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PROTECTION OF NAVAL SYSTEMS AGAINST ELECTROMAGNETIC EFFECTS DUE TO LIGHTNING

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Abstract—This study investigates possible lightning threats to naval crafts, especially those sailing in the shallow waters of tropical oceans where thunderstorms prevail throughout the year and Far-East Asian region where dangerous positive lightning is a significant characteristic in winter thunderstorms. It is empathized that sea water acts as nearly a perfect conductor thus lightning electromagnetic transients propagate over the sea with almost zero attenuation of amplitude and high frequency components intact. The ratio between the peak electric fields at 5 km from the lightning channel, after fields propagate over dry soil and over sea water is 0.75. The ratio between the peak electric field derivatives under the same conditions is 0.1. Such small ratios are observed in the magnetic fields and their time derivatives as well. Apart from the conductivity, the topological irregularities of the plane over which propagation takes place also contribute to further attenuation of fields and their time derivatives. This makes marine naval systems more vulnerable to lightning induced effects than their ground-based counterparts. The paper discusses in detail the lapses of existing naval standards in the defense of electrical and electronic systems against both direct lightning currents and induced effects of nearby lightning. Consequently we propose the development of a dedicated standard for the lightning protection of naval systems, with the inclusion of several significant recommendations specified in this paper.

1. INTRODUCTION

All electronics are susceptible to damage due to voltage and current transients generated, basically by lightning and also by switching

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operations and power anomalies. The degree of damage depends on the characteristics of the surge and the response of the electronics.

Naval crafts are rarely hit by lightning. However, a naval craft docked at a port will frequently encounter electromagnetic effects due to lightning that strikes other objects in the close range. A lightning that strikes within about one kilometer from the power and signal systems of a naval craft can induce large enough transients that can permanently or temporarily damage the electrical and electronic systems of the craft. It is worth mentioning that a majority of the busy sea ports in tropics are located in the most lightning dense regions in the world (Singapore, Kochi, Johor, Klang, Colombo, Legazpi etc.). Furthermore, many of the ports in Japan and Korea (such as Kobe and Busan) experience dangerous positive lightning during the winter [1–8]. In addition to the induced effects of distant/nearby strikes the current injection into electrical equipment (resistive coupling) due to a rare event of a direct strike into the masts or other parts of the ship cannot be overlooked.

2. INFORMATION AND OBSERVATIONS

2.1. Characteristics of Lightning Currents

In a single lightning flash to ground (Cloud-to-Ground or CG lightning) large currents, either impulsive or continuous in temporal variation, may flow into earth through the lightning struck object. A majority of lightning brings negative charge to ground, thus such lightning strokes are termed negative ground flashes. The strikes that bring positive charge to ground are termed positive ground flashes. In the thunderstorms that occur in temperate regions the positive lightning contributes to 5%–20% of the ground flashes whereas in tropics it is about 3%–5% [9]. Some exceptional statistical observations are reported in the winter lightning of Japanese and Korean coastal regions where the percentage of positive lightning may reach values as high as 70% [1–8].

In a single negative ground flash, lightning current may flow several times to earth, which gives the flickering effect of the lightning channel. The first stroke is usually large in peak current but slow in time at the rising edge. The subsequent strokes are most often lower in peak current but faster at the rising edge. There may be time intervals of few to several hundred milliseconds between consecutive subsequent strokes.

The current of each stroke has an impulse component of duration few tens of microseconds which is sometimes succeeded by a smaller steady current that extends for several tens to several hundreds of milliseconds. Such components are called continuing currents or long strokes. The impulse current (or short stroke) typically has a double exponential waveform of which the rise time can be as short as a fraction of a microsecond which results a maximum time derivative of current in the order of few tens of Giga Amperes per second [10, 11]. The peak current is about 30 kA on average for first stroke and about 15 kA for subsequent strokes of negative flashes [12, 13]. Positive flashes usually have a single stroke of which the currents have much larger peak value, slower rising edge and longer total duration [1, 4, 12, 13]. A majority of the positive return stroke currents carry a large amount of charge during the long stroke phase [12, 13].

Figure 1 (adopted from [14]) depicts the test current waveform specified by both IEC 62305 (2006) series and various IEEE/ANSI standards to represent the lightning waveform. The waveform is popularly known as 8/20 μs test impulse. IEC 62305 (2006) series also specifies another waveform known as 10/350 μs impulse for the testing of surge protection devices which are directly exposed to lightning currents. For a given peak value, 10/350 μs waveform contains larger energy and charge than the 8/20 μs waveform. Both waveforms poorly represent the fast rise times of most of the negative subsequent stokes. Hence, there are limitations to the expected efficiency of surge protective devices tested under these conditions. A detailed critical review on these two waveforms and proposed modifications are given in [14].

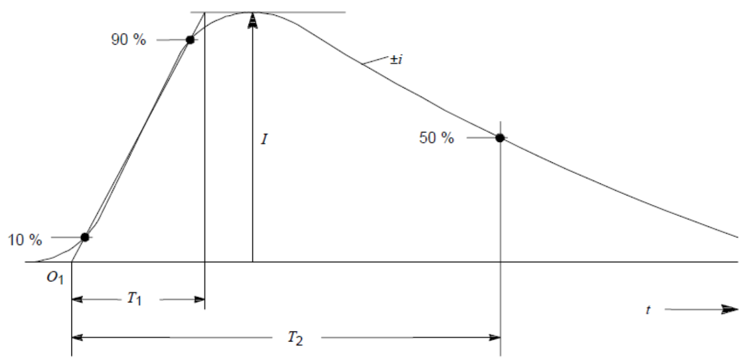

Figure 1. The profile of the test waveform specified in many standards to represent lightning impulse current. The time T_1 is approximately equal to the rise time of the waveform. The time T_2 gives the half peak width of the waveform. A certain combination of T_1 and T_2 specifies a given test waveform (adopted from [14]).

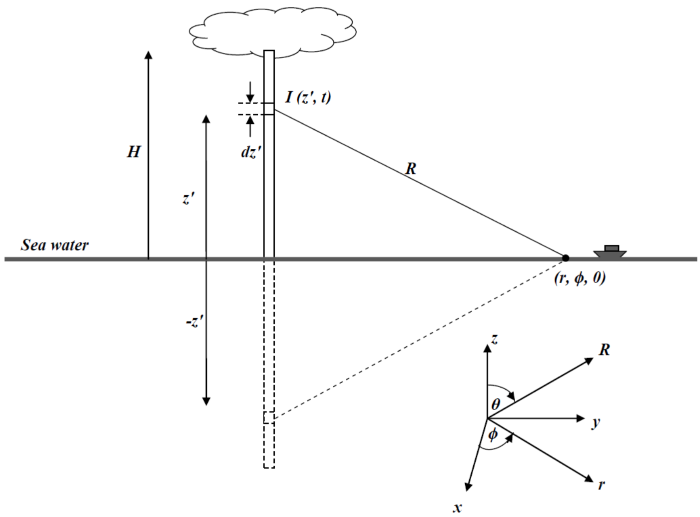

Figure 2. Geometrical parameters corresponding to the equations that calculate electric and magnetic fields at ground level over perfectly conducting plane (such as sea water).

2.2. Lightning Generated Electromagnetic Fields and Induced Voltages

The following set of expressions, in cylindrical co-ordinates, can be applied to calculate the electric and magnetic fields at ground level due to a vertical lightning channel of height H [15]. Geometrical factors in these equations are defined in the diagram in Figure 2. The equations are valid under the condition that the earth surface between the place of strike and the point of observation is perfectly conducting (infinite conductivity) and flat.

$$
\begin{aligned}
&E(r,\phi,0,t)\\
&=\frac{1}{2\pi\varepsilon_0}\left[\int_h^H \frac{2z'^2-r^2}{R^5}\int_0^t i(z',\tau-R/c)d\tau dz'\right.\\
&\left.+\int_h^H \frac{2z'^2-r^2}{cR^4} i(z',t-R/c)dz' - \int_h^H \frac{r^2}{c^2R^3}\frac{\partial i(z',t-R/c)}{\partial t}dz'\right] a_z \quad (1)
\end{aligned}
$$

$$B(r,\phi,0,t) = \frac{\mu_0}{2\pi}\left[\int_h^H \frac{r}{R^3} i(z',t-R/c)dz' - \int_h^H \frac{r}{cR^2}\frac{\partial i(z',t-R/c)}{\partial t}dz'\right] a_\phi \quad (2)$$

The first mathematical block within the square brackets of Equation (1) is called the static term (which depends on the change of charge along the channel). It decreases rapidly with distance from the channel base. The second one is the induction term (depends on the current along the channel) which decays relatively slow. The third block, termed the radiation component, decays at the least rate with distance. It depends on the time derivative of the channel current at each height. The Equation (2) has only the induction term and the radiation term.

In the case of electromagnetic induction on conducting objects on the path of propagation of fields, the time derivatives of the electric and magnetic fields (dE/dt & dB/dt) play equally significant role [16, 17].

Note that Equations (1) and (2) are applicable only when the ground plane is a perfect conductor with no topographic anomalies (smooth, horizontal, plane surface). Several studies done since the above study [15] showed that the electric and magnetic waveforms undergo severe frequency dependent distortion and attenuation as fields propagate over a ground plane with finite conductivity [18–26]. The selective attenuation at high frequencies severely affects the amplitudes of the time derivatives of electric and magnetic fields. Such effects are common to the electric and magnetic fields generated by both cloud-to-ground lightning and cloud flashes [26].

As given in [19], the peak of the lightning generated radiation electric field, generated by a negative first return stroke along a vertical channel, after traveling a distance D over finitely conducting ground with conductivity σ is given by Equation (3).

$$E_\sigma = \left(0.24\left\{\exp\left[\frac{-D/\sigma}{10^7}\right] + \exp\left[\frac{-D/\sigma}{50\times 10^7}\right]\right\} + 0.52\right) E_\infty \qquad (3)$$

where D/σ is measured in m^2/S. E_σ and E_∞ represent the electric field at the same distance, over finitely conducting earth and over infinitely conducting plane respectively.

Equation (3) is limited to a value of D from about 5 km to 300 km where the lower limit is governed by the fact that the static and induction terms are neglected (only the radiation term is considered) and the upper limit is governed by the fact that the earth's curvature is neglected.

Now consider a horizontal ground plane where the soil conductivity is in the order of 0.0001 S/m (common value for the soil conductivity of dry arid regions) and sea water of conductivity 4.8 S/m. At 5 km from the lightning strike the ratio between the peak electric field over the land (E_L) and that over the sea water (E_S) is approximately 0.75 (75%), as per Equation (3). The calculation also shows that compared to the land, sea water can very well be treated as a perfectly conducting, horizontal plane.

As per the outcomes of [18] the peak electric field derivative due to first return stroke of negative lightning, over finitely conducting surface $(dE/dt)_\sigma$, is related to that over perfectly conducting plane, $(dE/dt)_\infty$ (at the same distance D) by the empirical equation

$$\left(\frac{dE}{dt}\right)_\sigma = 22.7\left(\frac{D}{\sigma}\right)^{-0.31}\left(\frac{dE}{dt}\right)_\infty \tag{4}$$

Equation (4) shows that at 5 km from the point of strike, $(dE/dt)_\sigma$, is less than 10% of $(dE/dt)_\infty$ for propagation over land where the soil conductivity is 0.0001 S/m. Even at soil conductivity of 0.001 S/m, $(dE/dt)_\sigma$ remains less than 20% of $(dE/dt)_\infty$ at 5 km distance. The Figure 3 (adopted from [18]) shows how the electric field derivative of negative first stroke varies with distance over a surface of conductivity 0.001 S/m.

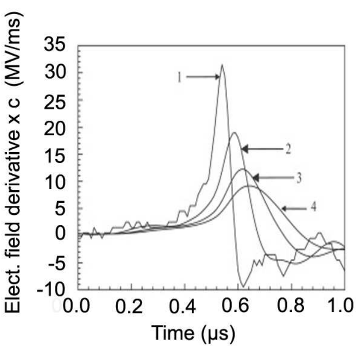

Figure 3. Variation of electric field derivative of a first return stroke as it propagates over ground of conductivity 0.001 S/m: (1) Undistorted field (i.e., infinite conductivity), (2) after propagating 1 km, (3) after propagating 4 km and (4) after propagating 8 km (adopted from [18] and the clarity of the diagram has been improved).

Similar attenuation on magnetic fields and their time derivatives have also been shown in other studies [27]. Figure 4 depicts (adopted from [27]) magnetic field time derivative (multiplied by the speed of light) at ground level at 1 km from the lightning channel as a

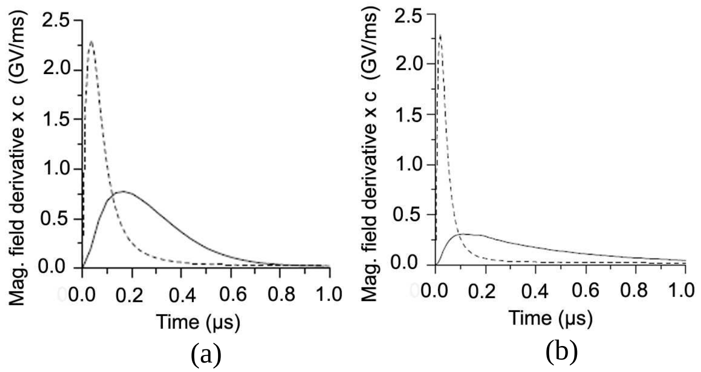

Figure 4. Magnetic field time derivative (multiplied by the speed of light) at ground level at 1 km from the lightning channel. The solid line shows the field over finitely conducting ground and the dotted line shows the corresponding one over perfectly conducting ground. (a) $s = 0.001\,\text{S/m}$ and (b) $s = 0.0001\,\text{S/m}$. The relative dielectric constant of ground has been taken as 5. (adopted from [27] and the clarity of the diagram has been improved).

comparison between the propagation fields over perfectly conducting plane and that over finitely conducting planes (conductivity of 0.01 S/m and 0.0001 S/m). The figure shows that the amplitude of the time derivative of the magnetic field reduces to a value less than 35% when the conductivity of the plane changes from infinity to 0.001 S/m and reduces to a value less than 15% when the conductivity changes from infinity to 0.0001 S/m.

For a given nearby lightning strike, the conducting parts on finite ground will experience distorted and attenuated induced voltages compared to the same system on a perfectly conducting ground [28–30]. Such attenuation and distortion is in addition to the similar effects on the electromagnetic fields as they propagate from lightning channel to the place of interaction with the conductors over finitely conducting ground.

There are further attenuations and distortions due to irregularities and anomalies of the topography of the land (mountains, uneven surface, buildings, trees, transmission lines and other conducting objects etc.) which has not been studied in details yet [24].

The above calculations and analysis clearly show that a naval-craft in calm sea is subjected to a lightning generated electromagnetic environment considerably more severe than the same experienced by a land based system. The electrical/electronic systems and signal networks of light crafts made of non-metallic or less-conducting materials are more susceptible to lightning-induced effects due to the low degree of shielding. In-built Radoms and open radar systems of large vessels with all-metal hull are also exposed to the large electromagnetic fields irrespective of the shielding provided to other parts of the systems.

2.3. Effects of Direct Strikes

In contrast to service systems of land-based buildings, in a ship, most parts of the systems and networks are exposed to direct lightning currents, due to the inevitable proximity of their locations to the passages of lightning current, in the rare event of a direct strike.

Most probably, an approaching stepped leader of a lightning will be intercepted by the mast of a ship as masts stands well above the top deck level. In most of the modern ships masts are hollow metal rods (metal pipes) of which the dimensions are selected based on the mechanical strength and the navigation purpose that it serves. Most of them are guy wired to the deck. In small recreational and sporting vessels such as brigs, schooners and sailing yachts, masts made of wood or composite materials (sometimes with metal cap at the tip) are commonly seen. In the event of a lightning strike, even in ships having multiple masts, the passage of current to top deck level will only be through a single mast as the masts are not interconnected at top level, in contrast to the system of air-terminations of a building implemented according to a proper standard.

Once the lightning current passes through the mast, a sizable potential drop will be built up along the height. The inductance of a hollow metal mast of reasonable cross-sectional dimensions is in the order of 1 μH/m. By considering a lightning current of peak derivative 30 GA/s (a representative value) one can show that the peak potential-rise at a 20 m height, by applying $V = Ldi/dt$, is 600 kV (even after neglecting the resistive drop). Now consider a guy wire fixed at one end to the deck and hooked or ringed at the other end to the mast at 20 m. In the event of a lightning strike to the mast, there is a high chance of having an arc-explosion caused by the above potential drop, at that mast end, deck end or most probably at the turnbuckle of the guy wire, due to the not-so-strong electrical contact at those points.

In the event of a positive lightning, large amplitude of the impulse part, followed by the often-observed long continuing current may create sufficient heat dissipation that melts the metal parts generating, a splash of red hot molten metal drops. Such splashing of hot metal parts may impose serious explosion/fire threat in a high risk environment (petrochemical, explosive, fibrous dust etc.).

If the masts are very tall and not very far away from each other (or there are extended parts of the masts which makes them electrically closer), there is a chance of arcing (or side flashing as it is regularly referred) between the mast that is being hit and nearby masts. Such arcing may create a grave safety threat, thus, should be avoided by all means. A series of properly connected guy wires may provide parallel paths to the lightning current thus reducing the development of dangerous potential drops.

The outcome will be much worse in the event of lightning strikes to non-metallic masts, especially in the presence of sails, as in such cases, triggering of fire is almost imminent. The metal caps at the tips (used for the fixing of sails and for the prevention of edge erosion) cause the situation even worse as the ungrounded metal cap, which acts as a floating electrode, may promote the lightning attachment via a bi-directional leader that joins the deck and the stepped leader tip. In such events, serious explosions may occur as the leader transfer to return stroke phase. Hence, in the case of non-conducting masts, the metal tip or intentionally installed air-termination should properly be connected to the all-metal hull or to an intentionally fixed earth plate. The connection should be done taking into account the fact that there are no other parallel paths to the current.

Once the current takes various paths at the deck level towards the final destination, the mass of water, for neutralization, various degrees of potential differences are generated between various parts of the current passage and the other metallic parts/systems which are either isolated or connected to the hull at distant places. These potential differences may range from few hundred volts to few hundred kilovolts. In such situations, the dangerous sparking should be prevented either by direct bonding wherever possible, or transient-bonding via suitably selected surge protective devices (SPDs).

2.4. Standards at Present

Interestingly, the IEC standards [31–33] which address important issues of ship-board electrical & electronic installations do not make any comment on the threats of lightning. In IEC Standard [34] a very concise one page introduction has been given on lightning secondary effects without providing any specifications or guidelines. In the same document section C.3.4 state that for power signal systems "*Lightning surges are not considered, as there are no external cables to conduct these into the ship*". This statement grossly overlooks the fact that lightning to nearby objects may induce significantly large transients in the conducting parts of the power and communication systems that may damage the electronics permanently or knock them off temporarily. Some of the induced voltage pulses are capable enough to drive the storage and operational systems into data errors or distortion of information that may lead to serious consequences. The IEC Standards on Electrical installations [35] in its 1997 amendment (Amendment 2; 1997-04) also provides a brief account on lightning secondary effects in Section 52 without providing any quantitative guidelines on the protection measures to be taken to prevent damage to electrical and electronic systems. The IEC Standard [35] simply recommends the usage of solely the natural metal components of the ship (masts and structural members and hull) as lightning interception and down conductor system. Even IEC Naval Standards specifically developed in order to address protection issues of equipment [36] or the subject of the Standard has direct influence of lightning; installation of generators and motors [37], transformers [38], insulation and cabling [39, 40], control systems and instrumentation [41] and LV/MV installation [42, 43]; have not made any appreciable attempt to address the lightning threats on the respective systems.

The IEC 62035 (2006) series [44], which is the most descriptive and elaborative document on lightning protection, available at present, focuses only on the continental or inland systems. The limitations and inadequacies of these standards in addressing the lightning protection issues of maritime systems are not yet investigated.

The only supportive document available for the lightning protection of naval crafts at present is the US Navy Standards MIL-STD-1310G: 1996 [45]. This Standard provides limited guidance for basically the protection against direct strikes to large scale naval systems. However, the standard [45] barely discusses the gravity of dangerous potential rises and arcing possibilities in the event of lightning under different conditions. The Standard [45] also overlooks the significance of the interconnection of live/signal metallic systems to the possible points of potential rise in the rest of the ship, via transient coupling devices (through SPDs). The other US military standards on EMC [46, 47] address the lightning-transient issues of naval systems peripherally, while giving more prominence, as they are intended to, to issues related to electromagnetic interference and shielding from intruding radiation fields. Under such circumstances the need for a comprehensive set of guidelines to protect (against direct and indirect effects of lightning), the equipment and structures, of naval systems that occupy littoral waters is a prime need at present.

3. DISCUSSION

The information and observations presented in this paper draw our attention to important issues related to the lightning safety of ships and other naval crafts.

The electric and magnetic fields and their time derivatives due to nearby or distant lightning are significantly higher at a point after propagating over the sea than the fields and derivatives at the same distance after propagating over the land. This in turn causes the induced voltages in conducting parts of ocean based systems considerably larger than their counterparts in land bound systems. The effects on naval systems by induced voltages due to channel tortuosity, horizontal parts and other complexities of the channel, branch currents, etc. should be further studied in detail by applying recently developed sophisticated models [49–53].

In contrast to buildings and other expanded structures on land, in the event of a lightning strike to a navel craft with mast/s the current will most probably take a single passage up to deck level due to the non availability of multiple paths. This may cause large potential rises along the mast creating dangerous sparks between non-sparsely separated or loosely connected metallic parts. The situation is aggravated if the lightning is of positive polarity that brings much larger currents and charge to ground than their negative counterparts.

The operational cabins of modern naval vessels contain several parts made of composites and glass, thus apart from cables routed in open spaces (which are strongly illuminated by the radiation fields of nearby lightning), the cables in these cabins can also be subjected to significant induced voltages [54]. The impact of induced voltages may be quite severe in such cases as the potential victims (electronics that aid navigation and various other operations) are in close proximity. A quantitative analysis of the response of signal and power cables inside a naval craft, to externally (nearby lightning) or internally (due to current flow along the masts or surface arcing) generated lightning electromagnetic fields can be done by either FDTD method or SPICE models [50, 55, 56].

In addition to complete breakdown (direct lightning strikes), even the radiation emitted by partial discharges along insulating surfaces separated by metallic parts (acting as either grounded or floating electrodes) caused by very high electric fields due to nearby stepped leaders or intense thunderstorms can cause damage to the electronics in the very near range [57].

Under such a background we strongly emphasize the development of dedicated international standards to safeguard the structure and cargo, equipment and occupants of naval crafts, especially, those which regularly occupy littoral zones of tropics. We make the following recommendations to be taken into account in the development of contents of such standards.

a. The splitting of lightning current into parallel paths from near the point of strike should be given. Such current sharing can be achieved through interconnection of masts at top level, installing properly fixed guy wires etc. The information such as materials, dimensions, installation procedures, location selection etc. should be clearly detailed.
b. The protection of small ships and boats with non metallic masts should be addressed separately emphasizing the prevention of possible fire risks in the event of direct strikes to the mast.
c. The human safety issues such as minimum separation from mast, guy wires and any other paths of concentrated currents; working guidelines with metallic systems under thunderstorm conditions etc. should be addressed.
d. Minimum separation of high risk locations (e.g., Petrochemical storages) of the naval craft and the possible points of hot-potentials in the event of a direct strike should be specified.
e. The exposure of many distribution points of a naval system to direct lightning effects makes the elevation of even sub-D boards of the LV system to Zone-1. This point should be adequately addressed in the standards. The shielding of LV wires may reduce the requirement of surge protection at regular intervals.
f. We emphasize the need for defining better test specifications for the SPDs meant for naval applications. The presently recommended test waveforms specified both in [44] and [48] should be revitalized for the naval applications. The study [14] clearly shows that these test waveforms should undergo a thorough revision even in the case of ground based applications.
g. A proper insulation coordination should be specified for ship-based MV/LV systems to prevent insulation failure (caused by common mode transients) due to both direct currents and large induced voltages that may be experienced by naval vessels in littoral waters. Proper SPDs are essential to prevent damage caused by differential mode transients.

4. CONCLUSIONS

We have analyzed the lightning environment experienced by ships and other naval crafts that sail in littoral waters with the view of assessing the lightning related threats imposed on the systems of such vessels. In tropical oceans thunderstorms prevail throughout the year and in Far-East Asian region positive lightning with large currents and massive charge is a special feature of winter lightning, hence the thunderstorm related risk for the naval crafts in such atmospheres is significantly high.

In our analysis we clearly show that sea water acts as nearly a perfect conductor thus lightning electromagnetic transients propagate with very low attenuation of amplitude over the sea surface. Furthermore the distortions at high frequencies are also negligible as the waves propagate over the sea. Under such conditions electrical and electronic systems of sea vessels are dangerously exposed to lightning related induced effects leading the systems to frequent failures.

The existing standards that deal with electrical installations and safety of naval systems barely address the defense of electrical and electronic systems against direct lightning currents and induced effects of nearby lightning. Based on our analysis we propose the development of a dedicated Standard for the lightning protection of naval systems, where inclusion of several specific cases is highly essential.

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