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Grounding Considerations for CARMA

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ABSTRACT

This memo discusses some of the factors that need to be taken into account in developing a grounding system: soil resistivity, grounding solutions, and grounding resistance and reactance. In particular, it deals with personnel safety and lightning protection considerations.

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Grounding Alternatives. The most common method of grounding relies on using one or more grounding rods driven vertically into the earth. The resistance to ground achieved by this method is computed using the formula

$$R = \frac{\rho}{2\pi L}\left(\ln\frac{4L}{a} - 1\right) \tag{1}$$

where ρ is the resistivity of the soil, and L and a are the length and radius of the grounding rod respectively. The soil resistivity depends on the composition and moisture of the soil. Typical resistivities vary widely from 2500 to 10 Ω m. Silty sands, or sand/clay mixtures, such as the soil at the Cedar Flat site, usually have resistivites between 50 and 500 Ω m. Soil resistivities are very dependent on the moisture content and consequently on the seasonal temperature variations, especially where the ground freezes. Ground resistance measurements for the ALMA interferometer, for example, find soil resistivities on Pampa La Bola during the summer of $\sim$ 300 Ω m increasing by a factor of 3 during the winter (ALMA memo #369). A grounding rod of 5/8" diameter driven 3 m into the soil will yield ground resistances in the range $15 - 150$ Ω for soil resistivities $50 - 500$ Ω m. Guessing a season-averaged resistivity for the soil at Cedar Flat of $\rho \sim 300$ Ω m, one of such grounding rods would provide a resistance to ground of $R \sim 100$ Ω.

How can this be improved? A common method is the use of multiple rods. Although connecting multiple rods in parallel effectively reduces the resistance, it is important to realize that they need to be spaced appart far enough to not interfere with each other. A rule of thumb is to separate them by at least their length. Even in that case, the resulting resistance is larger than $1/n$ times that of one rod by a non-negligible factor. To acheive 1/3 the resistance of one rod, one actually needs to use 4 rods spaced by their lengths. To acheive 1/10, 20 rods are necessary. Using 24 rods gains only a further 1%.

Another possibility is to increase the effective diameter of the rod. In practical terms, that means using chemicals to reduce the ground resistivity in the surroundings of the rod, which can be problematic in terms of corrosion, pollution, and requires maintenance. An alternative is to encase the rod or grounding wire in a cheap conductor, such as graphite loaded Portland cement. The resistivity of the conductive cement is 0.2 Ω m (Earthlink 101, for example), so it looks like a perfect conductor when compared to the ground. In the above example, encasing the rod (which does not have to be a rod anymore, but could now be a 4/0 stranded copper wire) in a 12" diameter augered hole filled with conductive cement will drop the ground resistance by a factor of two to $7 - 75$ Ω.

A variation on the vertical rod theme is the use of counterpoises, which are simply horizontal electrodes (wires). These are used where the soil resistivity is high and the rods cannot be driven deep into the ground without hitting the bedrock. The problem with counterpoises is that, if the wires are long, their self-inductance is high and they act poorly as grounds for impulsive voltages, such as those produced by lightning strikes. An improvement is to embed the wire in a conductive groundbed, increasing the contact area between the conductor and the soil thus shortening the wire for a given resistance. These groundbeds can be made with conductive concrete, or with a conductive volcanic clay called bentonite. Bentonite is an inexpensive, highly hygroscopic clay that is commonly used as the agglomerant in cat litter. When used to enhance conduction in groundbeds, it has two problems: 1) being hygroscopic, its conduction depends on having moist soils. Dry bentonite apparently is not a good conductor. 2) Bentonite expands when it absorbs water, and contracts when it dries up. As a consequence there can be contact discontinuities between the soil an the bentonite groundbed, making the ground even worse. The resistance of a groundbed (or a horizontal grounding strip) can be computed using

$$R \approx \frac{\rho}{2\pi L}\left(\ln\frac{2L^2}{wD} - \frac{1}{2} + \frac{2D}{L} - \frac{D^2}{L^2} + \frac{D^4}{2L^4} - \ldots\right) \tag{2}$$

where ρ is the ground resistivity, and L, w, and D are the groundbed length, width, and depth (negligible thickness is assumed). All else equal, a groundbed under the surface appears to supply a superior ground than a grounding rod of the same length owing to its larger contact area: according to the above formula one needs a groundbed 0.3 m wide by $\sim$ 2 m long at a depth of 0.75 m to acheive the same grounding resistance given by the 5/8" diameter 3 m long rod in our example. Performance degrades somewhat if the groundbed is trenched shallower. Furthermore, the impedance of a groundbed, for a given DC resistance, is typically smaller than that of a grounding rod providing a superior ground for lightning protection. The groundbed in the example has a self-inductance $L \sim 1.2\ \mu$H, a factor of ~ 3 lower than the grounding rod. Because the capacitance of a flat groundbed electrode is larger than that of a rod, the resulting impedance $Z \sim \sqrt{L/C}$ is smaller by factors of a few.

How Good is Good Enough? The purpose of grounding is to protect the equipment and the personnel when faults occur in the power distribution. A fault can be a shortcircuit between a phase and the (hopefully grounded) case of a compressor at the antenna, for example. In that example the case of the compressor should be electrically tied to the metallic structure of the antenna, which in turn is, through some resistance, tied to ground. People standing on the structure, in this example, would probably be safe until they try to come down the platform. If the grounding is poor, at the time they come down the ladder and touch the ground a circuit is closed between a 120 V phase and ground through a person, who can be modeled electrically as a 1,000 to 2,000 Ω resistor (depending on how dry his/her hands are, and what kind of shoes is he/she wearing). At the time of contact the person draws $\gtrsim 50 - 100$ mA of current through himself, which will cause fibrillation and death in most adults if sustained for more than a few seconds. Obviously, this is not acceptable. The grounding needs to be good enough to draw enough current from the faulty phase that a circuit breaker is tripped at the antenna when the fault occurs. Otherwise the protection is left entirely to the contact resistance at the point of fault, in the hope that if it is high enough there will never be 100 mA available to kill someone. Therefore, the acceptable resistance for the ground depends on the circuit breaker protection scheme and tolerances. A fault to ground should draw enough current to trip the breaker, or otherwise lower the voltage below a dangerous level.

Protection from Lightning Strike. Another role of a grounding system is to help protect equipment during lightning strikes. Grounding provides protection by limiting the raise of the local potential during the strike, reducing the induction currents, and routing the lightning current away from delicate equipment. The west coast of the U.S. is particularly benign in terms of lightning: the 10-years average lightning flash density map shows the Owens Valley/Cedar Flat region to be close to the 0.1 flashes km^{-2} yr^{-1} contour. By comparison the U.S. average is 2 or more, with ~ 6 close to Kitt Peak and ~ 3 at the location of the VLA. Nevertheless, because the site elevation may favor lightning, and because CARMA is a long-term operation, we should expect a few lightning strikes in the area of the array during its lifetime.

The median peak current carried by the primary discharge during a lightning strike is ~ 33 kA, but can reach over 100 kA in some cases. Subsequent discharges (secondary strikes) typically carry a third of that current. The rise time of the primary strike is ~ 4 μs, while secondary discharges peak faster (~ 0.7 μs) due to the fact that air ionization keeps the conductive channel open. This is why is important to keep the self-inductance of the grounding system low: a high inductance wire looks like an open circuit to these impulsive currents, and is thus ignored. So while long grounding wires, counterpoises, or grounding beds can be used to keep the DC resistance of the ground low, they do not necessarily provide great benefits during lightning strikes. Groundbeds, because of their large area and comparatively large capacitance, have considerably lower impedance than counterpoises are better grounds for lightning discharges. Furthermore, the wires that connect the grounded equipment to the grounding electrode should be as short and straight as possible. The moral is to keep the grounding wires short: thick is good, but short is better.

Obviosly the ground wire connecting the structure to the electrodes (grounding rods, counterpoises, or whatever they may be) needs to be able to withstand the lightning current without melting: otherwise we have just come up with an expensive fuse. The $\int I^2 dt$ integral for primary lightning discharges has a median of $\sim 60 \times 10^3$ A^2 s, and a 95% tail of 550×10^3 A^2 s. Subsequent secondary discharges are $\sim$ 10% of these values. Thus a grounding wire with $R = 0.1\ \Omega$ has to be able to take 6 kJ of energy without melting to be of any use, and better 60 kJ to be safe. Using the heat capacity for copper (400 J kg^{-1} K^{-1}), 60 kJ will raise the temperature of 150 g of copper to its $\sim$ 1300 K melting point. To put this in context, that is about the weight of a 6" long 4/0 solid copper wire. The resistance of such a wire is much lower than 0.1 Ω, but it is expected that most of the resistance (an thus the dissipation) will be at the terminal contact. In other words, it is important to keep the terminal contact resistance of a grounding wire to $\ll 0.1\ \Omega$ to prevent melting during a lightning discharge, and the mass of copper in the terminal contacts should be large to keep their temperature down. A 150 g copper terminal with 0.1 Ω contact resistance may melt during a lightning discharge and provide no protection.

There are two mechanisms to protect equipment from lightning strike in the power distribution lines. The first protection is to have surge arresters at the ends of the line that short to the local ground in the event of a discharge. *This is the primary manner of protecting the distribution transformers.* The second protection is to direct lightning away from the distribution network by judicious use of lightning rods.

Metal-oxide surge arresters are inexpensive, safe, and lossless. All transformers (both in pads and at antennas) should have them. They are mostly zinc-oxide nonlinear resistors that short at high voltages, and reopen after the fault has been cleared. They should be rated for the voltages and currents involved. Avoid or replace silicon-carbide and gap arresters if possible; their failure mode is to maintain the short after the strike is over, in the end melting. Under-oil arresters inside the transformer tank have excellent characteristics because the thermal dissipation is helped by the fluid. However, they are very problematic if they fail. In case of failure, the flash may puncture the oil tank and disable the transformer, and in any case an arrester failure is the same as a transformer failure since it requires removing the transformer from the line and taking it to the shop for dissasembling and repair. Presumably this means that they should be complemented, if possible, with external surge arresters. The literature recommends that arrester leads should be short, uncoiled, and the ground lead should be tied to the transformer tank.

Direct lightning hits will damage undeground power distribution cables. In fact, these cables attract lightning in soils of high resistivity in a region of tens of meters around them, in a manner that has been quantified by Sunde's model (the details of which are beyond the scope of this memo). Lightning strike will puncture the outer jacket and the concentric ground shield, and damage the inner jacket causing a fault to ground in one or more phases that requires replacing the cable. Possible defenses againts this strike include use of a grounded conductor closer to the surface, over the power distribution line in a "shield wire" type arrangement, and/or use of cables with so-called "semiconductor" jackets (polymer jackets which have lower resistivity than standard XLPE jackets, thus not allowing a potential large enough to puncture the jacket to develop during lightning). As far as I could find, the efficacy of either method is undocumented. Ultimately, if lightning strikes prove to be a major nuisance at the Cedar Flat site, installation of lightning rods at the higher peaks in the site away from antennas and the power distribution may prove to be the best defense.

My Recommendations.

1. Antenna grounding: Ideally ground every pad independently. In the central array area, at least ground every branch of the power distribution circuit at a pad between the circuit end and the transformer (e.g., the penultimate pad counting from the transformer) to minimize ground impedance.

2. Antenna ground electrode design: To obtain grounding of low impedance, best to protect equipment from lightning, surround the pad with a $\sim 2-3$ feet deep (below the soil freeze level), 1 foot wide trench, with compacted bottom. Pour a 2"–3" layer of conductive concrete. Embed 4 counterpoise 4/0 wires in the concrete, parallel to the sides of the pad. Bring wires out of the groundbed close to each antenna foot. This design has a lower impedance than simple grounding rods, and protects better against lightning. Cracking of cement electrodes by driving the transporter over them could be a concern: the electrode trench should have a compacted bottom and should be compacted after backfill. If the material cost per foot is ∼\$5, this will add ∼\$350 to a pad cost. Alternatively, if lightining is discounted as a major problem, grounding can be acheived by using multiple grounding rods per antenna. Encasing them in conductive cement has the advantage of lowering the ground resistance by a factor ~ 2 and diminishing corrosion problems.

3. Antenna ground electrode connection: Connect a short and straight length of wire (4/0) from the electrode to a point near each of the antenna feet. Contact resistance needs to be kept low to avoid melting during lightning strike — requires large surface area, no paint, and a mechanical design of the terminal that ensures good contact. Keep terminal mass as large as mechanically and economically practical to prevent melting.

4. Antenna breakers: Check that antenna breakers will trip if any one phase contacts ground, *even when the ground wire distributed with the power is left unconnected.* This test will demonstrate that the local ground is good enough to protect people from faults.

5. Transformer grounding: All pad mounted power distribution transformers should be locally grounded. The electrode design is similar to the antenna electrode. Ground could be supplemented by using grounding rods near the stream bed if practical.

6. Transformer protection: All transformers on site, including the antenna transformers, should be equipped with metal-oxide surge arresters. Older antenna transformer surge arresters should be replaced if possible with new metal-oxide surge arresters. Under-oil surge arresters should be supplemented with externally accessible metal-oxide surge arresters connected to the local mounting pad ground and to the tank of the transformer by short, *uncoiled* wires. The wires connecting the surge arresters to the phases should also be kept short and straight. Power distribution, pad-mounted transformers should have arresters on both the primary and the secondary side.

7. Underground cable protection: I do not recommend any especial protection to underground power distribution at this point. If lightning proves to be a problem the best solution is probably lightning rods mounted on high points on the side, well away from power distribution wires and antennas. Semiconductor jackets in underground cables could be preferred if available and if their cost does not increase much the cost of the overall power distribution.

8. Building grounding: Use a ground ring with counterpoise wire and conductive concrete around the correlator building, similar to that at the antenna. Construction and generator buildings could use a similar design, if cost effective. Especially at the generator building, it may make sense to supplement this ground ring with grounding rods near the stream bed area.

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