Lightning, a shockingly new unconventional electromagnetic exploration tool

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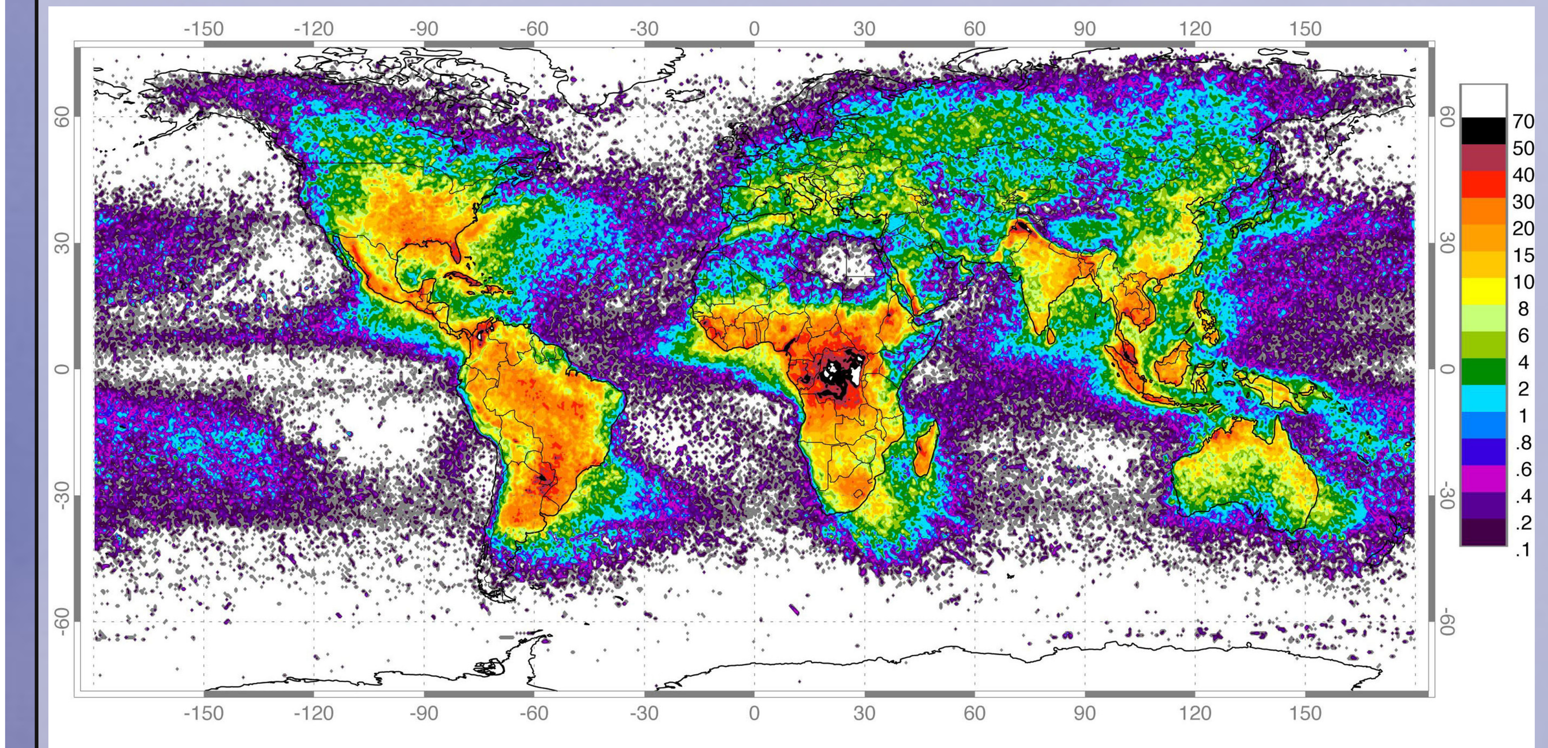
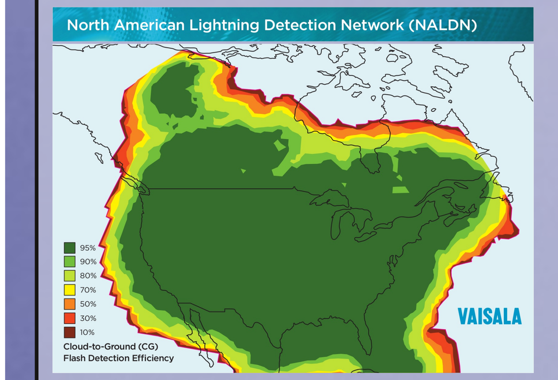
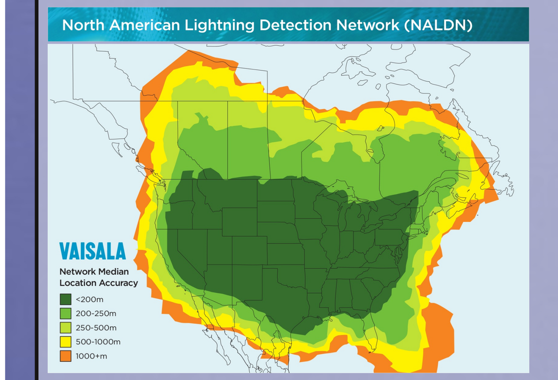
Lightning occurs everywhere. It can now be used by petroleum and mining industries for exploration. Naturally occurring cloud to ground electrical discharges have now been used as a geophysical exploration tool. This technology that can be applied to resource exploration, large scale basin studies, and geohazard, geotechnical and environmental studies.



High Resolution Full Climatology Annual Flash Rate

Global distribution of lightning April 1995-February 2003 from the combined observations of the NASA OTD (4/95-3/00) and LIS (1/98-2/03) instruments





Several networks exist for detecting, locating, and measuring cloud-to-ground lightning strikes. Two such networks are the National Lightning Detection Network (NLDN) and the GLD360 network, both operated by Vaisala.

The NLDN has recorded cloud-to-ground lightning in the contiguous United States since 1998, and the GLD360 network has recorded worldwide since 2011. Similar networks exist in most countries worldwide.

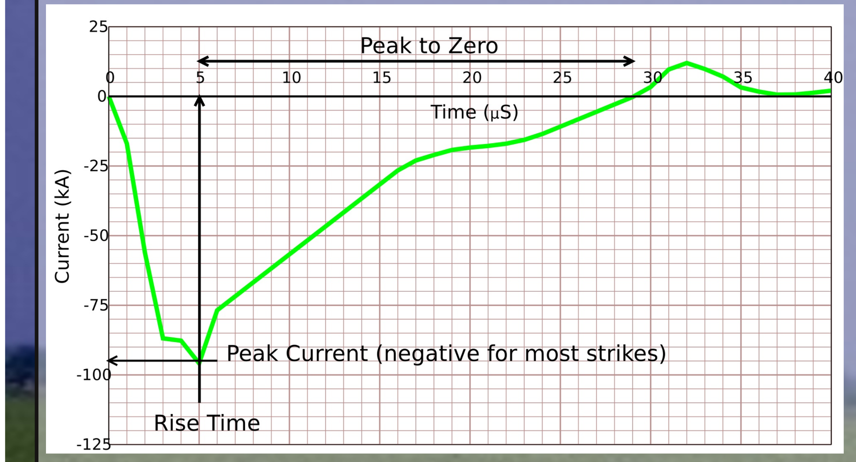
Although lightning is guided by meteorological conditions, the precise location and attributes of strikes appear to be guided by shallow, geologically related, perturbations of telluric currents. These electrical currents are influenced by lateral geological inhomogeneity caused by faults, fractures, mineralization, pore-fluids, and salinity variations.

The upper map on the left shows the detection efficiency of the NLDN for cloud-to-ground lightning. It is better than 90% over the whole of the continental U.S., including most of the continental shelf.

The lower map shows the accuracy of locations for detected lightning strikes. Over most of the continental U.S. the median location accuracy is better than 200 m, and we have found from experience that this median can be improved by discarding data with large location errors. This location accuracy is at the 3σ level.

The data available from the NLDN includes the onset time of the lightning strike, the location (in latitude and longitude), the peak current, the rise time, the peak-to-zero time, plus several measures of the accuracy and reliability of the data: chi-squared for the computations, the lengths of the semi-major and semi-minor axes of the ellipse of uncertainty for the location, and the number of sensors used in locating and measuring the strike. The definitions of these parameters are shown in the figure below.

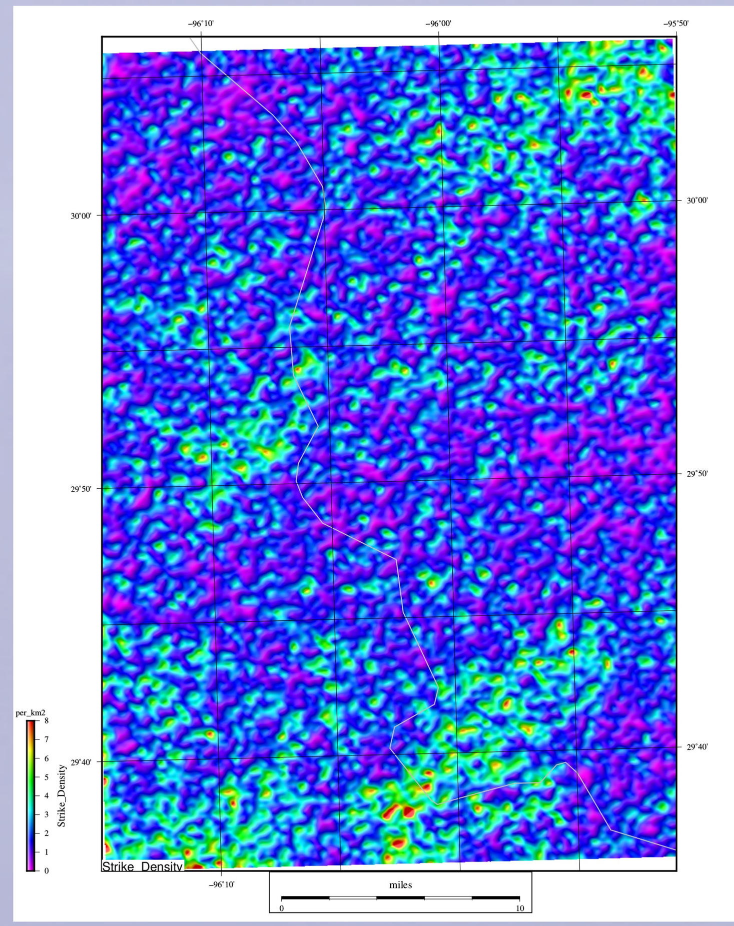
Note that the "zero" in the Rise Time and the Peak to Zero are measured not from the true zero but from when the lightning signal first appears above background noise (for Rise Time) or disappears into the background noise (for Peak to Zero).



For data analysis, the recorded lightning data can be "cleaned" by omitting strikes with excessively large semi-major axis, by omitting strikes with obviously erroneous values (such as a Rise Time of 0.0 μS), and by omitting strikes detected by only two sensors. Many strikes of doubtful accuracy are eliminated by more than one of these criteria.

In addition to the three actual measured parameters, we can calculate derived parameters such as Rise Rate, Symmetry, Frequency and "Energy" (area of the recorded pulse). For Peak Current, we can use absolute values or separate positive and negative strikes.

For any of the measured or derived parameters we can restrict a data set to a range of time, season, tide state, or of another parameter.

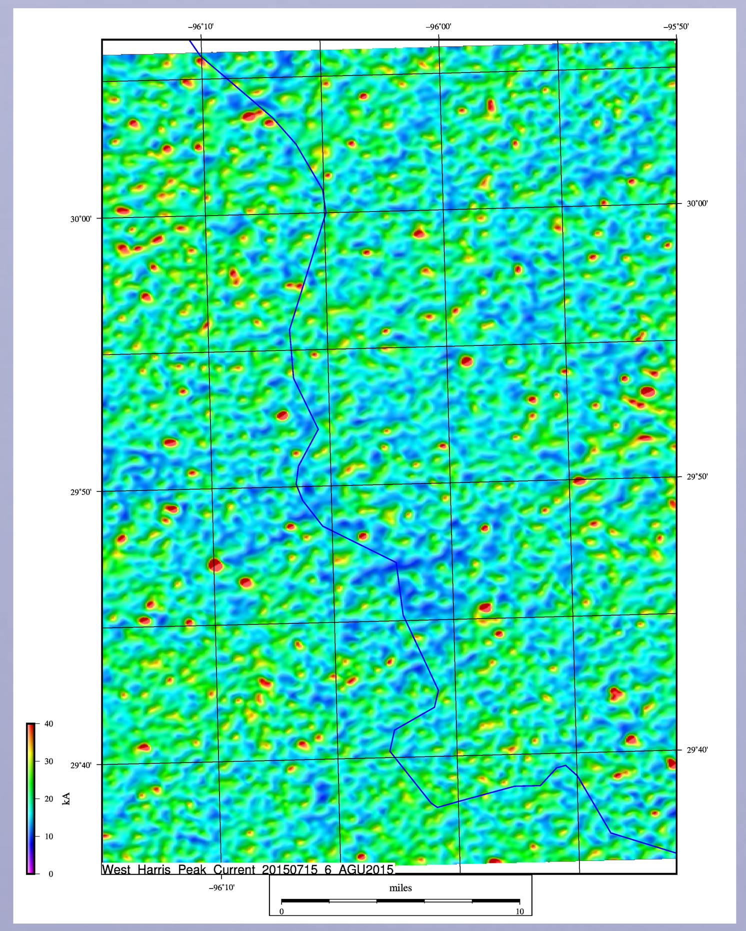


Each of the recorded or computed quantities can be plotted on a map. In many areas lightning strikes are at least locally so dense that plotting individual strikes over a reasonably large area is impossible. So we divide the area to be studied into small cells and average the lightning strike parameters over each cell. The first area we will look at is near Sealy, Texas, 47 miles west of Houston.

The cell size most often used is either 10 seconds of longitude by five seconds of latitude, or 2 seconds of longitude by 1 second of latitude. The first map on the left shows the lightning strike density in strikes per square kilometer per year, calculated from lightning strikes between the beginning of 2000 and September 2011.

This area is mainly agricultural, with the western limit of the Houston metropolitan area spilling onto the east side of the map, and the small town of Sealy just west of the center. The grey line wandering down the map is the approximate location of the Brazos River. There is a shallow salt dome just east of the river in the middle of the map, with an active oilfield around the eastern edge. Interstate 10 runs across the area close to latitude 29°47'.

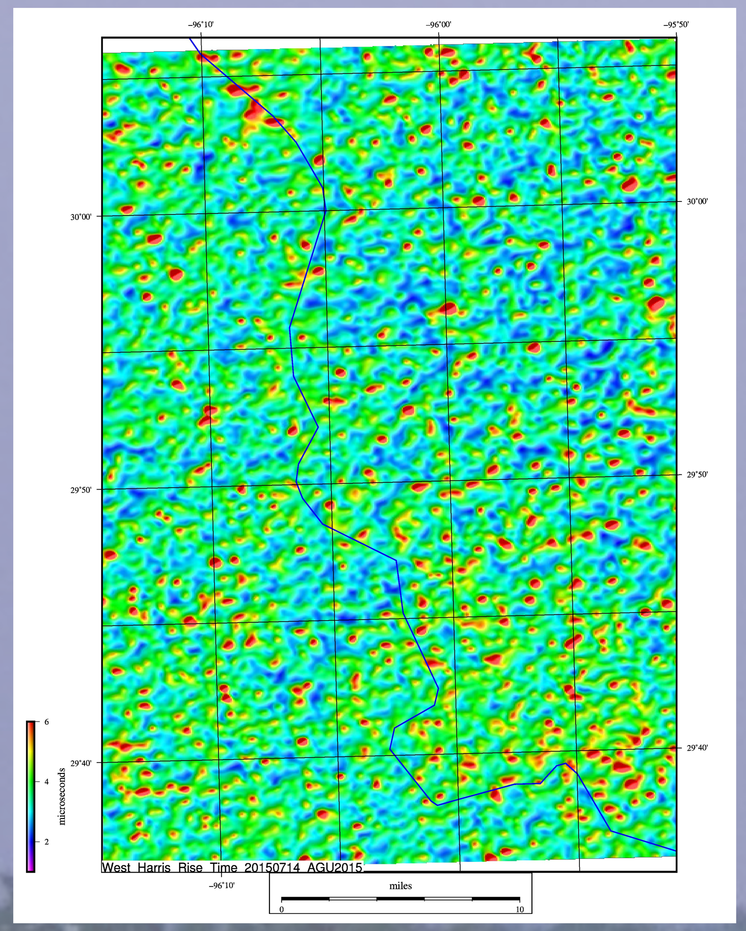
Lightning strike density is quite variable, with large areas experiencing less than one strike per square kilometer each year, while other places nearby have more than 10. There is no apparent topographic or cultural feature which can be easily correlated with this variation.

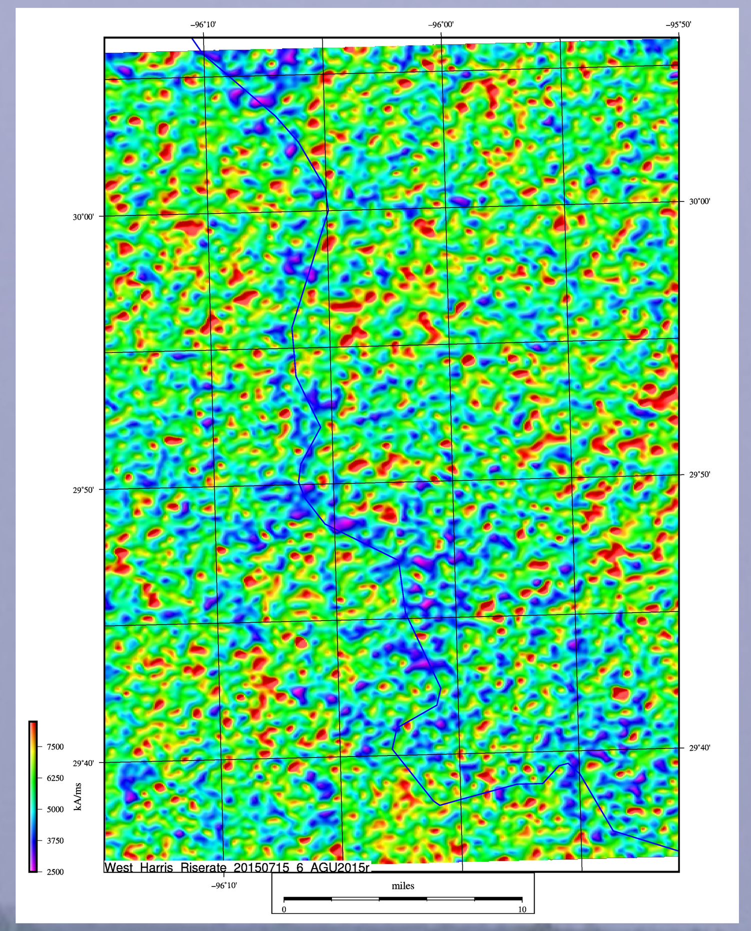


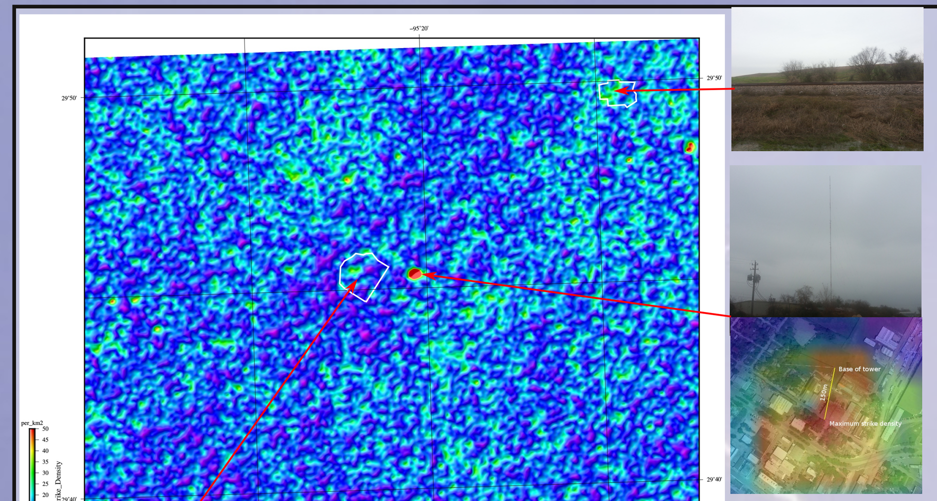
In a similar manner, the absolute Peak Current of lightning strikes seems to have a lot of variability. The map on the left shows the average value in each cell. These averages range from 3kA to 208kA. The map has been smoothed slightly, and has a range of 9kA to 94kA. Again, there is no cultural or topographic explanation for these variations.

The next map, lower left, shows Rise Time, the second recorded parameter of the lightning. There is a hint of an alignment of long rise times following the course of the Brazos River.

If we combine these last two parameters to give Rise Rate, defined as (Absolute peak current)/(Rise time), we get the map shown at the bottom right. Here low values of Rise Rate are clearly aligned along the Brazos River. Based on similar coincidences of watercourses with low values of Rise Rate, we conclude that low values of Rise Rate coincide with the presence of fresh water in the near surface. These anomalies are not seen associated with salt or brackish water.







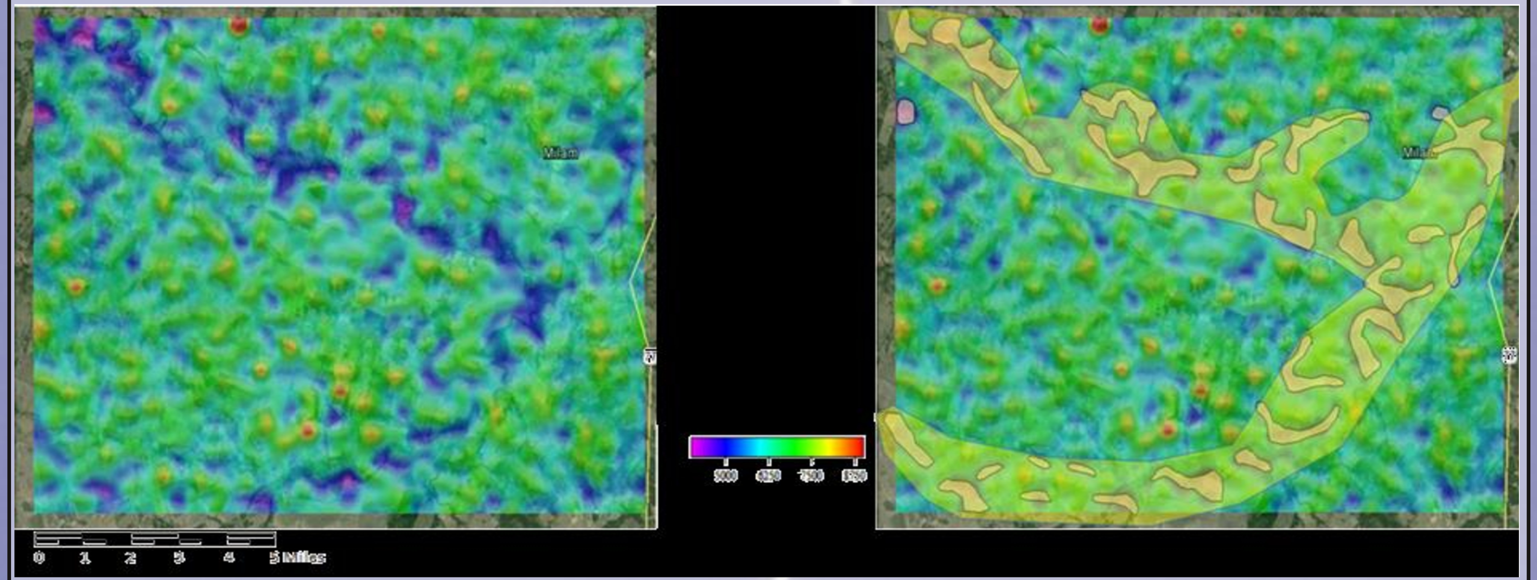
Infrastructure Effects

Houston, Texas. The white polygon in the center of the map is the Downtown area bounded by Interstates 10 and 45, and 69. This in an area of tall buildings (13 over 200m and two over 300m).

The white polygon in the northeast is a large landfill, which rises about 20m above the surrounding terrain. Part of this landfill is marked by a locally high strike density.

But the densest lightning strikes appear to be on a tower about 150m tall. The center of the anomaly is about 100m south of the tower, but the north-south dimension of the cells used for computing strike density is 30m, and the semi-major axis of the ellipse of uncertainty for each lightning strike is 200-400m.

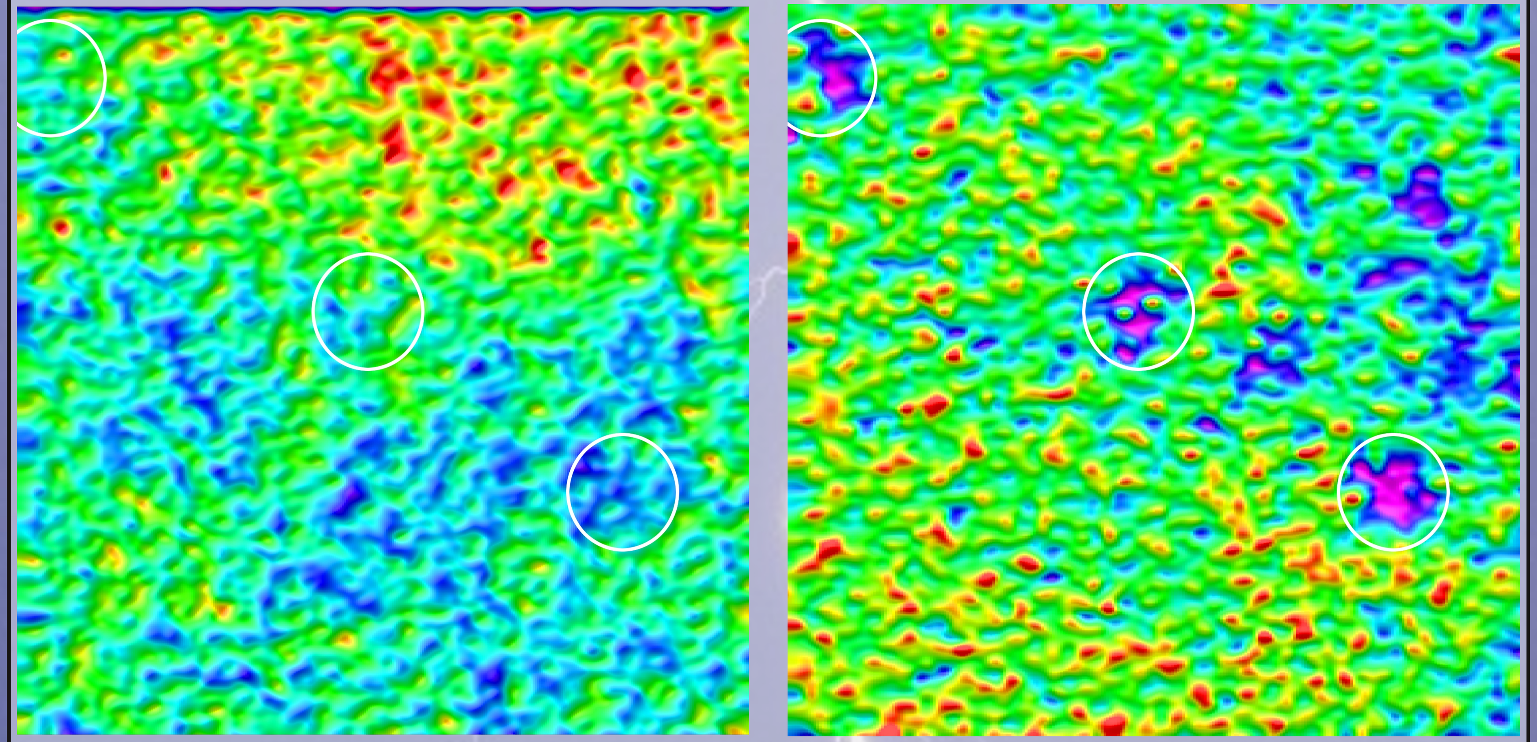
Geological Effects -- Sediments



The map on the left shows Rise Rate for an area in central Texas. Two rivers show up as chains of low values crossing the area. The confluence of these two rivers is in the central east part of the map.

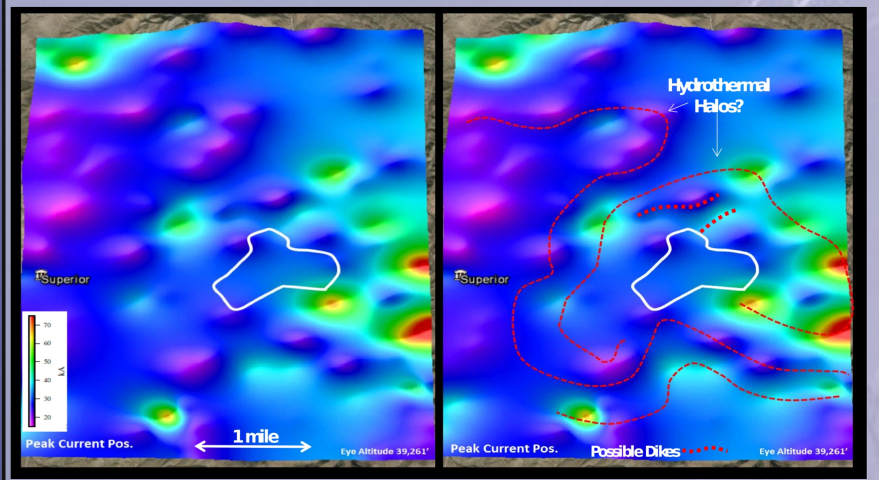
The right hand map shows the same map with interpretation of near-surface geology from the lightning data. The translucent coloring shows the interpreted flood plain, and the solid yellow patches are interpreted sandbars filled with fresh water. (Interpretation by H. Roice Nelson, Jr.)

Geological Effects -- Sediments



These two maps cover exactly the same area in Iberia Parish, Louisiana. The three white circles are three salt domes which are expressed on the surface as features about 30m above the surrounding marsh and shallow water.

The map on the left is strike density, and the map on the right is Rise Rate.



Geological Effects -- Igneous

The maps to the left show the location of the Resolution Copper porphyry mineralization east of Superior, Arizona (solid white line). The color background shows Peak Current (in kiloamperes) for positive lightning strikes only, recorded from February 1998 to October, 2014.

The left hand map shows the Peak Current data, the location of the mineralization, and the location of the town of Superior.

The right hand map is the same, with hydrothermal halo and possible dikes interpreted from the lightning data (interpretation by Louis Berent).

How can we use multiple lightning strokes at the same location (or close to the same location)?

We can reasonably assume that the electrical properties of the geology underlying the point where lightning strikes is unchanged in the short term. But some of the characteristics of each lightning strike depend on meteorology. In particular, the Peak Current will depend largely on the voltage applied to the earth resistance.

A lightning strike occurs when the voltage difference between the charged cloud and the induced charge underlying it in the earth is high enough to break down the insulating layer of air. If the resistance is mainly from the earth, not the atmosphere, at any one location the cloud height determines the breakdown voltage.

But the higher the cloud, the larger the area of induced charge on the earth's surface, and so the longer the average distance to from the lightning point strike to the induced charge location. The current formed by this discharge is not confined to the surface, but spreads into the subsurface, and the greater the distance it has to travel, the deeper the penetration. We can then reach some tentative conclusions:

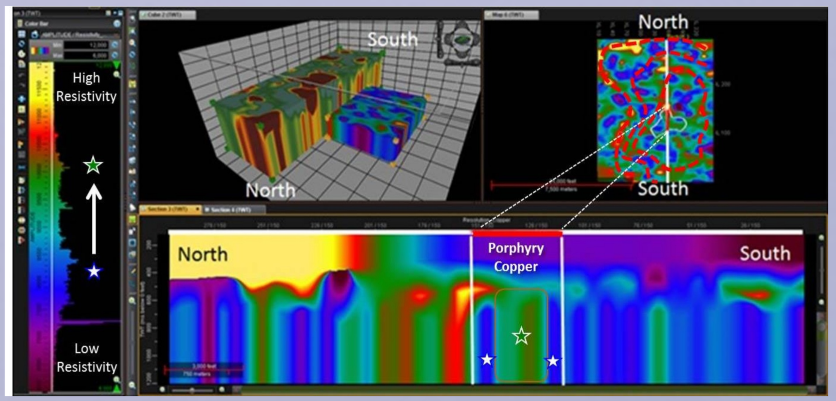
- At a single location, the apparent resistance through which a lightning strike is dissipated is approximately constant.
- Then the breakdown voltage (and thus the cloud height) is proportional to the peak current.

The discharge of the induced charge can be thought of as the discharge of a capacitor through a resistance. Such a discharge is an exponential decay with time. If we know the capacitance of the capacitor and the voltage to which it has been charged, any two points on the decay curve can be used to compute the resistance. A simple model can give the capacitance. The higher the cloud, the larger the area of the capacitor, and the deeper the geology penetrated by the discharge current.

If there are multiple strikes close to the same location, an approximation of resistance as a function of depth can be calculated.

If the rise time is greater than zero--and it always is--the discharge circuit must include either inductive or capacitive elements. If we assume it is all capacitive, we can estimate distributed capacitance or apparent permittivity as a function of depth.

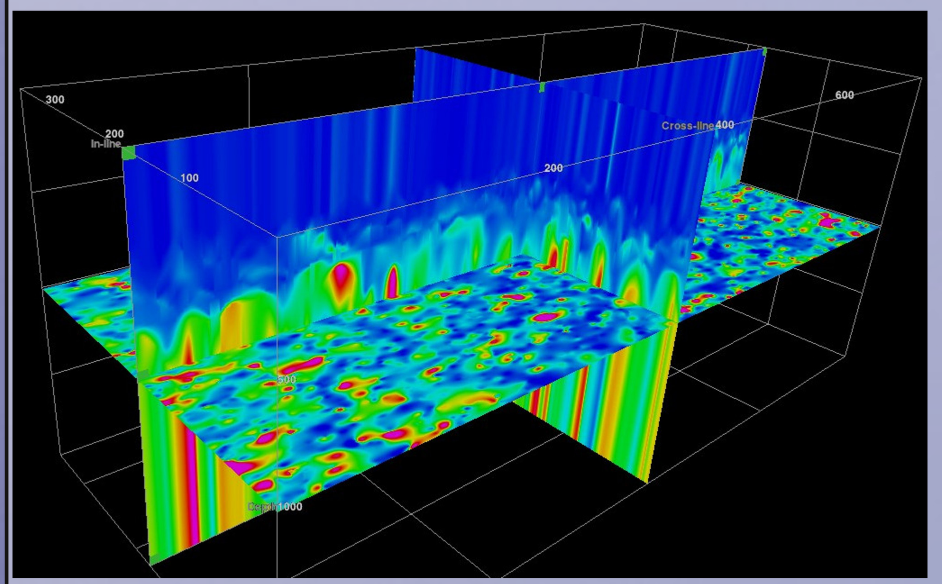
These calculations can give us three-dimensional volumes of both resistivity and permittivity as a function of location (X and Y) and depth (Z).



Apparent Resistivity Volume

On the left is a view of the 3D apparent resistivity volume over a large porphyry copper deposit in Arizona. The volume was generated from the recorded information for 5643 lightning strikes between 1998 and 2014.

Of these, 607 strikes were omitted due to uncertainties with the data.



Apparent Permittivity Volume

The figure to the left shows the apparent permittivity 3D volume computed from 1582073 lightning strikes between 1998 and 2011 over an area in Texas stretching 125km from near Bellville in the west to Baytown in the east, and 55km from Tomball in the north to Richmond in the south. This area includes most of the Houston metropolitan area, as well as several oil and gas fields.

The volume demonstrates the possibilities of acquiring large amounts of subsurface data over densely populated areas which include hundreds of thousands of land owners, areas with strict limitations on overflight, and areas with severe access restrictions such as airports and restricted waterways.

Conclusions

Lightning clusters and lineations appear to correlate to fresh water, near-surface fluvial depositional patterns, hydrocarbon seeps, salt domes, and mineralization.

This is a new, effective, quick, and inexpensive reconnaissance and near surface geophysical tool. With proper subsurface calibration, potentially powerful 3-D resistivity and permittivity volumes can be generated.

Acknowledgements

The authors thank Dynamic Measurement LLC for permission to present this paper.

The two maps showing the National Lightning Detection Network were made available by Vaisala.

We also acknowledge contributions to this work by H. Roice Nelson, Jr., Louis Berent, and Kathy Haggar.

Further Reading

L. R. Denham, H. Roice Nelson,Jr. and D. James Siebert, 2013, Lighting data and resource exploration, *SEG Technical Program Expanded Abstracts 2013*: 1961-1965.

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