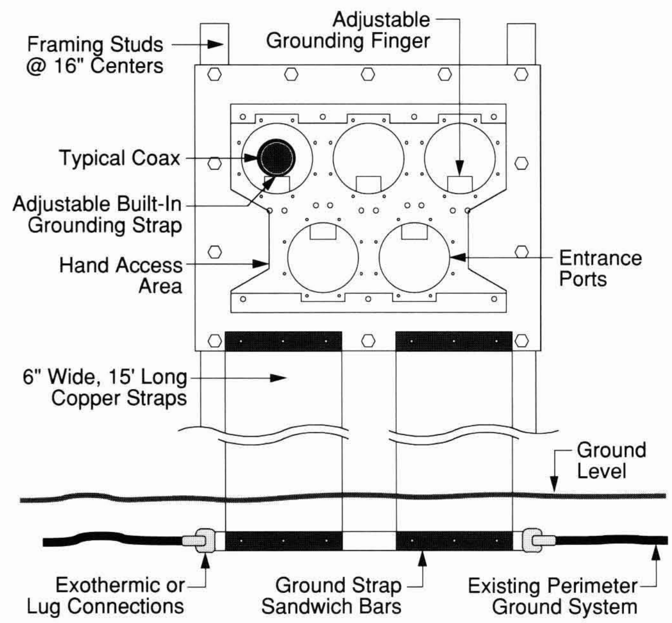


The Bulkhead Panel is grounded by cutting the perimeter ground and bonding the ends to it.

If the bulkhead plate is extended from the entrance hole along the exterior building surface and beneath the soil to the ground conductor, a low inductance interconnection to the ground system can be made. (Because of its large surface area (skin effect) and large W/H ratio, it should be less inductive than an equal height on the tower.) If the coax cable is grounded to such a bulkhead plate, lightning surge current will be stripped from the cable shield. (To do this a grounding finger should be used. The attachment to the cable must be weather protected by a boot.) The ease of installation (weight) and cost of such a full length copper extension plate may be prohibitive. A cost effective variation is to substitute copper strap material (.016" thick) for the thicker full length panel material going to ground. This makes it lighter, easier to install, and less expensive. The strap should be affixed to the building with silicone and then covered or painted for camouflage and wind resistance. (The PolyPhaser bulkhead panel system comes in a variety of port configurations and has a built-in grounding kit that is protected by its UV stable -60 F to +300 F weather boot. It uses multiple 6" wide copper straps for grounding to a buried sandwich bar that can be exothermically welded or lugged to the perimeter ground.)

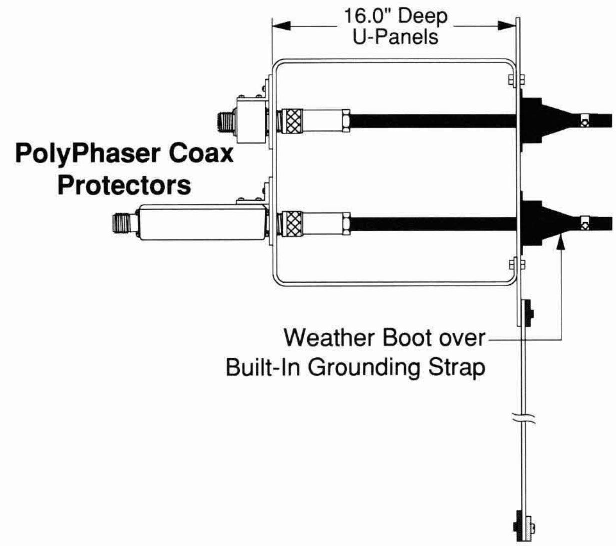
CENTER CONDUCTOR

Shield currents can almost be eliminated with proper techniques. However, the center conductors surge current should also be eliminated before the current damages the equipment. A dc blocked type lightning arrestor can prevent the center conductor's surge energy from reaching the equipment if it is mounted (grounded) onto the bulkhead panel. The use of a PolyPhaser Isolated Equipment type protector will further prevent the sharing of surge energy present on the coax shield due to the L di/dt of the copper strap to the ground system.



SUBPANEL

To further protect and restrict access to the coax-to-arrestor connection, a subpanel is mounted/grounded to the bulkhead. The subpanel is attached so it protrudes from the main panel through the penetrating hole and creates a secondary surface on which arrestors are then mounted and grounded on removable circular plates. All connector matings are accessible from inside the building for tests and changes. If waveguide is used, the round plate is simply not installed, because a protector is not needed. Proper grounding of the waveguide is accomplished by the grounding finger, under the weather boot. The subpanel is deep enough (16-inches) to be used for concrete block construction and handles any cable(s), that doesn't arrive completely perpendicular to the protector. The added depth allows for angle correction.



The best material to use for the bulkhead panel is 1/8-inch half hard C110 (solid copper). Only this hardness of copper can be properly tapped for screw threads. This copper weighs 5.81 pounds per square foot. Mounting hardware used to join the subpanel to the bulkhead is 18-8 stainless steel.

For small to medium size sites, the bulkhead panel should be the central grounding point inside the building for single point grounding procedures. Holes can then be drilled into the U panel for bonding straps and cable lugs emanating from the racks of equipment. The bulkhead panel serves as the master ground window or ground bus.

chapter 7

Inside Hut Grounding and Shielding

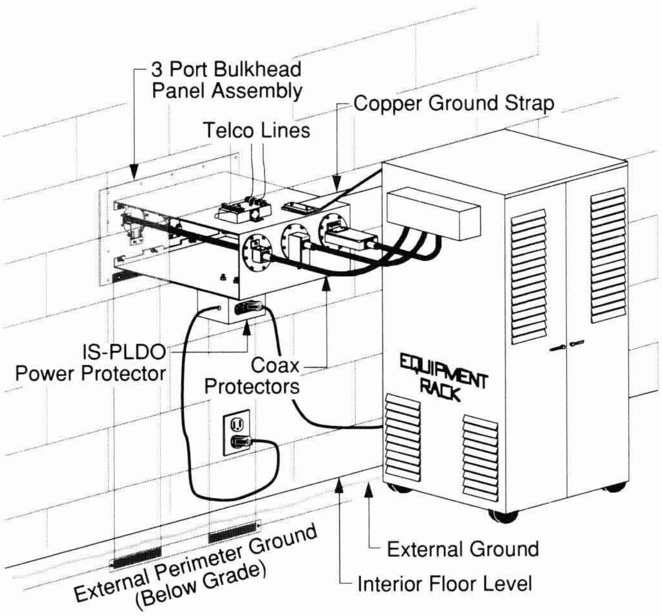
Surely everyone has heard of the safety procedure that says to keep one hand in a pocket while working around high voltages. If the body does not complete a circuit, no current flows and danger is averted.

To keep equipment safe in the event of a lightning strike, the same **one-connection** concept applies. **Single point grounding**, as it is called, is a grounding technique that ties all the equipment in a building together and grounds it at one common point. Implementing this technique is quite easy for small installations.

I/O PORTS

Example: A simple repeater installation with a telephone interconnect. From the equipment's perspective, there are three Input/Output (I/O) ports: the coax, power line and telephone line. These I/O's can function as either a lightning **source** or **sink.** Lightning surge energy may originate from one I/O and exit another I/O causing circuit damage. It is impossible to ground an I/O, so a surge protector must be provided for each.

The surge protector's purpose is to divert, absorb and isolate the equipment from the surge. Whenever a surge exceeds a preset voltage, the surge protector diverts the surge to a ground sink. By installing a surge protector at each I/O, it is possible to configure a grounding scheme that allows the equipment to survive a lightning strike.



Bulkhead Single Point Ground

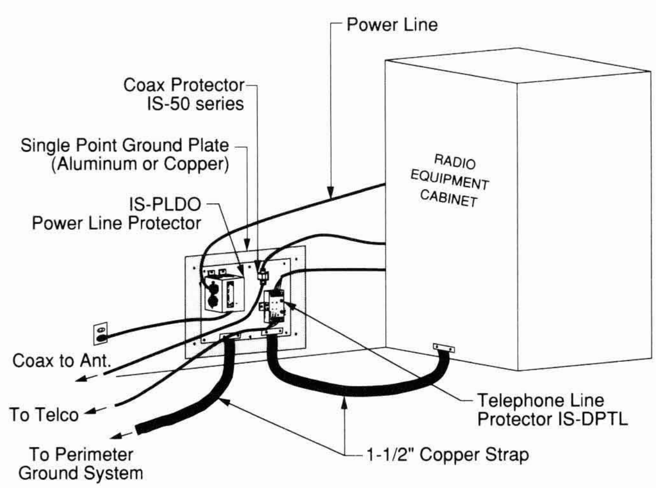
Preferred method of grounding I/O protectors for coax, telephone line and power line. The bulkhead plate in-turn connects to the perimeter ground outside the equipment hut.

A single point ground system would be created, if all the I/O surge protectors were grounded/mounted onto a bulkhead panel or onto a metal plate grounded to the exterior ground system with the equipment chassis also bonded here. Surge energy stripped from the lines by each of the surge protectors is diverted to ground via a single path. Imagine each I/O to be a hand or a foot. If a hand or a foot touch a high-voltage dc source at a single point, no current would flow through the body, thus, no injury. (The surge current necessary to elevate the body up to this higher voltage might be felt.) The body must therefore be insulated from everything else; no other path for current flow can exist.

Likewise your equipment must be properly isolated using insulators which elevate the racks away from the conductive concrete floors. Some people may think this is unsafe for workers, because there will be a difference in potential between the floor and the equipment. This is true, but the smart person will not be working at the site during a storm! By mounting the surge protectors on the same bulkhead or metal plate which is grounded to a common ground, no surge current flows between the I/O's and no voltage drop is created. Damage does not occur since the equipment chassis is also grounded to this same point. The surge protectors have a low impedance between them so no voltage drop can develop.

PROTECTOR MOUNTING

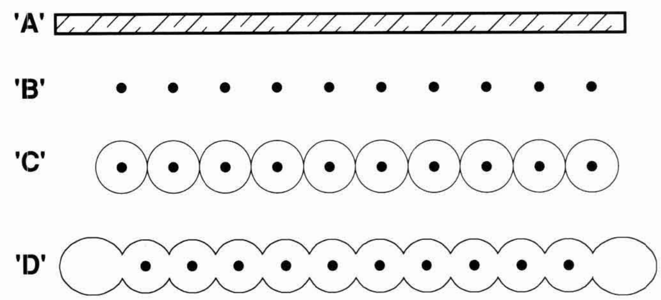
Current that is diverted by the protectors to ground should be conducted by a path whose inductance is as low as possible. If a grounded bulkhead panel, with its large surface area, low inductance, ground straps, is not used, the best place for mounting the surge protectors would be on an inside, floor level, wall mounted plate, with a low inductance interconnection to the perimeter ground. (This location is not as important in a high rise building room, unless the equipment is in a separate roof mounted hut.)



Example of Single Point Ground without Bulkhead

If the bulkhead plate was not installed at the time the equipment hut was built, an alternative grounding method may be used. Although the interconnect inductance of copper strap is greater, protectors may be mounted to a copper plate, which is connected by strap to the perimeter ground.

Flat strap is the best conductor. It has maximum surface area, for skin effect and low inductance. If it is necessary to bend the conductor, such bends should be no sharper than an 8-inch radius. Strap actually has less inductance than wire for a given angle bend. Mutual inductance, the cross coupling of the magnetic fields at the bend, is the reason for the added inductance of a bend. The distance from one side of the strap, when bent, is further away from the opposite side of the strap by the angle it makes, plus the width of the strap. The distance is greater so the mutual coupling is less. Also, the magnetic field susceptibility is maximum at its edges and it is similar to a dipole antenna. Therefore, it intercepts less tower magnetic fields if its flat side is oriented towards the tower.



A) Copper strap may be looked at as if made from an infinite number of infinitely small wires spaced infinitely close together **B)** the mag field of each wire **C)** is shown and they will add vectorially **D)** towards the edges.

No matter how low the protector path inductance may be, it still has some inductance (any conductor is also an inductor). Since the surge protectors divert current through this inductance, a voltage drop (L di/dt) is created. This voltage drop may cause problems for sensitive equipment. Control lines or balanced lines, for example, may become elevated above chassis ground. To ensure the equipment chassis is held to the same potential as the surge protectors, a low inductance connection between the equipment chassis and the bulkhead panel or protector panel is required. This conductor should have a lower inductance than the coaxial shield.

SHIELD CURRENT FLOW

If a Ufer ground with radials and a single point ground are installed, have all the possible problems been eliminated? NO! Surge current, however slight, could still flow on the coax shield within the equipment hut for two reasons:

(1) The equipment chassis or rack, like your body, has the ability to accept a charge (capacitance). The chassis is elevated to the **L di/dt** of the interconnection to the exterior ground. The current must flow to bring the chassis to this higher potential. This current flows along the coaxial shield.

(2) A large electromagnetic field is created by the pulsed current of the large lightning current surge. If the equipment is not in a shielded room (screen room), then the path from the equipment to the protector panel and to the ground system acts as an antenna. Since the ground system is a low-voltage, high-current point, the equipment end of the path, like the top of an antenna, is the high voltage point. This allows a portion of the pulse current induced by the electromagnetic field to flow along the coax cable shield.

This is an excellent reason to use PolyPhaser's Isolated Equipment (IE) type protectors. They will help reduce the coax shield currents to almost zero.

MAGNETIC SHIELDING

Lightning's high current means that the associated magnetic fields will radiate and cross couple to wire runs inside the equipment hut. Sites are usually designed to have a good 5 ohm ground system, but the building is placed right next to the tower with little or no magnetic shielding. The distance, between the tower and the hut, is usually kept small so the transmission lines are short. This places a heavier burden on your ground system to absorb and quickly conduct the strike energy away from the tower base. It also allows the magnetic fields to enter your hut.

Aluminum huts, like aluminum chassis, do little to attenuate low frequency magnetic fields. Concrete with steel mesh or rebar, which is ferrous, will show some attenuation. Steel shipping containers used as a hut, with either single or double walls, will act as a faraday shield for both radiated (plane wave) RF energy and magnetic (H) fields. The containers also provide a good uniform ground for your equipment from anywhere inside the hut. You may not need steel electrical metal conduit (EMT) for shielding inside the hut, however, for other non-ferrous huts you should run all electrical and sensitive lines in separate EMT conduits.

DISTANCE VS SHIELDING

The only alternative is to use distance. Magnetic fields drop off at one over the distance squared. To attenuate the strike's powerful H field from entering the circuit board and causing upset or damage, distance must be added. Distance will also add length to your transmission lines which gives additional inductance (voltage drop), forcing more surge current down to the tower ground. This is unlike adding length/inductance with drip loops. The difference is the straight run from the tower to the hut is orthogonal to the magnetic field from the tower and will not pickup any additional surge (the drip loops will). Speaking of H field pickup, the orientation of the bulkhead panel strap is such that it is at minimum coupling and the strap(s) can give some small amount of shielding to equipment close to it and opposite the tower.

LATENT DAMAGE

Attention to shielding is important because stress to electronic components can cause failure at a later date. The US military has spent large sums of money to study what has been termed "latent damage". Latent damage leads to premature MTBF (Mean Time Before Failure) of equipment. Lightning stress to high speed, small junction semiconductors, can lead to blue sky failures. Since the user does not have design control over the PC board layout, decoupling, trace length, proper I/O protection, or the equipment enclosure, the only choice you have is to pick the manufacturer with the best warranty and replacement service.

LARGE SITE GROUNDING AND SHIELDING

At very large sites (over 15m by 15m) where lightning shielding is important and steel sheets can not be used to make a screen room, manufacturers sometimes provide an internal ground halo as an inexpensive alternative. This halo is both for personnel safety (grounding door jams and louvers) and to intercept the low radiated frequencies of lightning, however, it is not very effective. It often is mistakenly used for (multipoint) grounding of equipment racks.

GROUNDING EQUIPMENT CHASSIS

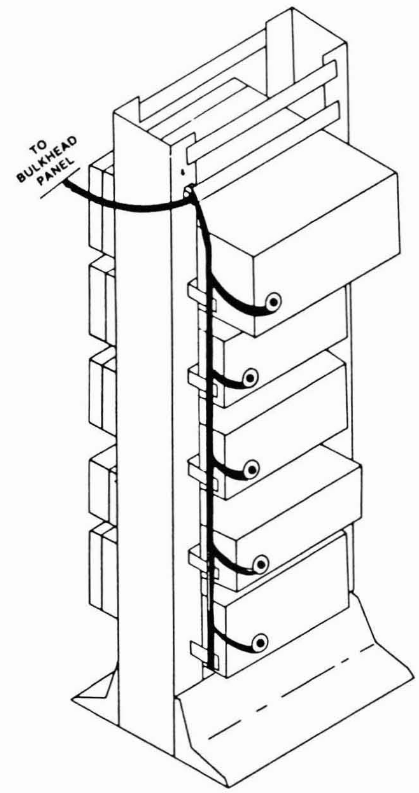
Racks are commonly used to mount larger base station equipment and repeaters. Rack panels may be painted or the rails they are mounted to may become oxidized. The paint and oxidation may have enough resistance to prevent the rails from being an adequate interconnecting conductor which ties all the rack mounted equipment together.

Under non-screen room conditions and within high RF fields, such as those found at broadcast transmitter sites, the contact between the dissimilar metals of the bolts, rusty rack rails, and equipment panels can form "diodes". These "diodes" have been known to cause all kinds of intermodulation interference and audio rectification.

A proper way to tie the equipment together is shown on page 37. The vertical ground bus is supported by insulators. Each piece of equipment is connected to the bus by a short strap. With this configuration, any "noise" created by poor joints and dissimilar metal contact within the rack is "shorted out" by the short loop.

The short loop may be a resonant antenna near the frequency of the strong RF field from a nearby or co-located high-power broadcast. It may be resonant near your operating frequency, or some other intermediate frequency used by your equipment. A grid dip meter may be used to determine whether the loop is resonant at a frequency that could cause a problem.

The loop's resonant frequency can be found with other methods. A spectrum analyzer may be link-coupled to the loop and observed to see where the noise floor rises when the loop is opened and closed. The same technique could be used with a service monitor tuned in the AM mode to a quiet channel. (Note: Front-end overloading could give false readings.)



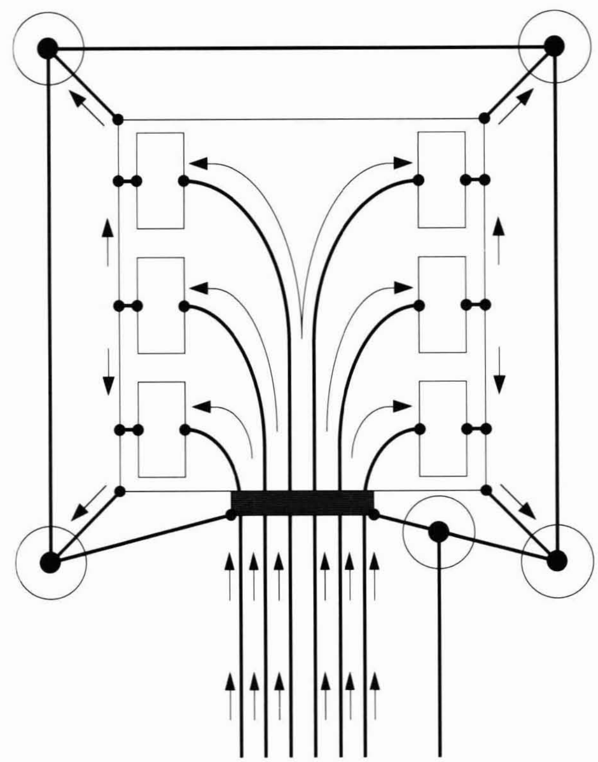
Each equipment chassis in a rack is connected by short strap to a vertical grounding bus suspended by insulators.

GROUNDED SCREEN ROOMS

Screen rooms work best for shielding equipment from high RF and electromagnetic pulse (EMP) fields associated with high-power transmitters, lightning strikes and high-altitude nuclear detonations. However, proper methods of grounding the screen room itself shouldn't be overlooked. The screen room manufacturer should be able to detail the techniques that ensure maximum screen room effectiveness.

MULTI-POINT GROUNDING

Some microprocessor equipment manufacturers have adopted multi-point grounding techniques in an effort to keep noise and RF off the logic ground bus when interconnecting to radio equipment. An example is found in cellular switch locations. Since most of these are large installations, it is not practical to install a low inductance interconnection (an inside halo) suspended in the air within the room (unless a screen room is used). Therefore, independent interconnects to the perimeter ground are the answer (multi-point). *Don't jump to this technique in haste. The problems that arise from not having a single point ground can be worse than the possible noise from the RF equipment.*

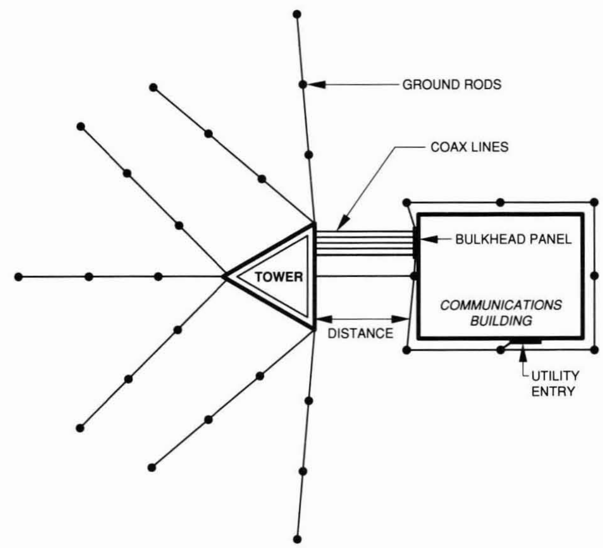


While single point grounding is in most cases preferred, large installations may make use of multi-point grounding to overcome the inductance of a ground interconnect conductor suspended in the air within the equipment hut. Careful design is required.

PROBLEMS WITH MULTI-POINT GROUNDING

Electrons take time to travel from one position to another (propagation time). For this reason, care must be taken in designing the perimeter ground system and in spacing the interconnects for a multi-point system. Serious trouble may result by too few interconnects to the perimeter ground. Remember, two hands (not one in the pocket) going to two different places can complete a circuit.

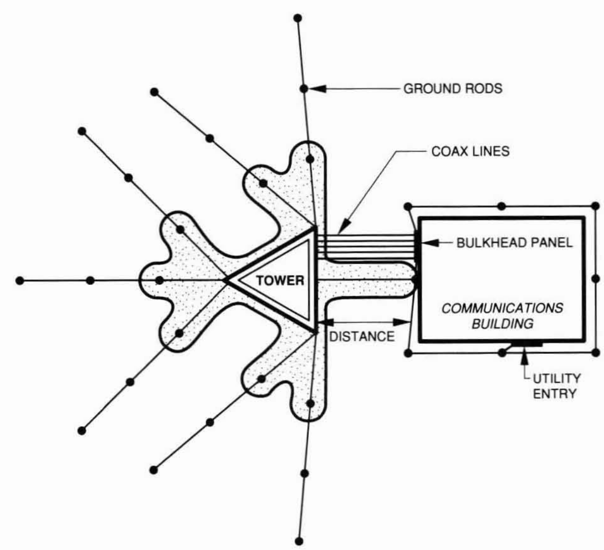
For **large** equipment rooms, using **many** connections to the perimeter ground is a viable method. As a result, some surge current will enter the equipment room. However, with multiple paths to ground, the current is divided by the total number of paths. In this way the current is reduced to a harmless amount, i.e., each **L di/dt** is small enough so no damage occurs in the equipment. Ideally, each path from each piece of equipment to the perimeter should be of equal length. This means that for a typical site, the paths to the perimeter ground system should be interconnected to the inside halo about every two feet! This is rarely done and is why the halo has problems! It is easier to do a single point ground system than it is to install so many halo to perimeter interconnections.



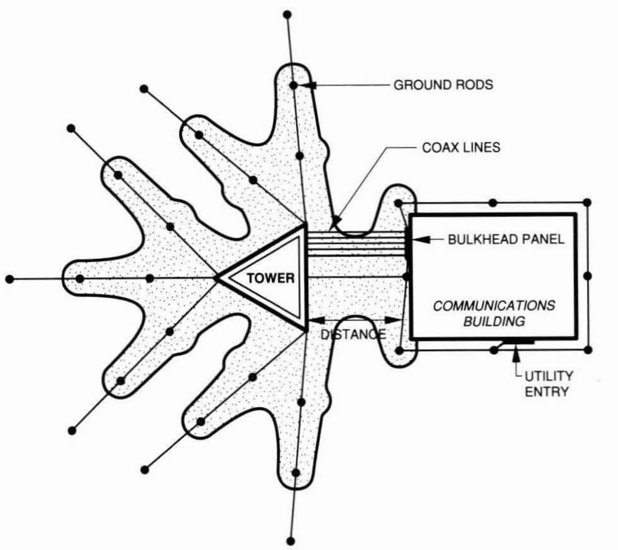
Recommended site grounding system about to be hit by lightning.

FAST PROPAGATION TIME

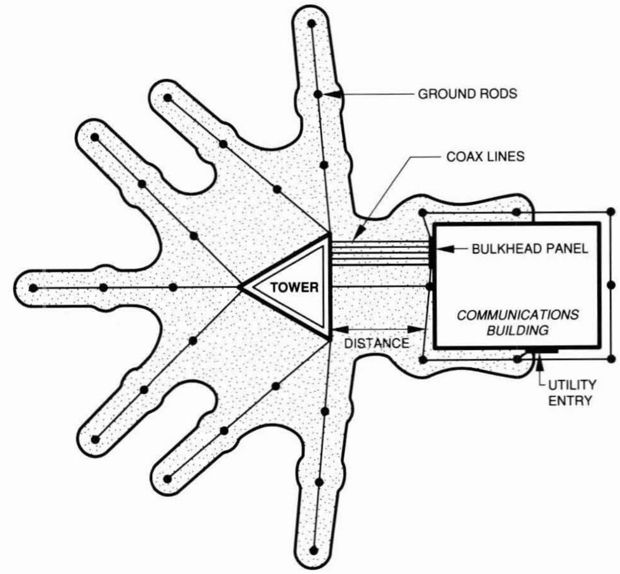
The multi-point ground design concept places more emphasis on the perimeter ground connections. Because the I/O's are the only means by which current may enter the room, the lower its interconnect inductance to the perimeter ground by the numerous parallel paths, the smaller the L di/dt voltage present. The propagation time of the ground system will be covered in detail later, but for now, the timing of the current in the earth around the hut can cause problems with a multi-point ground that is not present with a single point ground. Look at how the surge propagates in the following series of drawings. Note that the majority of the surge is diverted out and away from the building. Also note the time it takes to progress around the building. This is the reason why some currents traverse the parallel multi-point paths through the building in order to get to unsaturated perimeter ground locations. The race is between the speed of the perimcter versus the speed through the building. Normally if the ground system is any good, it will be faster than the slightly more inductive path through the building. You can wind up fighting yourself by adding more paths, making the voltage drop less, which then makes the propagation time faster through the building. This means more current will traverse through the building which is undesirable.



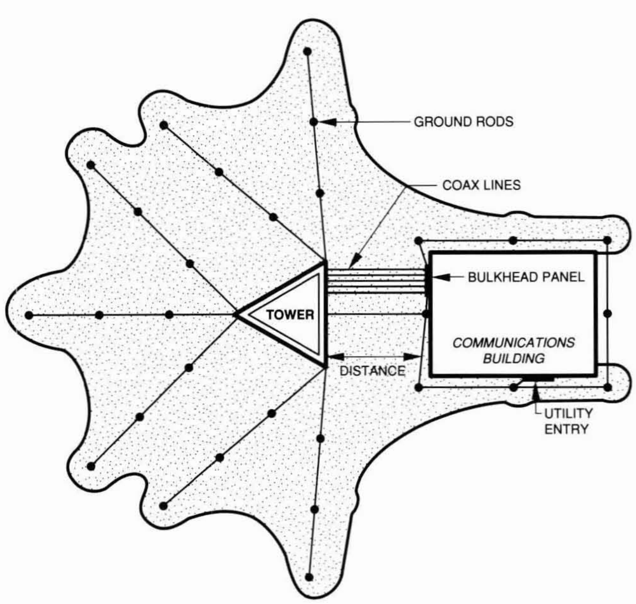
Neglecting the coax currents, the strike energy moves outward from the tower base along the radial line.



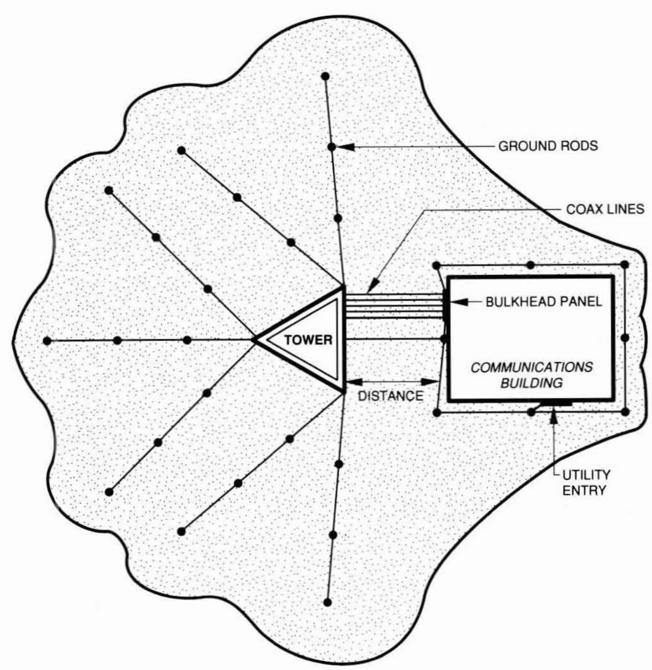
On a well designed ground system, the strike energy spreads out initially from the building.



As it spreads, it loses energy due to the spreading and I-R losses.



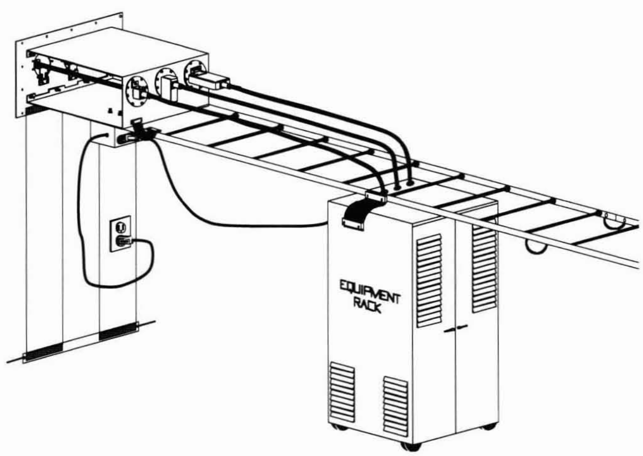
As it reaches and saturates the radial system, it will traverse the building perimeter.



By the time it surrounds the building, the radials have spread out much of the energy.

INSIDE HUT UFER

The Ufer ground on new building construction should not be overlooked. Wire mesh encapsulated inside the building floor can be used as a low impedance grid. If the aesthetics of wires emanating from various locations on the building floor are not acceptable, the wire mesh may be bonded to an inside bus ground just above floor level for easier distribution. Two feet should be the maximum separation between vertical interconnections bonding the ceiling halo and the mesh floor bus. The mesh should likewise be connected to the outside perimeter ground at the same 2-foot intervals.



Using Cable Trays as Ground Connection

CABLE TRAYS

Large installations may make use of cable trays to support overhead runs of coax lines and other interconnecting wires. One of the best things to do is ground the cable tray. This prevents any arc over from coax lines and acts, somewhat, as a partial faraday shield for low-frequency components of the radiated electromagnetic field generated by the lightning strike.

The tray joints should be jumpered to make the tray one conductive piece. The tray is an excellent way of grounding equipment racks together, because it has a very large surface area.

Remember - ground the tray to the bulkhead panel unless isolated equipment port protectors are used. The tray will then be grounded through the electrical ground to the perimeter ground and isolated from the bulkhead panel. Also, try to keep noisy lines from sensitive lines in the tray. Noisy lines should be put in EMT conduit to prevent cross coupling to other lines in the same tray.

chapter 8
Remote Equipment Power Protection

The incidence of damage to equipment in general, is higher from power line surges than by any other I/O. This is not to say more surges come through the power line, just that the damage is more visible here. Usually the damage is due to improper grounding techniques. The coax is still the path of the biggest surge current. It is the largest surface area, connecting to the direct source of surge current, the tower. Let's take a look at the power line I/O and see why it's the area of the most damage.

'FIRST WAY'

Surge current may be imposed on a power line by a lightning strike near the equipment building. The lightning may strike an overhead utility line. Current may directly enter buried lines when lightning strikes a street light or surge current may be conducted to a buried power line if lightning strikes a nearby tree. Which ever way the current enters, it causes a bi-directional flow of surge current on the power line. Current flows both toward the equipment building, and away from it.

When the surge flowing toward the equipment hut reaches the distribution transformer, part of the energy is diverted to ground. Energy not diverted to ground is coupled through the transformer by arcing (non-catastrophic) or capacitively coupling. Surge current continues toward the equipment building on both the "neutral" and "hot" conductors of the power line.

At the building's power line feed point, the neutral is tied to ground. This conducts some additional surge energy to ground.

Energy from the lightning strike remains on the "hot side". Since lightning is so short in duration compared to 60 Hz, the surge current takes the form of a ringing waveform riding on the 60Hz. It is impossible to state the peak amplitude, frequency and duration of this waveform because the impedances along the path would have to be defined. These impedances include the surge impedance, the load impedance and the line impedance. They are not easily defined.

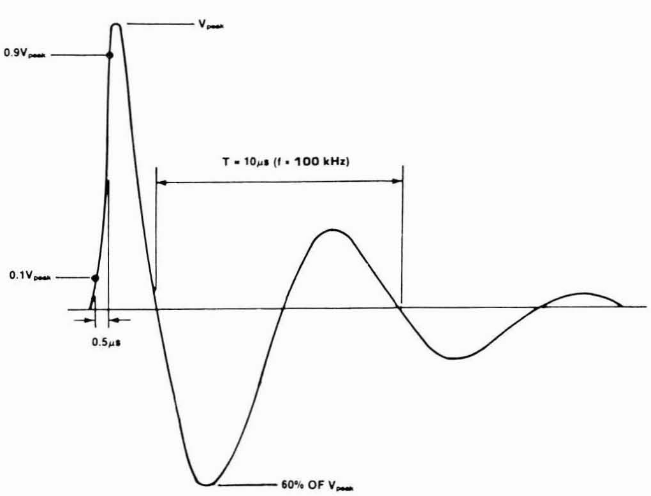
Surge source impedance differs on directly struck power lines and with nearby strikes. The impedance changes as the surge current is conducted by arcing or capacitively coupling at one or more transformers between the strike and the building. The surge impedance also depends upon the impedance of each ground connection along the path, including the transformers and the point at which the power line enters the equipment building.

Load impedance depends upon the amount of load inductance and resistance (power factor) placed across the line by devices such as air conditioners, heaters and lights.

Line impedance is governed by the length and number of lines, and the line resistance and transformer impedance.

Impedance values for each of these elements are independent variables representing an infinite number of possibilities.

Because the surge, load and line impedances cannot be defined, the voltage waveform that the surge energy takes cannot be defined. Nevertheless, some standards have been based on actual data for both lightning and equipment surges.



Category A waveform of IEEE standard 587-1980

One standard that has been formulated is designated IEEE Std. 587-1980 (now ANSI C62.41 and tested under UL's #1449). The standard is for power lines and has three categories. Category A is for "long branch" circuits such as long run secondary ac wall outlets. Its surge wave is a 6kV open voltage, 200A short circuit ringing waveform (damped cosine) with 0.5μs rise time and a frequency of 100kHz.

Category B is for "short branch" circuits, near the breaker box or close to it. The waveform is the same. Its rise time is 1.2μs and its decay time to the 50% point is 50μs. The unpolarized pulse is 6kV open voltage and 500A to 3kA short circuit.

It's obvious to anyone who has seen power cords blown off equipment by surge current from lightning, that the destruction could not be caused by as little as 3kA or from only 6kV. The IEEE standard is mentioned to show the difference between what it really takes to destroy cords and what the IEEE sets as a standard. The comparison shows the need for protectors both at the equipment and at the breaker box. It is by exceeding the voltage breakdown from a strike that destroys a cord. The breakdown (arcing) is fed by the 60Hz and the cord can be melted. Similarly, due to the presence of a power source, a surge failed power supply component can cause a domino effect of failures or stress to the power supply devices.

'SECOND WAY'

Surge current may arrive to stress equipment within the building via a second way - a strike to the communication tower. In an ideal installation, the tower, bulkhead, equipment and utility grounds are all tied together. Just as it is impossible to define the power line surge waveform accurately because many independent variables are involved, it is also difficult to predict exactly how much stress will be delivered to the power line I/O when lightning strikes the tower. A common I/O that is often overlooked is the **tower lighting.** The amount of surge entering from a tower strike through this I/O is tremendous. Protectors are available to prevent this surge energy from coming into the hut and distributing itself onto the hut's power lines.

Rules of thumb can be used to help predict the amount of stress expected for a single point ground system. If radial wires are installed with Ufer grounds at the tower base and connected to the guy anchors, surge current at the tower base is divided by the number of radials. A short radial (only one) should connect the tower base to the bulkhead panel. The perimeter ground encircling the equipment building should connect to the bulkhead and not to any radials. The utility ground should connect to the perimeter ground.

With this interconnect scheme, as we indicated in the previous chapter, it should be faster for the surge to propagate via the perimeter than it is to traverse through the building. If this isn't the case, major power supply stress will occur.

The one way to theoretically limit stress on the equipment's power supplies is to provide a lot of inductance (isolation) for the power line path inside the equipment hut. Higher inductance forces surge current into the outside perimeter ground path. The inductance can be made by using long power cords to the equipment, placing the lines in EMT conduit or cords with coils or knots. (Remember, like coax coils, there is a limit to the voltage isolation that can be achieved before breakdown.)

One possibility for damage remains in spite of this precaution. The hot lead for the 60Hz power may be at a voltage peak with the surge which can cause a breakdown. It is a good idea to use a local power line I/O protector to protect the equipment. The important thing is to mount/ground the protector on the bulkhead panel or equipment chassis. A wall-mounted protector, that plugs into a wall socket (the type often advertised in connection with computer/consumer equipment) will not protect the equipment because it is grounded* at the plug socket. The plug socket is "in the middle" of two inductances (the power cord inductance and the line running back to the breaker box) and is effectively removed from earth ground. Very few protectors will have another means to connect your ground system to , since UL will not approve a unit which plugs into the wall (called a temporary power tap) with a proper mounting/grounding flange. Only PolyPhaser's IS-PLDO series has this grounding flange. The series was approved by a Nationally Recognized Testing Lab (NRTL), that was setup by the US Congress and upheld by the US Supreme Court, as being equal to the UL approval. The importance of the grounding of the protector is to ensure it is in common with the chassis of the equipment. To accomplish this, it can't have the cord inductance and it must be mounted/grounded to the single point ground location where the equipment chassis is grounded. It also has a built-in isolating inductance and a 15-foot long cord.

* For applications where there are no other ground paths and the ac safety ground is the only ground available, this ground must be used. This is far from ideal!

TWO WAYS - TWO PROTECTORS

Surge current coming from lightning that strikes a power line some distance from the building (the first way), may be divided several times as it flows through transformers and other devices. It is important to design protection for the "worst case". Surge current flowing towards the building may be in the order of 10kA or more. A power mains protector is needed to protect the breaker box, lights, heater, etc. Protectors must be able to withstand line current surges much greater than those specified by the IEEE standard of 3 to 5kA.

PROTECTIVE DEVICES FOR POWER AND TELEPHONE LINES

There are many books, now on the market, addressing the design and components that go into the design of protectors. Most protectors use one or more of the following components:

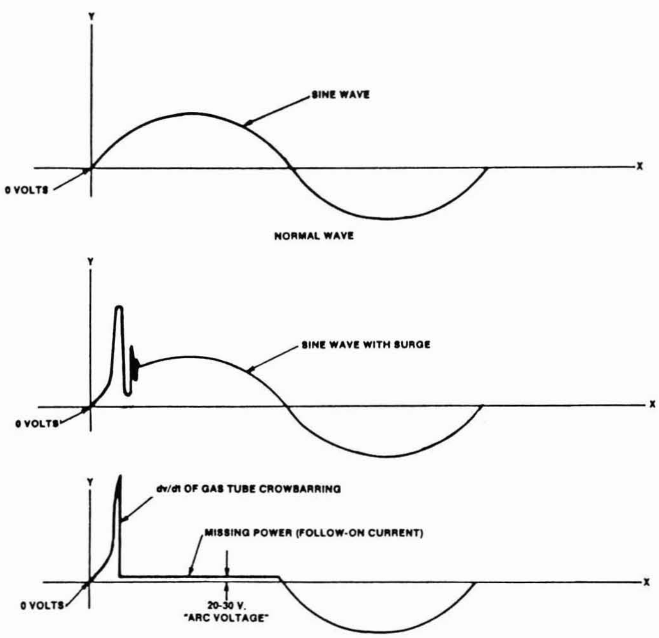
- Air gaps
- Gas tubes
- MOV's
- Zeners (high impulse)
- Four-layer semiconductors
- SCR's

AIR GAPS

Air gaps handle high currents, but are slow to act and require regular inspection. Altitude, temperature, humidity, pollution, corrosion, shape and spacing all effect air gap performance.

GAS TUBES

Gas tubes are better than air gaps, but both share the problem of "follow-on" current. When surge current occurs during the instant that 60Hz ac is at a zero potential, follow-on current is not a problem. If the surge arrives at any other time, triggering an arc, the arc is fed or sustained by the power from the 60Hz source. The arc extinguishes when the waveform voltage falls below the arcing voltage (about 20 to 30 volts). This voltage can be even lower if radioactive isotopes are used inside the gas tube. The US military now requires all gas tubes be non-radioactive.



Disadvantage of gas tube and air gap protectors. 60Hz waveform may sustain arc (follow-on current) across gas tube or air gap, interrupting power to equipment for up to 1/2 cycle.

Power loss of up to 1/2 cycle (8.3ms) can result, which may cause problems with sensitive equipment. The air gap and gas tube are much like Silicon-Controlled Rectifiers (SCR); once in a conducting mode, the energy source must be almost completely removed to turn it off.

One remaining dilemma with air gaps and gas tubes: As they "crowbar", the dv/dt that is created, is high in harmonic energy and can be coupled capacitively through power supply transformers causing problems.

MOV'S

The metal oxide varistor (MOV) does not "crowbar", it "clips" or "clamps", at a given turn-on voltage. MOV's handle moderate amounts of surge current up to 160kA and have a finite lifetime. The devices are made from zinc oxide granules. As the voltage across it rises above turn-on, electrons tunnel through and conduction occurs. At maximum rated surges, the granules heat and melt together. Melted granules cannot reunite to form zinc oxide. In the end, the MOV is mostly zinc and short circuits. With major usage, the MOV life is shortened. However, any protective component can suffer a reduced life from continuous pulse usage near its maximum limits.

Surge current conducted through the MOV creates a voltage drop. As current increases, the voltage rises. The action is non-linear and is often referred to as the "clamping ratio". In the ideal situation, the voltage remains the same regardless of current.

ZENER LIKE (SAS)

High pulse current zener diodes (also known as Silicone Avalanche Semiconductors - SAS) come in a variety of configurations. They have a more ideal clamping ratio than MOV's. Their lifetime is unlimited if the surge remains within its energy handling range. Unfortunately, SAS's do not handle much current, but its clamping ratio is better than the MOV. It is, however, far from ideal. SAS's and MOV's still act much faster than air gaps and even most gas tubes.

The MOV's and SAS's speed is due partially to its high capacitance. Surge current charges the capacitance making the effective response time of a leadless MOV less than a nanosecond. A large pulse-handling SAS may have high capacitance too. A leadless chip SAS reacts in less than a nanosecond.

FILTERING

MOV's and SAS's are rarely used leadlessly. Leads must be connected to these devices when they are used in a protector and the leads add inductance. Protectors that use either MOV and SAS components are often advertised as having sub-nanosecond response time. They use lowpass filtering to counteract the inductive lag thus insuring a quick response. Power line protectors advertised as having sub-nanosecond response time have misleading specs if they do not have lowpass filtering. Filtering is important to prevent small spikes, surges and noise. Although the voltage excursion of such spikes, surges and noise may not be hazardous, it may cause problems with some equipment.

FOUR-LAYER

The newest device on the list is the four-layer semiconductor. It is a "follower" or "negative resistance" device, much like the SCR. It handles more current than a SAS of the same size because of its crowbar action. Unlike the SCR, it has a "turn-off" voltage.

Four-layer semiconductor protection devices are not limited to power line applications. They may also be used on telephone or control lines. Sometimes they are used alone and other times in complex combinations (hybrids).

THREE ELEMENT GAS TUBE

The most popular protector for phone lines is the gas tube. It was originally designed to replace the older carbon buttons that became noisy with use and required maintenance. Actually, the carbon buttons weren't intended to provide lightning protection, but rather to protect personnel in the event a power line broke and came into contact with a telephone line.

Both the carbon button and the gas tube are inadequate for protecting equipment. On balanced telephone lines both the voltage above ground (common mode) and the voltage between lines (differential mode) are important. When individual crowbar devices are used, one for each side of a single pair (line), inevitably one device fires before the other. This creates a large differential voltage that can damage equipment.

The solution is to use a three-element gas tube. This device has a common gas chamber with two gaps, one on either side of the grounded electrode. When one side of the line reaches the ionization potential of the gas, both sides fire simultaneously to ground.

Once again, because of the rapid change (dv/dt) caused by the device firing, it is important to use some lowpass filtering.

Telephone lines or control lines are similar to power lines in that they provide two directions for the surge energy to flow. Since telephone and control lines generally use wires smaller than power line wire, they have more impedance (inductance and resistance). With higher impedance the physical damage caused by the surge current is less, but the cost of the damaged equipment may be more.

SCR

The last protection device on the list is the SCR (Silicon Controlled Rectifier). This device comes in a variety of sizes and can be very fast, especially when teamed up with the MOV. The MOV provides the speed and the SCR protects the MOV from long duration surges, thus extending the MOV's life. In power main applications, the SCR's dv/dt problems are buffered by the capacitance of the MOV and added filtering. This makes the perfect marriage between the MOV and the SCR for the really big job of power mains protection.

SECONDARY TELEPHONE LINE PROTECTORS

The entrance protector is required for telephone or control lines for the same reason an entrance protector is needed for power lines. The local telephone company usually supplies the building entrance station protector as part of their installation service. Generally, this is a single gas tube per wire type protector. If a better protector is desired, it should be used in addition to the utility's unit and installed after the demarcating block. Ground it to your perimeter ground system. The cables should be run to the bulkhead panel in EMT conduit to prevent surge radiation pickup. Install an additional secondary protector at the bulkhead panel for single point grounding.

The line running between the entrance protector and the secondary protector should be inductive and shielded. If the distance is short, inductance can be increased by using metal conduit or shielded (boxed) loops. The line may be enclosed by a metal conduit, grounded on the equipment end or it may be looped several times inside a steel (ferrous faraday shield) NEMA enclosure.

FEWER LINES NEED BETTER PROTECTION

Dedicated lines for dc remotes, tone remotes, data lines and audio lines should be treated in a manner similar to the telephone line. Since the total surge energy is a given amount, the more line pairs that enter the building, the less surge current per pair. A single pair, terminating at a piece of equipment, needs a better protector (multi-stage) than each pair of a 25-pair line terminating at the same piece of equipment.

For multi-pair installation, extensive use of matched MOV's provides both protection and capacitive filtering. The MOV's should be placed line-to-line and line-to-ground. To prevent pair imbalance that could induce a differential voltage, both of the line-to-ground MOV's should be selected so their turn on voltage matches to within 5%. The turn on of the line-to-line MOV is not critical.

PROTECTOR PLACEMENT

There are two recommended positions for protector placement:

1. Protectors should be placed on the bulkhead panel in buildings using the single point grounding technique. This allows each I/O protector (coax, power and telephone lines) to have a low inductance interconnection - to the perimeter ground, as well as each other. In an installation without a bulkhead, the I/O protectors should be placed on a single point grounding plate as described earlier.

2. The incoming power and telephone lines should be protected before they enter the hut. This will be in addition to the single point grounded protectors. These secondary protectors prevent the surge currents from entering the building and radiating inside your equipment room.

GENERATORS

All inside or outside generators must be grounded to the perimeter ground. Both the neutral and the metal housing are to be grounded. All fuel tanks must be grounded, even if they are buried or tar pitched (insulated). The location of the mains protector may be changed slightly, depending on the quality of the generator. Some generators like to hunt or vary their frequency or output voltage which can cause some equipment trouble. Most want to place the protector on the output or load side of the transfer switch so the protector will take out some of the voltage peaks. The problem is, the protector may not be designed to handle this type of long duration (compared to lightning) surges. If it's a lightning protector, don't treat it like a voltage regulator. Buy a unit designed for the job (regulating) using SCR's and load resistors. Otherwise, purchase a better generator and place the lightning protector on the utility input side of the transfer switch.

BATTERY POWER

Some installations use batteries in combination with a charger to supply power to the equipment. The charger needs power line protection to survive a current surge from a lightning strike. On the dc side, batteries that are in good condition provide substantial line-to-line capacitance, but they don't protect from common mode surges (lines to ground). If the batteries are located near the charger and the dc power lines to the equipment are long (inductive), an over voltage protector may be needed at the equipment.

In non-screen room installations, long dc power lines will pick up the electromagnetic pulse of a nearby lightning strike. A capacitor bypass network is used to shunt the pulse to ground. The network should have four parallel capacitors connected with very short leads. Values of 0.01μF, 0.1μF and 10μF are recommended. A high pulse current SAS may also be incorporated to clamp over voltages and reverse spikes from the equipment's dc power line. Be sure the turn-on voltage is high enough so the battery surface charge will not be bled off by the SAS. The SAS, like the MOV lightning protector, should not be used as a shunt type voltage regulator.

Another effective method is to run the dc lines through metal conduit. The conduit is then grounded only at the equipment end.

The batteries should not use the earth ground bus in the equipment room as a means of providing a return circuit. Separate conductors for positive and negative connections should be run to each piece of equipment, otherwise equipment noise could be spread throughout the ground system.

Some manufacturers ground the negative side of the equipment chassis. This sometimes can't be helped. It does reinforce the need for some local over voltage protection because the chassis ground potential follows the rest of the ground system's potential during a lightning strike.

Stress will occur at the battery charger output because of the difference in lead lengths (inductive delay) between the positive and negative outputs and chassis ground. The problem can be solved by using MOV's. The MOV's capacitance should be balanced (equal) to prevent hum pickup. They should be placed between each floating output and chassis ground.

The MOV's prevent an arc breakdown from occurring within the charger. Such a breakdown could damage components. Choose a MOV rating high enough to allow the batteries' maximum dc voltage to pass. Additional MOV's may also be installed at the equipment to provide local over voltage protection.

Connections inside the equipment hut should be free of paint and clean of all contaminants. Joint compound is recommended. PolyPhaser provides a tested copper joint compound in its Copper Cleaning Kit (CCK). The connections should be tested when made as a preventative maintenance procedure. A Fluke 8012A-01 Digital Volt Meter (DVM) will measure down to a milliohm and is battery operated. At battery operated sites, the ground may have dc current flowing through the joint under test and a negative resistance value may be displayed. Whether displayed or not, the DVM will need to measure the joint in both directions (switch leads). The algebraic sum or the difference between the two readings, if both are the same polarity, will be the real ohmic value.

SOLAR PANELS

At installations using solar power, photoelectric cells and the lines connecting them to the regulator can act as an antenna that captures the radiated surge fields of a lightning strike. Spike voltage line-to-line may be low because of the solar cell's impedance, but the surge voltage from each line-to-ground may be quite high.

The high line-to-ground voltage could stress and even cause premature failure of the series pass regulator. Any regulator failure means eventual outage for the equipment. MOV's can be used to control the spike, but with their poor clamping ratio and bipolar response, they may not be enough. A hybrid consisting of a properly sized gas tube (turn off voltage), MOV's, and high pulse current SAS diodes, with air inductors, has been found to be effective.

Never attach a lightning rod to a panel support, no matter how exposed a solar panel is to a direct lightning strike. This is an open invitation for a strike to hit very near the panel. The most effective way to protect your panels is to use a lightning strike divertor and have it hit some distance away from the panel. (See Chapter 15.)

chapter 9
Tower Top and High Rise Radio Equipment Sites

To better understand how to make tower top equipment survive, equipment categories will be divided into two segments: tower top preamps and tower top repeaters.

Tower top preamps are often used to obtain a better overall system noise temperature. A cost comparison must be made between a preamp and small coax versus a much larger lower loss coax. The ice and wind loading factors for the tower should also be a consideration.

To keep the number of wires to a tower top preamp to a minimum, dc power is often injected onto the center pin with the shield as the return. With a lightning strike most people think the antenna input side of the preamp is at risk. When a proper dc grounded (shunt-fed) antenna is used and the preamp is physically located on the tower at the same height, with just a short coax jumper, the chances of front end damage are small. Besides, most commercial preamp systems incorporate interdigital front end filters which are dc grounded and acts as a front end protector.

PROTECTION

The problem is with the output of the preamp. The tower, acting as an inductor, creates an instantaneous voltage drop. This means a sharing of surge current will exist with the coax shield. Since the shield will couple energy (both E and M fields) to the center conductor, a bump (surge) will exist.

The lightning surge current will propagate down the coax shield and center conductor with different speeds and amplitudes. At any instant the shield will be at one voltage while the center conductor is at another.

RF AND DC SEPARATE

The surge generated on the shield meanwhile heads towards the equipment hut where it finds a dc injector that combines the dc and the RF. The surge will penetrate through the injector to the dc power supply, causing it to fail to the rail voltage.

If the dc power supply has an SCR over voltage crowbar or protector, the **dv/dt** action of the SCR crowbar will be coupled back through the dc injector and onto the coax cable. It forms a broadband step waveform, exciting the coax line. The line probably does not have a 50 ohm terminating impedance for these lower frequencies at the preamp pickoff end. (The preamp's impedance is only 50 ohms in its operating bandpass.) This reflected waveform can reach hundreds of volts at the preamp. The voltage amount depends on the waveform, coax length and the preamp's (and dc pickoff's) impedance. This reflected waveform will be delivered to the preamp's power bus, stressing all active components.

Even if a dc continuity type coax protector was installed that had a dc turn on of 75 to 90 volts, it would be ineffective. With the power supply voltage between 15 to 36 volts, neither the preamp nor the power supply could withstand the dynamic voltages necessary to turn on this type of protector. (A **good** 90-volt gas tube won't fire until 140 volts under dynamic rise times!) Even if fired, the power supply would feed the arc until a failure occurred.

ONE SOLUTION

The only way to solve this problem is to either make a dc injector and pickoff with enough built-in protection, or make one that separates the RF from the dc, protects each, and recombines the two together all in the same box. This later one is system transparent.

Most tower top manufacturers utilize PolyPhaser's dc injector (IS-DC50LN) and pickoff (IS-GC50LN) combination. As good as these protectors are at protecting the equipment, it still means the surge current must enter the equipment hut before it can be taken back out to the perimeter ground system. PolyPhaser's model IS-DC50LNZ, is system transparent and allows users of bulkhead panels to prevent almost all of the surge current from ever entering the hut.

The duplexing (combining) of the preamps output with multiple transmitters on one line reduces coax cost and tower loading. At 800MHz, multi-channel lightning protectors for transmitters and receivers, with the separate dc injector and pick-off, are available (PolyPhaser's IS-CBT50LN).

TOWER TOP REPEATER AND MICROWAVE EQUIPMENT

For tower top repeaters, the I/O's are the most important to protect. Tower, telephone or control lines often are overlooked. The coax line protector may be eliminated if similar conditions exist as previously stated for the preamp's front end.

Power line protectors must be local and single point grounded at the top with the equipment. The need for power protection is doubled for tower top repeater installations where 120 or 240Vac is being fed up the tower.

Above 18GHz, microwave equipment usually has a Gunn downconverter located on the back of the dish, powered through one or two coax cables. These line(s) also handle the uplink and downlink frequencies as well as AFC (Auto Frequency Control) error information. Protectors are available (IS-MD50LNZ) to protect these microwave units and like the tower top preamps, it will take two locations, tower top and bottom, to properly protect the system. The IS-MD50LNZ is similar to the IS-DC50LNZ mentioned above, in that it is completely transparent to all existing voltages and signals from the microwave equipment.

Whether it is a tower, high-rise building or water tower installation, the "single point ground" concept should be carried throughout the grounding scheme. All I/O protectors must be tied together on a grounded plate and then tied to the equipment. It doesn't matter that the equipment will be a few hundred thousand volts above true earth ground. In these installations it only matters that a ground to the supporting structure exists, so everything will rise and fall together with the strike. The protectors will perform the function of preventing equipment damage by allowing survivable voltages on the I/O's relative to the equipment's chassis.

HIGH-RISE BUILDINGS

The same single point grounding concept, as previously discussed, will work for high-rise placed equipment. Tall buildings usually are steel framed so grounding is reduced to finding a convenient location to ground the single point ground panel to structural steel. If the building has no structural steel, locate the equipment room near a utility corridor or fire riser. A utility corridor is a vertical shaft that runs the height of the building. A large copper strap, or 750 MCM cable, should be used to tie into the power ground at the power service entrance. A fire riser is a six to eight inch pipe that runs from the super charging pump at the water mains entrance to the roof. This riser may be safely used if the pump is jumpered and power protected. Local code may also require a safety jumper to the utility service ground. In either case, a direct ground connection is made, in addition to the normal power safety ground. This will provide a good ground path for the surge energy. Single point grounding is the only way to protect your equipment inside the room.

GROUNDING ROOF MOUNTED ANTENNAS

Antennas on parapet walls or on building tops, should use the fire riser or the existing lightning protection (rods) if local code allows or permission is granted by the building owner. (Note: the owner can overrule local code, but does so at their own risk.) The only other alternative is to use a large copper strap or 750 MCM cable. An elevator shaft used to be a grounding means, but with microprocessors on board, a diverted strike could be costly!

chapter 10

Exploding the 'Myths' About Lightning Protection

One practice, still in use, is to add a lightning rod and a copper down conductor running the length of the tower to the ground system. The concept was to divert the lightning energy around the tower. Normally, the joint resistance between tower sections, averages about 0.001 ohm and will create a voltage drop during a tower strike. Thinking that copper would be a better conductor than the steel of the tower, the practice was born. However, the strike's inductive voltage drop, for either the copper cable or the tower, far exceeds their resistive voltage drops. The tower inductance, however, is many times smaller than the down conductor's inductance (due to the much larger surface area or skin effect, even with the ferrous effects of the tower steel). Therefore, there is no advantage of having the copper down conductor. The voltage difference between the conductor, attempting to carry the strike with its large L di/dt voltage drop, and the tower, will be further increased by the induced opposite EMF voltage on the tower. This huge voltage difference will be so great it can arc 1.5 feet! Unless they are separated by this ridiculous distance, they will be connected by an arc and the strike will traverse the tower anyway. Furthermore, the proximity of the cable to the tower's vertical legs can be detrimental. Rain water* coming into contact with copper can carry ions that react with the galvanized coating, causing it to wash off. This can decrease the life of the tower (and its safety) as the tower rusts.

* Natural rain water (not acid rain) has a pH of +5.5 to 6.0, which is acidic. Acids will attack copper and with time eat it away.

TOWER GROUND CONNECTION LOCATION

Emphasis has been placed on the 8-inch minimum radius bends for lightning carrying leads, suspended in air, to minimize inductance. Higher inductive right angle bends or connections should be avoided if possible, but the alternative trade off may be worse.

Take the situation of grounding a tapered-base tower. A Ufer ground is not used and the nearest ground rod is some 24-inches from the concrete pad. The choices are:

1. Run the interconnection through the air from the ground rod to the top-most plate. This has the minimum amount of bending and is mostly vertical.

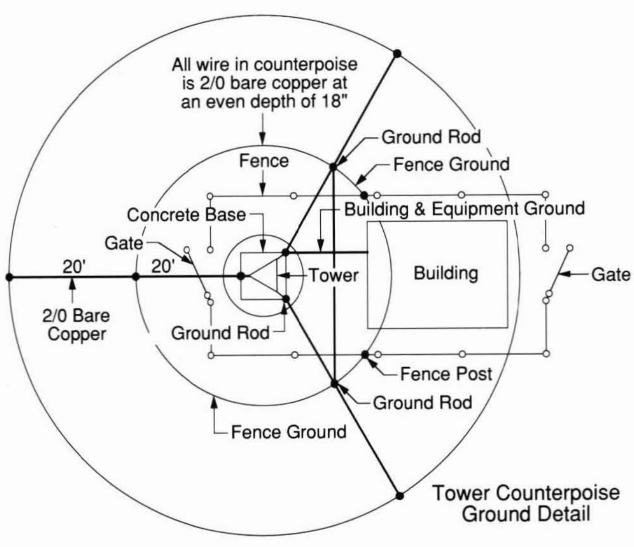
2. Connect the ground rod directly to the second plate - a compromise.

3. Make a connection directly from the lowest plate to the ground rod. This path places the interconnection through the least amount of air, but has the most bends.

Assuming the wire gauge is #2/0, the inductance is then 0.32μH/ft. Knowing the distance, the inductance for each choice can be calculated. Each 90-degree bend develops about 0.15μH of additional inductance. Now with the distances, the correct choice can be calculated.

GROUND RADIAL CIRCLES

Another myth is to tie equally spaced ground rods (from the tower base) together to form a circle or circles.



Example of Wasted Materials and Effort

Concentric ground ring myth says radial wires should be interconnected by wire rings. The method doesn't improve protection.

If this type of ground system were installed at a site with a poorly conductive surface layer, the large inductance of the interconnections to the rings will make the rings ineffective. A ground ring will launch electrons mostly outside its circumference. Two closely spaced rings are like two ground rods attempting to couple charge into the same volume of earth. The electrons from each rod are repelled. It is not an effective use of installation time and materials. The cost of the wire and effort involved in installing these concentric circles would be better utilized by placing additional radials from the tower base.

RADIAL REFLECTIONS

Some people have questioned that since a radial is like a lossy transmission line, energy that is not absorbed by the time it reaches the end of the radial, would reflect back to the tower base. This would seem to indicate not enough radials in a poorly conductive soil since the soil will become saturated and not absorb any more electrons. This is a reason to have more radials not just longer ones. The radial system is emulating a solid plate. The capacitance of this plate to true earth will determine the amount of charge that can be absorbed. The resistance will dictate the time constant in which the plate will be elevated (saturated) above earth. Adding more radials with ground rods will increase the surface area (capacitance) and decrease the resistance.

TO GROUND OR NOT TO GROUND

One of the best sayings is really not a myth at all: A grounded tower is more likely to be hit. As we saw in the graph in chapter one, the taller an object the more frequently it's struck. Why ground a tower if it means that it is more apt to be hit? Look at it from the reverse point of view - if a tower that isn't grounded is hit, who would have control of the situation, the tower owner or Mother Nature? With a properly grounded tower, the owner has control. The whole concept of lightning protection is to control and direct the lightning surge energy so it does the least amount of harm or damage.

NOTHING WILL SAVE YOU

Another great myth: Nothing will save the equipment if the tower takes a direct strike. This myth was invented by those who did not plan or install proper grounding techniques. It is difficult to allocate additional funds for the materials and labor needed to include a good ground system, when a new site is under development. Often the lowest bidder gets the job of erecting the tower. Unless a specified grounding plan is written in the bid package, the bare minimum is quoted or grounding is omitted altogether. Those of you who think that three, eight foot rods, around the tower base is a good ground system, are on the right track, for a tower to be erected at a beach at high tide. (You probably think the EIA's RS-222 standard is adequate too!)

Even with planning, no one can predict if an installation will or will not survive, since the intensity of a hit is a variable. It is safe to say that less damage (if any) will be sustained with a properly grounded tower.

Remember it is always cheaper to do lightning protection initially than it is to retrofit. Plus, it usually is done correctly, if planned ahead of time.

DETERRING LIGHTNING MYTHS

Some people think if you have a bunch of sharp points around a tall object, it will give off enough ions to enshroud the object and ward off the evil "Thor" god. If this were true, towers with many antennas, or trees in a forest, would never be hit! Now, trees are not the best conductor, but with the very high impedance of static E fields, they do conduct, as is evident since lightning does hit them.

One of the proposed selling points for wire brushes is they reduce the potential voltage between the charge center and the site. This is indicated as being done with a ground system that takes the electrostatically induced voltage in the ground and creates ions, via the brush, which are then blown away by the wind. This would be a great idea, but the ground can provide the induced voltage faster than the brush can create ions. Imagine, the site as a three dimensional object in free space. The site's surface area has an ability to store a charge. This is the site's capacitance. The brush (or a few sharp points) can create a current, in an E field of 10kV/m, of about 0.5A. This is a 20k ohm load. The R·C time constant of this discharge, in comparison to when the site is plugged into the ground (typically 5 ohm,) is (20k/5 = 4000) 4000 times faster. This means earth can provide the electrostatically induced voltage 4000 times faster than the brush can dissipate.

What about wind? These wind blown ions will not, as some think, cancel the cloud charge and prevent a strike from happening. If no wind is present, the ion space charge will drift upwards. These ions make the air more conductive and can help direct the step leader (precursor to the strike) to the brush resulting in a return stroke. As we will learn, the step leader doesn't pick out a point of attachment until it is within 150-feet of the object. The brushes will not stop the formation of upward going streamers. They may help stop corona from a sharp object under lab conditions, but under real site conditions, with wind, it is not effective.

Those who sell this "snake oil" claim many happy customers with no equipment damage. Only those who do <u>not</u> have a good ground system would buy such devices. When they are installed, a good ground system is always included with the installation. (I wonder why?) A US Navy report, done in cooperation with the USAF, NOAA, and the FAA, states that after several years of study, brushes have not prevented any lightning strikes. (If they worked, NASA would be using them extensively.) The FAA even did another study on the brushes and have video tapes showing them being hit again! You can't fool Mother Nature!

(PolyPhaser has a series of inexpensive Lightning Strike Counters (LSC-10, LSC-20 and LSC-30). The counters are for towers, power lines and telco lines, respectively.)

MORE MYTHS

The myth we want to hear: "We don't know if all the money we spent for lightning protection was worth it. We haven't been hit yet!"

Well, how does one know that a strike hasn't occurred! Undamaged equipment is not a true indicator. It only takes one strike. If lightning protection **was** installed, then "no news is good news".

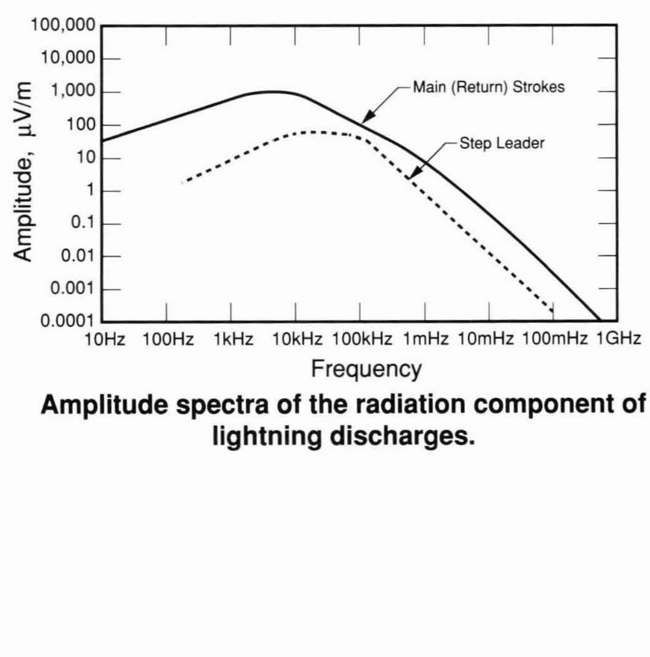
chapter 11

Protecting Equipment From EMP Damage

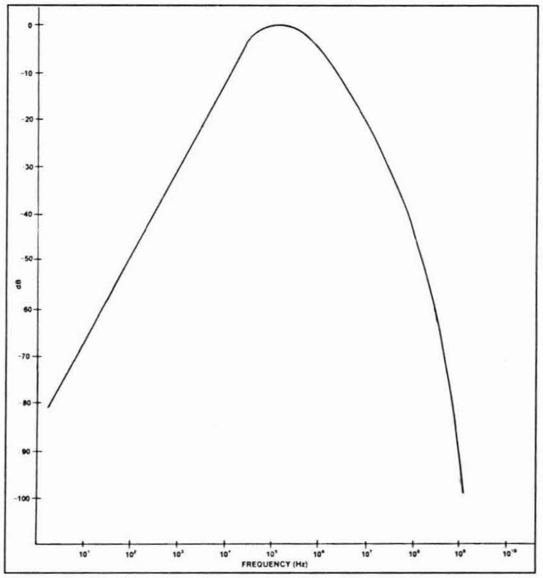
Lightning is a very destructive localized event. Although previous chapters have dealt with protection and grounding techniques for lightning, attention has been recently focused on the much wider geographic effects of a nuclear explosion on radio communications.

ELECTROMAGNETIC PULSE

The sudden release of gamma rays (high energy rays) in a high altitude nuclear explosion will cause almost instant ionization (the removal of electrons from atoms) of the atmospheric gases that surround the detonation. Free electrons are driven outward. The gamma rays can travel great distances ionizing the atmosphere. The forced movement of these electrons, which will again recombine with the atmosphere atoms (Compton Recoil Effect), creates a pulsed electromagnetic field or ELECTROMAGNETIC PULSE (EMP). This is also referred to as NUCLEAR ELECTROMAGNETIC PULSE (NEMP). About 99% of the NEMP is radiated in a broad spectrum between 10kHz. and 100MHz. Most of the energy is below 10MHz. For comparison, lightning's power density spectrum is from dc to 1 MHz (for the -3dB point).



Amplitude spectra of the radiation component of lightning discharges.



Normalized NEMP spectrum shows most RF energy from pulse falls at frequencies below the 10MHz amount. 99% of energy is within the spectrum from 10kHz to 100MHz.

The radiated pulse's fast rise time (10 nanoseconds) and short duration (1.0 microsecond) causes any antenna to ring, much like a direct lightning strike. The ringing amplitude depends on the amount of captured energy. The antenna's capture area, pattern relative to the blast, tuned frequency and bandwidth, all affect the ringing voltage. This ringing voltage will attempt to propagate down the transmission line to the equipment. Since the antenna is not equal to the line's characteristic impedance over the entire EMP spectrum, the line also may collect EMP energy if additional shielding precautions are not taken. This energy takes the form of a complex waveform on the transmission line. Large voltages may be created due to line resonances. These high voltages can cause damage to unprotected equipment or cause arcing in the line or at the antenna. Cable shield grounding kits help prevent the lower frequency components from being present on the line and thus change the high voltage resonance locations.

Cavities can actually make NEMP matters worse. The small bandwidth (high Q) of the cavity causes larger ringing voltages to be present to the equipment. Quarter-wave shorting stubs type protectors, depending on their "Q", may also worsen the effects.

Coaxial lightning arrestors with a 50ns response time are too slow for the NEMP ringing pulse for systems above 10MHz.

NEMP PROTECTORS

Only NEMP coaxial units with a 1.0 to 7.0ns response should be considered for protection. NEMP protectors with dc continuity (non-PolyPhaser) must have at least 10-feet of coax between the protector and the equipment. The coax propagation factor, gives the protector time to operate. (Needless to say, this technique does not work for the slower rise time of lightning!) Otherwise, if this type of NEMP protector were placed directly on the equipment, a receiver (for example), would have to develop an L di/dt voltage drop across the receiver's static drain inductor large enough to allow the protector to operate. The drain inductor value (which depends on the receiver's frequency), the maximum current/voltage for the inductor and the threshold of operation for the protector, will all determine the survivability of the receiver.

NEMP protectors with no dc continuity (PolyPhaser type), will work on **all** equipment and do not need special precautions. They work for lightning as well! Lightning's locally radiated energy is called LIGHTNING ELECTROMAGNETIC PULSE (LEMP).

TYPE OF CONDUCTOR	RISE TIME (SEC)	PEAK VOLTAGE (VOLTS)	PEAK CURRENT (AMPS)
Long unshielded wires (power lines, large antennas)	$10^{-8} - 10^{-7}$	$10^{5} - 5 \times 10^{6}$	$10^{3} - 10^{4}$
Unshielded telephone and	$10^{-8} - 10^{-6}$	$100 - 10^{-4}$	1 - 100
AC power line at wall plug	$10^{-7} - 10^{-5}$	$10^{3} - 5 \times 10^{4}$	10 - 100
HF antennas	$10^{-8} - 10^{-7}$	$10^{4} - 10^{6}$	$500 - 10^{4}$
VHF antennas	$10^{-9} - 10^{-8}$	$10^{3} - 10^{5}$	$100 - 10^{3}$
UHF antennas	$10^{-9} - 10^{-8}$	$100 - 10^{4}$	10 - 100
Shielded cable	$10^{-6} - 10^{-4}$	1 - 100	0.1 - 50

Typical EMP energy collectors exhibit different responses to EMP.

POWER LINES

The coax line is not the only major I/O for NEMP energy. The power line can deliver a lethal pulse to the equipment.

Utility lines act as a bandpass filter to the NEMP pulse. Transformers attenuate energy below 1MHz and capacitively couple energy above 10MHz. Since less danger exists to equipment connected between phases, 120Vac power line protection with response times of 50ns and less should be used and located with the equipment to protect it from deadly common mode (line to ground) energy.

TELEPHONE/CONTROL LINES

Twisted pair lines (data and telephone) can couple some NEMP energy. It will not be as much as the coax or power lines. The higher inductance/resistance balanced configuration used for these applications limits the total energy delivered to the equipment. Metal oxide varistors, capacitively matched, can safely limit the NEMP to the equipment.

The NEMP pulse does not have the same amount of energy as a direct lightning strike. It doesn't last as long and doesn't generate the high peak currents (20kA) of lightning. However, on very long runs of power lines, the current could theoretically reach 50kA. The typical coupled voltages, currents and rise times are shown earlier in this chapter. Rise times are a function of the coupling impedance to the unit under test, as well as the unit's dynamic surge impedance.

All of the grounding techniques for lightning protection discussed, apply to NEMP. The most important part to remember is that long equipment interconnection lines can capture significant NEMP energy. Long lines will also have larger voltage drops across them because of the faster rise times involved ($E = L\ di/dt$). To eliminate this coupling, extensive individual shielding of the lines is necessary. The most cost-effective way to provide shielding for a room full of equipment is with a screen room enclosure. Next, provide a ground system that will actually dissipate the NEMP pulse. The only way to determine this is to dynamically test the ground.

chapter 12 The Dynamic Testing of Grounds

If the earth were a metal sphere, a lightning discharge would create a measurable ringing gradient on the sphere. The earth is not a perfect conductor and the earth's resistance limits the current and locally dissipates the energy. The event becomes a mere pebble in the pond.

When a lightning strike is delivered to a ground rod driven into poorly conductive soil, the rod will be surface charged with a calculable velocity factor, to a level at which the concentration of E field lines causes soil breakdown at the rod point. This breakdown will momentarily increase the surface area of the rod. As the charge is being transferred, depleting the source, the E fields at the rod tip will decrease below that which the arc is sustained. The charge will disperse onto the surface of each grain of dirt. (A charge can exist on an insulator, i.e. - a glass rod after being rubbed with a piece of silk.) Because of the irregularity of the granular surface, the bumpy E fields inhibit the charge dispersal beyond a small range (sphere of influence).

$$VF = 1-(10.7575 \log_{10} s/W-8)^{-1}$$

where s is length and W is width.

Velocity Factor is relative to the speed of Light (λ). This formula is borrowed from antenna theory. If a ground rod is in poorly conductive soil, we can equate this to a rod being suspended in air. At the time of breakdown, rod inductance must be taken into account. This can be calculated via:

$$L = \frac{377}{\dfrac{2\pi\,(492 \bullet VF) \times 10^6}{2s}}$$

where VF is the Velocity Factor and s is the total length of the rod in feet.

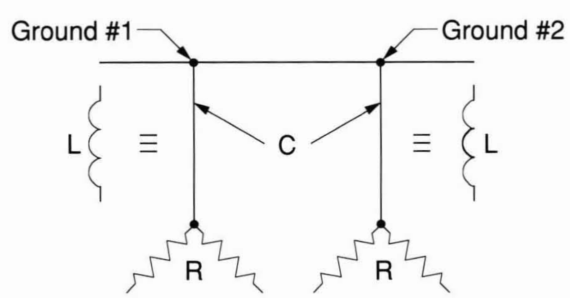
Now the voltage drop due to the inductive creation of a large magnetic field is:

$$E = L\ di/dt$$

where "di" is the lightning strike peak current, typically 18,000 amps, and "dt" is the rise time, approximately $2\mu s$.

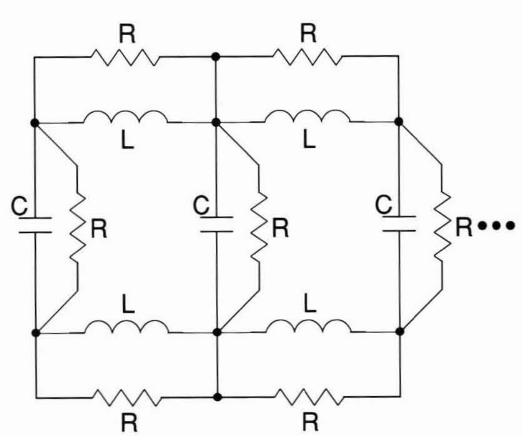
This shows there is a length limitation that a single ground rod can penetrate poorly conductive soil. The limitation is where the top section of soil breaks down due to this instantaneous voltage drop.

By having two long rods connected in parallel, the overall inductance can be reduced. The spacing is important so each rod is able to "dump" into different volumes of earth. (Since this dictates that the spacing be rather large (>20 feet), the mutual inductive coupling between the rods should be small.) Connecting to the same volume of earth will cause saturation of that volume and limit the passage of any further charge in the given time span of the lightning strike.



Connecting a capacitance meter between two well-spaced rods will show capacitance is present in the soil. Here, the soil surrounding each rod is resistively separated, forming two electrodes of a leaky capacitor.

At this point, distributed resistance, inductance and capacitance has been proven to exist. All can exist simultaneously. The basic interconnecting of these lumped elements is equal to that of a lossy transmission line or lowpass filter. (Since earth R is so large compared to the wire R, it is omitted here.)



The only condition where both L and C can be eliminated is when R → 0 ohms.

Because the earth can be simulated by lump constants when not in a non-linear arc mode, then a velocity factor (VF) could be calculated if L and C are known.

$$VF = \frac{1}{\sqrt{LC}}$$

If the soil is equally conductive at all depths, then calculating the surge impedance would be easy. However, we need a tester to measure the ground system surge impedance.

Conventional ground testers are glorified ohm meters. They operate at 70 to 100Hz range and were originally designed for the electric utility industry for ground fault resistance measurements. Here the reactance of 30-feet of wire is <.004 ohms at 60Hz. The same 30-feet could have an inductive (E = L di/dt) voltage drop of over 100kV for a typical 18kA lightning strike.

The type of tester we want has to have the following attributes:

- No Stake(s)
- No Ground References
- Will Show L, R, & C
- Usable for Lightning and NEMP

To design such a tester, we look to Mother Nature for the answer. To simulate a cloud with its collective charge relative to earth, we substitute a sphere which is charged relative to the Ground System Under Test (GSUT).

The lightning strike is the switch that connects the cloud to ground. The sphere is charged via an extremely high impedance dc supply (>1000 meg ohm) so at a preset voltage, an arc connects the sphere to the GSUT.

GROUND SYSTEM UNDER TEST

As the sphere is discharged into the GSUT, a small shielded precision current viewing resistor is used to measure, display and store the current waveform on a digital storage oscilloscope. The recorded rise time and peak current is indicative of the inductance and resistance values respectively. Any ringing of the ground system will show up as a capacitance. This is a Dynamic Ground Tester (DGT).

After repetitively discharging the DGT into the GSUT, an average is displayed and stored on the scope. The DGT connection to the GSUT is then disconnected and connected to a simulator. The simulator is made up of components that equal the sphere and have thumb wheel variables for L, R, & C. The simulator is fired repetitively, and by varying L, R, & C, an overlaying scope pattern to the GSUT pattern is produced. The values of L, R, & C for the GSUT can then be read from the thumb wheel switches.

The pulse duration from the tester into the GSUT is much shorter than a typical lightning strike, therefore, the energy is much less. The purpose of the tester is to obtain the L, R, & C values and not to take the GSUT into the non-linear arcing mode in the earth. In fact, only a small amount of energy is used during the test which is advantageous, since operating equipment can have their ground systems measured safely.

The shorter pulse does have a disadvantage for the DGT. When transforming from the time domain into the frequency domain, the frequencies are much higher than those found in a typical lightning strike. This accentuates the L and C components, making them easier to measure for mountain top ground systems, where L and C are prominent.

Looking at this, the rocky mountain top is not conductive when dry and the radials can be considered in free space. The DGT pulse would excite the radials and the feed point impedance will be different for each frequency represented by the output pulse. The current waveform would therefore be a conglomeration of the varying impedance with frequency. After storing this waveform, substituting the variable L, R, & C simulator and finding values to obtain the best waveform overlay, the simulator values will only be true for this waveform. However, it will not necessarily be accurate for the lower frequencies found in lightning. Even if the DGT output pulse were lengthened so the lower frequencies were present, there is no hope of coping with the infinite variations of rise times and decay times that natural lightning exhibits.

Ufer grounds make an excellent body to dissipate the surge energy especially on bare rock sites. Under dynamic conditions, the mass of partially conductive concrete will form a leaky line by shunting the inductive length of the rebar or mesh, spreading the charge through the concrete and leaking charge to the surface of the rock. Because its R is low in value, no reflected power will be present since no resonance will exist (low Q value). The DGT would be able to show true L, R, & C values for a Ufer ground, where as conventional testers would be useless.

Someday, our DGT may point the way to the construction of more effective ground systems for difficult to ground locations and to augment existing ground systems to better handle the discharges from Mother Nature.

chapter 13
Mountain Top Grounding

Mountain top locations are great for radio propagation, but it is difficult to achieve a proper lightning ground. In the past, several techniques have been tried with varying levels of "success".

Stone Mountain, outside Atlanta, Georgia (USA), has a TV transmitter site at the barren top of the mountain. Around the base of the mountain is a man-made series of lakes and rivers. The TV station is grounded via a very large cable that runs down the steep cliff to the more conductive soil. This system is an acceptable means of providing a ground for this site since the inductive voltage drop, due to a lightning strike, for this long ground interconnecting cable, will be less than the inductive voltage drop for the power service lines.

One can readily see the need for power mains protection to protect the equipment. This entire site will be elevated with respect to the rest of the world during the strike event. This is the same as locating your equipment at the top of a tower, it places more emphasis on the quality of the I/O (input/output) protectors, as well as placing more stress (energy) on the protectors, since more energy than usual will be routed through them.

Low frequency ringing may occur when the strike excites the entire ground system. Think of the site as a capacitively loaded vertical (parasitic) antenna being excited by a broadband (arc) noise generator (the lightning strike). The ringing will stress the power line and telephone line protectors.

By creating a copper strap counterpoise on the rock surface the radials charge up like a capacitor and spread the charge onto the surface, just like a static charge on a glass rod after being rubbed by fur. The sharp edges of the strap will help breakdown the air and form arcs on the surface of the mountain. This action will not affect the equipment and is beneficial; since, like arcing in the soil, it will reduce the amount the entire ground system will elevate in voltage. We are still dealing with an antenna (the tower) and ground plane (the radials) which can ring. By increasing the rock's surface conductivity, the lower resistance will dampen and dissipate the strike energy. This may be as simple as having light rain just before the strike event. A little moisture will greatly enhance the rock's conductivity.

Avoid the concept of drilling holes in a mountain top and filling it with conductive material like charcoal or bentonite clay. Most "Mount Baldy" locations do not have fissures in the rock which allow water to collect to make these paths conductive. With solid rock, it is not going to be any more conductive in a hole than on the surface of the rock. Besides, what happens to the hole after it has some electrons in it? Since the electrons repel one another, they will not enter the hole. Like water, the electrons will spill onto the surface of the rock and spread. Unlike water, the repulsion of electrons will mean fewer are needed to fill the hole and, once filled, the spreading on the surface will have an added force. The best way to disperse the electrons is by having a radial ground system.

Chemical additives, such as rock salt, copper sulfate and/or magnesium sulfate, will help reduce the R (resistance) value so some dissipation can occur. This will dampen the ringing, transforming the surge energy into the form of heat. The latter two chemicals are less corrosive than rock salt. Magnesium sulfate will have much less of an environmental impact than the other salts. All salts will lower the freezing point of the moisture, which is important at higher elevations. About 2 kilograms (kg) of salts will dope 2 meters of a radial run for one year. About 5 kg (minimum) is necessary for each ground rod. Make sure the salts are watered in or they may be blown away.

Encapsulation of radials in conductive gels or carbon materials is an alternative where little or no soil exists. It is not recommended because it is more expensive than adding more copper strap radials. Acrylamide gel, silicate gel, and copper ferrocyanide gel are mentioned in the order of increasing conductivity. All involve toxic and/or hazardous materials. An easy alternative is to use concrete to make a Ufer ground.

chapter 14
A General Review and Standard

This is a general standard and practice to install an effective ground system and proper protective devices to provide equipment protection, personnel safety and have a minimum of problems. This must be divided into two sections: those with a bulkhead/single point ground system and those with a multi-point ground system.

OVERVIEW OF WORK

An overview of the tasks to be performed for a single point ground system/bulkhead panel is outlined in the following:

1. Installing tower grounding kits on coax and waveguide lines.
2. Installation of a bulkhead panel to give mechanical support, electrical grounding and lightning protection for coax cables entering the equipment hut.
3. Installation of an earth ground array (driving ground rods, laying radials).
4. Connecting outside metal structures to the earth ground array (towers, metal fences, metal building and guy anchor points).
5. Connecting the power line ground to the earth array.
6. Connecting the bulkhead to earth array.
7. Installation of a vertical bus or a main rack ground bus on each equipment rack to interconnect to each piece of equipment in that rack, or to insure the paint is removed on the rack and each piece of equipment in the rack, so the rack may be used as a grounding means. Each joint is tested with a DVM so no more than one milliohm exists between the rack rail and any piece of equipment.

8. Connecting power line protectors and telephone line protectors on a rack ground bus or on the bulkhead panel(s).

9. Connecting the rack Equipment Ground Bus (EGB) to the bulkhead panel(s).

10. Installing power line protectors and telephone line protectors at the utility entrance(s) and bond to perimeter building ground.

Connect the following items to the bulkhead panel: chassis racks and cabinets of all radio equipment, all auxiliary equipment (chargers, switchboards, conduit, metal raceway, cable trays, telephone line protectors and all other protectors).

The design and application of this ground system minimizes ground loops and interaction with other conductors. There should not be any intentional connection made between the dc distribution system common bus (if present) and the bulkhead panel, or to any other ground systems except as indicated. All inside conductors used in the ground system should be insulated or stood off from other metal support structures. (All metal buildings may use the skin provided if it has been determined the skin has adequate conductivity throughout.) For the outside ground system to be effective, ground rods must be driven below the normal frost line to penetrate to the permanent moisture level.

Connections that are soldered only are not allowed for outside use. Crimped, brazed and exothermic connections are preferred for both indoor and outside locations. To make a proper bond, all metal surfaces must be clean, any finish removed to bare metal and surface preparation compound applied. All connections should be protected from moisture by joint compound.

BULKHEAD AND TRANSMISSION LINES

All coax and waveguide lines that are installed must include grounding kits for grounding the transmission lines at the antenna. On conductive structures, this may be done by grounding the tail of the grounding kit to the structure itself. All non-conductive paint and corrosion should be removed before attachment. **Do not drill holes and do not loosen any existing tower member bolts.** Antenna clamping hardware may be used or an all stainless steel 18-8 hose clamp, of the appropriate size, may be substituted. Dissimilar metal joints can not be made. A buffer metal, which is between the two metals to be joined on the galvanic chart (page 18), may be used, provided an appropriate joint compound is applied to prevent moisture from bridging the union.

The location of this tower top grounding kit is not as critical as the bottom grounding kit or other kits. For structures taller than 150-feet, additional grounding kits should be evenly spaced, every 75-feet, between the 150-foot kit and the tower top kit.

On non-conductive structures, a 1 1/2-inch, or larger, copper strap must be run down the structures. The top transmission line grounding kit will then be bonded to this down run. This strap should be kept as far away (a distance separation of two feet is preferred, 18-inch minimum,) from all other conductive runs (i.e.: aviation lights, other coax and wave guides). If any other ground lines, conduit or already grounded metallic structural members, must be traversed and are closer than 18-inches, they too must be grounded to this strap to prevent flashover.

In the event of multiple non-conductive legs (three and four legged forest fire observation stations, for example), a complete ring must be formed **at each platform** where antennas are to be mounted, joining **each leg's** down conductor. This should also be 1 1/2-inch copper strap. Care must be taken to prevent bends, if possible, sharper than 8-inch radius.

At the point where the coax or waveguide separates from a conductive structure (metal tower), a coax and waveguide grounding kit must be installed to the largest vertical structural member. This must be as close to the tower leg base as possible. (This last requirement is not as much of a concern, if the cables emanate from a center tower face and a large/multi-strap grounded bulkhead plate is used. The bulkhead plate, with its built-in grounding kit, takes most of the remaining surge current to the ground system.) Dress the kit tails in a straight, 45-degree, downward angle to the tower member. On non-conductive structures, a metal bus bar must be used. The bar must be grounded to one or more of the vertical down conductors and as close to ground level as possible.

A grounded bulkhead panel should be used on the equipment hut wall, through which all transmission lines will penetrate and be grounded. The bulkhead should use large surface area straps to bond to the ground system attachment point, or be placed as close as possible to the ground so a short, low-inductive ground strap interconnection to the ground system can be established. Where inside cable trays are used, the tray will establish the bulkhead's height.

Panel size depends on the spacing, number and size of the coaxial lines interconnecting through the bulkhead panel. The panel should be copper or brass, but can be aluminum. It should not be steel or stainless steel. The purpose of this panel is to provide a low inductance path to ground for lightning currents. This will strip off most of the remaining surge currents from the coax and waveguide lines and prevent their entry into the equipment hut. To accomplish this, the bulkhead panel must have an inductance-to-ground equal to or lower than the inductance of the cable/waveguide grounding kit's inductance-to-ground via the tower.

Coax lightning protectors must be mounted at the grounded bulkhead panel. Since the panel is at a lower inductance point than the equipment or the transmission line ground point on the tower, wave guides and coax lines should have another grounding kit at the bulkhead panel. (PolyPhaser's bulkhead panels have built-in grounding kits under the entrance boot.) For other panels, all externally installed grounding kit tails should be angled downward at a straight 45-degree angle using 1/8-inch stainless steel hardware to the grounded panel. The lug on the tail end should be flat against a clean spot on the panel. Joint compound will be needed for aluminum bulkheads and should be used on copper panels as well. (Included with PolyPhaser's bulkhead panel package.)

The bulkhead panel will be used as the central grounding point for all the equipment inside the building. To ground a bulkhead panel, cut the copper straps, if necessary, and sandwich them with the included joint compound. The building perimeter ground should be cut and each end bonded to each side of the panel below grade. Measure the dc resistance with a Fluke 8012A-01. It should be no greater than 0.001 ohm total between ground system and panel. This measurement should be done on an annual basis.

The type of lightning protector installed on the bulkhead panel should **not** be an air gap because they are susceptible to air pollution, corrosion, temperature, humidity changes and the manufacturer's tolerances. The turn-on speed is a function of all of these. A simple gas tube-type arrestor is an improvement, but both of these dc continuity-type protectors do not operate on shunt-fed cavities, isolators or receivers with static drain inductors to ground (which most have). This is because these voltage-sensitive crowbar devices are "shorted out" by the dc paths to ground. The L di/dt voltage drop is usually not enough to fire the protector, but is enough to destroy the inductor and then the receiver front end.

The recommended protector does **not** have dc continuity on the coaxial center pin, input to output, and doesn't have a ferrite inductor core to saturate, causing additional losses with each strike event.

An even better unit does not have dc continuity on the shield or the center conductor. This forces all surge current into the bulkhead panel, preventing it from entering the equipment hut.

INTERNAL INSTALLATION

An internal ground bus should be run from the bulkhead panel so all racks, or pieces of equipment, inside the equipment vault or hut can be connected to it. This run can be the cable tray, if properly bonded at joints.

EQUIPMENT GROUND BUS INSTALLATION

An equipment ground bus (if the rack rails are not being used for this purpose) is a bare #6 AWG copper wire, mounted on insulated standoffs on the rear of the left rail (viewed from the rear) to provide a convenient earth ground for all equipment in the rack or cabinet. Solid copper should be used. Every rack or cabinet taller than 30-inches should be equipped with such a ground bus.

After installing the #6 vertical bus, connect the chassis of each item of equipment in the rack or cabinet to this bus. Attach a #14 insulated stranded wire (hereafter called a chassis ground wire) to the equipment chassis. Do not use screws in rack rails for this bonded connection. Select a point in the main body of the chassis. If the equipment chassis is not of sufficient physical size to establish a bond, a self-tapping screw may be used to secure the terminal, along with internal tooth lock washers, to help achieve the required mechanical and electrical connection (one between chassis and terminal and one between terminal and screw head). Apply the appropriate surface compound to prevent this joint from oxidizing. Attach the other end of the chassis ground wire to the equipment ground bus.

Attach the respective rack ground wire to each rack ground termination point in the following manner: Cut wire to proper length. Strip wire and install crimp lug. Fasten lug to rack ground termination point using appropriate hardware. Note that the equipment ground bus is also attached at this point.

EARTH GROUND

Since the conductivity of earth is a variable which is dependent on the availability of electron carriers, there isn't **one** grounding procedure that will cover all soil conditions. Only general guidelines can be stated. If these guidelines are implemented, then the external ground system must be tested to determine if the system is adequate.

The function of the external ground system is of paramount importance. Ideally, the resistance should be as low as possible. Resistance, though, is not the only component. Inductance, as well as capacitance, can be inherent in all systems. In highly conductive soil, the effects of inductance and capacitance are minimized because the soil's conductivity "shorts-out" these components. Then, only the inductance of a wire in air, such as the interconnecting wire between a bulkhead panel and the external ground system, need be of concern. In poorly conductive soil, attention to inductance and capacitance values is very necessary.

Since a resistance earth tester only tells half the story (resistance only) and because rods cannot be placed in rock for such a tester, a dynamic ground tester offers the only way to obtain the system's true surge impedance (Z).

FORMING A GROUND SYSTEM

To prevent a flash-over, all nearby fences, buildings and tanks must be tied together to form one ground system. Any radial that comes within four feet of a conductive structure or material must have a junction wire interconnecting the two. This interconnecting wire should be buried, if possible, and should approach the radial at a 45 degree angle, pointing towards the surge origin (tower). All of the above should be followed unless the radial run is terminating to this structure or material, then a separate interconnecting wire may not be necessary.

The size of the bare conductor for the radial (or for an interconnecting wire) will vary depending on soil conditions. On rock, a bare 1 1/2-inch copper strap is recommended. Solid copper strap should be covered with soil or rocks. In normal soil conditions, the radial should not be smaller than #2 copper wire. For dry, sandy, upper layer soil sites, solid copper strap is recommended to reduce the inductance between ground rods.

The interconnecting radial wires should be continuous and buried as deep as possible. The first 6 to 10-inches will have the most benefit. Going below 18-inches will not be cost effective, unless dry, upper sandy soil condition exists and by going down further the water table can be reached; where ground rod penetration is shallow or where the ground is often frozen.

If some soil exists, it should be used to cover the radials. It is more important to cover radials in the area near the tower than it is at greater distances. If soil only exists at the outer distances and cannot be transported to the inner locations, this soil should be used to cover the outer portions of the radials.

When soil is present, ground rods should be used along the radial lengths. Spacing between ground rods is affected by the depth each rod is driven - the shallower the rod, the closer the required spacing. Since the ultimate depth a rod may be driven cannot always be predicted by the first rod driven, always use a maximum spacing of 15-feet when selecting a location for each additional rod. Drive rods at building corners first then fill in the space between the corners with additional rods.

Rods spaced closer than the sum of their driven depths add little to the overall system performance of the ground array. Therefore, it is better to use a wider spacing for each rod, making a concerted effort to achieve maximum depth, than to use multiple rods closely spaced. Ground rods should be driven in place, not augured, set in place and then back filled. The soil compactness is never as great on augured hole rods when compared to driven rods. The only exception is when a hole is augured or blasted for a ground rod or rebar and then filled with concrete.

All connections between the radials and the ground rods should be either exothermically welded or clamped with appropriate joint compound, and buried to the same depth as the radial run.

If a Ufer ground is used in the tower base concrete, it should be designed with ample pigtails to facilitate the tying of all radials for the ground system. These pigtails should be exothermically welded to the rebar cage and brought out of the concrete side wall at the same depth as the radials. The rebar cage should be interconnected to the anchor bolt cage (if separate) or by an additional pigtail to the tower foot pad.

If a Ufer ground is not being implemented, then radials should be used. A minimum of three radials, of #1/0 wire, spaced at 120-degree angles, may be exothermically welded to the tower foot.

For large based self support towers, the radials will be going to each leg pad. The radials may then be brought up out of the soil (in air) and each attached to spaced locations around the foot of the tower pad. Remember - if a space between these in-air sections can be maintained, less mutual inductance (coupling) will exist and the system's surge impedance will be less. Under certain conditions they may have to be tied together first and then joined to the tower's foot pad.

It is desirable to have a continuous, one piece perimeter ground ring with rods around the hut. This ring should connect to the tower at only one point. The ring must be buried to the same depth as the radials it interconnects. The previous guidelines given for radials should be followed for this ring. The power line ground must be connected to this loop. **(Warning: substantial current may flow if power line ground is connected to this ring. Please follow the procedures outlined for maximum personnel safety.)**

Install a ground rod, (if the utility company has not already installed one and if soil conditions permit) putting it immediately outside the generator vault and connect this rod to the perimeter vault ground ring. Route a #1/0 insulated, copper cable from the main power panel inside the generator vault to the ground rod outside the vault. Cut this cable to length, strip both ends, and connect one end to power line neutral at the main power panel in the generator vault. Connect the other end to the ground rod. **(Warning: use care when making this connection as a hazardous voltage may exist between the power line neutral and any point at earth potential.)**

Do not remove any existing earth ground connections to the power line neutral, especially if already installed by the power company. This may be a violation of the local Electrical Code. The principle here is to insure that the power line neutral is connected to the external vault perimeter ground, to minimize any noise present on the neutral and to conduct this noise outside to earth ground.

GROUNDING OTHER STRUCTURES

Any conductive structure or material within 48-inches of a radial run should be interconnected to that radial. Guy anchors also play a part in lightning protection because a good percentage of the strike current can be dispersed into the earth via the guy wires and anchor grounds.

To use guy wires and anchors to conduct surge current, they must be grounded. For grounding guy anchors in soil, galvanized clamps and wire are used, so no dissimilar metal joints are made. A transition joint should be made from the galvanized wire to copper wire in areas subject to above-normal snow or flood levels. Copper wire is then exothermically welded to a ground rod vertically beneath it. This ground rod may, in poor soil conditions, need to be interconnected to two other short (20-feet) radial runs with ground rod terminations.

In non-soil conditions, the anchor must have its own radial system or be encapsulated in concrete. The encapsulation should be at least 3-inches thick on all sides around the embedded conductor. The length will depend on the size of the embedded conductor. On a typical strike, about 4.0kA will be delivered to each anchor. This means that 1/2-inch rebar should extend at least 2-feet into concrete to be safe (capable of 9.0kA surges). The dynamic ground tester measurements of the anchor grounds should be less than 10 ohms, total Z.

If the antenna feed lines do not enter the vault via a bulkhead panel, they should be treated in the following manner:

1. Outside, mount a feed line ground bar on the wall of the building approximately four inches below the feed line point.

2. Connect the outer conductor of each feed line to the feed line ground bar using an appropriate grounding kit.

3. Connect a 3 to 6-inch wide copper strap between the feed line ground bar and the external ground system. The joint should be an exothermic or silver-solder connection.

4. Inside, mount a single point grounding panel on the wall and provide a 1 1/2-inch to 3-inch strap to the outside ground system.

5. Mount coaxial, power and telephone protectors on the panel and have a 1 1/2-inch strap (for runs less than 10-feet, larger for longer runs) from the rack(s).

ADDITIONAL PROTECTIVE DEVICES

Power mains protection is important to prevent surges on the power mains from damaging battery chargers, air conditioning and heating equipment, tower navigation lights and water pumps. The recommended types of units mount via a breaker box knock-out and shunt across the incoming lines. They are locally breaker protected so the building power is not disrupted in case of protector failure. A relay senses protector voltage and gives a dry contact reversal for remote signaling.

Localized power line protection is recommended for all 120Vac powered equipment. Telephone protectors for incoming interconnected lines should be installed at the building entrance, as well as on the bulkhead panel or at the equipment. The local telephone operating company can supply building entrance gas tube type protectors. A balanced MOV type protector for punch down block should also be used. For mounting at the equipment, single-, double-, and six-pair protectors are available that allow the 24 AWG solid copper interconnect wire to act as a fusible link, while limiting equipment voltages to 220V maximum.

Dc control lines must be treated the same as telephone lines, using the same protectors. Tone remotes and audio lines have the same need for protectors as the telephone and dc remote lines, but the damage threshold is much lower. Protectors with suitable turn-on voltages should be incorporated at the building entrance and at the equipment.

Dc power lines from the battery room can intercept the radiated strike energy as an antenna, coupling it to the equipment. Suitable protectors should be incorporated at the single point grounding panel and on each piece of equipment from each line side to chassis ground. A SAS diode should be placed across the line to insure that the surge will not cause a voltage reversal to the equipment. A similar unit can be placed across the charger output.

Solar panel sites should have an appropriate protector to protect the battery's series pass regulator. Since the long lines to the panels can have a large induced voltage and current, the protector must be similar to those described in the previous paragraph and should protect for voltage reversals (PolyPhaser's IS-12VDC-50A or IS-24VDC-50A).

chapter 15
The Step Leader and Its Implications

RADIUS OF PROTECTION, SIDE-MOUNTED ANTENNAS AND TALL TOWER GROUNDING KIT LOCATIONS

We have all seen the remains of fiberglass covered gain antennas that have taken a direct lightning strike. This causes down time, tower crew costs and creates the need to stock duplicate antennas for your sites.

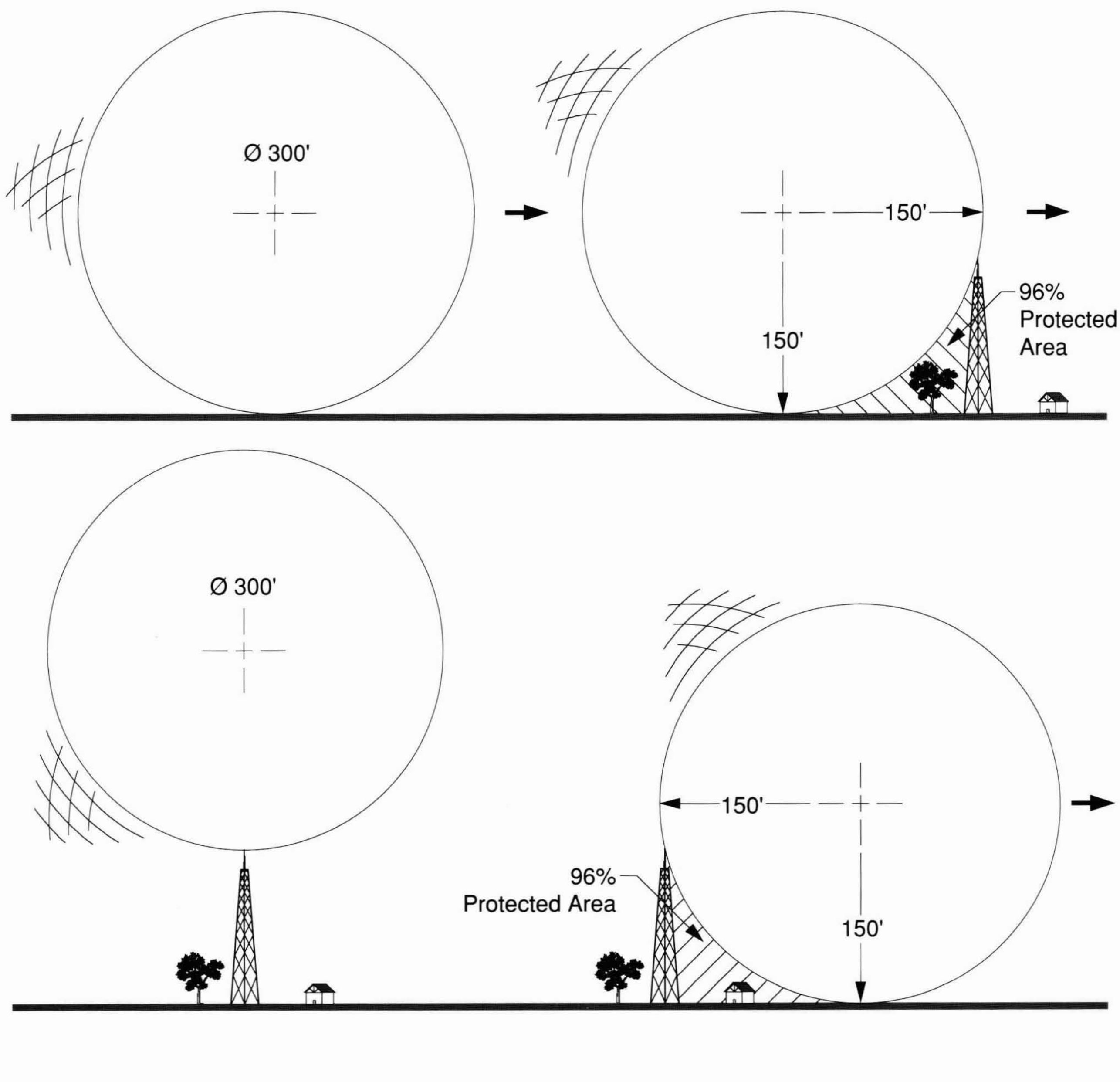
Earlier we covered the step leader which moves in steps of 150-feet (50m). It is from this observation of nature that we can determine that above the 150-feet point, the probability of a strike is higher and the area of protection from a lightning rod is different. If your tower is over 150-feet, side-mounted antennas are vulnerable to direct hits. Since 1980, the NFPA (National Fire Protection Association) has been advocating in their Lightning Protection Code #78, that 45-degree cone angles do not give effective protection. Picture a silhouette of your tower site and imagine a 150-foot radius sphere rolling over all outlined objects. Everywhere the sphere touches could be hit by lightning. This must be repeated for each compass line, since we are dealing with a three-dimensional image. When the sphere bridges between two points, the area beneath the sphere is a 96% protected zone.

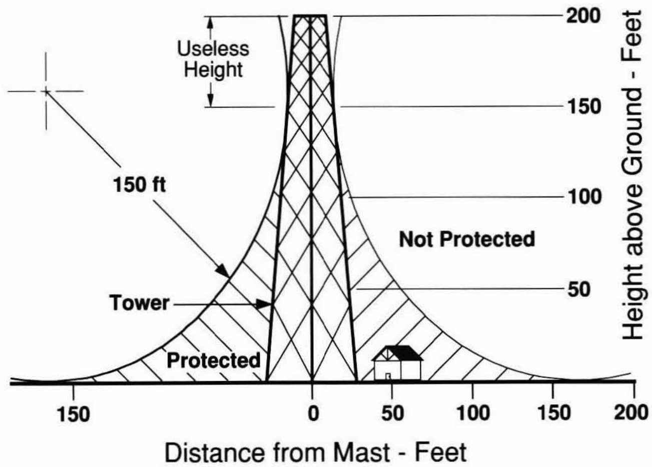
As you roll the sphere up the tower, you can see it will begin to touch side mounted antennas above the 150-foot mark. For guyed towers, the sphere will need to be rolled not only for each compass line around the tower base, but also around each compass line for each guy anchor point. The mesh that is created will cover the tower, like a canvas on a circus tent. The area above the tent is unprotected and the area below is the protected region.

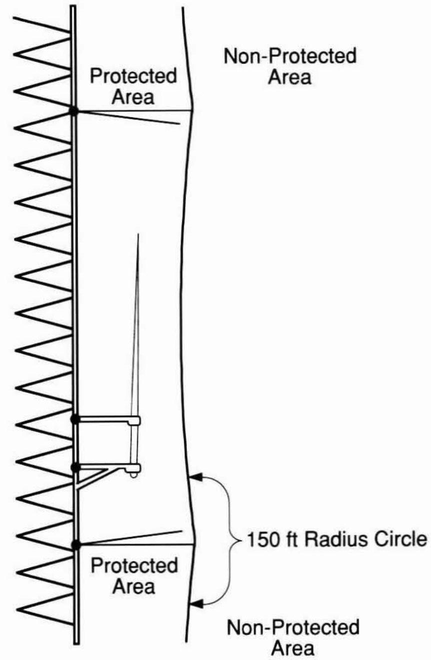
Even on guyed towers, side-mounted antennas, near the top or in sections not covered (protected) by the guy wires, can be prone to a direct hit. One way you can protect these antennas is to have two or more horizontally mounted lightning rods attached to the tower right above the top and just below the antenna. Now as you roll the 150-foot radius sphere up or down the tower, you want the length of the horizontally mounted lightning rods to protrude outward from the tower so the sphere does not touch the antenna. For a 20-foot long antenna, side-mounted above the 150-foot height, the horizontal rod(s) should protrude a minimum of 6-inches beyond the antenna. This gives a 96% degree of protection against direct strikes to the side-mounted antenna. Since they are horizontal and are located in the end nulls of the antenna pattern, no changes will be made in the system's performance.

The rolling ball concept is based on the step leader jumping distance. The larger the charge in the cell, the larger the jumping distance. The smaller the charge, the smaller the distance. This is why the percentage of protection for the zone is 96% and not 100%.

Theoretically a small strike could penetrate the zone, but it would be a small strike with little damage capability. However, on a tall tower above the 150-foot point, the transmission line grounding kits should be spaced so a side strike to the tower will not have to travel far before a union between the tower and transmission line(s) occur. This will help prevent side flashes which could produce water invading pin holes in lines. A recommendation is for 75-feet to no more than 100-feet, separation between grounding kits above the 150-feet point - unless the rolling ball concept shows guy line protection.




Useless Height
150 ft
Tower
Protected
Not Protected
200
150
100
50
Height above Ground - Feet
150
0
50
100
150
200
Distance from Mast - Feet


Protected Area
Non-Protected Area
150 ft Radius Circle
Protected Area
Non-Protected Area

chapter 16
Security Cameras

For Security Camera installations, it is important to have protection on both the camera end and the switcher end. The reason for this is if the lightning strike occurs at the building housing the switcher, the surge energy will also exit through the coax and control lines to the camera ground. Since the ground surrounding the building can absorb the strike current only so fast, this momentarily saturates the grounding system and will cause the entire area to become elevated in potential with respect to the camera. Surge voltages will flow on the conductive control and coax lines to the camera in an effort to go to ground. Once at the camera, the surge energy can take several damaging paths. These paths can depend on how the camera is powered.

First: if locally (120Vac) powered, the coax shield will deliver surge current to the camera shell (case ground) and stress the power supply inside the camera. The surge current on the center conductor will be of the opposite polarity from the shield and can destroy the video output stages.

Second: if the coax or separate lines supply power to the camera, surge energy can over stress the B+ line, causing extensive damage when the camera is locally grounded.

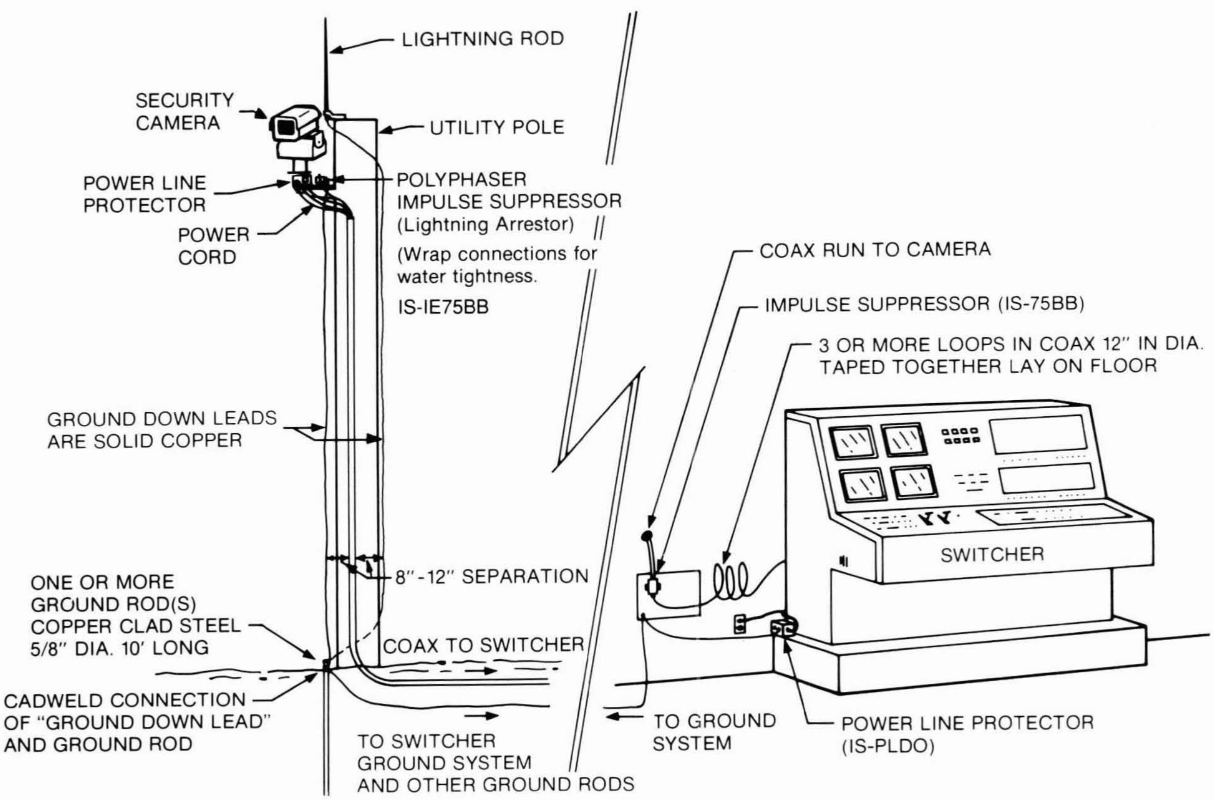
One would logically deduce that we could remotely power and not locally ground the camera and it would survive the strike. Assuming this configuration (no camera ground), the lines to the camera would act as a long wire antenna, bringing major surge currents into the switcher, even from not-so-nearby lightning strikes. The protectors at the switcher would activate. Since the protector ground is not perfect, a certain amount of the surge would be reflected to the camera. Unless a locally grounded protector exists at the camera, it will be doomed.

This scenario illustrates the necessity of a grounded protector at each end. It is also important that the grounds be a low impedance or at least interconnected to prevent hum. Hum or hum bars are created when a potential difference exists between grounds. The 60Hz, which is radiated from power lines, is "picked up" by this difference in grounds (ground loop). Connecting the grounds together prevents this from occurring, or at least minimizes it, but if the interconnect wire is bare and buried, the overall ground system's impedance at both locations is improved (reduced).

If this can't be accomplished, install a hum canceling network to buck the ground loop current. This will change the needs for the type of protector required. If a common protector is used between the hum bucking network and the coax run, a ground path will exist around the network to the camera. This requires an isolated ground type protector be used. This is a protector that only makes a momentary connection to the local camera ground when the surge exceeds its voltage threshold. Consequently, no ground loop currents can exist.

If this hum canceling circuit is not being used, an isolated ground protector can be used at either one end or the other. (Most likely, the switcher or monitor end will connect to a good ground system so the isolated ground protector should be at the camera end.) This type of protector has a dc path for the video and will protect it from voltage excursions over ±2.8V. It also has a local earth ground connection that is only "switched" to the rest of the protector (coax shield) when a preset voltage is exceeded and remains connected until another lower voltage condition is met. This solves the problem of protecting difficult to ground systems, where ground loop currents are a problem.

The need for power protection, either 120Vac or dc, is also brought to light in this scenario. The power line protector for the camera should be mounted **at the camera**, so it can divert any energy from hot and neutral to the camera ground, in the 120Vac case or to prevent over voltages from occurring onto the B+ bus, in the dc powered case.



At the switcher, 120Vac power line protection is very important and should consist of two stages.

The first stage is a power mains protector to prevent strikes, down-the-road to the utility line, from entering the building. The protector is located where the mains enter the building. It should be physically mounted on the breaker box.

The second stage prevents strike energy from entering the switch. Since the protector is to be installed on a secondary distribution breaker, it is called a Secondary Power Line Protector ("secondary" does not mean "less important"). It is important to have this protector in common with the switcher chassis and to have it located at the same point as the ground system connection to the switcher. This will prevent surge currents that are diverted by the protector from going through the switcher chassis in order to reach ground.

Finally, two important notes. If the camera is far from the switcher, the coax jumper lines between the coaxial protectors and the switcher location, could be coiled loosely a time or two. It is far enough away from the strike that the magnetic fields will not couple additional energy. (Keep the diameter of the coil small (< 7cm) to reduce capture area or place the coils inside a steel enclosure.) The coil inductance will help prevent the surge current, diverted by the secondary power protector, from traversing the coax shields to the camera ground. It will be directed to ground by way of the power protector's ground.

For a camera-mounted on a non-conductive pole, a grounded lightning rod should not be overlooked. The lightning rod will divert direct strike energy to ground. Your communications lines should be separated 8 to 12-inches away, because of the large magnetic fields involved on its down lead. This will prevent a side flash from occurring between the ground lead and your camera lines.

Side flashes are caused by the inductive impedance of the down lead. This cannot be eliminated, but can be helped by using copper strap instead of wire or cable. Since surface area is maximized with strap, the inductance is reduced. The strap must have sufficient cross-sectional area so it doesn't fuse open with a direct strike to the lightning rod. Skin effect for lightning does not penetrate more than 3 mils. This current depth is a gradient. In order to have most of the current in this 3 mils, there must be at least 2.7 times this or 8 mils. Since strap is double-sided, the minimum thickness is close to 16 mils. With 1 1/2-inch wide by 0.016-inch thick, the cross-section is larger than a #6 gauge wire which is sufficient to handle direct lightning strikes. This size strap will also have over six times the surface area of a #6 wire.

Even with this strap, the inductance can produce an L di/dt (instantaneous voltage drop) in excess of 100kV, depending on the length. This driving function will force some current onto the coax shield and to the protector at the switcher end.

chapter 17
CATV

Practically everything discussed so far can be applied to a CATV head end. The trunk line amplifiers are very similar to the tower top amplifiers already described. They are powered with a slightly drooping 60Hz squarewave, 60Vac waveform injected onto the coax line. The need to provide proper protection of both the 60Vac power, as well as the RF bandwidth, should be obvious. Protectors, much like the tower top preamp protectors, separate the ac and the RF, protecting each and then recombining them.

From the tap drop to the customer's house, the normally installed grounding blocks do nothing to suppress the center conductor energy. The relative voltage between center conductor and coax shield can still do damage to the decoder/tuner boxes and/or the customer's equipment. A dc blocked cable protector should be used. NEC grounding, together with this coaxial protector will end service calls. For older houses and for locations where bonding to the power ground is impractical, PolyPhaser's isolated type protectors will provide both excellent lightning protection/isolation while preventing hum bars.

The power line neutral ground (at the utility entrance) should be interconnected with the cable drop ground. This interconnection must be made using a bare, buried ground cable or strap. The placement can be troublesome if flower gardens or walkway/driveways are obstructing the most direct path. It can be simplified if the cable entrance point is located close to the power ground location.

A power mains protector is necessary to have complete surge protection. (Additional local 120Vac protection is also highly recommended.)

chapter 18

Telephone Central Offices and Host Computer Networks

Central offices and computer rooms have many things in common. Central offices are computers. Computers on the other hand, tie into LAN (Local Area Network) lines that directly interface with the phone company's channel banks (T-carrier).

Almost everything we have discussed pertaining to a radio site is applicable to a central office (CO) or computer room. Not all CO's have microwave relay towers or other radio equipment. However, those that don't will have one less I/O to protect. The remaining I/O's are the same for CO's and computer rooms.

VOICE/DATA I/O'S

For short hauls, fiber optic cables, with non-metallic armor or strength members, are the best way to go if it is affordable. This eliminates one I/O hazard.

If wire pairs are used, protectors are required. The gas tube type arrestors used for wire pairs by the telephone companies (telcos), will soon be outdated. The large dv/dt created with the crowbar action of the gas tube will cause spike problems with digital equipment. Lowpass filtering is important to limit the harmonic energy created by the crowbar action of the gas tube on wire lines. Non-crowbarring protectors such as capacitively-balanced MOV's are recommended.

For L-carrier coax, a coax grounding kit should be used prior to the coax entering the CO. A coaxial protector should be used to protect the equipment for the center conductor's surge energy.

For T-carrier pairs, (and LAN) special protectors with high bandwidths and low (logic level) turn-on levels should be used. Special units for telco (span line) repeaters (current loop) are available.

POWER I/O

Telcos have batteries to run some equipment. The ac powered equipment should be run from inverters. This collective process forms an Uninterruptible Power Supply (UPS) for the entire system. A UPS is basically a battery charger, battery and inverter. Power mains and local power line protectors should be installed to protect the "battery charger" portion of the UPS from power line surges. All computer equipment should have the same line-up of equipment to prevent brown-out/black-out, bumps, glitches, surges, sags and any other power line maladies.

Always use anti-static floor material to prevent Electro Static Discharge (ESD) to your equipment. Other means such as ion generation may also be helpful.

Lastly, for raised computer room floors, ground the metal support posts. EMP gasket material should bond the cast aluminum tile squares to the structural posts. This technique not only aids in ESD, but also forms a nice ground plane.

A common problem occurs by not maintaining a low inductance interconnect path between protectors (L & T-carrier, power and other incoming pairs) and the system ground.

The most common problem found in CO's and computer rooms is the practice of running lines that can carry surge current with other lines that should be quiet. (For example, ground lines from protectors, being run together or crossing with other ground lines, such as battery return lines and data lines.) The coupling of the surge onto the other clean lines can cause major equipment glitches and down time. As we have previously indicated, EMT conduit grounded on one end is the best way to provide faraday shielding.

Following these guidelines will prevent such problems. It takes some thought to determine the "best way" for laying out a ground system, but in the end it will be worth the effort. Documentation for the ground system is necessary. As the system grows, the ground system plan must continue to be updated and compared to the system goals of good grounding. Otherwise, the system becomes a sprawling and unwieldy mess, with the potential for detrimental consequences.

chapter 19

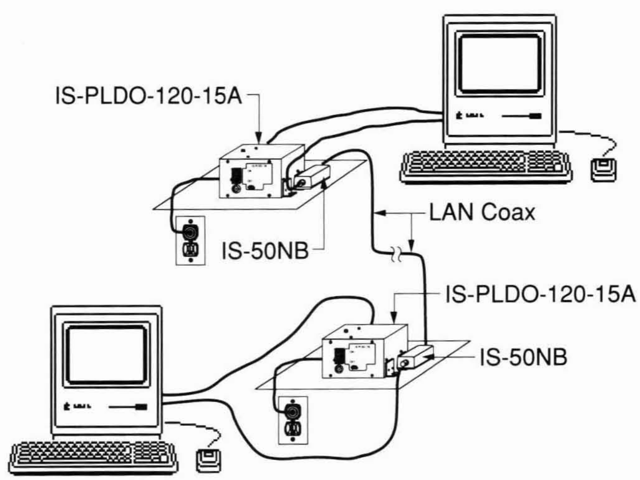
Local Network Computers

Communication lines traveling from one floor to another or from one building to another, can pose a surge threat to electronic I/O equipment, as well as incurring hum (ground loop) problems. Computer data lines use either twisted pair or coax.

Locally grounded coax systems have a more serious problem with ground loop currents as opposed to balanced line systems. The coax is normally grounded to the signal ground at each end, which in turn is then grounded to the power line neutral/earth ground. This often creates two different earth-ground locations which causes ground loop currents to flow on the shield. One method of alleviating this problem is to supply earth ground on only one end. The other end is isolated from earth by using an isolated type protector.

The isolated protector only couples the data from one isolated coax connector to the other. The unit itself is tied to a local earth ground. This isolated coax protector can withstand up to 90V without breakdown. Incoming coax cable shield is not directly connected to the remote equipment's local earth ground. Protection is provided while still insuring the data quality.

For protection at the main terminal end, a standard coax protector may be used. This protector has no isolation and is tied to both system and earth grounds.

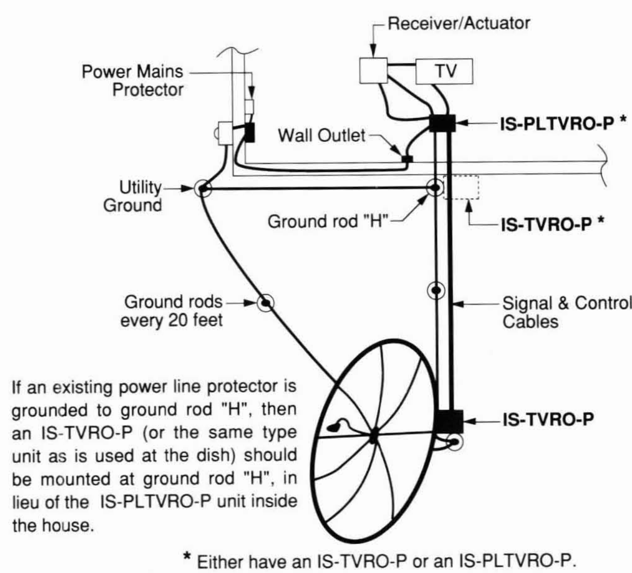


chapter 20
TVRO Systems

UFER GROUNDING

Most TVRO antenna pier supports are encapsulated in concrete. Typically a 4-inch pipe is submerged, 4 to 5-feet in an 18-inch diameter (augured) hole, it provides a good Ufer ground. (For more on Ufer, see Chapter 2.) In areas of good soil conductivity (100 ohms meter or better), this may be adequate for the antenna ground. It is desirable to trench (ditch witch) interconnecting bare copper ground wire from the antenna pipe to the electrical (power) ground rod. The wire should be 1/0 gauge or larger, buried 8-inches or deeper and spaced 2-feet or more from any other buried dish lines. It should be exothermically welded to the pipe. This will ensure a good mechanical connection as well as a good electrical connection. Exothermic welding is a simple process which joins even dissimilar metals without a problem and requires a fixture (mold).

The Ufer ground should be augmented with coupled pairs of 10-foot rods placed 20-feet into the ground and spaced 20-feet apart. The first ground rod location can be right at the antenna. The second should be 20-feet away, in the direction of the equipment enclosure (building). It is also advantageous to have a ground rod located where the cables enter the building.



* Either have an IS-TVRO-P or an IS-PLTVRO-P.
Either should be grounded to ground rod "H".

Additional radials should be used to augment the Ufer grounding. RF and control cables for the system should follow the line of grounding rods which are spaced 20-feet apart.

If the installation is in a rocky area making it virtually impossible to install ground rods, then the radials are needed. Grounding may be accomplished by laying 10 or more lengths of 1 1/2-inch copper strap, at least 50-feet long, in a radial fashion around the antenna base. Bury the straps if possible. Once in place, the hub must be interconnected to the utility ground at the house entrance.

In sandy terrain, use the same radial concept, with 10-foot ground rods every 10-feet along each radial run.

These guidelines are based on information that can vary from location to location. It is best to measure the soil conductivity and design a 5 ohm ground system. By using the proper I/O protectors, the equipment will survive even direct strikes.

The system may have the following I/O's:

1. 120Vac power
2. RF coax cable
3. dc polarization control
4. actuator/positioner cable

The power line I/O that can be like a two-way street. If a lightning strike occurs away from the system, but near a utility pole, it can travel to the equipment. A direct strike to the satellite antenna, causes currents to flow toward the equipment, elevating it and exiting to the utility line, causing damage in the process. A power line protector is needed to prevent this. What kind, how many and where it is located and grounded are questions whose answers will make all the difference.

A power line protector that plugs into the wall not only has the power cord inductance from the equipment to it, but also has an even longer run to the distribution panel before reaching the utility ground rod. In essence, it is not grounded at all because of the fast rise time of the lightning strike and its associated voltage drop.

The best way to protect the equipment is to have two protectors. The first is a power main protector which is mounted directly on the breaker box across the 240Vac mains. It can protect the whole house from incoming surges from the utility lines. The second is a protector mounted or grounded directly to the equipment chassis. It will divert surge current to a ground stake just outside the cable entry to the house.

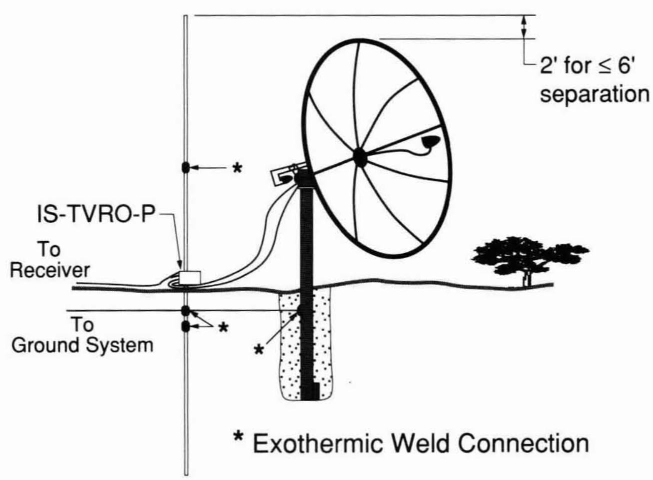
RF CABLE PROTECTION

The next I/O of interest is the RF cable. Surge current will propagate on the coax lines so that, in as little as 15-feet, the center conductor energy can become devastating to the equipment at either end. What is needed is a coax protector that will clamp at the dc voltage level for LNB's and have low loss and good VSWR over the 450 to 1450 MHz range (PolyPhaser's IS-SB75F and IS-DB75F).

The polarization rotor or polarity switch cable is another I/O line that can deliver surge current to the equipment. This, together with the actuator, must be protected.

The system will obviously need two sets of protectors - one at the antenna and the other at the house Both are to be commonly grounded.

To this point, I/O protection has been covered, but in the event of a direct strike to the feed, damage to the LNA/LNB can still occur. To stop direct strikes from putting weld marks on the feed, use a 3-foot section of ground rod, or purchase an appropriate lightning rod, and mount it to the top of the antenna on the back side. Since the antenna could have greased joints, it may not have a good ground path except through the coax lines. It is best to connect a separate down conductor, using #2 gauge copper wire, to the Ufer (pipe) ground which is bonded to the rest of the ground system.



To protect the system from a direct strike, a lightning rod, 2-feet taller than the highest point of the dish, should connected to the Ufer ground.

The rod should provide a good area of protection for the antenna and feed. If the 3-foot lightning rod and stand cannot be located, a pair of 10-foot ground rods can be coupled together and exothermically welded. This assembly can be partially driven into the ground and then interconnected to the ground system. The rod top should be 2-feet or so higher than the highest part of the antenna or feed.

This covers some aspects for protecting a TVRO system. We have covered other usable techniques for such sites throughout this book. Together, these concepts will reduce equipment failure dramatically.

chapter 21
Utility Pole Supports and Towers on Buildings

Utility poles made of wood, or other non-conductive material, are unfortunately used as support structures for antennas. (Addressed in Chapter 14, "A General Review and Standard".) From a lightning protection standpoint, a wooden pole can only be used by placing a down conductor to help share the lightning energy. With directional antenna usage, mount a lightning rod on the pole top with a separate down conductor to the ground system. This down conductor (in addition to the antenna down conductor), should be separated as much as possible from the antenna down conductor and coax line. (See Chapter 16 "Security Cameras".)

These conductors should be a least #1/0 gauge or larger (copper strap is best). Ideally, the total conductor surface should be at least equal to or larger than, the total surface of all the coax lines running down the pole.

Towers on top of buildings have similar needs for down conductors. On buildings with steel frames, towers can be grounded via the steel members. Wooden frame buildings must use multiple down conductors to reduce the inductance to the ground system and to help cancel the magnetic fields inside the building.. These conductors may exit the tower base in different directions. If only one direction is viable (shortest path), then they should be spaced at least 1-foot apart to reduce the mutual inductive coupling between down conductors.

Protective devices should be placed near the equipment. Some installations may require that the surge current be removed before entering the building. If the coax is penetrating the building roof, this may require a protector that is grounded to the tower base. It would be wise to include an additional protector at the equipment. This grounds the coax shield relative to the equipment as well as removing any left-over center conductor energy.

Finally, telco and power line protector requirements are the same as other systems already covered in this book.

EPILOGUE

This concludes our book on proper grounding and protection techniques. If you have questions or would like to have our complete catalog of protection/grounding products, please contact our Customer Service Department at PolyPhaser Corporation, (702) 782-2511. Our business hours are 7 AM to 5 PM, Pacific Time Zone, Monday thru Friday.

APPENDIX 1

INTERESTING INFORMATION AND CONJECTURES

The earth's atmosphere always has some electrostatic charge present. Ben Franklin proved this over 200 years ago. He set up his storm warning bells which used the static voltage build up to ring the two bells. Normally, this electric (E) field averages about 150 volts per meter. The E field can climb to over 1000V/m on a dry day. This means there may be as much as 1800V between head and toe on a 6-foot person. (This is a static voltage and cannot be used to solve the world's energy problem. Just the presence of a conductor will change the E field's contour.)

The earth is constantly loosing electrons. The current is extremely small per square kilometer (3μA/km), but this totals globally to about 2000 amps continuously! Mother Nature's way of balancing the process is with 150 lightning strikes per second.

The upper atmosphere is conductive due to solar radiation, meteors and other particles. It is especially conductive in the 100km to 350km range above sea level. Beyond this are the highly ionized Van Allen belts which are not always at a constant height above the earth. They are lowest at Miami and Rio de Janeiro due to the earth's magnetic field. These locations have a fair amount of lightning activity. The solar activity, according to Holzworth and Mozer, can increase the E fields by 5 to 10%. This could increase global lightning activity by as much as three times. These conductive layers are like one plate of a capacitor with the conductive earth forming the other. While the sun charges the atmosphere and the earth looses its charge, an imbalance occurs. The capacitor can only withstand a given voltage differential before a strike happens.

The radiated radio energy from a strike can be heard hundreds of kilometers away on any standard AM radio tuned to the bottom of the band. Longer distance strikes (3000km can be detected at lower frequencies. Strange whistling sounds have been heard and associated with lightning in the 10kHz to 20kHz range. They last only a few seconds and sweep downward in frequency from approximately 20kHz to 6kHz.

We hope to have more on this and other interesting aspects of lightning strikes in future issues of our newsletter "Striking News".

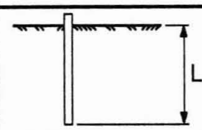
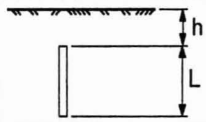
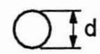
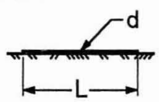
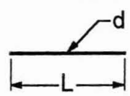
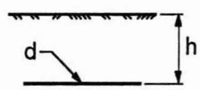
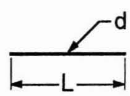
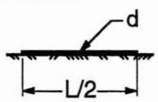
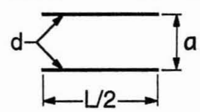
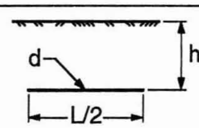
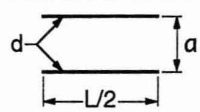
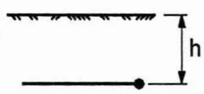
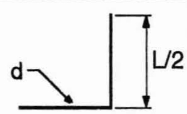
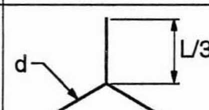
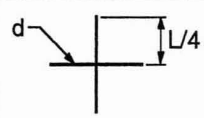
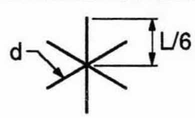
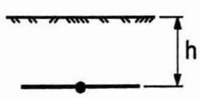
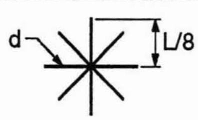
APPENDIX 2

WATER AND SOIL RESISTIVITIES

TYPE OF WATER OR SOIL	RESISTIVITY IN	OHMS
Water in oceans	0.1-	5
Ground water, well, and spring water	10-	150
Lake and river water	100-	400
Rain water	800-	1,300
Commercial distilled water	1,000-	4,000
Chemically clean water	250,000+	
Clay	25-	70
Sandy clay	40-	300
Peat, marsh soil and cultivated soil	50-	250
Sand	1,000-	3,000
Glacier	3,000-	10,000

APPENDIX 3

FORMULAS

Type of Electrode	Side View	Top View	Formula	Ref.
Vertical electrode on surface			$R = \frac{\rho}{2\pi L}\left(ln \frac{8L}{d} - 1\right) = \frac{\rho}{2\pi L}\, ln \frac{4L}{1.36 \cdot d}$	①
Vertical eletrode buried			$R = \frac{\rho}{2\pi L}\, ln \frac{4L}{1.36 \cdot d} \cdot \frac{2h + L}{4h + L}$	①
Strip on surface			$R = \frac{\rho}{\pi L}\, ln \frac{2L}{1.36 \cdot d}$	①
Strip buried			$R = \frac{\rho}{2\pi L}\, ln \frac{L^2}{1.85 \cdot hd}$	②
Two strips on surface			$R = \frac{\rho}{\pi L}\, ln \frac{L^2}{2 \cdot 1.85 \cdot da}$	③
Two strips buried			$R = \frac{\rho}{2\pi L}\, ln \frac{L^4}{16 \cdot 3.42 \cdot hdaA}$ $A = \sqrt{a^2 + 4h^2}$	②
Two strips buried			$R = \frac{\rho}{2\pi L}\, ln \frac{L^2}{1.27 \cdot hd}$	②
Three strips buried			$R = \frac{\rho}{2\pi L}\, ln \frac{L^2}{0.767 \cdot hd}$	②
Four strips buried			$R = \frac{\rho}{2\pi L}\, ln \frac{L^2}{0.217 \cdot hd}$	②
Six strips buried			$R = \frac{\rho}{2\pi L}\, ln \frac{L^2 \cdot 10^3}{9.42 \cdot hd}$	②
Eight strips buried			$R = \frac{\rho}{2\pi L}\, ln \frac{L^2 \cdot 10^4}{2.69 \cdot hd}$	②

Ref. Table: ① $d \ll L$ ② $d \ll 4h \ll L/n$ ③ $d \ll a \ll L/n$

APPENDIX 4

COMMERCIAL SITE GROUNDING AND PROTECTION STANDARD

1. General Grounding for Lightning Protection

    1.1. Grounding for a communication site must take into account not only the soil conductivity, but also the total land area for the site and the soil depth available for a ground system.

    1.2. Indoor grounding techniques are only important where shielding or attenuation of the strike's EM (Electromagnetic) fields have not been incorporated.

    1.3. There is but one grounding system. No separate ground rods that are not interconnected in the main ground system will be allowed.

    1.4. Only in environmentally sensitive areas will chemical treatment of the grounding system not be utilized.

    1.5. Guyed towers with conductive guys and properly grounded anchors should be used where possible, since they can minimize the strike current to the equipment hut compared to a self support type tower.

2. Background on Grounding

    2.1. All ground systems have a frequency response. The lower the resistance of the ground system the larger the frequency response.

    2.2. All ground systems have inductance and capacitance which will attempt to narrow the frequency response if it is not shunted by the soil resistance.

    2.3. Soil (earth) is made conductive by the moisture and ionic salt content. Therefore, as the temperature reaches freezing, the conductivity goes down (resistivity goes up) drastically.

    2.4. Since all ground systems have an impedance (surge impedance), there will be a rise in voltage during a lightning strike. This rise will be larger; the larger the resistance value to the globe (true earth).

    2.5. A ground system is much like a lossy or leaky transmission line and must be looked at in terms of being RF conductive. A good ground system should make a good counterpoise (for a ground mounted antenna). However, the opposite is not always true, a counterpoise does not always make a good ground system since an RF counterpoise does not have to be on the ground.

    2.6. Like RF, the connection to the ground system, (the part that is in air and thus not shunted by the ground's conductivity,) should be as direct with low inductance as possible. This means that a large surface area conductor should be used and installed with as few bends as possible. When bends are necessary, they should be gradual and not be smaller than an 8" radius arc segment. Generally a flat strap will use less copper and have less inductance than a round member type conductor.

    2.7. As in RF, skin effect will be present on all the grounding conductors. All high frequency strike energy components will be impeded less on large surface conductors. The general goal for all conductors that are in air (not in conductive soil) is a surface-to-length ratio of no more than 10:1 for major strike conductors to the ground system and no more than 50:1 for secondary conductors.

2.8. The routing of all surge carrying conductors must be no closer than 12" from any other conductive material. This prevents cross coupling to other wires and prevents mutual coupling which will add unwanted inductance and voltage rise above true earth ground.

2.9. Conductors that must be routed through conductive conduit must bond to the conduit as it enters and exits the conduit. This should not be cause to use non-conductive conduit since the wire alone will be more inductive than if it were not used together with conductive conduit.

2.10. Grounding conductors can not penetrate any conductive material wall. Magnetic fields around the ground conductor during a strike event will create eddy current in the conductive wall which will increase the inductance of the grounding conductor and impede the surge current to ground. It should white metal bond to the conductive wall, then directly on the opposite side of the wall, another conductor should be used to again white metal bond and continue to your ground system.

2.11. The below grade part of the ground system must be made of the same material throughout. No dissimilar metals can be used unless it is intentionally for cathodic protection purposes and designed to be sacrificial.

2.12. All connections should be made to metals that are free of water, grease, and oxidation. The conductors should be taken down to the "white metal" which is clean and bare.

2.13. All compression type joints should use a joint compound. The compound should be suitable for the metals being joined.

2.14. All bonds should be measured and logged. They should exhibit no more than one milliohm (.001) and should be measured using either a Fluke model 8012A-01 or a good earth measuring tester that can also read down to this level.

3. Tower Ufer Grounds

3.1. All towers that are ground mounted will need to have a concrete base. This base will need to be reinforced with steel rebar or steel mesh. This material can help in lowering the ground impedance of the grounding system. Concrete absorbs water and retains it for long periods. It is also conductive, although not as conductive as some types of soil. This should not prevent its use, since it simply means the ground system will absorb more of the strike energy than the tower base. The Ufer ground is not intended to be the only ground in the ground system, but is intended to augment an in-the-ground system or is used in conjunction with an arcing radial system on mountain tops.

3.2. There must be at least 10' of half-inch or larger rebar in the foundation. The recommended method of connection is to bond a 2/0 cable to a rebar and then bond the outer most joints of the rebar cage (corners) together so their is a total circumference of 10' around the perimeter. This 2/0 cable should be bare and run vertically so as to protrude above and be bonded to the tower foot.

3.3. Bond an additional 2/0 to the rebar so it may run horizontally below grade and interconnect to the remaining ground system.

3.4. Buildings that have an on-site poured concrete flooring should also make use of floor rebar or mesh by bonding from this to the internal principal ground window (PGW) or bulkhead master ground plate. This also applies to any footer poured for a prefabricated hut or generator pad.

3.5. Ufer grounds should also be used at the guy anchors. If the anchor steel is tar or pitch covered, use 20' of 1/4" galvanized cable. Spiral the cable (if possible) in the base of the concrete anchor, then bond to the steel at a close convenient location.

4. Waveguide and Coax Grounding

4.1. Since the precursor of a lightning strike (the step leader) travels in steps, a distance of about 150', all transmission lines, tower light conduit, etc. must be grounded to the tower at its uppermost point and the lowermost point, if the tower is less than 150' tall. If the tower is taller than 150', then the grounding must be at the uppermost point and at intervals of no more than 75', until the bottom 150' section is reached. It may span this distance until the lowermost point where another grounding to the tower must occur.

4.2. Coax and waveguide lines must use grounding kits designed for grounding the shield. Coax that is not hard-line or rigid line should not be used since a proper weather tight shield bond can not be obtained. All grounding kits must be properly weatherized to prevent bond deterioration.

4.3. All transmission lines, tower light conduit, etc. must be grounded again before entering the equipment hut. For tower lighting conduit/cable, this may be accomplished by using a lightning protector that is mounted to the building and has a low inductance grounding path to the grounding system (such as the bulkhead entrance panel etc.) and a transition clamp (with appropriate joint compound) to bond the conduit if conductive.

4.4. Due to the typical step leader's jumping distance, side mounted antennas that are above the 150' point are susceptible to a direct lightning strike. The only way to prevent this is to provide two sets of two horizontal lightning rods. Each set must protrude one foot beyond the antenna and any radials, such that it places the entire antenna in a zone of protection. This means one set will be at the antenna base and one will be at, or just above, the antenna's top. Since they are at the antenna's null points and also horizontal, they will have no effect on the desired radiation pattern.

4.5. There is no need to provide the tower with any lightning rods, unless the top beacon light is in need of protection. In this case a conductive mast of similar metal should be installed so as to survive all local weather conditions. No separate down conductor is needed and none should be installed, especially if it is of a different metal. Down conductors only add weight, wind/ice loading and do not add any conductivity or much surface area. To prevent arcing due to the inductive voltage developed during a direct strike, the down conductor would have to be stood off at a ridiculous 3' on a 150' tower and 6' on a 300' tower.

5. Lightning Protection Devices

5.1. All Inputs and Outputs (I/O's) of the equipment hut must have an appropriate lightning protection device that is mounted/grounded via a low inductive path to the ground system. The preferred path/location is outside the hut. (See Section 7 and 8).

5.2. I/O's are any electrical or electronic lines that can not be directly grounded.

5.3. All power lines, telephone lines, coax lines, and external generator lines must have protection devices as they enter/exit the hut.

6. Location of Equipment Hut to Tower

6.1. As mentioned, the grounding system will act like a lossy transmission line. The velocity of propagation will dictate the minimum time to absorb the strike energy. Since time equates to distance, the further the hut is from the tower, the more time the grounding system has to disperse the strike energy before it reaches the equipment. Also, the longer coax lines will be more inductive, thus choking off the strike current and forcing more strike energy to the tower base ground.

6.2. The minimum separation distance between tower and hut will depend on the total ground system's impedance at the tower base and at the hut's bulkhead or perimeter ground. Basically, more separation is better, but there is a tradeoff with transmission line losses and how they effect the overall link budget of the communication system.

6.3. Grounding the transmission lines' grounding kits as low as possible on the tower is the absolute best installation. This provides a near zero voltage across the tower-to-ground segment. Thus most of the strike current is forced into the tower base ground. The transmission lines could either enter the building at grade level (preferred) or be grounded at the tower base and then angle up to enter at the cable tray level. It is mandatory in either case to provide a low inductance path to the ground system to handle an additional transmission line kit and divert the center conductor energy being picked off by a coaxial protector.

6.4. If none of the above preferred methods are implemented and a grounded elevated cable ice bridge is used, it should be isolated/insulated, if possible, by as much as 6" on either end or else even more surface area will be present to conduct the strike energy/current over toward the equipment hut and less will traverse the last segment of the tower to the tower base ground.

7. Shielding Effects of the Hut

7.1. The Electromagnetic (EM) radiation (plane wave) of the lightning strike is well documented. In the near field of the return stroke (lightning strike event) the magnetic field (H field) is predominant. Most equipment manufacturers shield to meet FCC Part 15 and perhaps for ESD (Electro Static Discharge). With the low frequency response of lightning, (DC to 1 MHz range,) the need for H field cable shielding is obvious. Shielded cables that interconnect between equipment have little to no attenuation to H fields in this frequency range. (This causes a differential voltage to occur between center conductor and shield on a coax line during the strike event. This can also be expressed as "transfer impedance" of the coax). Even prefabricated huts of reinforced concrete offer only a few dB attenuation to these H fields.

7.2. It is recommended that double wall steel huts be used in order to provide magnetic field attenuation. Used cargo shipping containers which are normally single wall steel will provide large field losses. Since the H field drops at a rate of the inverse square of the distance, using steel huts can equate to a major separation between tower and hut. Still a separation is desired in order to have the time factor for the tower base ground system to absorb the strike. Even though a steel hut will allow a true single point ground at any location inside the hut, the I/O protectors will work harder and have a shorter life if the separation is not provided. This is because the ground system and the hut will be elevated during the strike event and the protectors will fire to dump surge energy onto external I/O lines (such as power and telco lines) that are leaving the elevated area.

8. Type and Location of Protective Devices

8.1. The best protective device is an in line (series) type. An in line offers more stages to protect the equipment. Much like a cascading waterfall, the in line protector can transform a harsh surge with high voltage and current, into a survivable voltage with minimal current sharing with the equipment if a single point low inductance ground path exists.

8.2. With the recommended double steel wall hut structure, which is all conductive, the inductance between I/O protectors would be unimportant.

8.3. In non-conductive huts, I/O's should be protected at the point of entry/exit to the hut. These "primary" protectors should be bonded in a low inductive fashion to the external ground system. Additional protectors should be utilized at the main or principal ground window (PGW) which forms a single point grounding system inside the hut. This means that all I/O's will be protected and the protectors will be located and bonded at the single point called ground (PGW). This point is best located at the coax entry, or next to this location, because this is the entrance of the largest (direct tower hit) surge energy and should be the location of a large/low inductance path to the external ground system.

8.4. If dual protectors are used as in the above installation, the first (I/O entrance) protector may be a shunt type if the second protector (at the PGW or bulkhead) is an in line type. A mix, as opposed to both being the same, is desirable.

8.5. If a generator is used, the power mains protector may be located on the load side of the transfer switch. This will help prevent voltage surges from generator hunting, etc. and will help protect the generator's control electronics from the inevitable ground rise that will occur from a tower hit. The down side for this location is a hit down the road or a large ground rise can cause an arc over of the transfer switch if the site happens to have changed over to the generator (thus disconnecting the protector from the mains). Only if two mains protectors were used could this be prevented. (See Section 8.4).

8.6. If auxiliary telco protectors are added at the PGW or bulkhead panel, the telco supplied entrance protectors may be used provided that the grounding conductor used to bond to the external ground system be at least equal in surface area to the surface area of the incoming telco cable and that the armoring of this cable also be bonded to this same grounding conductor. If auxiliary telco protectors are not installed (not needed on normal telephone lines with battery plus ringing in steel huts), attempt to install a very large surface area conductor to ground the telco supplied entrance protectors to the PGW. This will not be the best scenario since this conductor can and will radiate the conducted surge inside the building. For steel huts, try to get the telephone company to install their protectors outside so that skin effect can be best utilized. Auxiliary protectors are recommended for lines that are for audio/data only with no battery or lines that have battery but no ringing because the telephone company supplied protectors will have too high a turn-on voltage to be effective. For sites that have more than a 6-pair cable, a simple shunt type protector block may be used, since the incoming surge will be coupled and shared among the number of wires so the amount of surge on any one wire will not be so great as to warrant the need of a series type protector.

8.7. Coaxial protectors with no DC continuity (capacitor blocked) from center pin to center pin and with no inductor to ground on the antenna side (this inductor, if ferrite, will saturate during the strike and orient the ferrite resulting in increasing insertion loss, plus it will easily couple strike energy to the protected side conductors) should be used. This patented type protector gives minimal loss and offers attenuation of the low frequency components of the strike. Thus the low strike throughput energy amount that is allowed through the protector can be defined. These coaxial protectors must be grounded via a low inductance path to the external ground system in order to be effective. This path must not incorporate the coax shield as part of that path, either before or after the protector. The grounding path must emanate separately from the protector unit mounting/grounding flange to the ground system.

8.8. The best way to provide a low inductance path to the ground system is via a bulkhead panel. This panel may provide a means ("U" panel) to keep all coax connection joints and the protectors inside the hut (for non-conductive huts). If a bulkhead panel can not be incorporated, a surface mount panel or PGW bus may be used inside to mount/ground all I/O protectors (and to provide chassis grounding of the equipment racks).

9. Internal Grounding System

9.1. Single point grounding is by far the best. As mentioned, a PGW, bulkhead panel or both can be used as the single point for all equipment and protector grounding.

9.2. In non-conductive huts, it is recommended that a halo ground be installed at both the ceiling and at the floor level. They should be bonded together at the hut corners and along the wall, where possible, at intervals of no more than 6' in separation. These down conductors must be 6" from all other conductive material whether grounded or not. This grid system is not to be used for equipment grounding since this would destroy the attempt for single point grounding. The purpose of this grid is to bond window, door and louver frames, halon containers, (unless the container is already grounded via the safety electrical ground; if so, don't ground to the halo or a loop will be formed which will destroy the single point grounding for the equipment) and other non-electrical but conductive bodies so that a quasi-Faraday cage might be formed. This grid/cage system should be grounded to the external ground system as often as possible, but the minimum number of connections should be equal to and at the same locations as the vertical down conductors. The reason for the above 6" separation is to prevent flashovers. The voltage drop from the PGW/bulkhead to the external ground system due to the current from the shield and center conductor as removed by the coax protector (50% of the energy will be on each conductor, which reinforces the need to keep the paths to the external ground system as short as possible by having the coax leave the tower and enter as low as possible to the ground) will elevate all the equipment that is attached to the single point ground. Therefore it is important that there is no other path to ground which would invite the surge to go into the equipment hut. For example, the equipment racks should be insulated from a concrete floor since the floor is a partial conductor (Ufer). This would not be necessary if the entire hut were a conductor.

9.3. In non-conductive huts, ground loops should not be allowed. Conduit for electrical power should not be bonded to equipment racks. However, safety ground (green or bare) will violate this loop rule since chassis will be bonded to the PGW. (The PGW is bonded to the external ground system as well as the utility neutral ground which is to be bonded to the external ground system in order to form one ground system). If local code will permit, try to use only the PGW for the safety ground and avoid the loop. Most equipment will probably be operating via station battery, so this should not be a problem. However, it is recommended that if AC powered equipment must be used, it should be powered by an inverter (run via the batteries) and the chassis/safety ground be bonded directly to the PGW with a master bond from the neutral of the inverter to the PGW.

9.4. Many existing sites that use a station battery use the typical telephone standard of grounding, whereby the battery return (B+), signal return, and chassis each have a separate ground run to the PGW (isolation). The reason given is to reduce noise. The only problem is no attention is given to the location of these grounds in the cable tray where mutual coupling can negate these efforts. Also, many manufacturers supply separate ground connections externally only to tie them together internally and thus create a loop in the ground system.

9.5. Normally battery return is run back to a return bus, this bus is then grounded to the PGW which also has a run to each rack/chassis. On equipment that does not have "isolation" (see Section 9.4), some battery current will be shared via the PGW back to the battery return. This can make joint resistance measurements a problem if the recommended Fluke 8012A-01 is used since it injects DC to make its measurement. If this occurs, take two readings, one with probes in one polarity and again with the probes reversed. The true value is the summation of the two readings (one reading will have a negative number).

9.6. For high-rise sites, the same single point grounding should be used. The only difference will be in the antenna grounding and in the grounding of the single point to a real earth ground. These are both covered in the external grounding section.

10. External Grounding System

10.1. For locations that are not environmentally sensitive, where the site is ground-mounted (non-high-rise) and some soil conditions exist, a chemically activated grounding system will provide the lowest ground potential rise in the smallest size parcel of land.

10.2. A controlled system that monitors the far earth resistance of a site by means of a distant ground electrode or by any other dynamic means can be used to control a pressure pump which forces a saline solution through a conductive network which leaches the solution around each conductive part of the system, thus increasing the conductivity of the soil resulting in an overall reduction of the ground system's surge impedance. A calibrated controller may be adjusted to provide a given impedance for the ground system. If the unit is unable, for some reason, to maintain the desired impedance, an alarm contact will be used to indicate this higher impedance condition.

10.3. The external ground system must bond together the utility neutral, the tower base Ufer, the building Ufer, conductive fences, tanks, generators, etc. and any ground based conductive bodies or in-the-ground conductive materials such that when bonded together they will form a single ground system so that it will perform adequately for dispersing direct lightning strikes.

10.4. The grounding system should be 5 ohms or less. This value will change with temperature, water and salt content. Salt content can change if the site is in a high precipitation area. Generally, the higher the salt content the less water is needed to reach a given resistance value. Also the more salt, the less variation in temperature since the freezing point of water (which is the point where water changes to an insulator) is decreased.

10.5. All ground systems must be measured and a log kept with the time, date, site, temperature and last known precipitation. Normally the measurement may be done by using a Biddle earth resistance meter and following the procedures given in their book titled, "Getting Down to Ground." The book covers the fall-of-potential 3-stake method and 4-stake method. Just remember that large ground systems require the use of long wires to stretch between measurement stakes. Not only must the resistance of this wire be taken into account, but a larger amount of real estate without utility grounds will be necessary. Utility grounds equal to or closer than the ground system under test will give a false lower reading! All measurements must be done outside of conductive chain link fencing.

10.6. For environmentally sensitive sites with soil, standard radials with ground rods are the most effective means to achieve a low impedance grounding system. The radials must be run from the tower base and away from the hut. (This is because the ground can couple the launched surge energy from a nearby radial back into the hut's perimeter ground and cause an imbalance which could be conducted through the hut, especially if a multi-point grounding system is already installed inside the hut, such as a halo ground ring system in which the equipment is interconnected.) This in-ground coupling is why in-the-ground utility runs, which are often thought of as lightning immune, can actually have more surge energy induced on them than if aerial. One and only one radial run will connect the perimeter run around the hut to the tower base. The rods should be the same metal (cladding) as the radial. The rods must be hammered into place. (Auguring will disturb the compactness of the soil and will not provide the same benefit due to the air in the soil.) The soil conductivity must be measured on small (30M by 30M) parcels since it may be impossible to achieve a 5 ohm or less ground impedance system. Standard IEEE formulas can be used to determine if a parcel can make the 5 ohm limit without the use of chemicals.

10.7. Remember the earth resistance meter operates at low frequencies and is not sensitive to inductance. Therefore, it can not indicate the true surge impedance of the grounding system. Likewise, the leaky transmission line model should indicate there is a law of diminishing returns for a given radial, and after a length of about 50' to 75', the effectiveness for the amount of material and effort involved is perhaps better spent in installing new radials, emanating from the impact point the tower base.

10.8. At a site, the first ground rod should be measured as it is hammered into position. This will tell a lot about the soil's conductivity. If there is an abrupt change in readings at a given level, the soil may not be consistent in salt or water composition. If the upper level soil is poorly conductive, larger radial wire should be used to reduce the inductance between rods (since the soil is not shunting the radial inductance as it would if this layer were conductive), and the spacing between rods should be decreased as well. Likewise, if at a depth the resistance value does not change for a reasonable increase in penetration, this can indicate a non-conductive layer exists. This can cause a high concentration of the

E fields which can cause arcing in the soil to occur at the rod's end. Such arcing, with its high temperature will fuse the soil into a glass material. This glass material will no longer be conductive because it no longer contains water and cannot absorb water. Glassification of ground rods is a maintenance problem that is often overlooked and can lead to equipment damage. The only way to avoid this is to do routine measurements and inspection of the ground system. The best way to check for glassification is to first suspect that this might be occurring (by measuring and logging the rod's resistance at installation) by looking at the historic readings of the site and then digging around the rod, looking for glass. The next way is to routinely pull upward on the rod; if it moves, the chances are that it is glassified.

10.9. At sites with little to no soil, where rods cannot be used, only radials can be installed together with the Ufer ground(s), etc. To minimize the in-air inductance, it is recommended that flat strap be used. Advantages to the strap are its ease of installation and the sharp edges are beneficial in arcing to the soil or rock where it can disperse the strike energy. For mountain top location, if precipitation occurs before the strike event, the rocky surface will be surprisingly conductive. Another method to artificially reproduce this is to have an early warning system that releases water or a saline solution over the straps, so it will spill onto the rocky surface before the strike event. For locations that do not have a water supply, a saline cistern may be used. An alarm may be sent to indicate this spillage has taken place so that a refill may be arranged. The sensor may be either electrostatic or a low frequency receiver-detector with a counter on a self-resetting timer.

11. High-Rise Buildings

11.1. Choose a site with lightning protection-grounding in mind to make the task much easier. Buildings that have a steel structure are the best. The building steel will act like a tower and the only difference will be where the equipment room is located "on the tower". If the room is at the first floor or basement, choose a location near a vertical utility corridor or near the fire riser. (A fire riser is not the same as the feed for the sprinkler system, but is a vertical water main that traverses the entire height of the building.) At the ground/basement floor typically there is a supercharging pump of large horsepower. This pump must be protected on its electrical feed and must be electrically jumpered with a large surface area strap from its intake pipe joint to its output pipe joint, to prevent pump failure. (This has been done many times in Florida without pump failure). The riser may also be used if the room is not at the first floor.

11.2. Since the corridor most likely will be used for the coax line entry, and since the riser runs inside the corridor, this makes it ideal for grounding the bulkhead/PGW. Remember the telephone and the electrical service must be protected at the PGW/bulkhead before going to the equipment.

11.3. On the roof the antennas must be grounded. Again, it is best if it is bonded to the fire riser since this will reduce the current on the coax lines. However, many buildings have Franklin rods (air terminals or lightning rods) that already have a grounding system to an earth ground. Beware that some codes do not allow the grounding of antennas to the grounding system and may cause an insurance problem. Since the building's Franklin rod system goes to a separate grounding system and does not interconnect (sometimes they never interconnect to the utility ground) to the utility ground until the ground level of the building, it may not be the best and lowest inductance path to earth. If this is used, it is recommended that a strap also be used to provide another path to ground. (Do not run the strap back to the PGW unless it is the only route available. It would be better to run it to the same point that the PGW is grounded than to run it to the PGW itself which would then have the additional voltage drop from the PGW to this grounding point.)

BIBLIOGRAPHY AND FURTHER READING

Decibel Products Inc. About Lightning.

Eaton, J.R. "Impulse Characteristics of Electrical Connections to the Earth". General Electric Review, October 1944.

Fagan, E.J. and Lee, R.H. "The Use of Concrete Encased Reinforcing Rods As Grounding Electrodes. IEEE Transactions On IGA, July/August 1970.

Freeman and Sachs. Electromagnetic Compatibility Design Guide. Sachs/Freeman Assoc. Inc., 1981.

IEEE Transactions On Broadcasting. Vol. BC-25, No 1, March 1979.

Lightning Protection Code 1983, NFPA 78.

Schure, Alexander. Electrostatics, New York: John F. Rider, June 1958.

Towne. Lightning Arrester Grounds. G.E. Review, 1932.

Ufer, H.G. "Investigation and Testing of Footing Type Grounding Electrodes for Electrical Installations" IEEE Transactions Paper #63-1505, Power Apparatus Systems Vol. 83 pp 1042-1048: Oct. 1964.

Uman, Martin A. "All About Lightning" and "Lightning", New York: Dover Publications, 1986, 1984.

Viemeister, Peter E. The Lightning Book. Cambridge: The MIT Press, April 1972.

Weiner, Paul. "A Comparison of Concrete Encased Grounding Electrodes to Driven Ground Rods". IEEE I&CPS Conference. May 1969.

Military Handbook 419A, Grounding, Bonding, and Shielding for Electronic Equipments and Facilities, December 1987.