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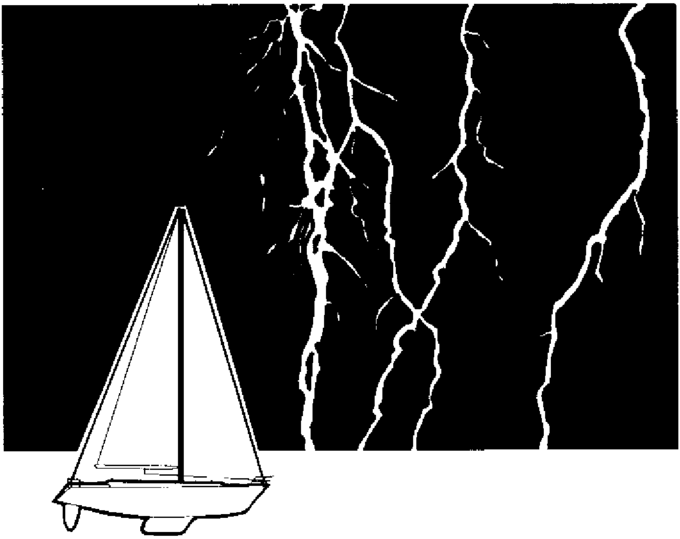
Lightning & Sailboats



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Lightning and Sailboats

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Introduction

The sight of a jagged lightning bolt licking the not-too-distant horizon undoubtedly gives rise to concerned thoughts in the minds of many sailors. Few actually act on their thoughts. And very few understand the phenomenon well enough to act confidently.

Questions abound: "What do I do if a lightning storm is approaching or on me? What happens when lightning strikes a boat? Does a lightning protection system help? But if I do install a lightning protection system, won't it attract lightning? How do I install a protection system anyway?" Other questions relate to lightning itself: "Does lightning go up or down? Do the light and thunder originate at the same time? What causes thunder? Why does lightning sometimes flicker? What dictates whether lightning will strike an object on the ground or water?"

In this Bulletin, and in the Sea Grant video "Lightning and Sailboats"[1] we attempt to answer these questions. We describe the physics of lightning at a layman's level, discuss how a lightning protection system is supposed to work, and explain some of the technical details necessary for the correct installation of a protection system. A more technically oriented paper is published in the technical literature.[2]

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[1] Available for $15 from Florida Sea Grant, University of Florida, P.O.Box 110409, Gainesville, FL 32611. Make checks payable to the University of Florida.

[2] E.M.Thomson, *A Critical Assessment of the U.S. Code for Lightning Protection of Boats*, Institute of Electrical and Electronic Engineers Transactions on Electromagnetic Compatibility, Volume 33, Number 2, pp. 132-138,1991.

Thunderstorms

From the sailor's point of view, thunderstorms are best avoided. There are several techniques that can be employed to recognize a growing storm and track one that is moving in your direction. The thunderstorm, or cumulonimbus cloud, is best recognized in its forming stages by its tightly-packed "cotton wool" appearance. This occurs because a tremendous amount of energy is being released to produce powerful convection inside and around the cloud. Of course, if the thunderstorm is forming directly overhead the cotton wool appearance will not be visible, only a grey overcast that slowly darkens and eventually produces torrential rain, lightning and strong winds. The first few flashes of lightning in a thunderstorm typically do not reach the ground and may be completely invisible during daytime.

One way to determine what is going on in the area is with a cheap AM radio. (Note: FM radios do not work nearly as well for lightning detection.) The characteristic crackle that we call "static" on an AM radio is caused by lightning. A common problem in summer is that there are too many storms within radio range, which may be hundreds of miles. In order to lower the sensitivity of your radio to distant storms, tune it to a local radio station, or, if the signal is too strong, slightly off tune. Any loud static can then be interpreted as a warning that things are charging up.

Once a thunderstorm starts to produce lightning that hits the ground or "ground flashes", these can be used to locate a thunderstorm. One method is to track a collision course using a handbearing compass: if the bearing to the lightning does not change, on average, the storm is heading your way and it is time to adjust your course. Another method that works once the thunder can be heard is to count the time between the light and the thunder. Since the light arrives almost instantaneously and the thunder travels at a speed of 1/5 mile/second, this time divided by five gives the distance to the lightning. For example, if the thunder starts 30 seconds after the lightning, the flash is 6 miles away. See Figure 1.

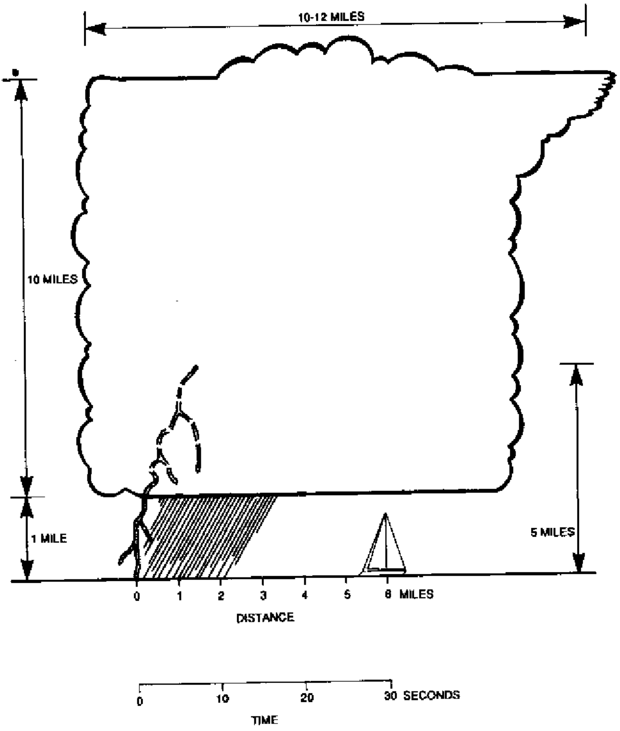


Figure 1. Thunderstorm ranging using time to thunder.

Note that the thunderstorm is about 10 miles across and that ground flashes originate anywhere inside the storm at a height of about 5 miles. Further, lightning channels usually slant away from vertical and can even emerge from the side of the storm (the classical "bolt from the blue"). The danger to the boat is obvious. That boaters frequently underestimate this danger is borne out by those whose boats have been struck by lightning, a typical comment being that there were no thunderstorms in the area just before their boats were struck.

Others signs of imminent lightning are even more obvious. St. Elmo's fire and buzzing sounds off radio antennas arise when a boat is in the large electric field directly below an electrified cloud. Although lightning may not yet have begun, its occurrence in the immediate vicinity is exceedingly probable when these electrical phenomena are observed. Act as if your boat is about to be hit by lightning, as described below.

Lightning

The only type of lightning that need concern sailors is the ground flash, since lightning that does not reach the ground does not damage boats. Ground flashes can be expected to hit from 4-20% of all moored sailboats per year in Florida. Cruising sailboats typically get hit at least once in their lifetimes. The standing records for the total number of strikes to a single boat is five (in Sarasota, Florida) and the highest strike repetition rate is twice within ten seconds (in the Indian ocean).

The typical ground flash starts at a height of about 5 miles above water, inside a region of the thunderstorm that is charged negatively. The path, or channel, that eventually connects this negative charge to ground begins here. As the channel extends towards ground during the "stepped leader" phase, negative charge is funneled from the cloud into a spark channel. When the tip of the stepped leader is about 30-100 yards above ground level, another spark, this time positively charged, is launched from the ground. A massive amount of power is generated when this positively charged attachment spark and the negatively charged stepped leader connect. At this time the peak lightning current is generated, during the "return stroke". Although cresting at ten thousand to hundreds of thousands of amps, it only lasts for about a millionth of a second. Longer lasting currents of a few hundred to a few thousand amperes may persist for much longer times (on the short time scale of the lightning) during a "continuing current". These long-lasting continuing currents are responsible for large heating effects and are thought to be responsible for forest fire ignition. After a short pause, subsequent leaders may reenergize the channel, followed by more return strokes and, on occasion, continuing currents. A typical ground flash has about three leader/return stroke sequences. Lightning frequently appears to flicker because each return stroke lights up the channel, and the time between them is sufficiently long enough to be seen by the human eye.

The return stroke heats up the lightning channel to a temperature about six times as hot as the sun. This causes the surrounding air literally to explode. We hear this explosion as thunder that appears to last for much longer than the lightning, which is all over in less than a second, because the lightning channel network covers several miles. The speed of sound is only about 600 knots and so thunder from more distant parts of the cloud arrives later than thunder from closer parts. The important thing is that the light and sound are generated at the same time since they are both caused by the return stroke.

Lightning Interaction with a Sailboat

Attachment

As the negatively-charged stepped leader moves downwards, it induces a positive charge on the ground below. When the tip of the leader is about 30-100 yards above ground level, the induced positive charge becomes so concentrated that a new spark forms at the ground. This positively charged spark is the crucial process as far as the attachment to a boat is concerned. If it starts at the tip of a boat mast, then lightning strikes the mast. Unfortunately, there is no scientifically accepted technique to prevent this spark from forming. Even if a device was effective in diverting the attachment spark, it would not be a good idea to mount it on the masthead as the attachment spark may start elsewhere on the boat or crew. The likelihood of lightning attaching to the masthead is a safety feature as far as the crew is concerned.

Consequently, lightning protection means minimizing the damage caused by lightning in the event of a strike, rather than preventing a lightning strike. In general terms, a protected boat is one in which there is a continuous conducting path from the water to the mast tip. The current needed to feed the attachment spark is conducted through the protection

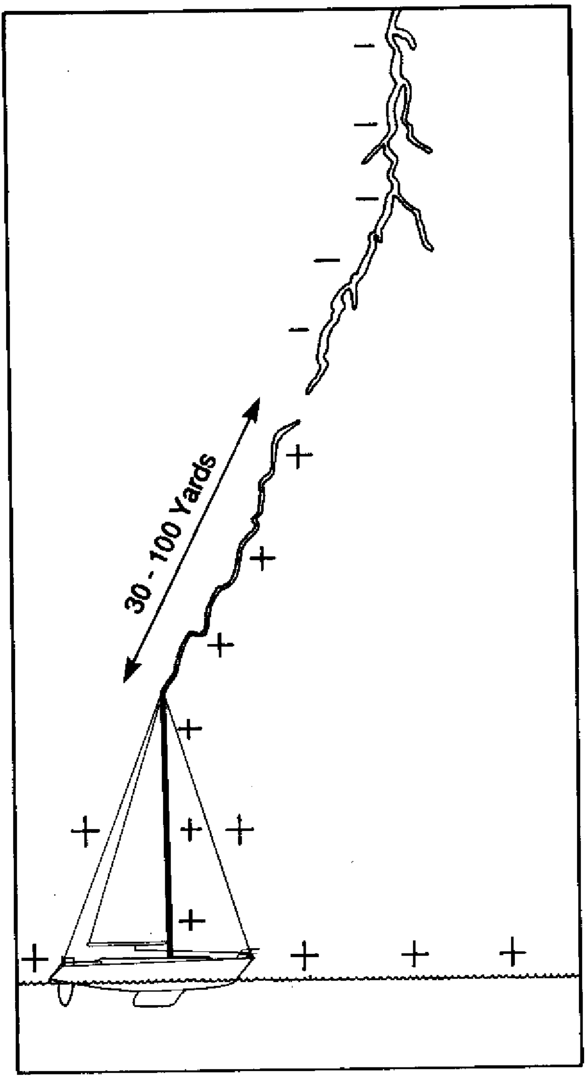


Figure 2. Lightning attachment to a sailboat.

system from the water. That is, the path that the lightning takes in the boat is forced to be that of the conductors in the protection system. If this conducting path is not continuous, for example, in a boat which is not well grounded, there is little difference as far as the top of the mast is concerned. The attachment spark still begins there as this is where the positive charges have concentrated. The difference is what happens where the conducting path, the mast, ends. Since current cannot flow from the ground to feed the growing attachment spark, a negative charge accumulates at the base of the mast and eventually arcs across in the general direction of the water or a nearby conductor. (For this exercise, crew members are conductors!) The result is an unharnessed electrical discharge between the bottom of the mast and the water.

According to the above argument, the likelihood that lightning will strike a boat does not depend on whether the boat is well grounded or not. There is some support for this in the experiences of marine surveyors. Nine marine surveyors in Florida, each of whom had surveyed more than 200 sailboats in their career, reported that between 2% and 67% (on average 34%) of the boats they surveyed for any reason had a lightning protection system. Of the boats that they surveyed because of a lightning strike, they reported that between 0% and 67% (on average 29%) had a protection system. While the individual estimates varied widely between surveyors, there is no support for the argument presented by some sailors that they should not ground their sailboat since it will increase the chances of it being struck by lightning.

Sideflashes

Data obtained from sailors whose boats have been struck by lightning are consistent with the above scenario: boats that do not have a protection system do indeed suffer more damage. The type of water, whether salt or fresh, is also important. Damage is much more extensive for boats struck by lightning in fresh water than for boats struck in salt water because fresh water is a worse conductor. Consequently, it is much more difficult to design an adequate protection system for boats in fresh water than for boats in salt water. Figure 3 summarizes these data for a sample of 71 boats that were struck by lightning. The bars show the percentages of boats in each category that received various magnitudes of hull damage. The four categories were boats with/without protection systems in salt/fresh water. The damage indices indicate the severity of hull damage as shown in Table 1.

In boats with a hull damage of 2 or higher the lightning had formed its own path(s) through the boat hull. If a lightning protection system was present it malfunctioned. As the statistics show, malfunctioning protection systems are very common in fresh water: 40% of protected boats in fresh water experienced this effect. The most likely way that this happened was through the formation of "sideflashes".

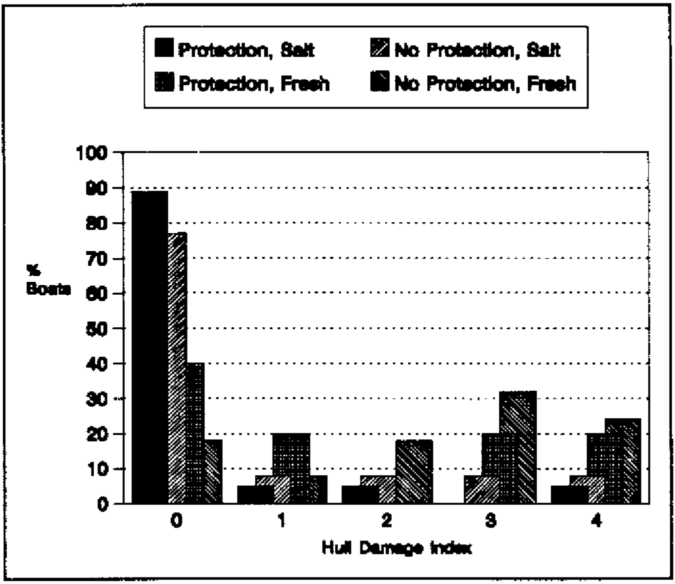


Figure 3. Proportion of boats struck by lightning suffering hull damage of varying degrees.

Table 1. Severity of hull damage.

Hull Damage Index	Type of hull damage
0	No hull damage
1	Small non-leaking cracks or burns
2	Small holes that did not leak seriously
3	Holes larger than 1/4 inch diameter above waterline
4	Holes larger than 1/4 inch diameter below waterline

These are sparks that form between the lightning protection system and ungrounded conductors or the water. Basically, in order to dissipate a lightning current in fresh water a much more extensive underwater grounding system is needed than that usually found in "protected" boats. This is described in more detail below.

Technical Aspects of the Lightning Protection System

Overview

Although lightning protection needs to be designed on a boat-by-boat basis and ideally installed during manufacture, there are three major considerations in a good protection system: (a) grounding; (b) bonding, and; (c) electronics protection. The grounding system is intended to provide an adequate conducting path from the point of lightning attachment, usually the masthead, to a system of conductors in the water, without producing sideflashes. The bonding system protects the crew and consists of conductors that short out large metal fittings so that large voltages cannot develop between them. Electronics protection limits power supply and transducer voltages through a combination of transient protection devices and careful wiring techniques.

Grounding

The idea of the grounding system is to divert the lightning current through a predetermined path so that it does not make its own explosive path through fiberglass, teak, crew members, etc. Figure 4 shows

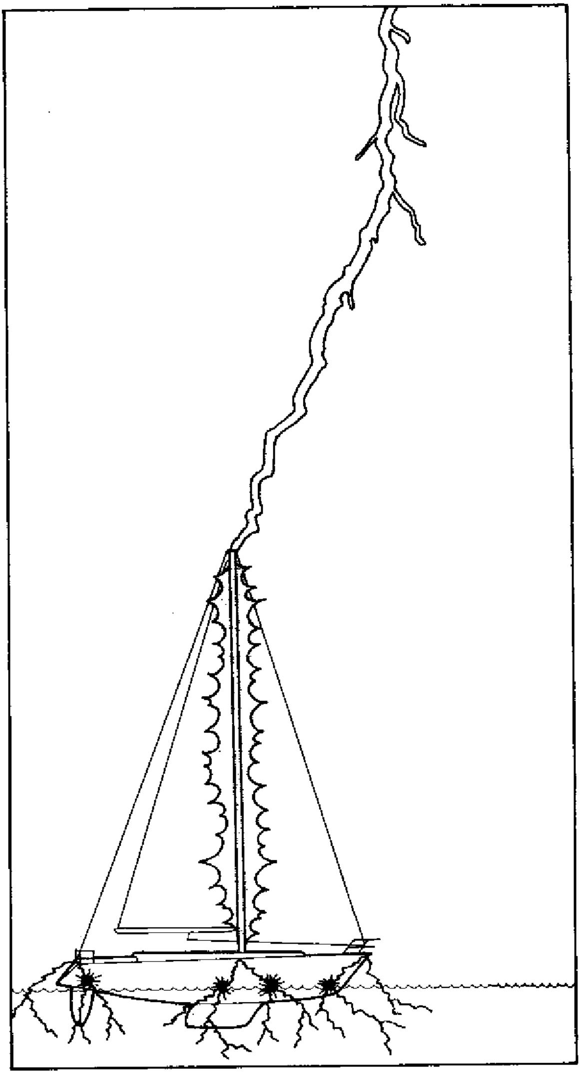


Figure 4. Possible effects of a lightning strike to an ungrounded boat.

what can happen when lightning strikes an ungrounded fiberglass boat with an aluminum mast. The lightning charges all of the rigging but no conducting path exists to channel the charge into the water. The result is destructive sparks between the lower parts of the rigging, such as the mast base and chainplates, and the water. Wherever these sparks travel through bad conductors (fiberglass hull, teak bulkheads, through-hulls, porta-potties, etc.) sufficient heat is generated to explode the impeding material into a nicely conducting plasma that is hotter than the surface of the sun.

The components of the grounding system are: (i) an air terminal at the top of the mast; (ii) down-conductors, and; (iii) grounding conductors that are immersed underwater ("ground strips" or "ground plates"). The air terminal is the point where the lightning is supposed to attach, the down-conductors conduct the current from the air terminal to below the water, and the grounding conductors dissipate the current into the water without forming any sideflashes. Usually the aluminum mast is connected in as part of the down-conductor network.

On a sailboat with a VHF radio, the masthead VHF antenna usually serves as a sacrificial air terminal. In fact, one of the first signs that lightning has struck a boat is typically that shards of antenna material are scattered around the deck. The presence of a VHF antenna or other expensive masthead transducers makes a separate air terminal highly desirable, although this will degrade the performance of the VHF. The top of the air terminal should be sufficiently high that the angle from it to any other masthead object is less than 45 degrees. That is, the air terminal provides a "cone of protection" that attracts lightning (or, more accurately, launches an attachment spark) preferentially to any other object that is below a conical surface whose apex is on the top of the air terminal and that has a 90-degree apex angle.

An aluminum mast is the preferred down conductor, being a much better conductor than stainless stays. If the mast base is on top of the cabin, a down-conductor is needed to connect the mast base to the ground strips. Use at least #4 gauge copper with preferably bimetallic copper/stainless connections to prevent galvanic corrosion. Alternatively, make a strong mechanical connection and additionally braze or solder, to improve the electrical contact and lessen the chance of contact corrosion, then paint with an insulating coating. A keel-stepped mast similarly needs to be connected to the keelbolts with at least #4 gauge copper.

The ground strips in contact with the water should be connected to the down-conductors with care to avoid galvanic corrosion. In salt water a single grounding conductor of a square foot or more in area is usually enough. In this respect, a lead keel connected to the down-conductor via the keel bolts is adequate. If the lead is either painted or encapsulated in fiberglass, minor repairs may be needed after a lightning strike. However, the paint or fiberglass does not seriously compromise the ballast lead as a lightning ground. Note that this system does not work in river mouths where there may be a less dense layer of fresh water riding on top of a salt water "wedge". The situation in fresh water is much more complicated as the voltages involved during a lightning strike are about a thousand times larger than those that occur on a boat in salt water. A good start is to lay a flat or "D" cross section strip of 3/4" x 1/8 " stainless or brass along the outside of the stem of the boat. Connect this to the forestay, mast base, and backstay with #4 gauge vertical copper down-conductors. However, this is not usually enough. In addition, extra ground strips are needed just outside the hull close to metal fittings such as gas tanks, metal-cored plumbing pipes, wiring, etc. Connect these to the grounding system using near-vertical down-conductors. Under no event should these down-conductors run close to the hull except where they penetrate the hull to connect to the grounding strip: otherwise the conductor may cause a sideflash through the hull. The engine, propeller shaft, and propeller should be regarded as part of the grounding system and tied in appropriately.

The manner in which a correctly grounded boat reacts to a lightning strike is illustrated in Figure 5. The lightning charge that flows onto the rigging does not accumulate to the point where it forms destructive sparks, as was the case for an ungrounded boat. Instead, it is discharged into the water over a wide region. The more evenly the charge can be discharged into the water, the less likely it is that a sideflash will occur through the boat hull.

Bonding

The difference between the grounding system and the bonding system is only one of degree since both are interconnected and both will conduct current during a lightning strike. Whereas the grounding system is designed to handle the full lightning current, the bonding system consists of mainly horizontal connections between metal fittings to short out any voltages that might otherwise develop. Bonding is a measure that is intended to protect the crew and enable them to work the boat without getting shocks. This can occur from nearby lightning as well as from direct strikes. Smaller gauge conductors than the

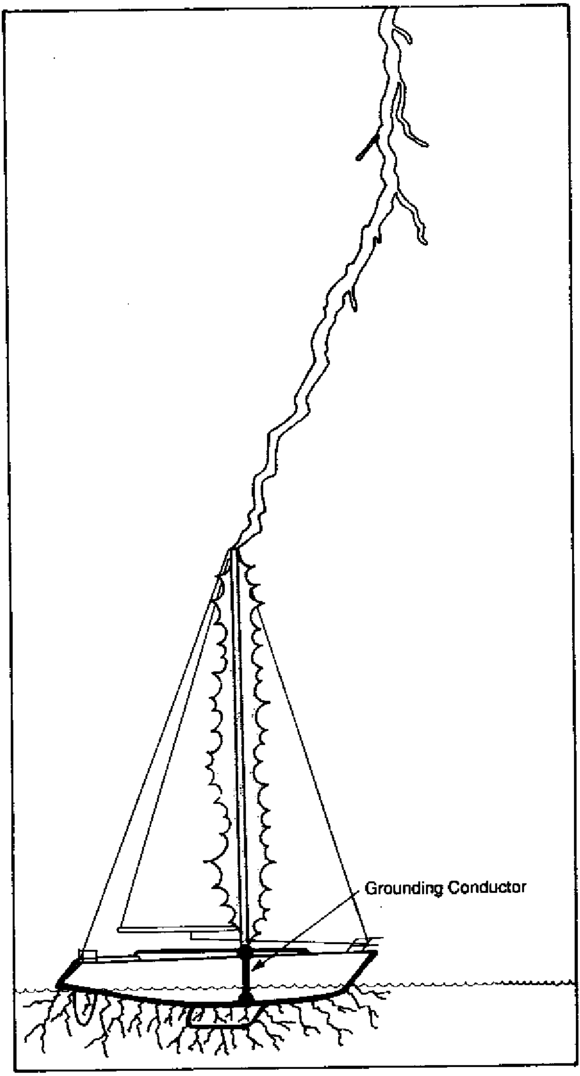
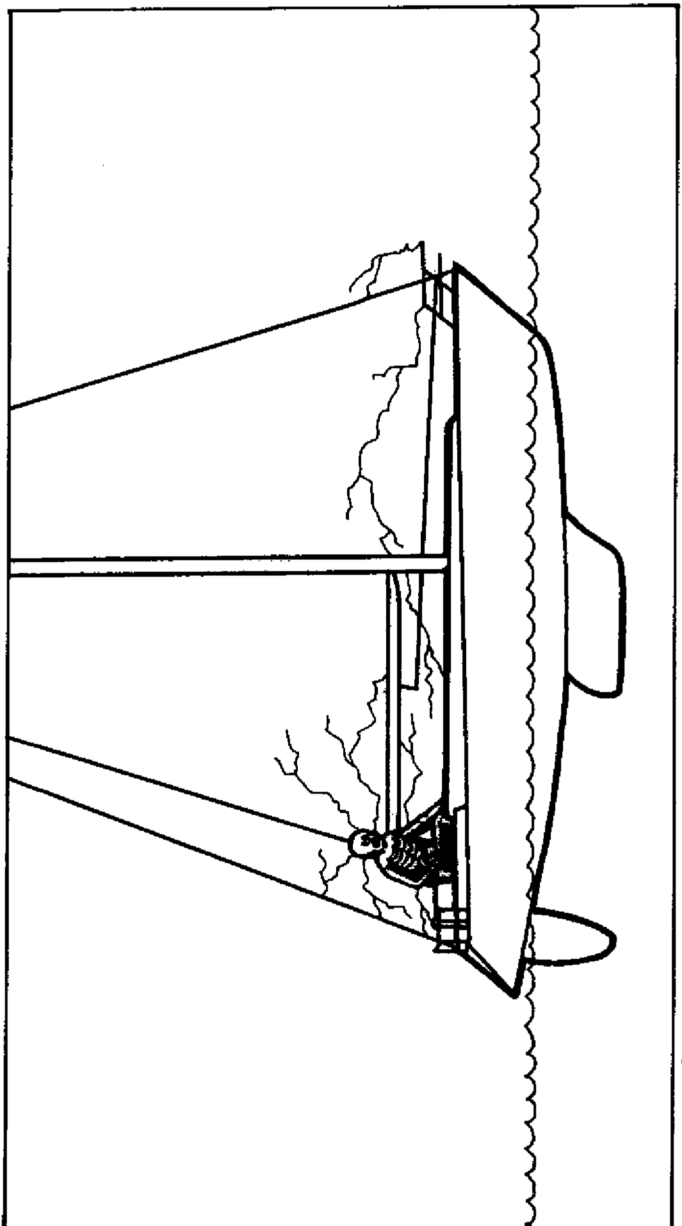


Figure 5. Effects of lightning strike to a grounded boat.

grounding system are adequate in the bonding system, down to #8 gauge copper. As with the grounding down-conductor connections, all bonding connections should be made to minimize galvanic corrosion. Metallic fittings that should be bonded to the grounding system, using horizontal connections as much as possible and avoiding the hull, are toe rails, chain plates, steering wheels, motor controls, bow and stern pulpits, antenna bases, the ground wire for the electronics, etc.

The illustrations in Figure 6 show what happens on board a bonded and unbonded boat during a lightning strike. On the unbonded boat large voltages develop between the mast, chainplates, forestay, backstay, wheel, rudder post, toe rails, electronics, wiring, metal reinforcing in plumbing fixtures, engine, etc. These make working the boat extremely hazardous, even if lightning is not striking the boat directly. On the bonded boat these voltages are shorted out by bonding conductors. Note, however, that the large magnetic fields associated with a direct lightning strike make the concept of an electrical "short" a misnomer. Appreciable voltages can develop between the ends of long conductors even if the conductors are connected together at their other end. The helm is a particularly dangerous place owing to its proximity to the engine controls, boom, rudder post and backstay. The helmsman in Figure 6 (bottom) would not be smiling if he had one hand on the tiller and the other on the engine controls, for example. (Note that he is steering with one hand in his pocket to minimize the risk of making a connection between two conductors at different voltages. This is not as safe as throwing over the anchor and going below!) For stations such as the helm that are usually manned, it is crucial that the bonding conductors should be kept as short and straight as possible.



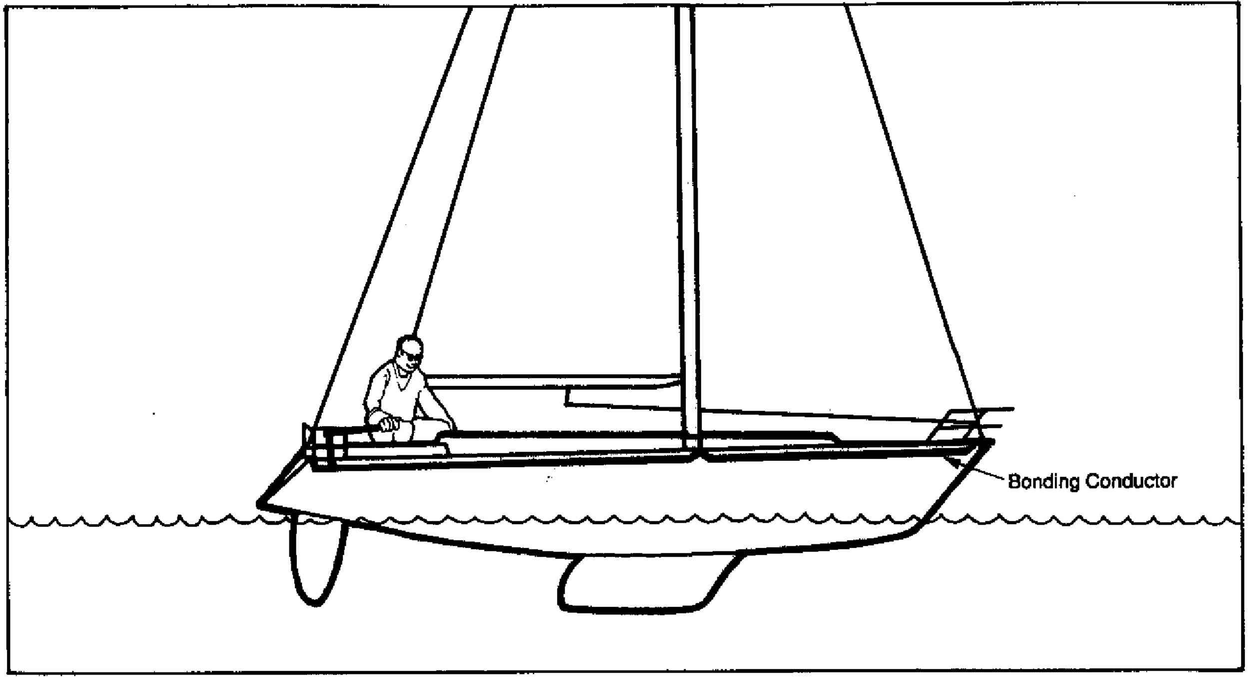


Figure 6. (Top) Lightning effects on an unbonded boat. (Bottom) Lightning effects on a bonded boat. *Note: Being in contact with a wheel or tiller during a lightning strike is extremely hazardous, even in a grounded, bonded boat.*

Electronics

Electronics-killing overvoltages may be introduced through the DC power wires, antenna input, or any other external connection such as a lead to a transducer. Electronics on a small sailboat that are struck by lightning are particularly difficult to protect since it is impossible to divert the lightning current any appreciable distance away from the electronics. This difficulty, and the pervasive nature of electronics damage, is illustrated in Figure 7 that shows the percentages of boats with electronics damage of different magnitudes.

In this case there is less of a distinction between boats struck in fresh water versus salt water as there was for hull damage, but the same trend is evident: boats with protection systems in salt water fare best and boats with no protection systems in fresh water fare worst. More notably, 96% of all boats sustained damage to at least some electronics items. Apparently a lightning protection system, as installed on the boats in the survey, does not necessarily save the electronics. Note that for these boats "lightning protection" merely meant that the boat was grounded, not necessarily bonded with transient protection devices, as explained below.

In order to protect electronics, more is needed than merely diverting the current to ground (water) without its blowing a hole in the hull. Due to the low voltages typically used in modern marine electronics, just a few extra volts is enough to cause extensive damage. However, techniques that are used to protect computers, cable TV and radio equipment on land can also be used in shipboard DC and AC equipment. Some devices are readily available from electronics stores. Radio antennas can be protected using lightning arrestor hardware designed for cable TV.

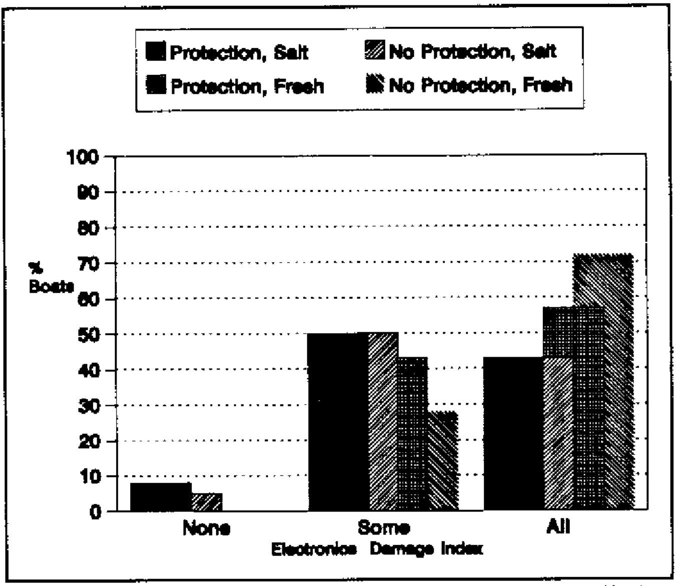


Figure 7. Proportion of boats struck by lightning suffering electronics damage of varying degrees.

Connect the "ground" connection to the lightning grounding network. AC transient protection outlets or plug-in metal oxide varistors (MOV) work also on boats but need to have their ground connection connected to the shore ground wire. Ideally this ground should also be connected to the lightning protection ground but this circuit arrangement can cause ground current problems in marinas. As for protection of DC electronics, which are probably the most important, transient protection devices are available to clamp voltages at the point where each piece of equipment is connected to the DC supply. These are available from companies such as General Electric or from mail order electronics distributors. They can be found under the generic name "Transient Suppressors" and are of various types: metal oxide varistor, silicon avalanche diode, and surge suppressor zener diode. It is important to locate this protection device immediately next to the equipment and each piece of equipment should have its own device. The overvoltages that appear at DC inputs can be reduced by using twisted-pair wiring in wiring harnesses, ideally with a conducting sheath that is connected to the bonding system. The overall philosophy here is to minimize the spacing between positive and negative DC lines. If a main control center exists, surround it with a conducting enclosure that is connected to the bonding system. Through-hull transducers are especially vulnerable. Due to the typically vertical alignment of the cables connecting these to their main electronics, they should be regarded as being part of the lightning grounding system. Since the wires used in these cables are of an insufficient thickness to withstand a lightning strike, a #4 gauge copper wire should be placed parallel to any cable that leads to a through-hull transducer. The top of this copper wire should be reconnected to the lightning grounding system and the bottom to a ground strip close to the underwater transducer on the outside of the hull.

As with all aspects of lightning protection, 100% effectiveness cannot be guaranteed, even if all the above measures are taken for electronics systems. Disconnecting equipment in advance of a storm helps isolate it from voltages induced by lightning, and the larger the lead separation the better. Use disconnects in preference to knife switches, and these in preference to switch panels.

Personal Safety

Consider the worst case scenario for a lightning strike to a sailboat - a small boat in fresh water. If the boat has been provided with a well-built protection system it is still an exceedingly hazardous situation. If lightning protection does not exist, the situation is life threatening. In both cases the areas to avoid are close to the waterline and close to large metal fittings. In the unprotected boat an additional danger zone is beneath the mast or boom. Even in the unprotected boat it is unwise to get in the water as electrocution is highly probable if lightning strikes nearby. In fact, there is no safe place on an unprotected small sailboat, and in a protected boat only places of relative safety. There is, however, one place that is more hazardous than a small unprotected sailboat, that is a small unprotected boat without a mast. Every year there are multiple deaths of boaters in open boats caused by lightning strikes, but very few reports of sailors in sailboats killed by lightning.

The above general rules also apply to larger sailboats. These are generally safer, if protected, since it is possible to get away from the waterline and large metal objects, and yet still stay dry inside the cabin. As far as unharnessed electricity is concerned, a dry human body is much less attractive than a wet one.

Conclusions

Lightning protection on a sailboat means diverting the lightning current into the water without its causing any hull damage, personal injury, or electronics damage. This involves providing a continuous, mainly vertical, conducting path from above any vulnerable masthead transducers to grounding conductors immersed in the water (the grounding system) and a network of mainly horizontal interconnected conductors attached to large metal fittings, including the grounding system (the bonding system). Transient suppressors are needed on each piece of electronics equipment, and wiring should all be twisted pair for protection of electronics.