Recommendations for protecting Organ Control systems from Lightning damage in the UK.

In this short document we have tried to cover a complex subject in an easy to understand and quick guide. For reasons of brevity most of the scientific reasoning has been omitted and the results are presented as facts with no explanation. We are always happy to explain more details if asked. We are indebted to W J Furse & Co Ltd and The British Standards Institution for some of the information contained in this guide. This UK version of the document uses language, localities and technical terms relevant to the area. These terms do not apply to the North American market which is covered in a different document.

Background.

Thunder storms in the British Isles are by no means as common as many other areas where our equipment is installed. Information published by the World Meteorological Office shows that Britain has an average of 5-10 thunderstorm days per year depending on the area while some areas of the USA have 100.
This is important as we shall see, there is no absolute way to protect against lightning. As I write this document an airliner crashes in Toronto during a thunder storm and the airport reports that their lightning warning system was disabled as it was struck by lightning!
So this is balance of careful planning, money and materials. This is why meteorological statistics are important as less storms means either less money or less failures.
It is assumed that lightning strikes have currents of up to 200,000 Amps. If this amount of energy hits our equipment directly there is little chance it will survive; think of a 100 Amp welder. However as our equipment is housed in a building there are a series of barriers that we can erect, each one will minimise the damage.

Where does the danger come from?

We are concerned with the secondary effects of a strike.

High Voltage Lines:

Strikes to high voltage cables are common and produce what we call “transients” in the power. The term transient comes from the brief time the high voltage exists, sometimes also referred to as spikes due the shape they appear on a graph of the voltage against time. The transient voltage is limited to about 6,000V by the equipment in the electricity distribution system at which point it enters the building.

Direct Hits to the Building:

The lightning strike will travel to earth by the most conductive means available. In a church this should be the lightning conductor. If there is any structural steelwork in the building this will become charged and must be electrically bonded to each other and to earth to dissipate this charge. If not the current will find whatever means it can which could be the earthed electronics with catastrophic results. I have not heard of any effects from the electrically charged metal pipes in an organ but they will become charged during a storm.

When lightning strikes an object a large current flows through that object and into the ground. The rate of change of this current is also very important; a strike reaches full current in about 5 micro-seconds. This both helps protection methods and complicates them.
Energy changes this fast do not obey the laws of electricity that you are familiar with. In a car accident for instance it is often the rate of change that hurts people not the speed. The rate of

change means that for an instant the current in one piece of a wire is not the same as in another piece of the same wire. Earth is no longer earth.

When a strike hits the earth it spreads out like the ripples in a pond after a stone is thrown in. If you happened to be measuring two points in the earth during a strike you would be able to measure voltage even though it is the same wire. However, these ripples occur so rapidly during a strike that any electronics equipment in the path is unable to respond fast enough and cannot ride the level or float on it. As in the car crash example it is the rate of change that is important.

So, having destroyed all of the things you regard as given, let us put them back together in another way.

As the current flowing to earth rapidly builds up it radiates an electromagnetic field at 90 degrees to its direction of flow, this field induces current in any other conductor travelling in the same direction as the lightning current. This effect will occur even without a lightning flash.

When storm clouds are overhead the negative charge draws a positive charge from the ground to attract to the negatively charged clouds. Current will flow in a vertical direction dissipating in the air. If this positive charge attracts enough negative energy from the cloud a flash occurs and we see the effect.

Protection of the Building

Historic practice was to fit at least one lightning conductor to the top of the tower or spire and take it down the outside of the building and deep into the earth. More recently an attempt to enclose the building in a cage of conductors has been found to be more effective. It is now necessary not only to protect the building shell from damage but also the contents. The quality of this earth should be regularly checked by a qualified engineer to ensure that it retains a low resistance even in dry weather. A well protected building will have multiple lighting conductors bonded together to encourage an even distribution of charge over the building.
Metal roofing requires particular attention and must be adequately bonded but having done so, such a roof helps protect the organ by shielding it.
If you suspect that there is inadequate protection to the building ask the contractor if the earth system is to BS 7430? Also refer to BS 6651 "Protection of Structures Against Lightning"

Position of the Organ.

Generally the position of the organ is not negotiable and so the organ builder should acquire a drawing of the lightning conductor positions so the internal structure of the organ wiring can be adjusted to suit. Conductor positions should also be verified by a walk around the perimeter to check that the drawings are up to date as they may not include previous attempts at protection.
This is important because the lightning conductor radiates electric field during a storm, even if it is not struck. As we have seen earlier this field will be induced into any conductor in the same direction. This includes magnet wiring travelling vertically in the organ. The amount of energy induced in the organ wiring is inversely proportional to the square of the distance. This means if you double the distance of the wiring from the lightning conductor the energy will be reduced to a quarter.

Understanding the concept of induced currents is vital to the success in designing and organ that will be more reliable in a storm. Organ wiring acts like an aerial, picking up induced currents which then find a way to earth. Organ consoles are rarely damaged because the wiring is short. A swell organ high up above the main organ is particularly vulnerable as is an antiphonal organ that is directly wired through the roof space to the main organ in the chancel. Wiring does not have to be vertical, remember the ripples in the pond analogy earlier. Cables across the floor will receive an induced current from the current flowing in the earth beneath. "Earth is not always earth"

Damage to the Organ.

In all these examples we only consider the secondary effect of lightning striking another object in the vicinity of the organ. There are three types of damage that may occur from a strike.

1. Incoming voltage surges (transients) on the mains supply.
2. Induced current in the magnet wiring.
3. Induced current in the data cable wiring.

1. **Mains Transients:** Transients are reduced in stages as they travel through filters installed in the mains wiring. BS 6651 defines three zones as A, B & C where C is the most hostile and hence closest to the outside. The organ is defined as being in a category A environment unless it is wired within 20m of the incoming feed to the building. It is possible that blowers should be considered category B. Transient suppressors should be fitted to all incoming power wires that conform to these categories.
   Transients can occur in any combination of the conductors, adequate protection for organ power supplies requires live to earth, neutral to earth and live to neutral protection. Protectors should give a constant display of their status.

2. **Induced Current in Magnet Wiring:** The polarity of the organ DC is not relevant here as the induced voltages will easily exceed any existing voltage. Also it is important to remember that the current flowing is created within the wire and so the two wires adjacent to each other will have the same voltage on them even if one is the positive return and the other the feed wire.

   Rule 1. As short as possible.

   Rule 2. Route all wiring away from external conductors and internal steelwork.

   Current only flows when the voltage is different and so routing the return wires in the same bundle as the individual magnet wires will reduce the current flow through the magnets and hence reduce the possibility that they are damaged.
   Lightning strikes may permanently magnetise the coils and prevent them from working in the future.
   SSOS MultiSystems have zener diode protected outputs which limit the voltage on the magnet wiring to 48V. This helps to dump excessive charge to the negative power cable during a storm but as cable runs become longer the charge built up may be too strong to be absorbed and a breakdown through the driver occurs. This damage is normally localised and can be repaired with a replacement module. Some systems adopt an optical barrier approach in an attempt to allow the driver module to float with the charge which helps for minor charge changes but has the potential to allow widespread damage if the voltage rises above the barrier, which with a close strike it can easily do.
   Longer cable runs from the MultiSystem plane should use a TauNet optical coupler system which provides protection up to 50KV and has built in surge protection for each chest. In this case we also recommend a local power supply at the remote chest and feeding the mains through a category A filter as described above. The TauNet system will protect the main organ system against damage and in the event of a serious strike will prevent the damage spreading. However it is recommended to provide local earth paths as described above to dump the charge as it has to find a path to ground. Floating is not an option in the same way as not suppressing coils in normal organ wiring is not an option, the charge will build up until it finds a path to ground.

Diode coupling systems are more vulnerable to driver damage as the circuitry does not have built in suppression in the same way and should not be used to drive long cable runs.
The term long is of course related to the proximity to hazards and so is not defined as an absolute number.

3. **Induced Current in Data Cables:** Data cables travel between parts of the organ and are hence vulnerable to storm damage. Special opto-coupler and state of the art high speed voltage trip circuitry at each end of the cable protects against surges.
SSOS provides an earth terminal on each connection point which is used to dump excessive current induced in the cable to earth. This earth must be a direct connection to the building earth busbar. This earth must be verified to have a resistance of less than 10 ohms.
SSOS can also supply a fibre optic line driver system for areas of particular vulnerability but this must only be used in conjunction with the other protection systems. Using a fibre optic cable for long fixed runs where the cable is not going to be subject for movement and physical abuse removes the source of charge induced in that piece of data cable but it does not remove the problem incurred with a difference in potential across the building.
SSOS engineers have evaluated fibre optic solutions several times over the past 15 years and offer them as an option for highly prone environments that introduce other complications such as termination and offer few benefits in an average environment which is why they are not used in almost every commercial network installation that does not require them for ultra high speed long distance (more than 500 metres) communications.
It is important that the reference point for all the earths for a location in the organ is the same. However each earth should be wired back to this point independently, that being the data cable earth, the power supply mains earth and any other equipment connected in the vicinity such as the music desk lamp. It is OK to use normal mains earth routing for the mains powered equipment as long as it is verified that the earth is connected to the same reference point. Remember, "earth is not always earth"
Earth cables should be at least 2.5mm^2 (12 AWG) although there is no real need to exceed this.
The system is designed to protect the processor units from damage but may itself fail if the strike is large and the protection weak.

Calculation of risk:

The risk of damage is related to

a. geographic location
b. height
c. plan area
d. electrical connections to the building
e. proximity of other buildings of the same height

Check List

1. Building Protection is designed to protect the contents not just the external structure
2. Incoming mains wiring is filtered at each stage
3. Mains earths for each location of the organ as defined by the MultiSystem is fed to the incoming mains earth busbar
4. Mains earthing has a resistance of less then 10 Ohms (not the wire but into the earth)
5. All MultiSystem earth points are connected independently via a 2.5mm^2 12 AWG cable to the incoming mains earth busbar. Two boards in the same location should each have a wire.
6. Organ wiring is as short as possible and devices such as TauNet are used for long cable runs.
7. Organ wiring chest returns are bound with the magnet wires.
8. Organ wiring is as far a possible from lightning conductors including internal large scale structural steelwork.
9. Long DC cable runs are avoided by using a distributed AC system and local power supplies.

Example

Westminster Abbey:

BS 6651 states that London is located in an area of lightning flash density (N_G) of 0.5
The Abbey is 157m long and has an estimated area of 10,000 sq m for the purpose of this calculation.
The effective collection area for charge is related to the interconnections with related buildings and cables and soil resistance. We will assume the soil resistivity value to be 100Ωm and hence the collection radius D will be 100m. If the height of the building exceeds D then that figure is used instead, in this case the abbey is only 69m high and so this is not used and D remains at 100.
Therefore the collection area $A_E = \Pi D^2 = 31{,}415 m^2$

The collection area should also be calculated from the incoming power cables which the length is unknown. We will assume 1,000m. The effective collection area of the cable is 0.1 x D x L (0.1 x 100 x 1,000) = 10,000. Each additional cable will add more collection area but cables in the same duct will count as one.

The total collection area A_E is in this example 31,415 + 10,000 = 41,415m^2

The probable number of lighting strikes (P) is given by:

$P = A_E \times N_G \times 10^{-6} = 41{,}415 \times 0.5 \times 10^{-6} = 0.21$

Other factors are also relevant:
The area is largely flat which gives H=0.3
There are many other buildings in the area of similar heights G=0.4
The building is long and an irregular shape, and difficult to modify so the type of structure factor F=2

The overall risk R is calculated from
R = P x F x G x H
R = 0.21 x 2 x 0.4 x 0.3
R= 0.0504

1 / R = 19.8 which tells us that there will an average of one over-voltage transient every 19.8 years caused by lightning.

By these calculations Westminster Abbey is a low risk environment. Many churches in exposed positions and areas of high flash density in the USA get hit several times per year.