

Amateur Radio Station Grounding and Lightning Protection



May 4th 2004, Independence, Mo, during a severe thunderstorm Photo by Mark Coldren
<http://www.publicdomainpictures.net/view-image.php?image=685&picture=lightning-strike>

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Amateur Radio Station Grounding and Lightning Protection

Preface

Grounding and lightning protection are critical to the safe and legal operation of an Amateur Radio station. Safety from the human, dwelling, and equipment aspects; legal from the city or regulatory codes, ordinances and laws. This simple sounding topic is quite complex in theory and practice, fraught with misunderstandings, legal liability issues and confusing regulatory codes.

These topics, however, do not lack for publications, documents, studies or opinions. The purpose of this (yet another) document is to provide the technically savvy Amateur Radio Operator the ability to understand the critical need for lightning protection and grounding basics.

I find much of the published material is too little or too much theory for the average Amateur Radio station. From a practical implementation standpoint the subject is so complex and burdened with minute (but critical) details that much of the material simply states - specific installations each require careful attention to detail, design and implementation. Even more frustrating to Amateur Radio operators is the lack of support from distributors or manufacturers - probably due to legal liability concerns. The common response is "we are not grounding experts and so refer to EIA/TIA222 (for tower erection and grounding) or the NEC/UL standards". The better, but sales biased, information is from protection equipment manufacturers.

This document is my attempt to first; present sufficient theory for an Amateur Radio operator to understand the detailed analysis necessary for proper grounding and protection, and secondly present sufficient material and examples to allow implementation of that theory. Recommendations are based on the obscure codes and standards - at least seemingly so to Amateurs - without a bias to any particular products or manufacturers. Also, practical and common sense approaches are referenced from the Amateur Radio community, that have established credibility.

This document supercedes "Lightning and Amateur Radio" that was distributed in 1989. Both documents were done originally for a Longview East Texas Amateur Radio club program. Preparing for a repeat presentation in 2011, I updated the material and decided that others might benefit from this hand-out also, so I published it on my web site.

This document is available in PDF format, www.bwcelectronics.com/articles/WP30A190.pdf, with reference hyperlinks enabled.

Disclaimer

The use of this document is for educational purposes only. While this document is based on information from authoritative sources, it still is my interpretation thereof and not a legal document for the construction, design, operation or installation of any system for which local or federal codes or laws apply.

It is the individual user's responsibility to ensure lightning protection and/or Amateur Radio station installation complies with local regulatory codes and laws.

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Amateur Radio Station Grounding and Lightning Protection

Introduction

This document is intended as an introduction to Amateur Radio Station grounding and lightning protection. The reference material quoted is from listing agencies and recognized researchers. While this subject appears simple, it is actually quite complex and requires a dedicated effort to understand and implement properly. Hopefully this document will simplify the subject's complexities and provide a basic understanding of grounding and lightning protection, while also providing realistic approaches for the average Amateur Radio station.

Laws are in place that are based on NEC (National Electrical Code), UL (Underwriters Laboratories) and NFPA (National Fire Prevention Association) codes and standards, and often appear in local city codes. It is the reader's responsibility to ensure all such legal requirements are satisfied by their installation. This document is offered as an introduction and guide to assist one in understanding and implementing the requirements of local codes and good engineering practices.

This document's title begins with "Grounding" but the text begins with a description of lightning. As with any engineering problem, defining the problem to be solved is the first step and while grounding must satisfy other requirements, lightning protection may be the most complex aspect. Certainly, the lightning phenomenon is a complex subject in its' own right and one under continual scientific study. A description of lightning is presented to familiarize the reader with the phenomenon and define the problem of lightning protection grounding.

Next, the "myth" of "ground" is explored. While earth ground does indeed exist, so do our misunderstandings of it. In electronics, ground is considered to be a common point, a point of zero potential and an infinite sink of electrons. In reality, most points we consider "grounded" are far from this perfect state. Earth ground is described in the context of lightning protection, safety and operational performance. Included are descriptions of "bonding" and galvanic isolation which are critical to effective "grounding". Also addressed are regulatory and agency grounding requirements.

Lastly, practical grounding methods are presented that are based on the foregoing considerations. In the context of a practical approach, risk management for Amateur Radio Station lightning protection is explored. Safety ground implementation, meeting regulatory codes and operational performance are also discussed. Pragmatic approach does NOT imply a haphazard or careless approach, but rather one that emphasizes details and options for protection and performance.

The appendices support and expand on the text. I suggest the references be studied for a more in depth understanding of this topic, even though some of the material can become somewhat overwhelming. Point-in-case Mil standard MIL-HDBK-419A volumes 1 and 2 are exceptional for factual, engineering based information but total some 1200 pages^F.

Note the use of alphanumeric superscripts throughout the text. Numeric superscripts refer to "References" included at the end of the document. Alpha superscripts refer to "Appendices" also located at the end of the document.

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Description of Lightning

Lightning overview

“All creatures on the surface of the earth have experienced lightning”, I don’t remember where I read this, but how true.

In order to design and implement lightning protection and grounding systems, we need to first define the threat. For that definition, let us start with an overview of the phenomenon and then try to model it for the sake of our design effort.

In perspective, lightning is not a common killer even though it is one of weather’s more frightening events. For example, in a single year (2007) the NHTSA¹ estimated 41,059 Americans died in automobile crashes with another 2.5 million injured.

Lightning on the other hand averages a yearly death rate of 73 Americans, according to NOAA² records for the 30 years prior to and including 2009, with another few hundred injuries. Now, before you decide to walk rather than drive, consider some lightning characteristics and effects. Table 1 statistics are from NOAA and other published sources. My research produced some conflicting information, in which cases I use the NOAA data. Collection of lightning data is not an easy task but technology, especially satellite monitoring, is improving the world wide data base.



Figure 1. Aug 23, 2003 - Toronto thunderstorm taken by John R. Southern from Toronto, Ontario, Canada

Table 1. Lightning Characteristics and Effects*

Average US yearly lightning strikes	22,000,000
Number of yearly US insurance claims filled for lightning damage	307,000
Estimated yearly US lightning damage cost	\$330,000,000
Continuous worldwide lightning strikes	44 strikes per second
Lightning ionization channel temperature	15,000 to 30,000 °C (About 3 times the surface temperature of the sun)
Average peak current	25,000 Amps
Average strokes per flash	4
Average channel blast wave energy	Equivalent to 200 pounds of TNT

* Based on data from: NOAA and [Lightning and Lightning Protection](#), Hart and Malone

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Formation of lightning

Lightning occurs during nimbostratus clouds in snow storms, dust storms, nuclear explosions and volcanic eruptions.³ For the purpose of the analysis presented here, only thunder storm lightning is pursued. Figure 2 shows schematically the charge centers in typical cumulonimbus clouds that are responsible for most cloud to ground lightning events. Over the years, conflicting theories have been accepted regarding how these charge centers develop. Recent advances continue to expand the scientific community's understanding, but

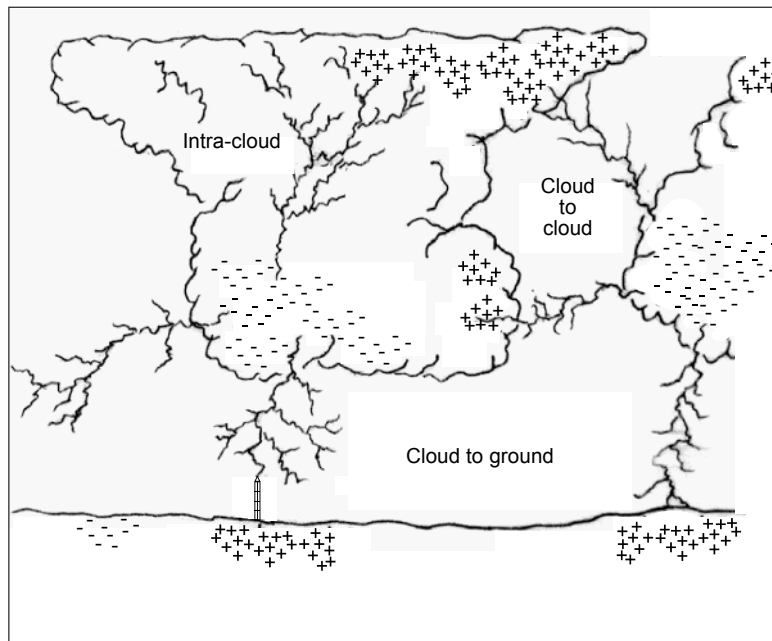


Figure 2. Schematic representation of cumulonimbus clouds with typical location of charge centers. Note, the inter-cloud lightning event is more common than cloud to ground lightning.

these theories are beyond the scope of this document - the referenced material will provide more detailed descriptions for those interested.

For our purposes it is known clouds do become charged and typically take on the form of Figure 2. Normally the lower portion of a storm cloud will take on a negative charge (excess electrons) while the upper portion will lose electrons and accumulate a positive charge of ions. The actual charge center distribution is not really so clear cut however, as oppositely charged pockets are known to form within both regions of the cloud to some extent. Also, as the storm reaches the dissipative stage, the charge centers may reverse as the charge equalization process concludes.

Common cloud to ground lightning results from the movement of electrons from the cloud to earth and is the basis for almost all lightning models. Measurements are less available for "positive lightning" with electron movement ground to cloud. Some data suggest "positive lightning" is particularly violent and can strike 25 miles ahead of an approaching storm reaching from the anvil to ground.

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The lightning flash

About half of observed lightning flashes produce 2 to 4 strikes, these pulses of current occur a few milliseconds apart and are responsible for charge equalization between cloud and earth. While scientist continue to study and theorize the exact process, we know a flash starts when the atmosphere around a charge pocket begins to ionize, that is to become charged due to the charge center's intense electric field.

This pilot streamer is a charged column that takes on almost the same potential as the charge center from which it originates. Although it is a simplification, let us consider this to be a downward moving column (actually many leaders may form to produce a multi-forked display). Once the process starts, the ionization channel travels at about 100 mph for 100 to 150 feet. Once this forms another more intense discharge occurs lowering even more negative charge into the step leader thus triggering another step to form.

The exact path an ionization channel takes is uncertain and numerous changes in direction are common giving lightning the familiar jagged appearance. The ground has no influence on this process until the last few steps form just above the earth's surface. Older theories have been updated and it is now believed that structures less than 150 feet above average terrain do **NOT trigger** lightning. However, a structure above the average terrain **will attract** a forming channel whose last prior step is within 150 feet. This provides an area of protection once referred to as "the cone of protection". More recently the right angle cone has been replaced with a rolling sphere.

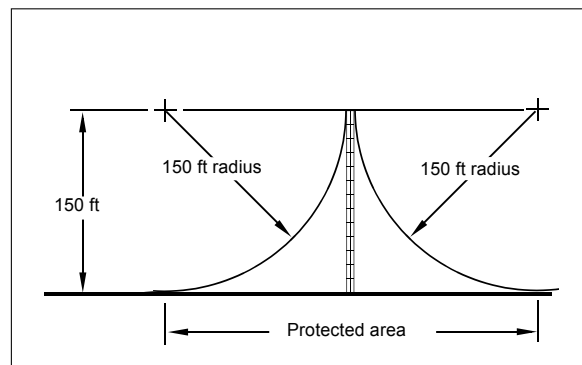


Figure 3. Rolling sphere area of protection. This definition of protection replaces the older right triangle method.

The UL "Application Guide - Lightning Protection"⁴ describes this as a 150 ft spherical radius. Figure 3 depicts this concept in a two dimensional drawing, but it actually applies around the entire horizontal radius of the structure. The result of this new concept is to reduce the amount of protection surrounding a tall object. **Warning** this "zone of protection" identifies the area that is thought to be safe from a direct lightning strike. It does **NOT** imply a safe area to take refuge. Lightning danger still exists in this area as will be explained further.

A tall pointed object (that is one with limited surface area) intensifies the electrostatic field of the earth, which is becoming positively charged as the developing channel approaches. It is suggested by researchers that at this point an earth terminal will send up a positive streamer to meet the approaching downward step leader and therefore will "attract" it if within 150 feet.

Once the earth bound streamer and the step leader meet, a complete conductive channel is formed from the cloud's charge center to earth. This initiates the lightning stroke, which is referred to as the "return stroke". Note: while electron current flow is from negative to positive, the electrical engineering community has

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Table 2. Lightning Characteristics - number of lightning flashes that have values exceeding those listed.*

Parameter	90%	50%	10%	Maximum Observed
Crest Current	2 to 8 kA	10 to 25 kA	40 to 60 kA	230 kA
di/dt	2 kA/ μ s	8 kA/ μ s	25 kA/ μ s	50 kA/ μ s
Single stroke duration	0.1 to 0.6 ms	0.5 to 3.0 ms	20 to 100 ms	400 ms
Interval between strokes	5 to 10 ms	30 to 40 ms	80 to 130 ms	500 ms
Crest rise time	0.3 to 2 μ s	1 to 4 μ s	5 to 7 μ s	10 μ s
Number of strokes in the flash	1 to 2	2 to 4	5 to 11	34

* Based on data from: [Lightning and Lightning Protection](#), Hart and Malone - newer data available, but this source is still representative and applicable.

always used “conventional current flow” in theoretical analysis and equations, therefore consistent with circuit theory the positive ground charge produces a returning current. Table 2 shows lightning flash’s range and characteristics. 90% of lightning flashes contain 1 or 2 strokes, whereas 10% contain 5 to 11. These multiple strokes, spaced a few milliseconds apart present a flickering appearance.

The lightning channel is composed of ionized gases which are converted to conductive plasma during the lightning flash. Plasma is a state of matter as are gases, solids and liquids. The conversion of the lightning channel to the plasma state increases its’ conductivity to almost infinity.⁵ The highly conductive lightning channel transfers tremendous charge as the channel’s temperature ranges from 15,000 to 30,000 °C or approximately 3 times the sun’s surface temperature. Researchers estimate “most of the energy dissipated during a lightning flash goes into the air with about 75% dissipated as heat”.³

These extreme temperatures cause a violent shock wave to propagate outward from the channel at a speed faster than sound, causing a nearby observer to hear a “crack” or “snap” almost simultaneously with the flash. Estimated energy in these shock waves is equivalent to 200 pounds of TNT. The shock wave becomes modified as it travels outward degenerating into and combining with the sound wave. The resulting sound is thunder. The many presentations of sound accompanying thunder are due to atmospheric and geographic reflections combined with the prolonged travel time of sound as it reaches the observer from further points along the channel.

Sound travels at approximately 333 meters per second at ground level (dependent upon air density and humidity), or about 1100 feet per second. When a lightning flash is seen, its’ distance from the observer can be estimated by measuring the time (in seconds) for the associated thunder to be heard. Dividing by 5 (5 seconds/mile) provides the approximate distance in miles.

Figure 4 shows a typical lightning flash containing four individual strokes. The basis for this figure is a study done for the FAA by Georgia Institute of Technology.⁶ An interesting aspect of this study is the finding that current can continue to flow during the time between strokes (many milliseconds). This adds a very low frequency component to the pulsing return stroke current.

The study goes on to explain that the continuing current flow between strokes is most likely to cause damage by melting or igniting solid materials. In contrast, the short-duration high-current peaks tend to tear or bend

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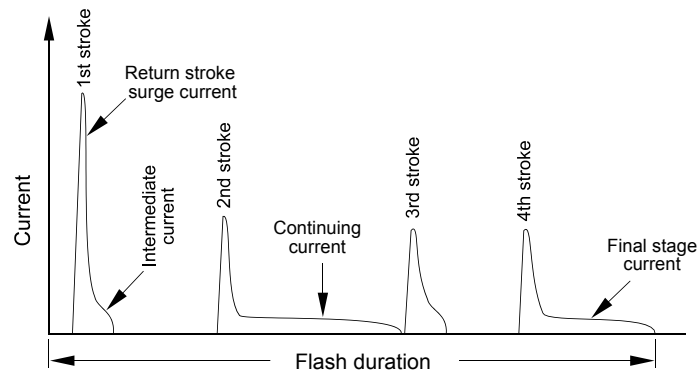


Figure 4. A lightning flash consisting of four individual strokes. Note the time duration is not to scale. Typically the total flash duration is 100's of milliseconds whereas the stroke durations are in microseconds.⁶

metal parts by the electromagnetic forces that develop in proportion to the square of the instantaneous current. In protection systems the need for mechanically strong bonding and conductor sizing is often necessary to withstand these magnetostrictive forces and high temperature melting potentials. Even so, highly conductive (and low inductance) materials survive much better than restive materials.

Restive materials tend to ignite when struck by lightning and high water concentration materials tend to explode due to the conversion of water to steam. Figure 5a is a good example where water turned to steam causing a violent explosion. This photo also shows a tree does **NOT** provide a good refuge from lightning, but rather is a dangerous place.

Lightning Model

The previously stated purpose of this document describing lightning first, was to define the grounding and lightning protection problem. But it seems that so far the description of lightning presents a phenomena of widely varying parameters unsuitable for an engineering analysis. In order to develop some consistency for protection products and methods, models have been developed. Models such as the ANSI/IEEE and Military Standards define the “expected” event parameters for aircraft, power lines, entry panels and earth terminals



Figure 5a. Materials containing water often explode when struck by lightning. This Eucalyptus tree photographed by C. Goodwin in 2006 in Walcha, NSW, Australia is a good example.



Figure 5b. Conductors sometimes do not survive a lightning strike either, as did not this section of RG-59. It was at the top of my 100 foot tower. The center conductor and shield were vaporized.

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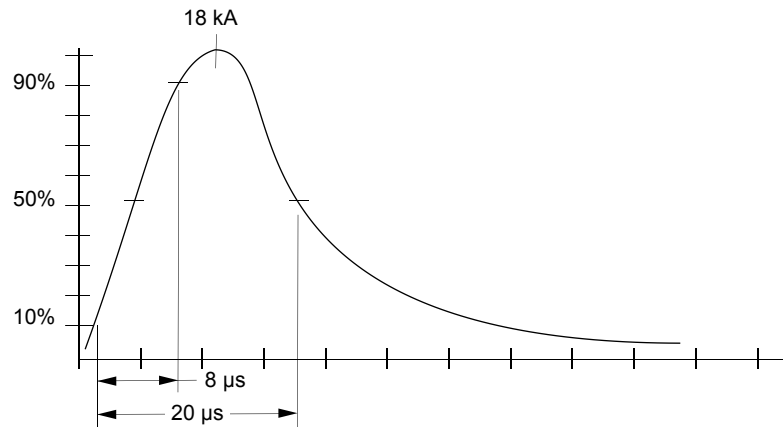


Figure 6. IEEE 8/20 waveform for the first of three pulses in this lightning model. The second and third pulses are approximately half the amplitude of the first. The 10% to 90% rate of rise is considered to be 2kA/μs. Note this is quite a simplification from the observed lightning events in Table 2. and Figure 3.

(towers and antennas). Understanding these models could be an entire course of its' own and beyond the scope of this document - see referenced documents for further study.⁷

The IEEE 8/20 model is commonly used in specifying lightning protection devices. Figure 6 shows the first of three strikes defined as a “typical” lightning flash. It is generally thought that this model is equal to or greater than 50% of lightning events. But, it should be remembered that the other half are more powerful than this model predicts.

The lightning channel itself can be treated as a transmission line and various rather complex analyses treat this subject, but for our purpose the above model will be treated as a constant current source - that is sufficient voltage is available that any resistance encountered is insignificant. Therefore a single earth bound object struck by the model pulse is subjected to an 18 kA current pulse which will either flow through the object to ground or on to other objects in parallel paths to ground.

We can now put the protection engineering problem in perspective. At this point let us see what happens to a copper wire extending from a perfect ground (imperfect ground discussed latter) to a height of 40 feet. For a wooden non-guyed pole with a single #4 copper down conductor, the reactive voltage drop from the top to ground is given by;

$$V = IR + L(di/dt), \text{ where} \tag{Eq. 1.}$$

- V = voltage from pole top to ground
- I = crest current (18kA)
- R = wire resistance (DC)
- L = wire inductance
- di/dt = pulse wave-front current rate of rise (A/s)

assuming the wooden pole is dry and non-conductive. For #4 copper wire 40 feet long the resistance, from a wire chart, is (40 feet) x (0.2485 mΩ/ft) = 0.00994 Ω.

The inductance is given by;

$$L = 0.00508l(2.303 \log 4l/d - 0.75) \mu\text{H}^8, \text{ where} \tag{Eq. 2.}$$

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l = length in inches
 d = diameter in inches

the permeability of copper is 1.00, for magnetic materials the inductance will be greater. For this example then the inductance is;

$$L = 0.00508 (40 \times 12)[2.303 \log (4 \times 40 \times 12)/0.2043 - 0.75] \mu\text{H},$$

or $L = 23.32 \mu\text{H}$.

This pole and down conductor is a common power line support that sometimes is used as an antenna support. So with our fictitious “perfect ground” the total voltage between the pole top and ground will be, per equation (1);

$$V = (18\text{kA})(0.00994 \Omega) + (23.32 \mu\text{H})(2\text{kA}/\mu\text{s}), \text{ or}$$
$$V = 169.2 + j46,640 \text{ volts.}$$

The first term of 169.2 volts is due to the DC wire resistance and is negligible compared to the inductive voltage of 46,640 volts. The primary purpose of this example is to show the high voltage developed across a “good” conductor during a lightning strike. Assuming an equal and continuous voltage gradient along the conductor, the unit length voltage is over 1000 volts per foot. Two connections to this wire spaced 12 inches apart will have over 1000 volts between them.

Emphasis is being placed on the wire’s inductive voltage as it leads into lightning protection and grounding principles. Those unfamiliar with these subjects probably think a #4 copper wire is a good conductor and sufficiently large for a “ground conductor”.

Inductively coupled lightning

Reference 6 explores inductively coupled lightning in considerable detail presenting equations for single loop coupling and geometric effects. This document will not attempt to explore inductive coupling to that depth, however, it must be at least mentioned. The NEC and UL codes and listing requirements specify lightning down conductors are to be spaced away from signal and power conductors and/or shielded from them with ferrous metal raceways. This spacing and shielding requirement is necessary because the lightning strike’s high di/dt produces a very strong electro-magnetic field that couples into nearby parallel conductors.

Depending upon many variables, it is possible for induced currents to damage power circuits and very possible to damage signaling and RF circuits. Induced currents from tower legs to parallel running feed-lines can easily damage coax. Bear in mind, this is magnetic coupling which can only be reduced effectively with ferrous shielding (copper or aluminum are ineffective). Also, one must be careful to reduce current flow in the shield to prevent it from becoming a radiator itself.

So what about a feed-line running down the tower leg? The tower acts like a transmission line even though one does not think of it as such. The propagation time of the tower and the coax are surely different - complicating the effort to reduce stress on the feed-line. My experience and the advice offered by respected lightning protection companies is to ground the coax at the very top and very bottom of the tower. The tower and coax are in parallel, with the tower’s larger surface providing the lower impedance path and therefore conducting the larger share of the strike current.

Figure 5b is a section of RG-59 that came from the top of my 100 foot tower. A lightning strike vaporized the center conductor and shield for several feet. The coax was grounded at the top of the tower, but my tower bottom disconnect (at the time) removed the ground connection. I am not sure if the bottom connection would have produced less damage or not, but the present modeling indicates it would have.

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Electro-statically coupled Lightning

Flash-over or side-flash are names applied to lightning leaving a conductive path and instead traveling through the air to a different conductor. Equation (1) and the example that follows, clearly show a lightning strike develops high voltages across conductors that are normally thought of as quite good. Poorer conductors develop extremely high voltages, resulting in side-flash where the lightning energy travels (or arcs) to another conductor in the vicinity.

A repeater, for which I was once responsible, was co-located with an EMS repeater and shared its' 300 foot tower. One late spring afternoon the tower took a direct lightning hit. The hard lines left the tower at the 8 foot level and passed through a concrete block wall into a hospital stairwell. I don't remember the actual feed-line protection scheme, I did not install it, but I do remember it was minimal. The EMS feed-line made a relatively sharp 90 degree bend - probably minimum bend radius - whereas the club's feed-line continued straight across the room.

The right angle bend hard-line was blown apart at the bend and a side flash traveled several feet across the stairwell and blew a hole in the facing concrete block wall. Our feed-line survived as did the repeater - well except for the output transistors. The nice thing about VHF and UHF transistors, they are very low resistance *and* inductance so they make a really good short for lightning, saving the rest of the circuitry.

By the way, the EMS repeater was still smoking when I arrived - the output transistors did not save it and I am quite sure it would have actually caught fire if not for the fact it contained fire retardant materials. So the high inductance sacrificial feed-line bend did not stop enough energy to help the repeater survive - so much for drip loops. To be completely honest, the EMS antenna was above ours and certainly took the brunt of the strike current.

Air terminal

A lesson to be learned from this and in keeping with the UL "*Application Guide - Lightning Protection*" an air terminal should be bonded to the tower that exceeds all tower mounted antenna systems by sufficient height (see Figure 3) to intercept incoming lightning strikes. The damage to the coax shown in Figure 5b was connected to a tower top antenna without the protection of an air terminal. The antenna and feed-line below this level were undamaged.

Hopefully it is clear now, as we prepare to consider actual grounding and protection methods, that lightning strikes pose a significant challenge. No not loose sight of the fact the model used to specify many surge protectors only represents half of the known lightning event severity.

Obviously two major challenges are becoming apparent. First, since earth is not a perfect conductor, how effective is it as a ground and what electro-chemical processes occur during a lightning strike. Second, how can equipment be protected from lightning when such a short, large diameter wire is ineffective as a ground conductor.

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Description of Ground

The myth of ground

Perhaps I make a bit of an overstatement calling “ground” a myth, but like anyone with a cause, a bit of exaggeration is acceptable to make your point, right? Well right or not, the concept of ground in terms of electrical properties is more complex than one may realize.

A connection to “ground” is more correctly “defined as the process by which an electrical connection is made to the earth”.⁶ Ground rods, buried wires, metallic pipes and other conductors in contact with the earth are termed the “earth electrode”. The purpose of this system is to;

- a. dissipate lightning stroke energy in a manor that protects the surrounding area,
- b. provide a low impedance connection back to the AC power mains ground or neutral to reliably clear fault conditions,
- c. reduce the step potential gradient to safe levels,
- d. form a natural sink for atmospheric and radiated noise,
- e. provide an electrical antenna counterpoise.

The last purpose listed delves into antenna systems and theory - a subject within itself that will not be covered in this document. Some of the characteristics that make a good ground, as will be defined here, also facilitate antenna grounding. Other antenna system grounding requirements may however pose special criteria not covered by this document.

A little trivia before the mental task of understanding earth ground. In college, my physics and mechanical engineering texts used the ground symbol of Figure 7a to represent a fixed earth attachment. However, the IEA and other agency that decide such things use Figure 7b to represent earth ground and consider Figure 7a to represent a chassis connection. Figure 7c has come into widespread use representing the various common points in complex electronics that are isolated from one another except for a single point. However, engineering trade journals use Figure 7b as the symbol for common points regardless of earth connection. Collins Radio/Rockwell also used 7b for all circuit commons, as well as for earth ground, as do I if the circuit will continue to work properly with those points connected to an earth terminal.

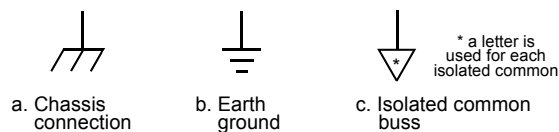


Figure 7. Ground symbols and industry standard usages. However, engineering trade journals and some well respected electronics companies use b. for all circuit commons regardless of an earth connection.

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The earth as ground

Even though earth ground is not a myth, it also is not a perfect conductor, so what is it really? Well, this is another subject all unto itself, but we need some basic understanding of earth for the purpose of this document.

To start with, let us consider earth ground as an infinitely large resistor, with geographic location as a primary factor determining soil resistivity. It is not hard to imagine that soil resistivity (or conversely soil conductivity) is much different from the marshy swamp lands to the dry sandy desert or high rocky mountains.

Soil resistivity also varies with water content and temperature. Water content would surprise hardly anyone, but temperature may not normally be thought of as a factor. Soil resistivity increases as temperature drops, say from 40 °C to near freezing, at which point it increases rapidly as temperature goes through 0 °C - similar to the heat of latency. Once temperature goes below 0 °C the resistivity continues to increase inversely but less dramatically with temperature. Therefore, the ground electrode should be below the local frost line to minimize this undesirable temperature effect.

Another somewhat obscure factor is soil drainage. A loose sandy soil that drains fast is normally more resistive than one might think. This is due to the fact rapid water movement through soil leaches away minerals that otherwise would promote ionization and improve conductivity.

Typical soil resistivity is shown in Table 3 for uniform homogeneous soil. For layered or non-uniform soils it becomes more difficult to predict the effective resistance of a ground electrode system. If the top soil is loam or gumbo and the lower layers are sandy or rocky the ground current will concentrate in the upper layers, reducing the overall effectiveness and increasing a vertically driven ground rod's resistance to ground.

Table 3. Soil resistivity for typical uniform mediums.⁶

Medium	Resistivity (Ohm-cm) ^A		
	Minimum	Nominal	Maximum
Rocky soil	10 ³	5 x 10 ⁴	10 ⁵
Dry sandy	3 x 10 ⁴	5 x 10 ⁴	5 x 10 ⁵
Clay, shale, gumbo, loam	3 x 10 ²	4 x 10 ³	2 x 10 ⁴
Gravel, sand stones	5 x 10 ⁴	10 ⁵	10 ⁶

In poor sub-soils cases, horizontal buried ground conductors can be used to establish a lower resistance contact to earth than may be possible with driven rods.

In uniform soil, the resistance of a driven ground rod decreases as it is driven deeper, but not linearly. Figure 8 shows the typical resistance to ground for a driven rod vs depth. As can be seen from the figure, resistance drops rapidly for the first couple of feet the rod is driven, after which it continues to drop with increasing depth but in a slower and non-linear fashion. After about six feet of depth the resistance change with depth becomes more linear again, but actually drops very slowly. The common 8 foot ground rod is about optimum for a single earth contact. Decreasing earth electrode resistance further is accomplished most effectively by using two or more rods in parallel.

Amateur Radio Station Grounding and Lightning Protection

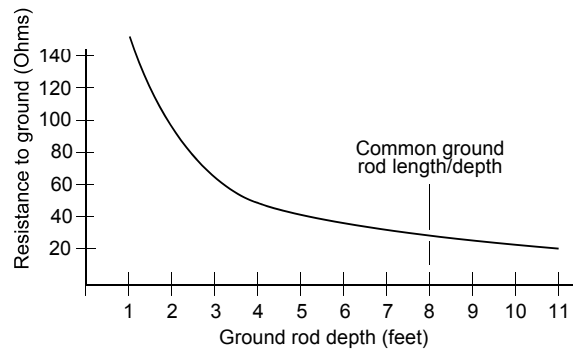


Figure 8. Effect of ground rod length on earth terminal resistance. Data represents and vertically driven rod in uniform soil and moisture content.

But, an additional requirement must be met in order to realize lower earth contact resistance. Figure 9 depicts the current distribution in the soil surrounding a vertically driven ground electrode. The current density is highest near the rod and drops nonlinearly in a radial pattern from there. The area defined by πx^2 in Figure 9 is considered the rod's area of influence. Rods must be spaced a distance of $2x$ apart to prevent interaction of their fields.

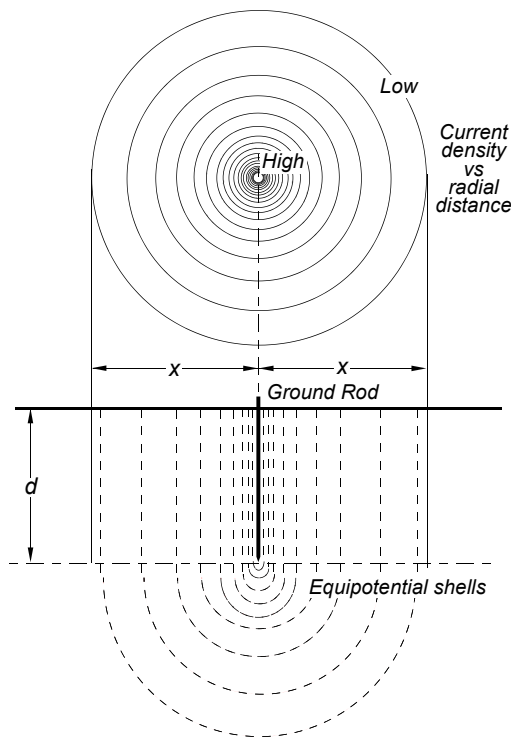


Figure 9. Current density surrounding a vertically driven ground rod. The circular distribution at the top is looking down on the rod and shows the current distribution as it spreads radially from the rod. The bottom view is looking horizontally through earth at the current distribution with respect to depth.

Therefore, to effectively lower a ground system's resistance, using 8 foot ground rods, requires they be spaced 16 feet apart in a matrix pattern. Interconnecting below the surface with bare wire will further reduce the total system resistance. Burying the top of the ground rod improves the ground electrode performance, but requires the use of direct-bury clamps or welded connection between the ground rod and the ground lead.

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It also is possible to reduce the step potential, that is the incremental ground voltage that develops when lightning is conducted to ground, by burying the top of the ground rod 18 inches or more. However, to reduce the step voltage, the ground wire must have high voltage insulation, which increases the inductance of the ground wire.

Measuring and effecting ground resistivity

Reference 6 describes ground resistance measurement techniques. While these techniques are beyond the scope of this document, a brief overview is necessary. The “Fall-of-Potential” method for measuring ground resistance is accomplished using three ground electrodes. The three are spaced apart sufficiently so that at equidistance from one another there is no overlapping sphere of influences. A known AC current (non-integer multiple of the local AC power frequency) is passed through the outer most rods while the third is moved, in a straight line, along the ground between them. The resultant voltage readings are plotted vs position and a voltage level will be found that changes little or not at all with position. This voltage divided by the known injection current equals the effective ground resistance.

Local ground resistivity varies so widely that geographical mapping may not prove exact at any specific location, even though it does provide a reasonable estimate. Techniques for reducing ground resistance use chemical seeding, such as magnesium sulphate, $MgSO_4$ (Epsom salt), or similar chemicals; the use of which increases electrolysis and therefore corrosion problems. Techniques for lowering ground resistance require additional study and information from other sources. Pursuing ground resistivity and effectiveness to the state of the art could cost the average Amateur Radio Operator more than is spent on the actual station equipment. Since that is not the intent here, it is left to the reader to pursue this topic further if need be.

Step potential

Before we consider ground electrode connections, let us look at one more critical aspect of the ground electrode. Refer to Figure 10a. where the step potential is shown around a single ground rod in the presence of an 18 kA lightning strike. A typical ground rod should have a resistance less than 25Ω , but when large amounts of current are dumped into the soil, the area will become less resistive as suggested in Figure 10a where the surge resistance = 10Ω .

Even so, the top of the rod will rise to 180,000 volts and the charge distribution into the ground will cause a step potential that decays as it moves radially from the ground rod. This nonlinear charge distribution will cause the ground surface to develop a voltage gradient that also extends outward radially. Figure 10a shows that a few feet away from the rod the voltage gradient is 10,000 volts per foot. Here again is proof that refuge should not be taken near an object likely to be struck by lightning. As well, this defines another protection factor for electronic equipment located in the vicinity.

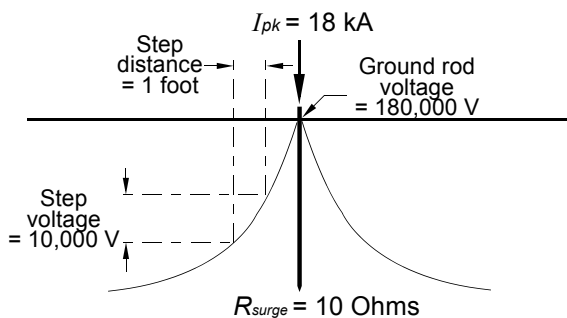


Figure 10a. Step potential due to a ground electrode conducting a 18 kA lightning pulse to ground.



Figure 10b. Soil blown out around the top of a totally buried ground rod due to a lightning strike.

Amateur Radio Station Grounding and Lightning Protection

Ground conductor bonding and galvanic corrosion

Connections to ground electrodes involves permanent or semi-permanent bonding. Welded or brazed connections are preferred, but where impractical a mechanical clamp and bolt is used. Strong low resistance connections are necessary to withstand the electro-mechanical and electro-thermal forces of high current lightning strikes. Solder should not be used because of its' low melting temperature, higher resistance and tendency to degrade with exposure to naturally occurring elements. Bolt and clamp sets should be agency approved for above or below ground use (as required) and installed carefully per the engineering specifications. This includes surface cleanliness and preparation, proper mating of contact surfaces, bolt torque and protection from corrosion.

Because "grounding" is an electrochemical process, it promotes metal corrosion problems. Refer to the galvanic series, Table 4 and reference 6 to study this further, but basically it is important to minimize connections involving dissimilar metals, such as zinc and copper. The less noble metal will, in the presence of a solution (such as contaminated rain water), go into solution eroding the anode. Special clamps are available for interconnecting dissimilar metals when it must be done. Listed clamps should specify the metal types with which they can be used. Also, sealing a connection from moisture penetration will greatly reduce the corrosion problem.

A common galvanic problem occurs at the tower base and guy anchors. Commonly the tower, guy lines and anchors are galvanized (zinc) plated steel. In the presence of a normal atmosphere, the galvanized coating protects the steel because it is the less noble metal and so erodes faster than the steel. But, when a copper conductor and ground rod are connected to these structures the galvanic reaction shifts into high gear with severe erosion of the zinc and then steel - copper is more noble than both zinc and iron.

For improved lightning protection a tower's guy lines should be grounded with a conductor that bypasses the turnbuckles. However, tower collapses have been reported where the failure of a guy anchor was caused by galvanic corrosion. Investigation into the premature failure revealed the corrosion was accelerated by the copper/zinc/iron electrolysis produced by the copper ground rod and conductors.

EIA/TIA222 Standard for tower installation requires all grounding material to be galvanized steel. The use of copper wire, rods or hardware is DISALLOWED.

Probably the simplest approach for the Amateur Radio station is to use galvanized cable clamped above the guy line turnbuckles, that is then bonded to a ground rod. Conversion to copper can be done by connecting the galvanized cable to copper wire above ground (above the surface water level) which then bonds properly to a copper ground rod.

No doubt, serious study and liability avoidance drove the EIA/TIA standard that is based on the expertise of those in the business.

Table 4. Galvanic series for selected metals in flowing seawater.⁶ Note this differs somewhat from the EMF series used in chemistry.

Anodic end (less noble corroding end)
Magnesium
Zinc
Aluminum
Cadmium
Iron
Lead
Tin
Nickel
Copper
Silver
Graphite
Gold
Cathodic end (most noble non-corroding end)

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Not to dispute the industry standard, but in my limited experience, I find galvanized steel rusts within a few years - when in ground contact - even in the absence of electrolysis. I have not found any corrosion problems with copper ground rods at the base of my towers. Another observation is the large number of galvanized guy lines and guy anchors used on power lines that also have copper down conductors on the associated poles.

I have not tried this, but I think I may install galvanized 2" strips to each tower leg and then connect them to 2" copper straps that bond to copper ground rods. This puts the first galvanic corrosion danger where it is easily inspected as it consumes a sacrificial and replaceable strap. Sealing the joint should make this fairly maintenance free. This still does not address the buried zinc to copper issue however.

Figure 11 is one of the towers at W8JI. This installation uses all copper, bonded with high temperature silver solder (not plumbing solder). Note the use of straps and a copper bonding wire around the base. I would burry this for slight reduction in impedance, however, the earth will be so ion saturated during a lightning strike it will not make much difference.



Figure 11. W8JI tower ground. Note the copper straps to pad corner ground rods and copper wire bonding the rods together. See www.w8ji.com for this and other practical installation guidelines.

While I am talking about methods that do not meet standards requirements, I have also used 10 foot rigid copper water pipe for ground rods. I cut the "driven end" with two orthogonal saw cuts along the axis. I then bend these in slightly and tilt the leading edge out to form a mini-augur. I then clamp a water hose on the top end and use the water pressure to augur the pipe into the ground. This method is not allowed by code - which requires a **driven** rod. The code so states because a driven rod is in closer contact with the soil. Whereas, the water pipe method displaces soil as the water flushes the entry. But in reasonably good soil I have found a little patience for the rod to "grow" or the soil to re-form around it, produces a good earth terminal. I have several of these that have been in the ground for over twenty five years with no sign of deterioration. On the other hand I have seen aging copper clad steel rods shed their copper cladding.

Notice W8JI has copper pipe installed at the tower base shown in Figure 11. I do not know if these are driven or augured into the soil.

Bonding individual ground terminals

Connecting otherwise isolated ground terminals together is **imperative** and required by the NEC, code section 810-21(j). Residential power, signal and RF lines are required to be grounded at the entry point to the structure. This normally is accomplished by connecting the phone and cable TV grounds to the AC power ground.

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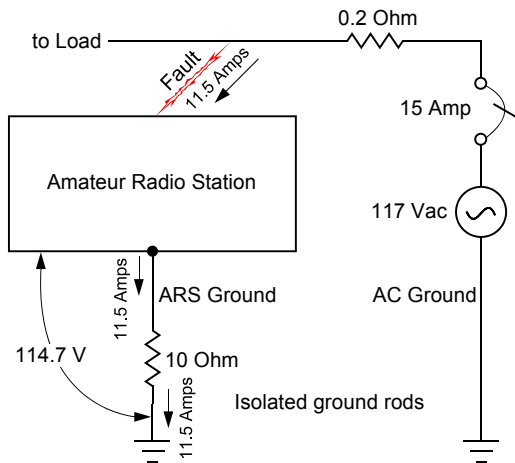


Figure 12. AC power line fault condition with an isolated ARS ground system. Note equipment rises to almost 115 Vac with respect to power line ground. This dangerous fault condition will last indefinitely, dissipating in excess of 1300 Watts.

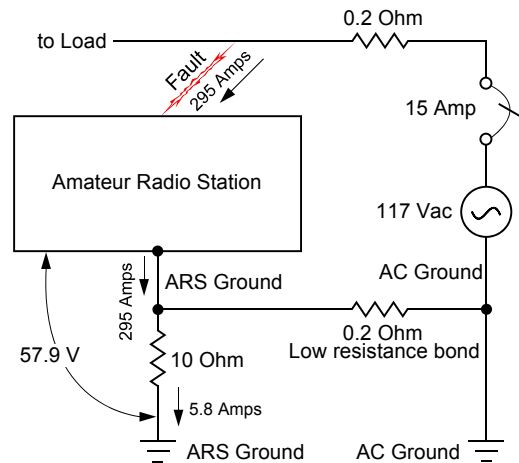


Figure 13. AC power line fault condition with a properly bonded ARS ground system. Note the fault condition will only last a few milliseconds - until the breaker trips.

The purpose of bonding is to;

- protect equipment and personnel from lightning discharge hazards,
- establish fault current return paths (safety ground),
- provide stable signal current paths,
- minimize RF potentials on enclosures and housings,
- provide static charge dissipation.

An Amateur Radio station (ARS) is also required to have antenna and station grounds bonded to the incoming AC power ground (NEC 250-81. **Grounding Electrode System**). It is important that an AC power line fault has a very low resistance path back to the AC power line ground. For 117 VAC line fed from a 15 Amp breaker, the ground resistance should be less than 5 Ohms, thus ensuring sufficient current to quickly trip the breaker. Actually the bonded ground resistance should be more like a few tenths of one Ohm.

Figures 12 and 13 show why all grounds should be bonded to the AC power line ground, otherwise an equipment and personnel hazard occurs during an AC power fault condition. Do not be misled by the 11.5 Amp fault current in the isolated ground condition. The ARS equipment chassis will rise to almost 115 Vac and stay there indefinitely. Not only is this an equipment and personnel hazard, but it is dumping 1300 Watts into the ground, creating another hazard around the ground rod. With properly bonded grounds of Figure 13, the fault current is 295 Amps, but it lasts only a few milliseconds until the breaker trips. However, this brings to mind another point. AC fault ground wires, bonds and connections must be able to handle the same, or higher, levels of current as the AC line they are associated with.

As for other aspects of grounding, such as ground loops, the bonded grounds will have a lower ground loop voltage, for a given leakage current, than the isolated grounds. In some cases a bonded ground system may even be used for a signal return path, but not always. If ground loop problems arise they should be solved using balanced lines isolated from ground, but not by isolating ground connections.

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As a side note, I use 0.001 μ F, 1kV RFI bypass capacitors from either side of the AC line to the third wire safety ground (and chassis) in my designs. I know similar AC line bypassing is done in commercial products also. When a “cheater” or improperly wired convenience outlet is used to power such equipment, a voltage divider is established between the 117 Vac line and the return, putting the chassis at approximately 60 Vac. The results are similar to the circa 1950 equipment which had electrostatic coupling from the power transformer primary to the chassis (no third wire grounds used then) giving you a tingling sensation. However, today’s solid state equipment does not do well with “tingling sensations”, not mention the personnel hazard.

For static discharge and lightning protection, incidental conductors in and around the Amateur Radio station should be bonded to the common ground system and connected to the AC power ground. Even though the NEC specifies this to be done, it may fall short on the methods needed to provide optimum lightning protection. Methods that will satisfy both requirements will be presented in “practical grounding methods”.

W8JI has an excellent explanation on his web site of why all grounds must be bonded together and to the AC power ground; *“Radios that operate from power mains stand a chance of having the power line accidentally fault to the chassis. Worse yet, a linear amplifier with high voltage power transformer might develop a secondary to primary short, and that short might cause the chassis to rise to peak secondary voltage plus peak primary voltage! An amplifier with a 2400 volt RMS transformer operating on 120 or 240 volt USA power mains might have a chassis voltage as high as 3600 volts from a secondary to primary failure inside the transformer.*

Any advice saying our equipment doesn't require a safety ground connection is very bad advice. All power mains operated amateur radio gear, especially devices with HV inside, requires a safety ground.

The safety ground does not really need a ground rod, it actually only requires a connection back to the power mains service entrance ground though a very heavy conductor. It may be desirable to augment this safety ground connection with a few extra earthing ground rods. As with lightning grounds, any special safety ground must bond to the utility entrance ground. A good lightning entrance ground also makes a good safety ground, provided it is brought from the entrance point panel to the operating area where equipment is bonded into the ground. Do not go outside beyond the entrance panel barrier with this ground lead.

Equipment with properly installed safety ground plugs, provided wiring and plugs are up to current codes, do not require a special safety ground connection. They are grounded through house wiring.”

Amateur Radio Station Grounding and Lightning Protection

Practical grounding methods

Improper grounding can cause more damage than none. So then, let us see what practical lightning protection and grounding methods an Amateur Radio operator can employ without falling into this trap. Protection and grounding is not black and white, but rather occurs in degrees providing more or less protection in proportion to the extensiveness of the system - as long as no serious mistakes are made. Details are critical. A minute oversight can be catastrophic. The following material is intended to encourage thorough and complete evaluation of ARS grounding and lightning protection systems.

Other cautions;

- a. the preceding material in this document is a prerequisite for what is to follow,
- b. the “practical grounding methods” is not a step-by-step how-to guide,
- c. local codes are not covered per se - the local building inspector can provide,
- d. the reader should understand the theory and be technically capable of proper installation techniques or enlist the assistance of someone who is.

Single point ground

As already covered, all grounds must be bonded together, including to the AC power ground. I have talked to Amateur Radio operators who are uncomfortable with this concept, but it is not only required by the NEC but vitally important. However, how this is done is an important aspect not well covered in the NEC. The most important aspect of grounding an ARS is the **single point ground**.

While working for Collins Transmission Systems Division, I was somewhat involved in MCI’s lightning protection efforts for their transcontinental MW systems. We had an unacceptable module failure rate caused by lightning strikes to MW towers scattered across the plains. Some of these sites had in excess of 10,000 volts between two adjacent equipment racks - both of which were “grounded” properly according to the current facility design guides. In such cases, the tasks of grounding is considerable more complex than an ARS, but even so it was basically solved, though with more resources than most ARS operators have.

The **single point ground** must be a part of any ARS lightning protection plan that is to succeed. The concept is as simple as a bird setting on a 33,000 volt power line. The bird is at 33,000 volts with respect to ground, but he is protected because he is at 0 volts with respect to his roost. **Every** single metallic object in the ARS must be connected to a single ground point that then connects to an earth terminal. The plan is to have that earth terminal voltage as low as practical, but more importantly all metal objects in the ARS must be at 0 volts from one to the other, even if the entire ARS rises to 10,000 volts above distant ground.

Here is the first, and probably the most serious, mistake that will validate the worse than none comment. If any item whatsoever is not included in the single point ground it may well be near the distant ground potential allowing perhaps 10,000 volts between it and the ARS equipment. An arc or inadvertent contact with the ARS equipment is then disastrous.

Figure 14 is a block diagram of a properly grounded ARS, including the NEC required ground bond to the AC power line ground. Close attention must be paid to **ALL** conductors in and within close proximity to the ARS. If a single conductor enters or leaves the ARS without surge protection to, or direct connection to, the common ground then not only is the protection compromised but most likely lightning damage will actually be worsened.

If an uninterruptible power supply (UPS) is used for the computer, it may be preferable to use it as the AC surge protection also. The “back-up” output powers the computer and the “surge protected” output powers

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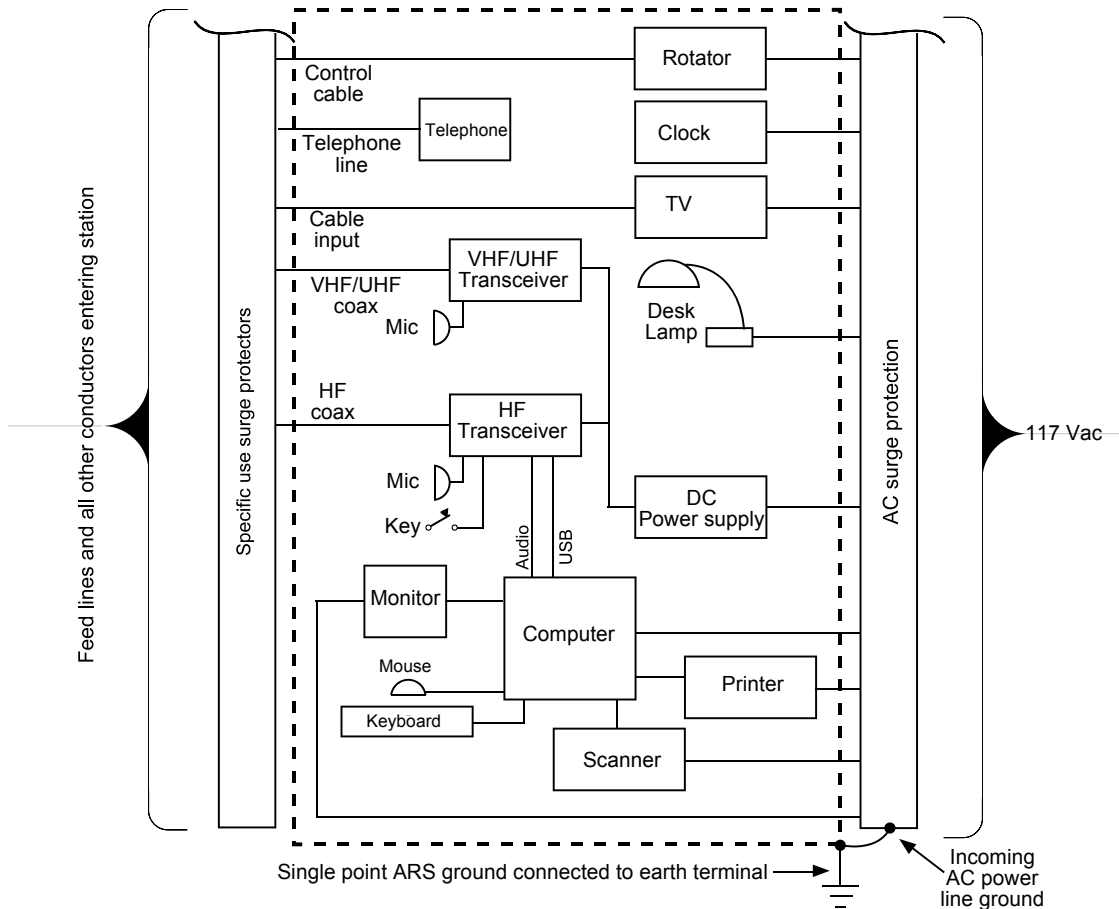


Figure 14. Block diagram of a properly grounded ARS. All ground connections terminate at a single point - preferably on a copper or aluminum plate - which then connects to a dedicated earth terminal that also is bonded to the AC power line entry ground.

the ARS. No surge protectors should be used beyond this point. I strongly recommend surge protection, but do not offer product specific advice. Research appropriate to each individual's situation should be done to find a specific product.

The UPS load side (outputs) should connect to the single point ground - NOT the NEMA 5-15P input power cord - which should only connect to the incoming AC power. The UPS has MOV or similar surge protection devices on the incoming power line that connect to the third wire ground. If a lightning induced voltage transient is clamped, a large pulse of current flows in the third wire ground. Considerable voltage may be developed across the power cord ground wire that does not need to be imposed on the ARS equipment.

Figure 15 shows a simple MOV^C type surge protector that has a 5 foot NEMA 5-15P, 16 AWG power cord. The ground wire has about 5 μH of inductance which in the presence of a 200 A/ μs pulse will develop 1000 V between the input plug and the output socket. If the input plug ground is connected to the ARS single point ground and the ARS equipment is plugged into the output socket, there is 1000 V imposed on the equipment. If you have experienced near-by lightning strikes you no doubt have heard convenience outlets arc. We do not want that to occur in the ARS.

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Done properly, the output socket ground is connected to the ARS single point ground providing a zero volt potential from equipment to ground. The power line cord, socket and house wiring will be 1000 volts or more above the ARS equipment and single point ground. Once again proof it is imperative the ARS equipment be totally isolated from conductors other than the ones entering through the single point ground plate. As can be seen from this example, the devil is in the details. It is critical for the protection of the ARS that small details are thought through carefully.

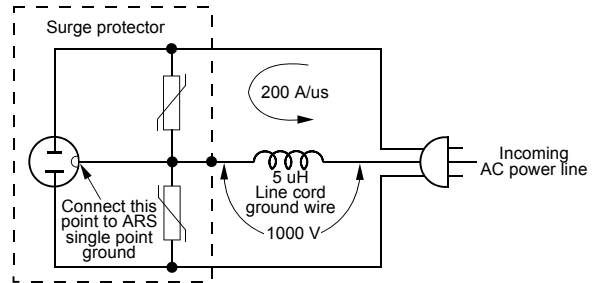


Figure 15. Connect the surge protector's output ground to the ARS single point ground.

This example also shows AC surge protectors that have no, or minimum leads, are preferable to “surge protected outlet” strips commonly sold at the home improvement stores. I am also not comfortable with the quality and design care of the low end surge protection devices^C.

Figure 14 also shows all RF, signal, telephone and control cables pass through specific use (designed for the line being protected) surge protectors. All surge protectors must connect directly to the ARS single point ground. The NEC requires all conductors entering the dwelling do so through the appropriate surge protector either on the outside or inside of the wall through which the conductor enters^B.

Figure 16 is an outline drawing of a simple ARS single point ground plate. The drawing shows a 0.063” plate, but 0.125” is preferable. Note that **NO** surge protectors should be used on the station side of the grounded AC power outlet. If one is used it could conduct before the panel mounted one, producing the same ill effect as described with the example in Figure 15. Also note the panel mounted AC surge protector grounds to the single point ground plate by way of its’ mounting hardware, without any additional lead length.

The antenna surge protectors are coaxial types designed specifically for the frequency range of interest. The rotator surge protector is a low voltage type designed to protect control lines. All these surge protectors ground directly to the single point ground plate. This simple example should be used as a guide to more complex stations. All additional lines entering or leaving the station should pass through the plate, just as these do, with appropriate surge protectors.

For a somewhat more complex ARS see Figure 17, which is a picture of W8JI ARS entrance panel (single point ground). Even though much more complicated than the outline drawing of Figure 16, the same technique of bringing all conductors through a common ground plate is employed.

As a side note, Tom Rauch, W8JI¹⁰, has this to say about surge protectors; “By the way, despite having two 300-ft tall towers, four 130-ft wire verticals in a four square, a 220-ft tower, a 200-foot rotating tower, and miles of receiving feedlines covering distances up to 3/4 mile... I don't use coaxial lightning surge protectors^B. I have bulkhead entrance panels and use common point grounds and a few MOV's on power lines, but none of my feedlines have surge suppression devices. All of my feed and control cables stay connected during lightning storms, last count that was about 50 cables. My equipment stays connected to power mains through a main disconnect switch.”

Tom continues by saying; “Every cable enters through bulkhead connectors attached to a plate like those above. This plate is tied into the common ground at my station entrance. That ground is common with power line and utility entrance ground to the house.

Despite multiple hits every year on my tall tower, I never suffer equipment damage. This is all due to my use of proper grounding protocol. Everything entering my operating room, including power line safety grounds, bonds to a single point at the entrance point of my operating tables.”

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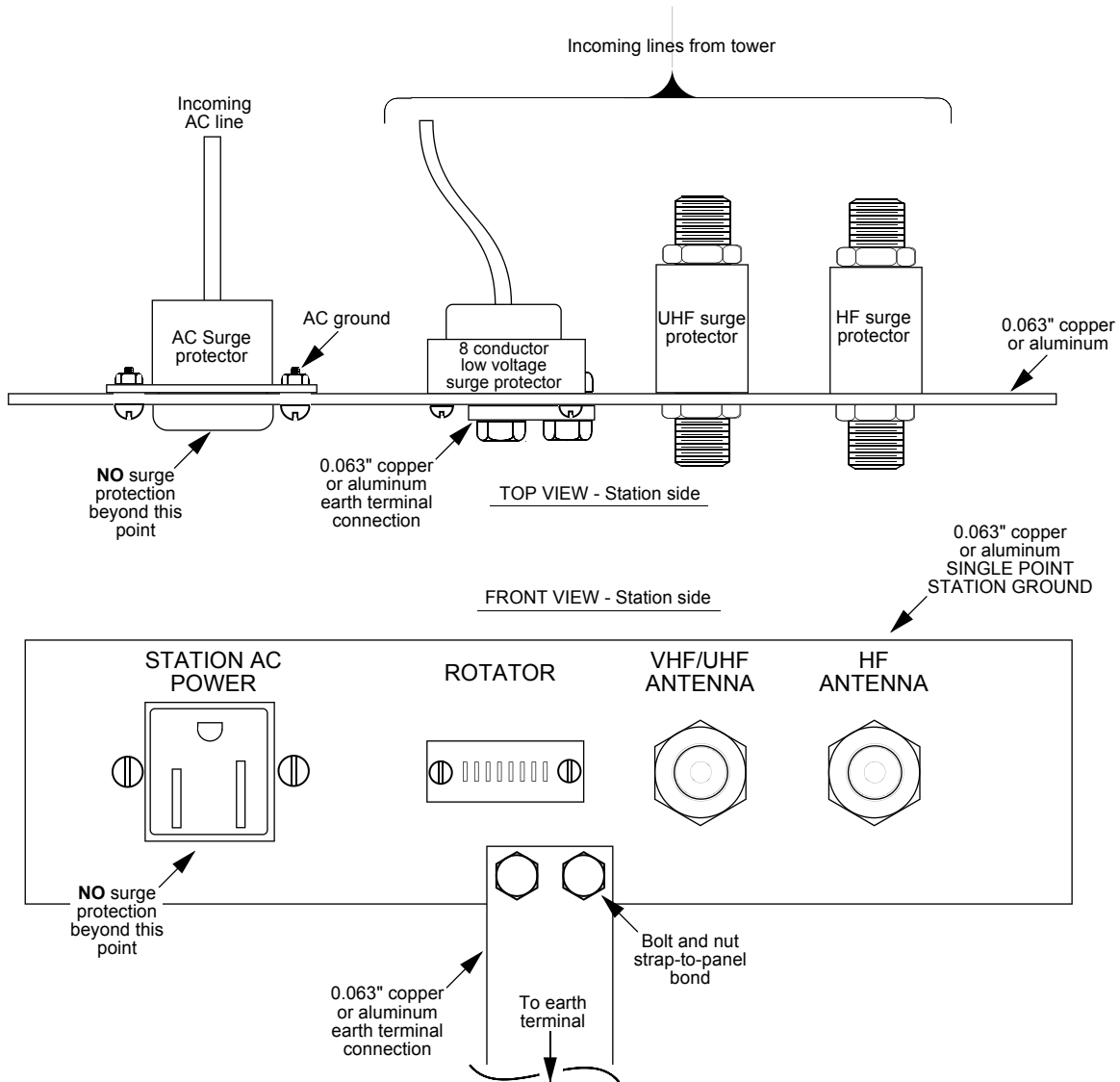


Figure 16. Outline drawing for a single point ground plate. Simple example should be expanded for more complex stations using the techniques shown here.

Figure 18 shows bulk head panels that Tom fabricates for his station. The use of these or other single point ground plates is critical, but there is no reason they can not be home made. It may even be preferable to do so, that way the plate can be customized for the site requirements and specific needs.

I fabricated the entrance panel for KA5AZK, my wife's station, using 0.063" aluminum bonded to the ground system with 4" aluminum strap. The panel passes all outside lines; RF, telco, DSL, antenna switch, and rotator; while the UPS AC power ground connects to the same plate/strap connection. I was able to enclose all of this in a small equipment closet, see Figure 27, in the garage which shares a common wall with our study where the ARS is located. See Appendix E for additional entrance panel information.

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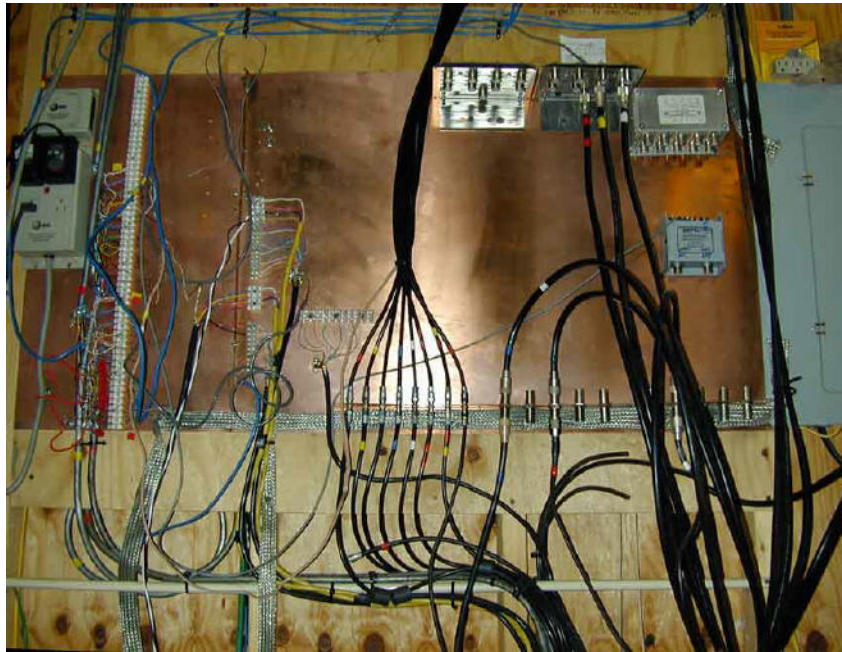


Figure 17. W8JI ARS entrance panel. This complex panel adheres to the vitally important single point ARS ground.^D



Figure 18. Shop made bulk head panels for single point grounding of incoming feed-lines. Picture from W8JI, www.w8ji.com.

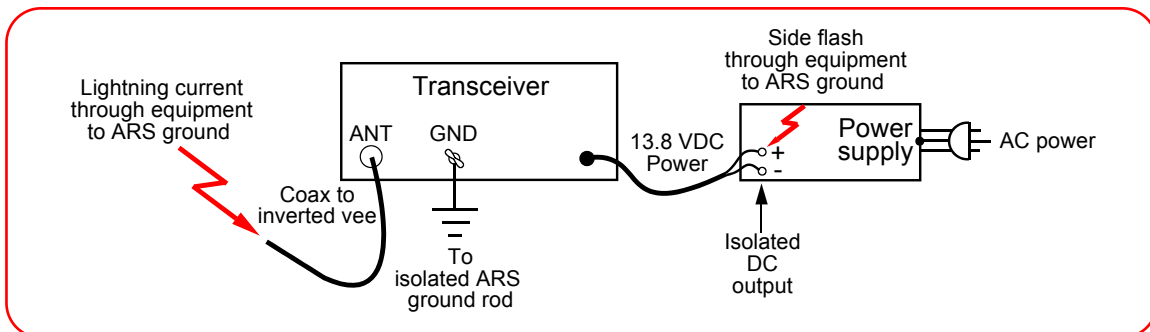


Figure 19. How **NOT** to ground an ARS. The antenna connection may be obvious, but the power supply is equally dangerous. A significant power line surge will arc through the power supply to the "isolated" DC output terminals and through the transceiver to ground.

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ARS earth terminal

Number one objective is to keep every conductor in the ARS at the same potential, even during a lightning strike. If this objective is not achieved, all else becomes almost unimportant. The second objective is to keep the ARS single point ground voltage as low as practical during a lightning strike and still meet the AC fault protection requirements presented previously.

The ARS may not be a safe location during lightning events - even with the best of surge protection. For one thing it is difficult for the operator to avoid penetrating the ARS single point ground zone of protection; doing so endangers both the equipment and the operator. So do not fall victim to thinking the surge protection extends to the operator.

A proper ground system (not just a ground rod) can reduce the danger beyond the single point ground. But it is the ground system and an effective bond to it that provides this protection - not the surge protection. Figure 10a demonstrates the high voltage that develops at the ground rod top when conducting a lightning strike to ground. Equation (1) demonstrates the unbelievable voltages that can develop across good conductors during a lightning strike. So how does the ARS single point ground effectively connect to the earth and how can the earth terminal be made more effective?

Most importantly, the earth terminal should be as extensive as one is willing to construct. A single 8 foot ground rod is insufficient, especially if bonded to the power line ground rod with insulated wire - causing a high inductance connection. Codes require all metallic site structures be bonded together including towers, fences, guy posts and buildings. If this is done with buried un-insulated wire a better ground system will result. Or even if buried un-insulated radials are bonded to the ground rod, a lower impedance connection to earth will occur, as illustrated in Figure 20. Un-insulated wire contacts the soil which absorbs energy much like a resistor and therefore damps out the wire inductance allowing more lightning energy to traverse the length of the wire. In poorly conductive soil, copper strap should be used to reduce the radial's inductance. Even better results are obtained by connecting the radial ends to another ground rod - still spaced for minimal overlapping ground fields. Even though the three ground rods at the tower base share the same volume of earth, therefore not reducing ground resistance, the surface temperature of each is lowered by being in parallel as they share the lightning strike current.

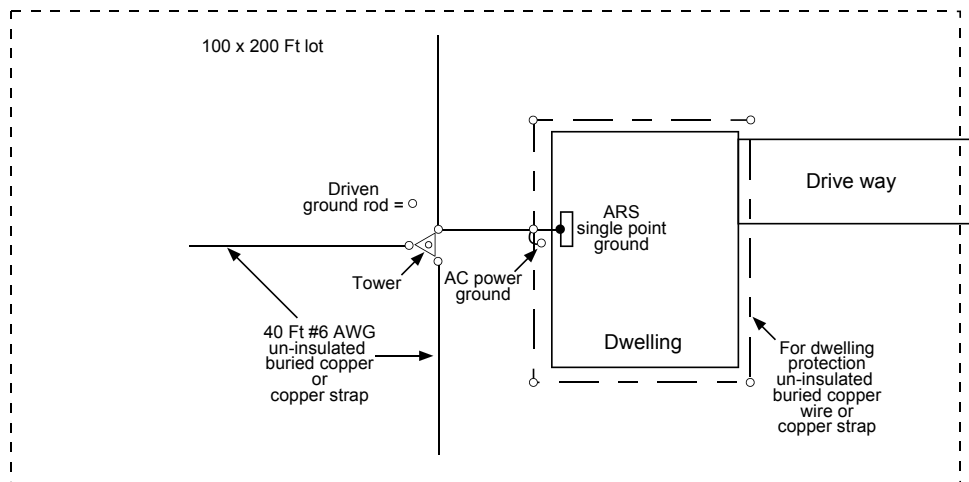


Figure 20. Grounding system with multiple earth contacts and bonding of tower, AC power and ARS grounds. Additional ground rods can be added along the un-insulated ground wires at a spacing that prevents ground field overlapping.

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Burying the rod tops and interconnecting wire at least 18 inches will minimize the step potential. But remember, to be effective the connection to this buried radial system must be with insulated wire that can withstand very high voltage. Otherwise the entire system will elevate the surface potential in the surrounding area, similar to Figure 10a.

If the ground system of Figure 20 achieves a very low resistance, say 1 Ohm, it is still possible for 18,000 volts to develop on the ground system, with respect to distant ground, during a 18 kA lightning strike.

However, the key term is “distant ground” as the end-to-end voltage of the buried un-insulated conductors may only be a 100 volts or so.

To protect the entire dwelling, an un-insulated conductor should be buried around the perimeter that is bonded to the single point ground rods as well as ones at the corners (or more spaced for non-overlapping ground fields). Further protection is offered by burying ground radials from the corners. The rise in potential of the ground system may still be several thousand volts, but the differential interior voltage will be near zero.

As we next consider how to connect to the earth terminal, or ground system, an aspect common to both needs mentioning. As previously discussed, all conductors have inductance - to an extent based on their geometry and type of conductive material. This inductance distributed over a distance and with the unavoidable capacitance to other objects produces the effect of a transmission line. That is, lightning propagates along conductors at a finite speed that varies based on the physical and electrical properties of the conductor and surrounding area.

The point is, the models presented here and in the reference material simplifies the transmission line effect, but in reality it produces ringing at all of the parasitic (and intentional) resonant frequencies of the system. Even though a lightning strike is basically a low to medium frequency event, the rise times are capable of exciting resonant circuits up to the low VHF range. A high pass filter or DC blocking will **not** protect equipment from these higher frequency components energized by the lightning event.

Bonding to the earth terminal

Likewise, the connection to the earth terminal or ground system must be effective over the frequency range of DC to VHF. If the ARS is in a basement and actually part of the ground system this requirement can be met, but a challenge exists for the station located in a ground floor or above dwelling. Remember, a 19 inch round wire in free space is resonant in the 2 meter band. The inductance of a straight wire is given by Equation (2) and as seen in the example (of the down conductor) that follows, it becomes obvious that effective bonding to the ground system is impractical or even impossible using wire.

The best conductor between the ARS single point ground and the earth terminal is a rectangular non-ferrous strap.⁶ DC resistance is insignificant in this application simply because it will be a fraction of the reactance of any suitable conductor. The inductance of a non-ferrous rectangular strap is;

$$L = 0.002l \left[2.303 \log \frac{2l}{w+t} + 0.2235 \frac{w+t}{l} \right], \text{ where} \quad (\text{Eq. 3})$$

L = inductance in μH ,
 l = strap length in cm,
 t = strap thickness in cm,
 w = strap width in cm.

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Reference 6 tabulates various strap ratios of thickness vs width, but I recommend a minimum strap thickness of 0.063 inches. For a 2 inch wide strap the incremental inductance only drops about 0.002 μH per foot between 0.063 inch and 0.125 inch thickness, so the thickness becomes insignificant. However, the length to width ratio is important. It is recommended that the l/w ratio be 5 to 1 or less, preferable 3 to 1. The strap inductance drops non-linearly over the range of ratios from 10 to 1 by about 64%.

These ratios may not be practical, but even so a 2 inch strap 36 inches long has less inductance than a 4-0 AWG copper wire, see Table 5. Using the 2 kA/ μs di/dt model, we see the 4-0 AWG will raise the single point ground approximately 1800 volts above the earth terminal, whereas the 4 inch strap will raise it approximately 1000 volts. All bends in either wire or straps should be as large a radius as possible. Bends increase the conductor inductance and encourage mechanical damage due to magnetostrictive forces.

Table 5. Conductor inductance for a length of 36 inches.

Conductor	Inductance in μH
4-0 AWG (0.460" dia.) copper wire	0.914
2" w x 0.063" t strap	0.745
4" w x 0.063" t strap	0.530

Based on a 18 kA lightning strike with a 2 kA/ μs di/dt the ARS single point ground may be 19,000 volts above distant ground. Not a very comforting thought is it? So what else can be done?

Isolating the single point ground from strike current

If a perimeter ground ring is used around the dwelling, protection should be sufficient regardless of the ground system voltage. However, one other important detail must be observed. Assuming the tower grounds are properly included in the ground system then the next step is to bond all feed-lines to the bottom of the tower - not 1 to 10 feet above ground like is so common. As stated earlier the top of the feed-lines should be bonded to the tower top also. I strongly recommend buried feed-lines. I bury mine in 3" S&D PVC which protects the lines from UV radiation, physical damage and stray RF coupling. I still have in use lines buried 25 years ago that have survived four separate lightning strikes.

If the feed-lines leave the tower above ground level, they will surely bring with them a highly elevated strike voltage due to the tower's inductance and the di/dt of the pulse, greatly enhancing the fraction of current flowing to the station. Even though buried feed-lines are not totally immune, over-head feed lines are more susceptible to electromagnetic and electro-static coupling.

Referring to my wife's station again, the tower is 160 feet from the house. The feed-lines are buried in 3" PVC in a ditch common with a fresh water line. I did not bury an un-insulated copper wire (in contact with the soil) along with the lines. 25 years ago I did not think to do so, but would now. Anyway, I isolated the tower ground from the station single point ground and disconnect the feed-lines at the station common ground plate.

However, to reduce side-flash I ground the feed-lines where they enter the house - some 25 feet from the station, see Figure 21. This ground is bonded to the AC mains ground with #6 AWG (not in soil contact) so the NEC requirement is met, but there is no help for lightning protection. Figure 10b shows what happens

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Figure 21. Feed-line entry ground. The PVC pull-box protects the connectors. The aluminum plate grounds the coax shields to the ground rod shown in Figure 10b.

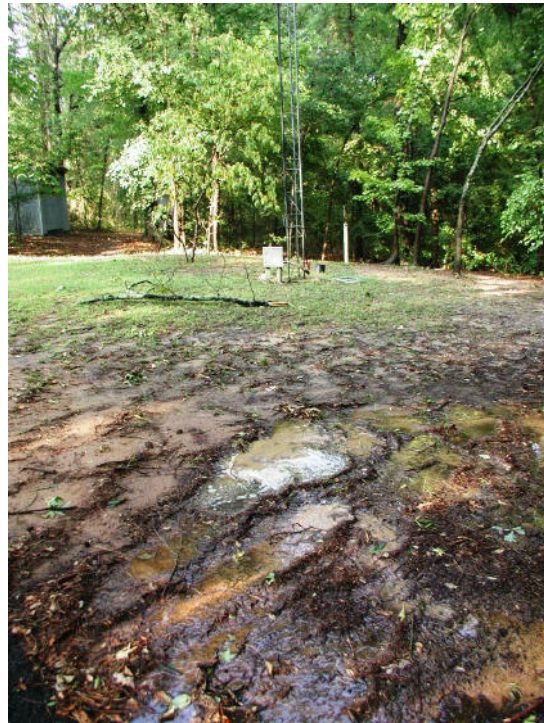


Figure 22. Exploded water line caused by induced lightning current from a strike dissipating into surrounding soil. Note the tower in the background. Buried feed-lines run parallel to and in the same ditch as the water line.

when the tower is struck by lightning. The single ground rod protected the building entry, even though the ground current probably exceeded a single ground rod's current limit. No side flash occurred inside the house and the station single point ground protected the station. Figure 23 shows concrete fragments that were blown off of the foundation footer next to the ground rod.

However, the fresh water line ($\frac{1}{2}$ " schedule 40 PVC) co-located with the buried feed-lines exploded about 25 feet from the tower, see Figure 22. The buried feed-lines were undamaged.

The tower ground and guy line grounds also were undamaged. However, for the second time I had a guy insulator shatter in the top guy during the lightning strike. I found fragments as far as 75 feet from the guy. The guys are $\frac{3}{16}$ " EHS galvanized steel cable and are under-tightened at about 150 pounds. I am not sure, my research provided no clear answer, but it appears a spark gap is needed across guy insulators.

Disconnect

Many Amateur Radio operators are able to disconnect their station when lightning threatens. I remain convinced this is still the best possible protection. I know



Figure 23. Concrete fragments from footer of foundation. Slab was undamaged, but the over-pour had these fragments blown off - from near the ground rod in Figure 10b.

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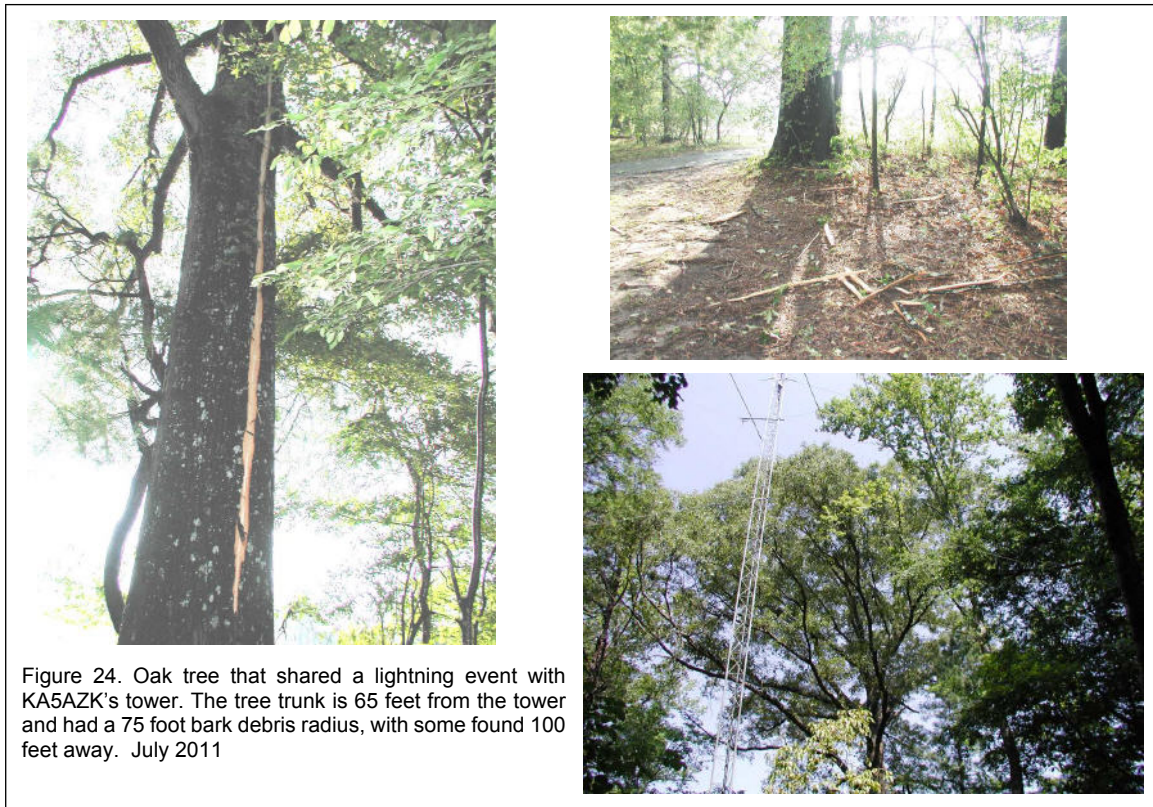
there are cases where it is not practical or possible, such as the club repeater mentioned earlier, but if at all possible all lines to the ARS should be disconnected and physically isolated from it. Again I'll emphasize the absolute best surge protection and grounding should not entice one to operate their station during a lightning event, so just go ahead and disconnect it - and do it before the storm arrives.

Properly grounded and surge protected ARS will survive most lightning events. A creditable example is W8JI¹⁰, whose station reportedly survives lightning strikes to its' towers on a regular basis. As mentioned earlier MW, cell and broadcast towers routinely are struck without damage to the associated equipment - though not always.

Commercial and military sites that operate during lightning events are designed from the ground up (pun intended) to provide equipment and personnel protection. These installations include features not normally (if ever) found in domestic dwellings. The rebar in the concrete floor may be welded (though not required) at the crossings and is bonded to a perimeter ground ring, as are steel structural members and all incoming metallic materials. The ground ring is bonded to the AC power, antenna towers, fences, communications lines, etc. and connected to an extensive ground terminal consisting of multiple rods and buried conductors. Even buried un-insulated copper wire connects the ground system to the AC mains utility pole ground.

An ARS in a domestic dwelling can be made almost this safe, using all the techniques described in this document and especially the reference material, but I still recommend staying clear of the ARS during lightning.

Figure 24 shows the tree to tower location and bark damage associated with the July 5, 2011 lightning strike. In the middle of one of Texas' worst droughts we thought it strange to have a little isolated thunder storm pop up and do this.



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Well that was just the beginning. On July 25, 2011 another little storm popped up and struck two pine trees, one at our front fence (about 600 feet from the house) and another at our west fence line (about 1000 feet from the house). We've never had this level of activity even during "wet" years - makes one wonder, doesn't it?

The strike at the front fence appears to have found a conductive path 400 hundred feet down the field fence to within 20 feet of our automatic gate opener. I designed it with surge protection and earth ground which worked well protecting the AC/control lines and circuitry. But, the limit switch circuitry (all internal to the opener) was damaged. Also, an externally mounted photo switch and low voltage lights were destroyed.



Figure 25. Pine tree at west fence struck July 25, 2011. Notice bark damage ends at the top barbed wire. Visual explanation for staying away from fences during lightning storms.



Figure 26. Pine tree at front fence struck July 25, 2011. In this case the field fence at the tree base provided a conductive path some 400 feet from the tree to our automatic gate opener.

Figure 27 is the interior disconnect panel for KA5AZK's station. The ARS is located on the other side of the wall directly behind the cabinet. The outbound feed-lines go up through the attic on the way to the entry ground panel in Figure 21. When disconnected the outbound feed-lines are positioned outside the cabinet. The ARS stays grounded to the plate and the 4 "aluminum strap connected to earth ground.

The DC power supply shelf and the DSL modem-router shelf each have their own thermostatically controlled fans with filtered air intake and exhaust ports.



Figure 27. Equipment cabinet containing disconnect panel, UPS, DC power supply, emergency power battery, DSL modem and router. Disconnect panel is the station single point ground which connects to a power line bonded ground rod by way of the 4" aluminum strap seen at the left side of the cabinet.

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Conclusion

Even though each ARS installation is unique with its' own physical and electrical peculiarities, I hope it is now clear that common protection and grounding guidelines can be used to meet individual requirements. Whatever a specific situation requires, to be protected properly it needs;

- (1) a single point ground,
- (2) all site grounds bonded together,
- (3) all ARS conductors surge protected,
- (4) all incidental conductors entering the ARS grounded to single point ground,
- (5) surge protected AC line,
- (6) properly grounded tower or antenna support,
- (7) a good ground system - not just a single ground rod,
- (8) and if all possible - a dwelling perimeter ground ring.

Lightning protection is necessary even though some unprotected Amateur Radio stations have never had damage. Depending upon the local keraunic level (thunderstorm days) it is simply a matter of time before an unprotected station is damaged. We lived in a Dallas neighborhood for years and never had a strike to our 40 foot tower. We then moved to rural east Texas and built in a heavily wooded area. We have had numerous strikes to a 100 foot tower and surrounding trees. So ignoring lightning protection is playing Russian roulette. **However, proper grounding is important for AC line fault protection even if there is no thunderstorm activity in one's geographical location.**

Good grounding and lightning protection can be installed without the exuberant cost associated with commercial grounding systems. However, it requires purposeful design and exacting installation of the basic concepts presented in this document and the reference material. The requirements of the NEC are the bare minimum and generally not considered adequate for ARS protection, whereas adequate protection meets and exceeds the NEC requirements.

The references contain detailed information that expand upon this document's text. I encourage the material be studied so a good understanding of grounding and lightning protection is had. Proper grounding is complex enough that it does not lend itself well to 'how-to' implementation without a good understanding of the subject.

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9. <http://www.alcatel-lucent.com/bstj/vol15-1936/articles/bstj15-1-167.pdf>
10. http://www.w8ji.com/station_ground.htm
11. *NFPA 70: National Electrical Code*, 2005 Edition
12. [MIL-HDBK-419A, Volume 1](#)
13. [MIL-HDBK-419A, Volume 2](#)

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Appendix

Appendix A

Soil resistivity varies with geographical location and local conditions. Type soil, moisture, drainage, temperature and ionic content establishes the resistivity at any given time. Further study of the reference material will describe the chemical process in detail. One important definition I find missing in some of the material, is that of the term resistivity. For the readers convenience, resistivity of a material is defined as the voltage developed across a cube of the material divided by the forcing current. Figure A1 shows a cube with current injected into the face of the cube and conducted out the back side.

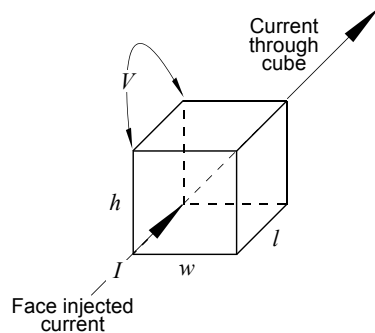


Figure A1. Cube of material for determining the resistivity of a material.

Resistance is;

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

and for $h = l = w$, this is the resistance of a cube of the material. The Greek letter ρ is used for resistivity and is defined as;

$$\rho = R \frac{hw}{l}$$

and in the MKS system, results in;

$$\rho = R_{(\text{Ohms})} \frac{h_{(\text{cm})}w_{(\text{cm})}}{l_{(\text{cm})}}$$

and therefore the familiar term for resistivity of Ohm-cm.

Appendix B

A copy of the National Electrical Code is commonly available at public libraries. It will be in the reference section and is not an easy read, but rather written in legal language. However, it is the recognized standard for meeting **minimum** requirements. It does not attempt to optimize design, ensure future expandability or provide specific methods. It simply establishes the minimum requirements to ensure human and property safety where electrical power is installed.

I encourage the reader planning a new ARS installation or upgrading an existing one to spend some time reading selected NEC articles. Start with Article 810 and follow the references to other articles from there. Also, keep in mind local codes usually are written around the NEC and the “authority having jurisdiction” (the inspector) is required to tell you the specific code in violation if an installation is not acceptable. **Important note**; beyond this the inspector can be easy to work with or not - so pick your battles carefully and be as agreeable as possible.

An example of an NEC article;

Chapter 8, code section 810, subsection (C), subsection 57 of the NEC covers “*Amateur Transmitting and Receiving Stations - Antenna Discharge Units*”. As this is applicable to Tom’s, comments on page 24, it is copied below.

810-57. Antenna Discharge Units - Transmitting Stations. Each conductor of a lead-in for outdoor antennas shall be provided with an antenna discharge unit or other suitable means that will drain static charges from the antenna system.

Exception No. 1: Where protected by a continuous metallic shield that is permanently and effectively grounded.

Exception No. 2: Where the antenna is permanently and effectively grounded.

As I read this, the coax shield bonded to ground, meets exception No. 1 and therefore surge protection is not required on the coaxial feed-lines to meet code requirements.

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Appendix C

AC line surge protection is important and should be installed into the AC power entry panel across the 240 Vac panel feed, the installation should be performed by a qualified individual or licensed electrical contractor. The sooner any incoming surge can be clamped to the ground system the better the site can be protected.

The MOV, metal oxide varistor, is a commonly used surge protection device. It consists of a slab of metal oxide, often zinc oxide, sandwiched between two conductive plates. Intrinsic reaction times are fast, though not normally specified and hindered at the application level by fairly high capacitance (1000 pF or so) and lead inductance.

MOVs have been referred to as “voltage variable resistors”, behaving more like a resistor than a diode. They are bipolar (insensitive to polarity) and have a fixed, fairly high resistance. However, unlike normal resistors, their resistance changes with voltage. This voltage variable resistance stays high for voltages up to the “knee” at which point it drops drastically effectively “clamping” the voltage to a relatively fixed value.

An MOV normally has considerable margin between breakdown and operating voltages. This is not desirable from the application stand point, but required to prevent premature device failure stemming from repeated non-destructive overloads. The MOV is capable of immense peak power dissipation, note the term dissipation, unlike gas discharge type devices, the MOV actually dissipates much of a surge pulse’s energy as heat.

Unfortunately this same characteristic causes them to fail catastrophically if subjected to an extended overload. With either, many slight overloads over time or a one time major event, the zinc oxide may form into almost pure zinc and become quite conductive. Poorly designed protection devices using MOVs have been accused of starting fires due to the fact that under certain current limited conditions, they can become very hot. With very high current feeds they also can explode. These are not issues in properly designed surge protection devices.

Power distribution lines use pole mounted MOVs. Typically these are series connected pucks (normally silicon carbide) imbedded into ceramic or polymer housings and are common on 13.8 kV residential lines. The other end of the applications spectrum is tiny surface mounted MOVs used in portable electronics such as cell phones.

Appendix D

Figure 17 shows SO-239 and PL-259 type coax connectors. Tom, W8JI, makes the comment this is by design. The “UHF” type connectors have a higher break down voltage capability than type N coax connectors. I have found they also are more rugged, less expensive and quite satisfactory for HF and even VHF. For precision 50 Ohm interconnects and UHF frequencies the type N is superior, but when used in feed-lines with 1.5 to 5 SWR at 7 MHz the advantage is wasted. Even though type N have a moisture gasket, I would not trust them in an unprotected outdoor environment anymore than a UHF connector.

Appendix E

Times Microwave offers a “Smart-Panel” for shelter and base station (fixed station in Amateur Radio terms) coax cable entrance. Figure E1 is copied from their spec sheet. Notice again the single point ground connection. Provisions are also made for bonding to the perimeter ground ring.

Other suppliers may be found on line.
<http://www.erico.com/products.asp?folderID=165>
www.polyphaser.com
<http://www.rohnet.com/rohn-products-catalog>



Figure E1. Times Microwave “Smart-Panel” coax cable entrance. Notice copper ground buss bar (single point ground). From http://www.timesmicrowave.com/products/protect/downloads/smart_panel.pdf

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Appendix F

Military standard MIL-HDBK-419A, volumes 1 and 2 contain 1200 pages of excellent information. While this was not a primary reference for this document, the other references are supported by the Mil standard. Links to these two volumes are available from several web sites, including mine using the following links; www.bwcelectronics.com/mil-hdbk-419a-vol1.pdf and www.bwcelectronics.com/mil-hdbk-419a-vol2.pdf.

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Notes: