Lightning Protection

String of Pearls

Fall 2012

Risk

You are probably going to die from heart disease. or cancer, not from a lightning strike.

In weather related incidents in 2011 no boaters were killed by lightning. [1] Others killed by lightning were mostly outside in the open (a total of 26.)

In fact of the 1096 killed by weather events in 2011, most were killed by tornados (553 people.) Tornados never occur on the ocean or by the sea, so tornados are no risk for you.

Heat killed 206 people - not likely to affect those who live on the ocean. Flooding killed 113 people. Winter events (ice, storm, Avalanche) killed 28 people. Thunderstorm wind killed 56 people, presumably from trees falling down etc.

In summary, according to the NWS, all the people killed by weather events in 2011, were on the land, or on the shore (41 people were killed by rip currents.)

But according to the USCG, weather was the primary contributing factor in 54 boating deaths in 2011- none of the deaths was caused by lightning. There were a total of 758 deaths in 2011 while boating. Most boaters drowned (70%.)

Looking at the causes of death in the USA for 2009 (the latest statistics,) approx. 600,000 people died from heart disease, and 570,000 from cancer. Respiratory disease were next with 138,000 deaths, followed by Cerebrovascular disease at 129,000. Accidents accounted for 117,000 deaths, suicide for 36,000. Outside the major causes of death, 470,000 people died of which less than 15,000 died from the same cause. Of course, these statistics are for the general population - sailors won't be exposed to some risks at all. If you don't fall off the boat, you won't drown (caused 530 deaths.) If you navigate sober, you won't hit an obstacle or another boat (caused 98 deaths.) You are much more likely to have an accident on the land (caused 117,000 deaths.)

So, all in all, the risk of death by lightning while on a boat is about zero.

[1] US and American islands nws.noaa.gov/os/hazstats/light11.pdf

Why worry?

You shouldn't worry at all. Your life is in the hands of God, who has made you a sailor, and placed you on a substantial boat, where hardly anything can harm you. He did the same for Noah. Neither floods, nor tornados, nor lightning is any concern to you. But what about hurricanes?

In 2011, there were 9 deaths attributed to hurricanes - all of them on the land.

There are stories of people caught up in a hurricane while in their boat: one couple found themselves resting on the top of a tree when it was all over - they survived.

I met a man who had been trapped in hurricane Hugo (a cat. 4 hurricane) on a trawler with his son. They couldn't reach a safe place in time and were forced to secure the boat to a heavy marker post with a chain. The boat became airborne a few times, and the windows smashed in, but they survived.

Not much to worry about, at all, especially about being killed by lightning.

But though you will survive a direct lightning strike on the boat, your electrical machinery and electronics will probably be toast.

Lightning - intro

Lightning is a bolt of fire which you must constrain in non- flammable channels until it enters the sea which will cool and smother it. Imagine that some malicious entity poured a gallon of burning gasoline down your aluminum mast, wherever it flows it will start a fire. You set up the conduits for the gasoline. Whatever you connect to the mast is going to burn.

- If it is the ships safety ground, everything connected to it will catch “fire,” including engine, inverters, computers, microwave, refrigerator and television.
- If it is the thru hull bonding system, the flames will melt the fiberglass around the thru hull.
- If it is the radio RF ground, the radios will burn

You are warned that it is coming. You can hear the crackle on your radio, long before you see the flame. Now is the time to move inside the boat, and prepare the equipment for a possible strike. Though the chance of a strike at sea is small compared to a Florida marina, the consequences of a strike at sea can be serious if you are dependent on electronics for navigation. And more serious if the strike makes holes in the hull below the water line.

Hopefully you have wooden plugs for the thru hulls, in case the fire melts the fiberglass and they fall out of the boat., And have a back up GPS in a safe location. And a place to store the weather radio. And. And a way to communicate with the Coast Guard even if the antennae are destroyed. And a non electrical wind vane steering system.

What? You think that the is little risk that you will get hit? In Florida 1 in 3 boats gets hit by lightning during its lifetime, and suffers damage.

I have two friends in my marina in South Carolina that were hit by lightning at the dock (one of them twice - years apart,) and all electrical devices were “burnt.”

I consider the threat, of sailing into a lightning storm at sea, so serious, that I will sail a day out of my way to avoid lightning clouds ahead of me.

The power in lightning

Strangely, the actual power in a lightning strike is quite small. Though it makes a lot of noise and can damage the boat, a typical lightning strike has no more charge in it than a small lithium battery - such as one in a computer. In fact computer batteries are more likely to start a fire than lightning strikes. During the period

1999-2003, computers and peripherals were involved in an estimated average of 360 reported structure fires per year, resulting in an average 9 civilian injuries, and $16.6 million in direct property damage. Lithium batteries can no longer be shipped in large quantities as cargo, and recently the FAA has recommended that passengers remove all Lithium batteries from electronics before take off.

Let's look at the power in a battery compared with lightning.

Charge is measured in coulombs. 1 coulomb represents the charge of 6.2×10^{18} electrons. If the current from a battery is 1 ampere and it flows for 1 second, then 1 coulombs worth of electrons have travelled from the battery to the load.

Typically, a computer battery delivers 3 amperes for 3.3 hours or so. That is equal to 3 x 3.3 x 3600 (secs per hour) coulombs = 36,000 coulombs.

A typical lightning cloud stores just 400 coulombs.

http://www.lightningsafety.com/nlsi_info/Fundamentals-of-Lightning-Rakov.pdf

Download this PDF and see page 21 for the charge transferred during measured lightning strikes, which measured 330, 180 and 400 Coulombs.

The Power in a portion of the strike dissipated in the mast and wiring is calculated from QV/t watts, where V is the Voltage difference between the top of the mast and the prop shaft or lightning ground touching the sea. If this path is low inductance and low resistance, then the voltage difference from the mast top to the inside the boat will be small, in the order of hundreds of volts. The entire boat may be tens of thousands of volts higher than some part of the sea. The majority of the power in the strike will be the work done in dissipating the charge by heating up the ocean, not the boat.

If the charge is 20 coulombs and the Voltage difference is 100 Volts and the strike lasts 10 milliseconds Power P=20 x 100/0.01 =200 kilowatts

Energy in W-Hrs = Power x time (s) /3600, here 200000 x 0.01/3600 = 0.5 W-Hrs which is approx. 430 calories.

Even if the charge in the cloud is 400 coulombs which is the highest measured, the energy absorbed by the boat will be only 10 W-hrs. The same amount of energy in our computer battery above.

This energy 10 W-hrs is equivalent to 9000 calories of heat, and the sea water around the boat will be heated only a fraction of a degree (imagine the heat from a 100W lightbulb burning for 6 minutes which consumes 10 W-hrs of energy.)

If the strike lasts only 100 microseconds, then the power will increase 100 x , but the total energy is, of course, the same - 10 W-Hrs.

Other people have made the error of multiplying the current by the electric potential of the cloud and thinking that this measures the power. At the beginning of a strike there is potential difference between the cloud and the sea, of thousands of volts, but no current flow, so no power is being generated. When the flash occurs current flows, and the charge is transferred directly to the sea. The voltage difference drops to zero in a few hundred microseconds, so within much less than a millisecond the power also drops to zero.

When you think about it, a small battery can generate enough heat to melt any wire across its terminals and start a fire. There are more houses destroyed by 9V batteries than lightning.

Of course, lightning can produce very strong magnetic fields that can couple to sensitive electronics and damage them. But this will not melt the electronics, or start a fire inside the boat.

The Lightning Attachment Process and Risk Management of the Hazard - National Lightning Safety Institute

- When lightning strikes at or near a critical or high-value facility, stroke currents will divide up among all parallel conductive paths between the attachment point(s) and earth. Division of current will be inversely proportional to the path impedance Z (Z = R + XL, resistance plus inductive reactance). The resistance term will be very low, assuming effectively bonded metallic conductors. The inductance and

> corresponding related inductive reactance presented to the total return current will be determined by the combination of all the individual inductive paths in parallel —the more parallel paths, the lower the total impedance. **National Lightning Safety Institute**

On the land, commercial buildings that house electronics are protected from lightning strikes by directing the strike to a tall tower outside the building. The flash is channeled into a system of metal rods buried in concrete below the tower. Any wires from the tower that lead into the house are equipped with devices that stop any flash current and redirect it into the same ground system. This prevents any flash from reaching the computers and communications equipment in the house.

> - Lightning can be considered as a current source, i.e., output current is independent of load impedance. A given stroke will contain a certain amount of charge (coulombs = amps x seconds) that must be neutralized during the discharge process. If the return stroke is 50 kA, then that is the magnitude of current that will flow, whether it flows through one ohm or 1,000 ohms. Therefore, achieving the lowest possible path impedance serves to minimize the transient voltage developed across the path through which the current is flowing [$e(t) = I(t)R + L\,di/dt$]. Path impedance is directly related to lightning frequency. Efficiency, in part, is a function of EES volume and direction (see IEEE 1100-2005, section 4.8 for further details). Field experience, verified by Finite Difference Time Domain analysis, shows the application of ring electrodes augmented by radial electrodes to have significant advantage over ordinary rod electrodes. **National Lightning Safety Institute**

In a boat we place the tower slap in the middle of the room, close to all our precious equipment. Any wires in the tower (our mast) such as the VHF co-ax and the instrument cables are already penetrating our house and we must somehow stop the flash current that travels down those wires from getting to our equipment.

But we can't use the same devices that are used in a house. My advice is to remove all wires going up the mast - no antennae, no instruments, no lights. The best we can do is to constrain the flash current to the mast only.

More than likely a small charge will run up your propellor shaft, through the engine block, into your negative battery cable and through your ships wiring to get to the mast, or via the VHF co-ax cable shield to reach the antenna on the top of the mast. This charge will attract the charge in the cloud and the electrical stress between the mast head and cloud will breakdown the air which is normally a good insulator, and the charge in the cloud will be dumped onto the top of your mast. We want that charge to travel straight to the sea where the energy will be dissipated in heating up the water.

But if the charge meets an obstruction on the way to the sea, very high voltages will be created at the top of the mast in a few microseconds and these voltages will flash over to everything in your boat that is connected to the ships ground. You will lose all your electronics and electrical machinery, and probably have engine bearing damage too.

To understand what is needed to protect your boat, you need to understand what is happening during a strike, and what methods are used to make your boat safe for the crew, and how to limit the damage to equipment.

To begin to understand this article you need to know something about the physics of electricity. If you are not an engineer, you can still follow the guidelines here and just do what it recommends.

Following is an explanation by the **National Lightning Safety Institute**.

- A complete cloud-to-ground lightning event, referred to as a flash, consists of one or more return strokes. Return strokes are high-peak-amplitude (tens to hundreds of thousands of amperes) current pulses, each lasting for a few hundred microseconds. Analysis of a large quantity of lightning flash data shows the average number of strokes (multiplicity) per negative (the most common type of lightning) flash to be between three and four. Approximately 25% of all negative flashes also exhibit several hundred amperes of continuing current during an interval lasting hundreds of milliseconds following at least one return stroke. In a given flash, consecutive return strokes may strike the ground within several meters of each other, or as far apart as eight km. Analysis of data (as reported by Dr. Phil Krider) indicates that flashes exhibit a “random walk,” having a mean interstroke distance of 1.8 km. Ground-flash density data used in this paper is based upon the first stroke of each flash—detected by the National Lightning Detection Network (see below)—regardless of stroke amplitude or flash multiplicity. The author is unaware of any strike probability estimates that take into account the area encompassed by a multi-stroke flash and/or the current-amplitude distribution of strokes in the flash. Finally, note that the statistically less frequent positive lightning flash usually consists of a single stroke having average and maximum peak amplitudes that are significantly higher than for negative lightning. It is accompanied by continuing current and has a total duration as long as one to two seconds. **National Lightning Safety Institute**

- Absolute protection from lightning may exist in a thick-walled and fully enclosed Faraday Cage; however, this is impractical in most cases. Lightning "prevention" exists only as a vendor-inspired marketing tool. Important new information about lightning may affect sensitive facilities. First, the average distance between successive cloud-to-ground flashes is greater than previously thought. The old recommended safe distance from the previous flash was 1-3 miles. New information suggests that a safe distance should be 6-8 miles (Lopez & Holle, National Severe Storm Center, 1998). Second, some 40% of cloud-to-ground lightnings are forked, with two or more attachment points to the earth. This means there is more lightning to earth than previously measured (Krider, Intl. Conf. Atmospheric Electricity, 1998). Third, radial horizontal arcing in excess of 20 m from the base of the lightning flash extends the hazardous environment (Sandia Labs, 1997). Lightning is a capricious, random, stochastic, and unpredictable event. At the macro level, much about lightning is understood. At the micro level, much has yet to be learned.
- Downconductor pathways should be installed outside of the structure. Rigid strap is preferred to flexible cable due to inductance advantages. Conductors should not be painted, since this will increase impedance. Gradual bends always should be employed to avoid flashover problems. Building structural steel also may be used in place of downconductors, where practical, as a beneficial subsystem emulating the Faraday Cage concept.
- Bonding assures that unrelated conductive objects are at the same electrical potential. Without proper bonding, lightning protection systems will not work. **All metallic conductors entering structures** [2](e.g., AC power lines, gas and water pipes, data and signal lines, HVAC ducting, conduits and piping, railroad tracks, overhead bridge cranes, roll up doors, personnel metal door frames, and hand railings) should be electrically referenced to the same ground potential. Connector bonding should be exothermal and not mechanical wherever possible, especially in below-grade locations. Mechanical bonds are subject to corrosion and physical damage. HVAC vents that penetrate one structure from another should not be ignored, as they may become troublesome electrical pathways. Frequent inspection and resistance measuring (maximum 10 million ohms) of connectors to assure continuity is recommended.
- The grounding system must address low earth impedance as well as low resistance. A spectral study of lightning's typical impulse reveals both a high and a low frequency content. The grounding system appears to the lightning impulse as a

[2] In our case the mast, stays, and keel (poss. co-ax cable and other wires from the mast head) enter the structure.

transmission line where wave propagation theory applies. A considerable part of lightning's current responds horizontally when striking the ground: it is estimated that less than 15% of it penetrates the earth. As a result, low resistance values (25 ohms per NEC) are less important that volumetric efficiencies.

- Equipotential grounding is achieved when **all equipments within the structure(s) are referenced to a master bus bar,** [3] which in turn is bonded to the external grounding system. Earth loops and consequential differential rise times must be avoided. The grounding system should be designed to reduce AC impedance and DC resistance. The use of buried linear or radial techniques can lower impedance as they allow lightning energy to diverge as each buried conductor shares voltage gradients. Ground rings connected around structures are useful. Proper use of concrete footing and foundations (Ufer grounds) increases volume. Where high resistance soils or poor moisture content or absence of salts or freezing temperatures are present, treatment of soils with carbon, Coke Breeze, concrete, natural salts or other low resistance additives may be useful. These should be deployed on a case-by-case basis where lowering grounding impedances are difficult an/or expensive by traditional means.
- Corrosion and cathodic reactance issues should be considered during the site analysis phase. Where incompatible materials are joined, suitable bi-metallic connectors should be adopted. Joining of aluminum down conductors together with copper ground wires is a typical situation promising future troubles.
-

Crew Safety

- Lightning safety should be practiced by all people during thunderstorms. Measuring lightning's distance is useful. Using the "Flash/Bang" (F/B) technique, for every five seconds — from the time of seeing the lightning flash to hearing the associated thunder — lightning is one mile away. A F/B of 10 = 2 miles; a F/B of 20 = 4 miles, etc. The distance from Strike A to Strike B to Strike C can be as much as 5-8 miles. The National Lightning Safety Institute recommends the 30/30 Rule: suspend activities at a F/B of 30 (6 miles), or when first hearing thunder. Outdoor activities should not be resumed until 30 minutes has expired from the last observed thunder or lightning. This is a conservative approach: perhaps it is not practical in all circumstances.

[3] With any mast, the ground system can be made external to the cabin by running straps over the deck to external metal plates or straps, fastened to the hull. Internal metal must be connected to this external ground system at a single point - the mast. This forces the voltage of the interior metal to be the same as that above your head, so you are then in a Faraday shield, and protected.

- If one is suddenly exposed to nearby lightning, adopting the so-called Lightning Safety Position (LSP) is suggested. LSP means staying away from other people, removing metal objects, crouching with feet together, head bowed, and placing hands on ears to reduce acoustic shock from nearby thunder. When lightning threatens, standard safety measures should include the following: avoid water and all metal objects; get off the higher elevations including rooftops; avoid solitary trees; and stay off the telephone. A fully enclosed metal vehicle — van, car or truck — is a safe place because of the (partial) Faraday Cage effect. A large permanent building can be considered a safe place. In all situations, people should avoid becoming a part of the electrical circuit. [Benjamin Franklin's advice was to lie in a silk hammock, supported by two wooden posts, located inside a house.]
- Every organization should consider adopting and promulgating a lightning safety plan specific to its operations. An all-encompassing general rule should be: ¡§If you can hear it (thunder), clear it (evacuate); if you can see it (lightning), flee it.¡¨ NLSI

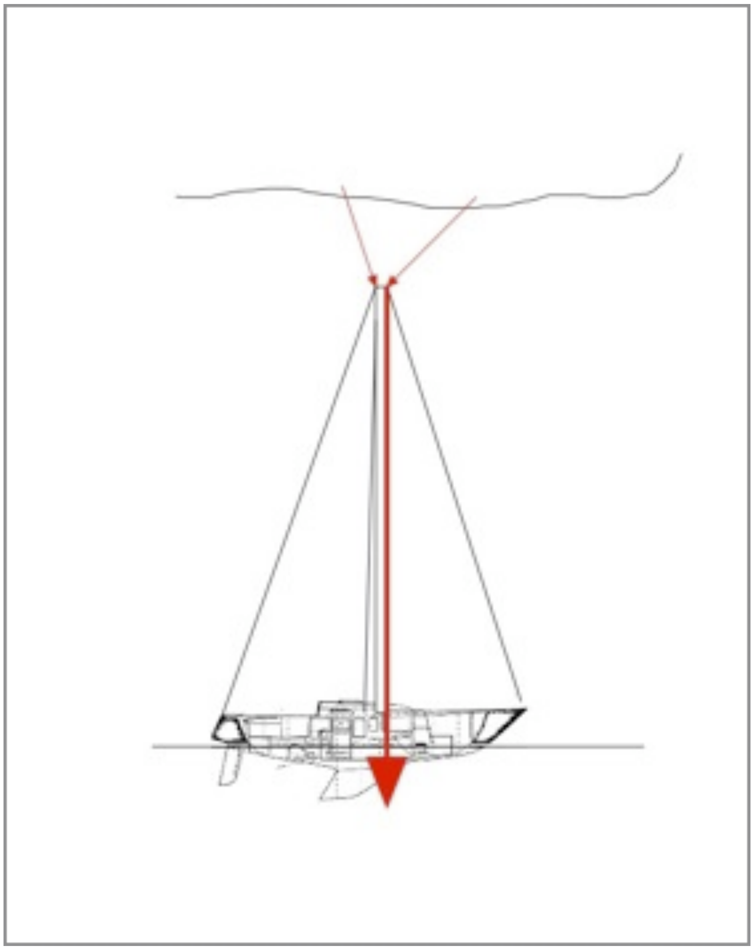
Background on Lightning Technology (PDF)

0.5 Farad Capacitors

The charge of electricity stored in a lightning cloud is around 400 Coulombs. That's not a very big charge - I have designed a 150 KV system that transferred a charge of 75,000 Coulombs in just a few milliseconds. The controlled current was 1 Ampere and the voltage 150,000 volts. But during a spectacular flashover lasting only 1 millisecond, the current reached 90,000 Amperes (every component in the tank was destroyed - blasted to pieces.)

A device that can store charge is a called a capacitor. If it can store 75000 coulombs at 75000 volts it is said to have a capacitance of 1 Farad. In my HV tank, one of the 0.5 Farad capacitors was charged to +75 KV, the other to - 75 KV.

The lightning cloud and sea directly below it store charges just like the capacitors



shown here.

High voltage experience

I am an engineer and the designer of high voltage generators. The CD 150 a 150,000 volt capacitor-discharge generator, for making x-rays, was my first design. Shown here is the high voltage tank.

The destructive power of high voltage was demonstrated dramatically when we tested the safety of this HV system by stressing it above its maximum operating voltage at 180,000 volts during our UL compliance testing. Something flashed over and most of the components in the tank, spewing transformers oil as high as the ceiling of our lab - we had an open inspection port in the top of the tank. Brian, my HV engineer, was drenched with oil. I don't know how much current was flowing during the flashover, but we can estimate - the charge on the 1 Farad capacitors we knew was 90,000 coulombs. If the flash lasted only 1 millisecond, then the current would have been 90,000 Amperes.

This is very similar to lightning strikes, which have been measured more than 100,000 Amperes, producing voltages at cloud level above 200 kv.

My second high voltage design.

A few years later I designed an entirely different machine. It was a high voltage inverter that could generate 100 kilowatts of power at 100 kv and 1 Ampere. It was designed to be used in a cardiac cath. labs for cine angiography. What was novel about the design was that the inverter operated at 10 kHz and in those days no-one had a clue about how to do this. I had to switch 480 volts at more than 200 Amperes at a rate of 10,000 times a second.

How I know all this stuff

When I started my engineer career in the UK, I was part of a design team for a Radar fuzing system for the W144 H bomb. When it was tested in simulated bomb drops, I was the flight trials engineer sitting in the airplane fuselage monitoring the radar signals.

In the 60s I designed a prototype Personal Locator Beacon for airmen which could operate on both civilian and military frequencies.

In the late 70s, in Toronto, I designed an angiographic imaging system for both peripheral and cardiac studies using high speed video recording for instant playback - a first in the Industry.

I designed a grid control device that used RF energy to generate control signals at the cathode potential of a 100 KW grid-x-ray tube which operated at - 75KV.

Boat systems design

•Antennae for many yachts from 30 to 120 feet, using long wire, vertical radiators, and resonant radiators.
•A Solar power systems of 400 Watts.
•RF systems for SSB, HAM, VHF on my own boat.
•A VHF antenna for secure communications on Ray Kroc's Megayacht.
•SSB antenna for AirSea Marine Megayacht.
•Directional VHF antenna for a yacht club.

I was a HAM operator but all my communications now are via satellite and cell phone. It costs $1500 to install a Ham radio system. You can buy a Sat Phone for $750. The cost to use the Sat Phone is around $1 a minute. From a safety standpoint the Sat Phone is better, as you can call the Coast Guard direct.

You can still listen to the nets on Ham and Marine frequencies using an inexpensive receiver that has SSB, and needs no external antenna tuner, nor special antenna.

The receiver can also collect NOAA weather charts which can be displayed on an iPad, iPod or iPhone using HF Weather Fax from the App. store. This is the radio I use, Available on eBay for $400.

With the addition of a tuned antenna ($400) you will also be able to transmit during an emergency. The International regulations allow anyone licensed or not to call on any frequency when safety of life is an issue. This radio has the capability of transmitting on both HAM and Marine services during an emergency. The antenna I recommend - a marine outbacker - is made by Terlin (Australia) and sold in the USA by Jim Burns jfburns@windstream.net

Here is another nice radio used by yachties. An ICOM 735 $400 typical used which can transmit on all frequencies by clipping a diode.

Lightning suppression.

The co-ax cable coming into the radio requires a surge protector which is bolted to the lightning ground, and put in line with the antenna cable.

Model TT3G50 series specifications: Surge Handling: 500 joules at 50 kA 8/20 us waveform (IEEE); Turn-On: 350 Vdc typ <3 ns; Throughput Energy: typically less than 500 uJ depending on waveform and model; Repeatability and survivability: We lab test for 3000 surges, 20kV at 10kA; Response time: <80 nsec; Insertion loss (N connectors): 0 thru 1 GHz, <0.1 dB; 1 thru 2 GHz, <0.2 dB; 2 thru 3 GHz, <0.5 dB. The above numbers are "typical" and dependent on lab calibration and "jumper" cables.

Lightning stories

Thank God, I have never had any experience with a direct lightning strike. Though I have sailed 10,000 miles in the Atlantic and Pacific in my own boat and witnessed many lightning storms from a distance of several miles at sea, I always managed to steer a path clear of them.

I have met several boat owners who have had direct strikes, two were in the same marina as me. Until I heard their stories first hand, I wasn't concerned about strikes, as I figured that my boat was safe - how little did I know.

After chatting with one of them, who had all his electrical and electronics equipment destroyed in one strike including the melting of the cable harness to the engine, I became curious as to how a boat should be protected.

He had connected all his metal tanks, engine, mast and shrouds to a central bonding point, but he had no way to connect this to the sea except through the engine and shaft. His bonding system also extended to the thru hulls, battery ground, and radio ground.

I decided that what he had for a bonding system wasn't good for the radio. And after some study I decided it wasn't good for lightning safety. So, I began this investigation into lightning protection that you can read here.

As an engineer I am able to understand technical articles about lightning, and I can translate their guidance into practical advice for yachties. Now, this article is only a description of what I am doing on my yacht for lightning protection, radio installations, and corrosion protection. There is no promise that what I do for my boat will be the best method for you. But, hopefully, you will begin to understand what you need to do in order to protect your own boat and equipment.

Lightning and impedance

In a direct strike, the charge from the cloud is transferred to the boat and finally to the sea. The charge will run down the mast and hopefully go directly to the sea by a route that has the lowest impedance. If there is no low impedance path for the charge, it will transfer to various parts of the boat and voltage will build up until there is sufficient to flash over to the sea. During the final leap to the sea, the arc will jump an air space of several inches.

When a car is hit by lightning, the arc has to jump from the frame to the ground, because the tires act as a barrier.

On a boat the path might be through wires running along the inside of the hull, or bolts in the hull that are attached to the shrouds. The flash will have to penetrate the hull to reach the sea. In the process fiberglass will be damaged as the moisture inside the fiberglass vaporizes due to the high temperature of the flash.

Strikes always consist of several flashes close together but you see them as a single flash. Flashes usually continue for several milliseconds. Some, linger on for up to two seconds.

Commercial lightning protection equipment has to be tested for certification. The industry standards are a test with an electric charge of 6KV and 200 A which is transferred to the device under test in a short pulse of 20 microseconds with a current rise time of 8 microseconds. The waveform is similar to that seen in natural strikes - though much lower energy, as the energy of natural strikes is too dangerous to create in the lab.

When an engineer looks at the path the flash travels, he calculates not only the resistance but also the impedance (inductance primarily) of the wires. The flash pulse travels mostly on the surface of wires, and the effective resistance is more than that taken from a wire gauge table. Inductance is by far the biggest obstacle to the flash, and at the speed the flash current builds up, inductance effects are more than they would be at say 60HZ, so ordinary calculations for inductance at low frequencies can't be depended upon.

The electrical formula for the voltage on a wire with inductance L is

V=Ldi/dt, where L is in Henries, and di/dt is the rate of change of the current with time. In boats, the inductance of the wiring to the sea could create 100 kilovolts at the mast head. At 100 KV at the masthead, there will be flash over to nearby objects. In dry air the flash over rate is 3kv/mm, so 100 KV would flash over a 33 mm gap (1.4 ins), but in the wet air around the mast, it could flash much further, taking out the mast head equipment and flashing to the shrouds. Some people have installed a spike at the masthead which is higher than the highest instrument (often a VHF antenna) and offset from the instruments to help protect them. But this won't help if the lightning bonding system has high inductance, because the voltage will increase dramatically and flash over the limited spacing that is possible at the masthead (6 inches or so.)

Usually the first thing an insurance adjuster wants to know is whether or not the VHF antenna melted - this is an indication of a direct strike. What causes the antenna to melt is the extremely high voltage generated by the inductance in the antenna coil plus the inductance in the wires at the base of the mast which impedes the flow of current. This happens in microseconds. The temperature generated by this voltage reduces the ss wire of the antenna to a molten mess.

The charge moves down the mast at 0.6 x the speed of light - at approx. 200,000 KM/S. As the charge runs into obstructions, voltages built up on each piece of wiring, and it is possible to experience thousands of volts difference at various locations along the path to the sea.

If every metal object in the boat is interconnected, then the charge is spread all over the boat, creating havoc for all those devices not designed to carry the lightning charge .

The RF co-ax cable from the VHF antenna provides two paths for the charge, one in the core and one along the shield. The flash down the shield reaches the end of the cable first and so produces a huge voltage difference, and flash over to the core can be expected with thousands of volts applied to the RF connection at the radio.

No matter how big a wire you use to connect the mast to the ocean, you must expect the mast to be thousands of volts above the sea voltage. What you want is for all metal in the cabin and cockpit areas to be at the same voltage, so that you can't be electrocuted.

There have been documented cases of people in a car suffering no injury during a direct strike, while another person outside the car at the window was killed. Inside the car the voltage was the same in every corner. Even though the voltage inside the car may have been in excess of 10000 volts, the occupants were also at 10000 volts - everyone safely clear of the ground, insulated by the rubber in the tires. Like birds sitting on a high voltage wire, no-one in the car experienced the voltage.

What you must do is make your boat like a car body, which encloses the occupant in a protective "shield". By connecting every piece of metals <u>above your head</u> to the sea - i.e. toe rails, genoa tracks, lifelines, mast, dodger, house (if metal,) by as direct a route as possible to the sea, using heavy gauge wire (aluminum or copper) you will be making a protective shield.

But, don't connect your ships wiring and ground systems to this lightning ground. You don't want to encourage the lightning to find its path to the sea via your electronics, or via you battery wiring and negative bus. If you do, the flash will take out all your electronics, melt some of the wiring, and could damage vital mechanical devices, such was the main bearings in the engine or the propellor shaft (both of these things have have been experienced by boat owners.) One owner only discovered the engine damage after the insurance was settled for the visible damage.

Connecting internal wires and tanks to the lightning ground only increases the inductance of the system unless they are each directly connected to the sea. If the current path requires the flash to travel first to a tank, then to a wire, finally to a thru hull, each contributing to the inductance, the voltage created will perhaps be enough to cause a side flash to other wires.

Impedance

Impedance is the electrical term for the resistance to the flow of charge. On a boat impedance consists of the actual DC resistance of the mast and wires to the sea, plus the inductance of that mast and those wires. The measurement of inductance depends on the frequency characteristics of the strike. The faster the strike, the higher is the inductance. Inductance is a measure of how strongly the build up of charge is delayed by the wire. A pulse of lightning with a very fast rise time would exit the path we have designed for it if the ground wire bends 180 degrees. The charge will exits the wire by burning through the insulating jacket and flashing over to something that is nearby, which might be a crew member.

The electrical formula for the voltage on a conductor due to an inductance is:

V=Ldi/dt, where L is the inductance in Henries, and di/dt is the rate of change of the current with time.

For a lightning strike in the air above the mast, the duration of the initial flash can be as short as 0.1 milliseconds with a 200,000 Ampere flow of current. If the inductance of your mast and wiring is 0.000005 Henries, then the instantaneous voltage generated at the top of you mast compared with the bottom would be 0.000005 x 200000/.0001 = 0.05 x 200000 = 10,000 Volts. No wonder the VHF antenna melts.

And such voltages has been measured in strikes.

Although our aluminum masts have quite low inductance, the wires carrying the charge to the sea could be quite inductive.

Using an app from the web. http://www.eeweb.com/toolbox/wire-over-plane-inductance

Lets look at a #8 Ga wire 2 feet long.

- Inductance is *569 nH.*
- Resistance is *0.001 Ohms*
- For a strike current of 200,000 Amperes
- *V(R)=200 volts + V(L)=569 x* 10^{-9} *x 2 x* $10^{5}/10^{-4}$ *= 1138 volts*
- So, the inductance of a straight 2 foot length of #8 wire creates more of a problem than the resistance of the wire.

You might think that since inductance slows the passage of the flash, it would be good to have a huge inductor at the top or bottom of the mast. But all this would do is create enormously high voltages that would flash to shrouds, antennae, and anything within a few feet of the mast. The initial flash from the cloud has passed through perhaps a mile of air without stopping and a few feet of air space from mast to deck won't stop it. Remember energy cannot be destroyed - it can only be converted from one form to another (charge to heat for instance.)

So for safety sake we have to channel the flash along a safe path to a safe place where it can be converted to heat without damaging anything. That's why we set up an air terminal to catch the flash before it flashes to the deck and cabin. The mast channels the flash safely to the sea.

How can we do this?

Making the single point lightning safety ground.

On a boat the aluminum mast connects to the sea and this is the point that is to be used for the lightning ground. The charge is to be transferred to the sea at this point.

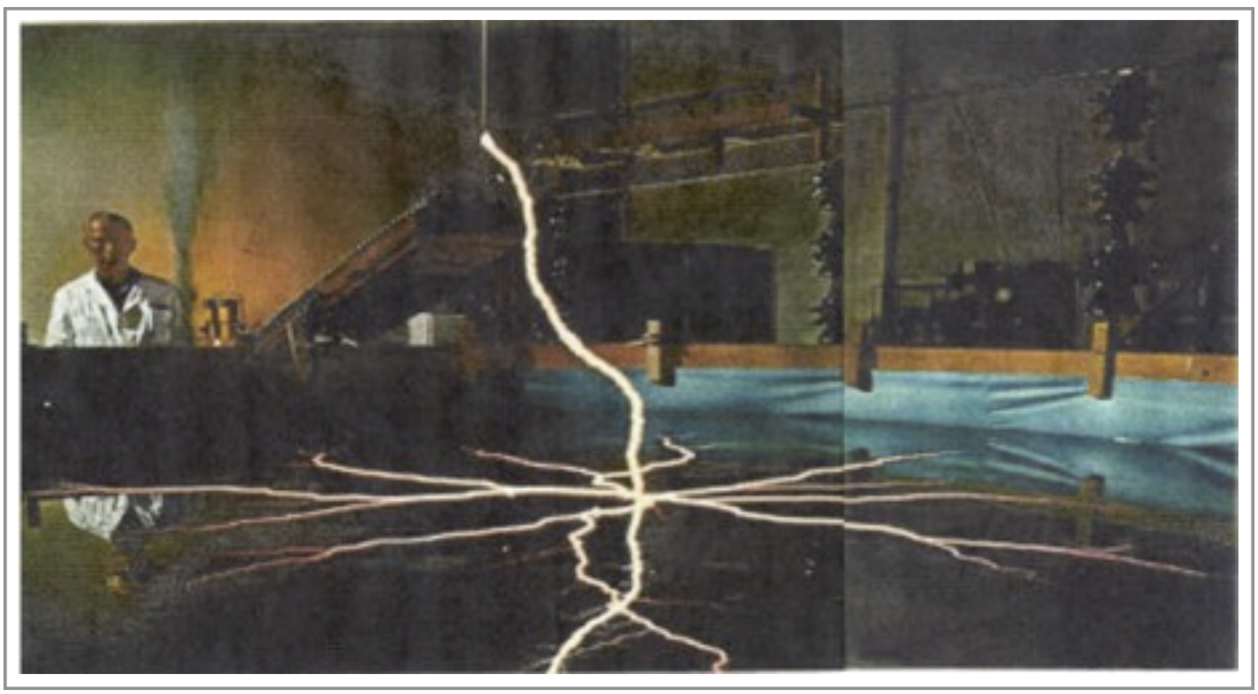
Wire the mast to the metal keel using a short aluminum tube (such as bimini tubing) or short heavy copper wire. [4] There should be no bends more than 45 degrees.

- Braided bonding straps should not be used because they corrode too quickly and can be a point for RF interference.
- Avoid differences in potential. Do not install separate grounding electrode systems. Follow NEC 250/IEEE 142/FAA 019d requirements here. NLSI

[4] You must expect corrosion between the copper wire and the mast, where it is connected to the mast, and you will have to clean the connection, so make it where you can get to it. Don't paint over it as that increases the inductance. The connection to the ss keel bolt should be okay as ss and copper get along okay if the keel bolt is always dry. On my boat the keel bolt adjacent to the mast is always dry - it is only a few inches below the cabin sole.

You can't always depend on the keel bolt to make a perfect connection to the sea, as the lead keel may be encased in glass or epoxy. We want the sea water to absorb the energy from the flash not the hull. But the keel may absorb some of the energy and damage its insulating coating (my boat has 1/8 of epoxy on the keel. So you may finds pin holes in the keel after a strike. That's a small price to pay. Best to sand away the epoxy coating for at least a square foot (sea water - 4 sq ft. in fresh water.) Still, the keel has to be scrubbed clean regularly.

If your sump is deep and the bolts are way down you will have to do something else for your sea connection. There are commercial hull attachments which can carry the charge to the sea. Mounted outside the hull at the waterline and running for a few feet each side, they are connected by wire to the mast. Commercial terminals for the hull cost about $500 each.



Article describing the distribution of charge in the ground/sea. This is a PDF file.

The mast and shrouds

The area of the mast that connects with the flash is referred to as the air terminal (this is where the air strike terminates.) On houses and churches the air terminal is a metal rod that sticks up higher that anything else. The idea is that the strike will touch the air terminal rather than other roof structures, but there are many reports of the strike preferring gutters and drain pipes. The air terminal is usually pointed but the best shape has been shown to be a 1/2 inch to 1 inch diameter blunt end.

On my boat there is nothing electrical on the mast head.

- A little bitty lightning rod cannot carry all the current and voltage. Where they gonna go? They will attach to all conductors, and flow according to impedances.
- Alternatives to rods: Overhead grounded shield wires and free-standing nearby conductive masts/poles. These indirect designs often are better than rods...so says NASA E-0013 and USAF AFI 32-1065. In some cases (for example, steel radio tower), no rods may be the answer. A rod design is very high maintenance. NLSI

The is no guarantee that a metal spike will protect mast head electronics, and one is not needed if there are no mast head instruments. You must assume that there will be side flashes that will go down the stays and shrouds, even though the ss shrouds are nowhere as attractive as the alloy mast which is a 10 x better conductor , so the shrouds and stays must be connected to the lightning ground also. I use a #6 ga. wire. The shrouds connect to an alloy chain plate which is connected to the bulkhead by 5/16 inch ss bolts, so any other wire material (copper, aluminum) connected to the bolts will suffer corrosion if any moisture is present. On my boat this area is dry, so I haven't seen any corrosion in 35 years - the chain plates have never leaked. In any case I check these wired connections visually, annually.

If you have an insulated backstay the wire going to it from the antenna tuner will be ungrounded and you must then provide a way for this bit of wire to be grounded otherwise high voltages can develop on the backstay and destroy the antenna tuner. Devices are available that will short out for a few milliseconds and safely carry the strike current to ground. In fact all antennae on the boat must be protected in a similar way.

More safety considerations

Never allow a thru hull to become part of the lightning ground. There have been many cases where the thru hull has been damaged. Sometimes they have been blown out causing the boat to sink in the owners absence. At the very least the fiberglass would be damaged around the thru hull. Thru hulls don't make a good electrical connection to the sea when closed, and in most cases the thru hull is painted over. They are way too small to carry the energy of a strike, and they will get hot and vaporize the moisture in the glass laminate perhaps causing an explosion that can blow the fitting out of your boat.

If the boat is at the dock, leave the boat for a building or the car as soon as you hear thunder less than 6 miles away (count 30 secs from flash in the clouds to the sound.) It has been reported that lightning can produce high voltages on masts when the strike is five miles away. If the lightning is closer don't go outside because you will be at risk.

If you are caught in the boat during a storm stay inside in the middle of the boat, not touching any of those metal parts during the storm, and stay there 30 minutes after you think the lightning is over.

If your mast is exposed in the cabin, insulate it with rubber that is rated for 10,000 volts. Also insulate metal grab rails, which, if they are longer than a foot, should also be wired to the same ground as the mast.

If you have not already disconnected the radio and electronics from their antennae and power, don't touch them. Don't even touch light switches. But read on to see what you should do to protect the electronics.

The electronics

There are two ways to protect the electronics. Remove from power and other connections and place ten feet away from the mast, or install all devices in a Faraday cage (an aluminum box) and place surge suppression devices on each wire that enters the box.

On my boat all small electronics are placed into a metal box during a storm - portable VHF, small GPS, phones etc. This box is not wired to the lightning ground - it is safely tucked beneath a bunk and insulated by 3/4 ply and a 5 inch bunk cushion. There are no wires in the vicinity of the tank, so it is unlikely to be flashed to. It will raise in voltage from static charge, but the entire box will have the same charge. The tank is bonded to the fiberglass and the charge will quickly bleed out to the sea via the hull.

Computers are disconnected and can be stowed aft in a quarter berth, if there is no special box for them.

Outside NAV instruments are mounted under the frame of the solar array, and this frame is joined to the mast and to the sea and is part of the lightning ground.

A Faraday cage is formed by the solar array frame (10 ft x 4 ft), alloy toe rails, genoa tracks and lifelines, all wired together with #6 ga. wire. Inside the boat is another Faraday cages for the electronics. Any wires that travel between cages must have suppression at the entrance to the cage, because voltages can build on any wire in the boat, sending currents into sensitive equipment.

Thru hulls

These are not to be connected to the lightning ground. On a fiberglass hull, bronze thru hulls should be isolated from one another. You don't want the flash to enter the sea via your thru hulls. Some have instruments in them (log and depth) and in any case high currents could damage them. There have been cases where wired thru hulls with non-conductive parts were vaporized, and the boats took on water. Many ball valves have ss balls in a PTFE seal and if the valve is closed the flash path to the sea would be inhibited by the stainless steel ball (some use chromed brass) which is insulated from the bronze housing. Though the ball still connects to the sea even when closed, stainless steel is a 10x worse conductor than bronze, and may heat up enough to melt the PTFE. The bronze valve housing itself may be poorly connected to the sea, and the thru hull itself may overheat enough to damage the fiberglass.

If you use a thru hulls as a way to connect your radio safety ground to the sea, you should use an isolating capacitor (0.2 microfarads) between the radio ground lug and the rf grounding foil, so that only rf flows to the thru hull.

This method avoids the flow of dc that can result from wire-bonding thru hulls to the ships grounds (also through the battery connection,) which would cause corrosion of the fitting.

In order to protect transducers, you have to disconnect them from the instruments. A length of wire more than a foot or so can experience high voltage along its length if it is close enough to the mast and running parallel to the mast, such that the rapidly fluctuating magnetic field around the mast couples to the wire. It is this magnetic flux that destroys electronics that may not be touched by a flash directly.

You must put the electronics in a safe place during a storm. Best protection comes from a Faraday cage designed for the purpose. A steel oven may be sufficient, but stainless steel is not a good magnetic conductor, and is a relatively poor electrical conductor. A Faraday cage of aluminum or copper won't do much to reduce the magnetic field. I have put my NAV equipment in a steel safe that was meant for a home use. It was so heavy I couldn't lift it. After many years of never being hit by lightning, I removed it. I may put another one back in just to protect the laptops - it will have to be 18 inches inside and 14 inches deep. That will be a heavy safe! There will be space for the SSB and other small radios. I use a small Yaesu ham radio and no antenna tuner and it will fit.

Antennae

A reminder: antennae tuners are vulnerable when they connect to the backstay. The ground nut is also connected to the sea. This combination makes a low impedance path for the flash, and the unit will be damaged. Disconnect the AT during a storm. This means that you have to be able to easily reach the connection to the AT or the backstay, and you have to be able to cut the connection - no tape to unravel. Use a quick dc disconnect such as a waterproof trailer hitch plug for the wire to the backstay. If you are using a tuned antenna as I do, then use a DC disconnect at the pl259 connector connecting to the antenna. Also protect the rf switches and the cable at the radio. It is best to run all cables inside the faraday cage for their entire length.

I have the co-ax within a cage except for a 4 foot length that passes the mast at right angles which reduces the magnetic coupling but is a bit too close to the mast to avoid capacitive coupling of the flash current.

None of the NAV equipment is connected to the ships DC ground, nor the lightning ground (of course) as it is run from a separate sealed battery located in the NAV station fwd. of the mast. This battery is charged from its own isolated solar panel that is by design isolated from the frame which is part of the lightning ground system. There is no connection to the ships dc charging system.

I have a 20 foot small gauge galvanized wire that can be hoisted by a halyard and connected to the SSB co-ax. by an adapter. It is resonant on 12 MHz and requires no tuner. Other lengths work on other frequencies.

Small instrument protection

I have a small (20 gal) Faraday cage that was once a water tank under a bunk about 4 feet from the mast. It is made of Monel. It has a 5 inch access port which is big enough for all my NAV instruments except computers.

Material properties

To find the voltages that appear on the lightning ground system, you must take into account each item along the path of the flash.

Junctions have little inductance, so you can ignore this factor, but a poor joint can cause a voltage to appear across it. Commercial practice is to jumper the joint with a heavy cable even if the joint is welded. This is especially important where two dissimilar metals are involved - such as a copper wire terminal bolted to an aluminum mast. Bi-metallic connectors are available commercially which stop any corrosion. You can also prevent corrosion by coating the junction with a grease that is conductive (silver conductive grease - 6 ozs costs $30.) The grease fills the voids to prevent moisture ingress. Since there is no electrolyte present at the junction there is no corrosion.

You need to calculate whether the voltage differences created by the resistance and inductance of the various lightning paths are going to be enough to cause a flash over to another conductor, or sufficient to shock someone.

To calculate resistance use the formulae

$R=p\ l/A$

p is the specific resistivity of the material in micro-ohm cm

l is the length in cms of the wire or metal segment carrying the flash current.

A is cross sectional area in square cms of the conducting segment.

Aluminum has a p=2.65 micro-ohm cm

Steel has a p= 16.62 micro-ohm cm

Copper has a p=1.68 micro-ohm cm

Voltage drop along the segment is calculated using

Vdrop=IR where I is the current in Amperes, and R is the resistance in Ohms.

Assume a flash current (max) of 200,000 Amperes and a duration 10mS.

Let's look at the mast first.

MAST

Typically the mast is an oval shape. Say, long dimension is 8 ins and short is 6 inches (20 cm x 15 cm) and wall thickness is 0.5 cm. The approximate length of the cross section of the mast is 50 cm. So it's area is 50x0.5 = 25 sq cm. if the mast is 1500 cm long.

R=2.65 x micro ohm cm x 1500/25 =2.65 x 60 micro-ohms = 159 micro-ohms. If the flash current is 200,000 Amperes, the voltage drop along the mast is .000159 x 200000 V = 31.8V which is a very small.

Now let's see what size copper cable would be needed to carry this flash current down a wooden or carbon mast with the same effectiveness as the aluminum mast.

A (sq cm) = pl/R, where p (Cu) is 1.678, l = 1500, and R is the same 159 micro- ohms.

A = 15.8 sq cm which is a smaller cross section than the aluminum mast (25 sq cm) because the conductivity of copper is somewhat better than Aluminum. The wire diameter is calculated from A = pi x d x d/4, or d = sq root of A x 4/ pi = sq rt (15.8 x 1.27) = 4.5 cms or 1.8 inches!

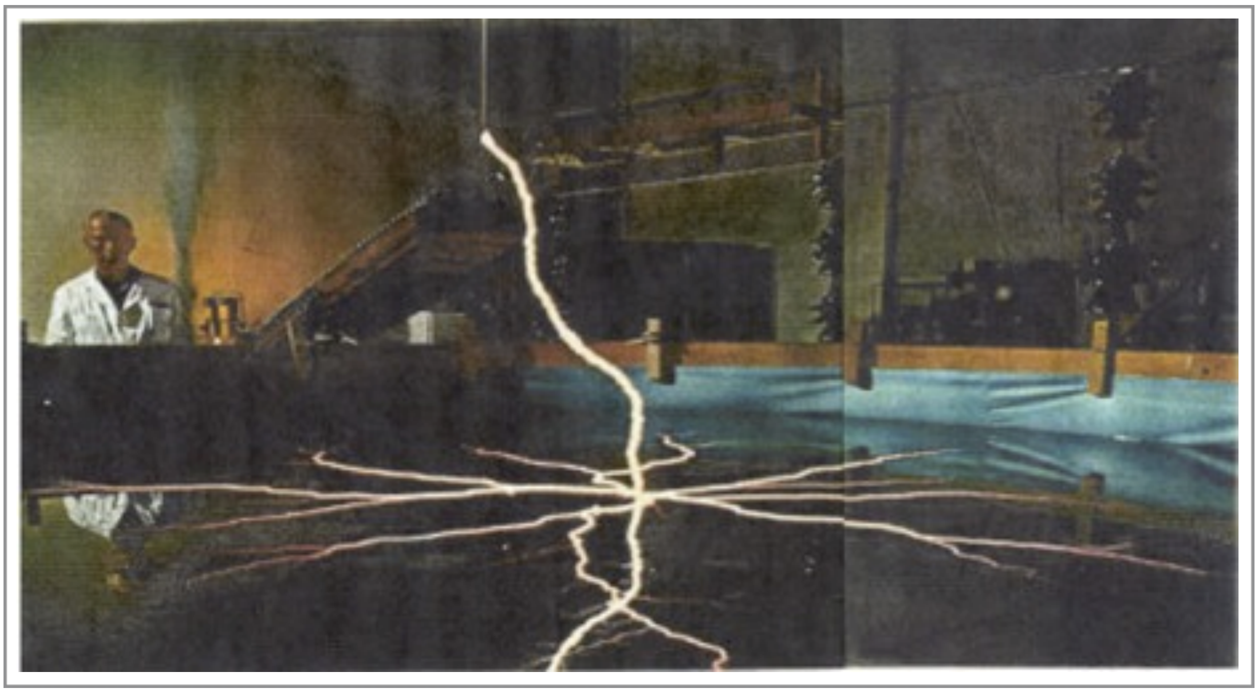
A copper wire 1.8 inches in diameter weighs 9.6 lbs per foot. A 50 feet long wire would weigh 480 lbs and cost $5,000.

Realistically a smaller wired would have to be used, but what would this do to the voltage?

If we uses a # 4 ga copper wire the resistance would be 0.75 ohm and the voltage difference between the top and the bottom of the wire would be 200000 x 0.75 Volts or 150 kilo-volts! this would cause the lightning flash to arc over to everything within a few inches of the mast, including shrouds, wet sails, Radar, and mast mounted lights.

An aluminum mast is a better way to conduct the flash current. It will prevent flash overs and it won't heat up much because very little energy is dissipated in the aluminum. Of course the energy from the flash has to dissipated somewhere. We want that place to be the sea and not our hull and wiring.

The sea adjacent to the hull is not a ground - i.e it is not zero volts. The flash



energy is dissipated along multiple paths from our boat into the sea. The voltage at the sea adjacent to the hull may be thousands of volts, slowly reducing in voltage as the energy gets absorbed by the water.

Sea water has a resistivity of 0.2 ohm M which is hundreds of thousands of times more resistive than lead and copper. If the exposed lead is 1 M below the surface, the path to the surface charge (which is where the flash is headed) would measure 0.2 Ohms. Of course, the flash would distribute itself so that there were multiple paths, and the current per path would be much lower. In the photo above (Nat Geo) there are more than 10 paths. Even so, the voltage created at the keel would be several thousand volts. You are not any better off if there is a direct connection to the sea at the waterline. The resistance of the sea will still create high voltage at the boat sea terminal. Even a long piece of metal attached to the hull exterior will be charged enough to create flashes. But some boats can't use the keel as a terminal because they are encased in fiberglass, or the keel bolts can't be reached, so an external metal terminal is necessary to avoid damage to the hull.

Resistivity of common materials

- Lead is 2.2×10^{-7} ohm M
- Copper 1.68×10^{-8} ohm M
- Aluminum 2.82×10^{-8} ohm M
- Drinking water 2 - 20 ohm M

Flash current can travel many miles in the seas before its dissipates completely. A flash into the sea five miles from your boat, can still be felt.

So, during the flash the metal parts of the boat and the sea adjacent to the boat, are charged by the flash to thousands of volts.

It is important that people in the boat are at the same voltage as anything they are likely to touch or anything that they are very close to. It is important that they don't have their hands touching things that are at different voltages during the flash. Ben Franklin suggested lying in a silk hammock in the middle of the boat!

What I would do, if I am caught out at sea, is sit on a bunk away from the mast (in the quarter berth which is shielded above by the solar panel frame and the toe rail) or, if in the cockpit, under the solar panel and on the fiberglass seat away from the tiller (which is stainless steel.) I always rather avoid storms by changing course, sometimes reversing course for many hours.

You can see from this discussion that the primary purpose of the lightning ground system is to keep voltage differences generated within the interior of the boat to very low values, so that crew will be safe. The secondary purpose is to prevent flashing to other wiring and the ship's equipment.

The lightning ground will not prevent damage to electronics. As I said before you have to hide the equipment from the flash, either physically or electrically using isolation devices.

Now, let's look at the flash path to the sea from the mast.

The flash path

At the mast there must be a low resistance path to the sea. On my boat there is a short 18 inch # 4 ga copper wire (300 micro-ohms per foot) a which has a dc resistance of 450 micro-ohms. It runs in a straight line to a ss keel bolt and is fastened to the bolt through a copper lug installed when the boat was built. If we ignore the connection resistance, voltage drop from the foot of the mast to the keel bolt at a flash current of 200,000 Amperes would be 90 volts i.e. the mast would be only 90 volts above the keel bolt, so if I stood on the keel bolt and touched the mast at the base (a stupid act,) I should survive, even though the mast was 10 KV above the sea.

The #4 ga wire wouldn't heat up enough to melt its jacket, which otherwise might burn something nearby.

Remember from basic physics that voltage is the measurement of charge differences between two locations. In a lightning strike, a large charge is transferred from a cloud to the sea. If there is no clear path to the sea, the inside of the boat will charge up until there is sufficient voltage between the hull and the sea to punch a hole through the hull and allow the charge to dissipate. Often a charge produces enough voltage to flash over to wires that run to the engine and from there it goes out the shaft into the sea. The engine wires may be discolored and any plastic insulation melted.

It is important that voltage difference between the hull and the sea doesn't reach a level where the fiberglass will break down. Fiberglass is used for high voltage insulation. It requires a very high voltage to punch through 0.5 cm of fiberglass, yet there are many reported cases of just that. Fiberglass hulls have air voids and also water pockets which appear as bubbles in the gel coat. Lightning will easily find these pockets. Normally dry glass fiber will support a voltage gradient of at least 500 kv/inch. Flashover in air will occur when the gradient is 20 kv/ inch or more. So, the flash will preferably flash-over through the air to a nearby wire bundle (six inches away) than go through a

0.5 cm glass hull. If it does penetrate the hull it will probably be at a location where the hull is thinner, above the water line, but close to the sea. If the boat is heeled at the time of the storm and is struck, the exit point for the flash may be close to the metal toe rail, especially if it underwater!

Toe rail as grounding device?

The aluminum toe rail on my boat runs the entire length of the deck. If it is connected to the mast above the deck, the wire and the toe rail will form a Faraday cage to protect the crew inside the boat. An aluminum flat bar run from mast to toe rail amidships (5 feet) that has a large enough cross section to keep the toe rail less than 100 volts lower than the mast at deck level, should be adequate.

Let's see what I would need:

The resistance of the path would need to be <0.5 milliohms. (100V/200000A.)

p=2.65 for aluminum (we use aluminum because it won't corrode when joined to the aluminum mast and aluminum toe rail using aluminum fastenings.)

l = 125 cm

A = pl/R, =.00000265 x 125/.0005 = .00265 x 250 = 0.4 sq cm = 400 sq mm, and 1 sq mm = 1000 circular mils, so 400 sq mm is equivalent to 400,000 circular mils. Now 0000 ga is 212,000 circular mils and is 1/2 inch in diameter. We would need an aluminum or copper wire twice that area about 3/4 in diameter. Or a aluminum bar 5mm thick x 80 mm wide (3 inches approx.) Select thickness that allows the aluminum to be bent to conform to the deck profile, and low to the deck so that crew won't trip on it.

If the rail is not in the sea, charge will build on the rail until the voltage is sufficient to arc to the sea. In wet salt air with wet hull and decks the arcing voltage will be still be high but much less than 3kv/mm of dry air. If it is perhaps 50 kv it would arc across the 6 inches of free board on my boat

More to come.

Recommended Grounding Guidelines

Prominent lightning engineers and major technical codes and standards agree as to proper grounding guidelines. We present summaries of those generally accepted designs. **NLSI**

1. From Golde, Lightning, Academic Press, NY, 1977, vol. 2, chapter 19 by H. Baatz, Stuttgart, Germany, p. 611:
"Equalization of potentials should be effected for all metallic installations. For lightning protection of a structure it is of greater importance than the earthing resistance...
The best way for equalization of potentials utilizes a suitable earthing system in the form of a ring or foundation earth. The downconductors are bonded to such a ring earth; additional earth electrodes may be unnecessary…"
2. From Sunde, Earth Conduction Effects in Transmission Systems, Van Nostrand, NY, 1949, p. 66:
"Adequate grounding generally requires that the resistance of the ground , at the frequency in question, be small compared to the impedance of the circuit in which it is connected. By this criterion, it may be permissible in some instances to have a ground of high resistance, several thousand ohms, as in the case of "electrostatic" apparatus ground, the impedance to ground of insulated apparatus cases being ordinarily quite high. In other [situations], however, a resistance of only a few ohms may be required for effective grounding."
3. From Horvath, Computation of Lightning Protection, Research Studies Press, London, 1991, p. 20:
"The earthing of the lightning protection system distributes the lightning current in the soil without causing dangerous potential differences. For this purpose the most effective earthing encloses the object to be protected. The potential increases on the earthing and on all earthed metal parts of the object relative to the zero potential at a distant point. It may reach a very high value but it does not cause any danger if the potential differences inside the object to be protected are limited. Potential equalization is realized by the bonding of all extended metal objects." 4. From Hasse, Overvoltage Protection of Low Voltage Systems, Peter Peregrinus Press, London, 1992, p. 56.
"Complete lightning protection potential equalization is the fundamental basis for the realization of internal lightning protection; that is the lightning overvoltage protection for the electrical and also the electronic data transmission facilities and devices in buildings. In the event of a lightning stroke, the potential of all installations in the affected building (including live conductors in the electrical systems with arrestors) will be increased to a value equivalent to that arising in the earthing system -- no dangerous overvoltages will be generated in the system…
Nowadays lightning protection potential equalization is considered indispensable. It ensures the connection of all metal supply lines entering a building, including power and

(when sailing hard on the wind.) The rail and mast and the other metal parts connected to the lightning ground will be at this voltage for the strike

communication cables, to the lightning protection and earthing system by direct junctions across disconnection spark gaps, or arrestors in the case of live conductors."
5. From IEEE Emerald Book, Powering and Grounding Sensitive Electronic Equipment, IEEE Std 1100-1992, IEEE, NY, 1995, p. 216:
"It is important to ensure that low-impedance grounding and bonding connections exist among the telephone and data equipment, the ac power system's electrical safety-grounding system, and the building grounding electrode system. This recommendation is in addition to any made grounding electrodes, such as the lightning ground ring. Failure to observe any part of this grounding requirement may result in hazardous potential being developed between the telephone (data) equipment and other grounded items that personnel may be near or might simultaneously contact."
6. From International Standard IEC 1024-1, Protection of Structures Against Lightning, International ElectroTechnical Commission, Geneva, 1991, p. 23:
"In order to disperse the lightning current into the earth without causing dangerous overvoltages, the shape and dimensions of the earth-termination system are more important than a specific value of the resistance of the earth electrode. However, in general, a low earth resistance is recommended.
From the viewpoint of lightning protection, a single integrated structure earth termination is preferable and is suitable for all purposes (i.e. lightning protection, low voltage power systems, telecommunication systems). Earth termination systems which must be separated for other reasons should be connected to the integrated one by equipotential bonding…"
7. From FAA-STD-019b, Lightning Protection, Grounding, Bonding, and Shielding Requirements for Facilities, Federal Aviation Administration, Washington DC, 1990, p. 20:
"The protection of electronic equipment against potential differences and static charge build up shall be provided by interconnecting all non-current carrying metal objects to an electronic multi-point ground system that is effectively connected to the earth electrode system."
8. From MIL-STD-188-124B, Grounding, Bonding and Shielding, Department of Defense, Washington DC, 1992, p. 6 and p. 8:
"The facility ground system forms a direct path of known low voltage impedance between earth and the various power and communications equipments. This effectively minimizes voltage differentials on the ground plane which exceed a value that will produce noise or interference to communications circuits." (p.6)
"The resistance to earth of the earth electrode subsystem should not exceed 10 ohms at fixed permanent facilities." (p. 8)

9. From MIL-STD-1542B (USAF), Electromagnetic Compatibility and Grounding Requirements for Space Systems Facilities, Department of Defense, Washington DC, 1991, p. 19:
"This Standard, MIL-HDBK-419, and MIL-STD-188-124 do not recommend the use of deep wells for the achievement of lower impedance to earth. Deep wells achieve low dc

duration. Hopefully you and the crew will be within a Faraday cage formed

resistance, but have very small benefit in reducing ac impedance. The objective of the earth electrode subsystem is to reduce ac and dc potentials between and within equipment. If deep wells are utilized as a part of the earth electrode subsystem grounding net, the other portion of the facility ground network shall be connected to them."

10. From National Electrical Code, NEC-70-1996, National Fire Protection Association, Quincy MA, 1996, Article 250 - Grounding, p. 120 & p. 144:

"Systems and circuit conductors are grounded to limit voltages due to lightning, line surges, or unintentional contact with high voltage lines, and to stabilize the voltage to ground during normal operation. Equipment grounding conductors are bonded to the system grounded conductor to provide a low impedance path for fault current that will facilitate the operation of overcurrent devices under ground-fault conditions." (p. 120)

"Metal Underground Water Pipe. A metal underground water pipe in direct contact with the earth for 10 ft. (3.05 m) or more (including any metal well casing effectively bonded to the pipe) and electrically continuous (or made electrically continuous by bonding around insulating joints or sections or insulating pipe) to the points of connection of the grounding electrode conductor and the bonding conductors. Continuity of the grounding path or the bonding connection to interior piping shall not rely on water meters or filtering devices and similar equipment. A metal underground water pipe shall be supplemented by an additional electrode of a type specified in Section 250-81 or in Section 250-83. The supplemental electrode shall be permitted to be bonded to the grounding electrode conductor, the grounded service-entrance conductor, the grounded service raceway, or any grounded service enclosure." (p. 145)

11. From MIL-HDBK-419A, Grounding, Bonding, and Shielding for Electronic Equipments and Facilities, Department of Defense, Washington DC, 1987, p. 1-2, p. 1-6, p.1-102 and p. 1-173:

"The value of 10 ohms earth electrode resistance recommended in Section 1.2.3.1a represents a carefully considered compromise between overall fault and lightning protection requirements and the estimated relative cost of achieving the resistance in typical situations." (p. 1-2)

"At fixed C-E facilities, the earth electrode subsystem should exhibit a resistance to earth of 10 ohms or less." (p.1-6)

"All metallic pipes and tubes (and conduits) and their supports should be electrically continuous and are to be bonded to the facility ground system at least at one point." (p. 1-102)

"Water pipes and conduit should be connected to the earth electrode subsystem to prevent ground currents from entering the structure." (p. 1-173)

by all this metal, and so at no risk of being electrocuted. Don't touch anything, sit in the middle away from the mast.

In a study of people in cars struck by lightning there were no injuries from touching the interior metal. But boats do not have a Faraday enclosure like a car, where metal surrounds the occupants.

Don't run your lightning ground wires close to the bunks, or anywhere the crew is likely to be sitting during the storm. Side flashes can happen if the main path for the flash is blocked.

The Faraday cage

During a lightning storm, The steel body of a car and steel containers act as a shelter which, during a direct strike, force lightning to go around the occupants, who otherwise would make an attractive path for the flash.

Although the charge on the steel walls could reach thousands of volts, the occupants wouldn't feel it because they would not connected to ground - they would be as safe as birds sitting on a high voltage wire. And anything in the steel box would be safe as long as it does not touch anything outside the box - wires leading outside the box, for instance.

On a steel boat, occupants are protected as long as they are sitting on an insulated bunk with arms folded.

To provide the same protection on a fiberglass or wood boat, a metal framework must be created to emulate a steel enclosure. It isn't necessary to make a solid enclosure. What is important is that there is some metal structure above the crew that is electrically connected to the ocean below them.

