Lightning data and resource exploration.

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INTRODUCTION

Lightning data for at least two years is now available over much of the world, and in the U.S. for 13 years. Lightning strike locations and character may be significantly controlled by telluric currents, which in turn are controlled by resistivity distribution in the subsurface.

The process of lightning begins within a thunderstorm when supercooled (with a temperature well below freezing, but not frozen) droplets and/or ice collide and electrons are separated from, or added to, molecules (ionization) as shown by Rakov and Uman (2003). The neutral atmospheric molecules (droplets, ice or other suspended particles) become electrically charged as they collide with other particles with a greater or lesser amount of energy. The electrical discharge initiates as a channel of high ionization propagates through the air. This can occur with both positive and negative charges. Such channels are the beginning of a leader that reaches toward the ground in a cloud-to-ground discharge as it initiates the first return stroke. This may occur after cloud-to-cloud discharges have occurred over distances up to 200 km or more. The first stroke is initiated by a stepped leader. In a typical event, the flash of the first return stroke ascends as soon as the descending stepped leader makes electrical contact with the ground. In many cases the process is aided by short ascending ground streamers which seem to almost explode or radiate with a greater intensity. The return stroke is what produces most of the brilliant light associated with lightning and it is also where most of the electrical charge transfer takes place as discussed by Rakov et al. (2005). All of the subsequent strokes are initialized by a dart leader usually following the same channel as the stepped leader and thus the appearance or form of the lightning tends to look the same with the remaining return strokes.

The entire process of the return stroke occurs within a few tens of microseconds and much of this time is spent in a long decay period following the early rapid Rise Time to Peak Current. Both the current and propagation speed decrease with height and this can become more of an issue with what can be considered taller lightning of cloud-to-ground strikes which may reach into the stratosphere, as shown by Baba and Rakov (2008).

In the more common negative cloud-to-ground strikes, the return stroke deposits the positive charge of the preceding negative leader channel, thus charging the ground negatively. In negative cloud-to-ground lightning, multiple return strokes are common and thus there tends to be a more impressive light show. With positive cloud-to-ground events, the return stroke deposits the negative charge on the preceding positive leader channel, thus increasing the positive charge on the ground. This behavior was analyzed by Cooray et al. (2004).

Positive strikes tend to have only one return stroke, are stronger than most negative flashes, and occur more frequently toward the end of a thunderstorm. With regard to cloud-to-ground lightning and surface issues, there are three considerations.

- First, the lightning flash is formed between 4,500 and 7,500 m (15,000 and 25,000 feet) above the ground in most seasons and locations.
- Second, as mentioned previously, a flash comes to the surface in steps, and when 30 to 50 m from the ground, it decides what to hit.
- The underlying ground's composition is for the most part considered irrelevant by most meteorologists, including Jerauld et al. (2007), but it is also widely known that this aspect of lightning has not been fully researched and is an important key to this paper. The connection within that 30 to 50 m (90 to 150 feet) radius at the lower tip of the lowest branch typically goes for a contact of opportunity which in many cases is the highest and/or tallest object; but lightning paths are still considered unpredictable and most researchers still categorize it as a random event.

There has been some research done looking at the frequency of oak trees being struck over some other types of trees, by Baba and Rakov (2008), but the results seem to be tied to local geographical (and geological) issues more than the oak itself. The third factor of the surface is the topographic change needed to initiate a storm. In general, in humid areas, elevation changes of at least 300 m (1,000 ft) are needed to make much of a difference. There may be a sharp increase in lightning along mountain ranges or escarpments. An example of this would be a ridge of 1,000 to 1,700 m (3,000 to 5,000 ft) in eastern Arizona facing south toward the Gulf of Mexico and the moisture during the summer monsoon. Coastlines are also very efficient producers of lightning boundaries due to differential heating in very humid places.

It should be noted that all lightning originates due to meteorological processes aloft where the essential thresholds of updraft, hail and ice particles, and supercooled water need to be present. It is our premise that there is a correlation between the subsurface of the Earth and where contact is made with a cloud-to-ground lightning strike. This idea is expected to lead to a completely new area of research in the meteorological community.

THEORY

The intensity of the electrical field set up by an infinite plane sheet of charge is independent of the distance from the charge is given by $E = 2\pi k\sigma$, where E = Electrical Intensity, k = proportionality constant of Coulomb's law. The force between two point charges is given by $F = \frac{kqq'}{r^2}$. The constant k depends on the units, q is charge 1, q' is charge 2, and r is the distance between q and q'. σ is the surface density charge or the charge per unit area. Some conclusions from these relationships are:

- $E = 0$ for all points within a conductor, when the charges in the conductor are at rest. Therefore the entire excess charge on the conductor must be located on the outer surface of the conductor.
- Charge, q, is uniformly distributed on the surface of a conducting sphere of radius R. Radius of Earth is 6,378.1 km.

Lightning can be thought of as breakdowns in a self-repairing capacitor formed by the conducting ionosphere and the conducting earth, separated by the non-conducting lower atmosphere. Lightning strikes (dielectric breakdowns) are going to occur where perturbations create larger E and F on the Earth side of the capacitor. Since F is inversely related to r^2, as the distance between the positive (Earth) and negative (Ionosphere) decreases, due to increases in topography, F increases, resulting in additional lightning at higher elevations.

Likewise, when E increases because σ, the charge per unit area, increases there will be additional lightning strikes. The charge per unit area in the infinite plane sheet of charge (the surface of the earth) is altered by variations in resistivity within the conducting body. These might be caused by chemical reactions or mechanical stresses; movement of rocks or fluids within the pore space of rocks, including magma and groundwater; local vertical geological features such as volcanic pipes; changes in pore fluids, including variation of water salinity and presence of other pore fluids such as hydrocarbons; variations in mineral composition of the matrix of a porous rock or of the composition of a non-porous rock; phase changes in pore fluids, which depend on temperature and pressure; approximately planar and vertical geological discontinuities such as faulting; approximately horizontal geological discontinuities such as geopressure depth variations and stratigraphic bedding and unconformities.

More specifically E increases in the infinite plane sheet of charge when geothermal alteration or electrically conductive brines along faults create linear conductors, high salinity of fluids adjacent to salt domes create circular conductors surrounding circular resistors (salt), or large hydrocarbon accumulations at pinchouts create linear resistors.

RECORDING THE DATA

The character of a lightning strike can be determined by recording the electromagnetic pulse created by the strike. A single recording is of little use for determining the location, but a network of fixed interconnected recording stations, each of which can detect the time and direction of these pulses, allows the location to be determined within a few tens of meters (Figure 1).

Each stroke can be recorded as a full waveform, but most recording only includes a few measurements. Figure 2 shows the waveform from 14 consecutive lightning strokes in central Texas over a time period of 50 minutes on May 14, 2010. The attributes recorded for all lightning strokes[1] are date, time, latitude, longitude, peak current (kA), absolute peak current, chi-squared value for the location values, semi-major and semi-minor axes of the error ellipse, rise time (the time in microseconds from the detected onset of the stroke to the peak absolute current), peak-to-zero time (the time in microseconds from the absolute peak until the signal from the stroke drops below ambient noise), and the number of sensors from the network used in the measurements.

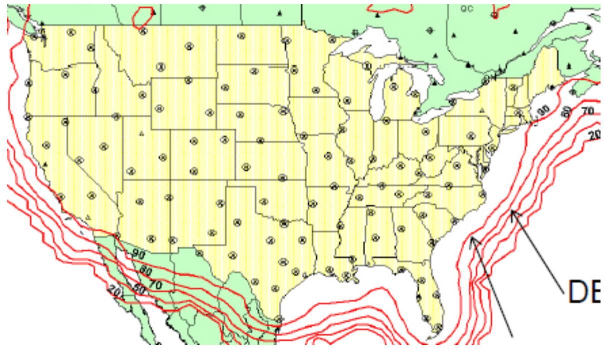

Figure 1: The U.S. National Lightning Detection Network (after Murphy et al. (2007))

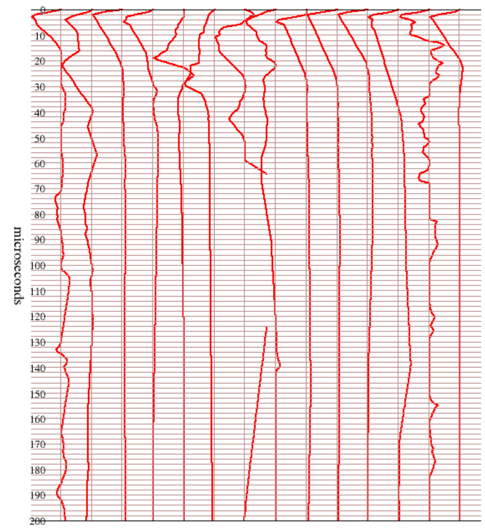

Figure 2: Full lightning waveform (first 200 microseconds)

The lightning waveform shown in Figure 2 shows a general similarity to an unprocessed seismic trace. With greater knowledge of what affects lightning, the development of processing similar to seismic data processing – designed to remove non-geological effects, partially invert the data to a geological model, and reduce random noise – could lead to data volumes similar to 3D seismic data volumes.

[1] By the U.S. National Lightning Detection Network

INTERPRETATION

While interpretation of lightning characteristics is in its infancy, correlation between geology and lightning density and character is already established in some areas. In some cases a correlation between lightning density and hydrocarbon production is apparent.

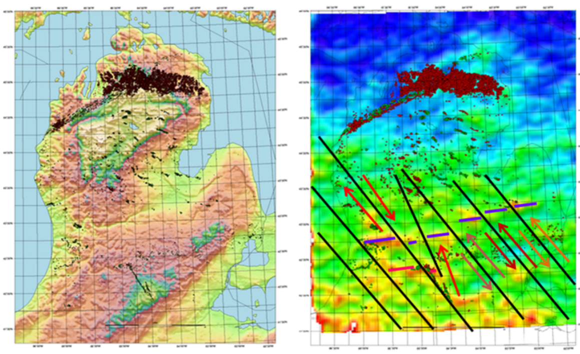

Figure 3: Michigan. On the left is topography, with oil wells in green and gas wells in red. On the right is the lightning strike density, with fault interpretation from lightning data (from Nelson et al. (2013))

Figure 3 shows the southern peninsula of the U.S. State of Michigan, topography on the left and lightning strike density on the right, with oil and gas wells overlain on both maps. The map on the right has interpretation of faults based solely on the lightning data. Two features of lightning strike density are obvious from this map: the strike density decreases towards polar areas, and there is no noticeable change at the lake shoreline. There also appears to be little correlation between lightning strike density and large topographic features such as the high running to the northeast from the south-central part of the state have no expression at all in the lightning density map.

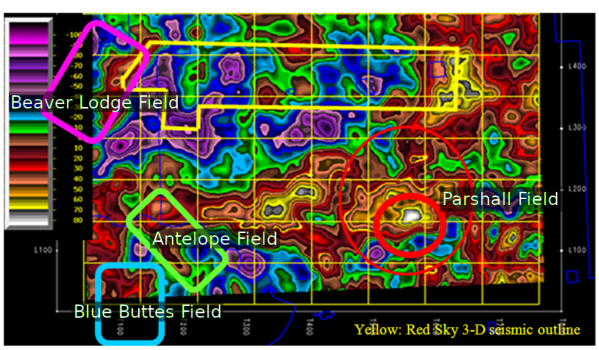

Figure 4: Mountrail County, ND, showing lightning strike density at high lunar tide and some oil fields, modified from Nelson et al. (2013). The yellow outline of the Red Sky 3-D survey shows an anomaly on the east edge correlating to a fault seen with well data and not with seismic. The red circle defines the most productive portion of the Parshall Field, and the rectangles on the west highlight the named fields.

Figure 4 shows the density of lightning strikes occurring at the high values of lunar tidal effect, showing an apparent correlation with several oilfields.

OTHER VARIABLES

Lightning is also affected by topography, vegetation and man-made objects. Allowance for these factors needs to be made in the interpretation.

Topography

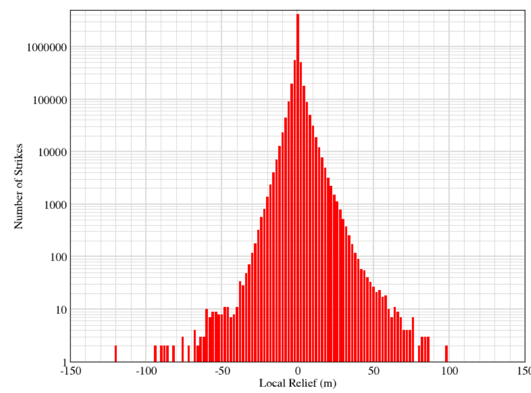

Figure 5: Topographical effects: a positive value indicates that the strike point is above the smoothed surface.

The effect of topography on lightning stroke locations is shown in Figure 5. This is a plot with the number of lightning strikes over a ten year period as the Y axis, and the local topography as the X axis. The local topography is measured as the elevation of the strike point relative to a smoothed elevation surface (smoothed with a Gaussian filter with 6 sigma width of 2.0 km).

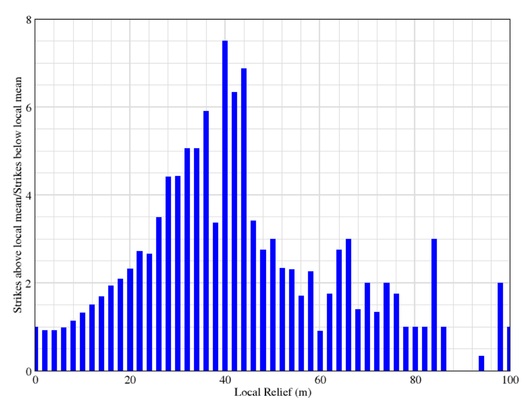

Figure 6: Topographical effects higher/lower

If topography had no effect, this plot would be symmetrical about the zero X value, but it is not. Figure 6 shows the ratio of the number of strikes higher than the surrounding topography to the number of strikes lower (the Y axis) as a function of the difference from the smoothed surface. There is little effect for differences up to about 10 m, but a point 20 m above the surrounding average is more than twice as likely to be struck by lightning as a point 20 m below the surrounding topography. This data set is over the whole of North Dakota, a fairly flat area. Over 98% of the lightning strikes were within 10 m of the smoothed surface.

Atmospheric and other effects

Although atmospheric variables also have a large effect on lightning, averaging lightning strikes over several years can largely remove these effects. Some natural phenomena which might be expected to affect lightning, such as sunspots (Figure 7) and solar winds (Figure 8) do not appear to have a measurable effect, though there is some evidence tidal gravity variations do have a slight effect.

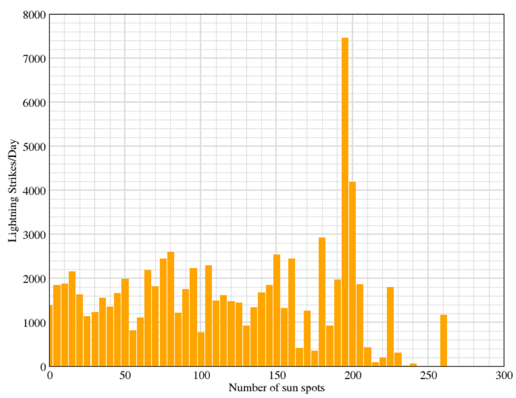

Figure 7: Sunspot number plotted against number of lightning strikes in North Dakota using data from Erwin (2009): this database is no longer available, but similar data is available from NOAA: Denig (2013). There is no consistent relationship. The spike in lightning strikes with 190 to 200 sunspots represents fewer than thirty days over ten years, mostly a time of declining sunspot activity.

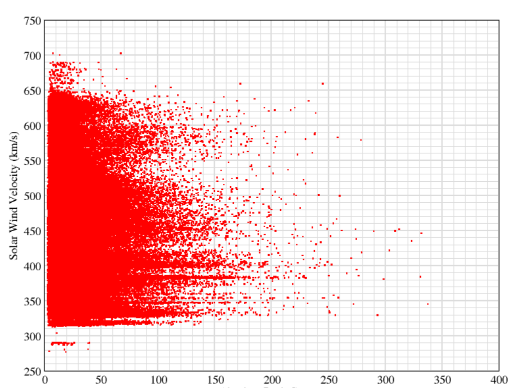

Figure 8: Solar wind velocity and lightning strike peak current (solar wind data from ACE (2008))

Manmade objects

Many parts of the world have large concentrations of man made objects which could affect lightning strikes. One examples is buildings, which give the same effect as topographic variations, but for resource exploration a more important consideration is the use of conducting materials such as steel in structures such as pipelines, railroads, and oil or gas wells (which often have an electrical conductor – the casing – extending thousands of meters into the earth).

We have been unable to detect a significant contribution of such structures except in exceptional circumstances, such as very tall masts, which sometimes have frequent lightning strikes. For example, the lightning strike density map of Michigan (Figure 3) shows no concentration of strikes either in areas with many oil or gas wells, or in the Detroit metropolitan area, which has tall buildings, railroads, and factories.

CONCLUSIONS

Lightning data has potential to be a unique exploration tool because it is much lower in cost than other geophysical data, does not require physical access to the area being evaluated, and is immediately available without permits or extensive planning. The technique shows promise in detecting and measuring changes in resistivity in the subsurface: while the immediate cause of lightning stroke is meteorological rather than geological, the geology remains constant as the changing atmosphere produces many lightning strikes in or near the same location. This allows statistical removal of the atmospheric variations. The somewhat consistent remaining variations in lightning strike density and character should represent geology.

ACKNOWLEDGMENTS

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