LIGHTNING PROTECTION
FOR HIGH ALTITUDE OBSERVATORIES

by Richard Kithil, President & CEO
National Lightning Safety Institute (NLSI)
rkithil...at...lightningsafety.com

1. ABSTRACT.
One of the first recorded lightning insults to an observatory was in January 1890 at the Ben Nevis Observatory in Scotland. In more recent times lightning has caused equipment losses and data destruction at the US Air Force Maui Space Surveillance Complex, the Cerro Tololo observatory and the nearby La Serena scientific and technical office, the VLLA, and the Apache Point Observatory. In August 1997 NOAA’s Climate Monitoring and Diagnostic Laboratory at Mauna Loa Observatory was out of commission for a month due to lightning outages to data acquisition computers and connected cabling. The University of Arizona has reported "lightning strikes have taken a heavy toll at all Steward Observatory sites." At Kitt Peak, extensive power down protocols are in place where lightning protection for personnel, electrical systems, associated electronics and data are critical. Design-stage lightning protection defenses are to be incorporated at NSO’s ATST Hawaii facility. For high altitude observatories lightning protection no longer is as simple as Franklin's 1752 invention of a rod in the air, one in the ground and a connecting conductor. This paper discusses selection of engineered lightning protection sub-systems in a carefully planned methodology which is specific to each site.

2. BACKGROUND.
Lightning behavior is arbitrary, capricious, random and stochastic. The statistical probability of lightning strikes to high altitude facilities is low. The consequential damages may be high. Since there is ample evidence of lightning-caused upsets to observatories, it is a prudent organizational policy to analyze facilities and operations so as to identify lightning vulnerabilities. Proactive designs and operational means to mitigate potential accidents should be developed. For the lightning hazard, safety should be the prevailing directive.

3. LIGHTNING CHARACTERISTICS.
3.1. Physics of Lightning. Lightning’s characteristics include: current levels peaking at about 600 kA with the fifty percentile being about 20kA; temperatures to some 15,000 C; and voltages in the hundreds of millions. The phenomenology of lightning flashes to earth, as presently understood, follows an approximate behavior: a) the downward Leader (gas plasma channel) from a thundercloud pulses toward earth b) ground-based air terminators such as fences, trees, blades of grass, buildings, people, power poles, rocks, metallic objects etc., etc. emit varying degrees of induced molecular activity; c) they may respond at breakdown voltage by forming upward Streamer; d) in this intensified local field some Leader(s) likely will connect with some Streamer(s) ;e) the "switch" is closed and the current flows. Lightning flashes to ground are the result. A series of return strokes follow.

3.2 Lightning effects. When lightning strikes an asset, facility or structure (AFS) return-stroke current will divide up among all parallel conductive paths between attachment point and earth. Division of current will be inversely proportional to the path impedance, Z (Z = R + XL, resistance plus inductive reactance). The resistance term will be low assuming effectively bonded metallic conductors. The inductance and related inductive reactance presented to the total return stroke current will be determined by the combination of all the individual inductive paths in parallel. Essentially lightning is a current source. A given stroke will contain a given amount of charge (coulombs = amp/seconds) that must be neutralized during the discharge process. If the return stroke current is 50kA --- that is the magnitude of the current that will flow, whether it flows through one ohm or 1000 ohms. Therefore, achieving the lowest possible impedance serves to minimize the transient voltage developed across the path through which the current is flowing [e(t) = I (t)R + L di/dt)].
4. LIGHTNING PROTECTION DESIGNS.
Absolute lightning safety is impossible. Mitigation of lightning consequences can be achieved by the use of a detailed systems approach. Defenses are described below in general terms.

4.1 Air Terminals. Since Franklin's day lightning rods have been installed upon ordinary structures as sacrificial attachment points, intended to conduct direct flashes to earth. This integral air terminal design can limit physical damage but does not provide protection for electronics, explosives, or people inside modern structures. Inductive and capacitive coupling from lightning-energized conductors can result in significant voltages and currents on interior power and signal conductors. Overhead shield wires and mast systems located above or next to the structure are code-suggested alternatives in many circumstances. These are termed indirect air terminal designs. Such methods presume to collect lightning above or away from the sensitive structure, thus avoiding or reducing flashover attachment of unwanted currents and voltages to the facility and equipments.


4.2 Downconductors. Downconductor cable pathways should be installed outside of the structure. Rigid strap is preferred to flexible cable due to inductance advantages. Conductors should not be painted, since this will increase impedance. Gradual bends always should be employed to avoid flashover problems. Building structural steel may be used in place of downconductors where practical as a beneficial subsystem emulating the quasi-Faraday Cage concept and to sub-divide currents.

4.3 Bonding assures that unrelated conductive objects are at the same electrical potential. Without comprehensive bonding, lightning protection will not work. All metallic conductors entering structures (ex. AC power lines, gas and water pipes, data and signal lines, HVAC ducting, conduits and piping, railroad tracks, overhead bridge cranes, roll up doors, personnel metal door frames, hand railings, etc.) should be electrically referenced to the same ground. Connector bonding should be exothermal and not mechanical wherever possible, especially in below-grade locations. Mechanical bonds are subject to corrosion and physical damage. HVAC vents that penetrate one structure from another should not be ignored as they may become troublesome electrical pathways. Frequent inspection and measuring (maximum 1 milliohm per Fed. Aviation Admin.) of connectors to assure continuity is recommended.

4.4 Grounding. The grounding system must address low earth impedance as well as low resistance. A spectral study of lightning’s typical impulse reveals both a high and a low frequency content. The grounding system appears to the lightning impulse as a transmission line where wave propagation theory applies. A considerable part of lightning’s current may respond horizontally (radial arcing) when striking the ground. As a result, low resistance values (25 ohms per NEC) are less important that volumetric efficiencies. Ground rods, with a significant impedance of some 2.4 microhenries (8 ft. long X 5/8 inch diameter), are a poor selection option in most rocky environments. Equipotential grounding is achieved when all equipment within the structure(s) are referenced to a master bus bar which in turn is bonded to the external grounding system. Earth loops and consequential differential rise times must be avoided. The grounding system should be designed to reduce AC impedance and DC resistance. The use of counterpoise or "crow's foot" radial techniques can lower impedance as they allow lightning energy to diverge as each buried conductor shares voltage gradients. Buried ground rings (counterpoise) encircling structures are useful. Proper use of concrete footing and foundations (Ufer grounds) increase volume. Where high resistance soils or poor moisture content or absence of salts or freezing temperatures are present, treatment of soils with carbon, Coke Breeze, conductive cements, Bentonite, chemical ground rods, natural salts or other low resistance additives may be useful. These concepts should be deployed on a case-by-case basis where lowering grounding impedances are difficult an/or expensive by traditional means.

4.5 Corrosion and cathodic reactance issues should be considered during the site analysis phase. Where incompatible materials are joined, suitable bimetallic connectors should be adopted. Joining of aluminum down conductors together with copper ground wires is a typical error. Inserting copper conductor leads directly into concrete is another issue.
4.6 Transients and Surges. Ordinary fuses and circuit breakers are not capable of dealing with lightning-induced transients. Surge protection devices (SPDs aka transient limiters aka TVSS) may shunt current, block energy from traveling down the wire, filter certain frequencies, clamp voltage levels, or perform a combination of these tasks. Voltage clamping devices capable of handling extremely high amperages of the surge, as well as reducing the extremely fast rising edge (dv/dt and di/dt) of the transient are recommended.

Protecting the AC power main panel and protecting all relevant secondary distribution panels and protecting all valuable plug-in devices such as process control instrumentation, computers, printers, fire alarms, data recording & SCADA equipment, etc. is suggested. Protecting incoming and outgoing data and signal lines (modem, LAN, etc.) is essential. All electrical devices which serve the primary asset such as well heads, remote security alarms, CCTV cameras, high mast lighting, etc. should be included.

SPDs should be installed with short lead lengths to their respective panels. Under fast rise time conditions, cable inductance becomes important and high transient voltages can be developed across long leads. SPDs with replaceable internal modules are suggested. In all instances the use high quality, high speed, self-diagnosing SPD components is valuable. SPDs may incorporate spark gaps, diverters, metal oxide varistors, gas tube arrestors, silicon avalanche diodes, or other technologies. Hybrid devices, using a combination of these techniques, are preferred. Avoid SPDs using internal potting compounds. SPDs conforming to the International CE mark are tested to a 10 X 350 us waveform, while those tested to IEEE and UL standards only meet a 8 X 20 us waveform. It is suggested that SPD requirements and specifications conform to the CE mark, as well as ISO 9000-9001 series quality control standards. All mode protection is essential.

Uninterrupted Power Supplies (UPSs) provide battery backup in cases of power quality anomalies...brownouts, capacitor bank switching, outages, lightning, etc. UPSs are employed only as back-up or temporary power supplies. They should not be used in place of dedicated SPD devices. Correct IEEE Category A installation configuration is: AC wall outlet to SPD to UPS to equipment.

4.7 Detection. Lightning detectors, available at differing costs and technologies, are useful to provide early warning to outdoor personnel and for equipment shutdown purposes. Users should beware of over-confidence in detection equipment. It is not perfect and it does not always acquire all lightning data. Detectors cannot “predict” lightning. An interesting application is their use to disconnect from AC line power and to engage standby power, before the arrival of lightning. A notification system of radios, sirens, loudspeakers or other means should be coupled with the detector. See the NLSI website for a more detailed treatment of detectors: www.lightningsafety.com/nlsi_lhm/OverviewDetectors.pdf. A Lightning Safety Policy should be a part of every site’s overall safety plan.

4.8 Testing & Maintenance. Modern diagnostic testing is available to “verify” the performance of lightning conducting devices as well as to indicate the general route of lightning through structures. With such techniques, lightning paths can be forecast reliably. Sensors which register lightning current attachments are available. Regular physical inspections and testing should be a part of an established preventive maintenance program. Failure to maintain any lightning protection system may render it ineffective.

5. CODES AND STANDARDS.

In the USA there is no single lightning safety code or standard providing comprehensive guidance. The NFPA-780 lightning protection installation standard applies only to “ordinary structures”. US Government lightning protection documents should be consulted. The Federal Aviation Administration FAA-STD-019d is valuable. Other recommended federal codes include military documents MIL HDBK 419A, Navy NAVSEA OP5, NASA STD E0012E, MIL STD 188-124B, MIL STD 1542B, MIL B 5087B, Army PAM 385-64 and USAF AFI 32-1065. The IEEE Emerald (IEEE-1100) and the IEEE Green (IEEE-142) series Technical Standards are invaluable. The International Electro-Technical Commission IEC 62305 series for lightning protection is the single best reference document for the lightning protection engineer. Adopted by many countries, IEC 62305 is a science-based document applicable to many design situations. Ignored in most Codes is the very essential electromagnetic compatibility (EMC) subject, especially important for explosives safety and facilities containing electronics, VSDs, PLCs, and monitoring and security equipment.

6. CONCLUSION.

Lightning has its own agenda and may cause damage despite application of best efforts. Any comprehensive approach for protection should be site-specific to attain maximum efficiencies. In order to
mitigate the hazard, systematic attention to details of grounding, bonding, shielding, air terminals, surge protection devices, detection & notification, personnel education, maintenance, and employment of risk management principles is recommended.

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