PolyPhaser

White Paper

The Lightning "Event"

an INFINITE company

The Lightning “Event”

There are volumes of information available on what we believe lightning is and how we think it works, most of it beyond the scope of this modest textbook. We will indulge in a form of pragmatism focusing on a practical approach to equipment protection at a communications site during a lightning “event.” The science of grounding (earthing) for lightning events encompasses both the laws of physics and RF design. Throughout this textbook are proven concepts, which will protect your valuable equipment from direct or induced lightning damage. Whether your equipment is at radio site, pipe line, utility sub-station, telephone central office, maritime, military, or sensitive security installation, the same requirements apply for protection devices, proper device placement, and earth grounding.

The Stepped Leader And The Upward Going Streamer

As the electrically active cloud stratifies its charge in preparation for a cloud to ground strike, it produces an opposite polarity “mirror image” area in the earth directly below. Most cloud to earth strikes are negative (electron flow downward), some are positive, and an occasional event is bipolar. Positive strikes are usually more severe and have been associated with cyclone activity (tornadoes/hurricanes). To keep things consistent throughout this book we will be using negative strikes in our examples.

As the “E” Field (voltage) builds in potential between the charge center in the cloud and earth, it reaches a state where the atmosphere begins to break down and a “stepped leader” from the cloud tentatively reaches out and down towards the earth. Although the stepped leader is almost invisible, it is forming the beginnings of an ionized path that the strike(s) will follow on its way to an upward going streamer (also known as a “return stroke”) or direct earth contact. The stepped leader jumping distance is determined by the charge in the cloud. The smaller the charge, the smaller the jump. A typical jump (96%) is 150 feet or greater. The stepped leader will move this distance in 1 microsecond, pause for 49 microseconds, and then make another jump.

As the end of the stepped leader (which has the same potential as the charge center in the cloud) approaches the earth, the “E” Field gradient between the end of the step leader and any high “earthed” conductor (trees, towers, “lightning rods!”) exceeds the breakdown of the atmosphere around the “earthed” conductors. A corona forms around the part of the conductor closest to the incoming stepped leader. If the stepped leader approaches closer, the corona grows in to what we call an “upward going streamer” representing the opposite charge in the earth. This streamer can reach out 15 to 20 feet in an attempt to join with the stepped leader to form a conductive path for the main series of strikes to follow.

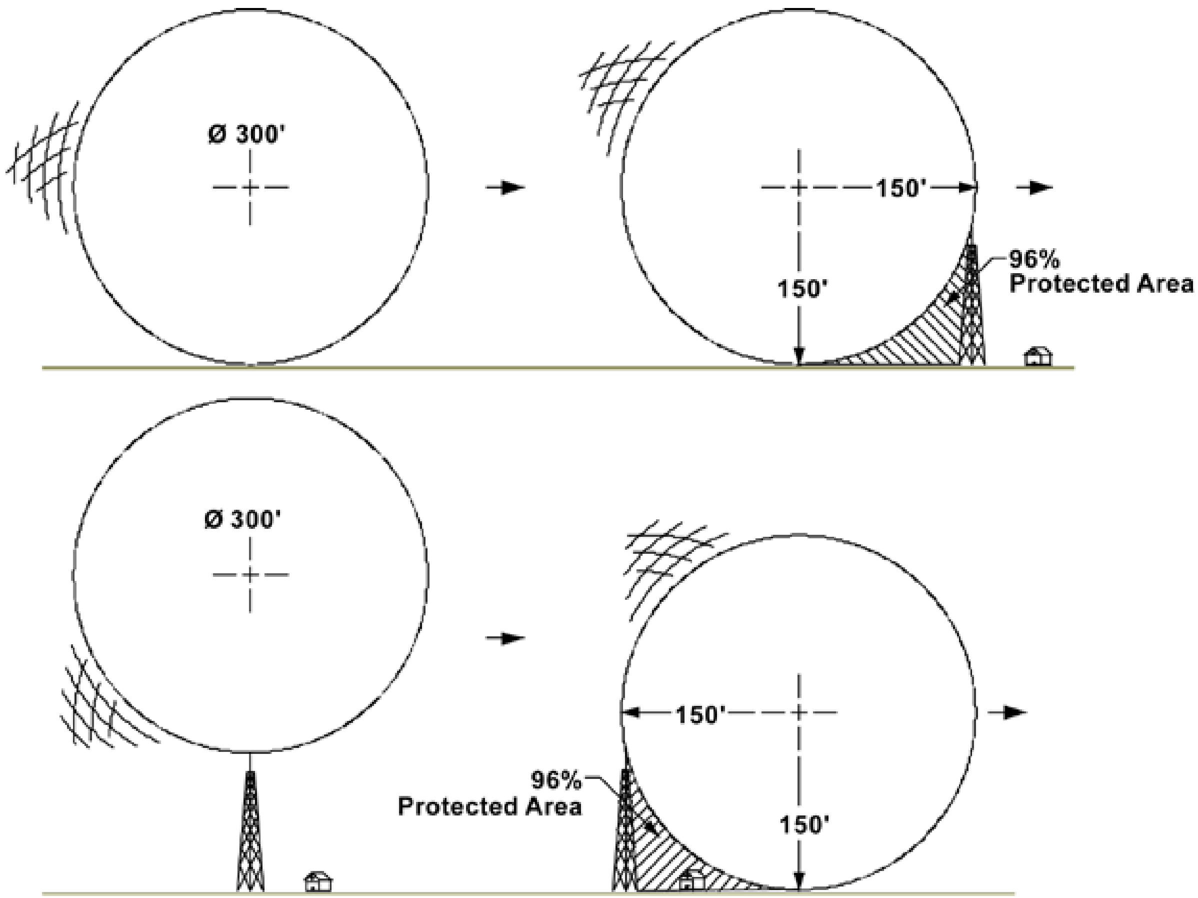
Once the stepped leader and streamer are joined, large currents will flow as a consequence of the high potentials involved. The amount of current flow in each stroke is determined by the ability of the cloud to migrate more electrons to the discharge point, and the overall inductance of the ionized path and struck object. This entire discussion is applicable only until a newer and better theory comes along!

Step Leader Implications

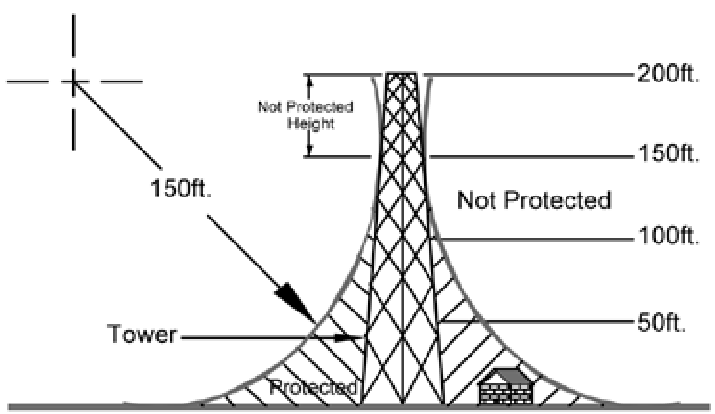
The “Rolling Ball” Theory

If the tower is over 150 feet tall, side-mounted antennas are vulnerable to direct hits. Since 1980, the NFPA (National Fire Protection Association) has been advocating in their Lightning Protection Code NFPA #780, that a 45-degree cone angle from the top of the tower towards the earth does not describe an effective protection area.

Visualize a tower site, and imagine a 150-foot radius sphere (representing a step leader typical jump) rolling over all outlined objects, everywhere the sphere touches could be hit by lightning. The sphere must be “rolled” 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 the sphere rolls up the tower, 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 canvas on a circus tent. The area above the tent is unprotected and the area below is the protected area.

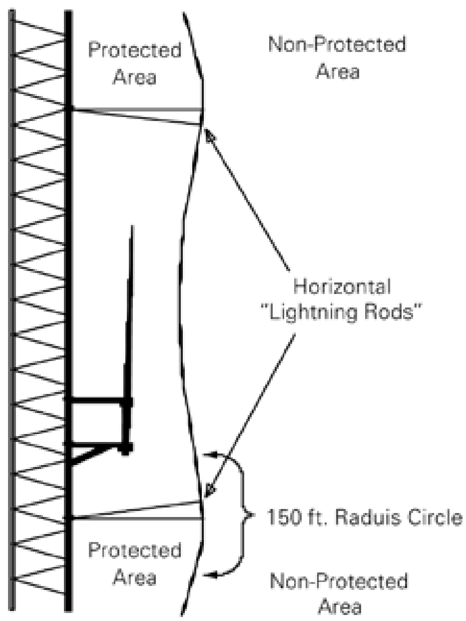


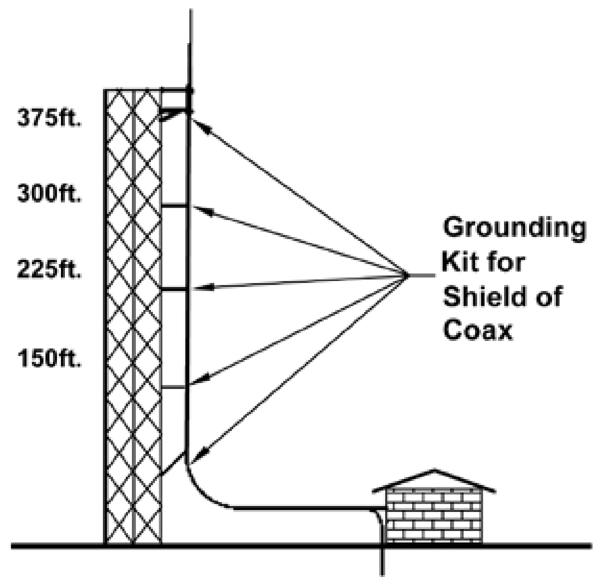
Side-mounted antennas near the top, or in sections not covered (protected) by the guy wires, can be hit. One way to protect these antennas is to install two or more horizontally mounted “lightning rods” attached to the tower just above and below the antenna. As the 150-foot radius sphere rolls on the tower, the length of the horizontally mounted rods 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 will give a 96% degree of protection from direct strikes to the side-mounted antenna. Since diverter rods are horizontal and are located in the end nulls of the antenna pattern, no changes will be made in the systems performance.

The rolling ball concept is based on the step leader jumping distance. The larger the charge in the cloud, the larger the jumping distance. The smaller the charge, the smaller the distance. This is why the percentage of protection for the zone (96%) is not 100%. Theoretically a small step leader could penetrate the zone, but it would be a small strike with little damage capability.

A tall tower, above the 150 foot point, should have coax cable grounding kits spaced so a side strike to the tower will not have to go far before a bond 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' to no more than 100' separation between grounding kits above the 150' point- unless the rolling ball concept shows guyline protection.





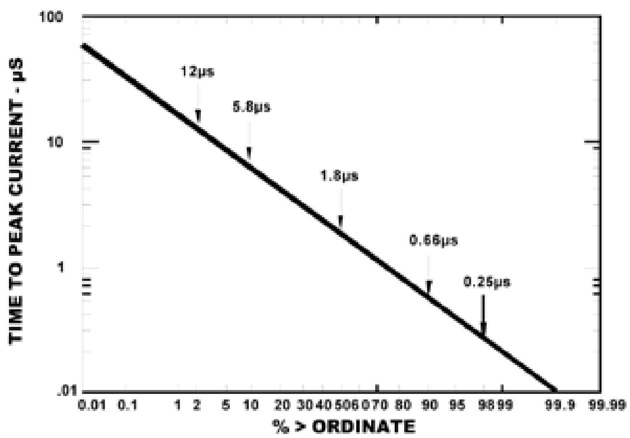
Strokes And Strikes

One IEEE Standard is an 8/20μs, 3kA current wave-shape for lightning (see Chapter 7 for wave-shape and discussion). This is the wave-shape expected to occur at the equipment after the series inductance of the tower and interconnecting conductors rolls off the fast rise time (conserving some of the rise time energy in the resulting magnetic field), and reinserts the conserved energy at the end of the stroke, affecting the pulse decay time. This standard was originally for ac power applications and has been carried over to coaxial cable entry expectations. With today's heavily loaded towers and multiple coax runs to the equipment, one can expect a much faster rise time and larger current flows.

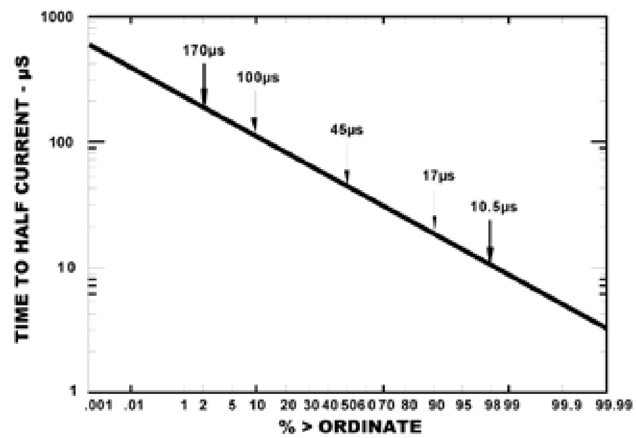
Lightning typically takes the form of a current pulse with a very fast rise time. Recent studies have shown that lightning pulse parameters can vary geographically. The measurement test setup and the inductance of the struck conductor can also affect results. The pulse statistics in this book are for illustrative purposes showing the kinds of pulses that could occur and were taken from a series of measurements done in the U.S. during the 1970's.

A typical strike (in this series of measurements) could have a 2µs rise time to 90% of peak current and a 10 - 45µs decay to 50% of peak current. 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 event.

DISTRIBUTION OF TIME TO PEAK CURRENT

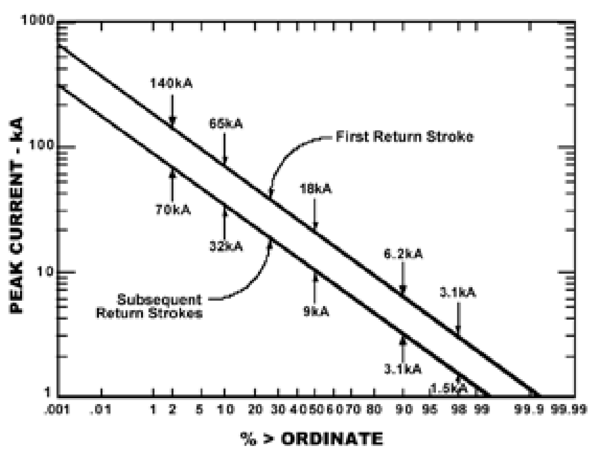


DISTRIBUTION OF TIME TO HALF CURRENT



A strike is a constant current source. 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 (I2 x 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



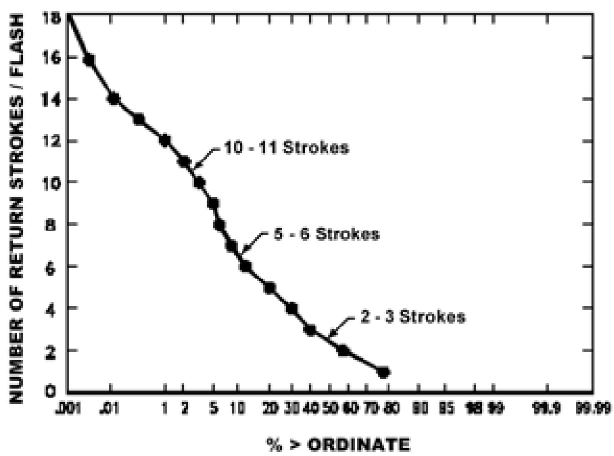
Why Tower Sites Are Damaged

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 is 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, typically less than .001 ohms.

The E=IR drops are considerable when 18kA is traversing, but even larger peak voltages are present during a lightning strike.

Grounding wire can be estimated by using the tables below. Every conductor has inductance. The amount of tower inductance is dependent upon its geometric configuration. The width-to-height ratio will determine the total inductance of a tower. A theoretical self supporting 150 foot tower, with a 35-inch side width, 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:

DISTRIBUTION OF THE NUMBER OF RETURN STROKES/FLASH



Coax Diameter

Length in Feet	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	100.0	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

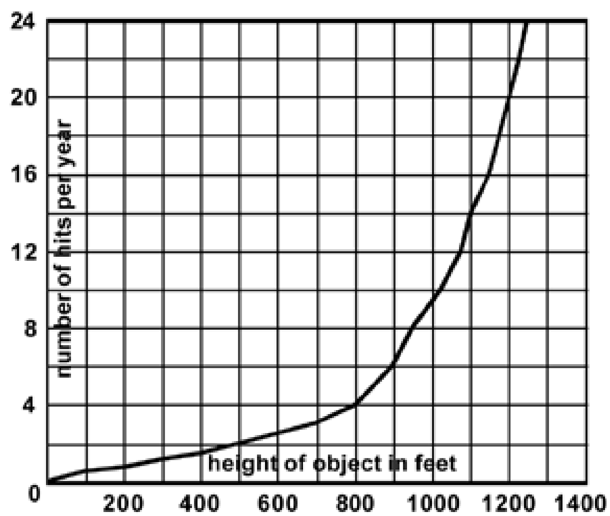


Chart shows susceptibility versus height
based on Westinghouse data.

Size and (Diameter)

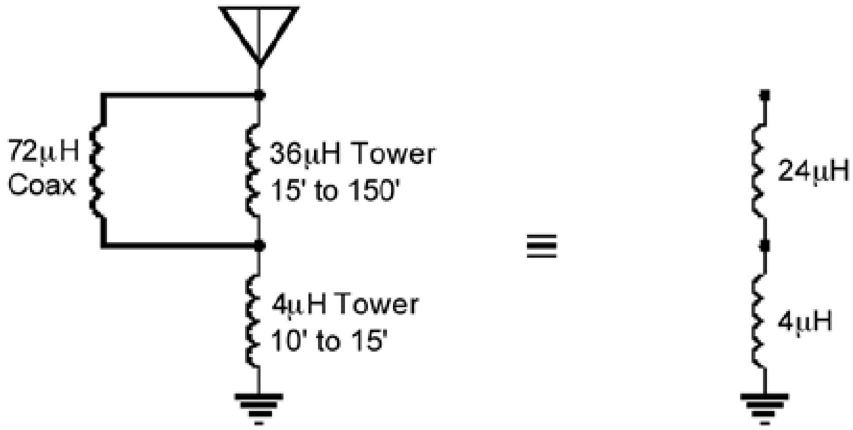
Length in Feet	Strap 6"	3"	(0.46) 1-1/2"	(0.365) 0000	(0.257) 00	(0.162) #2	(0.102) #6	(0.064) #10	#14
5	1.07	1.28	1.49	1.68	1.75	1.86	2.00	2.14	2.28
10	2.56	2.98	3.39	3.78	3.922	4.13	4.40	4.70	4.98
15	4.21	4.83	5.46	6.04	6.25	6.57	7.00	7.42	7.85
20	5.96	6.80	7.63	8.40	8.70	9.10	9.70	10.25	10.81
25	7.78	8.83	9.88	10.85	11.20	11.70	12.44	13.15	13.85
30	9.67	10.93	12.19	13.35	13.78	14.40	15.26	16.11	16.96

Approximate Inductance in Microhenries
for Conductors

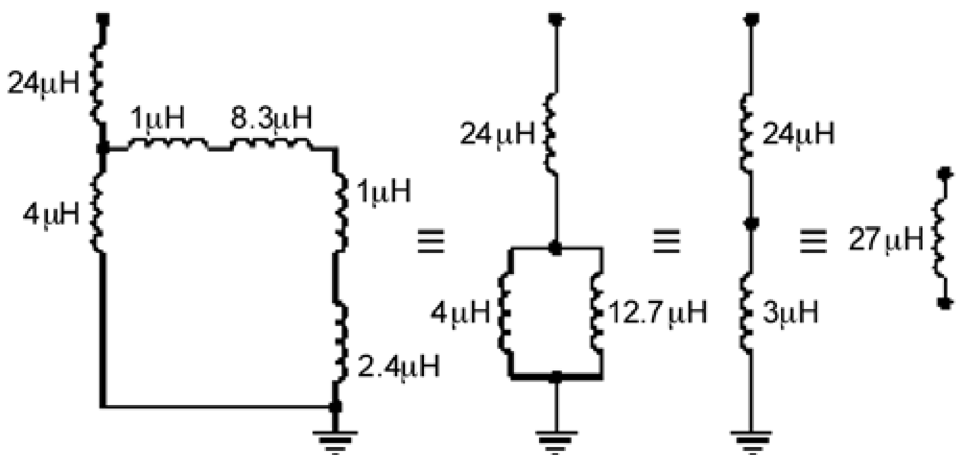
$$\frac{468 \times 10^6}{2\,(\text{H in feet})} = f$$

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

Inductance for either coaxial lines or single conductor grounding wire can be estimated by using the tables below.



Consider a ½-inch diameter coax running down 135 feet from the top of our theoretical 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 see is not optimal), then the total inductance of the tower would be:



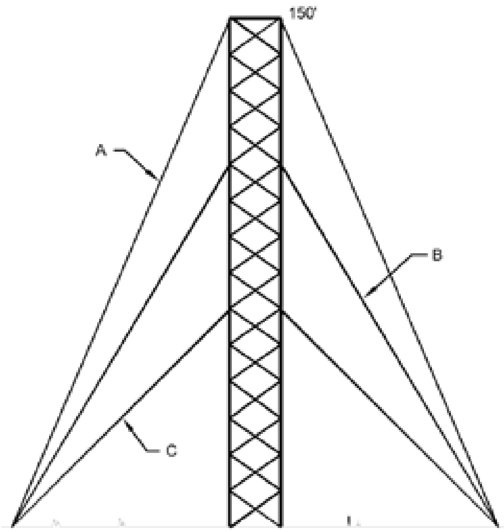
If the coax line is pulled away from the tower at the 15 foot level, traverses 20-feet horizontally to the equipment building and goes to a ground bar having a 6-foot long, #6 ground wire, the total shield inductance for this path is 12.7μH. To account for each directional change, one for the coax bend at the tower and one for the ground plate, 1mH 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.

If a perfect conducting ground system (with a non-inductive connection) were present, a 2ms rise time, 18kA, constant current strike, hitting the tower would develop an -L di/dt drop of 243kV between the top of the tower and the bottom. The height at which the lower coaxial cable shield kit is bonded to the tower and pulled away from the tower toward the equipment determines the voltage that is present on the coax shield. creates current flow through all the additional paths to ground attached to it.

Guyed Towers

We have looked at a self supported tower and can reasonably conclude that, without proper protection and grounding, our equipment will suffer damage.

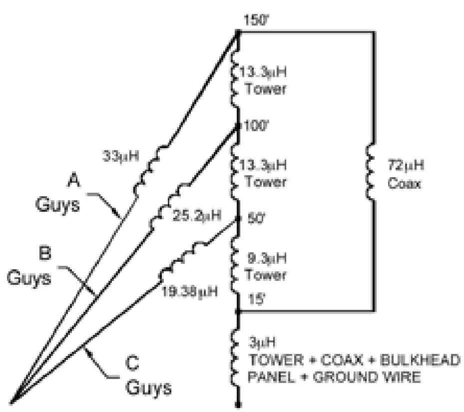
Looking at the current distribution on a guyed tower, we see the guy wires and grounded guy anchor points perform an important role during a ligh The same 150 foot tower, with 35" side widths, will be used as the example. The use of ½" diameter guy wire with no insulators would look like the drawing to the right.



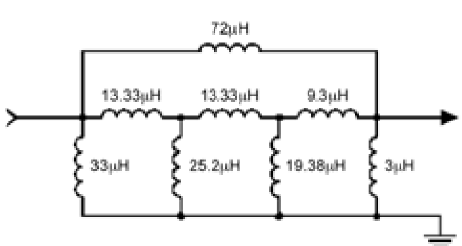
On a triangle base tower, where "A" is approximately 180 feet long or about 99μH each, there would be 3 "A's" in parallel or 33μH total inductance. This will significantly change some of our L di/dt values! Likewise, the lengths of "B" and "C" would be used to calculate their inductance contributions.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

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

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



Re-drawing the tower circuit:



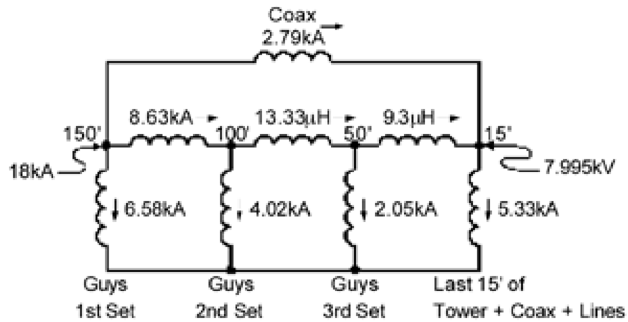
When the 18kA lightning strike occurs, it will have a voltage drop of

from top to bottom ground.

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

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:



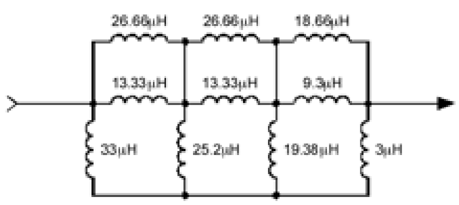
Average Coax Current is 2.79kA

The coaxial cable run to the ground outside bar 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!

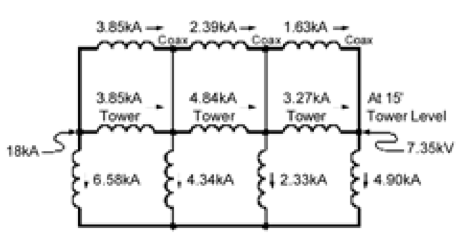
Before you pull down your self-support tower, remember, in our example we kept the same tower side width of 35 inches and just added guys. A guyed tower might not be this wide, but we wanted to point out the improvement that the guys make by using the same size tower in our calculations.

All of the previous calculations assume the guys are without insulators and the guy anchors are bonded 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.

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.

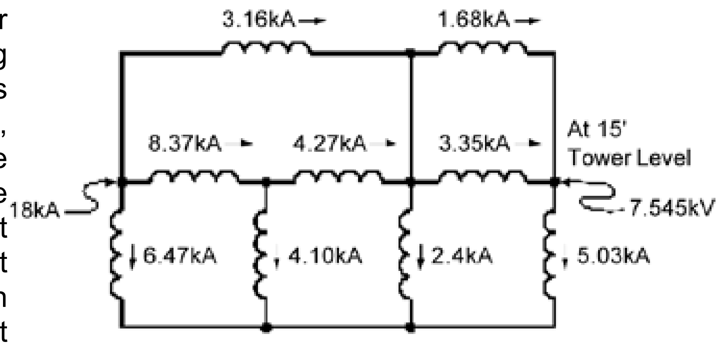
Average Proportional Coax Current is 2.733kA. Any additional grounding of the coax, say to every tower section, would not provide any benefit for this size tower (150 feet and less). However, it is important to ground the coax lines more often when above this 150-foot level. The guy wire paths to ground 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? 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.

Mutual Coupling

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. We estimated this coefficient to be 0.166



Using the formula:

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

where k is 0.166 and L1 and L2 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!

Additional worst case consideration might be given to the possibility of a low inductance self supporting structure with a single coax running down the side. Depending on how the coax was attached, if the structure was tall (> 150 feet), and the coax shield was grounded to the structure at the top and bottom only, there would be a large difference in inductance between the two paths. Magnetic field coupling (k) between the two paths would create a reverse EMF on the coax, opposing the downward energy flow. At some point, approximately in the middle of the structure, there could be a high peak voltage differential between the coax shield and the structure. This high peak voltage differential could arc through the coax PVC outer jacket to the structure, damaging the coax shield. Additional grounding kits could solve this problem.

In the guyed tower, the coefficient of coupling would be the same. But since there is less total inductance with current flow on the guys, there will be less current on the coax, making the dv/dt less dramatic. The grounding of the coax shield along the tower will segment the amounts of mutual inductance. The mutual coupled inductance will then add about 7% to all inductances and voltages we have calculated on all combinations of coax shield grounding.

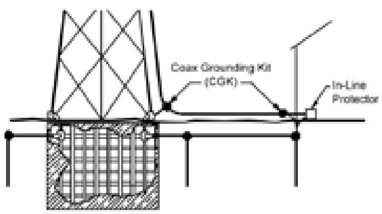
So far, we have taken a look at the current distribution on two theoretical towers for a typical strike. What happens to the coax line and the connected equipment in the building when this potential is present?

It's Wrong!

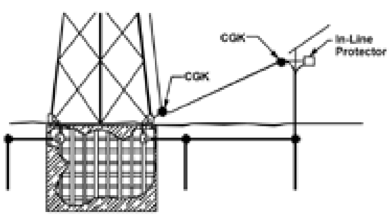
If we look at where the coax leaves the tower on its way to the equipment building, we see the tower will carry the major part of the surge to earth. The outside master ground bar will have 4.3kA delivered to it by the coax and be elevated to 7.3kV above earth ground. The master "ground bar" **is no longer a** ground, but instead a source for elevated potential to be transferred to whatever equipment is connected to it! The above current and voltage examples are 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 sends a significant amount of energy through the coax shield towards the equipment. There is a better way.)

The Real Fix!

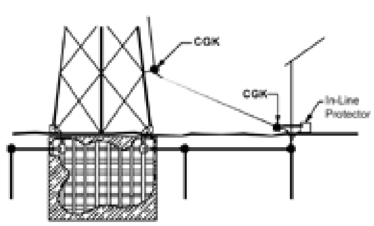
Even though this is accepted practice, and what you will see most often in the field, it is incorrect. By continuing the coax further down the tower to almost ground level and then grounding the shield to the tower (just above the tower leg ground connection), the instantaneous voltage gradient on the coax shield would be almost zero. Theoretically, the coax shield current would also be almost nothing. “Theoretically” because both the tower ground system and the equipment ground must not only be interconnected (grounded) below grade to have this be true, but they must also be large enough so that ground saturation will be minimal. Running additional ground wires from the coax ground kits to the tower base will not help either, unless you can find the theoretical zero inductance conductor!



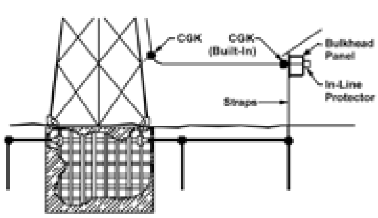
BEST



GOOD



OK



ACCEPTABLE

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

Please contact us for questions or further information on this topic.

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