Protecting Electronic Equipment in Composite Structures Against Lightning

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CTIT

CTIT Ph.D. Thesis Series No. 15-364

Centre for Telematics and Information Technology

P.O. Box 217, 7500 AE

Enschede, The Netherlands.

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ISBN 978-90-365-3858-9

ISSN 1381-3617 (CTIT Ph.D. - Thesis Series No. 15-364)

DOI-number: 10.3990/1.9789036538589

<http://dx.doi.org/10.3990/1.9789036538589>

Printed by Gildeprint Drukkerijen, Enschede, The Netherlands.

Cover photo curtesy of Alasdair Baverstock

PROTECTING ELECTRONIC EQUIPMENT IN COMPOSITE STRUCTURES AGAINST LIGHTNING

PROEFSCHRIFT

ter verkrijging van
de graad van doctor aan de Universiteit Twente,
op gezag van de rector magnificus,
prof. dr. H. Brinksma,
volgens besluit van het College voor Promoties
in het openbaar te verdedigen
op 18 juni 2015 om 16.45 uur

door Mihai Alexandru Blaj
geboren op November 15, 1981
te Deva, Roemenië

Dit proefschrift is goedgekeurd door de promotor:
Prof. dr. ir. F.B.J. Leferink

To my dad

Summary

Damage resulting from an interaction with lightning current in a military naval vessel, especially in a conflict zone and at the time of a conflict, which leads to the incapacitation of vital activities on the ship, is unacceptable. Because many potential conflict zones are in littoral areas, and because of the increase in lightning activity, both now and expected in the years to come, the provision of protection for naval vessels sailing in those waters should be a high priority. The fact that many standards exclude both naval vessels and the littoral area transforms this work into a potential contemporary solution.

With the knowledge about the formation of charge layers in the atmosphere, and about the influence such weather phenomena as fog, clouds, and aerosols have on the transport of additional charge particles, it is possible to understand the formation of lightning. A review of the existing thunderstorm prediction models, and finding a way to verify and update the accuracy of such, is equally important at this stage.

Merely understanding the root cause of the problem will not be enough to solve the problem, and therefore an extensive evaluation of the available literature, with a special attention to standards, also has to take place. Evaluating risks and finding what was previously accomplished by others, and any stones they have left unturned, can improve the life expectancy of a system or building block when applying and improving the existing technology.

Conventional lightning protection measures serve as points of departure to reach the goals of this research. Such issues as positioning, zoning, and proximity to other components more attractive to lightning strikes must not be overlooked since these are equally important. The rolling sphere concept, as described in civil standards, is applied to naval vessels, and serves now as a basic tool within THALES to estimate the risk of lightning, and possible damage and/or interference.

Steps taken by other branches of industry in this direction is investigated too. Investigation and a thorough analysis of other protective methods will help to generate the right ideas to tackle the issue and to improve lightning protection of electronics enclosed by composite structures against both direct contact with the lightning current, and the indirect effects of the associated electric and magnetic fields. Diverters are used by the aircraft industry and the possible use to protect

radars under a composite non-conducting radome has been investigated experimentally.

The constant increase in our dependency on composite panels throughout many branches of industry, including the naval and maritime sectors, make it necessary to quantify and measure all the risks associated with lightning strikes. Evaluating risks, and where necessary fixing them, will guarantee the successful use of this technology. The lack of shielding properties, and the high likelihood of deterioration and damage as a result of a lightning attachment, mean improvements are essential to make the use of complete fiber reinforced polymer (FRP) composite structures completely safe. A novel idea has been presented, and evaluated via modelling and simulation, as well as via experiments, where the shielding properties of thin materials is used in combination with the coupling of the electromagnetic field, as generated by the lightning strike, into cabling. It has been shown that a smart combination of the shielding and coupling aspects can be very beneficial.

Another novel concept is the use of pre-loading of ball bearings. This pre-loading results in a continuous conducting path between the rotating and static part, such that no sparks and hence no damage will occur. A patent application has been filed by THALES Nederland

.

Samenvatting

Schade door blikseminslag aan een militair schip is niet acceptabel, met name op plaatsen en in tijden van conflict. Het kan functies uitschakelen die belangrijk zijn voor de missie en de overlevingskansen van het schip en haar bemanning. Nu conflicten zich meer en meer afspelen in gebieden dicht onder de kust wordt de kans op blikseminslag groter omdat in die omgeving meer bliksem voorkomt. De verwachting is dat dit in de toekomst erger wordt. De noodzaak om militaire schepen tegen bliksem te beschermen neemt zo alleen maar toe. Het feit dat veel standaarden zowel de kustwateren alsook militaire installaties uitsluiten, maakt dat dit document in potentie als leidraad zou kunnen dienen voor toekomstige ontwerpen.

Met de kennis van de opbouw van lading in lagen van de atmosfeer en de invloed van weerfenomenen als mist en wolken in combinatie met vervuilende aërosols op het transport van geladen deeltjes, is het mogelijk het ontstaan van bliksem te verklaren. Het is belangrijk om de bestaande modellen om bliksem te voorspellen en schade te minimaliseren te verfijnen en te verifiëren om hun nauwkeurigheid te verbeteren.

Alleen het doorgronden van de oorzaak lost het probleem niet op. Een uitgebreide studie van de beschikbare literatuur op dit onderwerp met aandacht voor de bestaande standaarden en oplossingen is eveneens noodzakelijk. Door de risico's en de oplossingen van anderen te evalueren met aandacht voor aspecten die nog niet of onvoldoende bestudeerd zijn, worden nieuwe oplossingen bedacht om bestaande technologieën te verbeteren en zo de levensduur van een systeem of bouwsteen te vergroten.

De gangbare methodes van bliksem bescherming dienen als uitgangspunt om het doel van dit onderzoek te bereiken. Zaken als positionering, toepassing van zones en gebruik van nabijgelegen geleidende objecten die kunnen dienen als transportweg voor de bliksemstroom (bliksemafleiders) moeten zeker niet over het hoofd worden gezien omdat ze even belangrijk zijn. Het geometrisch elektrisch model (Rolling Sphere model) zoals het in de civiele standaarden wordt beschreven, wordt toegepast op marine schepen en dient nu als standaard gereedschap binnen THALES om het risico van blikseminslag en mogelijke schade en/of storing in te schatten.

De aanpak bij het voorkomen van bliksemschade in andere industriële disciplines wordt eveneens onderzocht. Hieruit komen de juiste ideeën voort om elektronica in composietstructuren te beschermen tegen bliksem. Daarbij wordt zowel rekening gehouden met het vermijden van directe blikseminslag alsook met de reductie van de indirecte effecten van bijbehorende elektrische en magnetische velden. De toepassing van bliksem afleiders zoals die worden gebruikt in de vliegtuig industrie zijn experimenteel beproefd voor de bescherming van radars onder een niet-geleidende composiet radome.

De gestage toename van onze afhankelijkheid van composiet panelen in vele takken van de industrie inclusief de scheepsbouw vereisen meting en kwantificatie van alle risico's die bliksem met zich meebrengt. Evaluatie van de risico's en, waar nodig, toepassing van reductie maatregelen, garanderen de succesvolle toepassing van deze technologie.

De afwezigheid van afschermende werking en de grote waarschijnlijkheid van aantasting en beschadiging bij contact met bliksem maken dat verbeteringen essentieel zijn om volledige vezel versterkte polymeer composiet structuren helemaal veilig toe te passen. Van daaruit wordt een nieuw concept van bliksembescherming ontwikkeld en beproefd via experimenten, modellering en simulatie, dat gebruik maakt van de afschermende eigenschappen van dunne metaalfolie om de koppeling van elektromagnetische velden, zoals die worden gegenereerd door de blikseminslag, op bekabeling. Aangetoond wordt dat een slimme combinatie van afscherming en inkoppelings aspecten erg voordelig kan uitpakken.

Een ander nieuw concept is de toepassing van voorspanning op kogellagers. Deze voorspanning veroorzaakt een continu geleidend pad tussen het roterende en statische deel van het lager zodat er geen vonken optreden en dus geen schade zal ontstaan. THALES Nederland heeft hierop patent aangevraagd.

Contents

1.	Introduction	1
1.1	The history of lightning, or lightning in history	1
1.2	The history of lightning research.....	2
1.3	Types of lightning.....	7
1.4	Impact of lightning on modern equipment	8
1.5	Scope of this work	9
1.6	Structure of this thesis	11
2.	Risk of lightning in littoral area	15
2.1	General concept.....	15
2.2	Lightning formation.....	17
2.2.1	Lightning formation as result of inductive charging, induction between particles	18
2.2.2	Lightning formation as result of inductive charging, photoelectric charging ..	18
2.2.3	Non-inductive charging, tribo-electric charging.....	19
2.2.4	The effect of chemical (composition) on the particles	20
2.3	Formation of charge layers	20
2.4	The influence of fog, clouds, and aerosols	22
2.4.1	The fog.....	22
2.4.2	The clouds.....	22
2.4.3	Aerosols	23
2.5	Initiation of discharge in the atmosphere	24
2.6	Using numerical models to simulate lightning activity.....	25
2.7	Thunderstorms, lightning flashes, and climate change	26
2.8	Particularities of the littoral areas.....	28
2.9	Summary.....	30
3.	Risk of lightning strike on board of ships	33
3.1	Risk of lightning	34
3.2	Lightning standards of interest	36

3.3	Probability and risk of lightning to tall structures onboard naval vessels in the littoral environment	38
3.4	Lightning protection	41
3.5	Properties of lightning	46
3.5.1	Direct lightning	46
3.5.2	Indirect lightning	48
3.6	Summary	50
4.	Conventional lightning protection measures	51
4.1	Zoning for naval vessels	51
4.2	Composite structures in LPZ 0	53
4.3	Lightning issues on composite structures in LPZ 0	53
4.4	General lightning protection methods and concepts	57
4.5	Summary	59
5.	Direct lightning protection measures	61
5.1	Modern radar systems, rotating	62
5.1.1	Long Range Radar	62
5.1.2	Medium Range Radar	67
5.1.3	Multifunctional Herakles Radar	70
5.1.4	Multifunctional Sampson Radar	71
5.2	The Integrated Mast Family	71
5.3	Direct lightning protection in other domains	73
5.3.1	Aerospace	73
5.3.2	Wind turbines	75
5.4	Summary	77
6.	Indirect lightning effect, L-EMP	79
6.1	The challenge of composite materials for naval ships	79
6.2	Electric induction of current surges to surfaces	80
6.3	Shielding effectiveness of thin metal	81
6.4	Coupling of electromagnetic fields to transmission lines	86
6.5	Induced effects due to coupling of L-EMP	89
6.5.1	Without shielding	89
6.5.2	With thin metal shields	92
6.6	Summary	93
7.	New lightning protection concepts	95

7.1	Thick metal plates to shield the composite structure against both direct and indirect lightning.....	102
7.2	Thin metal plates to shield the composite structure against both direct and indirect lightning.....	105
7.3	Validation of calculated and simulated results thru testing.....	107
7.4	Effect of lightning rods and diverters on a radome	115
7.5	Current path thru bearing.....	119
7.5.1	Conventional bearing.....	120
7.5.2	Pre-loaded bearing	122
7.6	Summary.....	126
8.	Conclusion	127
8.1	Conclusions	127
8.2	Recommendations	129
	References	131
	Acknowledgements	139
	Biography	141

1. Introduction

1.1 The history of lightning, or lightning in history

Although for many centuries human beings have tried to tame lightning with various rods, so-called Franklin rods, in recent decades the knowledge in the field of lightning protection has expanded and developed considerably. Many centuries ago it was seen a “sign from the gods”, a punishment, or a fire starter, but once people started to understand the phenomena, their fear was transformed into a thirst for knowledge. Scientists and researchers nowadays are no longer merely content with protecting all types of structures and objects against lightning, they eventually want to understand and control all aspects of the lightning discharge as well.

The lightning flash and the thunder play an important role in various religious and cultural beliefs in almost every civilization on this planet. All over the world and throughout time, human beings have had their own interpretation of the phenomena. The ancient Egyptians depicted hieroglyphs with Seth, and similarly in ancient Mesopotamia seals from as far back as 2200 BC have been found depicting local gods and goddesses generating and throwing thunderbolts towards their enemies. In the north of Syria, a relic dated 900 BC portrays a local god handling thunderbolts. The best known image is of Zeus, in ancient Greek legends, holding a thunderbolt in his right hand as a symbol of his power. Cultures in the Far East, such as China, have “the five ministries of thunder” made up of mythological people. India has Indra as the son of Heaven and Earth, who decorated his chariot with thunderbolts to impress the mortals. Buddha himself is sometimes represented by statues holding a thunderbolt in one hand. The lightning bolt became not only the most common tool for the gods to punish the mortals, but also to fight against each other. Jupiter, in ancient Roman mythology, used it to keep the other gods at bay. However, some Roman sculptures and writings from that era introduce the idea of a “lightning protection device”, the laurel bush. For this reason, various Roman emperors are now immortalized in sculptures wearing laurel wreaths on their heads. From this point on, the presence of lightning in literature and artistic representations will gain

momentum and be perceived as a regular presence in the sky, alongside meteorites and birds.

The northern hemisphere has its share of lightning-related mythology as well, with the God of Thunder and Lightning himself, Thor. Thor could harvest the power of lightning by lifting his hammer Mjolnir and redirecting it towards his enemies. And the Native Americans attribute the origin of lightning to a magical thunderbird flying high in the sky.

The world is full of information about lightning and the symbolic of the lightning flash, and to cover all that is available, plenty of research and dedication is required. Our generation is lucky nowadays to be able to have access to contributions from such scientists as Prinz [1], Uman [2], Gary [3], amongst other things to also learn about this aspect of lightning science. Another important step forward in lightning research was achieved when people started to take a particular interest, and many times record, when important edifices sustained damage or were destroyed by lightning. Recordings of such facts started many centuries ago. In the Middle Ages, scholars and priests in monasteries and around churches used their knowledge of writing to record such incidents. Most incidents they recorded involved church towers. Bell towers were often the tallest building in the area during those times. But surprisingly, some important buildings still standing today avoided such damage, or there is no information available about them sustaining damage. Buildings such as Solomon's temple in Jerusalem or the cathedral of Geneva were "armed" with devices that can be considered the predecessors to lightning rods. Only centuries later, in 1773, did Benjamin Franklin say: "buildings that have their roofs covered with lead or other metal and spouts of metal continued from the roof into the ground are never hurt by lightning" [4], [5]. But on the ground or in the water, no one was safe in those days. Ships also ended up amongst the victims of lightning strikes. During thunderstorms inside or near harbors, many ships saw their wooden masts severely or totally damaged. Harris [6], [7], [8] mentions in his records that around 150 incidents took place on British ships alone, with nearly 100 lower masts destroyed. Several sailors lost their lives or got wounded in these incidents.

1.2 The history of lightning research

The first steps in serious researching lightning were taken in May 10, 1752. That particular day, in a small village near Paris called Marly-la-Ville, Thomas Francois

Dilibard laid the foundation for an experiment. He unsuccessfully tried to launch a kite during a thunderstorm, while having it connected by a hemp string to a metal piece, the anchor, in the ground. One month later, Benjamin Franklin attempted the same experiment, this time with success. Soaking wet, the hemp string became conductive and channeled the lightning charge to the ground, as shown in Figure 1-1. This discovery gave Franklin the idea to use such conductive paths to “drain” the clouds of charge, which was the birth of the Franklin rod.

Figure 1-1. Benjamin Franklin and his son experimenting with atmospheric electricity. From [125]

Nevertheless, in other parts of the world, such as Russia, England, Sweden, or the Netherlands, men and women were also doing similar tests and were active in this field of science. Over time, the kite evolved into balloons, mortars, and nowadays even to rockets. Armed with such devices, scientists bring clouds and ground “close together”, using the conductor for the initial current path, resulting in a plasma channel of charge between the clouds and ground [9], [10].

Over time, the way people use lightning rods has evolved as well. People no longer used the rods exclusively to “drain” the charge from clouds and avoid lightning strikes, they also started to use the rods to channel all that destructive energy and to provide protection for structures. The town hall in Siena Italy, on April 18th 1777, was one of the first buildings on record to use such method of protection.

The 19th century is important for another aspect of lightning research. Once photography and spectroscopy had advanced far enough, it was time for the lightning spectrum to be investigated. Scientists such as Herschel [11], Gibbons [12] and Clark [13] determined that gases, such as nitrogen, are responsible for the colors in the lightning spark. However, the full identification of the spectrum lines was the result of Schuster's work [14] in 1880.

The arrival of the 20th century fueled the quest to gain more insight into the characteristics of the lightning flash, and saw scientists use Schuster's [14] discovery to add more knowledge about the spectrum. Among these, Slipher [15], [16], Dufay [17], and Fries [18] made important steps during the first half of the century, while Orville [19] and Uman [20] did this in the latter part of the century. The use of still photography in lightning observation is what made the difference at that time, but the capacity to record moving images generated a huge step forward in lightning research.

The invention of streak cameras by Boys [21], soon afterwards, was the impulse for new results from such researchers as Schonland, Colens, and Malan [22], [23]. Impressive for that period in time is the quality of their results, leading to a full description of the lightning process. From initiation of the step leader in the cloud to end in one, two, or sometimes more subsequent flashes, which were now all caught on camera, as shown in Figure 1-2.

Figure 1-2. Lightning sequence – down leader initiation. From [126]

Catching the lightning strike on film stimulated the curiosity of scientists. Simply to know more and more about the process and its characteristics, it pushed them to try and record the flash on other media, such as oscilloscopes. The first results on this

matter were obtained in Russia and the United Kingdom (UK), soon to be followed by the United States (US) in the middle of the 20th century.

The ability to measure and record the electrostatic charge on the ground and in the clouds, as well as to measure both electric and magnetic fields from the lightning channel, opened up another branch of lightning research: lightning detection systems, or what were later to become Lightning Location Systems (LLS). When the electromagnetic characteristics of cloud and ground are established, every single variation of these parameters can represent a potential lightning strike in the area where measurements take place. The detection, identification, and interpreting of these variations is performed by LLS by means of acoustic, visual, and electromagnetic measurements. The acoustic location is based on the acoustic signal time of arrival (TOA) technique and the ray tracing technique. Another, but very rudimentary, acoustic method is to identify the lightning by the source, the thunder. This technique is not as useful, especially since there are no differences between clouds to ground, cloud to cloud, or intra-cloud lightning that the observer can perceive. In vast, remote areas, this method is still a good enough source of information in signaling the approach of a thunderstorm, where people in the countryside play the role of specialist. There are various visual methods, which consist mostly of recording images from the ground or space to determine the location of each flash related to the distance from a designated point of reference. Such limitations as pollution, dust, and water in the air make these methods less precise. Or like when looking at the satellite imagery and trying to make a good distinction between three types of lightning, only to find that these three types are practically impossible to distinguish from each other. Therefore, the most reliable method for LLS up to now is the method of measurement of the EM fields. Lightning frequencies range from 1 Hz up to 300 MHz on the electromagnetic energy spectrum. Certain traces have also been discovered at higher frequencies, ranging from microwave frequencies to visible light (10^{15} Hz). At very high frequency levels the precision in locating the source of a disturbance is high, for instance 1 m radius at 300 MHz, but at low and very low frequencies (LF & VLF) the precision drops and the location radius increases to hundreds of meters. An example is shown in Figure 1-3, and is taken from [24]. Several red dots representing lightning strikes in the sea are visible too. After several discussions, the authors of the papers estimated that these dots are a measurement error of the systems due to the limited accuracy, and could not confirm their location. This is a

first sign of how complicated the problems with the littoral areas are, and how big the necessity is for additional research.

Figure 1-3. Location of LF LLS (squares), and measured lightning strikes (red dots). From [24]

The photo imaging from satellites together with the Schumann resonance technique for the location of lightning is a mixed method between visual detection and EM field measurement in the extremely low frequency (ELF) spectrum. The principle of Schumann resonance [25] is to consider the space between the highly conducting earth and ionosphere as a waveguide, assuming that the speed of an electromagnetic wave equals the speed of light (c), and using the radius of the earth (r_e), results in a fundamental resonant frequency (when mode $n=1$ [1]). After subsequent derivations, and in relation to a certain speed of propagation $V(\sigma)$ with σ representing the conductivity, the resonant frequency of the n^{th} mode ($n>1$) is produced [2].

$$f_n = \frac{c}{\lambda_n} = \frac{c}{2\pi r_e} n \approx 7.5n \quad [\text{Hz}] \quad (1.1)$$

$$f_n = \frac{V(\sigma)}{2\pi r_e} \sqrt{n(n+1)} \approx 60\sqrt{n(n+1)} \quad [\text{Hz}] \quad (1.2)$$

Following this approach, three independent stations, relatively far away from each other in order to maximize precision, record the same oscillations generated by lightning in the ionosphere. The peak value is used for reference in time and value.

The initial accuracy is very poor, but the advantage is that lightning can be detected worldwide.

1.3 Types of lightning

The understanding of lightning reached higher levels in more recent decades. The types of lightning discharge and the specific terminology generated new results. The two corona emissions from cloud and ground were now called leaders. An upward leader is when corona reaches to the sky and a downward leader is when it rushes to ground. Because of temporal evolution, the time steps necessary to achieve all stages of development, and correlated with the sideways descent of downward leaders, in a “stair-like” shape movement, brought it the name of downward step leader. These new names, correlated to the type of charge transferred in the process, give the following types of cloud to ground lightning as shown in Figure 1-4. However, since the focus of this work is on objects and structures that would not reach or exceed 100 m in height, most references throughout the text apply to types a & b.

a) downward negative lightning;

b) downward positive lightning;

c) upward positive lightning;

d) upward negative lightning.

Figure 1-4. Cloud to ground lightning typology. From [127]

As mentioned earlier, cloud to ground is not the only type of lightning. Another lightning variant is cloud to cloud, or in the case of very large clouds intra-cloud lightning.

The main research challenge and focus of this work is to develop new lightning protection measures for naval systems constructed with non-conducting composite materials in a naval/marine environment. Nevertheless, to put the information in a context everyone can relate to, there is one category of objects exposed to both types

of lightning. Airplanes suffer the highest exposure to lightning, including cloud to ground lightning during takeoff and landing, as well as cloud to cloud or intra-cloud during normal flight. And airplanes are also interesting to look at from other perspectives, such as the extensive use of composite material in modern airplanes, their direct exposure to high risks of lightning, and the demands for high reliability. In the aviation industry, a lot of experience has been gained which can be used in the research for the best protection measures of electronic equipment in composite structures, in a naval/marine environment.

By simply passing through a moderately strong electric field region, an airplane could trigger a lightning strike. Studies at NASA revealed that the fields at the nose of the aircraft were enhanced by a factor of about ten, where fields at the tips of wings are enhanced by only a factor of seven, and fields at the tip of the stabilizer are enhanced by a factor of three. With the combination of increased field densities around the extremities of the aircraft and relatively strong existing field densities in the region, lightning can be triggered by the aircraft at the point when the enhanced field exceeds the minimum breakdown strength of the air [26]. Data from the National Transport Safety Board, comprising 26 years of data (1963 to 1989), identified injuries due to lightning strikes on aircraft. Over that period, 40 lightning-related accidents occurred, ten involving commercial flights and 30 involving private aircraft, causing 290 fatalities. Of these flights, four commercial airplane accidents accounted for 260 of the fatalities, and 14 non-commercial airplane accidents accounted for the remaining 30 fatalities.

1.4 Impact of lightning on modern equipment

With the discovery of the EM fields as a result of the lightning channel, another major problem was uncovered: the indirect effects, or the induced currents and voltages in conductive wires and objects found, at a close distance from the lightning channel. In the early days, the immunity levels of the electric and electronic components, such as vacuum tubes, were high. Now, semiconductor components with very low overvoltage capabilities are used everywhere and the susceptibility of such devices and components is an increasing problem. To provide some sort of protection against the effects of indirect lightning to such electronic equipment, many measures, such as shielding, grounding, or overvoltage protection devices, have been developed in the last decades, beginning with airplanes [27].

Shielding and grounding are difficult to achieve with composite (parts of) airplanes. Conventional designs for lightning protection in metal airplanes have required basic lightning current flow solutions. More recent designs, using such advanced materials as composite structures and highly integrated systems, require more critical electrical bonding, shielding and overvoltage protection designs [26]. In general, the composites referred to throughout this work are materials made from two or more component materials, bonded together, each with their own properties, to provide a new type of material with new characteristics different from each individual component. In particular, the focus is on fiber-reinforced polymers (FRP) composite panels.

Damage to the structure at the location where lightning attachment occurs is called ‘direct effects’. Modern passenger jets have kilometers of wires and dozens of computers and other instruments that control everything from the engines to the passengers’ music headsets. As mentioned earlier, these electronic systems are highly vulnerable to voltages and currents induced by the electromagnetic fields due to lightning. This is because the shielding provided by the embedded layer of conductive fibers or screens only protects against the components of the EM field in higher frequencies. A major part of this thesis is therefore devoted to this challenge.

1.5 Scope of this work

Conventional naval radar systems used metal reflector antennas in the exposed environment, i.e. exposed to the weather and lightning, while all electronic equipment was located in a protected, below deck, environment. This has changed over the last two decades, and is about to change again in the near future. More and more electronic parts are going to be used in the exposed environment. There will be potential unrestricted connections between the antennas, these very complex dipoles, through patches or strip lines driven down to the semiconductor amplifiers, or directly connected to the semiconductor low-noise amplifier inputs. To reduce the weight of the entire system, especially in mast-like integrated structures, the trend is to construct the housing of the radar systems, or parts of it, from (non-conducting) composite materials instead of full-metal plates. This poses huge challenges for the design if the risk of lightning is to be taken into account.

Whether designing a new installation, or when extending functionalities of existing systems, these key processes have been followed:

- Define the scope based on existing standards. If standards for your subcategory don't exist, apply the root category standards and document your findings (might help in the development of the missing standard one day).
- Analyze and understand the phenomena, the outside and inside environment, "know thy enemy".
- List all constraints, environmental as well as constructive, important in the functionality of the system.
- Relate to similar systems, understand and emulate their abilities in order to reach the expected results.
- Write the rules that will ensure the best functionality of the system (from construction to installation).
- Build the model as well as the end product with care and with respect to the rules you imposed.
- After construction check and recheck the system as well as retrace all the steps as the last form of verification.
- Measurements. Confirm and validate your expectations via practical results.
- Fine tune or address the unwanted results after validation.

These processes can be individually identified in the following chapters, but the complete work for this project covers much more.

During the research period, the research work was about finding available and new lightning protection concepts for electronic equipment in composite structures, which then led to the questioning and seeking of answers on other topics such as:

- Determine the risk of a lightning strike
- What is the threat level for surface ships in a littoral environment?; the current models are not applicable for naval environments [28], [29], [30], [31]
- Investigate the basic solutions for redirecting lightning, using diverters to conduct the high intensity currents, using external conductors, gauze, or laminated metal layers. Is it possible to use these techniques, and what are the consequences for radar performance?
- Is it possible to use novel active techniques (active diverters), by ionizing the air just before the strike, or to use high power lasers to divert the lightning. And to challenge things, such as why TC81 from the International Electrotechnical Commission (IEC) states that there is insufficient information available on these techniques.

- Try, when possible, to modify existing models used for the effect of lightning on infrastructures to match the effects onboard naval vessels. Determine the effects on electronics, cabinets.
- Investigate the effect of thin shielding layers, such as gauze, expanded metals (aluminum, copper, or steel), metalized cloth, such as Shieldex, conducting paint, or carbon fibers. This is because so far most simulations have been performed taking only the first order effects into account. The focus of this research activity was extended, so not only the shielding effectiveness, but especially the effects of induced voltages on interfaces were included as well.
- Methods to determine the current path, for the high frequency as well as for the high-energy low frequency effects have been created.

Consequently, after following these steps in each case, and using the models and lightning testing facilities at the former Hazemeijer factory in Hengelo (Tuindorpstraat), THALES, and at the University of Twente in Enschede, various materials have been investigated focusing on the impact of lightning on actual (parts) of products. With the support of THALES Netherlands, evaluations of current protection techniques were proposed and used for the SMART-L Long Range Radar, Medium Range Radars, for the family of Integrated Masts, and were performed using both simulations and experiments. Samples and scale models were used to perform measurements, mainly via transfer functions in time domain. A vast majority of these tests and their findings will be described in the following chapters. Computation and simulation tools, such as MATLAB®, MathCAD®, and CST (Computer Simulated Technology) Studio Suite®, have been evaluated and compared, used and validated, to ultimately improve, extend, or generate models on coupling of EM fields into transmission lines in time domain.

The survey of literature studies, discussions, and interviews with researchers actively involved in these fields, supported by the attendance of numerous lightning conferences during these past years, made it possible to expand the research and integrate many of these findings into this work.

1.6 Structure of this thesis

The lack of knowledge with regard to the littoral area is one key aspect of this work. This work is intended to provide new guidelines, supported by arguments and the rather limited available literature, which would allow a risk assessment for future

composite naval vessels so they can operate in these areas without taking extensive risks. The unpredictable weather behavior of modern times, the continuous rise in the number and intensity of hurricanes (Rita, Katrina, Ike), as well as the growth in electrical activity during regular thunder storms all around the globe, has pushed this work to review the existing maps for lightning activity. This is done in Chapter 2. Once the risk of a severe thunderstorm is determined, the chance of a lightning strike somewhere near the coast is many times greater at a particular moment in time. But how important is this in the design phase, for instance, for integrating the lightning protection? Designing the lightning protection for systems/structures must consider, above all, the following aspects:

- Intercept and redirect the lightning current (is this the tallest structure?)
- Provide enough shielding capabilities (immunity) to withstand and/or suppress the electromagnetic radiation resulting from the lightning channel
- If needed, add overvoltage protection measures

To determine the optimum position of the structure/object is crucial. Equally important is also the placement or positioning of the lightning rods. Based on location, and with or without conducting objects in the surrounding area, the Lightning Protection Levels (LPL) can be assigned. This is described in Chapter 3. The actual assignment of the Lightning Protection Zones (LPZ) and LPLs together with the introduction of two new approaches for aluminum lightning rods in stainless steel sockets and “down conductor” solutions are described in Chapter 4.

In Chapter 5, concepts and solutions available to attract and channel the lightning current after a direct attachment for a naval vessel in a littoral area are described.

The indirect effects of the lightning channel cause large EM fields. An innovative and smart combination of the shielding effectiveness of thin layered shields, with the coupling of fields into cabling, provides a potential application for lightweight composite structures. With this concept, a thin layered shield acts as a low-pass filter, rejecting high frequencies, while the coupling of fields becomes more effective at higher frequencies. The analysis and application of this concept is described in Chapter 6.

For various reasons, composite structures can be fitted with metal frames for different purposes, such as to improve the strength of the assembly or to guide the cable trays. By integrating the frame of the structure in the lightning current path, protection against direct strikes can be achieved. Crafting an outer shell that contains enough conducting material to distribute the charge and achieve safe levels for

voltage, which would also lead to a reduction of the EM field caused by the lightning channel, is the topic of Chapter 7. This thesis ends with a conclusion in Chapter 8.

2. Risk of lightning in littoral area

A good understanding of the phenomenon is the key to good design. By properly outlining the cause and the effects on each threat, the proper steps are taken to overcome them and a right level of protection is achieved. Understanding the lightning phenomena from creation to initiation and ultimately strike will lead to a proper lightning protection system (LPS). This chapter is a compendium from past research, and the information gathered here should be considered necessary in the design of any LPS.

Lightning does not behave in a singular manner all over the world; each location brings its own peculiarity. For most cases, existing standards provide sufficient information with general principles to follow in order to insure protection against lightning for structures and services [28], [29], [30], [31]. But sometimes the solution to a problem can be outside the scope of a particular standard or series of standards. What if, for example, the working problem concerns railways systems, or vehicles, ships, aircrafts, offshore installations, underground high pressure pipelines, or telecommunication lines? All of these are explicitly excluded in the basic series of standards on lightning, the IEC 62305 series [28], [29], [30], [31]. In some areas, such as aircraft and railway systems, special standards have been created. But these areas are still not included in any lightning standards, so all the system designers and manufacturers face a major problem. Whereas in the past the operational area for naval vessels was the “blue water”, the open ocean, this has changed over the past decade. The operational environment has shifted to the littoral area, another aspect that is not incorporated in the standards, at the time of this work. The following sections describe the risk of lightning in these areas, and why it is important to know this before designing protection against any type of lightning effects.

2.1 General concept

The atmospheric conditions on Earth provide a good opportunity for charge layers to form [32] and to favor phenomena such as thunderstorm electricity and fair weather.

The process of electrification is only one of many processes to take place in the atmosphere and that can influence a lightning strike. Certain interactions between clouds and aerosols are well known and understood by now. Things like an increase in the concentration of aerosols inside warm clouds will affect the number of raindrops produced. However, when looking to understand lightning, many things have yet to be explained or are still open to debate. The conductivity of the Earth's surface is considered good [33], with exceptions in hot and dry areas, or at the poles, where the conductivity decreases significantly. Areas with high concentrations of silicate residue, on the other hand, are the areas of increased conductivity. This makes the planet look more like a "leaky capacitor" than a "conductor" [35], [36]. In the atmosphere the story is different. The best atmospheric conductivity is reached at altitudes exceeding 80 km in the upper atmosphere. Inside thunderclouds and in fair weather regions, the air conductivity depends on such factors as pollution, altitude of the cloud, and the geomagnetic latitude of that particular location [32]. Upper and lower conductive layers feed the areas with intense thunderstorm activity. This allows the global electric circuit to exist and to continuously deliver ions into the atmosphere via the conduction current. The main contributors for charged particles over 60 km in altitude are the free electrons, as shown in Figure 2-1.

Figure 2-1 Energy balance in the atmosphere. From [40]

Below 50 km, ions are produced by the natural radioactivity of the earth and cosmic rays, and at altitudes between 10 and 16 km the positive charge is stored in the upper

part of the clouds. The lower parts of the clouds, at lower altitudes, store the negative charge. Ions with diameters between 0.1 to 1nm and a lifespan of 100 s are common in this low altitude area. Moving closer to ground, at altitudes of around 1 km, the cosmic rays will continue to play an important role in the creation of ions. This theory is in direct contrast to the popular belief that once it is close enough, it must be the ground itself that has the most influence on charge formation. It is now plausible to think of clouds as vertical dipoles or huge batteries [33]. The charge generation phenomenon is presumed to have a reduced influence on the current circuit of the Earth at low altitudes compared to high altitudes [35], [39]. Around 90 km in altitude, free electrons start to dominate the ionosphere and the Earth's magnetic field. Close to 105 km in the ionosphere, the free electrons alone are responsible for conductivity. But over 140 km, ions once again take lead and assure the atmospheric conductivity.

Deep convective clouds provide the best environment for charge to build up. There are upward and downward currents travelling between the stratosphere, the atmosphere, and the ionosphere [33], [39]. Within thunderstorms, conduction currents are predominantly upward currents, while in the fair region currents have a downward flow. These currents form the DC (direct current) circuit of the Earth while the lightning discharges generate the AC (alternating current) circuit. The atmospheric conductivity, on the other hand, is the most important phenomenon for determining the global electric circuit and its properties. During rain showers, the negative charge collected in the lower levels of a cloud is transferred to the rain droplets, which in turn transport the charge to ground and so generate a conduction current. The earth produces about 10 million pairs of ions $\text{m}^{-3}\text{s}^{-1}$ on land and at sea level, while at high altitudes this number increases by a factor 30 [37],[39]. When compared to the earth surface, one peculiarity of big water surfaces is a small quantity of radioactive emissions, leading to a 2:1 step up in ion production by comparison.

2.2 Lightning formation

The entire cloud electrification process still cannot be explained by a single phenomenon. It consists of cooperation between processes with time-dependence dominance and variable effectiveness. During freezing, melting, evaporation, and deposition, the correlation between the environmental conditions and properties of

particles give different charging regimes, independent from any pre-existing external field. The charge generation process starts with cosmic rays and UV solar radiation, and charge lost by meteoroids while entering the atmosphere, as result of friction, pressure, and chemical interactions with the atmospheric gases, causing the meteorite to heat up and radiate energy. It continues with friction between desert and volcanic dust particles adding to the existing charge in the clouds, to ultimately result in a huge quantity of charge ready to discharge through lightning.

2.2.1 Lightning formation as result of inductive charging, induction between particles

The pre-existence of a global background electric field – the “fair weather” – ensures the polarization of the water particles suspended in the atmosphere. Therefore, in a vertical field directed downward, this type of polarization will result in an excess of positive charge on the lower part of the atmosphere and negative on the upper part. Positive charge is carried upward on light ice crystals by the updraft, while large ice particles and the graupel bring the negative charge to the ground by falling towards the ground [37], [38], [41]. Graupel particles are the initial ice crystals forming as the moist air reaches a height where the temperature is below zero. According to literature [34], [35], [37], [38], [39], [41], [42], [43] the induction has a less important influence in the early stages of cloud electrification. However, in later stages of cloud electrification, the importance of the induction grows until it becomes of secondary importance, mostly when the field of the cloud exceeds the strength of the “fair weather” field.

2.2.2 Lightning formation as result of inductive charging, photoelectric charging

According to measurements in the last few years [32], [41], [42], the characteristic of aerosol particles presents the peculiarity of accumulating positive electric charge. This charge is the result of incident energetic radiation assisting the release of free electrons from the outermost layer of solid surfaces or particles. Most affected in this case are the dust particles in the upper layers of the atmosphere. The galactic cosmic rays and the ultraviolet part of the solar spectrum both release charge all over the atmosphere depending on the solar activity and the magnetic field of the planet at that time. In the case of thunderstorms, the charge released by the galactic cosmic

rays can provide the final charges required to start the breakdown process and end up with the lightning flash. The transient electric fields generated by the lightning flash end up interacting with the positive ions and the electrons present in the lower part of the atmosphere, and so contribute to a new cycle of inductive charging.

2.2.3 Non-inductive charging, tribo-electric charging

Tribo-electric charging represents the charging process of solid particles by way of friction during transient contact with another solid particle. The nature of the particles (chemical composition), their conductivity, morphology, and the surface properties, are some of the factors that eventually influence the total charge induced on both particles after separation. Dust [32] and ash [51], [52], [55] particles that rub against other suspended particles, or solid surfaces, will become electrically charged. The total tribo-electric charge accumulated on the surface of the particle(s) after separation depends mostly on the duration of the contact between the two particles. The duration of contact between the particles depends on the size of the contact surface, the roughness of both particles, and the geometry of the impact. A big contact surface leads to a longer duration of contact and subsequently to a higher net charge transferred at the end of the separation. In recent years, the study of tribo-electric charging has focused on colliding particles with the same composition, such as ice – ice and graupel – graupel particles. Nevertheless, since more and more pollutants find their way into the air, new studies are required. In the case of dust storms [32] or volcanic plumes [55] the tribo-electric charging is of even greater importance. Large quantities of particles are suspended in the air and collide with each other, they move with the wind in the upper layers of the atmosphere, and help in the formation of the clouds. The resulting charge from this process is then “released” to the ice crystals in the clouds. The transfer process inside clouds also depends on the situation outside the cloud [47], where the fair weather field limits the movement of charge between the dust particles and the ice particles in the cloud during their collision [41]. This exchange also proves to be of major importance in the context of thunderstorm charging. The polarity of the ice particles in normal thunderstorm conditions is positive, and because they are smaller in size and weight than the graupel, the vertical air movement takes them to the upper side of the cloud. Conversely, gravity pulls the graupel to the lower part of the cloud, turning it negative. The normal polarity of the cloud is thus determined after multiple encounters between ice crystals and graupel in prevalent conditions of temperature

and content of liquid water [43], [44]. From the temperature point of view, the particles with a higher temperature lose negative charges and mass to the colder particles. This means the ice crystals become negatively charged and the graupel positively charged. Attempts were made in several laboratories and on various occasions to determine the correlation between the quantity of water, ice and graupel and the exact quantity of charge transferred. But even under specific laboratory conditions, the charge transferred during these collisions reported different values on every occasion. In other words, the mixture used in these experiments was never the same, and any change in the ambient condition influences and even changes the polarity conditions.

2.2.4 The effect of chemical (composition) on the particles

In the liquid and ice phase of the water, inside the clouds, the presence of soluble ionic substances has an important effect on the charging process. The high concentrations of different impurities and their interaction with their surrounding environment increases the outcome of the charging process. As in the case of water freezing to crystallized ice, in the presence of sand particles, after losing the Cl ions during the transition from liquid to ice, the crystals will gain a surplus of Na⁺ ions from the sand. In this case, without any doubt compounds of ammonium, sulfur, and halogen have an important influence in the charging process and the eventual structure of the cloud [49].

2.3 Formation of charge layers

The Earth allows the formation of independent layers of charge, the one important factor in both the development of thunderstorms and in fair weather conditions. In extreme climate areas, e.g. deserts, ionizing conditions exist that strongly influence the formation of charge layers. The conductivity is directly related to the altitude in the atmosphere. But this last observation differs from area to area, from oceanic to continental zones. Above oceans, big electric fields are present simply because the layer of positive charge from the atmosphere is not neutralized by negative charges. Such negative charges are normally released by radioactive dust particles over the ground. Free electrons in the air help create a good conductive environment with their high mobility and lightness. However, when these accumulations of positive ions are not compensated by the same amount of electrons rising from the ground,

they produce the electrode effect. Observed more above the oceans and less over the continental areas, the electrode effect is the creation of the space charge layer. On any place in the atmosphere, if subjected to a vertical electrical field, the positive and negative ions start to move with opposite trajectories. Some positive and negative ions from the air and aerosols are lost because of a recombination process. In 2007, scientists observed a strengthening of the electric field on the ground area as a result of the electrode effect, when Hawaii was considered to be a continental surface of reduced size, [48]. The agitated vertical movements of charged particles generate a charge layer 200 m thick. Another factor in generating this layer is the positive charges released during the sea spray. These same charges eventually arrive ashore carried by the air currents flowing at the water surface. But the maritime aerosols can have another effect, such as the reduction of conductivity in the atmosphere over those areas. In coastal areas, the cold air from the continent filled with dust arrives over the water, where it finds the warm air filled with moisture from the oceanic area moving towards the coast. This warms up the cold air, and the dust rises to reach the ionosphere, producing more ions with the help of the galactic cosmic rays. The result of all this is large and electrically violent thunderstorms in the littoral areas [32], [42], [45].

Another theory developed by viewing the islands as a miniaturized representation of continents came from Williams et al. in 2005 [55]. They explain the differences in lightning strike frequencies between the continental and oceanic areas by means of differences in temperature between these areas, with the capacity of the soil to heat faster than the water. The same faster heating process also increases the instability, convection, and in the end, the frequency of flashes. During the 1980s, differences between the oceanic and continental convection at the tropics were reported too [56]. On the continental area, the updraft during a thunderstorm reaches over 50 m/s while in the case of oceanic areas it is slower and reaches only 10 m/s. This ratio between the two velocities explains the differences in electrification of thunderstorms and the number of flashes counted between the two areas. So therefore, the updraft in the electrification process plays a significant role in determining the number of flashes. Where there is an increase in the pollution and the dust particles in aerosols lifted from the ground, the charge transfer in the clouds leads to an intensification of the thunderstorms. Especially in the littoral area. Once over the sea/ocean, all the particles collide and transfer charge to and from the salt particles present in the air and in the clouds.

2.4 The influence of fog, clouds, and aerosols

2.4.1 The fog

A low atmospheric conductivity caused mostly by free ions sticking to the aerosols or dust particles in certain areas will have an effect in the formation of charge layers at the upper and lower extremities of the clouds or aerosol layers. The charging of the water droplets [49] is responsible for quasi-stationary distribution of field, as well as for most of the fluctuations of the field inside the clouds and fog. The fog lowers the conductivity and raises the electric field together with the creation of charge densities on the upper limit of the fog layer. In the clouds and in the aerosols, the modifications of the charge densities caused enhancements compared to the fog, but at high altitudes, these values drop in all cases.

2.4.2 The clouds

A normal situation in the case of thunderstorm electrification is the formation of charge layers. The external currents form the electrical structure of a thunderstorm and play an important role in the electric circuit of the atmosphere. The charging of particles and droplets by electrical conduction current in the atmosphere influences the positioning and the behavior of the cloud. The different type of clouds as well as their position in relation to altitude is depicted in Figure 2-2.

Figure 2-2 Common types of clouds. From [128]

In the global circuit, a current layer travelling between a lower and an upper boundary, creating charge layers at these extremities, constitutes the representation of a thunderstorm. In the atmospheric column, the clouds and the water vapors create areas with low conductivity. In at least two cases the charge layer formation is important. The first case is in thunderstorms, the second is in the fair weather phenomena. Discharges that start on the lower part of the clouds lead in most cases to cloud to ground lightning with negative polarity, while the transient discharges between the upper parts of clouds and the ionosphere with positive polarity. The positive flashes based on the narrow layers of positive charge have a formation point around the 0°C isotherm. In the melting mechanism of the ice crystals, the positive charges separate from the negative ones. As a result of the melting process, the electric field grows from 30÷120 kV/m in between 5 to 35 minutes.

2.4.3 Aerosols

Cloud droplets are formed from certain ultrafine particles in clean air, known as aerosol particles, after about 5 to 10 hours. These aerosol particles are in turn formed from cluster ions and vapor condensation. The ultrafine particles are not capable of forming water droplets immediately after condensation, mostly because of their reduced size. A minimum size of 100 nm is needed to result in a water droplet. However, just because they are small in size it does not mean they only have a minor influence on the global electric circuit. And because they are so widely spread, they actually have a major influence. Most of the aerosols can accommodate one elementary charge, but there are cases on record where some large aerosols were “housing” more of these charges [34]. Attached to pollutants, droplets, cluster ions, and ice crystals, large aerosols can carry ions of both polarities, or they can be without charge, i.e. not carrying any charge at all. Figure 2-3 offers an insight into the formation and development of such aerosols. The effect of aerosols in the charging process of clouds and atmosphere materializes in the charge transfer between the ions that form them and other particles. The aerosol dispersion in the atmosphere basically differs depending on the altitude, reaching a maximum level at the boundary level of the atmosphere.

Figure 2-3 Visual representations of aerosols in clouds. From [129]

2.5 Initiation of discharge in the atmosphere

The electrons represent the charge carriers in any electric discharge in the atmosphere. At low altitudes, magnetized electrons from the mesosphere facilitate the discharges by reducing the critical electric field. From the ionization point of view, the process is relatively smaller in the upper layers of the atmosphere, but still present due to the mixture of electrons and ions. A reduced effect on the ionizing process is caused by the penetration of cosmic radiation and the consequences of this process. The introduction of this electric field into the neutral atmosphere liberates the electrons and turns their movement into an accelerated movement. In some areas of the atmosphere, ions can grow until they are able to form new particles on their own. Similar to the troposphere, in the upper layers of the atmosphere the intensity of the field does not have to be as strong in order to have a discharge. The only problem is the formation of charge layers in order to have an electric field between them. After a series of internal modifications and ionizations in the final process, atmospheric gases have to withstand an electric discharge. Between charge layers or between charge layers and the ground, an electric field is generated until it reaches the critical value, and this results in a discharge, as shown in Figure 2-4. Sometimes the discharges are visible, bright, but in order to be visible, the energy of free electrons has to be able to excite the atoms during collision. The burst of light goes thru various lines of the electromagnetic spectrum, from infrared, to visible light, and to low X-ray radiation level.

Figure 2-4 Charge separations for various types of lightning. From [130]

2.6 Using numerical models to simulate lightning activity

In the quest to replicate the electrification process of thunderstorms and to help study the dynamics and microphysical evolution of various fields inside the clouds, the scientific community has turned amongst other things to numerical simulations. Starting with the formation of the clouds and following their development in time, certain simulations even end up looking at the very last stages of the process, such as the decay of field and charge. Based on the parameters that trigger the charge separation mechanism inside the clouds, and the ability to compute the electric field generated after the distribution of charge in the various particles of the cloud, most of these models lead to very complex equations. From the electrical point of view, the result will be a representation, as realistic as possible, of the behavior of thunderstorms. The accuracy of these models and their complexity has seen various improvements in recent times.

From a single cloud model through to complex cloud systems - a thunderstorm - the accuracy of the results of such simulations have ultimately been validated by comparison with the real data obtained during extensive observations in the field. At the same time, these results have confirmed the big influence that the charge separation process has on the formation, lifespan, and behavior of clouds.

Using the numerical model for fog as a starting point, a model for a thunderstorm can be developed by adaptation. The fog model replicates the charging process of water droplets and ice crystals in the far field or at the boundary with the clouds.

Such a model used for the littoral environment during winter thunderstorms on the Mediterranean Sea [44] shows intensifications and variations of the electric field inside the cloud up to the moment of the first flash. This demonstrates how big the influence is of non-inductive charging in the formation and first moments of a cloud's life. Three years earlier, Ataratz et al. [45] reported a reduction in the total number of rainfalls, but this reduction came at a price: an increase in the number of severe thunderstorms. In 2005, Alpert et al. built a model for the level of influence inductive charging has in the electrification of a cloud [46]. Their model incorporated the recent advances in knowledge about the formation of charge when ice crystals turn into water, i.e. the inductive charging. Starting in 2006, in-depth studies on the differences between thunderstorm behavior of continental and maritime environments, including littoral areas, gained momentum, with more and more answers found. The first model produced [58] recognizes many of these differences, with one particular conclusion: high quantities of water in the clouds will reduce the process of charge separation. At the time of publication of this work, only limited information was available concerning thunderstorm developments and lightning activity, and no model could be used to document the risk of lightning in the littoral area. With time as a major constraint, the approach chosen here was to use the knowledge gained as documented in this chapter, and to apply it to the very few, incomplete, models and limited information available on the littoral environment.

2.7 Thunderstorms, lightning flashes, and climate change

Even now there is no consensus among researchers when estimating the effect of climate change on lightning activity. According to their expertise, based mostly on observations, and the type of projections used, it is said that for each degree Celsius increase in the global mean temperature, lightning activity can be expected to grow somewhere between 5 and 100%. There needs to be a much greater level of consensus in order for forecasts of possible exposures and risk levels for lightning to become more meaningful and relevant. There is a strong link between the climate, which is normally influenced by radiation and heat coming from the sun, and the frequency of lightning around the globe. For example, at the tropics during the apex of the sun the lightning discharges reach their highest levels of frequency and intensity. The areas on the globe most heated by the sun can be presumed to also be

those areas where lightning discharges play an extremely important role during each thunderstorm [32], [34]. However, despite certain known correlations between dry areas with relatively low levels of humidity and lightning, this previous statement is not a constant truth. The difference in density at the boundary line between hot and wet air and cold and dry air leads to atmospheric instabilities and an intensification of lightning activity. The global hierarchy of lightning activity is led by Africa, followed by South America and Asia. If the quantity of rain is considered, this previous hierarchy is then turned upside down. “Dry” areas, not equally distributed on the face of the Earth, suffer more intense lightning activity on the northern hemisphere compared to the southern hemisphere. This is equivalent to the differences between continental and oceanic areas as explained earlier. On a seasonal basis, summer days are the most active days of the year for thunderstorms and lightning strikes. The continuous warming of the planet and the impact this effect has on thunderstorms, should - and sometimes does - raise some serious questions about the influence of external factors. In turn, any changes in lightning activity will also be accompanied by changes in the climate. Any new climate changes will lead to modifications, first in the convection of air and then in thunderstorms and lightning. These results have raised a discussion about the fact that in a dry climate positive lightning occurs more often than lightning with negative polarity [136].

Similar to the abovementioned dependency between temperature and lightning, any rise in global mean temperature, at ground level, even by only one degree Kelvin, will automatically lead to a boost in lightning activity. Hence the effects of greenhouse gases in the atmosphere and their contribution to global warming are influencing the climate system, and will ultimately modify the behavior and content of the clouds. Fair weather regions influenced by climate change will lead to modifications in the global electric circuit and in the microphysical processes inside of clouds. During the last few years, scientists have worked [51] to uncover more connections between surface temperature and lightning activity in the atmosphere. A more difficult task has been to find such modifications at a seasonal level as well as at a daily level. The main gases with a greenhouse effect in the atmosphere are water vapors. With their high capacity to absorb infrared radiation, the vapors help to increase the temperature in the atmosphere. In the hottest areas on the planet, thunderstorms are responsible for placing huge quantities of vapors in the troposphere, that subsequently lead to a temperature rise at ground level. With CO₂

levels in the atmosphere constantly moving upwards, they impact global warming by changing the way air currents move in the atmosphere and by changing the speeds of flows between layers of the atmosphere. The speed of updrafts will increase by 1 m/s [51] if the current level of CO₂ is doubled. Normally, water evaporating from the soil is pushed upwards into the troposphere by airflow, but when the environment dries out significantly, it leaves thunderstorms with less rain but more lightning activity. Such thunderstorms develop up to 26% additional electrical activity than a normal thunderstorm. Two versions of simulations have emerged for the future of climate and lightning on a warmer planet. The first shows a reduction of the electrical activity around the earth in a warmer atmosphere, where all the areas tend to have the same temperature. Whereas the second simulation would give an intensification of up to 10% in lightning activity for every 1° K rise in current global mean temperature [51].

Most recently, and in a similar way as done in this thesis, a research group in the USA reported in November 2014 figures that projected a 12 ± 5 % increase in lightning activity worldwide, per one degree Celsius increase in global mean temperature. An extrapolation based on the current upward trend in global mean temperature would lead to a projected increase of around 50% in lightning activity worldwide by the end of this century [59]. This is a plausible outcome based on the newly-developed global climate models (GCMs) and their proxy of choice, the product of convective instability, in the form of the potential energy resulting from the convective instability (CAPE) and precipitation rates (P). Expressed as a mathematical formula, this would read as follows:

$$F = \frac{\eta}{E} \times P \times CAPE \quad (2.1)$$

Where F is the lightning flash rate per designated area ($\text{m}^{-2} \cdot \text{s}^{-1}$), P and $CAPE$ as described above (in $\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}$ and $\text{J} \cdot \text{kg}^{-1}$ respectively). η/E represents a constant of proportionality, assigned with the dimensionless conversion efficiency η and the energy discharge per flash E .

2.8 Particularities of the littoral areas

The littoral areas on the planet are becoming more important for society. Firstly because of their maritime importance, most of our goods come from such areas with intensive shipping activities taking place. The general premise, at the time this work started, was to consider the lightning activity in the littoral, or coastal areas too, as

very different when compared to both the maritime and continental areas. Only during the past few years has some research been carried out into these areas, but a model for the lightning activity in these areas is still very much needed. One of the steps in lightning protection [28], [29], [30], [31] consists in creating a prediction model for thunderstorms and lightning over certain durations of time and a particular area [60]. The maritime and littoral areas in particular are excluded from [28], [29], [30], [31]. During the last decades, various models for thunderstorms in continental and maritime areas have been created, but for coastal/littoral areas only theories have been produced. Because of the global warming process and the newly-discovered effect of rising temperatures on lightning activity, even the existing models need to be updated. It has been found that the mix between continental and maritime conditions in the littoral area has some atypical characteristics. The effect of hot, dry air from the continent collides with the cold, moist air arriving from the sea/ocean to generate a place of increased instability, such as in Japan, causing the infamous high-intensity winter lightning storms. Figure 1-3 shows the measured lightning points in the coastal region. Hot, dry inland air filled with dust and other particles mixes with the moist and salty air from seawater evaporation, and moves large quantities of charge to the existing deposits of charge already in the clouds. This process is illustrated in Figure 2-5, which shows the distribution of lightning on a global scale.

Figure 2-5 Distribution of worldwide lightning strikes. Units: flashes/km²/yr . From [131]

This graphic highlights once more those areas where hot dry dusty air collides with the cold moist sea air to finally result in high-intensity lightning activity. In other

words, the recently-discovered effect of continental and oceanic air mixes on lightning activity, together with the increase in surface temperature of the planet and excess evaporation, has led to the development of what can be seen as a new meteorological model.

The attributes required in [28], [29], [30], [31], and [61] include the rate of occurrence together with the rate of increase, duration, amplitude, spectrum, frequency, source impedance and energy potential. The activity in the littoral area does not influence the general perspective of the global average of lightning strikes.

Another important piece of information from Figure 2-5 that is further applied in this work is the annual flash rate, or the average number of lightning flashes per square kilometer per year. These values can be used to estimate the maximum number of flashes per square kilometer that any large object, such as a ship, is likely to face during its lifespan if it is placed in that area. In the following chapter this piece of information, when combined with certain information on the object, such as the geometry and height, will help to determine the statistical average number of lightning flashes to hit an object.

In recent years, several new lightning detection systems have been developed. The European Cooperation for Lightning Detection EUCLID is a collaboration of research groups who have developed such system. One of the results is shown in Figure 2-6. One US system is Strike Star US, and a plot for 60 minutes is shown in Figure 2-7. Both diagrams show a larger density of lightning strikes on land, but also in the littoral area. This can also be observed for Japan, as shown in Figure 1-3. Based on the observations and analysis given in this chapter, it is assumed that the risk of lightning in the littoral area is fairly similar to the continental areas. But it is still very different from the ocean (blue water) areas.

2.9 Summary

It has been shown that lightning activity will increase due to climate change, and thus the risk of an object being struck by lightning is also increasing [60]. This analysis was recently confirmed by a study on the projected increase of lightning strikes due to global warming, published in Science [59].

The conventional use of naval vessels was in ‘blue water’, i.e. oceans, but is changing rapidly to deployment in the littoral area, near to the coast. The risk of lightning on the ocean is very low and therefore the interest in further research was

previously also low. An extensive literature study has revealed that the risk of lightning in the littoral has remained largely unknown. Also the basic standards for lightning, IEC 62305 [28], [29], [30], [31], explicitly exclude sea environments. Based on the literature analysis, and confirmed by recently published maps showing lightning density, it was however concluded that the risk of lightning in the littoral area is very similar to the risk of lightning in the continental region.

Figure 2-6 Lightning activity in Europe. From [132]

Figure 2-7 Lightning activity in North America. From [133]

3. Risk of lightning strike on board of ships

The analysis and description of the phenomena presented in Chapter 2 is the basis for the next logical step: defining the scope of the design research based on existing standards. If such standards do not exist, root category standards must be applied and the findings documented. This represents the starting point of the analysis, and will elaborate the appropriate protection of a particular device that might need to be protected. All constraints, environmental as well as constructive, are to be listed since these play an important role in the functionality of the system as a whole. The properties of the object/structure together with the characteristics of the lightning channel have an equally important role when designing the appropriate protections or when analyzing the damage levels that could be sustained in the event of an incident. A scale model test of a ship is shown in Figure 3-1, which shows that the tallest objects tend to be struck by lightning.

Figure 3-1 Lightning attachment to a naval vessel. From [75]

New developments in material technology and the increasing demands and expectations from electronics as a result of evolution in system designs bring the perspective that effective controls for the electromagnetic effects of a lightning strike can be implemented. Treating all external environments in a single unified approach can be an opportunity to reduce the time to find a proper solution as well as to reduce the chances for mistakes by reducing the number of scenarios to consider. Finding identical constraints, effects, and ultimately the potential solutions in other disciplines can sometimes help to speed up the process. Nowadays, certain standards tie together the electromagnetic effects from the lightning channel with effects from Electromagnetic Pulse (EMP) and their induced transients.

3.1 Risk of lightning

One or sometimes two fundamental conditions must be fulfilled in order to have a direct lightning strike to ground or to any structure erected on the ground. First, and enough in most cases of cloud to ground direct lightning strike, is the presence of a downward, occasionally branched, step leader that terminates on the ground/structure with a downward flash. Second, valid only with ground or structures that allow charge concentrations in one point and to enhance the already existing electric field, is the corona effect generated at such points. This newly-formed corona, the upward moving streamer, will deviate towards the branch of the down step leader, and will collide when in close proximity. This second situation can help to ultimately predict or determine the next plausible lightning attachment point. One certainty is that when the object/structure is removed, this termination point will shift to the next point capable of producing an agglomeration of charge.

Simply the presence on the ground of any elevation does not guarantee the presence of upward or downward flashes at that location. Important here is the size of such objects or elevations. Again, support for such statements is found in standards [28], [69], and existing literature. In 1987, Eriksson [63] elaborates a formula that ties together the total number of flashes N per year intercepted by an object/structure when the height H_s (m) is known and the ground flash density N_g ($\text{km}^{-2}\text{yr}^{-1}$) in the area is also known.

$$N = 24 \times 10^{-6} H_s^{2.05} N_g \quad (3.1)$$

The ground flash density (N_g) is one important parameter that was determined by Anderson et al.[64] with the following expression:

$$N_g = 0.04 T_D^{1.25} \quad (3.2)$$

This expression is considered to be the most accurate of all, and is independent of the location as long as the parameter T_D is known. T_D represents the total number of thunderstorm days on site, and for visualization it is represented by sets of isokeraunic maps of that particular area, as shown in Figure 3-2. Unlike Figure 2-5 in Chapter 2, Figure 3-2 focuses exclusively on the total number of thunderstorm days over predetermined ground surfaces, in the same way as in several other standards currently used today [28], [61], [68], [69], [81].

Figure 3-2 Isokeraunic thunderstorm days map, excluding sea areas. From [74]

But by overlapping Figure 2-5 and Figure 3-2, it is easy to see the correlation between the thunderstorm days and the number of lightning strikes at each location. And in line with the findings from Chapter 2, an improved version of Figure 3-2 can now be drawn to include areas covered by water, with a particular focus on the littoral areas.

Once the incidence of ground flashes has been determined at a specified location, the next parameter to find is the attractive radius R_a of the object/structure, or the area around the object/structure expected to have a high risk of being struck by lightning.

$$R_a = \alpha H_s^\beta \quad (3.3)$$

This area is different according to the type of structure (mast, building, tower, transmission line) and its height H_s . These coefficients, α and β , have been determined through observations, and sometimes their values can vary from one

observer [65] to another [66]. One important aspect mandatory for consideration when searching for an accurate value of N is the presence of other neighboring tall structures.

Objects of heights from 100 to 500 m will probably have to withstand downward as well as upward flashes, while anything below 100 m will only expect downward flashes. In the category of structures and objects below 100 m, it is mainly power transport/distribution lines that are subjected to downward flashes. Wind turbines are a special case, simply because they are in both categories. Ranging from 60 m to over 100 m in height, depending on their output power, large turbines are capable of causing upward flashes, and their size has continued to increase in recent years.

In the same category as the wind turbines are communication towers, some of which exceed heights over 100 m, and therefore these special towers seem ideal for measurements and observations of lightning behavior. However, in the case of maritime vessels, their situation is a bit more complicated. They are only occasionally and partially included in standards [67], [68], and because of their shape, like radar antennas on top of ships, they are more likely to be struck by lightning.

3.2 Lightning standards of interest

The vast majority of objects/structures are covered by existing standards. Recently, while this work was still ongoing, a large number of IEC standards were merged into the IEC 62305 series [28], [29], [30], [31]:

- IEC 62305-Part 1: General principles
- IEC 62305-Part 2: Risk management
- IEC 62305-Part 3: Physical damage to structures and danger to life
- IEC 62305-Part 4: Electrical and electronic systems within structures

However a small number of situations, like the littoral area, are left outside these standards for various reasons. Some of these reasons are, the limited research done so far in these cases, or because of their complexity, it makes it almost impossible to generalize these cases, so their presence in standards is therefore limited to the field with exclusions.

With the focus on objects and systems for naval use in littoral areas, as mentioned in Chapter 2, military standards such as STANAG 4370, AECTP 250 (Leaflet 254) [110], Mil STD – 461F [67] and Mil STD 464 [68] standards, as well as the United

States standard NFPA 780 [69], were also researched. Also such standards as SAE ARP 5414 [70] and DO 160 – F [71] were considered in relation to the additional aspects concerning the lightning phenomena that they cover, and that will eventually help to reduce the exclusions. Each country often has its own set of standards, but international standards such as IEC or STANAG (comparable to Mil-STD) that are used in this work provide the guidelines for most of these national standards.

Because of their use, these standards qualify as design standards, intended primarily to give a set of options and rules, or to help with the certification process later on. In the design of protective systems against lightning dependent on the locations, according to IEC 62305, the following steps must be followed:

- determine the necessity of lightning protection measures based on “acceptable risk” assessments;
- determine the maximum number of lightning flashes per square kilometer per year for the areas of the world the system will be required to operate in;
- determine the statistical average number of lightning strokes the system will receive based on its height above ground/sea level;
- determine the protection measures required to bring the likelihood of direct lightning damage in the “acceptable risk” range;
- design, install, and test this new protection system.

With the intention of designing a proper protection against indirect lightning, the direct effects must be considered first in the process, as presented in [29]. Specific lightning protection devices and components demand a new set of standards, the component standards [70], [71], [80] tailored to their specifications and usage.

To familiarize the reader with their own terminology and conditionality, these individual standards use their introductory part to explain to the reader some basic terms and definitions in use and some general information and parameters in relation to lightning strikes, as well as generic descriptions of the objects that are covered and their interaction with the surrounding environment and human beings. IEC 62305 [28] pushes this approach even further by dividing up the surrounding environment into risk zones, according to how likely it is for objects and human beings in those areas to suffer damage.

3.3 Probability and risk of lightning to tall structures onboard naval vessels in the littoral environment

Lightning has not been a serious issue for naval vessels because the risk of lightning in blue water operations is very low, as can be seen in Figure 2-5, and also in Figure 2-6 (Europe), Figure 2-7 (US), and Figure 1-3 (Japan). The lightning protection was very basic: providing a direct lightning attachment and assuring a current path towards the sea water, as described in Def-Stan 02-516, Guide to Lightning Protection in HM Surface Ships [91].

Furthermore, the radar was never at the highest position onboard a naval vessel, as shown in Figure 3-3.

Figure 3-3 Conventional naval vessel (formerly known as Hr. Ms. Abraham Crijnsen). From [134]

Conventional radar antennas are passive and only use a piece of metal for the reflector and the waveguide. The electronic front-end, the transmitter and receiver, on these radars was always located below deck and thus completely shielded. Hence the consequences of any lightning strikes were limited. As a result, knowledge and experience on the effects of lightning were also limited. But this has changed in the last few years because there is an increasing interest in lightning protection due to the change in operational use of naval vessels: from blue water to the littoral. Furthermore the electronics of modern radars are located near to, or inside, the

antenna, in the (EM) exposed environment. There is a trend to encourage the use of composites, with less EMI protection, in order to reduce the total topside mass, the maintenance work as result of corrosion, and the radar signature towards other friends or foes. But as previously mentioned, in an EM-exposed environment, composite structures do not protect against lightning, or any other EMI, in the same that thick metal structures do simply because of the limited thickness or conductivity of the shielding layer applied. The consequences of a direct lightning attachment on composite structures could therefore be severe. Each of these arguments will be discussed in the following chapters. The focus in this chapter is on finding a valid probability model for the risk of lightning in littoral environments that can be used in this project.

It is possible to calculate the risk of high elements onboard a ship being struck by lightning using the probability model given in the IEC 62305 series [28], [29], [30], [31]. However, this standard is said not to be applicable in a naval environment. The reason for this is unknown. But to analyze the risk of lightning to a radar antenna installed on top of a mast, or the mast itself, of a naval vessel, we can compare that to the risk of lightning to a (small) wind turbine. The IEC 61400-24 [80] analyses the risk of lightning for wind turbines. The frequency of lightning strikes on a wind turbine N_D is estimated using the local ground flash density N_g . The average annual frequency of lightning flashes attached to a wind turbine can then be assessed as

$$N_D = N_g A_d C_d 10^{-6} \quad (3.4)$$

Where A_d is the collection area of flashes to the structure and C_d is the environmental factor. IEC 61400-24 [80] assumes $C_d = 1$ for wind turbines on flat land and $C_d = 2$ for wind turbines on a hill or a mountain ridge. Although IEC 61400-24 [80] also follows the IEC 62305 [28] approach, which explicitly excludes lightning risks in the littoral, a note is made in the IEC 61400-24, page 23: ‘NOTE 2 Wind turbines placed off shore may have to be assigned an environmental factor C_d of 3 to 5 to get a realistic estimate of the frequency of lightning attachment.’ This suggests that the risk of lightning can be a factor 5 higher than on (flat) land, but there is no source for this information at all!

The collection area of a structure A_d is defined as an area of ground surface which has the same annual frequency of lightning ground flashes as the structure. For isolated structures such as sailing naval vessels, the equivalent collection area is the area enclosed with a border line obtained from the intersection between the ground

surface and a straight line with a 1:3 slope which passes from the upper parts of the structure (touching it there) and rotating around it. This is shown in Figure 3-4.

Figure 3-4 Collection area of a ship

To help us derive a rough estimate of the risk for lightning attachment to a naval vessel, the lightning flash rate by location is used, expressed in strikes per square km per year. NASA has published a detailed map of the lightning activity around the world, as shown in Figure 2-5. This map shows that certain areas around the globe record up to a maximum of 50 strikes per km^2 per year. Although a frigate or destroyer is a very tall vessel, at most 5% of all strikes within a square kilometer will actually hit the ship, since most strikes are too far away or cloud to cloud. The figure of 5% is calculated based on the collection area of the ship, which is around 0.01 km^2 for a ship rising 20 m above sea level, using the IEC 62305 procedure and a proportional hit rate.

Lightning strikes at extremely high currents (>200 kA) form the main threat; these can only occur in cases of positive discharges [24], which are rare around the globe anyhow, but common in Japan. Japan account for ratios of one to two and one to nine positive to negative lightning in winter and summer respectively [137]. Of all positive discharges, about 6% are expected to be extremely severe [137]. So from the above facts, it can be considered that for Europe, the rate of high current lightning strikes is in the order of once in a naval vessel's lifetime, or once in every 30 years.

An important part in designing and evaluating the capabilities of a particular product or device, if it has to withstand a lightning strike, is the part when the risks have to be evaluated. The tolerable risk (R_T) for loss of human life or permanent injury to personnel is 10^{-5} /year [29], a value always designated by the authorities. When evaluating the damage to a system or device, the following formula applies. The total risk evaluation R_X is:

$$R_X = N_X \cdot P_X \cdot L_X \quad (3.5)$$

Where N_X is the total number of lightning-related incidents the system will withstand during one year, P_X represents the probability for the system to be damaged, and is directly related to the materials the structure is made of. Typical damage produced by a lightning attachment to unprotected turbines, especially the ones with blades of composite materials, are at blade level. The lightning causes delamination or incineration of the composite layers and fibers of panels, damage to the metallic components from heating or melting (fittings, bearings), and the electronic equipment housed inside the nacelle [74]. L_X represents the consequent loss, or the total duration of the time when the system is offline/not running. So a good product as a result of good design must produce values for total risk evaluation (R_X) lower or at maximum equal to the tolerable risk R_T .

3.4 Lightning protection

During the development of [28], CENELEC TC 81 used the terms Lightning Protection Zones (LPZ) and Lightning Protection Levels (LPL) to describe the level of interaction between the lightning strike and the consequences inflicted on the environment. It is similar to the generic EMC zoning concept and topological design. The general principle is that the equipment should be located in a zone whose electromagnetic characteristics are compatible with the equipment immunity

capability. If the boundary between zones is penetrated by some interface, then this interface must be protected either by means of shielding or filtering (including/and/or overvoltage protection) in order to maintain the zoning protection. This approach is shown in Figure 3-5, from [76].

Figure 3-5 The Lightning Protection Zoning concept. Image courtesy of [Furse](#) [76]

The lightning protection zones represent the space surrounding a Lightning Protection System (LPS). There can be at least two, if not more, of such zones. Zone 0_A, or LPZ 0_A, is the most violent, with complete exposure to a direct strike. Everything located in this area has a maximum potential to be impacted by the lightning current and the full electromagnetic field. In the special case when such objects/systems located in zone 0_A present any form of protective shell, the volume under this shell becomes LPZ 0_B, or zone 0_B. The particularity here consists in the fact that such a shell protects this volume against a direct lightning strike. However, everything remains exposed to the full electromagnetic field.

Other zones are LPZ 1, where everything in these zones is only protected against direct lightning strike, and is partially affected by the lightning currents and the full electromagnetic field. A reduction of the lightning current is achieved with the help

of Surge Protecting Devices (SPDs). Each additional level of attenuation together with the reduction of the generated electromagnetic field, through the use of SPDs and shielding materials, will generate new zones, in the lines of LPZ 2, LPZ 3 and so on, up to the point when the remaining currents and electromagnetic field no longer represent a threat. Shielding is a basic protection which is discussed extensively throughout this thesis.

A comparable approach applies for the Lightning Protection Levels. These levels relate to the lightning currents, similar to the LPZ, hence the common point between the two, but also to various other parameters of the lightning strike. Peak currents, the amount of charge, di/dt levels or average steepness, all these parameters have different values according to each level. A maximum and a minimum value will represent each level, I to IV.

Based on these lightning parameters, such as rate of rise (di/dt), decay to 50% (i.e., of a 10/350 μ s pulse), or wave shape of the current discharge, that is all that is required nowadays to know, or to have a good estimate of, the maximum peak current I (± 200 kA), in order to easily determine the striking distance R . For that Equation 3.6 is used:

$$R = 10 \cdot I^{0.65} \quad (3.6)$$

where R is measured in meters and I in kilo-Amperes, and is based on the Rolling Sphere Method (RSM). The relationship is shown in Figure 3-6.

Figure 3-6 Relationship between lightning current and discharge distance

The following table provides an indication of the expected maximum and minimum values of the lightning current for each individual Lightning Protection Level. In other words, 100% of the lightning current is reached at Level 1, 75% for Level 2, and up to 50% for Levels 3 & 4 respectively.

Table 3-1: Maximum and minimum current levels and risk of interception for each lightning protection level [74]

Lightning protection level	LPL I	LPL II	LPL III	LPL IV
Maximum Current (kA)	200	150	100	
Minimum Current (kA) to achieve attachment	3	5	10	16
Probability current is greater than the minimum value (%)	99	97	91	84

With the minimum striking distance established in this way with the help of the Table 3-1, a basic engineering solution called the “rolling sphere radius” r should help achieve a visual description of the safe and unsafe areas. This approach is based on the hypothesis that the steps of the leader will “move” along straight lines with a given length that is based on the final peak lightning current. Based on that hypothesis, a small lightning bolt can reach locations that big ones cannot get at, as shown Figure 3-7.

Figure 3-7 Rolling Sphere Method. Image courtesy of [Furse](#) [76]

Using the RSM, it is possible to find the right location to position lightning rods, and to identify those areas now free from any direct lightning attachment. For a better understanding of this, by running a mental experiment with a minimum peak current

at 3, 5, 10, and 16 kA, this will generate a rolling sphere with a radius r , equal to 20, 30, 45, and 60 m respectively, that ultimately corresponds to protection levels I through IV. Eventually an additional row could be added to Table 3-1 to include the newly-determined values for the radius r .

The Rolling Sphere Method [28], [75], [77], [78], [79] assumes that the attractive effect of a lightning rod or other conductive point is a function of the striking distance, which is proportional to the eventual amplitude of this lightning current. A sphere of radius equal to the striking distance for a given lightning current that cannot be tolerated is usually employed to visualize the likely strike termination points, as shown in Figure 3-7. The RSM involves rolling the imaginary sphere of a certain radius over the surfaces susceptible to be hit by lightning. The sphere rolls up and over each structure on its path, as well as wires or other grounded metal objects intended for direct lightning protection. The equipment or the surface remains protected from a direct strike as long as it stays below the curved surface of the sphere by virtue of the spheres being elevated by other surfaces or devices. A piece of equipment that touches the sphere or penetrates its surface will not be protected in any way, also shown in Figure 3-7.

Another aspect of the RSM is the possibility to calculate the worst case of penetration between two or three lightning attachment points. All values for the lightning current that exceed the minimum levels that correspond to the sphere radius are expected to strike the designated attachment points. For the ones smaller, the threat remains active for any object in the path of any smaller sphere, even within the initial protection zone. And under these circumstances, new conditions must be put in place to guarantee safe passage of the current and that any object or structure exposed to should stay in operation to a specified extent.

It is now obvious that the engineer's mind has found multiple uses for this tool, some more practical than others. Another very practical use is to determine the minimum length of an air terminal, so that it is capable of intercepting any lightning flash that exceeds a certain current. But in terms of the damage previously referred to, what kind of damage can be expected in line with the information acquired so far?

The physical damage to the structure and the electrical or electronic components of the system due to direct attachment of the lightning channel and current flow, with side effects like puncture, tearing, bending, burning, vaporization, or blasting of hardware, is determined by means of several lightning properties.

3.5 Properties of lightning

3.5.1 Direct lightning

As discussed in section 1.3, lightning flashes are one of two basic types: downward or upward initiated. Both types of lightning are further sub-divided according to the polarity of the charge removed from the thundercloud. A negative flash lowers negative charge from the thundercloud to the earth. A positive flash results in positive charge being transferred from the thundercloud to the earth. The majority of lightning flashes are negative, making up about 90% of all cloud-to-ground flashes. Positive discharges make up the remaining 10% of all cloud-to-ground flashes. The positive flashes exhibit the most powerful current parameters, of importance for the direct lightning problem, while the negative flashes exhibit the steepest current impulses (i.e. highest di/dt), responsible for indirect lightning effects [137], to be discussed in section 3.5.2.

A positive lightning stroke can be regarded as a current source, and the four lightning current parameters of concern in connection with the design and dimensioning of lightning protection are: the peak lightning current (I), the steepness of the lightning stroke current impulses (di/dt), the charge transferred (Q) and the specific energy (W/R). The lightning current used for testing is shown schematically in Figure 3-8, taken from STANAG 4370, AECTP 250, Leaflet 254, Atmospheric electricity and lightning [110]. The MIL-STD 464C [68] is similar. The parameters are listed below in Table 3-2.

Table 3-2: Lightning parameters

Current Component	Description	$I(t) = I_0 (\epsilon^{\alpha t} - e^{\beta t})$ t is time in seconds (s)		
		I_0 (Amperes)	α (s ⁻¹)	β (s ⁻¹)
A	Severe stroke	218,810	11,354	647,265
B	Intermediate current	11,300	700	2,000
C	Continuing current	400 for 0.5 s	Not applicable	Not applicable
D	Restrike	109,405	22,708	1,294,530
D/2	Multiple stroke	54,703	22,708	1,294,530
H	Multiple burst	10,572	187,191	19,105,100

Figure 3-8 Lightning current as defined by STANAG 4370 AECTP 250, Leaflet 254. From [110]

The fast rise-time of the A-pulse is a main cause of indirect lightning effects, while the continuing current of the C-component is the main cause of damage due to direct lightning. The recorded value of lightning current produced by a single stroke is in the region of 2 kA to 300 kA. The maximum recorded values of charge transfer and specific energy are some tens and hundreds up to a thousand Coulombs, depending on the polarity of the lightning current, negative or positive respectively [24], [137]. These lightning current parameters govern the amount of physical damage that is done to objects and/or the lightning protection system hardware. The strike currents produce the high pressures that sometimes rupture composite structures. They also influence the magnitudes of lightning-indirect effects on electrical and electronic systems. The charge transferred produces melting at places of lightning attachment, such as the receptors, and at other places where lightning currents must pass across gaps in the current path.

The current in the A-pulse can be described by

$$i(t) = I(e^{-at} - e^{-bt}) \text{ [A]} \quad (3.7)$$

with $I=214980 \text{ A}$, $a=6341 \text{ s}^{-1}$, and $b=471500 \text{ s}^{-1}$ according to Table 254-C1 of AECTP 250 [110]. This is applicable for ground as well as sea.

One component of the lightning discharge that lasts way longer than all other components is generating local heating and is often a cause of damage. It is caused by the large quantities of charge transferred by the Integral of current over time

$$\text{Charge} = \int i(t) dt \text{ [C]} \quad (3.8)$$

The basic physical effects, such as heating and eventually melting of resistive materials, or even explosion in the case of poor conductors, are generated by the integral of current squared over time Action Integral [82].

$$\text{Action integral} = \int i(t)^2 dt \text{ [A}^2\text{s]} \quad (3.9)$$

Each lightning flash is different due to the natural variations in the thundercloud that produce it, and in the individual paths to ground. Probability distributions of the electrical parameters that are used to describe a lightning strike have been produced using direct measurements of actual strikes to tall towers. This statistical data on lightning current parameters is used in the lightning protection standards such as the IEC 62305 series. Further information is now becoming available worldwide from regional and national lightning location systems. These systems can record the location of a lightning strike and estimate the peak current.

The probability distributions that describe the current parameters of a lightning strike are different for each type of lightning (upward/downward and positive/negative). The appropriate probability distributions are connected to the typical wave shape of each type of discharge. The risk level indicates the probability of the specified current parameter of a particular lightning strike exceeding the tabulated value.

The most relevant parameters for a lightning discharge are shown in Table 3-3, which is derived from Table 254-3 of AECTP 250 [110]. These are used since they are responsible for the most likely damage/interference effects.

Table 3-3: Combined positive and negative discharge parameters for cloud to ground strikes [30][74]

Parameters		Units	Level
Maximum rate of change of current	$di/dt \text{ max}$	A/s	1×10^{11}
Peak current	i_{pk}	kA	200
Action integral	$\int i^2 dt$	A ² s	2.25×10^6
Charge content	$\int i dt$	C	200
Rate of change of electric field	dE/dt	V/m/s	10^{12}

3.5.2 Indirect lightning

When a nearby object is hit by a lightning strike, or if lightning currents flow through a structure, large magnetic fields are produced. If these changing magnetic

fields pass through a loop formed by wiring they may induce surge voltages and currents within that loop. The magnitude of the surge is related to the rate of change of the magnetic field and the area of the loop in question. This effect is called lightning electromagnetic pulse (L-EMP). The surge voltage is determined by

$$V = L \cdot \frac{dI}{dt} \text{ [V]} \quad (3.10)$$

Where L is the inductance and dI/dt is the rate of change of the lightning current I . Using the maximum lightning current peak values and the average steepness of the pulse, the electrical surge induced due to coupling of electromagnetic fields ends up generating effects such as malfunction or damage to electrical/electronic equipment. For the purposes of this work, it is useful to divide up the L-EMP surge voltages into:

- conducted partial lightning currents;
- inductive/capacitive coupling;
- transmitted by interfaces (power lines and/or communication lines due to lightning flashes to or near these lines).

Neither the MIL-STD 464C [68] nor the IEC 62305 [30] describe or include any interference effect to equipment. The STANAG 4370 AECTP 250, Leaflet 254 [110], describes induced effects, but it also states ‘test levels for ground-based and seaborne equipment are not addressed by this leaflet and must be decided in consultation with the National Authority’. So, with no data available, it was necessary to reenact the work done in Chapter 2 once more. The lack of existing and valid information meant this work had to investigate and test all the foreseeable situations. Insofar as any of the findings described here are not final, they will be included as personal hypotheses for the advancement of this work.

The electromagnetic interference due to a near lightning strike is considered to be covered by STANAG 4370 AECTP 500 [111], or MIL-STD 461F [67] or IEC 61000-4-5 [111], the IEC 61000-4-9 (H -field, 8/20 μ s, 25 kHz damped oscillation, $T_p=10 \mu$ s, 1000-300-100 A/m) [112], and IEC 61000-4-10 (200/500 ns, 1 MHz, $T_p=250$ ns, 100-30-10 A/m) [113]. These are equipment EMI standards, and set basic levels. Simulations carried out at THALES showed that the IEC 61000-4-5 [111] levels represent a lightning strike at 100 to 1000 m distance from cables, depending on the severity levels used. Depending on the cable layout used, a high current (low impedance) or a high voltage is the main cause of damage or

interference. The IEC 61000-4-5 [111] therefore contains a ‘short-circuit current’ (1.2/50 μ s) and an ‘open-circuit voltage’ (8/20 μ s) test.

3.6 Summary

With a good quantity of information on lightning formation and thunderstorm development acquired in the previous chapter, it was the objective of this chapter to introduce such notions as Risk Evaluation (Rx), Lightning Protection Zones (LPZs), and the Rolling Sphere Method (RSM) which can be applied to naval vessels. The international standards covering lightning-related activities were also introduced here and compared with each other. This chapter demonstrates again how crucial the positioning of an object onboard a vessel can be, especially the height of the object, and how this plays a role in the risk evaluation.

By using the LPZs, the position of an object, and the RSM, a risk analysis was performed. The lightning parameters identified in this chapter, as applicable for ships, are used throughout the following chapters

4. Conventional lightning protection measures

4.1 Zoning for naval vessels

In the earlier chapters of this work it was concluded that the likelihood of large thunder storms forming and generating intense lightning activity is increasing rapidly due to climate change, expected growth 50% by the end of the century [59], and that the risk of lightning in the littoral environment is also much higher than in the conventional ocean, or blue water, environment for naval vessels. Assuming a thunderstorm makes no distinction between a military system or a civil system, this work is based on the premise that modern civil standards should be used, which contain the latest scientific results.

The Rolling Sphere Method (RSM), the Lightning Protection Level (LPL) and Lightning Protection Zoning (LPZ) concept in current civil and military standards can be also applied for equipment, systems, and even human beings on a ship. In this thesis the focus is on a radar system positioned at a top level on or in a mast, but the methodology can also be applied for other equipment, as well as finding and evaluating protection measures to prevent direct and indirect lightning risks to people.

The standards gave basic rules in the 1960s, while new testing procedures were added in the 1970s. During the 1980s the subsystem environment was created, while the 1990s brought change to everything. Escalating costs associated with testing and certification forced the designers to rely mostly on off the shelf parts. These parts were already certified and compliant, and in many cases had already been used in proven technologies. The first decade of the new millennium brought new policies. The idea of integrated systems was introduced. Also the idea of evaluating each system during the development stage via models and simulations, and to use real testing only for certification purposes, came from that time too. These years brought changes in the way things were done at a design level, and how specifications and standards were developed. By often relying solely on off-the-shelf products, the military authorities were also forced to follow civil standards, but conversely it also

meant civil suppliers had to improve the performance specifications of their products to give the military what they wanted.

Protection against lightning is based on the zoning approach as described earlier. When applied to a naval vessel, it becomes obvious from this work that there are three challenges that have to be dealt with above all else:

- Direct strike, exposed (highest) environment of a ship: LPZ 0_A
- Indirect strike, for parts which present any form of protective shell, in the exposed environment of a ship: LPZ 0_B
- Protected environment of a metal ship: LPZ 1

The exposed environment LPZ 0 is not completely covered in standards for naval vessels. Def-Stan 02-516, on Lightning Protection in HM Surface Ships [91], follows a methodology similar to the LPZ concepts as described here.

For metal ships with metal masts, it is assumed that the metal masts are solidly connected to the hull, and do not need an air terminal or further primary protection.

For ships with a non-metallic hull, it suggests the use of air terminals for LPZ 0_A, made of a conducting bar (e.g. stainless steel), and which projected at least 300 mm above the top of the mast or any facility installed on such. A down conductor should be routed as straight as possible, with a minimum bend radius of ten times the equivalent diameter of the conductor, solidly secured to the ship's structure. The conductor size should be at least 5 mm in diameter (standardized from 75 mm²) made of copper or aluminum alloy.

Vessels with wooden or composite hulls need to have a lightning earth plate located on the outside of the hull in a position that is permanently immersed during operational conditions and which allows the shortest practical route for the down conductor.

Def-Stan 02-516 [91] assumes that the boundary between LPZ 0 and LPZ 1 is sufficient, since the bulk of cables are normally screened by the ship's structure. The measures for the protected environment LPZ 1 are similar to the generic EMI ones: overvoltage protection, screening, grounding/bonding/earthing, cable separation etc. The equipment standards for LPZ 1 are covered by the basic equipment EMI standards, including STANAG 4370 AECTP 500 [111], MIL-STD 461F [67], IEC 61000-4-5 [111], IEC 61000-4-9 [112], IEC 61000-4-10 [113].

4.2 Composite structures in LPZ 0

Composite structures (see section 1.4) are more vulnerable to lightning because the current paths are not defined, and their shielding effectiveness is limited to nonexistent. Similar situations are found in such areas as the aerospace and wind turbine sectors. Maden [114] published an extensive study on lightning protection of windmills, but only covered direct lightning attachment and currents paths. Some work was published via an Energie Centrum Nederland (ECN) workshop [115], which is now embedded in the IEC standard on protection of wind turbines [81]. The NATO Advisory Group for Aerospace Research and Development, AGARD-CP-283, published a document entitled Electromagnetic Effects of (Carbon) Composite Materials upon Avionics Systems [116]. The conclusion is disappointing: the topic of lightning associated to composite structures is too difficult. The same applies to NATO AENEP engineering procedures [117]: there are no solutions. Several discussions held with colleagues in the aerospace and naval domain revealed that limited knowledge is available on protecting electronic equipment housed in composite structure against the effect of lightning.

In the PhD thesis of G. James Sweers, entitled Methodology for the Design Assurance of Aircraft Lightning Protection Systems Continued Airworthiness [26], the focus is on direct lightning.

Neither the system level MIL-STD 464C [68], nor the IEC 62305 [30], describe or include any interference effect to equipment. The STANAG 4370 AECTP 250, Leaflet 254 [110], describes induced effects, but it also states ‘test levels for ground-based and seaborne equipment are not addressed by this leaflet and must be decided in consultation with the National Authority’. A more detailed analysis and state of the art description of direct lightning effects is therefore given in Chapter 5, while the indirect lightning effects in the exposed environment are discussed in Chapter 6.

4.3 Lightning issues on composite structures in LPZ 0

The parameters of a lightning discharge with the highest relevance, and the ones most likely to cause damage, are:

- Maximum rate of change of current (di/dt_{max}) in Amperes per second with levels between 1.1×10^{11} for ground and sea and 1.4×10^{11} for air environments;
- Peak current (i_{pk}) in kilo Amperes for a standard accepted level of 200 kA;

- Charge content carried in time $\int i dt$ in Coulombs with levels of 200 and 300 C for civil and military installations respectively;
- Action integral of current in time $\int i^2 dt$ in Ampere-squared times seconds with levels of 2.25×10^6 for civil installations and 3.75×10^6 for military installations, independent on the polarity of the lightning current;
- Rate of change of the electric field dE/dt in Volt per meter per second and levels of 10^{12} and 10^{13} for civil and military installations respectively.

These values are unanimously considered to represent the worst case scenario, with maximum damage as the expected consequence.

Laboratories nowadays have various methods for testing endurance/compliance and the capability to withstand a lightning strike [118]. To simplify the analysis, the wave form for the injected current is divided up into four components (A ÷ D) [31], [67], [110] and mentioned in section 3.5.1.

- Component A, the highest source of EM radiation, characterized by a very high peak level 200 kA ($\pm 10\%$), a fast rise time and short decay to 50% (50/350 μ s), and an action integral of 3.5×10^6 A²s ($\pm 20\%$);
- Component B, an intermediate stage, is a continuation of the current decay of component A at a much slower rate (5×10^{-3} s), a maximum charge transfer of 10 C ($\pm 20\%$), and average amplitude of 2 kA ($\pm 10\%$).
- Component C, considered a continuous current with amplitude to 600 A and a total charge transfer of 300 C ($\pm 20\%$). This component is responsible for melting, explosion, or welding of metals;
- Component D, the return current, very similar to component A but with a much faster rise time and decay (< 200 μ s), a peak amplitude of 100 kA ($\pm 10\%$), and an action integral of 0.25×10^6 A²s ($\pm 20\%$). Component D together with component A are responsible for the EM pollution resulted from the lightning strike.

In terms of consequences, structures struck by lightning, or affected by nearby lightning, will develop transient voltages and induced currents in the electrical wiring, resulting in equipment malfunctioning or occasionally permanent damage. Simply being in the proximity of a current path is sometimes enough to cause damage. With many military vessels, the mast ends up being the tallest structure on board, and for a downwards stepped leader the most likely point of attachment. As a full metal structure, the mast of military vessels is expected to provide not only an attachment point, but also a good current path for lightning. However, the situation

quickly becomes much more complicated with light vessels, civil or military, equipped with lightweight (wooden or composite) masts.

One aspect to always keep in mind, is that providing such masts with metal frames, lightning rods, and a proper current path, does not always guarantee the safety of the structure or of the entire assembly. Top to bottom lightning currents build important potential drops, and big hollow metal masts 20 m in height with 1 $\mu\text{H/m}$ inductance L , will eventually develop a peak potential rise upwards of 28 kV.

$$V = L di/dt \text{ [V]} \quad (4.1)$$

Used here is a maximum di/dt , as was found in various standards [31], [67], [110], of $1.4 \times 10^{11} \text{ {A/s}}$.

More aggravating circumstances arise if the current path between the rod, mast frame, and the hull is not fitted properly. In such cases, at the interconnection points, wires, bolts, and other fitting devices will explode, melt, or catch fire. This is all due to component C, while components A/D will make the system radiate like an antenna. Arcing must also be taken into consideration for large vessels with more than one mast or with more large structures close together. All parts, when electrically close to each other, represent a severe threat for injury and damage to personnel and systems onboard [31], [67]. Through good design, an improved path for the lightning current can be created, and bring this peak potential down from the order of kilo Volts to tens or hundreds of Volts. This should be low enough for the electronics on board, or otherwise surge protective devices (SPD) should be installed to add protection. But in relation to human interaction, all standards instruct the designer to avoid solutions that lead to the development of maximum differential voltages between parts that can be touched simultaneously by personnel [31], [67].

These are the potential damages and effects that can be caused by direct attachments, and which need to be overcome in the design if there are no protective measures. What about indirect effects? Does the inductive and capacitive coupling have the capability to develop dangerous voltages?

Power or signal lines in exposed areas to EM fields from lightning can eventually develop transients that can temporarily or permanently disable a system. Distance from the source is another vital aspect when assessing the presence of protection, since electromagnetic radiation from a distant “far field” flash will present no danger to materiel or components. The amplitude on this environment is inversely proportional to the distance from the flash. At a distance D ($5\text{km} < D < 300\text{km}$)

from the lightning channel and γ the ratio between the conductivity σ of the medium and distance ($106 \text{ } \{m^2/S\} < \gamma < 2 \times 10^9 \text{ } \{m^2/S\}$), according to Cooray [82] this will result in the following attenuation factor and electric field:

$$A_e = 0.24 \exp \left[\frac{-\gamma}{10^7} \right] + 0.24 \exp \left[\frac{-\gamma}{50 \times 10^7} \right] + 0.525 \quad (4.2)$$

When the attention is exclusively on the electric field E , the attenuation factor is determined by the ratio between the electric field over a finitely conducting plane E_σ and an infinitely conducting plane E_∞ , or $A_e = E_\sigma / E_\infty$,

$$E_\sigma = \left(0.24 \left\{ \exp \left[\frac{-D/\sigma}{10^7} \right] + \exp \left[\frac{-D/\sigma}{50 \times 10^7} \right] \right\} + 0.52 \right) E_\infty \quad (4.3)$$

In other words, the electric field over finitely conductive ground (when propagates over land for example) faces severe attenuation, compared to perfectly conducting ground (over the sea water) [84], [85], [86], [87]. As a result, a vessel in the sea, a few kilometers from the coast, has to withstand higher EM radiation levels during thunderstorms, compared to a similar structure inland (see Figure 4-1). In this figure, the conductivity of the land path is assumed to be 0.001 S/m. The length of the land path is (2) 10 km, (3) 50 km, (4) 100 km, and (5) 200 km. Figure 4-1 represents the electric field over perfectly conducting ground [82].

Figure 4-1 Electric field of a lightning return strike located over the sea at 100 km from the coast as it penetrates land. From [82]

So in the case of indirect lightning, the susceptibility level of the mast or electronic equipment in general, depends not only on its shell (metallic – nonmetallic, conductive – partly conductive – nonconductive) but also on its location. When this is added to the information in Chapter 2, the littoral area represents a dangerous place for an unprotected naval vessel to be in.

And if all these effects are not enough to convince anyone of the need for proper protection against lightning, it should be noted that some of the busiest harbors in the world are in thunderstorm-intensive areas (Figure 2-5).

4.4 General lightning protection methods and concepts

The basic categories of protection methods are as follows:

- Earthing systems – provide a safe and controlled pathway to channel the lightning current without additional influence into the nearby environment;
- Isolate all power supply sources – provide means to stop the galvanic, inductive, and capacitive coupling between power sources and lightning current paths;
- Cabinets and cable ducts – provide proper shielding, grounding, and routing of the cables in a way that avoids formation of loops;
- Cables – choose the right cables with proper shielding so that the last traces of EM radiation as a result of the lightning channel is kept away from the intended signal in the cables.

To achieve the proper earthing capabilities, the use of lightning rods and down conductors is sometimes restricted by the nature of a system and the way that particular system/object has to function. For this reason, the outside hull together with the frame itself can play the role of a lightning current path. It is the case of many naval systems that to achieve survival capabilities to a lightning strike must follow certain restraints in shape and materials. The application of such methods is described and analyzed in the following chapters, which involved the construction of models, the running of simulations, and the performance of live tests to validate the results, and ultimately some of the findings were shared thru publications [60], [79], [92], [93].

With respect to galvanic, inductive, and capacitive isolation, various transformer designs can be used as an alternative to a proper separation between the current lightning path and the signal paths. An example of this type of solution is the use of optical mediums, such as fiber glass, to carry signals and data. The aspect of optical

transmission is a hot topic nowadays, and the literature is full of papers and reports from around the world.

For those situations when the use of the outside frame and skin is not necessary to guarantee protection, and based on the zoning theory described in the previous chapter, the cabinets and cable ducts will need reinforcements in order to provide the required level of protection. The information in the following chapters was the result of research conducted into this aspect on a different scale.

Cables represent the ultimate barrier against the propagation of lightning interference. Either via galvanic coupling, or by inductive or capacitive coupling, these mediums provide access to components and other systems via ports. A proper protection at this level can make the difference between a temporary and a permanent failure of a system. In most cases this situation is solved by choosing the right cables and the right routing for the cables.

One of the theories used to describe the shielding capabilities of solid metal walls, and to evaluate the transient shielding effectiveness, uses elements of the transmission line theory. The shielding effectiveness is often described in frequency-domain, while the time-domain approach is used when dealing with single transient magnetic fields. Because the lightning strike occurs in the near field, we have to focus on the magnetic field shielding. The magnetic field caused by a lightning strike will couple into communication lines such as cables. Because of their dimensions, relatively long cables running along or curled inside electronic equipment and cable ducts may generate high surge voltages that will ultimately damage the electronics. Several concepts for shielding are analyzed and tested here to evaluate the best alternative, in terms of both quality and cost-effectiveness.

The major design variables of magnetic shielded enclosures, according to [88], are:

- Internal size and shape of the enclosure;
- Number of additional shells;
- Material and thickness for each shell;
- Amount of shell separation.

Concentric spherical shells, or a set of concentric infinitely long cylinders, represent the ideal shielding configuration. However, because such shapes are not practical to use, some concessions must (and can) be made depending on the designer's needs. In addition, shielding discontinuities become an issue in cases where the shielded objects are too large. Interconnection flaws between various parts of the system are common as a result of complicated fabrication process.

The two most important aspects when changing from an ideal to a non-ideal shape are:

- The effect on the gross shielding factor, and
- The total amount of distortions and changes made to the internal field.

At the boundary level, at the air-metal and metal-air boundaries, the mismatch of the wave propagating in air-metal-air (mediums with different impedances) results in losses via the main reflection of the wave, absorption in the medium, as well as the multiple reflections that take place in each field, as shown in Figure 4-2.

Figure 4-2 Transmission line approach for shielding.

The purpose of this part of the work is to put forward, probably for the first time ever, the idea of using the shielding properties of very thin metal foils or paints, when combined with composite structures, to use it as a “low-pass” filter for lightning. There are two chapters dedicated to this approach, one with the basic theory behind it, Chapter 6, and the second with simulation and tests, Chapter 7.

4.5 Summary

The analysis in this section shows that the Rolling Sphere Method (RSM), the Lightning Protection Levels (LPLs) and Lightning Protection Zones (LPZs) must be applied so that it is possible in the interests of this work to have a safe placement of

the radar system at the highest level on the deck, or in a mast-like structure. It was additionally found that similar methodologies and protection measures already developed for other domains can be applied for radar systems. The protection against direct lightning is discussed in the next chapter, Chapter 5. The protection against indirect lightning is discussed in Chapter 6.

5. Direct lightning protection measures

Many issues discussed in the previous chapters will be looked at in more detail in this chapter using practical case studies, in-depth analyses, and comparisons with other solutions that have similar effects. In particular, it takes a closer look at the case of direct attachments of lightning strikes on structures and objects.

For buildings or other similar structures in the continental area, a lightning rod represents a realistic solution against direct lightning. An air terminal attached to a metal conductor and terminated via a buried electrode, buried as deep as the earthing quality of ground requires, represents the necessary method to achieve protection in most cases. Some good examples are given in [4] and [90]. However, such basic protection measures from these other domains can be applied in ships too. In [91] that is an overview of the state-of-the-art for naval vessels, but it does not provide any details for radar antennas. A point can be made here, since fixed lightning rods, or poles, are the standard solution for air traffic control radars, as shown in Figure 5-1.

Figure 5-1 Protecting radar antennas against a direct lightning strike.

The position, height and number of rods are optimized using the Rolling Sphere Method (RSM). When dealing with radars, the presence of a free-standing structure or anything similar can block the visibility of the radar, and thus its performance. Under these circumstances the presence of a lightning rod must be avoided. The

Rolling Sphere Method mentioned in Chapter 3 will help with the placement of lightning rods in the designated areas. This has to be aligned with the positioning of the radar antennas and other communication systems on deck to avoid blocking. An alternative to the blocking problem is to position the rods on top of the radar antenna, or even a mast, in such a way that their frame can be used as a down conductor. In the following sections some of those solutions are analyzed.

5.1 Modern radar systems, rotating

All modern radar systems must, from the very beginning in the design stage, be in compliance with various regulations and standards, and be designed as such to guarantee proper functionality in its intended electromagnetic environment without being interfered by, or causing interference to, other pieces of equipment. This is the foundation of EMC engineering. Lightning is a major constraint for modern equipment, with sensitive electronics placed in above-deck areas, while the housing of such systems may be less effective as a shield, especially with low-frequency EM fields. The need to develop lighter structures, as well as the esthetic preferences of customers, has resulted in a trend of using more composite structures, often in the form of fiber reinforced polymers (FRP) composite panels. This has resulted in several measures for lightning protection. These solutions have been developed, analyzed, evaluated, and improved, and some of them have been implemented in current and future radar systems. The following examples are some of the most representative, and offer some ideas on how to exploit and further develop them in the quest for even better lightning protection, especially if composite materials are used.

5.1.1 Long Range Radar

The SMART-L Long Range Radar (LRR) developed by THALES Netherlands, as shown in Figure 5-2 and Figure 5-8, is an example of modern radar antennas. The housing is solid aluminum sheet metal, which in total is several millimeters thick. This assures a good shielding performance and all the electronic equipment is protected by the housing.

To assess the risk of lightning on an LLR antenna, for the purpose of this work the Rolling Sphere Method (RSM) was applied as described in [29], [75], [77], [78], [79]. From the beginning, during the visual assessment, it was clear that even

without being the tallest structure on deck, when left alone the LRR is not entirely protected and has to be considered as a lightning attachment point. As with the other tall structures on board, additional steps are necessary to achieve a higher level of protection.

Figure 5-2 Long Range Radar on a ship and rolling spheres relevant for various lightning protection levels.

The RSM equation [29], [75], [77], [78], [79] should be sufficient, in an initial phase, to determine the minimum peak lightning current I_{min} , and transform the LLR into a lightning attachment point (based on the surrounding objects):

$$R_{sphere} = 2 \cdot I + 30(1 - e^{\frac{-I}{6.8}}) \quad (5.1)$$

Figure 5-3 Long Range Radar with the secondary surveillance radar omni antenna on top. Picture [THALES Nederland](#)

When a quick evaluation has to be performed, and the computation equipment is not available, the engineers seem to prefer replacing (5.1) with (3.6), although both

statements are valid as long as the value of I is kept in [kA]. The lightning peak current is then 1.7 kA for a radius on the sphere of 10 m, or 16 kA for a 60 m radius. The secondary surveillance radar omni antenna, placed in the center on top of the LRR as shown in Figure 5-3, can withstand several kA. Therefore this antenna has to be protected against a severe direct lightning strike.

Figure 5-4 Rolling Sphere Model applied to the Omni IFF antenna

The RSM process is depicted in Figure 5-4.

Figure 5-5 Long Range Radar with lightning rods. Picture [THALES Nederland](#)

The approach was to place four lightning rods, one on each side of the omni antenna and two on the corners of the radar housing as shown in Figure 5-5.

The novelty here is that the lightning rods are not placed around the radar (which would increase the radar sidelobe level) but on top of the rotating radar. The bearing and a special lightning ring assures the conduction of the lightning current to the ship. Then RSM was used to determine the exact height required for such rod in order to protect this antenna against lightning currents.

The fixing supports for the lightning rods described above have to serve two distinct purposes. Firstly they have to serve as hoisting points to help position the antenna onboard the vessel. Secondly, once the rods have been installed, they have to serve as attachment points for the lightning rods. This interface has to facilitate the lightning current flowing through it. Because of the high currents and the internal resistance of the materials, the quantity of heat produced by the strike could result in welding between the threads of the two objects. Therefore, because the lightning rods were meant to be interchangeable with the hoisting facilities, the welding risk was investigated.

A lightning current test setup, as developed by Prof. Damstra, was constructed for the abovementioned testing purposes. This setup was located at the Tuindorpstraat in Hengelo, in the former factory of Hazemeyer. Details of the setup are described in [101]. The “welding test” results obtained have been published and presented in several papers [92], [93].

Figure 5-6 Hoisting fixture and screw (representing the lightning rod) during lightning current test

Figure 5-7 Current through test setup, as function of time.
Vertical level is 850 A

The first test consists of directing a test current through this metallic path, using only an aluminum screw and an RVS socket, identical to the one used on the LRR housing, as shown in Figure 5-6.

Considering the possibility that welding might occur between lightning rods and steel sockets, only two of the four components of the lightning current should be considered: components “A” and “C”. The approach in this situation was to test according to the current wave shape of component “A” alone and component “C” alone, both followed by evaluations. And in the final phase of testing the two components were united, “A” followed by “C” immediately, a situation very close to real life.

The current of the C pulse is shown in Figure 5-7. Tests were performed from 0.3 s and increased in increments of 0.1 s up to 2 s. The maximum current was 850 A. Before and after each test, the resistance of the entire assembly was measured with a micro-ohmmeter, using the aluminum screw (representing the rod) in loose as well as in tight position within the socket. The following two resistance values were found: 1.42 m Ω for the loose screw and 0.96 m Ω for a tight situation. After the first set of tests there was an increase of the resistance to $R = 1.6$ m Ω for the loose screw and $R = 1.1$ m Ω for the tight situation. So at the end of this verification and testing session, no signs such as welding spots or even flash-over could be observed, nor was any noticeable temperature rise of the assembly detected.

Figure 5-8 HMS Queen Elizabeth aircraft carrier with LRR fitted with lightning rods.

5.1.2 Medium Range Radar

A medium range radar antenna from THALES Netherlands, used by many navies around the world, consists of a metal Faraday cage inside a composite hull. The composite hull creates the weather barrier system between the exposed and the protected environments, for water, humidity and temperature. Where the metal Faraday cage is the electromagnetic shield protecting the electronic equipment against high field strength from the exposed environment, and to prevent unwanted radiated emission from the electronics to the outside world. Due to direct lightning attachment, the current will flow to the rotating part of the bearing and the rotary joint unit. Figure 5-9 depicts the rotary joint unit and support, the blue areas indicate rotating parts. The structure is symmetrical, but for clarity only one side is colored. A ground bonding strap is attached to the non-rotating part and connected to ground (not indicated in the figure).

Figure 5-9 Joint unit and support.

If the radar is not rotating, there is a good electrical connection through the bearings because the oil will be pressed away by the ball bearings. This effect has been verified by tests. The current of the direct strike will flow through the bearings, via the ground bonding and cable shield to the ground. The effect of the lightning on the bearing depends on the resistance of the bearing ring, which affects the energy deposited in the bearings. Many studies have been performed on the effect of lightning current on bearing rollers and walls. In [106] it is stated that static bearings do not suffer significant damage. Actually, no damage was found. The same

conclusion applies to the roller bearing of the roof of several stadiums, including the Houston Stadium [107].

If the system rotates, the common opinion is that the hydrodynamic layer of lubricant results in an insulating layer in the bearings. In Chapter 7, a novel concept to overcome this problem will be presented, but for the time being the conventional approach is followed in this chapter. In [106] it is stated that for such bearings which continuously rotate the insulating layer of lubricants cause a spark which results in pitting on race and rollers, even at relatively low current levels. The only electrical connection between rotating parts of the radar and the ground is the ground ring of the rotary joint. This is a safety ground and is not designed to withstand the full current amplitude of a direct lightning impact. Because the lightning current will stay on the outside of metal structures in accordance with Lenz' Law, it was initially assumed in this work that when flashover will occur it will be near the (insulating) bearing, and that no current will go via the safety ground inside the rotary joint. The current has a sharp di/dt and it is possible for flashover to occur from the rotating to the non-rotating part. If this results in a potential between rotating and non-rotating parts that is larger than the local breakdown voltage, flashover will occur. To verify whether flashover occurs, the inductance of loop I, indicated in Figure 5-10, has been further calculated. The path the current must follow from the rotating part to ground has a loop area of approximately 0.1 m^2 . This can be modelled as a circular cross-section of similar area; the radius of this circle is approximately 0.18 m.

Figure 5-10 Path followed by small current and loop determining inductance.

The inductance of this loop is calculated by $L=0.5\mu\pi R$ H. With $\mu=\mu_0=4\pi 10^{-7}$ H/m this results in: $L=2.8\cdot 10^{-7}$ H. The resulting voltage is calculated by

$$U(t) = L \frac{di(t)}{dt} \quad [\text{V}] \quad (5.2)$$

The resulting voltage is plotted against time in Figure 5-11.

Figure 5-11 Voltage over an open loop due to direct lightning attachment, as function of time.

The breakdown voltage of air is approximately 3kV/mm and that of a general lubricant, as found in a bearing, is assumed to be 30kV/mm. The space between roller and wall, taken up by lubricant, in a ball bearing is approximately 5 μ m. The highest breakdown voltage is thus 150V. An air gap of 4 mm between non-rotating and rotating parts of the structure is assumed to be a secondary path. This gap has a breakdown voltage of 12kV. Figure 5-11 shows that these values are almost immediately reached and breakdown occurs almost instantaneously over either the ball bearing or the air gap. This is illustrated in Figure 5-12, where the current through the internal ground ring is plotted as a red solid line and the total current in the strike is plotted as a blue dashed line, based on breakdown at 12kV which is worst-case for the ground ring. Flashover occurs almost immediately.

Figure 5-12 Current through the internal ground ring (red solid line).

The current before the point of flashover will flow via the ground ring. The amount of energy deposited in the ground ring is:

$$E(t) = \int_0^t I^2(t) R_{ring} dt \quad [\text{J}] \quad (5.3)$$

The resistance of the ground ring, R_{ring} , is approximately 16 mΩ. The energy in the ground ring is 0.3 J, which is harmless.

5.1.3 Multifunctional Herakles Radar

Figure 5-13 Herakles phased array radar with lightning rods.

The multifunctional Herakles radar shown in Figure 5-13 has been partly designed by THALES France, and is partly produced in the Netherlands. There are many differences compared to the LRR, but there are also similarities. One difference is the additional lightning rods on top of the antenna structure intended to provide a defined current path. In this case, the Rolling Sphere Method is used once more to determine the lightning current. The current is directed via highly conductive paths downwards. The interface between the rotating structure and the fixed part is very similar to the LRR. It consists of a ring of brushes which can conduct the lightning current. This concept has been proven in practice, as the LRR has been hit by lightning and no damage to the electronic system was observed.

5.1.4 Multifunctional Sampson Radar

The multifunctional Sampson radar shown in Figure 5-14 is fitted with long lightning rods. No data is available on the design and performance.

Figure 5-14 Sampson active phase array radar with lightning rods. From [94]

5.2 The Integrated Mast Family

The IMast family of systems, Figure 5-15, is based on the idea of stacking all the detection and communication antennas together, as well as their associated

electronic cabinets and peripherals, into one shielded enclosure. What was once scattered over the whole topside of a regular vessel is now condensed into a single structure. With this solution, instead of having several lightning protection devices and methods in place to protect each individual piece of equipment, a single solution can protect a single structure. Although this has many advantages, the main disadvantage of this solution is the complexity. The total amount of cables housed inside such a structure, plus the risk of interference between the components, makes the EMC engineering of an integrated mast considerably more difficult compared to a situation where the cables are far apart from each other.

Figure 5-15 The integrated mast - IMast – family. From [95]

The presence of a satellite communication antenna on top of a mast makes it difficult to position any conventional lightning rod on top of the radome. Lightning diverters, such as applied in aerospace to protect the nose radome of airplanes, are the basic solution here. Experiments have been performed and described in Chapter 7. When struck by lightning, the lightning current has to flow down to the ship's hull. A major advantage of the integrated mast with respect to lightning is the lack of rotating parts. Rotating parts are difficult to protect and special measures have to be taken for them, which are not necessary with an integrated mast. In the current configuration, the integrated mast is a large metallic structure constructed on a rigid frame. It not only provides an optimum low impedance path for the lightning currents, but also a well-shielded compartment, in the shape of a Faraday cage, to protect any sensitive components and equipment inside.

5.3 Direct lightning protection in other domains

Even though the focus of this work is on naval vessels, other domains have to tackle the same lightning-related problems. Such domains as avionics, wind farms, and wind turbines in particular, have come up with ingenious solutions through research. This can ultimately help to push the current research on protecting naval systems one step further. The following sub-chapters provide a description of the state-of-the-art in some non-naval fields.

5.3.1 Aerospace

Aerospace includes the fields of aeronautical and space engineering, and its solutions are used in airplanes to space shuttles. The fuselages of conventional airplanes are made from aluminum panels riveted together. Lightning has brought down planes. The last commercial aircraft crash caused by lightning in the United States occurred in 1963 over Elkton, Md. [26]. According to the National Transportation Safety Board (NTSB) report, a lightning strike ignited a fuel tank, causing the "explosive disintegration" of the left outer wing. All 81 passengers and crew perished. Most of the time, however, airplanes weather lightning just fine. The NTSB database, which contains reports on more than 140,000 aviation accidents dating back to 1962, lists only 24 incidents caused by lightning strikes, including the Elkton crash. Most of the other 23 incidents involved small private planes or helicopters, and in one case a hot-air balloon. Only four other incidents involved fatalities, with a total of 11 deaths.

The rapid advancements in composite technology have led to composite materials replacing metal in new airplanes and space equipment. Examples include the Airbus 380 and the Boeing 787 Dreamliner, but also many body parts of military planes are made of composite material.

The likelihood of an airplane or space shuttle being struck by intra-cloud (cloud to cloud) and cloud to ground lightning is high. According to various authors [26], [103], [109], commercial planes are struck by lightning on average more than once per year. In fact, aircraft often trigger lightning when flying through a heavily charged region of a cloud. Corporate and private airplanes are thought to be struck less frequently because of their smaller size and because they often can avoid weather conducive to lightning strikes. While parked or during takeoff and landing the airplanes are capable of initiating upward lightning. According to Uman &

Rakov [109], from all lightning incidents recorded on aircraft, about 90% are initiated by the aircraft itself, while for the remaining 10% the airplanes intercept an approaching lightning leader. Petrov et al. [102] used the “attractive area” concept R_a , which is based on the same idea as the Rolling Sphere Method (RSM), to determine the collection area around the plane. On the ground, the attractive area around an airplane-like structure for a lightning current of 100 kA is around 0.2 km² [102]. By using the Rolling Sphere Method the radius is:

$$R_{sphere} = 2 \cdot 10^{-3} \cdot 10^5 + 30 \left(1 - e^{-\frac{10^5}{6.8 \cdot 10^3}} \right) = 229.9 \text{ [m]} \quad (5.4)$$

According to the lightning models of Petrov, at cruising altitudes of 4,000 m the attractive area around a plane will increase from the 0.2 km² at ground level to 0.6 km². A thunderstorm with 2 flashes/min over a 10 km² surface means the chance of an airplane experiencing one of these flashes is once every 500 s it spends in that area. Additional information regarding dependence on different altitudes can be found in [102]. For space shuttles and satellite carrying rockets, protection before launch is assured by a multitude of lightning rods in place around the launching site. Rakov et al. give a detailed description of the situation at Kennedy Space Center in Florida, USA [108]. For airplanes, the radome represents the attachment or the initiation point for lightning and is thus the most vulnerable part. The purpose of the radome is to protect the antennas it houses [96], but if it is damaged the airworthiness of an airplane is no longer guaranteed.

Figure 5-16 Airplane radome with diverters. From [135]

It is not possible to use a full metal cover for the radome because of the radar and radio signals that have to pass to the antennas inside. However, one possible solution to protect a radome is the use of metal diverters. These strips of metal (aluminum or copper) provide the conductive path along the nose of the airplane to avoid puncture and flashover to the antennas and other electronics inside. A diverter should be small enough with respect to the wavelength of the radio and radar signal to be radar transparent. It is not always possible to achieve transparency with continuous strips, and for this reason a row of metal dots is applied, the so-called segmented diverter [26]. This diverter concept can be applied for naval radar systems installed onboard a naval vessel too, as in the case of the communication antenna on top of the IMast, or to protect composite structures. Analyzing, testing, and evaluating the effects of such a solution for naval radars is another component of this project, and is described in detail in Chapter 7.

5.3.2 Wind turbines

In Chapter 3 the model for the risk of lightning strikes is described. The standards [28], [29], [30], [31] exclude the littoral area. This work will, however, use lightning incidence in offshore wind farms for a comparison with a naval vessel. Wind farm technology and wind turbines in particular have undergone spectacular development over the last decade. Some aspects of wind farm technology are very closely related to our problem:

- the widespread locations, in some of the most remote places on the planet, and in the worst possible environmental conditions;
- the use of composite materials in blade engineering.

As with radars, the authoritative guide for the lightning environment and the parameters of lightning for wind turbines is still the IEC 62305 [28], [29], [30], [31]. A special working group produced a complete guideline for wind turbines in IEC 61400-24 [81].

The necessity of lightning protection for wind turbines either on land or offshore can be acknowledged either as a precautionary measure for future economic reasons, or to avoid potential hazardous conditions for humans and animals in the vicinity. This includes death caused by step/touch voltages or (parts of) detached rotor blades, as shown in Figure 5-17.

Figure 5-17 Delaminated and detached rotor blades after a lightning strike.

Similar to radars, all the protection methods and restrictions have to be considered at all levels, starting with the design, in order to avoid additional expenditure and man-hours being necessary for improvements once in use.

During intensive studies and research over the past decades, scientists have been looking at the effect of lightning on wind turbines [98], [99], [104], [105] by compiling statistics about damage events or creating several databases with over 4000 turbines. Table 5-1 gives an overview of data relating to the frequency of lightning damage collected in these databases. It summarizes the lightning faults per 100 turbine years for a minimum six-year period. It is clear that the greatest number of faults per hundred turbine years occurs in Germany. This is consistent with the higher ground flash density in Germany compared to Denmark and Sweden. What is not shown in the table is the percentage of lightning faults that are caused by direct or indirect strikes. Only the German database, better detailed, suggests that of all lightning faults 70% are caused by indirect lightning strikes[138], [139], [140].

Table 5.1: Lightning damage frequency for wind turbines

Country	Period	Turbine years	Lightning faults	Faults per 100 turbine years
Germany	1991 to 1998	9204	738	8.0
Denmark	1991 to 1998	22000	851	3.9
Sweden	1992 to 1998	1487	86	5.8

The indirect lightning damage on wind turbines plays an important role mainly because it affects the communication and the control systems, causing transients in the telephone network and power grid. According to each database, the electronic systems in the wind turbine are responsible for the greatest number of faults, and are the most damaged. For example, the component damage distribution from the

Danish database is shown in Figure 5-18. A similar pattern of damage distribution was observed in the German database.

Figure 5-18 Component damage distribution from the Danish and German databases. From [139], [140]

Most of the damage that occurs is to the electric systems, the power conversion, and the control system, while the most costly damage is caused to the blades. This is because the blades are extremely difficult to repair and the turbines have to go offline. The second most expensive category is the electrical systems, followed in third place by the damage to bearings. The lightning failures are responsible for 40% less power production and 20% more downtime [138].

To illustrate the implications of damage to wind turbines, both now and in the future, an overview of the current situation in Europe is given here. Nevertheless, the rest of the world is following a similar trend, with major development expected in China. According to such sources as Eurostat and EWEA [105], over the past 12 years wind power installations in Europe have increased by a growth rate of over 11% each year, to reach a total of 109.6 GW. This trend is expected to continue over the coming years. Of these new wind power installations, offshore installations are favored in such countries as the UK and the Netherlands, where available land is scarce, and for Europe as a whole 10% of all new installations are offshore.

The financial implications of failures, at the current and future levels, provide an incentive for protection against all sources of damage, especially lightning.

5.4 Summary

Several state-of-the-art solutions have been studied in relation to novel direct lightning protection measures for present-day radars on naval vessels. State-of-the-

art techniques employed in the aerospace domains and for wind power installations have also been analyzed. This work identified two possible solutions that will be sufficient to provide a high degree of lightning protection, for two distinct types of antennas, either by offering proper attachment points for lightning, and/or by offering an alternative current conducting path. The use of composite materials in naval radar structures could eventually lead to unique solutions for every design

The indirect effect on electronic equipment in a non-conductive composite structure will be discussed in the next chapter of this work.

6. Indirect lightning effect, L-EMP

6.1 The challenge of composite materials for naval ships

One of the challenges with any housing made of composite materials, not only for naval ships, is the apparent loss of shielding capability that traditional metal skins offer. The reason to go for composite hulls instead of metal is that ships can be built lighter and with greater freedom of shape, while retaining a structural strength comparable to steel, for instance. Since the term “composite” covers any combination of two or more materials, as stated in section 1.4, for the purpose of this project several varieties of FRP composite materials have been used. These composite materials are not conductive, offer no current path for direct lightning attachment, and offer no shielding effectiveness against electromagnetic fields from near (indirect) lightning. Traditional steel ships mitigate the threat of lightning in two ways. For direct lightning, the steel structural elements form a low-impedance path for the direct lightning currents to the seawater. For indirect lightning, the steel hull forms a shielding enclosure for electronic systems to protect them against the electric and magnetic coupling effects.

Composite structures on ships, in lightning-intense environments, will need to have similar provisions. For direct lightning, there needs to be additional attachment points, distributed over the exterior surface of the structure, where the lightning can contact the equipment, and where the lightning current is conducted to a point on the ship’s metal hull (or to a special electrode) that is immersed in seawater. These attachment points can be designed in several ways, such as solid lightning rods or diverters on a radome or any other non-conducting housing. The indirect lightning protection of composite structures is quite challenging, because the direct lightning current path creates a large magnetic field density. So in order to attenuate these magnetic fields, it is better to use thick and heavy metals, similar to the conventional approach. But when this work introduces the idea of a (very) thin conducting layer, either in the form of a metal paint, or conducting cloth, or foil, the observations

should point out to a shielding effectiveness for magnetic fields which is increasing with frequency, such as a low pass filter. On the other hand, indirect lightning, i.e. the magnetic field, induces currents and voltages with a time-derivative effect (di/dt and dv/dt). In other words, the higher the frequency, the more coupling. These two effects, namely some shielding - although limited - of thin metal layers, and the induced currents and voltages, compensate for each other up to a certain level. A comparable approach was published recently by people active in aerospace industry [119].

In the next section, the reasoning behind grounding/bonding/earthing metal parts is briefly described. Then the shielding effectiveness of thin metal layers is discussed. After that, the coupling of electromagnetic fields into transmission lines is discussed, with a focus on lightning electromagnetic field coupling. The combined effect in the time domain is analyzed in the last section.

6.2 Electric induction of current surges to surfaces

The induction of current surges on metallic surfaces will possibly result in high voltage spikes and/or common-mode displacement-type currents in connected cables. This is based on Gauss' Theorem in relation to the high rate of change of electric fields, the dD/dt as illustrated in Figure 6-1.

Figure 6-1 Induction of currents into a conducting surface

The incident electric field couples into any conducting surfaces it encounters. A displacement current is generated based on the rate of change of the electric field. That current can be evaluated in the time domain:

$$I_{induced}(t) = \frac{dQ(t)}{dt} = A_e \epsilon_0 \frac{dE(t)}{dt} \quad (6.1)$$

Setting A_e to 1 m², a “ball-park” estimate for these induced effects, can be found combining this equation for the electrically induced current with the rates of change given in section 3.5, as well as STANAG 4370, AECTP 250, Leaflet 254, [110] and MIL-STD 464C [68].

The induced current on the “equipment front plate” surface results in a low current, for instance 6 A for 1 m² area. For most equipment cabinets, this surface current should be no problem, as long as the panels are properly connected to earth (grounded). If they are not, the panel voltage will rise until the current is reached, either by spark-over or flowing through any other conductive paths, e.g. wiring.

6.3 Shielding effectiveness of thin metal

The analysis in the preceding section suggests that the magnetic field pulse from the lightning phenomenon is likely to be the most threatening effect for electronic systems in a composite/poorly-shielded environment. An FRP composite structure itself will offer no electromagnetic shielding whatsoever. Conducting material is needed to create the shielding effectiveness, but the thickness of the conducting material is limited due to weight considerations. The Shielding Effectiveness (SE) of an infinite metal wall is made up of three components [122]: absorption, reflection, and multiple reflections, as shown in Figure 4-2.

The absorption term SE_A is the result of the skin effect and is expressed by

$$SE_A = 20 \lg \frac{H_{incident}}{H_{transmitted}} = 20 \lg e^{\frac{d}{\delta}} \quad (6.2)$$

Where d is the thickness of the shield and δ is the skin depth, both in meters. With

$$\delta = \sqrt{\frac{2}{\omega \mu \sigma}} = \frac{1}{\sqrt{\pi f \mu \sigma}} \quad (6.3)$$

This becomes

$$SE_A = 20 \lg e^{\frac{d}{\delta}} = 131.4 d \sqrt{f \mu_r \sigma_r} \quad [\text{dB}] \quad (6.4)$$

where σ_r is the relative conductivity and μ_r the relative permeability. The absorption term increases with the square root of the frequency on a dB scale.

The reflection shielding SE_R is caused on the boundary mismatch of air-metal at the first wall, as well as the metal-air mismatch of the second wall. The shielding effectiveness reflection term is then [122]:

$$SE_R = 20 \lg \left| \frac{(\eta_0 + \hat{\eta})^2}{4\eta_0 \hat{\eta}} \right| \quad [\text{dB}] \quad (6.5)$$

With $\hat{\eta}$ the impedance of the metal and η_0 the wave impedance of the electromagnetic wave.

At a large distance from a source, with respect to the wavelength the wave impedance is $\eta_0 = 120\pi = 377 \, \Omega$, as shown in Figure 6-2.

Figure 6-2 Wave impedance as function of the frequency, for a dominant electric and a dominant magnetic source

Then the shielding effectiveness reflection term, assuming that the metal is a good conductor so $\hat{\eta} \ll \eta_0$, becomes

$$SE_R = 20 \lg \left| \frac{(\eta_0 + \hat{\eta})^2}{4\eta_0 \hat{\eta}} \right| \cong 20 \lg \left| \frac{\eta_0}{4\hat{\eta}} \right| \cong 20 \lg \left(\frac{1}{4} \sqrt{\frac{\sigma}{\omega \mu_r \epsilon_0}} \right) \quad [\text{dB}] \quad (6.6)$$

Using the relative conductivity (relative with respect to copper) and because for conducting material the permittivity equals the permittivity of vacuum ε_0 then:

$$SE_R \cong 20\lg\left(\frac{1}{4}\sqrt{\frac{\sigma}{\omega\mu_r\varepsilon_0}}\right) = 168 + 10\lg\left(\frac{\sigma_r}{\mu_r f}\right) \text{ [dB]} \quad (6.7)$$

For a lightning strike, generating a large nearby magnetic field, the wave impedance η_0 is much lower and the shielding effectiveness reflection term becomes:

$$SE_{R-m} \cong 20\lg\left|\frac{(\hat{Z}_w + \hat{\eta})^2}{4\hat{Z}_w\hat{\eta}}\right| \cong 14.6 + 10\lg\left(\frac{fr^2\sigma_r}{\mu_r}\right) \text{ [dB]} \quad (6.8)$$

The multiple reflection term is the residue of the reflected wave on the second wall of the metal shield that passes through the shield, is reflected again on the first wall, passes through the shield again to exit in the second wall, as shown in Figure 4-2. This residue is normally negligible, except for very thin metal shields. Then it becomes:

$$SE_M \cong \left| 20\lg(e^{\frac{2d}{\delta}}) \right| \text{ [dB]} \quad (6.9)$$

Figure 6-3 Shielding effectiveness for dominant electric and magnetic fields with the source at 1 km distance, as function of the frequency.

In Figure 6-3, the shielding effectiveness as function of the frequency is given for a solid, 1 mm thick aluminum screen, for a dominant electric and dominant magnetic field at 1 km distance from the source (such as a lightning strike).

Figure 6-4 Shielding effectiveness (top) or filter capability (bottom) of dominant electric and magnetic fields with the source at 10 m distance, as function of the frequency.

Assuming a lightning strike is at a distance of 10 m, then the shielding effectiveness is given as shown in Figure 6-4.

The results give a very confident feeling about the shielding properties of solid aluminum: very high shielding for dominant electric fields and good shielding for dominant magnetic fields.

If a composite material is used, and an additional thin metal layer of only 10 μm thick copper is applied, then the shielding effectiveness becomes as shown in Figure 6-5. Such a layer can be achieved by using metal paint or a metalized cloth like Shieldex.

Figure 6-5 Shielding effectiveness for dominant electric and magnetic fields with the source at 10 m distance, for 10 μm thick copper

These results confirm the hypothesis that electric fields are easily shielded, even in the near-field, but that magnetic fields are more difficult to shield, especially in the near-field.

At first sight, the dominant magnetic fields of an indirect lightning strike will thus not be attenuated by the thin metal layer. But the most important observation is that the thin metal layer acts like a low-pass filter. This behavior will be used in combination with the coupling of electromagnetic fields. In the next section, the coupling of electromagnetic fields into electronic circuits is discussed.

6.4 Coupling of electromagnetic fields to transmission lines

The coupling of electromagnetic fields to transmission lines is well known [121]. In [120] a review is presented, stating that, with a basic and valid approximation for our case, the extensive transmission line equations reduce to the basic well-known general transmission line equations as described in many textbooks, such as [122]. Paul [122] evaluated the induced current for each of the three orthogonal directions of an electromagnetic field, far away, with an optimal coupling with a cable, namely:

- sidefire excitation or magnetic coupling
- broadside excitation or electric coupling, and
- endfire excitation or hybrid coupling,

as shown in Figure 6-6, Figure 6-7, and Figure 6-8.

Figure 6-6 Sidefire excitation or magnetic field coupling

Figure 6-7 Broadside excitation or electric field coupling

Figure 6-8 Endfire excitation or hybrid coupling

The letters in the figures represent:

S	Poynting vector
E	Electric field
H	Magnetic field
Z_s	Impedance signal
Z_l	Impedance load
Z_c	Characteristic impedance
$I(0)$	Current at signal
$I(L)$	Current at load
$I(l)$	Current at an arbitrary point of the line
h	Height transmission line above reference plane
L	Length of transmission line
r_0	Radius transmission line

The terms sidefire, broadside, and endfire reflect the direction of the Poynting vector. The terms magnetic, electric, and hybrid coupling reflect the main type of coupling.

The transmission line equation gives the current at the terminals caused by the electric field for sidefire excitation as:

$$I_{TLM}(0) = \frac{2 \cdot E_z \cdot Z_c}{\beta \cdot D} \cdot \sin(\beta h) \cdot \left\{ \frac{Z_l}{Z_c} [\cos(\beta L) - 1] + j \sin(\beta L) \right\} \quad (6.10)$$

or

$$I_{TLM}(0) = \frac{2 \cdot B_y \cdot 120\pi \cdot Z_c}{\mu \cdot \beta \cdot D} \sin(\beta h) \cdot \left\{ \frac{Z_l}{Z_c} [\cos(\beta L) - 1] + j \sin(\beta L) \right\} \quad (6.11)$$

where

$$D = (Z_c Z_s + Z_c Z_l) \cdot \cos(\beta L) + j(Z_c^2 + Z_s Z_l) \cdot \sin(\beta L) \quad (6.12)$$

and

$$Z_c = 60 \ln\left(\frac{2h}{r_0}\right) \quad (6.13)$$

β is a constant equal to $2\pi / \lambda$

Similar results are obtained for broadside and endfire excitation.

As an example, assuming a cable length of 5 m, routed at 0.1 m above an ideal metal plane, and terminated in 0.1Ω and 0.01Ω impedances, the induced current for endfire, sidefire and broadside excitation is given in Figure 6-9.

Figure 6-9 Induced currents at the left side of a 5 m transmission line, for endfire (red), sidefire (blue) and broadside (green) excitation, in dBμA/V/M between 10 Hz and 10 MHz, for 1 V/m

Only when this work assumes a lossless situation and short-circuit (0Ω) termination, can the induced current be flat from very low frequencies. In all other (practical) cases the induced current shows a 20 dB/decade increasing curve, i.e. the di/dt effect, and thus a (first order) high-pass filtering.

So it is possible to conclude here from the equations that the induced current is proportional to the height of the cable/interface, the length, and the terminating impedance. By making the terminating impedance very high, the current will be decreased. This is a valid approach, but cannot be used in practice because then the

functional current path in a system will be impacted too. The main parameter is thus: decrease cable length and height, i.e. the loop area.

Most induced problems in equipment exposed to indirect lightning effects are expected to result from the magnetic field component. The induced voltage in a cable loop could immediately reach the connected circuits if the cable is not shielded, or protected by overvoltage devices such as SPDs.

6.5 Induced effects due to coupling of L-EMP

6.5.1 Without shielding

The conventional way to protect electronic systems onboard a naval vessel was to place the electronics in the ship's hull. But in future systems, the electronic equipment could be in a lightweight non-conducting composite structure on top of a mast. The additional conducting material applied to create shielding effectiveness must therefore be kept very thin.

This section evaluates the performance of thin metal shields against lightning induced voltages, i.e. to reduce the threat of the magnetic field component.

Analyses of the shielding capabilities are best performed in the frequency domain. Given the frequency domain description of the lightning surge, the effect of a shielding measure can then be evaluated as a transfer function. In the time domain, that would require a convolution integral. So after running all the computations in the frequency domain, it was necessary for the purpose of this work, and to get a proper impression of the effect on lightning surge magnetic field shielding, to convert the frequency domain results into the time domain with the inverse functions.

The lightning effects frequency spectra can be derived analytically from the time domain equations given in Section 3.5.1.

$$i(t) = I_0(e^{-\alpha t} - e^{-\beta t}) \quad (6.14)$$

Or when converted in the frequency domain:

$$I(j\omega) = I_0\left(\frac{1}{j\omega + \alpha} - \frac{1}{j\omega + \beta}\right) \quad (6.15)$$

Using the parameters shown in Section 3.5.1, the time domain graphs are drawn for components A, B, and D in Figure 6-10.

For simplicity the following time domain graphs have as initiation time 0, intentionally neglecting the discontinuity produced by such time derivative, (∞).

Figure 6-10 Time domain waveforms of A, B, and D pulse

Figure 6-11 Magnetic field time derivative of lightning components A and D

Using the Biot-Savart law, the currents can be converted into equivalent magnetic field values, using a near lightning strike at 10 m distance. For the “rate of change”, the derivative with regard to time is calculated and plotted for the components A and D in Figure 6-11.

The peak magnetic field rate of change @10 m in Figure 6-11, $2.2 \cdot 10^9$ A/m/s for the A-pulse, is indeed the value shown in the standards [68].

As a rough estimate for the order of magnitude, it is possible now to calculate the induced voltage in a cable loop via:

$$u(t) = A_e \frac{dB}{dt} = A_e \frac{\mu}{2\pi R} \frac{di(t)}{dt} \quad (6.16)$$

With R as the distance to the lightning strike and A_e the effective loop area, if the loop is small in diameter. Instead of taking the derivative with respect to time, the lightning current is multiplied with $j\omega$ and μ while keeping $R=10$ m, ending up with the induced voltage per Hz per m^2 as given in Figure 6-12. The A-pulse graph clearly dominates the D pulse.

This work will use the indirect effect of the A-component of the lightning pulse for all the calculations in the remaining part of this chapter.

Figure 6-12 Frequency domain lightning voltage induction per m^2

6.5.2 With thin metal shields

An important aspect is the weight of the shielding material. It is equally important for a standard radar product to know, in addition to the electrical characteristics, the final weight of the antenna, panels and foils. So for each type of shielding material, the thickness and densities are as follows:

1. 20 μm Shieldex, at $\approx 3.95 \text{ g/cm}^3$;
2. 200 μm stainless steel, at 7.95 g/cm^3 ;
3. 500 μm copper at 8.92 g/cm^3 ;
4. 1 mm aluminum at 2.7 g/cm^3

The magnetic field strength after being attenuated by the metal, as function of time, is shown in Figure 6-13.

Figure 6-13 L-EMP Magnetic field attenuation for different shielding materials.

Another conclusion that can be drawn in this case, is that the magnetic field of the lightning electromagnetic pulse is substantially reduced if an aluminum shield of 1 mm is used. This is a common solution for naval radar systems, at the cost of additional weight. But a thin layer of copper, in this case 20 μm , will also reduce the time derivative of the magnetic field, as shown in Figure 6-14.

Figure 6-14 Time derivatives of L-EMP and attenuated L-EMP

From the above curves it can be seen that the time derivative of an L-EMP (dH/dt) is substantially reduced through a metal plane. And as a result, the induced voltage will also be reduced.

6.6 Summary

The induced current due to an electric field generated by a lightning strike (actually during building up the strike) is negligibly small if metal parts act as shields, whereas composites offer no similar capability whatsoever. The induced voltage due to the magnetic field generated by a lightning strike is a time derivative effect, i.e. increasing with frequency. In other words, it is not the peak amplitude of the lightning current, but the peak of the time derivative of this amplitude, its rise-time, which determines the actual threat. In this chapter, this work tries to introduce the idea of providing shielding effectiveness to non-conducting composites through thin metal coatings. Even though the level of protection against nearby magnetic fields of thin metal foils is limited, it increases rapidly with the frequency and thus will act as a low-pass filter. The combined effect is a reduction in rise-time, a key element when using thin metal shields.

This analysis shows the feasibility of using thin conducting layers as a shielding measure to reduce the coupling of electromagnetic fields generated by an indirect lightning strike.

7. New lightning protection concepts

From supplying power to a wide range of electrical loads or for sending control signals, electrical power systems require a constant line voltage and a steady frequency in order to operate in the best possible conditions. An important component of the best possible conditions is immunity or shielding against various induced effects. Focusing on the effects of lightning current variation, direct or indirect, it was necessary for this work to determine up to what thickness and configuration could various metals, alloys, or special textiles, be used, individually or combined, in order to achieve the minimum level of protection required. However, we should never lose sight of the fact that some high-end electronics, such as modern pieces of equipment and weapon system platforms on a naval vessel, are DC fed and rely heavily on AC/DC convertors, and thus in turn they create harmonic/interference problems of their own.

Figure 7-1 Interference: 1 – Voltage peaks, 2 – Frequency variation, 3 – Brown-outs, 4 – Black-outs, 5 – EMI, 6 – Harmonic distortion

AC feeding is still necessary in certain instances, such as to feed large electric motors via soft starters and variable frequency drives (VFDs). It is important to emphasize once more the fact that all of these AC and DC power feeds must supply clean and continuous electrical power, free of interruptions, sags, surges, and

harmonic waveform distortions. Hence, it is essential to define and provide operating environments for power systems capable of achieving reduced EMI and improved operating efficiencies.

Power system disturbances as presented in Figure 7-1 often appear as transient voltages, current disturbances, or as waveform distortions, caused by various factors, the most common of which include lightning surges, load switching, power system faults, non-linear loads, and electromagnetic pulses (EMPs).

At this stage in this work, both the external and internal influencing factors have now been determined. The expected rate at which a naval vessel is struck by lightning in a certain area on the globe (with special attention to the littoral zones) is now known. Furthermore, the preferred type of Lightning Protection Systems (LPSs) that needs to be installed, depending on the position of the radar and communication antennas, has also been determined. And down to things like knowing the transfer impedance for cables that are in this case housed inside the non-conducting composite housing of the antenna. The task of this chapter is to evaluate each of the shielding alternatives presented in the previous chapters based on their performance, and when possible construct adaptations and improvements to complete this work. As described in the preceding chapters, the expected effects on the cables as a result of lightning are:

- The effects due to the direct attachment of the lightning flash to the equipment/system which will cause the actual lightning current to flow in parts or the complete system.
- The effects due to coupling of the lightning's magnetic or electric field, as a consequence of either a direct strike to the equipment itself or a nearby flash, resulting in transient voltages and induced currents free-flowing in wires, cables, an unavoidable situation if large loops are present.

Induced currents and voltages are determined and evaluated during platform-level evaluations. When testing large components and systems, equipment with special handling provisions, or high power equipment, deviations from the standardized testing procedures might therefore be required. Two such alternatives for the above deviations are:

- testing integrated equipment at the subsystem-level, because the actual electrical interfaces are evaluated rather than the electrical load; or

- evaluating equipment through simulations.

Performing a conducted susceptibility test on equipment, cable bundles, and individual cables, is a common practice in the aerospace industry. This way the resistance to lightning strikes is evaluated and any remaining weak areas are identified. Among the available testing methodologies, damped oscillatory sinewave tests and surge tests are used for military equipment and civil equipment alike. By applying pin injection tests on interfaces, the levels of damage (locally) is assessed together with the formations of unwanted current paths. This might also include the presence of induced effects into nearby components as a result of the EM fields produced. In this way, various types of transients were injected directly through the pins of the interface/connector. Cables and cable bundles are tested too in order to evaluate the upset level generated by transients and a determined EM radiation coupling into such wires. So to extend the notions, such tests apply not only to the object/system/component but also to interconnecting cables and cable bundles, as well as all other loads and power sources in the interconnection. With transient testing it is mandatory to include a variety of voltage and current waveforms that cover the principal coupling modes. The purpose of such tests is to determine whether the equipment can experience a given level of transient testing, using representative waveforms, and survive without damage or malfunction.

But when simulations are used, a level of doubt regarding the integrity of the simulation can persist up to the moment of validation. Therefore all the simulations presented in this chapter have been validated by experimental work. The tools used are the CST Studio Suite[®] for simulations, while measurements and validation took place at the Hazemeyer Stichting in Hengelo, under the supervision of Professor Damstra. The foremost evaluation was if either damage or total destruction occurs in the object/system/component as a result of direct attachment. This was followed by an assessment of the shielding capabilities of the outer shell, insofar as if it was able to provide any shielding at all. In the simulations, the approach was to create a situation as close as possible to a real-life scenario. These simulations can be replicated with a real device in the test field later on. Initially, various simulated solutions were evaluated, with such tools as REMCON-XFtd[®], EMC²[®], EMCos[®], and CST Studio Suite[®]. But as preparation for the simulations, several initial calculations were performed in MathCAD[®] and MATLAB[®], together with computer assisted drawings in AutoCAD[®]. Based on the ease of use and ability to integrate the

pre-calculated data and drawings from all these simulation tools, CST Studio Suite was chosen for the experiments and to present this work's findings.

Most of the energy of the lightning pulse is in a bandwidth up to several MHz. The radar antenna and the G-EUT are relatively small in size when compared to the wavelength of the disturbance, i.e. L/λ is small compared to a wavelength at 10 MHz (30 m). Lightning can thus be considered a low frequency phenomenon allowing the assumption that the electromagnetic fields are (quasi)static. For the high frequency components that exist, the new low-pass filter capability of these coatings, introduced and detailed as a shielding solution in this chapter, is expected to be a good match.

In the simulated environment, both the cloud and the ground are represented by a signal source; one source will generate the lightning signal while the other will measure the received signal and compare it to the original, to the reference signal. The lightning and return current paths were also emulated by using two “zero loss” conducting wires. This way any influence they might have in the simulation is avoided.

Figure 7-2 Idealized representation of the cloud to ground lightning scenario; the red cones are the lightning and control signal sources, the blue lines are the lightning current return path.

Several situations in the simulated model were hard to recreate in real life. Whereas in situations with real lightning, the distance between the clouds and the ground is several kilometers, it is impossible to recreate something that big in any laboratory

environment. It is impossible to create a current source capable of maintaining such a long streamer, and the use of short streamers brings the source very close to the EUT. And to follow up on an idea mentioned at the beginning of this chapter, most of such current sources end up being made with electric and electronic components operating at higher frequencies, which increases the risk of tempering and influencing the measurements. This particular situation is avoided when performing a simulation. The perfect environment used in simulations is at the same time the weak point of every simulation. It is what complicates both the process of replicating simulated environments in real life, and any attempt to transport a real life situation in a virtual world. Another point to make here is the multitude of parameters present in real life, some uncontrollable, that push the computation times to extreme lengths. But there is no better way of learning what to expect or how to interpret a certain phenomenon or event other than by through simulation.

In reality, the test setup situation is somehow different. The return path of the lightning current is different from the real-life lightning situation. But because it is far away, it is possible here, at first, to approximate that the field is similar to a transverse electromagnetic (TEM) wave, and that such a TEM can be replicated when using a coaxial-like structure. Therefore, such a coaxial-like structure was designed for the tests, and is shown in Figure 7-2, in CST and in real life, horizontally displayed for ease of handling and visual continuity. An important aspect was its usefulness in avoiding interference from the EM fields of the current source, and to keep the conducting path at an acceptable length. So in this new design the EUT was placed in the centerline of the coax, with the current-entry point on one side and the current-exit point on the opposite side. Parallel to the EUT and the entry and exit paths are eight copper tubes placed in the form of an octagon: the “shield” of the coax construction. Each of these tubes will channel 1/8th of the lightning return current. The EM interference generated by the test setup, as well as by the two current paths attached to it and the field produced by the eight copper pipes, will cancel each other out, since the currents they carry are identical and travel in opposite directions. For matching purposes this new design was also applied to the simulation with all the conducting elements made with perfectly conducting materials. Designing, drawing, rendering in 3D, and later on, constructing the entire test setup is only a part of what is needed to complete the simulation and validation process. In other words, a new framework was needed that has less to do with construction, but more with choice and implementation.

A generic equipment under test (G-EUT) was built to obtain a reference response of the structure and the wiring inside, see Figure 7-2 and Figure 7-3. This included lightning simulations and tests for each component of the lightning strike as described in section 3.5.1. The G-EUT is a mix of a mast-like structure and other radar antennas of various shapes, with a conductive framework and with composite panels. The frame is made of aluminum because of the lightweight properties as well as its presence in various antennas.

Figure 7-3 Generic Equipment Under Test, real aluminum structure

Figure 7-4 Generic Equipment Under Test, 3D model for simulation purposes

The lightning parameters as used in standards are given in section 3.5. The induced voltage and current waveforms as used for testing of equipment are from Table 7-1.

Table 7-1: Standard waveforms for equipment testing

Waveform	Characteristics	Mathematical representation
Intermediate Pulse (IP)	6.4/70 μ s	$i = 1.09405 I_p (e^{-\alpha_1 t} - e^{-\beta_1 t})$ use $\alpha=11354\text{s}^{-1}$ and $\beta=647265\text{s}^{-1}$ for metal structures
Short Pulse (SP)	100 ns rise and 6.4 μ s to 0 crossover	The derivative of I from IP $i = 1.09405 I_p (\alpha e^{-\alpha_2 t} - \beta e^{-\beta_2 t})$
Long Pulse (LP)	50/500 μ s 40/120 μ s	$i = K I_p (e^{-\alpha_3 t} - e^{-\beta_3 t})$
		<div>50/500 μs for composite structures $\alpha^4 A = 11,354\text{s}^{-1}$, $\beta^4 A = 80,022\text{s}^{-1}$, K1=1.104</div> <div>40/120 μs for aluminum structures $\alpha^4 B = 12,400\text{s}^{-1}$, $\beta^4 B = 45,000\text{s}^{-1}$, K2=2.2</div>
Damped Sinusoidal (DS)	See fig. 7.2	$I_0 e^{-\pi f t / Q} \sin 2\pi f t$ with I_0 is the initial amplitude @ $t=0$ f is the frequency in Hz, t is time in sec, and Q is the quality factor

a) Intermediate Pulse

b) Short Pulse

c) Long Pulse

d) Damped Sinusoidal Wave

Figure 7-5 Visual representation of the waveforms used for testing

Chapter 5 referenced the idea of a test setup capable of generating a Long Pulse alongside various other papers supporting this work that have been published and presented over the years, including the original paper of Damstra and Pettinga [101]. This latest reference is in fact describing the origins of this real-life test setup.

7.1 Thick metal plates to shield the composite structure against both direct and indirect lightning

Electrical and electronic systems are subject to damage from the lightning electromagnetic impulses (L-EMP). Therefore L-EMP protection measures need to be provided to avoid failure of internal systems. Protection against L-EMP is based on the Lightning Protection Zone (LPZ) concept: the volume containing systems to be protected shall be divided into LPZs. These zones are theoretically assigned volumes of space where the L-EMP severity is compatible with the immunity withstand level of the internal systems enclosed. Successive zones are characterized by significant changes in the L-EMP severity. The boundary of an LPZ is defined by the protection measures employed as described in standards [31].

As discussed in Chapter 6 the magnetic field generated by an infinitely long conductor, such as a lightning strike, transporting the lightning current, at distance R from that conductor, can be described as:

$$H(t) = \frac{i}{2\pi R} (e^{-\alpha t} - e^{-\beta t}) \quad (7.1)$$

The shielding effectiveness of thin metal shields is composed of absorption attenuation, reflection attenuation, and multiple reflection attenuation. The calculated shielding effectiveness of thin layers in the time domain has been analyzed in Chapter 6.

A simulation has been performed. The time domain representation of the effects, when recreating the test setup in CST Studio Suite®, is shown in Figure 7-6

Important here is to investigate the coupling effect into a generic shielded cable. An RG58 was used for this cable, as this represents a good quality single-shielded cable. The coaxial cable was positioned along the metal frame, in the same direction as the lightning current flow, and with its shielding attached directly to the frame.

Figure 7-6 Magnetic field and surface current distribution respectively on a single axis

CST Studio Suite® was used prior to testing, and to quantify the current amplitudes that can develop in the inside wire of the coaxial cable. And, of course, in order to be ready to handle the consequences when testing in real life. The inside wire (the core wire) together with the metallic shielding braid of the RG58 cable produce losses, since each presents an individual conductivity and impedance.

Figure 7-7 Current characteristics as used in the simulations

Figure 7-8 Resulting currents for thick aluminum panels

Different shielded panels were used for the simulations. The influence of various shield thicknesses is analyzed in each of the following sections of this chapter, according to their properties. By using thick metal/alloy plates on the outside panels, varying from 3 to 20 μm , this provides enough shielding capabilities, but has the disadvantage of a heavy weight structure. It is easy to imagine how complicated the

scenario of moving such large panels would be, and trying to replace any of them when required. Not to mention the economic factor of spending a lot of energy to “carry around” all that mass. So electrically, such thick panels provide a very good current conductive path for low as well as high frequency components. What is then left for the frame and implicitly the shielding of the coaxial cable to transport, are very small to no currents at all. Consequently, the induced current developed in the inside wire of the RG58 are now low to almost nonexistent, as shown in Figure 7-8. A simulation was carried out for 2 mm thick aluminum panels. The magnetic field distribution is shown in Figure 7-9.

Figure 7-9 Magnetic field distribution with 2 mm aluminum panels

A reduction in the conductive path of the panels by a factor 10, has led to observations of a more active implication in channeling the lightning current and thus a reduction of the magnetic field inside the G-EUT, and by consequence via the shielding of the coaxial cable.

7.2 Thin metal plates to shield the composite structure against both direct and indirect lightning.

When applying composite structures, additional conducting material is used to create shielding. The material, such as metal foils or paint, is very thin. The shielding effect

against magnetic field for 200 μm and 20 μm aluminum is shown in Figure 7-10 and Figure 7-11 respectively.

Figure 7-10 Magnetic field distribution with 200 μm aluminum

Figure 7-11 Magnetic field distribution with 20 μm aluminum

Comparing the magnetic field patterns between 200 μm and 20 μm foils, the differences are difficult enough to spot. A detailed view shows a slightly lower magnetic field distribution on the inner side of the G-EUT. The surface current distribution is shown in Figure 7-12 and Figure 7-13 for each of the two thicknesses.

Figure 7-12 Surface current for 200 μm aluminum

Figure 7-13 Surface current for 20 μm aluminum

With both simulation conditions identical, a thinner metallic outside shell will allow current to flow to only a portion of the total surface, mainly the high frequency component due to the skin effect. The high concentration of low frequency components are consequently forced to flow via other paths.

7.3 Validation of calculated and simulated results thru testing

The entire process of testing started with the reconstruction of the setup developed by Damstra and Pettinga, described in their paper [101]. Some components demanded improvements but the main functionality remained the same. The first three components of the lightning wave shape were available. The “A”, “B”, and “C” pulses proved sufficient for the scope of this work.

Depending on the test objectives, one component at a time can be used [92], or for special cases when more damaging situations are studied, two or all components will trigger in cascade [79].

A 120 kJ capacitor bank discharging in a low damped circuit through an inductive load will produce a gradual discharge in a damped periodic manner. Increasing the circuit resistance will transition the discharge behavior from periodic to aperiodic. To be capable of realizing an “A” component discharge, the capacitors require additional charging, up to 2.2 MJ minimum, as well as the use of diodes, or even a spark gap crowbar for convenience, in order to trigger.

For the “B” and “C” component discharges, a different technology is in place. An artificial line is used, created with a series of L - C (inductor - capacitor) sections, to obtain a flat top current.

The equipment under test, the G-EUT as described at the beginning of this chapter, consists of a series of cubical frames of different sizes assembled together with metal or composite panels to give the aspect of a box, as shown in Figure 7-15. Making a large EUT with the same size as an integrated mast, or a real radar system, would complicate the experimentation process making it impossible to realize. Because the physical dimensions of the real objects are still small when compared to the wavelengths of the intended signals, it is acceptable to use a G-EUT where the physical dimensions are 50x50x50 cm.

Figure 7-14 Damage at the corner of the first G-EUT

First rivets and later on screws became the solution of choice to keep all the subcomponents of the G-EUT together. The G-EUT used for the experiments was made from thick L-shaped aluminum bars deliberately riveted, later on screwed, together, but never welded. The change occurred after the first bar was damaged by the large high currents and the shock of the Lorentz forces in the bars. Part of the damage is presented in Figure 7-14.

Figure 7-15 The aluminum frame with and without panels, called the G-EUT

Previously presented tests [60], [79], [92], [93] showed that the structural integrity of this frame is maintained independent of the number of tests. What remains to be demonstrated is the current distribution, the EM fields and their alterations inside and outside the structure, as well as the shielding effectiveness of the various types of panels.

Measurements have been performed [123] to check the uniformity in current distribution along the four vertical bars of the G-EUT. If by any chance the currents flowing in these bars were not equal, by improper electrical contact of some sort or other outside factors, the test results would be compromised, see the discussion on TEM earlier in this chapter. So the frame was equipped with four identical current probes which were previously calibrated.

Figure 7-16 G-EUT in the test setup

The test setup is shown in Figure 7-16, with the G-EUT on the left and the capacitor bank on the right.

Figure 7-17 Current probe

A Rogowski coil was used to measure the total lightning current while 4 calibrated self-made current probes (coils) with a radius of 20 mm were used to determine the current flowing through the beams, see Figure 7-17.

The current probes were effective in the frequency range $100 - 10^6$ Hz. Due to the low frequency of the lightning pulse, a low-pass filter was used to correct the frequency response, starting at 300 Hz. This trick reduces the total response, in terms of Volts per Ampere, but since the amplitude of the lightning current pulse is so high, this is allowable. The measured currents are shown in Figure 7-18.

Figure 7-18 Recorded voltages induced by the current in each of the four legs of the G-EUT, without the coaxial like structure

Initially, the current distribution in the four legs varied considerably, noticed in the various induced voltages recorded by the probes. This was caused by the asymmetrical test setup (seen electromagnetically) in Figure 7-16. The current return path is at the right side of the test setup, leaving the right leg to channel most of the current, due to Lenz' Law. A coaxial test setup was built, as shown in Figure 7-19 to wipe the unwanted disturbances. Furthermore some resonance effect can be observed in Figure 7-18. Therefore the probe cables have all been terminated in 50Ω , to avoid ulterior reflections between the probe and oscilloscope.

Figure 7-19 Coaxial test setup

The coaxial test setup improved the uniformity in current distribution between the four legs, as shown in Figure 7-20

Figure 7-20 Recorded voltages induced by the current in each of the four legs of the G-EUT, when using the coaxial structure

With only the aluminum frame, the recorded voltages had a maximum amplitude of 30mV for a discharge current of 15kA.

To measure the magnetic field strength created by the lightning currents, a three axis probe which measures the flux variations has been developed too. This probe has been placed in the center of the box as well as at various distances from the vertical bars of the frame, both inside and outside the structure. This probe represents the response of a real conductor placed inside or near the given structure under the following transfer function:

$$V_{induced}(t) = -n \frac{d\Phi}{dt} = -n.A \frac{dB}{dt} \quad (7.2)$$

Where n is the number of turns and A is the surface of the coil, while Φ is the flux going thru the coils.

The G-EUT frame was equipped with four panels of identical size to measure the coupling effect. The following types of panels have been tested, first fitted to the frame with rivets and later on with screws:

- Solid aluminum 2 mm thick
- Fully composite panels, where the aluminum frame is the single conductor of the structure
- Composite panel with Shieldex, which is metalized (copper) cloth with 20 μm thickness

Figure 7-21 Recorded voltages induced by the current in each of the four legs of the G-EUT, when using 2 mm aluminum panels

The induced voltages using aluminum and with current probes placed on the four legs of the G-EUT is shown in Figure 7-21.

Figure 7-22 Recorded voltages induced by the current in each of the four legs of the G-EUT, when using with Shieldex on a composite panel

The composite panels gave similar results as the G-EUT without panels, as expected. The measurement result of the composite panel with Shieldex is shown in Figure 7-22.

Figure 7-23 Recorded voltages induced by the current in the 3 axis current probe, inside the G-EUT, with 2 mm aluminum panels

The induced voltages recorded by the current probes in all tested configurations, are difficult to analyze and validate only from the numerical values without all the data. However, the clearly visible traces improve these processes significantly.

The differences in traces, discharge pulse vs. distributed current, validate the initial assumption that the metal shield acts as a low pass filter, hence the induced effects are therefore much lower. A cable was placed in the G-EUT and the induced current was measured. The results for 2 mm aluminum panels and the composite panel with Shieldex are shown in Figure 7-23 and Figure 7-24.

Figure 7-24 Recorded voltages induced by the current in each of the four legs of the G-EUT, with Shieldex coating of the composite panels

The measurement results showed that the 2 mm aluminum panels reduced the induced effects at least 20dB, but especially reduced the high-frequency components. The Shieldex coating on the panels reduced the amplitude as well as the high-frequency components. A test using aluminum foil of 0.3 mm thickness gave similar filtering results.

7.4 Effect of lightning rods and diverters on a radome

The effect of lightning rods around, and diverters attached on, a non-conducting radome has been evaluated experimentally. A radome is in general used as weather protection for antennas, and is designed to be transparent for electromagnetic waves in a certain band. The radome was supplied by THALES Netherlands, and the tests were financed by THALES. The DC voltage was approximately 1 MV, and a metal part was at approximately 1 m above the test setup, so the electric field strength

before the lightning stroke was about 1 MV/m. The current of the stroke was approximately 10 kA.

The default protection for conventional radars is the use of lightning rods, as shown in Figure 5-1. Radomes with equipment inside can be protected in the same way.

Figure 7-25 shows the effect of a long lightning rod (left) and a short lightning rod (right). The lightning is attracted by all rods (see small stroke towards other rods) but the main current path is towards the rod at the backside of the radome. This figure shows that lightning rods will effectively attract the lightning stroke, also when the lightning rods are not the highest part. The lightning rods may, however, interfere with the equipment that is protected by the radome, unless this equipment is to a large extent pointing to zenith.

Figure 7-25 Lightning hits the long lightning rod (left) and short lightning rod (right). Image courtesy of [THALES NEDERLAND](#)

If the lightning rods are removed and metal parts are inside the radome, the lightning will try to find a path to the inside. The weakest spot is then followed to enter the interior. Figure 7-26 shows this effect. The current flows over the surface of the radome, until it enters the radome through a crack at the right side of the radome. This test was repeated, with the right side of Figure 7-26 showing the repeated test.

The lightning current which flows over the outside of the radome does not result in damage. The attachment point is shown in Figure 7-27.

Figure 7-26 Two lightning strikes for a single radome with damage at the right side (bottom). Image courtesy of [THALES NEDERLAND](#)

Figure 7-27 Radome after having been exposed to direct lightning. Image courtesy of [THALES NEDERLAND](#)

The local damage does reveal the potential weakness of protection by a radome only. Additional protection, using diverters, may be required to prevent undetected radome damage leading to damage to equipment when hit by lightning. Diverters have been added to the radome to attract the lightning and to make a defined current path. These diverters can be optimized for the wavelength of the equipment that is protected by the radome. Two examples have been tested, one with wide diverters with relatively large separation, and one with narrow diverters with reduced separation. The diverters have the same surface area, but the droplet width and separation can be optimized for a particular wavelength. The effect on lightning is shown in Figure 7-28. The lightning current is not entering the crack in the radome anymore, but is flowing in the path as defined by the diverters. The lightning stroke is still largely visible on the left picture with minor interruptions. The interruptions coincide with the vertical length of the diverters. On the right picture, the lightning stroke is visibility much reduced, and the copper droplets have a more visual impact because the conductive length of the droplets is longer.

Figure 7-28 Lightning hits the diverters, left: short/wide, and right: long/narrow.

Image courtesy of [THALES NEDERLAND](#)

7.5 Current path thru bearing

In a conventional system, slip rings are conducting the lightning around the bearing, in order to prevent arcing. This is also the conventional approach protecting arcing in radar system bearings

The upper structure of a rotating radar can be made such that the radar electronics are shielded properly. The direct lightning current will flow via defined current paths downwards. Between the rotating part and the static part, which is connected to the ship's hull, a bearing and rotary joint unit is used. If the radar is not rotating, there is a good electrical connection through the bearings, simply because the oil present inside the chamber is pressed away by the weight of the rolling parts. This way the lightning current will flow directly through the bearings, via the ground bonding strap and cable, and into the ground. The total effect on the bearing depends mostly on the resistance of the bearing ring, which ultimately affects the energy dissipated in the bearings. Many studies have been performed on the effect of lightning current on bearings, rollers, and walls. For the rotating case, [106] states that a hydrodynamic layer of lubricant is developed in bearings that continuously rotate, which will result in an insulating layer. If a high voltage is developed, ultimately a flashover will occur causing a spark, which will ultimately result in pitting on the race and rollers even at relatively low current levels. While rotating, the only electrical connection between the moving part and ground is the ground ring of the rotary joint. This ground ring is intended as EMC ground and is not designed to withstand the full current amplitude of a direct lightning impact. To prevent this unwanted current path, carbon brushes are often used in outer ring to provide a low impedance current path.

Pre-loaded bearings have been used many times to reduce the variations in movement. Various experiments with an electrostatic discharge gun on bearings showed (as expected) that static bearings were conducting and the rotating bearings were not conducting due to the oil film in-between the rolling elements and the rings. However that rotating pre-loaded bearings are eventually conducting.

Various experiments have been carried out to determine the effect of pre-loaded bearings, partial results are now available to the public [141].

Lightning current tests, including the fast A pulse, the B pulse, and the high-energy C pulse, have been performed by THALES in the lightning laboratory at the Tuindorpstraat in Hengelo on standard roller bearings and preloaded roller bearings. In the test-laboratory at the Tuindorpstraat three facilities are available:

- A-pulse test setup, cascade capacitor bank for short stroke electrical currents up to 100 kA / 40 kV
- B-pulse artificial line high current test setup, capacitor-coil circuit for currents up to 2 kA / 5 ms
- C-pulse test setup, 3-phase diode bridge circuit for DC currents up to 500 A / 500 ms

To perform a complete lightning test, the test setup is subsequently connected to each of the test facilities and loaded with the maximum output.

Table 7-1: Lightning pulses

Pulse name	Peak current	Front time	Time to half value	Duration
A	100 kA	9 μ s	240 μ s	
B	2 kA	0.4 μ s	140 μ s	
C	300 A	-	-	200 ms

To monitor the condition of the bearing system, axial, radial and tangential accelerations have been measured before and after each lightning test and at increasing intervals during the endurance test. The vibrations have been measured with a sample frequency of 2 kHz and a record length of 10 s.

From this raw data and FFT spectrum, the RMS value of the vibration was calculated by Rob Storck (THALES). After the endurance test, the bearings were disassembled and subjected to a visual inspection.

7.5.1 Conventional bearing

Lightning current tests have been performed on a greased bearing in stationary condition, and it was found that no damage occurred to rolling elements and raceways. This situation is comparable to a stationary radar, i.e. a radar which is normally rotating but is in a non-active mode. The weight of the radar is pressing through the lubricant and a direct contact between rolling elements and the raceway is made. Then no arcing is possible, and no pitting results

Figure 7-29 Pitting in the bearing due to a lightning stroke. From [THALES Nederland](#)

The effect of the lightning strike using a normal bearing is shown in Figure 7-29.

Figure 7-30 Damaged ball bearing due to a lightning stroke. From [THALES Nederland](#)

The damaged ball bearing is shown in Figure 7-30. The bearing was rotating at normal speed.

7.5.2 Pre-loaded bearing

To test the effectiveness of a spark gap, a high voltage of more than 25kV can be applied to the rotating part, with respect to the static part, while rotating the bearing. This means that the ball bearings should be covered with oil. On normal bearings it is possible to generate a spark. Using a pre-loaded bearing it was not possible to generate a spark because the bearing was causing a continuous conductive path. This was contrary to all common knowledge, namely that under any conditions the bearing rings and rolling elements are isolated from one another by either a thin film of oil or grease. Further research of THALES revealed that the possible cause could be the boundary lubrication which is available during very low speed, or during pre-loading. This is in contradiction to the common assumption that even at low speed there is film lubrication, creating an isolated layer. The concept of using a pre-loaded bearing has been filed in a patent [124].

Figure 7-31 Test setup for testing a bearing. Picture taken during the lightning test.

Figure 7-32 Schematic of test setup

A special test setup was built to test a typical pre-loaded bearing configuration under normal operating conditions, rotating at approximately 20 RPM, as shown in Figure 7-31 and Figure 7-32.

To simulate the currents typical for a lightning stroke, the setup was subjected to an A, B and C lightning pulse as mentioned in Table 7-1. The axial preload on the bearing-system was chosen for testing purposes at several tens of kN. Measurements of the bearing resistance before and after each “bang” showed values below 1 mΩ (typical between 300 and 700 μΩ). Before and after the various pulses, the operational vibrations were measured. To test the remaining operational life of the bearing system, an endurance test was also performed. Assuming that wear is equivalent to the total number of revolutions, the bearing system was set to rotate at a much higher RPM (around 120 RPM) in order to compress the total test time. The bearing temperature was monitored to assure normal operating conditions. The endurance test was stopped after 4 weeks at normal rotational speed. The RMS values of the measured vibrations during the endurance test are shown in Table 7-2.

Table 7-2: RMS values of measured vibrations during the endurance test, derived from Figure 7-33

Duration [hr]	0:31	0:58	2:04	3:37	5:52	29:52	29:52	53:52	53:52	170:58
Axial	0.790	0.775	0.769	0.807	0.796	0.777	0.826	0.793	0.740	0.714
Radial	0.400	0.406	0.424	0.641	0.613	0.627	0.510	0.502	0.456	0.429
Tangential	0.622	0.633	0.659	0.681	0.691	0.730	0.906	0.759	0.703	0.667

The differences between the subsequent measurements are of the same order of magnitude as the standard deviation of the set of measurement results. There are no differences in the shape of the spectra that might be caused by deterioration of the bearing system. Since the results of the vibration measurements indicate that bearings were not damaged, only the upper bearing of the test setup was disassembled after the endurance test. The results are shown in Figure 7-34. It is clear that the tested bearing is free of pitting or welding spots. To make a better comparison between a conventional bearing and the pre-loaded bearing, some pictures have been put together as shown in Figure 7-35, Figure 7-36, and Figure 7-37. The conventional bearing is severely damaged, and no damage can be observed on the pre-loaded bearing.

Figure 7-33 Results of vibration measurements during the endurance test.

Note: the graphs have been shifted slightly to give a 3D impression. The scales should be read as if every line starts on the bottom-left corner.

Figure 7-34 Ball bearings and bearing of the drive, using the normal pre-loaded situation: no damage. From [THALES Nederland](#)

Figure 7-35 Inner-race of bearings, left the pre-loaded, on the left side the pre-loaded bearing vs. a conventional bearing on the right side. From [THALES Nederland](#)

Figure 7-36 Outer-race of bearings, on the left side the pre-loaded bearing vs. a conventional bearing on the right side. From [THALES Nederland](#)

Figure 7-37 Rolling elements (ball bearings), left for the pre-loaded bearing and right for the conventional bearing. Picture: [THALES Nederland](#)

7.6 Summary

Throughout the years, several simulations and tests and have been performed to analyze the effectiveness of lightning protection measures. A novel conceptual idea is the use of thin metallic foils as shielding as a low-pass filter, and thus to reduce lightning induced voltages in the cables inside such a shielded structure. Aluminum and copper foils, varying from 20 μm to a couple of mm in thickness, and currently available metallic textiles have been tested. The test results show a good correlation between simulations and tests, as well as good filtering capabilities.

Another new approach for naval radar systems was to use lightning rods and diverters to protect radome-like structures. Where rods might block the visibility of the antenna, the diverters proved to be a viable solution. Various configurations have been tested with satisfactory results.

The ultimate achievement, equally new and revolutionary, was the mitigation of damage to bearings due to lightning by using pre-loaded bearings. After several tests it was possible to demonstrate the absence of any sign of damage in any of the bearing systems under test

8. Conclusion

8.1 Conclusions

This thesis presents the main parameters for lightning. Climate change is increasing the number of lightning strikes, and it is better understood now how almost all stages of a rainy day interact and influence our daily lives, as well as the objects in our daily lives. New ideas in evaluating the littoral areas have been investigated. Moving from small to big, from islands to peninsulas, and up to continents, such findings help the reader understand why we stated that the weather instability of the littoral area when compared to inland or blue water areas has increased, as well why this presents much higher risks in terms of lightning activity. It was assumed, argued, and shown from literature, that climate change will play an important role in increasing lightning activity. Thus the risk of an object being struck by lightning will increase too. New material published recently in Science magazine confirms the findings from this work.

It also brought to attention the lack of any strong documenting material directly related to the increased use of naval vessels in the littoral, as opposed to the open sea. Whereas in the ‘blue water’, i.e. oceans, the risk of lighting is very low and therefore the interest in further research was low, the extensive literature study performed revealed how the risk of lightning in the littoral was unknown. The basic standards for lightning, the IEC 62305, as well as other standards, explicitly exclude the sea and littoral environments. Through literature analysis, and confirmed by recently-published maps showing lightning density in the littoral, it is concluded that the risk of lightning in the littoral area is very similar to the risk of lightning in the continental region, and completely different from the risk of lightning in the open sea.

In the best interests of proper protection, it is essential that such concepts are mastered as the Risk evaluation (R_x), the Lightning Protection Zones (LPZs), and the Rolling Sphere Method (RSM). The same goes for the information available in the international standards covering lightning-related actions. The importance of the

position onboard of a ship, especially in relation to the height, and how this plays a role in the risk evaluation, have all been evaluated in this work.

Based on the analysis performed, with the use and application of the Rolling Sphere Method (RSM), the Lightning Protection Levels (LPLs), and Lightning Protection Zones (LPZs), it is possible to have an optimum placement of the radar system at the highest level on the deck or in a mast-like structure. By using the LPZs, the object position, and the RSM, the risk analysis was performed. Additionally, it was also determined that various similar methodologies and protection measures in use for other domains and industries can be safely applied to radar systems.

Several state-of-the-art solutions have been investigated, developed, and are currently being used as alternative direct lightning protection measures on present-day radars on naval vessels, in the aerospace domain, and for wind power installations. Two favorable conditions have been also introduced capable of providing a high degree of lightning protection. Two new approaches have been introduced, on two distinct types of antennas, offering either some proper attachment points for lightning, or an alternative current conducting path. By implementing composite materials in naval radar structures, this could eventually lead to unique solutions for every design.

The electric field generated by a lightning strike can induce negligibly small currents if metal parts are used. Unlike composites, metal parts will act as shields, while composites have no similar capabilities whatsoever. The induced voltage due to the magnetic field generated by a lightning strike is a time derivative effect, so it increases with frequency. The peak of the time derivative of this amplitude, its rise-time, determines the actual threat level, and not the peak amplitude of the lightning current. This new idea is introduced by providing sufficient shielding effectiveness to non-conducting composites through thin metal coatings. The level of protection against nearby magnetic fields of thin metal foils is known to be limited. However, it rapidly increases with the frequency and thus will ultimately act as a low-pass filter. The reduction in the rise-time is the basic argument when using thin metal shields.

Through several simulations and tests, performed as a major part of this work, various novel aspects were introduced. The attempt to use thin metallic foils as low-pass filter systems and to avoid lightning-induced effects in the cables inside, is just one of them. Together with aluminum and copper foils, varying from 20 μm to a couple of mm in thickness, currently-available metallic textiles have also been tested as alternatives to full-metal walls. A good correlation between simulations and tests

shows important filtering capabilities up to the lowest thicknesses for the foils and textiles used.

Another piece of novelty with respect to naval radar systems was the assembly of a system of lightning rods and diverters working together to protect any radome-like structure. If the visibility of the antenna might be blocked by the lightning rod, the diverters can prove to be a viable alternative. Multiple arrangements have been tested giving satisfactory results.

Another novel concept was mitigating the risk of damage due to lightning currents in bearings using pre-loaded bearings. This innovative idea is in contradiction to the conventional assumption that there is always an isolating lubricating film present between the ball bearings and the bearing. A patent has been filed. Several tests were performed to demonstrate the absence of any trace of damage in any of the pre-loaded bearing systems tested.

8.2 Recommendations

The effect of thin layers of metal and metal filaments wound into textiles to coat composite panels in order to provide shielding is a new concept, and to this extent it can be considered as having been demonstrated with this work. However, the maximum allowable cable current loop of the electronic equipment inside a composite housing has to be investigated. Of course, this maximum loop area depends on the susceptibility of the components connected. Other thin metal solutions should be investigated as well, such as metal meshes or paints.

The lightning current paths in very close proximity to radomes should be investigated to eventually optimize the design of such structures with respect to the possible blocking of the radar signals. Another issue, not covered in this thesis, is the use of isolation between parts to prevent large lightning currents. Of course, this will create a large voltage difference between the parts involved, and sparks must be prevented. But deferring current could be sometimes more useful than conducting current.

References

- [1] H. Printz – Lightning in History; Lightning, vol. 1, Physics of lightning; ed. R. H. Golde, New York: Academic Press, 1977
- [2] M.A. Uman – The Lightning Discharge, San Diego: Academic Press, 1987
- [3] C. Gary – La Foudre. Des Mythologies Antiques a la Recherche Moderne, Paris: Mason, 1994
- [4] V. Cooray – Lightning Protection, The Institute of Engineering and Technology, IET, 2010
- [5] V. Cooray – Lightning Electromagnetics, The Institute of Engineering and Technology, IET, 2012
- [6] W. S. Harris – On the protection of ships from lighting, Nautical Magazine 3, 1834
- [7] W. S. Harris – Illustrations of cases of damage by lightning in the British Navy, Nautical Magazine 3, 1839
- [8] W. S. Harris – On the Nature of Thunderstorms, London: Parker, 1843
- [9] E. P. Krider – Lightning rods of the 18th century, Proceedings of the 23rd ICLP conference, Florence – Italy, 1996
- [10] E. P. Krider – Benjamin Franklin and Lightning Rods, Physics Today – January 2006
- [11] J. Herschel – On the Lightning Spectrum, Proceedings of the Royal Society of London, Volume 17, 1868
- [12] J. Gibbons – Correspondence: Spectrum of lightning, Chemical News and Journal of Physical Science, Volume XXIII, 1871
- [13] J. W. Clark – Observations on the spectrum of sheet lightning, Chemical News and Journal of Physical Science, Vol. XXXII, 1874
- [14] A. Schuster – On Spectra of Lightning, Proceedings of the Physical Society of London, Volume 3, January 1879
- [15] V. M. Slipher – The Spectrum of Lightning, Lowell Observatory Bulletin, No. 79
- [16] W. G. Hoyt – Vesto Melvin Slipher: A Biographical Memory, National Academy of Sciences, Washington D.C., 1980
- [17] M. Dufay – Recherches sur les spectres des éclairs, deuxième partie: étude du spectre dans les régions violette et ultraviolette, Publications de l'Observatoire de Haute-Provence, Série A; no 26 ; 1949
- [18] H. Israel, G. Fries – Ein Gerat zur Spektroskopischen Analyse verschiedenen Blitzphasen, Optik, Volumen 13; 1956
- [19] R. E. Orville – A High-Speed Time-Resolved Spectroscopic Study of the lightning Return Stroke: Part 1. A Quantitative Analysis, Journal of Atmospheric Sciences, Volume 25, September 1968
- [20] M. A. Uman – Lightning, Dover Books on Earth Sciences, New York, 1984
- [21] C. V. Boys – Progressive Lightning, Proceedings of the Royal Society of London, Series A, Volume 122, 1928

- [22] B. F. J. Schonland, D. J. Malan, H. Collens – Progressive Lightning II, Proceedings of the Royal Society of London, Series A, Volume 152, 1935
- [23] D. J. Malan, H. Collens – Progressive Lightning III, Proceedings of the Royal Society of London, Series A, Volume 162, Sept 15, 1937
- [24] T. Wu, S. Yoshida, T. Ushio – The Most Powerful Lightning Discharges in Winter Thunderstorms in Japan Sea Coast, EMC 2014, Tokyo, pp. 390-393
- [25] K. Schlegel, M. Füllekrug – 50 years of Schumann Resonance, Physik in unserer Zeit, 33(6), 256-26, 2002 – via hese-project.org
- [26] G. J. Sweers – Methodology for the design assurance of aircraft lightning protection systems continued airworthiness, PhD thesis Cranfield University, 2010
- [27] J. A. Plumer, J. D. Robb – The direct effects of lightning on aircraft, IEEE Transactions on Electromagnetic Compatibility, Vol. 24, No. 2, May 1982, pp. 158-172
- [28] IEC 62305-1: 2013 Protection against lightning – Part 1: General principles, ed. 2.0
- [29] IEC 62305-2: 2013 Protection against lightning – Part 2: Risk management, ed. 2.0
- [30] IEC 62305-3: 2013 Protection against lightning – Part 3: Physical damages to structures and life hazard, ed. 2.0
- [31] IEC 62305-4: 2013 Protection against lightning – Part 4: Electrical and electronic systems within structures, ed. 2.0
- [32] P. Spichtinger, D. J. Cziczo – Aerosol – cloud interactions – a challenge for measurements and modeling at the cutting edge of cloud – climate interactions; Environmental Research Letters, 2008
- [33] R. G. Harrison, F. Märch – Heliospheric timescale identified in surface atmospheric electricity; Geophysical Research Letters, Vol. 34, 2007
- [34] G. S. Jenkins, A. S. Pratt, A. Heymsfield – Possible linkages between Saharan dust and tropical cyclone rain band invigoration in the eastern Atlantic during NAMMA – 06; Geophysical Research Letters
- [35] B. A. Tinsley – The global atmospheric electric circuit and its effects on cloud microphysics; Reports On Progress In Physics, Vol. 71, 2008
- [36] M. J. Rycroft, S. Israelsson, C. Price – The global atmospheric electric circuit, solar activity and climate change, Journal of Atmospheric and Solar-Terrestrial Physics 62, 2000, pp. 1563–1576
- [37] K. L. Aplin, R. G. Harrison, M. J. Rycroft – Investigating Earth’s Atmospheric Electricity: a role model for planetary studies; Space Science Review, Vol. 137, 2008
- [38] M. J. Rycroft, R. J. Harrison, K. A. Nicoll, E. A. Mareev – An overview of Earth’s global electric circuit and atmospheric conductivity; Space Science Review, Vol. 137, 2008
- [39] R. G. Harrison, K. L. Aplin, F. Leblanc, Y. Yair – Planetary Atmospheric Electricity; Space Science Review, Vol. 137, 2008
- [40] C. D. Ahrens – Meteorology today, an introduction to weather, climate, and the environment, Brooks/Cole, 9th ed. 2007
- [41] G. A. Bazilevskaya, I. G. Usoskin, E. Flückiger et al. – Cosmic ray induced ion production in terrestrial and planetary atmospheres. Space Science Review, Vol. 137, 2008
- [42] I. M. Brooks, C. P. R. Saunders, R. P. Mitzeva, S. L. Peck – The effect on thunderstorm charging of the rate of rime accretion by graupel; Journal of Atmospheric Research, Vol. 43, Issue 3, March 1997

- [43] R. A. Black, J. Hallet – Electrification of the Hurricane; *Journal of Atmospheric Sciences*, Vol. 56, Issue 12, 15 June 1999
- [44] Y. Yair – Charge generation and Separation Processes; *Space Science Review*, Vol. 137, 2008
- [45] O. Ataratz, O. T. Raisin, Z. Levin – Simulation of the electrification of winter thunderclouds using the three-dimensional Regional Atmospheric Modeling System (RAMS) model: Single cloud simulations; *Geophysical Research Letters*, Vol. 110, 2005
- [46] P. Alpert, T. Ben-Gai, A. Baharad, Y. Benjamini, D. Yekutieli, M. Calacino, L. Diodato, C. Ramis, V. Homar, R. Romero, S. Michaelides, A. Manes – The paradoxical increase of Mediterranean extreme daily rainfall in spite of decrease in total values; *Geophysical Research Letters*, Vol. 29, 2002
- [47] E. R. Mansel, D. R. McGorman, L. Ziegler, J. M. Straka – Charge structure and lightning sensitivity in a simulated multicell thunderstorm; *Journal of Geophysical Research*, Vol. 110, 2005
- [48] E. A. Mareev – Formation of Charge Layers in the Planetary Atmospheres; *Space Science Review*, Vol. 137, 2008
- [49] R. Markson – The global circuit intensity; *Bulletin of the American Mathematical Society*, Vol. 88, 2007
- [50] H. R. Pruppacher, J. D. Klett – *Microphysics of cloud and precipitation*; Reidel, Dordrecht, 1978
- [51] C. Price – Thunderstorms, Lightning and Climate Change; 29th ICLP Proceedings, June 2008
- [52] K. Sassen, V. I. Khvorostyanov – Cloud effects from boreal forest fire smoke: evidence for ice nucleation from polarization lidar data and cloud model simulations; *Environmental Research Letters*, Vol. 3, May 2008
- [53] W. A. Fernandes, I. R. C. A. Pinto, O. Jr. Pinto, K. M. Longo, S. R. Freitas – New findings about the influence of smoke from fires on the cloud -to - ground lightning characteristics in the Amazon region; *Geophysical Research Letters*, Vol. 33, 2006
- [54] B. A. Tinsley, L. Zhou – Initial results of a global circuit model with stratospheric and tropospheric aerosols; *Journal of Geophysical Research*, Vol. 111, 2006
- [55] R. A. Treumann, Z. Klos, M. Parrot – Physics of electric discharges in atmospheric gases: An informal introduction; *Space Science Review*, Vol. 137, 2008
- [56] E. R. Williams – Lightning and climate: a review; *Journal of Atmospheric Research*, Vol. 76, 2005
- [57] M. A. Lemone, E. J. Zipser – Cumulonimbus vertical velocity events in GATE. Part 1: Diameter, intensity and mass flux; *Journal of Atmospheric Science*, Vol. 37, 1980
- [58] R. Mitzeva, J. Latham, S. Petrova – A comparative modeling study of the early electrical development of maritime and continental thunderstorms; *Atmospheric Research*, Vol. 82, 2006
- [59] D. M. Romps, J. T. Seeley, D. Vollaro, J. Molinari – Projected increase in lightning strikes in the United States due to global warming, *Science*, Volume 346, Number 6211, Nov. 2014, pp. 851-854
- [60] M. A. Blaj, F.B.J. Leferink – A model for lightning in littoral areas; *International Conference on Lightning and Static Electricity*, 15-17 September 2009, Pittsfield MA, U.S.A.

- [61] IEC 61000-2-5 Electromagnetic Compatibility (EMC); Part 2 – Environment; Section 5 – Classification of electromagnetic environments, IEC, Sept. 1st. 1995
- [62] Jayakuma – Estimating power, energy, and action integral in rocket-triggered lightning, University of Florida, 2004
- [63] A. J. Eriksson – The incidence of lightning strikes to power lines; IEEE Transactions, PWRD - 2, 1987
- [64] R. B. Anderson, A. J. Eriksson, H. Kroninger, D. V. Meal, M. A. Smith – Lightning and thunderstorm parameters; Proceedings of International Conference on Lightning and Power Systems, 5-7 June, 1984
- [65] J. T. Whitehead – Estimating lightning performance of transmission lines II - updates to analytical model; Proceedings of Asia - Pacific International Symposium on Electromagnetic Compatibility, 12 - 16 April, 2010
- [66] C. A. Nucci – A survey on Cigré and IEEE procedures for the estimation of the lightning performance of overhead transmission and distribution lines, Oct. 1991
- [67] MIL STD 461F - Requirements for the control of electromagnetic interference characteristics of subsystems and equipment; Department of Defense, Dec. 2007
- [68] MIL STD 464 - Electromagnetic environmental effects requirements for systems; Department of Defense, March. 1997
- [69] NFPA 780: Standard for the Installation of Lightning Protection Systems, NFPA, 2000
- [70] SAE ARP5414: Aircraft Lightning Zoning, SAE Technical Standards, Feb. 2005
- [71] RTCA/DO 160 - F: Environmental Conditions and Test Procedures for Airborne Equipment, Sections 22.0 & 23.0, RTCA Inc., Dec. 2007
- [72] EN 50164: Lightning protection components (LPC); Part 1 - 7; European Committee for Electrotechnical Standardization (CENELEC); 2008
- [73] IEC 62561: Lightning protection system components (LPSC); Part 4 - 6, IEC, Nov. 2010 - Jun. 2011
- [74] Eritech® Lightning Protection Handbook; ERICO International Corporation, 2009
- [75] S. Grzybowski – Experimental evaluation of lightning protection zone used on ship. May 2007, IEEE Electric Ship Technologies International Symposium, pg. 215 – 220
- [76] <http://www.furse.com/pub/en/home>
- [77] M. Becerra, F. Roman, V. Cooray – Lightning attachment to common structures: Is the rolling sphere method really adequate? June 2008, ICLP 2008 International Symposium
- [78] S. Ait - Amar, G. Berger – A modified version of the Rolling Sphere Theory. June 2008, ICLP 2008 International Symposium
- [79] M. A. Blaj, F. J. K. Buesink, G. C. Damstra, F. B. J. Leferink – Lightning current tests to evaluate vulnerability of electronics in composite structures. Sept 2010. 9th International Symposium on EMC and 20th International Wroclaw Symposium on Electromagnetic Compatibility, Wroclaw, Poland; pp. 579-582
- [80] IEC 61400 – 1: Wind turbines, Part 1: Design requirements; IEC; Edition 3.0; August 2005
- [81] IEC 61400 – 24: Wind turbines; Part 24 – Lightning protection, IEC, August 2010
- [82] V. Cooray – The lightning flash, IET Power and energy series nr. 34; 2008 republished
- [83] C. Gomes, M.Z.A Ab Kadir – Protection of naval systems against electromagnetic effects due to lightning, Progress in Electromagnetic Research, Vol. 113 / 2011
- [84] F. Rachidi, C.A. Nucci, M. Ianoz, C. Mazzetti – Influence of lossy ground on lightning induced voltages on overhead lines, IEEE Transactions on EMC, Vol. 38 / 1996

- [85] F. Rachidi, C.A. Nucci, M. Ianoz – Transient analysis of Multiconductor lines above a lossy ground, *IEEE Transactions on Power Delivery*, Vol. 14 / 1999
- [86] C.A. Nucci, F. Rachidi, M. Ianoz, C. Mazzetti – Lightning induced voltages on Overhead lines, *IEEE Transactions on EMC*, Vol. 35 / 1995
- [87] C.A. Nucci – Lightning induced voltages on distribution systems: Influence of ground resistivity and system topology, *Journal of Lightning Research*, Vol. 1 / 2007
- [88] J.G. Harrington, R.B. Schulz – Design of minimum weight and maximum effectiveness of very-low-frequency shielding; *IEEE Transactions on EMC*, Vol. 10 / 1968
- [89] F.J.K. Buesink – “Theory of screened enclosures”; ECC Thomson CSF Signaal, 2000
- [90] G. Bargboer – Measurements and modeling of EMC, applied to cabling and wiring, PhD thesis Technical University of Eindhoven, the Netherlands, 2011
- [91] Defence Standard 02-516, Guide to Lightning Protection in HM Surface Ships, Issue 2 ,16 July 2003
- [92] M. A. Blaj, F. Wagenaar, F. J. K. Buesink, G. C. Damstra, F. B. J. Leferink – Lightning current test on radar system. *Proceedings of International Symposium on EMC*, 8-12 Sept 2008, Hamburg, Germany. pp. 281-284. Hamburg
- [93] M. A. Blaj, F. J. K. Buesink, G. C. Damstra, F. B. J. Leferink – Lightning protecting materials used on Radar Systems; September 2009, *ICOLSE 2009 International Symposium*, pg. 1 – 4
- [94] Sampson Active Electronic Scanned Array (AESA) Radar – BAE Systems (<http://www.baesystems.com/index.htm>)
- [95] Thales Integrated Masts Series (<http://www.thalesgroup.com/integratedmast/>)
- [96] A. Hall – Thunderstorm protection of aircraft radomes; September 2005, *ICOLSE 2005 International Symposium*
- [97] F. Rachidi, M. Rubinstein, J. Montanya, J-L Bermudez, R. R. Sola, G. Sola, N. Korovkin – A review of current issues in lightning protection of new generation wind turbine blades; *IEEE Transactions on industrial electronics*; Vol. 55; No. 6; June 2008
- [98] T. Sorensen, I. Cotton, B. McNiff, W. Zischank, P. Christiansen, M. Hoppe – Kilpper, E. Muljadi, S. Ramakers – The Update of IEC 62305 – 24 Lightning protection for wind turbines; June 2008; *ICLP 2008 International Conference*
- [99] V. Peesapati, I. Cotton – Lightning protection of wind turbines — A comparison of lightning data & IEC 61400-24; April 2009; *SUPRAGEN 2009 International Conference*
- [100] P. Y. Okyere, G. Edfu – Evaluation of Rolling Sphere Method Using Leader Potential Concept: A case study; *Proceedings of the 2006 IJME – INTERTECH Conference*
- [101] G. C. Damstra, J. A. J. Pettinga – Combined sources for lightning current tests. September 1989, *Proceeding of the Sixth International Symposium on High Voltage Engineering*, pg. 1 – 4
- [102] N. I. Petrov, A. Haddad, G. N. Petrova, H. Griffiths, R. T. Waters – Study of effects of lightning strikes to an aircraft; Published: February 24, 2012 in "Recent Advances in Aircraft Technology", book edited by Ramesh K. Agarwal
- [103] M. Uman, V. Rakov — The interaction of lightning with airborne vehicles; Published: January 2003 in *Progress Aerospace Sciences*, Vol.39, No 1, pp. 61-81
- [104] T. Sorensen, F. V. Jensen, N. Raben, J. Lykkegaard, J. Saxov — Lightning protection for offshore wind turbines, in *Proc. CIRED 16th Int. Conf. Exhib. Electricity Distrib. (IEE Conf. Publ. No. 482)*, Jun. 18–21, 2001, vol. 4, p. 1–5

- [105] Wind Power Annual statistics – The European Wind Energy Association (ewea): http://www.ewea.org/fileadmin/files/library/publications/statistics/Wind_in_power_annual_statistics_2012.pdf
- [106] Technical note "Lightning effects on rotating gearbox roller bearings under hydrodynamic conditions", RTD Program JOR3-CT95-0052, "Lightning protection of wind turbines", 26 Feb. 1998
- [107] A. Cheng — Lightning plays the stadium, Mechanical Engineering magazine, Feb. 2002
- [108] NASA Engineering and Safety Center Technical Consultation Report RP-06-39, Kennedy Space Center (KSC) Pad B Catenary Capability Analysis and Technical Exchange Meeting (TEM) Support, July 16, 2006
- [109] V. A. Rakov, M. A. Uman — Lightning: Physics and Effects, Cambridge University Press, New York, 2003
- [110] STANAG 4370, AECTP 250, Leaflet 254 — Atmospheric electricity and lightning
- [111] IEC 61000 – Part 4 Sect. 5 – Ed. 2.0 – EMC – Testing and measurement techniques – Surge immunity test
- [112] IEC 61000 – Part 4 Sect. 9 – Ed. 1.0 – EMC – Testing and measurement techniques – Pulse magnetic field immunity test
- [113] IEC 61000 – Part 4 Sect. 10 – Ed. 1.0 – EMC – Testing and measurement techniques – Damped oscillatory magnetic field immunity test
- [114] S. F. Maden — Interaction between electrical discharges and materials for wind turbine blades, particularly related to lightning protection, PhD Project 2004-2007, Technical University Denmark, DTU, Electrical Power Engineering
- [115] ECN workshop Harmonisatie en Differentiatie Windenergie 2000, ECN-C-01-025, Chapter 5 — Bliksembescherming van windturbines en systemen
- [116] NATO Advisory Group for Aerospace Research and Development, AGARD-CP-283 — Electromagnetic Effects of (Carbon) Composite Materials upon Avionics Systems
- [117] NATO ANEP 45 (Allied Naval Engineering procedure), Chapter 2
- [118] Cobham Lightning Testing Services — <http://www.cobham.com/about-cobham/aerospace-and-security/about-us/antenna-systems/specialist-technical-services-and-software/products-and-services/lightning-testing-services.aspx>
- [119] A. Jazzar, E. Clavel, G. Meunier, E. Vialardi — Study of Lightning Effects on Aircraft With Predominately Composite Structures, IEEE Transaction on Electromagnetic Compatibility, Vol. 56, No. 3, June 2014, pp. 675-682
- [120] F. Rachidi — A review of field-to-transmission line coupling models with special emphasis to lightning-induced voltages on overhead lines, IEEE Transactions on Electromagnetic Compatibility, Vol. 54, No. 4, August 2012, pp. 898 – 911
- [121] A. K. Agrawal, H. J. Price, and S. H. Gurbaxani — Transient response of multiconductor transmission lines excited by a nonuniform electromagnetic field, IEEE Trans. Electromagn. Compat., vol. 22, no. 2, pp. 119–129, May 1980
- [122] C. R. Paul — Analysis of Multiconductor Transmission Lines, New York, Wiley, 1994
- [123] M. A. Blaj, F. J. K. Buesink, G. C. Damstra, F. B. J. Leferink — Using thin metal layers on composite structures for shielding the electromagnetic pulse caused by nearby lightning, Proc. of the 10th Int. Symposium on Electromagnetic Compatibility (EMC Europe 2011), York, UK, September 26-30, 2011, pp. 440-444

- [124] EP2607727A1 — European patent Application, Pivot linking device with bearings comprising means for protection against high voltage transients, 21 December 2011
- [125] The daily beast — <http://www.thedailybeast.com/articles/2013/04/14/benjamin-franklin-america-s-first-storm-chaser.html>
- [126] Los Alamos National Laboratory (LANL) — <http://wsx.lanl.gov/images/lightning3.gif>
- [127] M. Lach — <http://martinlweather.blogspot.nl/2011/07/lightning-and-thunder.html>
- [128] M. Wenjen — <http://www.pragmaticmom.com/2011/11/weather-atmospheric-pressure-complicated-relationship/>
- [129] Pacific Northwest National Laboratory (PNNL) — http://www.pnl.gov/atmospheric/research/aci/aci_aerosol_indeffects.stm
- [130] Encyclopedia Britannica — <http://media-2.web.britannica.com/eb-media/78/7578-004-7C794BAD.gif>
- [131] NSSTC Lightning Team (NASA) — http://science.nasa.gov/media/medialibrary/2001/12/02/ast05dec_1_resources/lightningmap_large.gif
- [132] EUCLID — <http://www.euclid.org/realtime.html>
- [133] Astrogenic Systems — <http://www.strikestarus.com>
- [134] Wikipedia — [http://nl.wikipedia.org/wiki/Abraham_Crijnsen_\(fregat_uit_1983\)](http://nl.wikipedia.org/wiki/Abraham_Crijnsen_(fregat_uit_1983))
- [135] J. Nielsen — <http://airlinepilotguy.com/wp-content/uploads/2012/11/Radome.jpg>
- [136] S. Weart — The discovery of global warming, Harvard Univ. Press, rev. Ed. 2008
- [137] K. Miyake, T. Suzuki, K. Shinjou – Characteristics of winter lightning current on Japan sea coast, IEEE Transactions on Power Delivery, Vol. 7, No. 3, July 1992
- [138] The European Commission in the framework of the Non-Nuclear Energy Program JOULE III — Lightning Protection of Wind Turbines, Contract JOR3-CT95-0052, Publishable Final Report
- [139] M. Durstewitz, C. Ensslin, B. Hahn, K. Rohrig — +15 years practical experiences with wind power in Germany, <http://www.iset.uni-kassel.de>
- [140] M. I. Lorentzou, N. D. Hatziaargyriou, I. Cotton — Key Issues in Lightning Protection of Wind Turbines, WSEAS Conferences, Athens, Greece, 2004
- [141] F. B. J. Leferink, M. A. Blaj, E. Hogeman, R. Storck — Using Preloading to Protect Bearings against Lightning Damage, 2015 International Symposium on Lightning Protection (XIII SIPDA), Balneário Camboriú, Brazil, 28th Sept. – 2nd Oct. 2015

Acknowledgements

I would like to take this opportunity to say a “thank you” to all those who have made this possible. I would like to thank both the organizations and each and every person who has contributed in some way to this work.

With respect to organizations, my thankful recognition goes to Thales Nederland for providing not only the demand but also the financial support for this work. And Twente University for providing the infrastructure to allow me to investigate all these facts.

With respect to people, I want to start by offering my sincere appreciation to both my supervisors, Prof. Frank B.J. Leferink, and Prof. Damstra. Without their encouragement, guidance, passion, and patience, we would not have reached this far. I also want to thank Frits J.K. Buesink for his immense contribution throughout my work. His assistance and contributions when I was struggling with the theoretical approach to this work were priceless.

Rob Storck and all the mechanical knowledge he brought to this work, and his support building the bearing test setup, was the help we never knew was needed when starting an electrical-related work like this.

Lilian and Annemiek, our secretaries, each and every one earned my appreciation for making me feel at home, away from home, as well as for being there for me, through the good times and the bad times.

Riel, Jan F., Jan P., Peter, our team at Stichting Floris Hazemeijer, you all have my gratitude.

Last but not least, I want to extend my gratitude to my family. All those sleepless nights preparing the test setup, the conference papers, and this manuscript, impacted our interaction many times. However, the support of my wife, and the rest of the family, was always there. You deserve this “thank you” a lot.

Biography

Mihai Alexandru Blaj, Alex, (15.11.1981) arrived at the University of Twente after several years of mixing programs in both academia and in industrial environments all to the benefit of his career. During the time spent working on his postgraduate education, for the Bachelor's degree in particular, Alex began his professional career at an engineering firm, an activity he continued throughout the Master's program. In combination with the Bachelor and Master thesis he wrote, he was able to publish a first journal paper in his native country Romania, in the local Journal of Electrical Engineering, and wrote an extensive report on improving the catenary-pantograph interaction during his internship at Université Blaise Pascal, in Clermont-Ferrand, France. It was at that moment, in France, that his first contact with the University of Twente took place and set the foundation for this PhD program that is now concluded.

Among the achievements at University of Twente are several successful presentations and publications at various scientific conferences, in Europe and in the US, on the topic of lightning protection. These conferences include the EMC Europe conference and workshop, the ICLP (International Conference on Lightning Protection,), and the ICOLSE (International Conference on Lightning and Static Electricity) conferences.

Outside academia he began a consultancy career prospecting for customers in the fields of EMC, product compliance certification with international standards, energy conversion and UPS, and power distribution networks.

In what is left of his time, Alex enjoys traveling, as often as possible, both for work and for leisure, various sports activities, including snowboarding and swimming, and reading a good book. All these, of course, in the company of his family and friends.