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Verification Protocols for the Lightning Protection of a Large Scale Scientific Instrument in Harsh Environments: A Case Study

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Abstract

This paper is devoted to the study of the most suitable protocols needed to verify the lightning protection and ground resistance quality in a large-scale scientific facility located on a site with high risk of lightning strikes. We illustrate this work by reviewing a case study: the largest telescopes of the Northern Hemisphere Cherenkov Telescope Array, CTA-N. This array hosts sensitive and high-speed optoelectronics instrumentation and sits on a clear, free from obstacle terrain at around 2400 m above sea level. The site offers a top-quality sky but also features challenging conditions for a lightning protection system: the terrain is volcanic and has electrical resistivities well above 1 kOhm·m. In addition, the environment often exhibits humidities well below 5%, and strong winds pose challenging conditions. On the other hand, the high complexity of a Cherenkov telescope structure does not allow a straightforward application of lightning protection standards. We describe here how the risk assessment of direct strike impacts was made and how contact voltages and ground system were both tested. Finite Element Simulation (COMSOL Multiphysics) has been used to estimate the current flowing through the parts of the earthing system designed for the telescopes in the case of a direct strike impact. This work is intended to provide assistance to scientists and managers involved in the construction of scientific installations, particularly those in charge of defining verifiable reliability and safety requirements for lightning protection.

Keywords

Lightning Protection, Earth Resistance, FEM, COMSOL

1. Introduction

Specific standards are available to provide guidelines on lightning protection strategies. While NFPA 780 standard means to regulate the lightning protection systems in USA [1], in European installations the following two international standards are well known: IEC 62305 [2], which establishes the installation commitment of a lightning protection system, and IEC 62561 [3], which focuses on the components of lightning protection. The requirements of the EN 50536 standard [4], which determines the installation commitment of storm detectors, as well as the main characteristics thereof, must also be met. Also in some cases local standards must be considered.

While all these standards provide valuable information, they are mostly focused on the analysis of buildings and industrial installations, and some peculiarities of scientific installations are not always well covered by them. In particular, we focus this work on the risk and earth quality assessments, and apply this to an example of a large scale scientific installation: the largest telescopes of CTA-N observatory.

CTA-N has been conceived as an array of fourteen Cherenkov Telescopes of two different sizes, which will be constructed in La Palma Island, Spain. Cherenkov Telescopes can provide valuable information on different astrophysical sources from the gamma rays reaching the Earth's atmosphere. The largest telescopes of CTA are called Large Size Telescopes (LST's) and the construction of the first one was finished in October 2018. The design and construction of the LST Lightning Protection System faced a number of technical difficulties that were addressed with the protocols described in this paper.

2. Risk Assessment

Risk assessments for lightning protection must quantify the exposure of structures, their contents, their internal systems and involved individuals to direct and indirect lightning strikes. The assessment described in IEC 62305-2 Ed.2:2010-12 [5] was taken as baseline reference for the definition of the protocols described here. Two main types of loss apply to a large scale facility:

- Loss or injury of human life;
- Economic losses.

The risk calculation was carried out by analyzing two major points:

- Probability of direct strike impact;
- Severity of the damage.

The calculation of the probability of direct strike impact was made via the models available of international standards. These models typically make use of tabulated values of the average annual lightning flash density per square kilometer in the area, and take into account local parameters like the height of the structure and that of surrounding objects. However, a more convincing alternative for large scale facilities which must not comply with specific, rigid regulations might be the use of worldwide databases of strikes which take data from an array of ground sensors and are updated on real time [6] [7].

A systematic evaluation of the damage severity started with a preparation of a list of most feared events, which was based on:

- A mature Product Breakdown Structure, which enables one to identify the critical parts and their interfaces.
- An accurate cost model which accounts not only for the cost of the damaged item but also for the cost of the replacement. This is particularly relevant when the Installation is located in an area of difficult access.
- A basic knowledge of the foreseeable damage on subassemblies under risk, which should be supported by a reliability model, a failure analysis and lightning strike resilience tests made in a certified laboratory.

The rating of the most feared events must be performed with suitable risks scales. Large scale facilities are typically handled by wider scope risks plans and analyses, and therefore it is advisable to develop risks scales which harmonize with the other type of risks analyzed during the design stage: technical, economical, schedule, managerial, etc. [8].

The outcome of the risk assessment was followed by a decision-taking process in which a specific level of protection is approved. The physical implementation of the corresponding lightning strike protection system is then part of an iterative process in which a preliminary design must be reviewed and validated within a framework of requirements in terms of cost, schedule and technical feasibility.

CTA-N site was chosen for its suitability to astronomical observations, being free from terrain obstacles. Located at around 2400 m above sea level, it offers a top-quality sky but also features challenging conditions for a lightning protection system: the terrain is volcanic and features a high resistivity, in the kOhm·m range. The relevant ambient conditions to be considered for design and selection of materials are:

- Ambient temperature −20 to +40˚C
- Humidity 2% to 100% RH
- Extreme ice (snow covered) of <20 mm (see also picture below)
- Wind gusts up to 200 km/h
- Reduced pressure and air density as applicable at 2400 m altitude
- Increased solar radiation and exposure to UV as applicable at 2400 m altitude. Components used for the lightning protection must be resistant to UV radiation, especially plastics.

Due to solar radiation, the temperature of components can become significantly higher than the maximum air temperature. Component temperatures depend very much on their thermo-elastic properties resulting from their color and their surface finish. Component temperatures up to 100˚C are possible during hot summer days. On the other hand, due to thermal radiation to cold sky, the temperature of components can also become significantly lower than the minimum air temperature. Depending on their surface finish, component temperatures can be as low as −40˚C. During winter ice pile up may become a serious issue, especially for slender component. This happens occasionally.

In CTA, a failure or a damage of one telescope does not significantly influence the availability of the whole CTA system. This means, that an outage of one telescope due to a lightning strike does not have significant consequences, also not economically, for the whole operation process of CTA. In case of such an outage only the damage costs of the telescope being struck are to be considered for the economic losses. No follow-on costs exist.

The probability of direct strike was estimated from the database of Vaisala, where the strikes on a 10 km × 10 km area around the LST site were analyzed. A total of 138 strikes were registered from 2013 to 2017, with peak current densities ranging from 3.1 kA to 693.5 kA. We estimated a probability of one impact on one LST per 88 years by using the IEC-62305-2 standard model and Vaisala data. A probability of one impact per 25 years was obtained when using the same model but with the tabulated lightning flashes per km^2 per year that is assigned by this standard to Canary Islands.

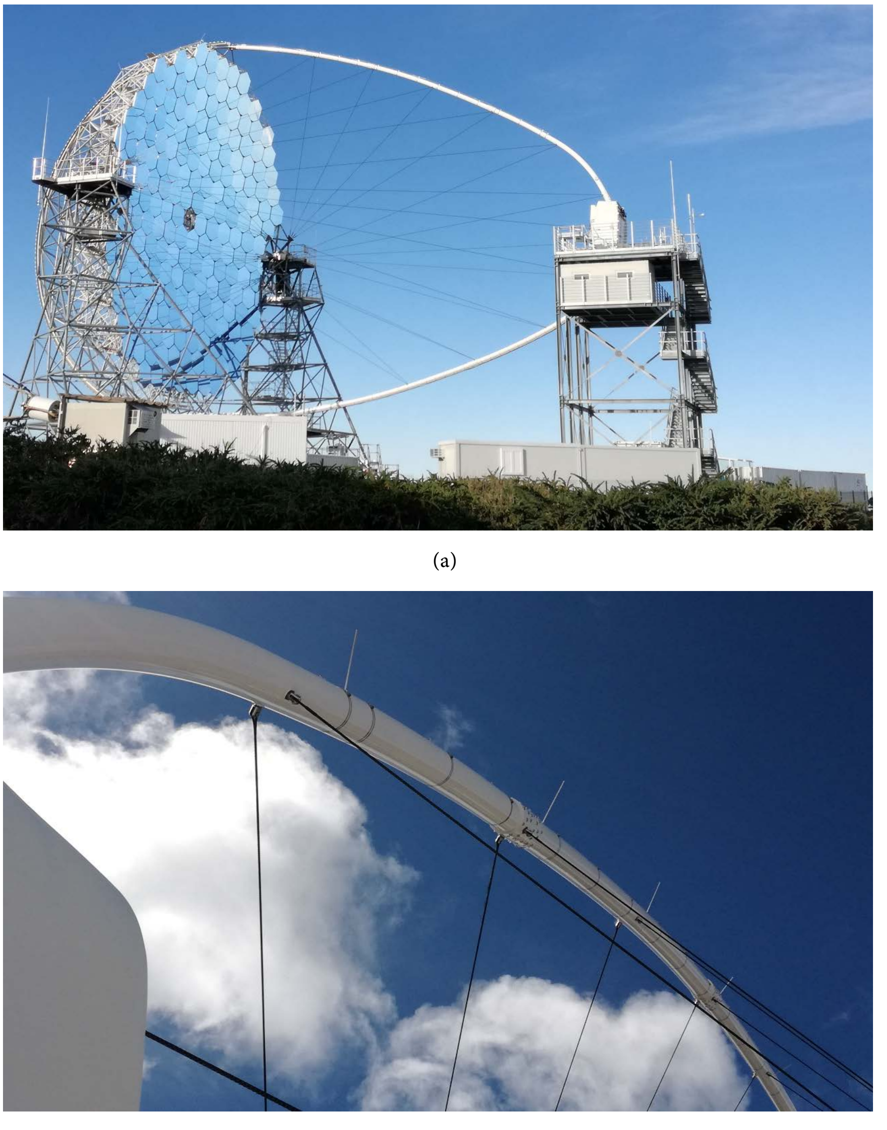
The result of the risk assessment concluded that the following protection measures were needed:

- A lightning protection system class III according to IEC standards, integrated in the LST structure;
- A certain shielding effectiveness of all the cabling and the electrical components (housings) on the telescope;
- Two level surge protection system at all cables entering the telescopes from the outside (equipotential bonding).

3. LST Lightning Protection System

The LSTs are the most complex and highest structures of the CTA Observatories. These instruments measure the Cherenkov light from an Extensive Air Shower generated by the interaction of very high energy gamma rays from the Universe in the upper atmosphere. An LST has a shape which resembles a large parabolic antenna, with a 23-meter reflective surface supported by a tubular structure made of carbon fibers and steel tubes. The reflective surface has 370 square meters and is made of an array of segmented mirrors that can be controlled individually by a subsystem of actuators. This surface collects and focuses the Cherenkov photons into the Camera, where 1855 photo-sensors convert the light in electrical signals that can be processed by dedicated electronics. The total moving weight of the telescope (excluding the rail) is around 100 tons. The dish is the support for all the elements of the LST segmented mirror and is designed to house 207 hexagonal mirror facets. The basic elements of the space frame are tetrahedral structures of Carbon Fiber Reinforced Polymer (CFRP) tubes of 60, 80 and 100 mm diameter.

Using Monte Carlo simulations, the sensitivity of the CTA Observatories were optimized between 20 and 200 GeV with a design of four LSTs of 28 m focal length. Figure 1 shows a picture of the first LST (LST1) constructed in Spain, together with a detail of the implemented Lightning Protection System. The high complexity of a Cherenkov telescope structure does not allow a straightforward application of lightning protection standards for accurate predictions of direct strike probabilities. The LST is an alt-azimuth telescope with a parabolic reflective surface, as can be seen in Figure 1(a). It is supported by a tubular structure made of CFRP, aluminum and steel tubes. The Camera Support Structure is stiffened by 26 tension cables produced by filament winding process. The main purpose of the tension cables is to limit the out-of-plane deformations. They have a cross section of 130 mm^2 and their length can vary between 17 m and 28.6 m. The installation of the mechanical structure, optics and camera started in July 2017 and was finished in 15 months.



(a)

(b)

Figure 1. The first LST of the CTA-North observatory (a), and detail of the lightning rods installed on the Camera Support Arch Structure (b).

Preliminary studies of the lightning protection system were performed based on an array of four standalone lightning rods surrounding the telescope structure. The efficiency of this system was studied by the Dynamic Electro-Geometrical Model (DEGM). The studies led to the conclusion that better efficiencies were possible by integrating an array of rods in the own telescope. The final design of the lightning protection system was carried out by the Rolling Sphere Method developed by Ralph H. Lee in 1977 for shielding buildings and industrial plants [9]. This method was extended by J.T. Orrell for use in substation design [10], and it is based on the principles and theories by Whitehead [11]. It is widely used in a number of standards, such as the IEEE Guide for Direct Lightning Stroke Shielding of Substations, the BS-EN/IEC 62305 or the NFPA 780 lightning protection standards, among others. The technique involves rolling an imaginary sphere over the surface to be protected. The sphere rolls up and over lightning masts, shield wires, fences, and other grounded metal objects intended for lightning shielding. A piece of equipment is protected from a direct stroke if it remains untouched by the sphere. Equipment that touches the sphere or penetrates its surface is not protected. This method meets different protection levels depending on the radius of the sphere.

The arch used for the camera support contains an array of air-termination rods having a length of 0.5 m which are angled with 45˚ to both sides to enlarge the protection area. The rods are fixed every 6 m from the camera up to the metal rail of the telescope base, passing by the upper arch and the periphery of the telescope dish. The carbon fiber parts of the dish were protected by a conductor around both edges. Half circumference down to the elevation platform was considered sufficient. The conductors are connected on top to the elevation arch and on bottom to the housing of the elevation bearing. The mirrors are sufficiently protected by the dish and the arch conductors. The elevation bearings were bridged by flexible strips at both sides. At each side two strips are connected between the metallic parts of the optical support structure and the tower head across the bearings. In this way the strips allow the elevation movement of the telescope dish. The lightning current from the telescope structure rods is guided to earth via both East and West side elevation platforms. Each of the two towers of the elevation system as well as the camera maintenance tower are protected by two four-meter lightning rods.

The lower structure is built with highly conductive materials and serves well to safely guide the excess lightning current to earth. However, in order to provide a clear electrical continuity, extra down conductors from the elevation bearings were installed and fed down to the azimuth locking system, where they are connected to earth.

The following Surge Protection Devices (SPD) were installed on various systems:

- SPD type 1 consists on a single-phase SPD that can also be used as 3-phase N AC network protection. It is used as primary protection, installed in the main panel power supply systems (it is DIN rail compatible). The installation of this device is compulsory according to EN 62305 and EN 60360 standards, and it can derive to ground currents up to 100 kA.

- SPD type 2 is dedicated to protect the most sensitive equipment. It can be used in common or differential mode, and provides protection against high currents up to 40 kA. It is installed in the diverted panels, close to the vulnerable equipment. It is DIN rail compatible.
- Specific SPDs were installed on telecommunication panels, data lines and low voltage distribution systems.

4. Specific Tests on Critical Components

The evaluation of the damage strike severity was made after the Failure Mode and Criticality Analysis of the whole telescope, and specific tests on the following critical elements:

- Mirror actuators, which are sensitive to possible damage by the induction of Electromagnetic Fields generated by the lightning currents.
- CFRP tubes, which might be impacted by a direct strike.

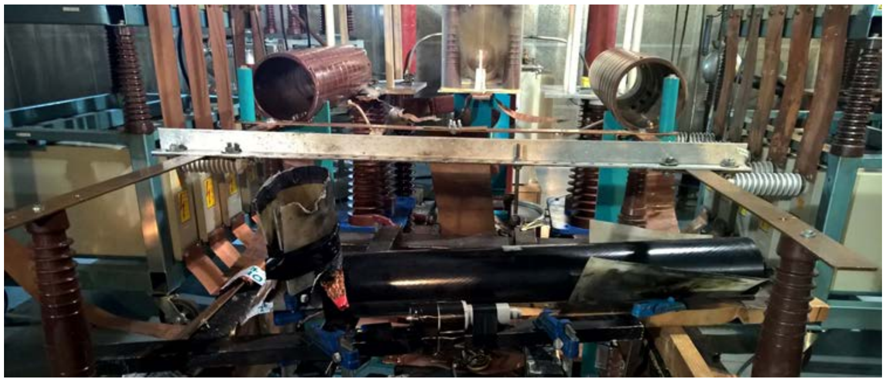
The definition of the most suitable protocol to assess the damage suffered by the actuators was a major issue. High quality studies on the lightning strike current waveforms can be found in [12]. Several standards propose models for lightning strikes current pulses. IEC-62305-1 suggests a 10/350μs current wave as reference for tests [13]. It simulates the first return stroke of a lightning event with a triangular like pulse where the rise time is 10 μs and the time to drop to 50% of the peak amplitude is 350 μs. Another widely used standard in Aircraft Lightning Tests is the EUROCAE-ED-84/ARP5412 [14].

The current strike tests were made at the high current facility of the Official Central Laboratory for Electrotechnic Tests (LCOE). **Figure 2** shows the result of the impact of a positive 200 kA strike on a sample of a CFRP tube using EUROCAE-ED-84 standard. Verification of Electromagnetic Pulse induction on the actuators was also made. The tests were made without energizing the actuator, which showed no damage after the strike.

The assumption that the actuator is not energized during a true lightning strike is justified by the fact that during storms these actuators are switched off. The resilience of the CFRP to the lightning strike was excellent due to the large conductivity of the material. Given the fact that the structural analysis of the telescope demonstrated that no single failures of a CFRP compromise the mechanical stability, these high current tests were an objective evidence that the risk of strikes on the structure is acceptable.

5. Foundation Earth Resistance and Soil Resistivity

Figure 3 shows the base structure and a detail of the LST1 foundation, which is made of reinforced concrete. The foundation of the remaining telescopes will have a very similar design but they will be dimensioned according to the specific conditions of the soil. The Rail is fixed to the foundation by means of a pedestal,

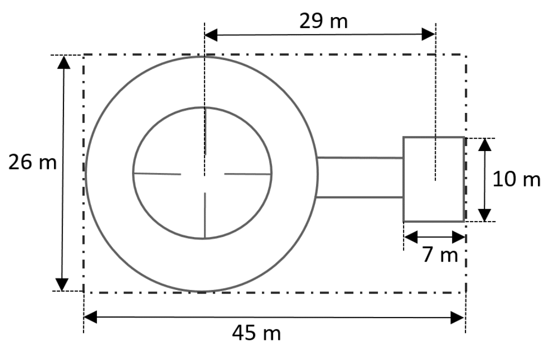


(a)

(b)

Figure 2. Detail of the damage made to a sample of CFRP by a strike with a peak current of 200 kA, by using the protocol described in EUROCAE-ED-84/ARP5412 standards at LCOE laboratories. Overview of the experimental setup where the yellow arrow indicates the place where the controlled impact of the current strike was applied to the carbon fiber (a), and detail of the damage produced after the strike (b). The actuators were located nearby to assess the robustness of the electronics to the electromagnetic field induced by the current strike.

(a)



(b)

Figure 3. LST1 Foundation: Schematics showing the size of the foundation ground, which was connected to the camera access tower ground (a), and foundation structure (b).

a curved I-beam. The I-beam is fixed on top of steel feet, in a way that allows small movements in radial directions that occur due to temperature expansion during the day and night. The steel feet are fixed to the concrete beam with anchor bolts.

The LST1 site posed special difficulties due to the abundant bushes and stones located on the terrain, which do not allow one to insert the rods in every needed point and to achieve the best electrode line directions. In addition, the high electrical resistivity of the soil limits the maximum electrode line length. In order to obtain a reliable measurement a total of 18, 3-point resistance measurements were made, distributed in three different electrode line orientations.

The LST1 earth resistance measurement gave values ranging between 11.7 and 14.0 Ohm, depending on the measurement method and electrode positions. The intersecting curves method and the slope method were chosen for the tests due to their high accuracy for large distributed grounds [15] [16]. Ground measurements were also made with the standard 62% method, providing a significantly higher value, in the order of 17 Ohm. The first two measurements were made during a day where ambient humidity was 12%, the 62% method measurements was made in a day where ambient humidity was 40%. The 62% method is one of the most popular among workers on electrical installations for ground resistance measurements. However, this method is not accurate when measuring large and complex earth systems, as is the case of the LST earth system. The reason is that the total length of the electrode line needs to be too long, around 6.5 times the characteristic size of the earth system, in order to properly apply the corresponding equations. Overlooking this condition leads to noticeable overestimations of the ground resistances.

The standard improvements which can be made to reduce the earth resistance in difficult terrains are generally based on

1) burying horizontal conductive plates or meshes,
2) burying vertical electrodes connected in parallel or
3) modifying the own terrain, which can be done by either changing the entire terrain material in a large volume or adding earthing enhancing compounds.

A combination of several procedures was also considered, inspired in the Taiwan Photon Source (TPS) storage ring design, which has a 0.2 Ohm earth system with 62 vertical electrodes and a grid of 4 rings. Bentonite was used to lower the resistivity of the terrain [17]. However, the earth resistance scales with the soil resistivity and the TPS ring were installed in a site with a resistivity having almost two orders of magnitude lower than the soil at LST1 site. Some theoretical models of earth resistances as function of conductor geometry and soil resistivity can be found in the standard BS 7430:2011 [18], the recent review of the Electrical Engineering portal [19], and the classical MIL-HDBK-419A for vertical electrodes [20]. Models for the calculation of the resistance of a grid with encased vertical electrodes can be found in the IEEE Std 80-2000 [21]. IEC 62561-7 standard discusses prequalification methods for ground enhancement materials [22].

A number of earth enhancement materials were considered. The most promising ones were materials containing cement, which after installation acquire properties that are very close to concrete [23]. However, they were finally disregarded due to environmental restrictions.

Finite Element Simulation software has been used to reproduce real-world conditions in terms of structure designs and soil profiles and have allowed us to evaluate the improvements that should be adopted to reduce the earth resistance of the LSTs [24]. We have considered how the earth resistance value changes as a function of the shape, size and number of horizontal and vertical electrodes depending the soil properties. The possibility of inter-connecting in parallel several telescopes has also been analyzed. The simulation results in [24] revealed that the best strategy in each case differs: when the soil is uniform, it is advisable to extend horizontal electrodes as far as possible from the foundation. However, when layers with different resistivity are present, to bury vertical electrodes that connect with deep high conductive layers is the best strategy.

Ample information can be found on recommended values of maximum earth resistances according to international standards. In line with the previous standard, BS 6651, the new S/EN 62305-3 standard recommends a single integrated earth termination system for a structure, combining lightning protection, power and telecommunication systems. This standard encourages an earth resistance requirement below 10 Ohm. NFPA and IEEE recommend 5 Ohm or less, NEC 250.56 25 Ohm or less, and 5 Ohm or less if sensitive instrumentation is installed.

Local Spanish norm ITC-BT-18 (REBT) [25] describes the regulations that are compulsory for the installation of earth termination systems, but no specific limits on earth resistance are specified. The regulation is focused on the contact voltages, which must be less than 24 V in conductors and 50 V elsewhere. The limit in earth resistance must be established from the current limit of the differential breakers in service, and taking into account the parasitic resistances of the ground wires. There is an additional regulation from norm BT-26 [26], which states a maximum earth resistance of 37 Ohm for buildings without lightning protection systems and 15 Ohm for those which have one.

Ronda *et al.* made a detailed study of the soil electrical resistivity of El Roque de los Muchachos Observatory [27]. Measurements were made using Wenner method [28] in six different locations of the telescopes: the four LST sites and two nearby similar instruments, the MAGIC telescopes. In addition, the resistivity at the sites was simulated with COMSOL Multiphysics software considering a simple single layer model and a three-layer model. While five of the studied places showed resistivity values compatible with a single layer structure (homogeneous), the sixth one, contained materials in the shallow layers with significantly higher resistivities, so it corresponds to an in-homogeneous, four-layer model in COMSOL.

On the other hand, it is well known that the electric properties of a ground system subject to high impulse currents are quite different from that at low frequency. It is not only the fact that the inductive behavior of electrodes becomes relevant with respect to its resistive behavior. In addition, large current pulses ionize the soil around the electrode, and this makes the impulse response typically nonlinear [29]. Numerical electromagnetic models can be used to simulate the lightning response of a grounding electrode, although recent work claims that accurate predictions of electrode behavior under a lightning strike can be made with impulse impedances, which can be obtained from special experimental procedures [30] [31].

6. Structure Equipotentiality

Several test points were chosen to perform a survey of the structure equipotentiality. The results of the measurements can be seen in **Figure 4**. The only points which exhibited a resistance above 1 Ohm is the plate covering the elevation bearing, which was fixed with an extra bond to the elevation access platform, and the catwalks for dish maintenance work.

According to the conceptual design, the wires chosen for the installation of the lightning down conductor cables should be of stainless steel and have a standard diameter of 10 mm. These wires have an ohmic resistance of 0.01 Ohm/m. In other words, a single wire of 10 m is already giving a resistance comparable to several contact resistances measured at the LST structure.

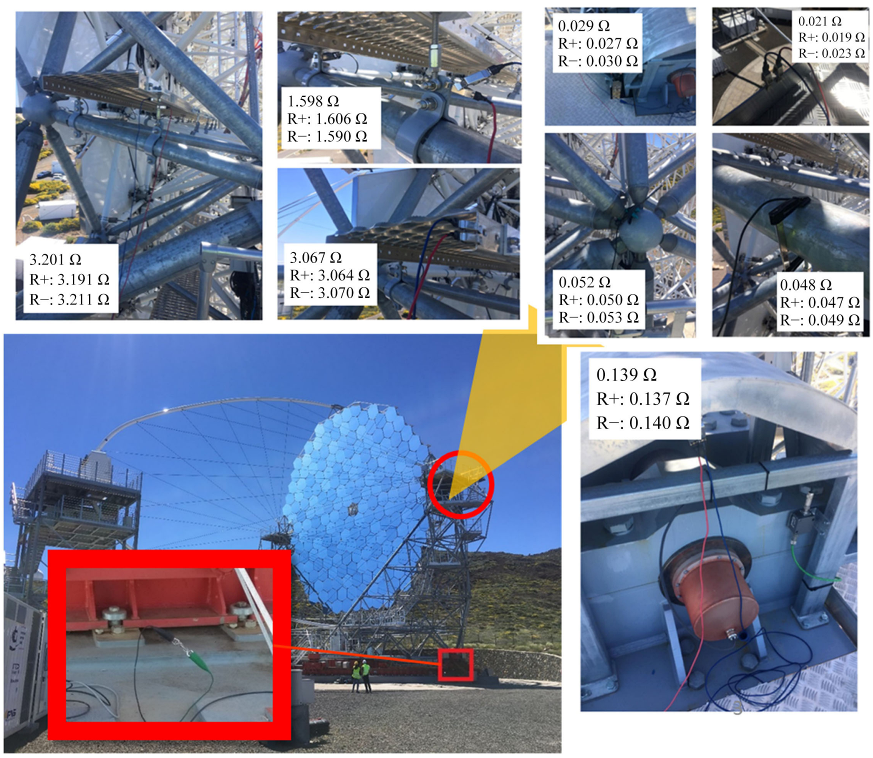


Figure 4. Survey of structure equipotentiality.

The wires foreseen to connect the lightning rods to the ground system of the LST1 are also in disadvantage against the LST1 structure in terms of high frequency impedances. A wire is, by its own nature, inductive, but the LST structure is not. The equivalent inductance of the LST structure is expected to be significantly lower than the one of a cable. A standard calculator predicts an inductance of 1000 nH/m for the wire proposed in a preliminary conceptual design. Therefore, a cable of 10 m may reach a reactance of around 6 Ohm for the strike characteristic frequencies (100 kHz), which is comparable to its ohmic resistance.

Increasing down conductor cable diameter doesn't help: 20 mm diameter only reduces inductance in 10%.

7. Electric Current Dissipation after a Lightning Strike

FEM has been used to estimate the current that will be dissipated during a lightning strike in a LST telescope, as well as to study how a high discharge current pulse is guided through the grounding electrodes to Earth.

The domain under study is depicted in Figure 5. It is a hemisphere that contains a recreation of the complete geometry designed for the earthing system of the LST, which includes:

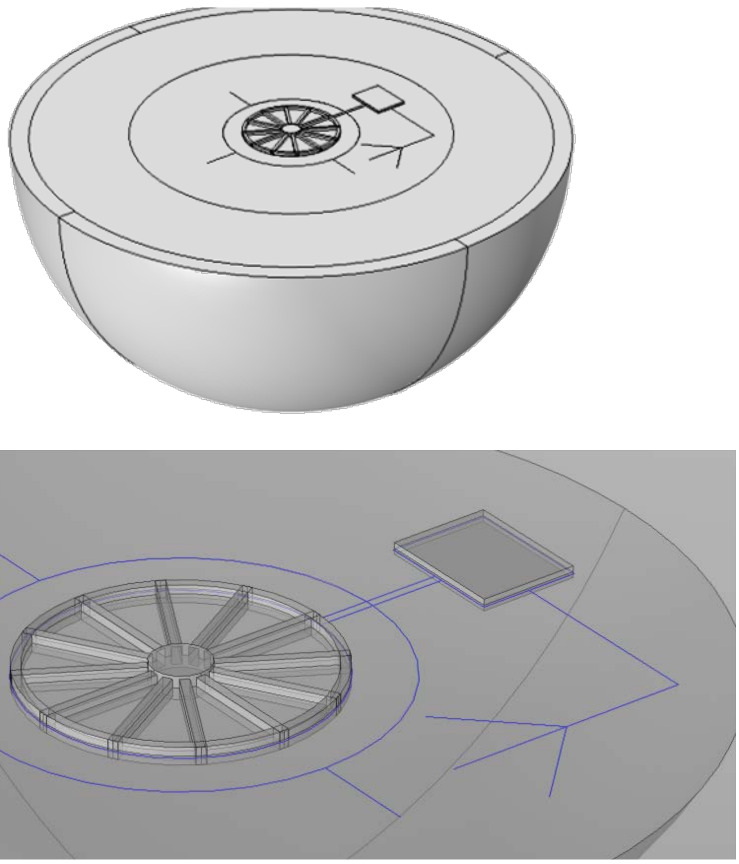


Figure 5. Implemented model geometry. Metal grid of the reinforce is displayed in grey color and metal plates surrounding it are in blue.

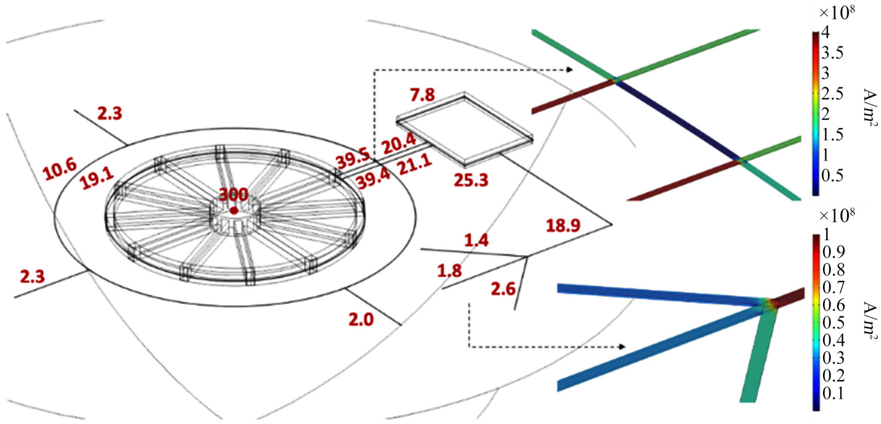


Figure 6. Averaged current in kA within the plates in the case of a 300 kA punctual current threat in the center of the structure.

- o The metal grid, which consists of two solid blocks. One of them is located under the telescope camera and the other under the mirror.
- o A composition of thin metal plates, which are surrounding and connected to the solid blocks. These metal plates are designed with 3.5 mm height and 30 mm width.

The material has the properties of structural steel (conductivity of 4.03 MS/m). The soil below earth resistance installation is considered with a homogeneous resistivity of 1.5 kOhm·m.

We have studied how the current in the case of a lightning strike in the centre of the structure is distributed through the earthing plates, according to the resistances of the different paths. A single injection of a stationary 300 kA current in the centre of the structure is simulated. This is a worst-case scenario, since the current in the structure is dissipated via two different down-conductor paths. Since the simulation is made with stationary currents, it cannot provide information on inductive effects. As the current that flows in the core of one plate can induce voltage in adjacent cables, we calculate the average current density in the surface of each plate. The results for the current flow thru the metal plate structure are shown in Figure 6. There is a reduction of around one order of magnitude between the original incident current and the one in the external parts of the structure. All these data are important for the design of the electric installation since it helps to evaluate critical design parameters, such as the minimum distance between earth plate paths and cabling feeding sensitive equipment.

8. Concluding Remarks

This paper illustrates that international standards on lightning protection are not always applicable in a straightforward way to Large Scale Scientific Facilities. In this work, we are proposing a design and verification protocol for lightning protection systems installed on scientific facilities which addresses critical issues that are common to installations on harsh environments. This protocol was applied to the lightning protection system of the large scales telescopes of CTA-N array, and covered the following items:

- Risk assessment
- Rolling Sphere based Design
- Destructive Tests on Critical Items
- Structure Equipotentiality verification
- Earth Resistance measurement and optimization
- Strike current dissipation assessment via Finite Element Method simulation.

The Risk Assessment was based on rating the lightning strike risks in a way that can be harmonized with other risks analysis that are usually encountered in the design study of a large scale facility, like technical, economical, schedule or managerial risks. The likelihood of a lightning strike could accurately be assessed by using a sensor network service able to provide strike statistics with high resolution and sensitivity. The Risk Assessment provided valuable input for the final design, which was based on an array of passive Franklin Rods mounted on the telescope structure and three adjacent buildings: the two elevation tower platforms. The rod system was dimensioned according to the rolling sphere method for a Class I system, well above the minimum requirement of Class III provided by the risk assessment of conventional lightning protection standards.

The ground resistance assessment is of major concern when soil resistivities are high, and the large and complex sizes of ground foundations encountered in large scale facilities demand the use of special techniques, like the curve intersection method. The case study presented here shows that conventional methods tend to significantly overestimate the ground resistances.

Finally, FEM simulations could provide an insight on the soil resistivity measurements and the earthing system structure functionality. We demonstrate its usefulness to do:

- Correlations between materials found in the geotechnical surveys and the measured resistivities.
- Strike current estimations expected in the plates due to the dissipation of a direct lightning strike, leading to a reduction of one order of magnitude in the case of the LSTs earthing system.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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