New Folder Name Lightning Protection

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Telefax Transmittal Sheet

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Dear Dr. Coles:

Following by FAX is a DRAFT report that we can use as a basis for further discussions. A photocopy is being sent by mail.

I will be tied up at AGU and Galileo meetings the rest of this week, but I will be back in my office next Monday.

Philip

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Lightning Protection

for the

Caltech LIGO Experiment

DRAFT REPORT

by

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11 December 1995

Introduction

The Laser Interferometer Gravitational-Wave Observatory (LIGO) that will be constructed by the California Institute of Technology (Caltech) will use two large sensors, one near Baton Rouge, LA, and one near Richland, WA. Each sensor contains two 4-km-long Beam Tubes arranged in the form of a 90-degree elbow, and a Corner Station is located where the tubes intersect. The effective area of each beam tube is about $6 \text{ m} \times 4 \text{ km} = 0.024 \text{ km}^2$, thus both tubes present 0.048 km^2 of exposure to a lightning hazard. The structures at the corner station have a total projected area of about 2700 m^2 or 0.0027 km^2.

Using 30-year thunder statistics (for both duration and daily frequency) for regions near Baton Rouge and Richland, I estimate that the average area density of cloud-to-ground lightning strikes in these regions is about $10 \text{ km}^{-2} \text{ yr}^{-1}$ near Baton Rouge and $1 \text{ km}^{-2} \text{ yr}^{-1}$ near Richland (see Table 1) with a standard deviation that is 30 to 40% of the mean. Therefore, the LIGO Project can expect roughly $(0.05)(10) = 0.5$ direct strikes per year to the apparatus in Louisiana, and about an order of magnitude smaller number in Washington state.

The lightning "striking distance" is about 30 m, and sometimes this distance is used in assessing the range at which lightning can cause severe damage. If we add the total area within 30 m of a beam tube, we get about a factor of 10 higher strike frequency or roughly 5 strikes per year in Louisiana and 0.5 per year in Washington.

Conclusion: The LIGO experiment can expect to receive a significant number of nearby and direct lightning strikes each year, and should implement as much protection as is possible for both personnel and the apparatus.

Before going any further, I would like to review the physical characteristics of cloud-to-ground lightning and the hazards that it presents.

Table 1. Estimates of Lightning Flash Densities Based on Thunder Statistics

City	Thunder		F_D	F_H
	Days (per year)	Hours (per year)	Flashes/km^2 (per year)	
Yakima, WA (West of LIGO)	6±4	7±6	1.0	0.5
Walla Walla, WA (East of LIGO)	8±4	6±5		
Baton Rouge, LA	70±11	111±29	9.8	9.7

Cloud-to Ground (CG) Lightning

The vast majority of CG discharges begin in the cloud with a process that is called the *preliminary breakdown*. After perhaps a tenth of a second, an intermittent, highly branched discharge, the *stepped-leader*, appears below cloud base and propagates downward in a series of rapid, discrete steps. Most leader channels effectively lower negative charge toward ground, but a few percent of such channels are positive. When the tip of the leader gets to its *striking distance*, typically about 30 meters above ground, the electric field under the leader becomes large enough to initiate one or more upward *connecting discharges*, usually from the tallest object(s) in the local vicinity of the strike point. When an upward discharge contacts the leader, the first *return-stroke* begins.

The return stroke is a very intense, positive wave of ionization that propagates up the partially ionized leader channel toward the cloud at a speed close to the speed of light. After a pause of 40 to 80 ms, another leader, the *dart-leader*, propagates smoothly down the previous return-stroke channel and initiates a *subsequent return stroke*. A typical cloud-to-ground flash contains several return strokes and lasts about 0.5 s. Lightning often appears to "flicker" because the human eye can just resolve the time-interval between successive strokes. In roughly one-third of all flashes to ground, the dart-leader propagates down just a portion of the previous return-stroke channel and then forges a different path to ground. In these cases, the discharge actually strikes the ground in two (or more) places, and the channel has a characteristic forked appearance that can be seen in many photographs. The return strokes present the largest threat to people or objects on the ground. Further details about CG lightning and the properties of return strokes can be found in Uman (1987).

Lightning Damage

When a building or power line is struck by lightning, or is exposed to the intense electromagnetic fields of a nearby flash, the currents and voltages that appear on the structure are determined by the lightning currents and fields and by the electrical response of the structure, including its grounding system, to the transient currents and fields. For example, the voltages that appear on the electronics inside a grounded metal building are usually produced by the fastest rising part of the return stroke current. This fast current excites resonant oscillations on the exterior of the building (like the resonances of a bell) that then couple into the structure via apertures in the metal, such as doors and windows.

Four properties of the return-stroke current produce damage: 1) the peak current, 2) the maximum rate of change of current, 3) the integral of the current over time (*i.e.*, the charge transferred), and 4) the integral of the current squared over time, the so-called "action integral." Statistics on these parameters are given in Table 2. For objects that present a resistive impedance, such as a ground rod or a long power line, the peak voltage on the object will be proportional to the peak current. For example, if a 30,000-A peak current is injected into a 400-ohm power line, a voltage surge of 6 million volts will propagate in each direction in the absence of flashovers. Such large voltages can produce secondary discharges that flash from the object that is struck to another object or the ground. These *side-flashes* can kill people who are standing close to any object that is struck, and can also produce significant property damage. The magnetic forces produced by lightning currents are also large and can crush metal tubes and pull wires from walls.

For objects that have an inductive impedance, such as the wires in an electrical system, the peak voltage will be proportional to the maximum rate of change of the lightning current times the inductance ($V = L\, di/dt$). For example, 1 m of wire has a self-inductance L that is

Table 2. Properties of Return Strokes That Lower Negative Charge to Ground*

Properties	Unit	Percentage of cases exceeding tabulated value		
		95%	50%	5%
Peak current (minimum 2 kA):				
First stroke	kA	14.0	30.0	80.0
Subsequent stroke	kA	4.6	12.0	30.0
Total charge:				
First stroke	C	1.1	5.2	24.0
Subsequent stroke	C	0.2	1.4	11.0
Entire flash	C	1.3	7.5	40.0
Impulse charge:				
First stroke	C	1.1	4.5	20.0
Subsequent stroke	C	0.22	0.95	4.0
Stroke duration:				
First stroke	μs	30.0	75.0	200.0
Subsequent stroke	μs	6.5	32.0	140.0
Action integral:				
First strokes	A^2s	6.0×10^3	5.5×10^4	5.5×10^5
Subsequent strokes	A^2s	5.5×10^2	6.0×10^3	5.2×10^4
Interval between strokes	ms	7.0	33.0	150.0
Flash duration:				
Including single stroke flashes	ms	0.15	13.0	1,100.0
Excluding single stroke flashes	ms	31.0	180.0	900.0

*Adapted from *Berger et al.* [1975]

on the order of 10^{-6} H. The peak *di/dt* in a return stroke is on the order of 10^{11} A/sec; therefore, 100 kV will appear across this length of conductor for the duration of the large *di/dt*, typically 100 ns. Figure 1 illustrates how the inductance of a grounding system can cause large differences in earth potential between two structures. Differences such as these can ultimately appear as transient over-voltages on any low-voltage signal cables that are routed between the structures.

The heating and subsequent burn-through of metal sheets, such as a metal roof or tank, are to a first approximation proportional to the total charge transferred by the lightning current. Generally, large charge transfers are produced by long-duration (tenths of a second to seconds) currents that are in the range of 100- to 1-A, rather than by the peak currents, which have a relatively short duration. A typical CG flash transfers 20 to 30 Coulombs of charge to ground, and extreme flashes transfer hundreds and occasionally thousands of Coulombs.

The heating of resistive loads is, to a first approximation, proportional to the action integral. About 1 percent of the negative strokes to ground have action integrals that exceed 10^6 A^2s. About 5 percent of positive strokes are thought to exceed 10^7 A^2s. In the case of brickwork or concrete, the heat created by the action integral will vaporize any moisture that is trapped in small cracks or fissures, and the resulting high-pressure steam explosion can be equivalent to hundreds of pounds of dynamite.

Two properties of the electromagnetic fields cause damage: the peak value of the field and the maximum rate of rise to this peak. For antennas or metallic structures that are "capacitively coupled," the peak voltage on the structure is proportional to the peak amplitude of the field. For other antennas, such as a loop of wire or an underground communication cable, the peak

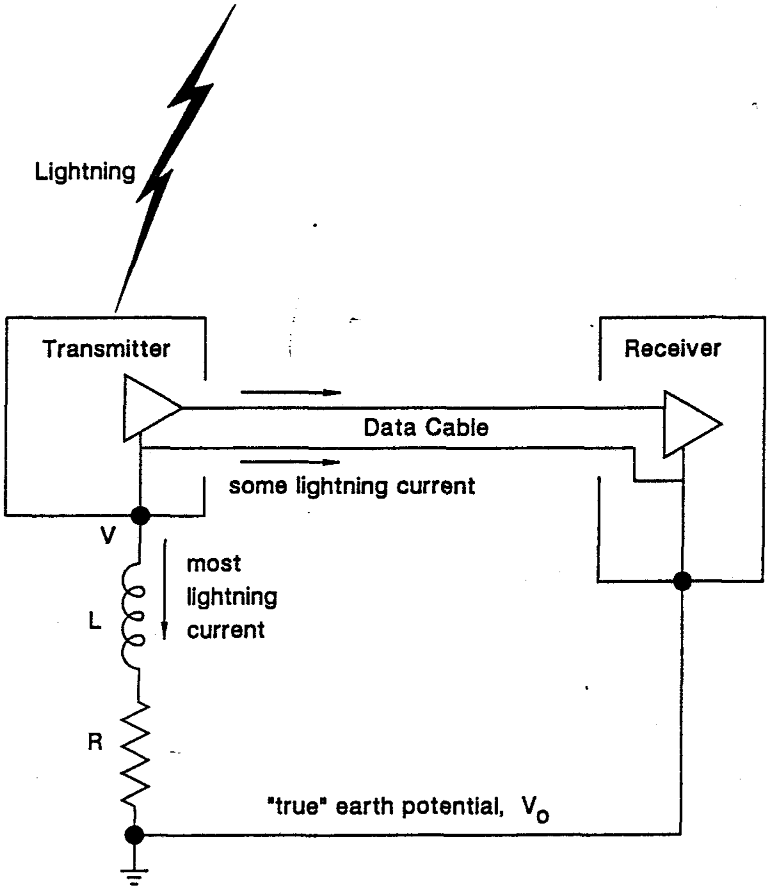

Figure 1b. *A common-mode overvoltage will be produced by a lightning strike to one building when a data cable goes to another structure [Figures 1a,b both adapted from Standler, 1989].*

voltage is proportional to the maximum rate of change of the field. The peak field radiated by a return stroke is on the order of 1000 V/m at 1 km, and the peak power is on the order of 1000 gigawatts.

Protection Techniques

There are two basic methods of lightning protection: 1) current diversion and shielding and 2) limiting the currents and voltages. On residential or commercial buildings, the diversion of lightning currents to ground via a standard system of lightning rods, down conductors, and grounds (Figure 2) is usually sufficient to protect the structure from damage and to reduce (by imperfect shielding) the damage to electronic equipment inside the structure. The function of the rod or "air terminal" in Figure 2 is to initiate an upward connecting discharge that will intercept the leader and thereby define and control the point of attachment to the structure. The function of the down conductors and grounding system is to divert the lightning current around the outside of the structure and deep into the ground as harmlessly as possible. The space that is "protected" by a vertical rod or overhead wire is often described in terms of a cone of protection (see Figure 3), but, of course, this is not absolute. Tall towers (> 30 m) are limited in the space that they protect (see Figure 3*c*). Further details about lightning rods and their installation are available in the *Lightning Protection Code* (NFPA, 1992).

In recent years, the concept of "topological shielding" has been developed that provides optimum lightning protection for most structures and their contents. This technique consists of isolating and then nesting layers of partial shields inside each other, and then "grounding" the outside surface of each inner shield to the inside surface of the next outer shield (see Figure 4). Any transient currents and voltages that might propagate into the structure on conductors are

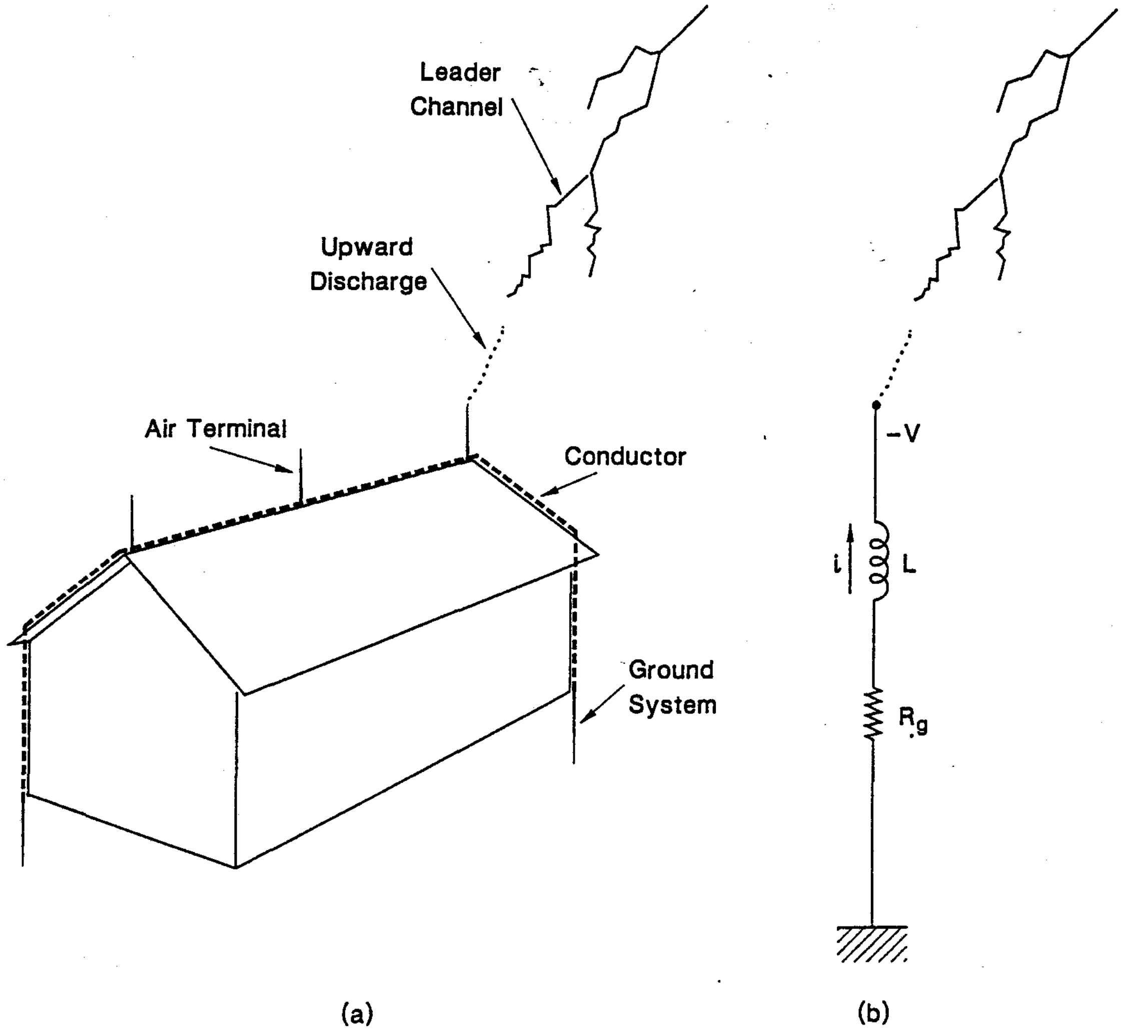

Figure 2. *(a) Sketch of a standard lightning-protection system that is appropriate for small structures, and (b) its equivalent electric circuit (Adapted from Krider, 1981).*

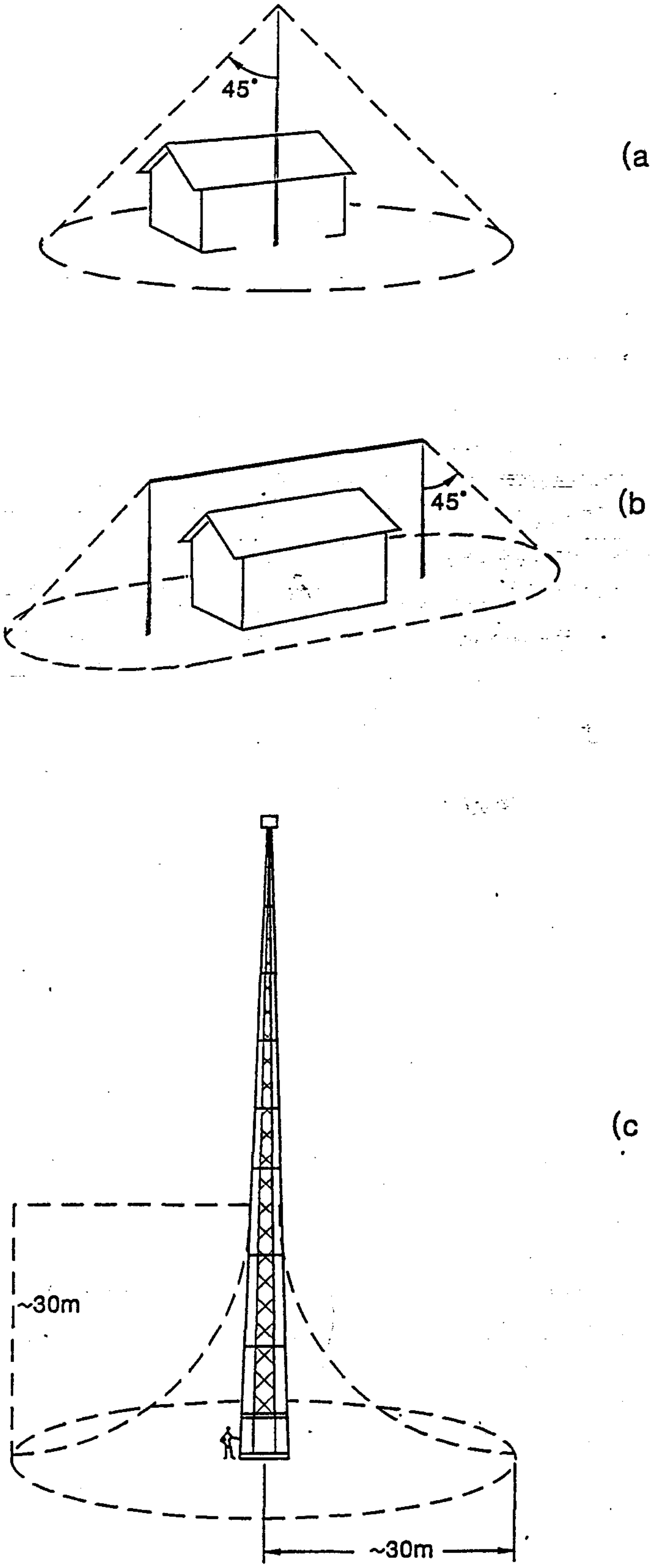

Figure 3. *The zones of protection provided by: (a) a vertical mast not exceeding a height of 15 m, (b) an overhead ground wire above a small structure, and (c) a tall tower (Adapted from Krider, 1981).*

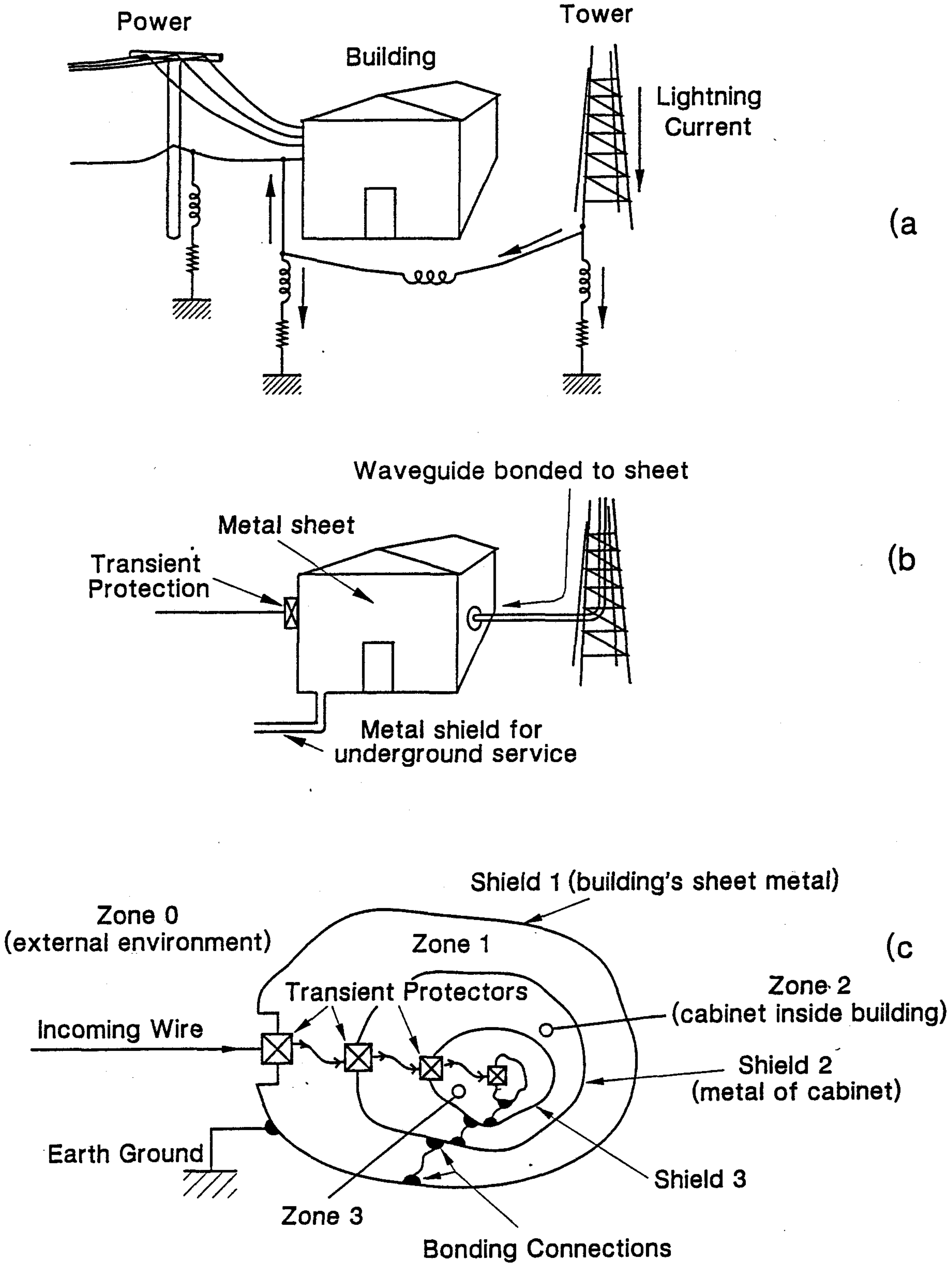

Figure 4. A diagram illustrating the principles of topological shielding: (a) building to be protected is served by overhead power lines and a communications tower (b) external view of building after topological shielding (c) schematic of the topological shielding (Adapted from Uman, 1986).

shunted successively to the outside surface of each shield layer, thereby reducing the hazardous voltage and power levels to acceptable values.

The detailed design and installation of the current- and voltage-limiting devices and the associated grounding circuits will depend on the nature of the system that is to be protected and the signals that are to be controlled. Three types of current- and voltage-limiting devices are commonly used: 1) voltage crowbar devices that switch any transient voltage to zero by short-circuiting the current to ground (the carbon block and gas tube arresters used in a telephone interface are examples of crowbar devices); 2) voltage clamps, such as metal oxide varistors (MOVs) or Zener diodes, that do not allow a transient voltage to exceed a given value; and 3) filter circuits that reflect away (or absorb) the higher and generally more damaging frequencies in the lightning transient. Frequently, all three forms of protection are used together in a coordinated way.

Recommendations

My key recommendation is to use topological shielding throughout the LIGO experiment.

Beam Tube

The large area of the 4-km long beam tubes and the associated base slab is the main LIGO exposure to lightning. Both the Beam Tube Enclosure sections and the base slab are made of concrete that is reinforced with steel mesh. *Bonding the reinforcing mesh in the individual BTE sections both to the base slab and to adjacent sections will create an excellent outer or primary shield that will protect the beam tube against both direct strikes and the electromagnetic transients from nearby strikes.*

Any conductors that penetrate the BTE shield should be equipped with transient surge protectors that are shunted to the *outside* surface of the shield via low impedance conductors.

The beam tube itself should be bonded to the *inside* surface of the outer shield.

The medium voltage power lines and any instrumentation and communications cables (including fiber optics) should be enclosed in metallic conduit and routed *inside* the BTE to minimize their exposure to lightning transients. The outer surface of the metal conduits should be bonded to the *inside* of the primary shield at periodic intervals. Transient protectors should be used at all points where any conductors enter or exit the conduits, and these protectors should be shunted to the *outside* surface of the conduit.

To minimize hazards to personnel, all doors and frames should be electrically bonded to the primary shield, and any wire mesh in the associated sidewalks should also be bonded to the mesh in the base slab and the BTE.

Explosive damage to the concrete in the BTE could be minimized by running a No. 4 (0.25" diameter) bare copper wire longitudinally and outside the full length of the BTE. This wire should be bonded to the BTE sections and "grounded" at periodic intervals.

Any metallic vents and heating or air conditioning ducts should be routed inside the BTE and bonded to the inside of the primary shield.

Structures

Any metal that is on the roof and/or sides of the corner station, end-, and mid-station structures, and the associated steel framework, should be electrically bonded to the base slabs of these structures and also to the BTE.

For optimum safety to personnel, all the above structures should be "grounded" with multiple ground rods and a buried counterpoise wire that is routed around the perimeter of the base of (and outside) the structure.

Lightning rods and appropriate "down conductors" can be used to define and control the points of lightning attachment to critical structures, where appropriate.

Again, all conductors that penetrate a structural shield (e.g., power and communications lines) should be equipped with transient surge protectors that are shunted to the outside surface of the structural shield. A "station class" lightning arrester should be used on the primary and secondary of all power distribution transformers.

All ac power, instrumentation, and communications circuits should be kept inside structure shields wherever possible. If such conductors must go between structures, they should be kept inside the BTE shield and/or in metallic conduit that is bonded to the BTE.

All exterior wiring for outdoor lights, security systems, etc., should be routed in metallic conduit that is bonded to the structural shield. Surge arresters should be applied at all points where such wiring penetrates the conduit or the structural shield.

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