Using Lightning for Exploration

Dynamic Measurement LLC

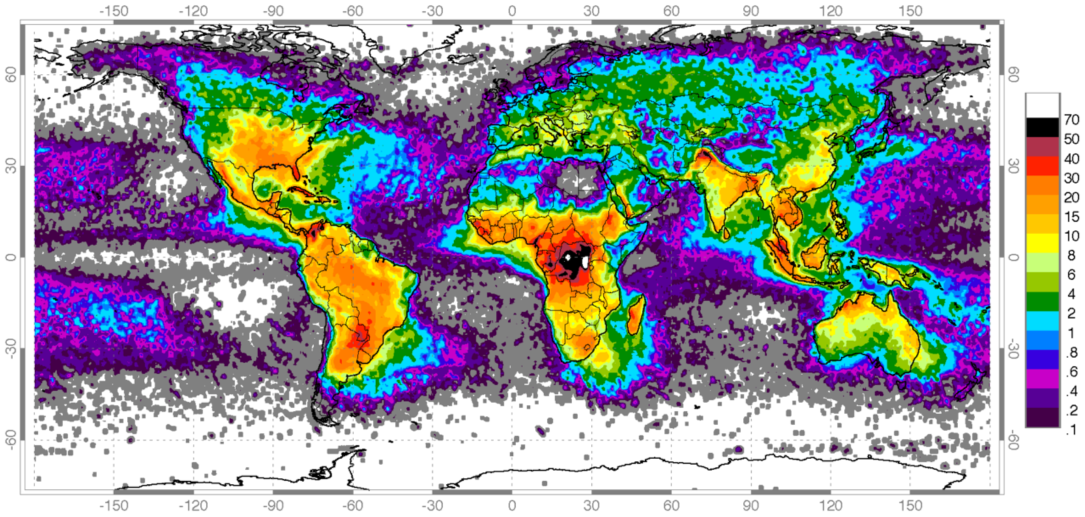
1. In this talk I will give an overview of using lightning in exploration. We will note briefly how lightning is recorded, what parameters are measured, and the quality control available. Then we will look at ways this data can be presented in a way relevant to exploration, and how more complex data products can be produced.

Lightning occurs everywhere. Both lightning strikes and lightning strike attributes cluster, based on geologic features. The skin depth of lightning strikes is measured in centimeters. However, electrical currents within the earth affect where lightning strikes, and these currents vary at the depths which are of interest to hydrocarbon exploration. Since geology does not change rapidly, geologic effects on lightning are constant for many years. Data from up to 16 years can be stacked, to improve signal and decrease noise.

A new development is a capability to create resistivity volumes. These can be created anywhere onshore in the continental United States and Canada, out to the shelf break, or about 300 foot water depths.

This presentation will share a status report of DML's most recent work. We will briefly summarize what can be done with the lightning data, and show examples of results from Texas, Louisiana, and Arizona.

2. This is a world map of average strike density, based on measurements from . I'll be using the term *strike* to refer to cloud-to-ground lightning, which is what we are interested in for exploration. Lightning *strokes* include both cloud-to-ground and cloud-to-cloud lightning. This map shows lightning occurring everywhere, but very rarely in polar areas and in some oceans.



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3. Lightning strikes are recorded by the National Lightning Detection Network (U.S.) and Global Lightning Dataset GLD360 (worldwide). These networks are owned and operated by Vaisala, a company based in Helsinki, Finland, which also makes the sensors. Many other countries have lightning detection networks often owned by national governments. Vaisala has supplied or installed lightning detection networks in 45 countries.

The number of lightning strokes worldwide is 40-50 per second. The NLDN detectors rely largely on the electromagnetic noise produced by lightning–which you can easily hear on an AM radio when there is a thunderstorm anywhere close–and usually record both the pulse itself, and (by using a radio direction finder) its direction. Most strikes are recorded by three or more sensors. The Global 360 network uses VLF receivers.

Every lightning strike is recorded. . .

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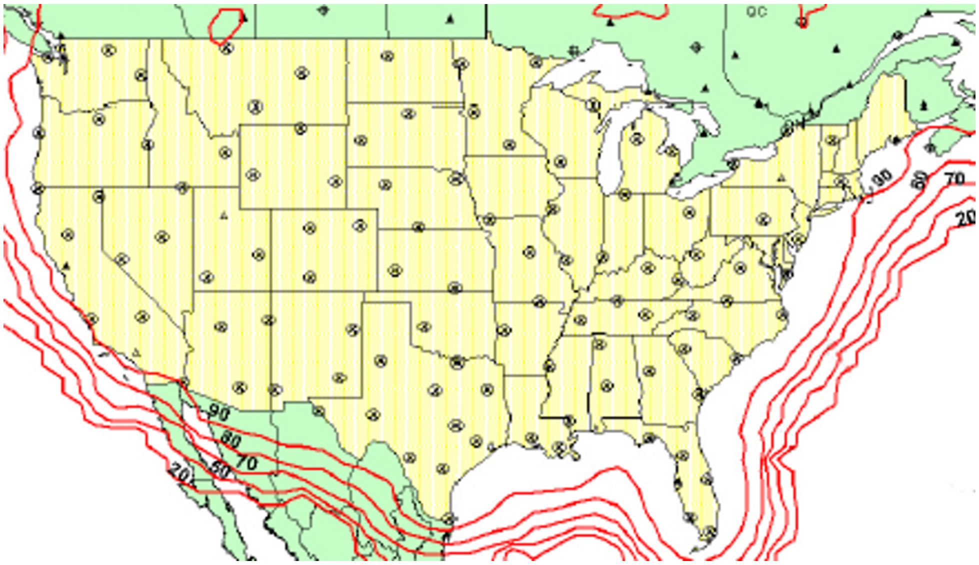
4. NLDN sensor locations. Contours give percentage of strikes detected. Note that more than 90% of strikes are recorded throughout the land areas of contiguous U.S., and for quite some distance out to sea along the east and Gulf coasts.



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5. The NLDN has been fully operational, with archives recorded, since January 1998

16 years contiguous U.S.

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6. The Global Lightning Dataset GLD360 network has been operational since July 2011

3+ years worldwide

7. What are the actual values recorded by Vaisala and supplied to DML? While the detectors can record complete waveforms, the bandwidth of data channels limits the amount of data actually saved in the database. Worldwide, there are 40-50 lightning strikes per second. We will go through the actual data items available. Some are actual measurements of each lightning stroke; some are estimates of the reliability or accuracy of these measurements.

What is recorded?

8. First, the measurements. The date at the prime meridian.

Date

9. Time at the prime meridian.

Time

10. Times are recorded to the nearest millisecond. There could be an argument that this is not accurate enough: the duration of a typical lightning strike is less than 0.01 ms.

to the nearest millisecond

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11. The same time zone is used worldwide for recording lightning data.

Both time and date in UTC

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12. The location of a strike is recorded as latitude and longitude on the WGS84 spheroid: EPSG 4326.

Latitude & Longitude

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13. The accuracy is to four decimals of degrees. For latitude, 0.0001° is approximately 11.1 m. At 30° latitude, 0.0001° longitude is about 9.5 m

±0.00005°

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14. Then there is the actual lightning information, the characteristics of an individual strike. What does an actual lightning strike look like, from an electrical point of view? We will be simplifying it because we do not have full waveform data.

The actual lightning strike

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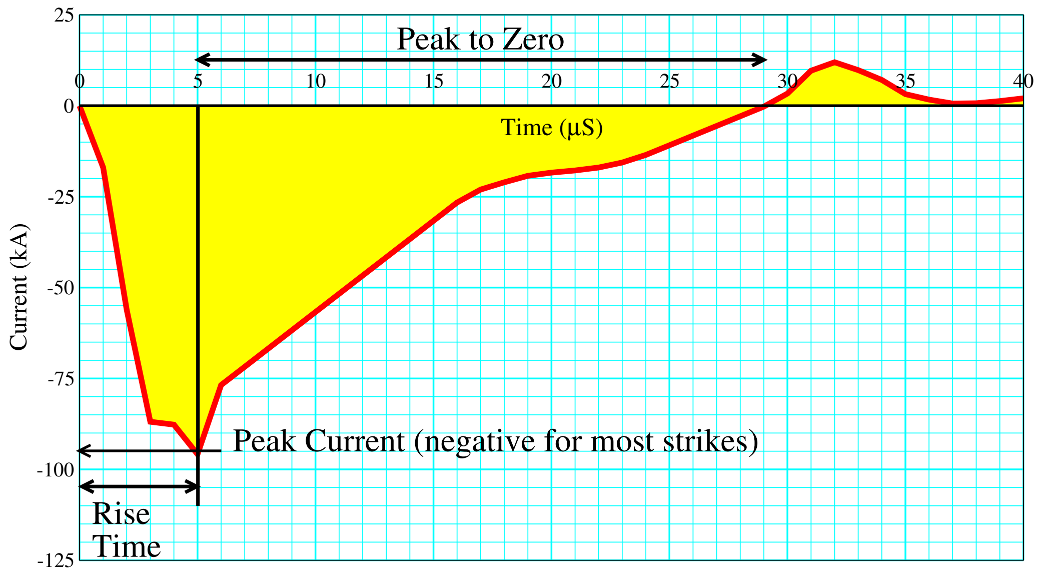
15. This slide shows a negative strike, because that is what about 90% of strikes are. This is a plot of current, in kiloamperes, versus time, in microseconds. The time of the strike is the instant of the peak current, though you can't be pedantic about this because the whole strike lasts less than 100 microseconds and the time of the strike is only recorded to the nearest 1000 microseconds.



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16. Peak current is the maximum value of current measured for the lightning strike. Measured values range from about -300 kA to +450 kA, but most are between -50 kA and -5 kA. Lightning strikes with the absolute value of peak current less than 5 kA are rarely recorded.

Peak current

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17. Values for peak current are given to the nearest 0.1 kA.

$$\pm 0.05kA$$

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18. Rise time is the time from when the lightning pulse rises above the background noise until the instant of peak current. Values typically range from 0.5 µs to 30.5 µs. Some lightning strikes do not have valid rise times recorded, so these strikes cannot be used in any analysis where rise time is used.

Rise time

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19. Rise time is supplied with a precision of 0.1 µs.

$$\pm 0.05\mu s$$

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20. Peak to zero time is the time from the instant of peak current until the signal disappears into background noise. The end of this time interval is often uncertain, and Vaisala has in recent years used an arbitrary cut-off value of 30.2 µs. Few strikes have valid values less than 5 µs.

Peak to zero time

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21. This too is measured to the nearest 0.1 µs.

$$\pm 0.05\mu s$$

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22. That is all the actual measurements we get for the lightning strikes. We do get four additional parameters which are not actual lightning strike measurements, but are evaluations of how accurate and reliable the data might be.

Some quality control data…

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23. The first of these is the value of χ^2 for the correlation between sensors of the data recorded for the same stroke at the different sensors detecting the strike. Values typically range from about 0.1 to 15.0.

χ^2 for the correlation of data between sensors

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24. The uncertainty in the location of a strike is given as an ellipse defining the limits, with a 97.5% probability. The azimuth of the major axis is determined during analysis, but is not included in the archived data.

An ellipse of location uncertainty (6σ)

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25. The parameters of the ellipse recorded are the lengths semi-major and semi-minor axes of the ellipse. Obviously, if one or both of these ellipses is very large–and values over 30 km are occasionally seen–the location of that strike is quite uncertain. But in most areas more than 95% of semi-major axis values are less than 5 km, and often 95% are less than 2.0 km.

defined by semi-major and semi-minor axes

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26. The measurements are givent to the nearest 200 m.

$$\pm 100\, m$$

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27. The number of sensors used in measuring each lightning strike is the last parameter. Typically, 80-90% of strikes are detected by three or more sensors, with most strikes being detected by 3-10 sensors. Occasionally, a strike is detected by more than twenty sensors.

Number of sensors used for measuring the strike

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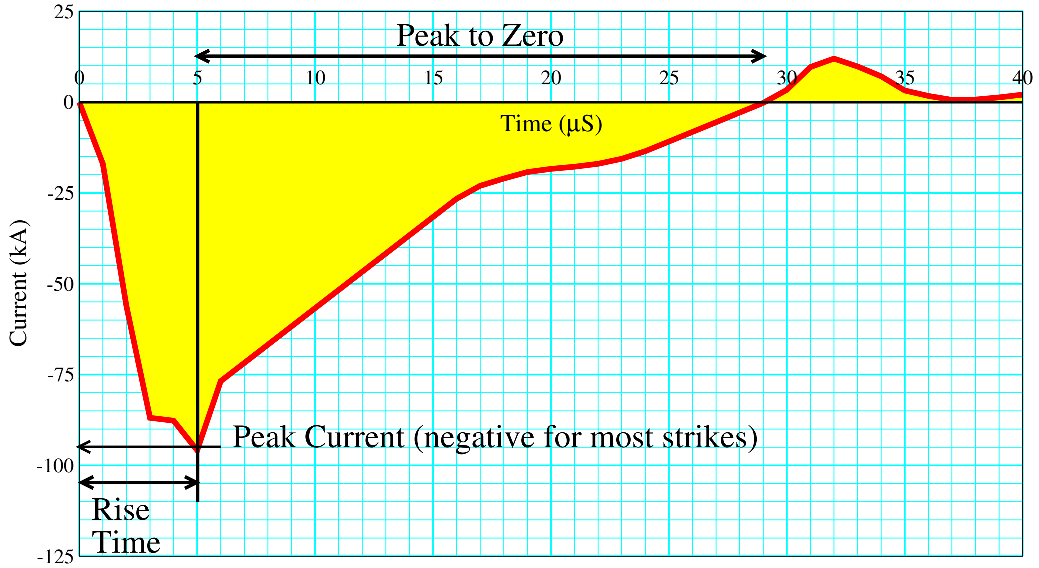
28. Remember, these are the measurements we have of each lightning strike: rise time, peak current, and peak to zero time. Of course, we also have the location and precise time of each strike.



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29. What can we do with this data that might give us geological information?

What can we do with this data?

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30. Just using the locations, we can map the variation in areal density of lightning strikes. Some places have more strikes than others, and it is not always due to something other than geology.

Map strike density

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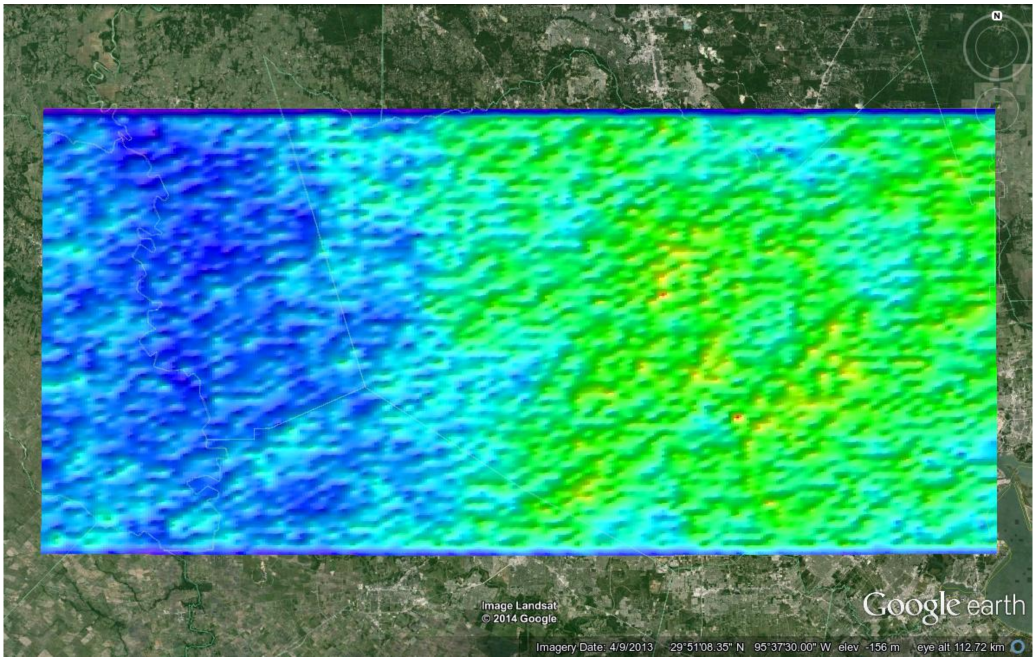
31. This is a map of lightning density for an area covering most of Harris county and extending west to about Sealy. The color scale is a rainbow spectrum ranging from zero to 95 strikes per square kilometers per year. Dark blue is 20, orange and red are 80 to 95.



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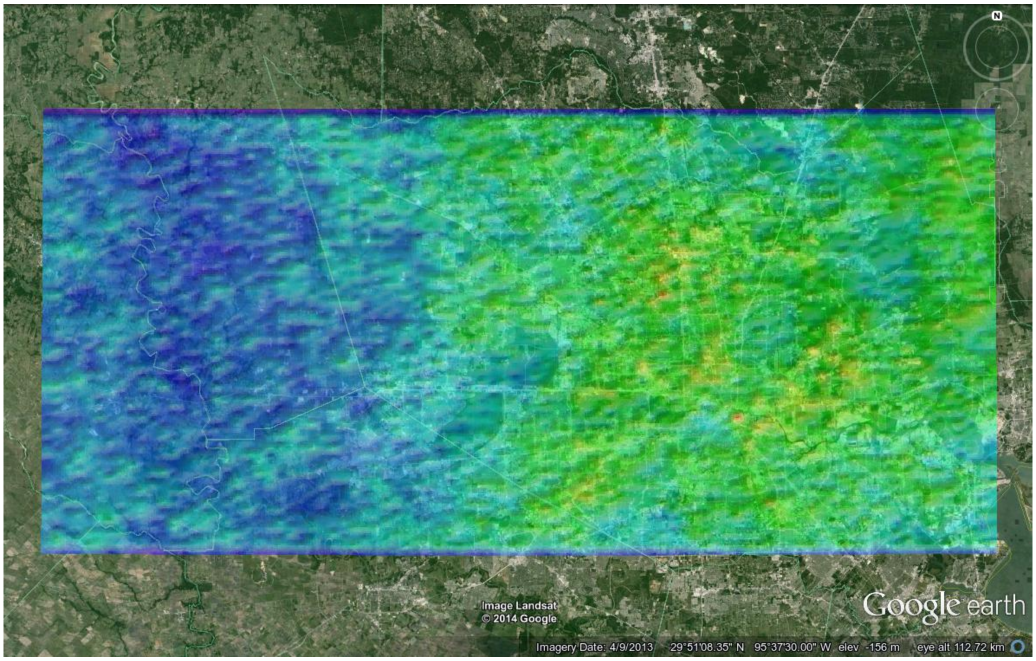
32. Making the map transparent allows us to see some of the places you probably know.



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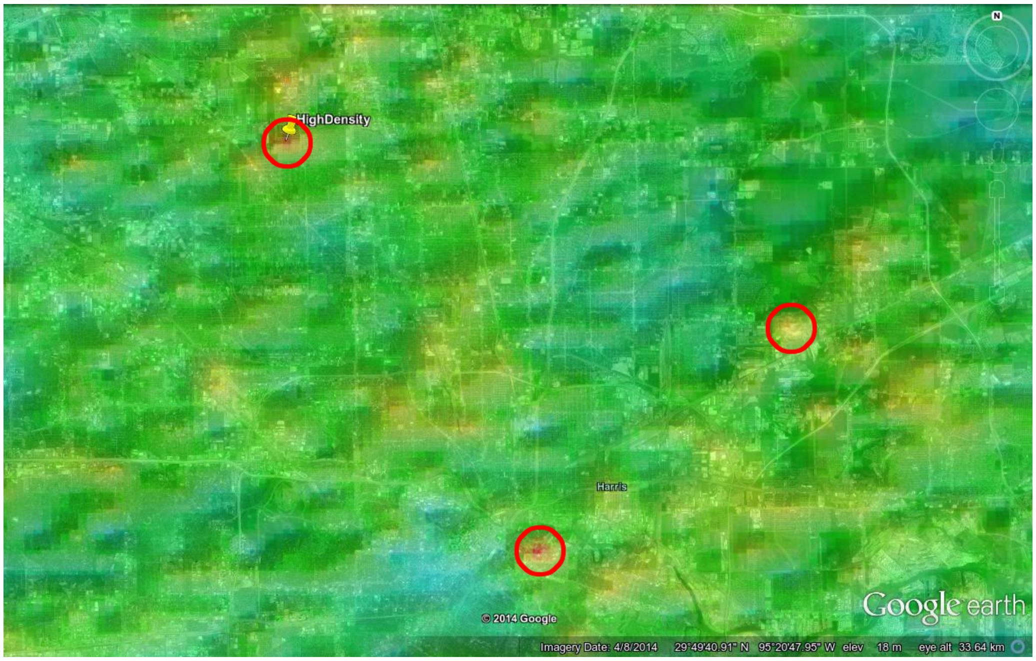
33. Let us zoom in to a few of the high density spots. There is one just near downtown Houston, one just south of 249, a mile and a half west of 45, and one just north of the Beaumont Highway, between 610 and Beltway 8.



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34. The one near 249 is easily explained: it is centered on a tall communications tower.

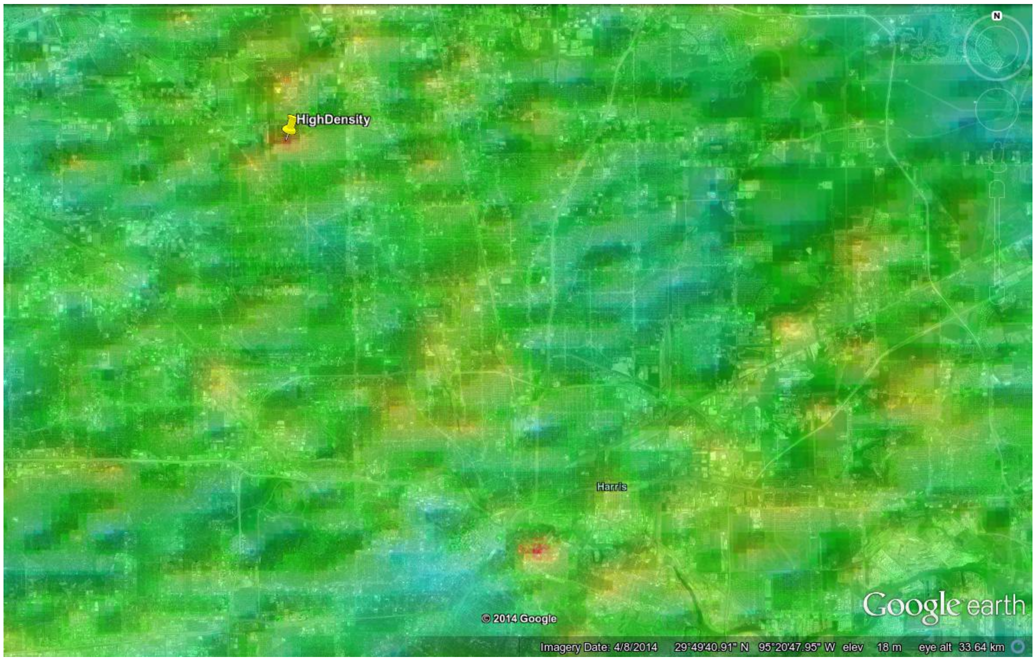
35. The one near the Beaumont Highway is obvious too: it is a close match to a major landfill. But why would a landfill attract lightning? Could it be because it leaks methane? Or is it just because it is a low hill in an otherwise flat region?

36. The one near downtown is also easily explained. It is not one of the tall downtown buildings (the tallest of which, Chase Tower, is around a thousand feet). It is located in an area of single storey warehouses and factories on Canal Street, between Nolan and North Palmer. The big difference with this one is it is not at all obvious on GoogleEarth.

The actual downtown area has a slightly lower strike density than most of its surroundings, and the spectacular Williams Tower, by far the tallest structure for several miles, appears to have had no affect at all on the lightning density.


2207

37. We need to look carefully at lightning clusters to make sure they are not explained by some obvious object in the infrastructure. How many other clusters on this image are caused by high towers?



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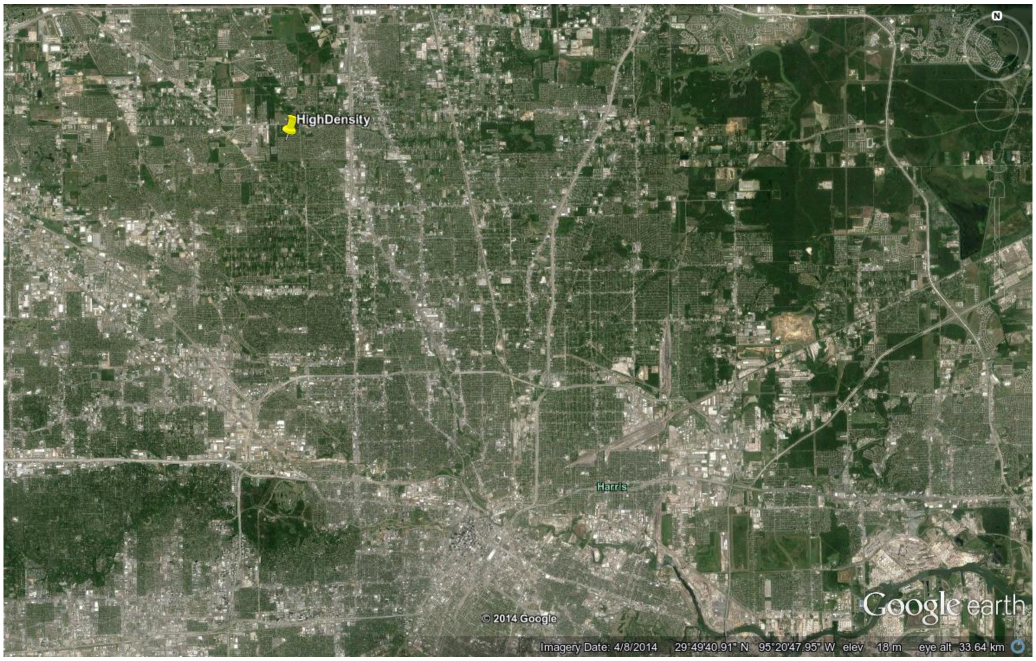
38. Here is the same view without the lightning data.



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39. We can map variations in average peak current in lightning strikes.

Map peak current

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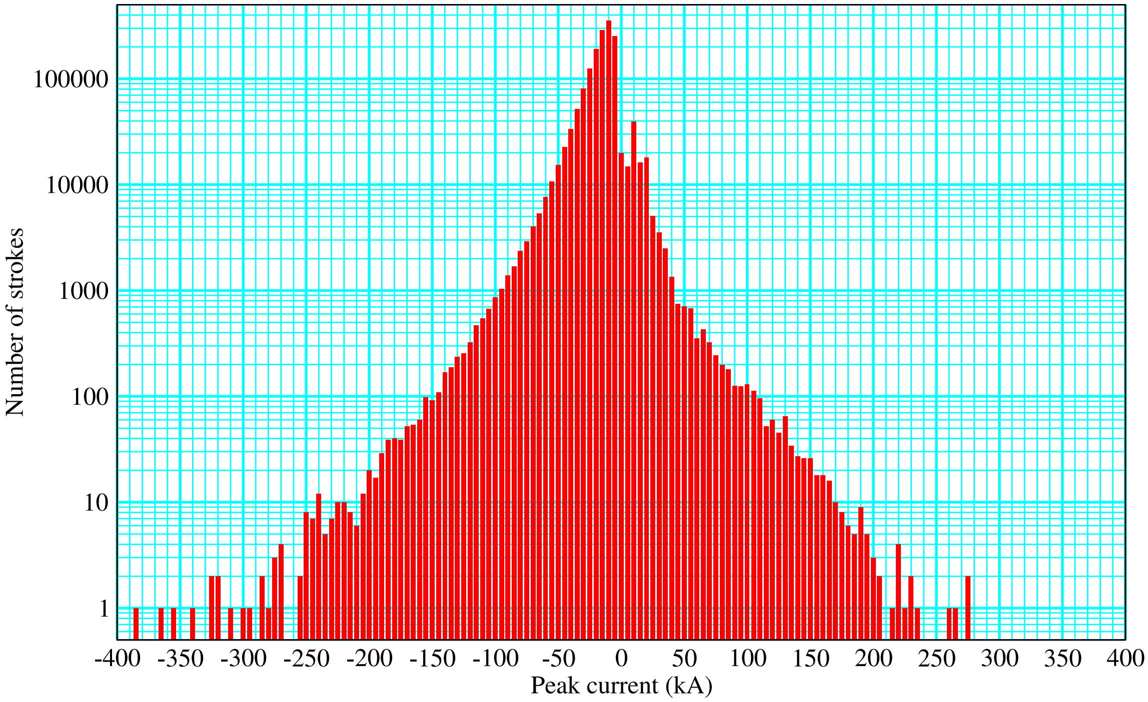
40. But there are some problems with handling peak current. We need to look at them

Before doing that we need to look at peak current a bit more closely. . .

41. This is a histogram of the number of lightning strikes as a function of peak current, in 5 kA steps. The area of this project is the Harris County data set of about 1.6 million strikes. Between -10 kA and -5 kA there are 350,000 strikes (the peak number of negative strikes), and between 5 kA and 10 kA there are 40,000 strikes (the peak number of positive strikes. But averaging the positive and negative values will not be very helpful. We need to consider the absolute peak current, or to handle positive and negative strikes separately. We usually do both.



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42. In other words, we need to separate the positive and negative or ignore the sign.

If we're going to make a map of these values, we need to separate positive and negative values

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43. We ignore sign by combining the positive and negative strikes, taking the absolute value of the negative strikes.

The simplest way to do this is to take absolute values

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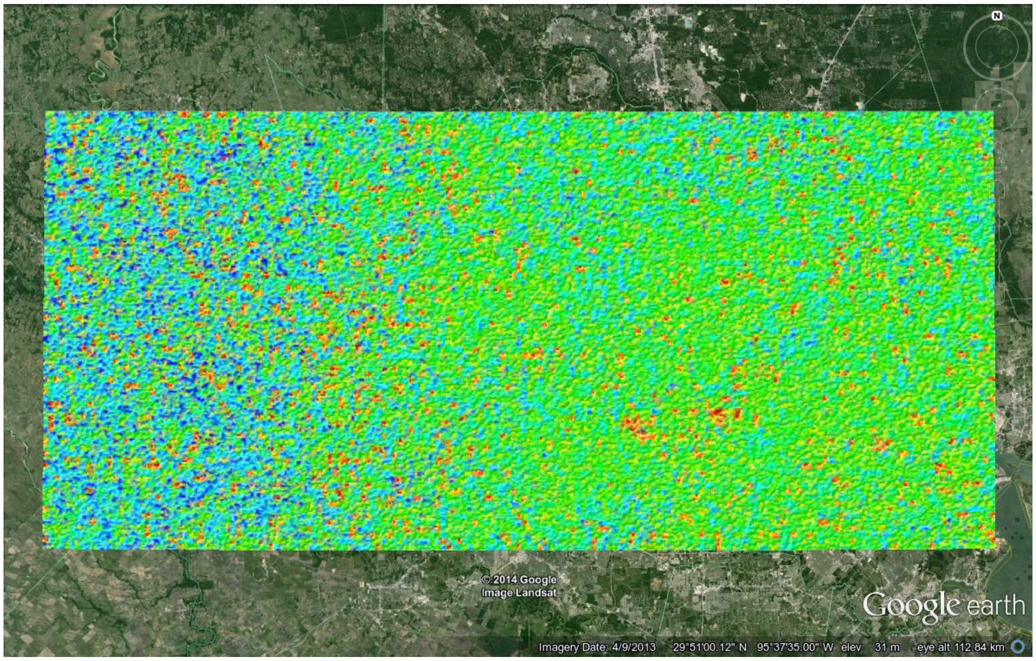
44. Here is the map of the variation in peak current over the Harris County project. Red spots have an average peak current of 30 kA, dark blue is 15 kA.



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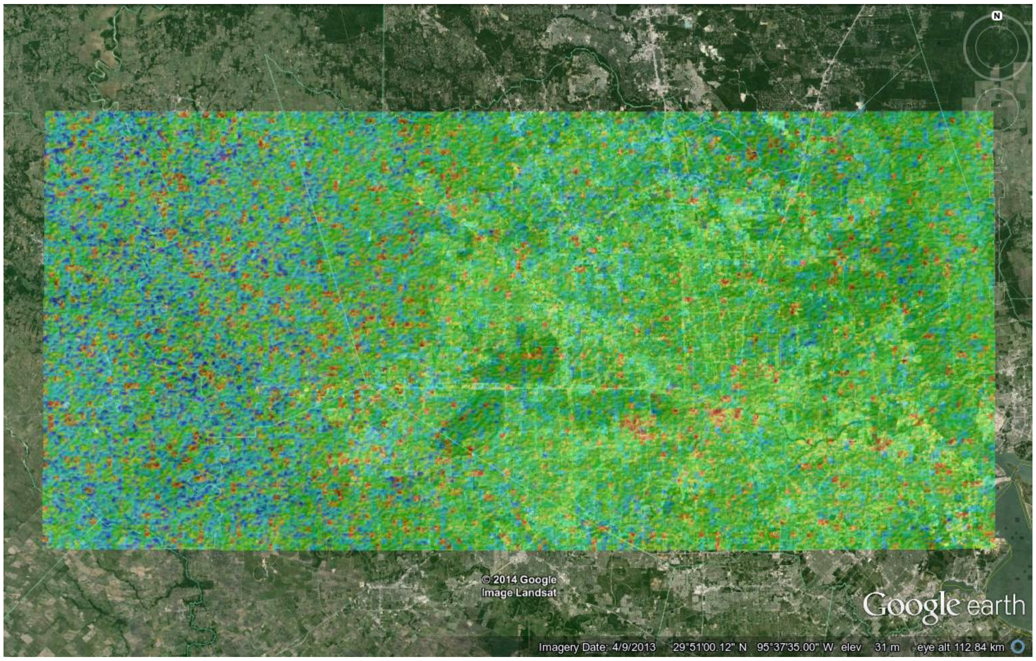
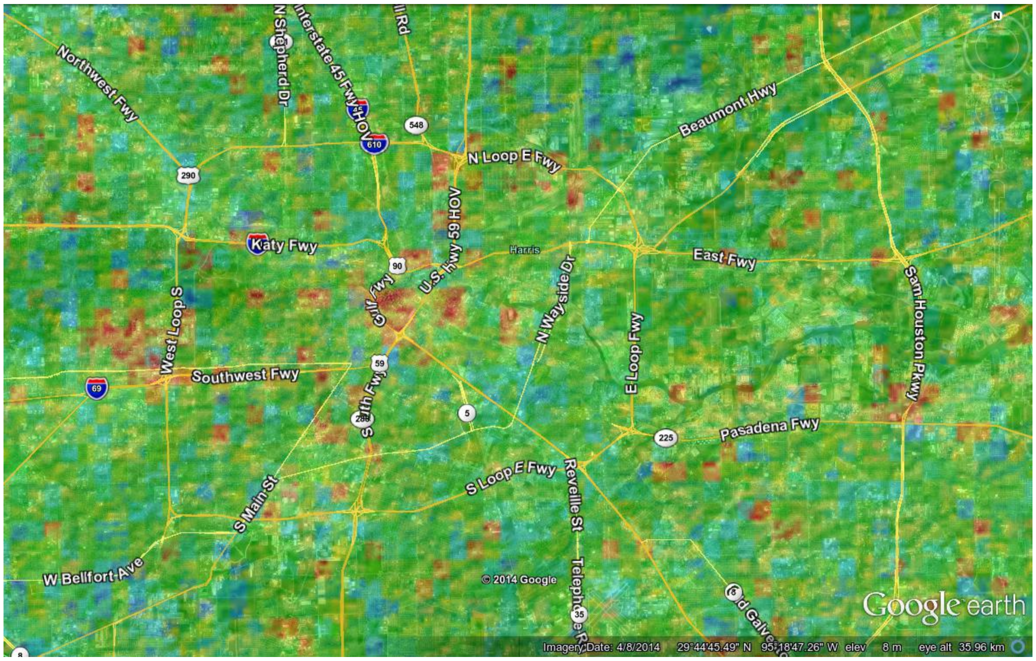
45. The same, with some transparency so we can see the locations of some of the anomalies.



46. The same, zoomed in, and with main roads. The tower near 249 has no anomaly. The landfill on Beaumont road has no anomaly. But that spot east of downtown, which had anomalously dense lightning strikes, also has anomalously high peak current. Downtown and the Galleria area also have anomalously high peak current. So also has Bayou Bend.



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47. Rise time is the next parameter we can map.

Map rise time

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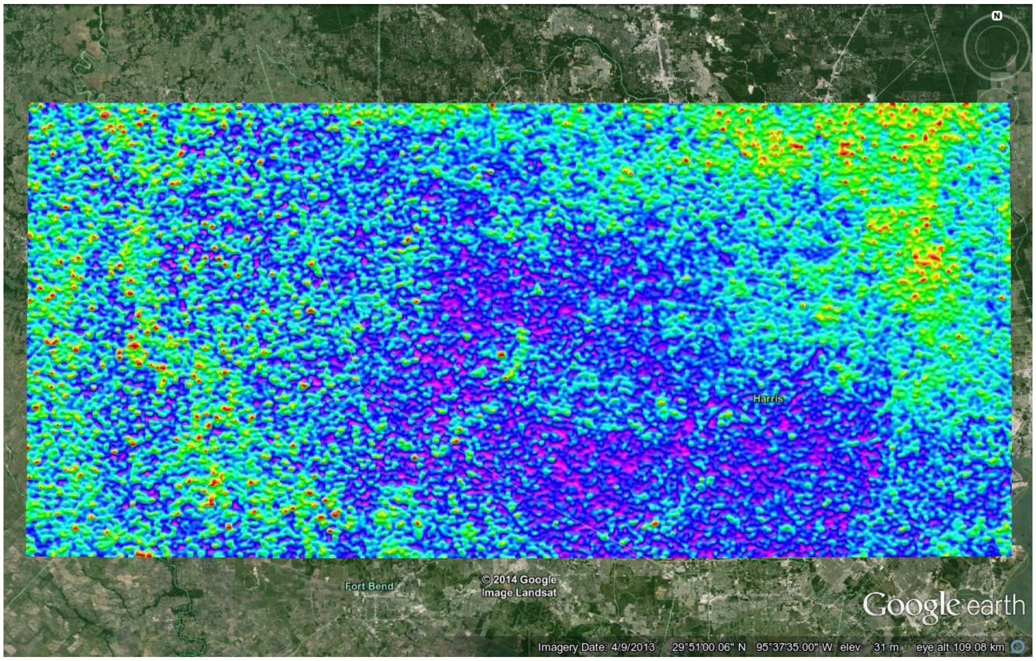
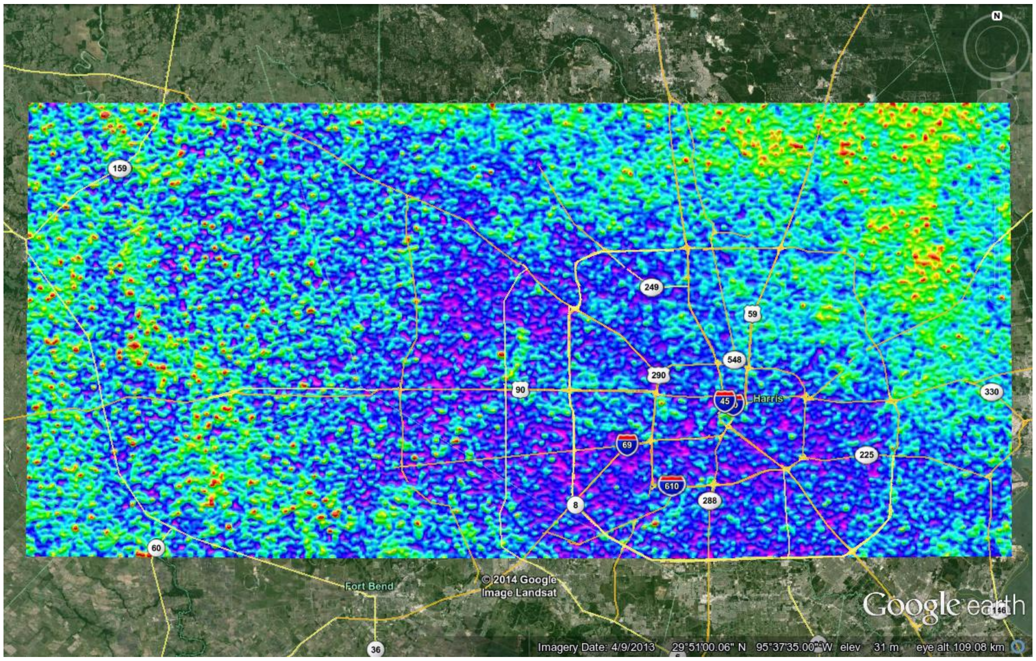
48. Here is the same project, showing rise time. Red is 5.0 µs, magenta 2.8 µs. Note in particular the meandering line of high values running from north to south in the western quarter of the map. This closely matches the Brazos River. In general, short rise times tend to be associated with grassland and developed areas, and long rise times with forested areas. In some places the boundary between a park and a subdivision is very closely aligned with a change in rise time.



49. This is the same map with main roads added.



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50. The final primary attribute is peak to zero time.

Map peak to zero time

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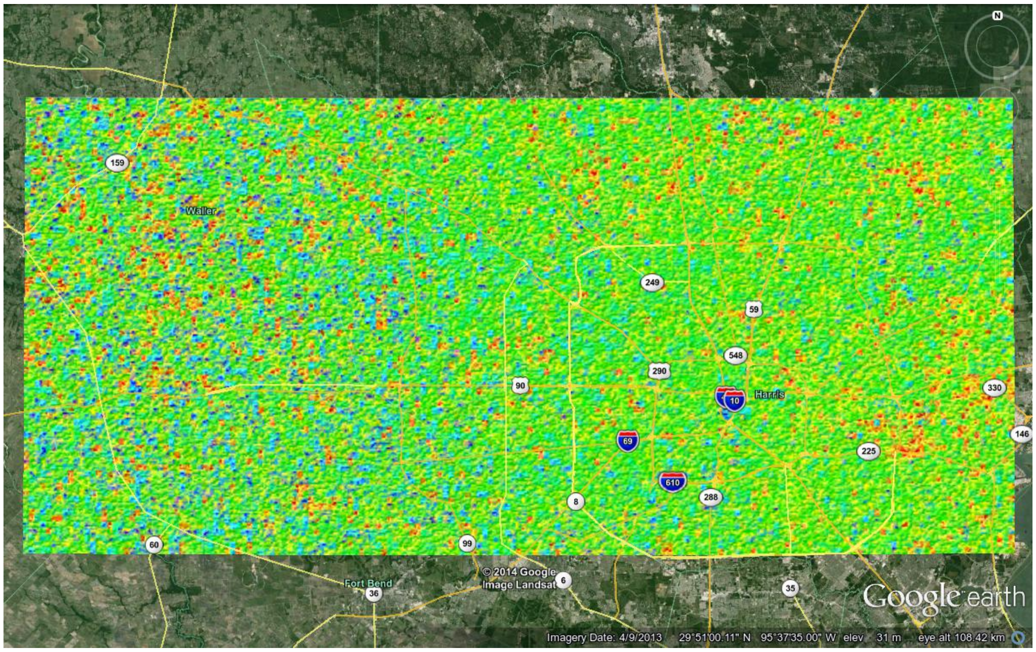
51. This attribute does not seem to have any obvious correlation with surface features. The Downtown area has anomalously short times, and the petrochemical industrial areas along the Ship Channel have some anomalously long times, but there is no consistency. The tall tower near 249 has no anomaly, neither does the landfill on Beaumont Highway, and there is nothing anomalous over the high density area east of Downtown.



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52. That is a brief summary of mapping the basic parameters recorded for lightning strikes: location (summarized in strike density), peak current, rise time, and peak-to-zero time.

That about covers the basic parameters we can map

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53. But just doing this is like using gravity measurements with out free air or Bouguer corrections, or using aeromagnetic data without leveling.

It’s like using gravity without any corrections, or just looking at raw magnetic intensity

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54. We can compute additional attributes by combining the measured values in various ways, or by combining them with known environmental values, such as the time of day, the tidal gravity variation, and so on. We can also select subsets of data on the basis of these variables.

But we can do more by computing derived attributes, or by using subsets of the data, or by looking at the value of environmental variables at the time of strikes

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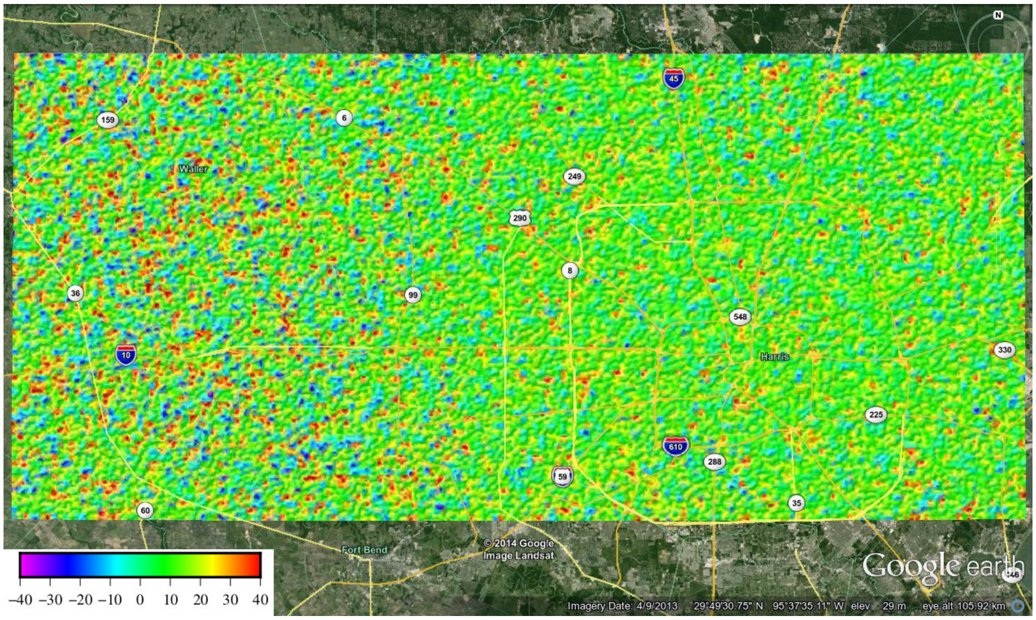
55. A simple example of a derived attribute is shown in this slide. We have calculated the tidal gravity (in microgals) at the time of each lightning strike, and gridded the resulting points. There are no anomalies of possible geological significance here. The scale gives values in microgals.



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56. We started off with Harris County because just about everyone here is familiar with it. Now let us look to the east, to some results of real geological significance.

Now we will look at another area: Iberia Parish, Louisiana

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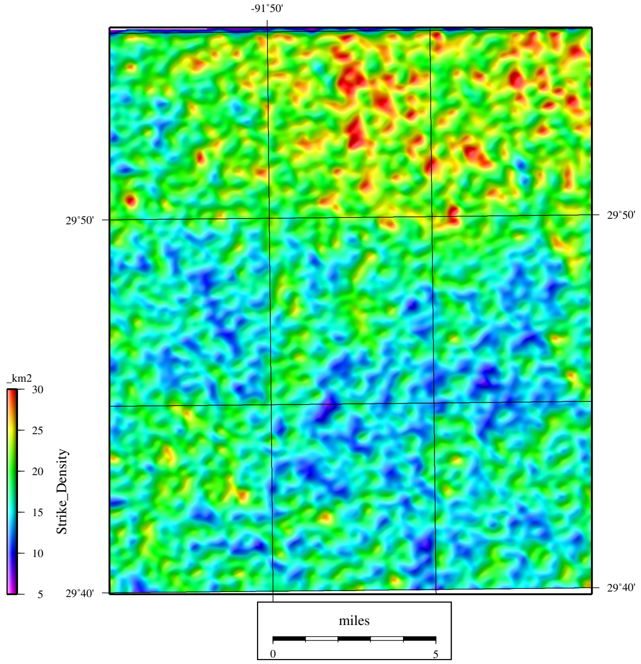
57. First, we look at the strike density map. The strike density within this small area varies from around five strikes per square kilometer per year to over thirty. There are definite highs and lows, probably with geological significance. This is an area near enough to sea level, apart from three shallow salt domes, which are not obvious in this map. So we will look at the next recorded attribute, rise time.



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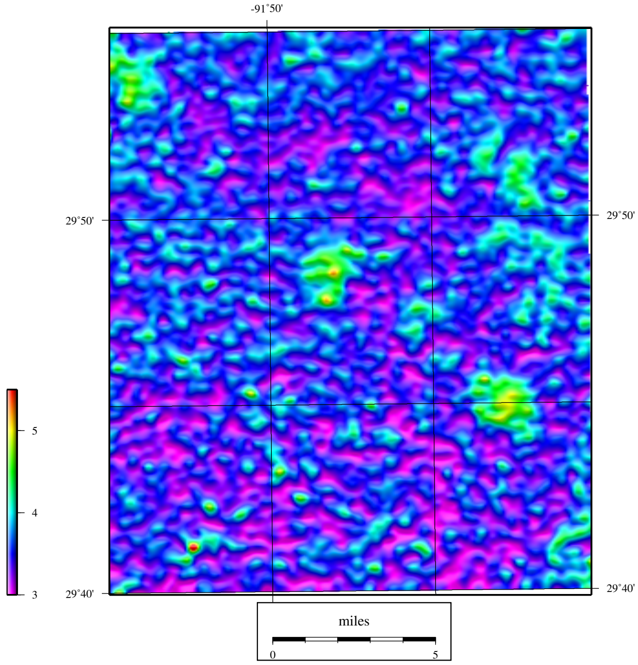
58. The three shallow salt domes are now clearly visible as areas of anomalously long rise times.



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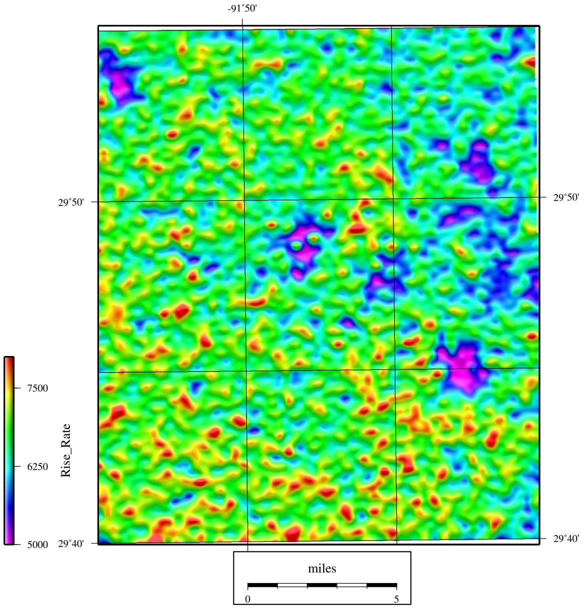
59. A computed attribute makes them just as obvious. This is rise rate, the peak current divided by the rise time.



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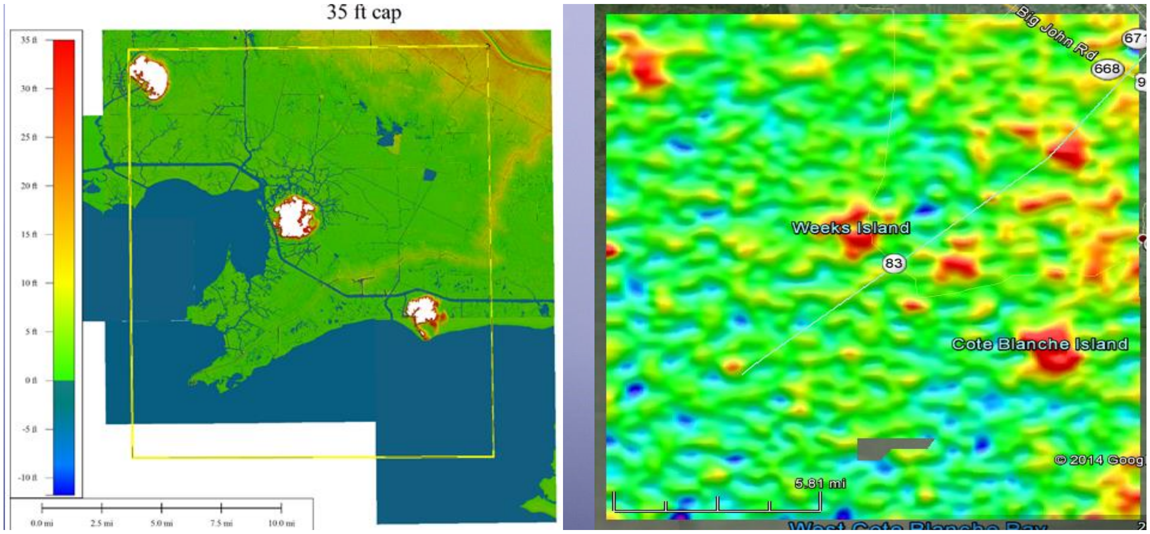
60. Here we compare the rise time map and a Lidar map. Note that the lidar map shows that each of the salt domes has significant topographic relief (significant for Iberia Parish is about 10 m), but this relief did not result in any increase in lightning density.



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61. Now we will talk some more about computed attributes, more complex computed attributes.

About computed attributes…

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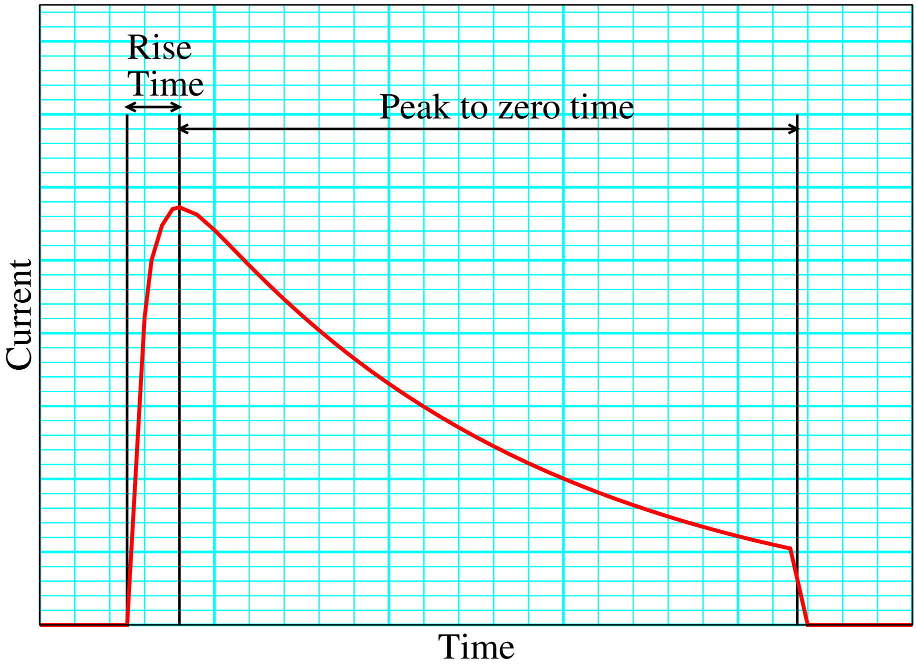
62. Here is a somewhat notional plot of the current in a lightning strike as a function of time. The rise time is probably not a straight line, but something resembling an exponential approach to the peak value. The peak to zero time is definitely not a straight line, but is more like an exponential decay. The end of it is either a disappearance into background noise, a oscillatory tail (like a seismic trace following the first break), or a sudden drop to zero when the current is no longer large enough to keep the path through the atmosphere ionized. The few full waveform recordings we have seen suggest the oscillatory tail is most common.



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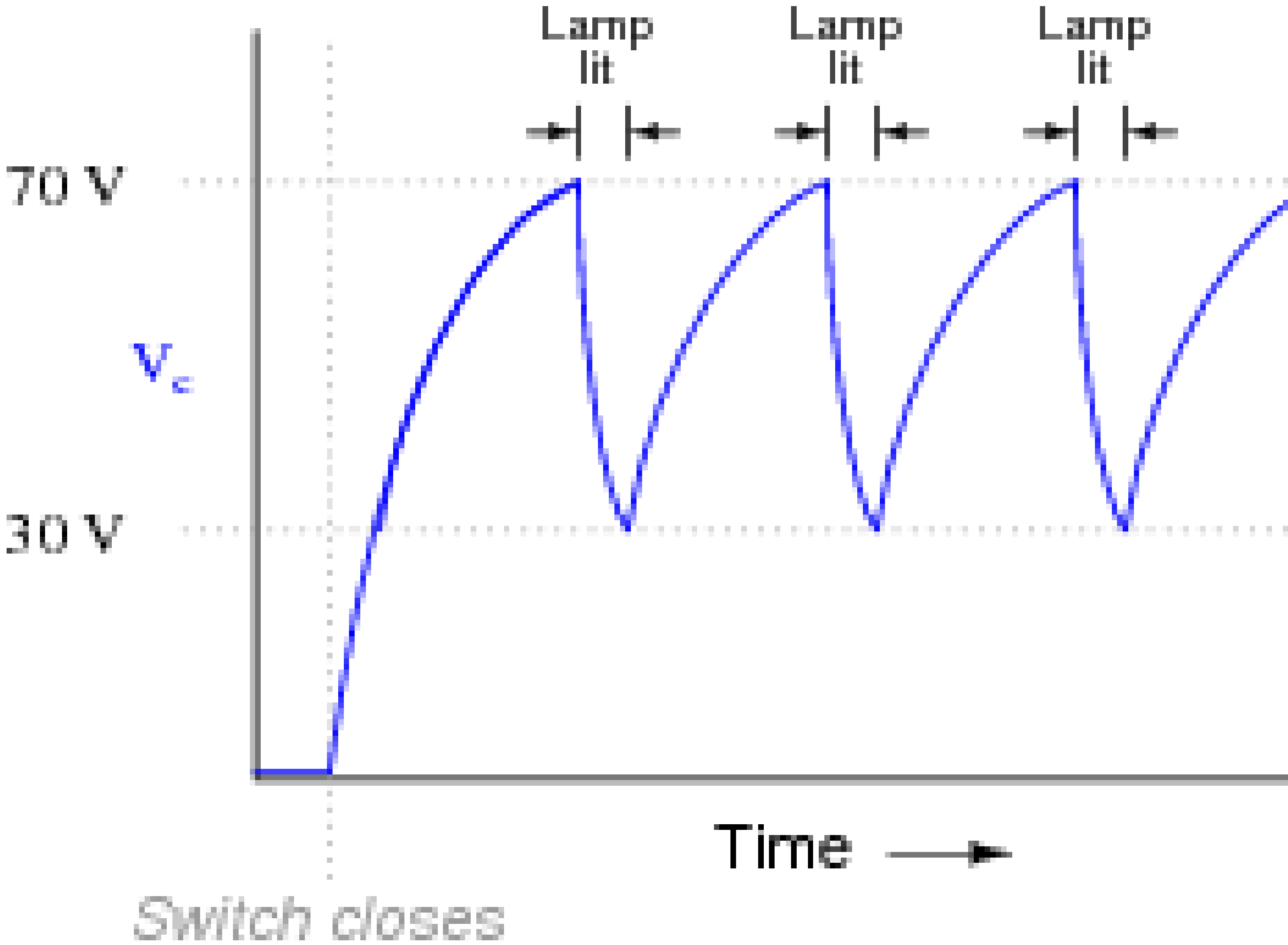
63. That general appearance suggested an analog to lightning. This is the waveform of the voltage across a neon tube in a simple circuit.



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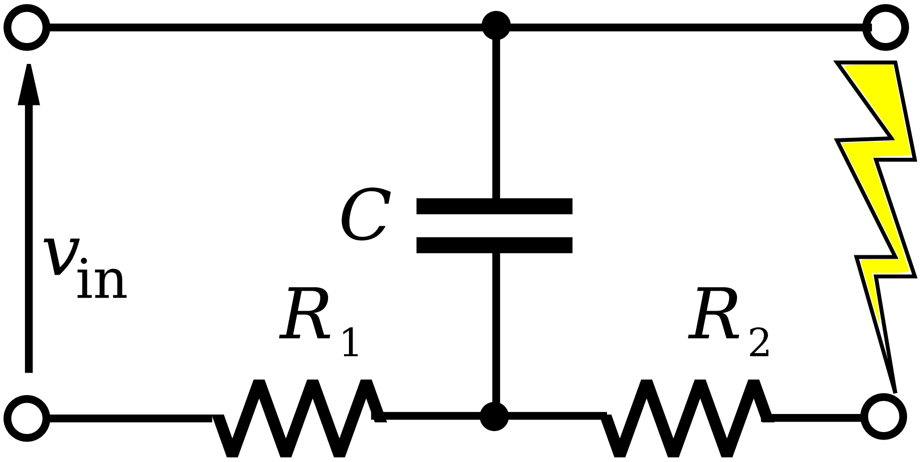
64. Here is the circuit: the Pearson-Anson relaxation oscillator, invented almost a century ago. An input voltage charges the capacitor C through the resistor R_1 until the gas in the tube breaks down, and the capacitor discharges through the ionized gas and through R_2. The length of the rise time depends on R_1, the length of the peak-to-zero time depends on R_2. In the lightning analogy, the input voltage is supplied by the separation of space charges within a cloud, usually by updrafts within the cloud. The (generally negative) charge at the base of the cloud is responsible for

most cloud-to-ground lightning. As the charge builds up at the base of the cloud, a matching positive induced charge forms at the ground surface under the cloud. The cloud base and the ground surface form the two plates of a capacitor, with the atmosphere forming the dielectric. When the atmosphere between the cloud and the ground ionizes, the capacitor discharges through R_2, which is the resistance of the ground material at and under the ground surface.



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65. The analog is important, because if the decay of current is exponential, we can define the curve. The starting point plus one other point on an exponential decay completely define the curve. We have the starting point–the instant of peak current–and the second point is the end of the peak-to-zero time.

Two points on an exponential decay define the curve

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66. The decay of current in a relaxation oscillator is exponential.

When a relaxation oscillator triggers, the discharge current decays exponentially

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67. The rate of decay is given by a simple equation.

The rate of decay is given by

$$I_t = I_0 e^{-t/RC}$$

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68. So if we accept the analogy between lightning and a relaxation oscillator, can we use this equation to define the value of R_2 in the case of lightning?

If lightning is similar, can we use the decay to measure resistance?

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69. Resistance is what we are interested in, so a little rearrangement of terms is needed.

This equation can be rearranged to

$$ln(\frac{I_t}{I_0}) = -\frac{t}{RC} \text{ or } R = -\frac{t}{ln(\frac{I_t}{I_0})C}$$

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70. We need the current at two times, and the capacitance, to get the resistance.

All we need is the current at two times (I_0 and I_t), and the capacitance (C) to get the resistance R

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71. It is quite obvious we have to make some assumptions: we don't know the current at the end of peak-to-zero time, and we don't know the capacitance.

Some assumptions to be made…

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72. If the capacitor is formed by the cloud base and the ground surface as the two plates, we need area of the plates, their separation, and the dielectric properties of the atmosphere. Fortunately, we know the electrical properties of air quite well, and they do not change much with humidity or temperature. But we do have to make some assumptions about cloud height, and the shape and size of the capacitor plates.

Capacitor formed by cloud base and ground surface

Capacitor plate shape and size?

Cloud height?

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73. We assume that within a small local area the cloud height is proportional to the peak current, and that the capacitor plates are circular with a radius proportional to cloud. This is, of course, an oversimplification. But if we use the same assumptions all the time, we should be just introducing some uncertain scaling factors.

Cloud height proportional to peak current

Capacitor plates circular with radius proportional to plate separation

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74. We also make an assumption that the measurements of resistance we get in this way include rocks down to a depth proportional to cloud height.

Resistance measurements include rocks down to a depth proportional to cloud height

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75. Because we have a large archive of lightning strokes available, we have many lightning strokes within a small area. For example, almost everywhere in the Houston area receives at least twenty lightning strokes per square kilometer per year, so there are over three hundred strokes per square kilometer in the sixteen year archive. An area 200 meters square has more than ten strikes. Each of these strikes will give a different estimate of resistance.

Multiple resistance measurements within a small area

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76. Because these measurements are each associated with a calculated depth of investigation, we can estimate apparent resistivity as a function of depth.

Estimate apparent resistivity vs. depth function

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77. We can do this anywhere we have access to this kind of lightning archive. That includes all of the U.S., Canada, and a number of other countries.

Anywhere

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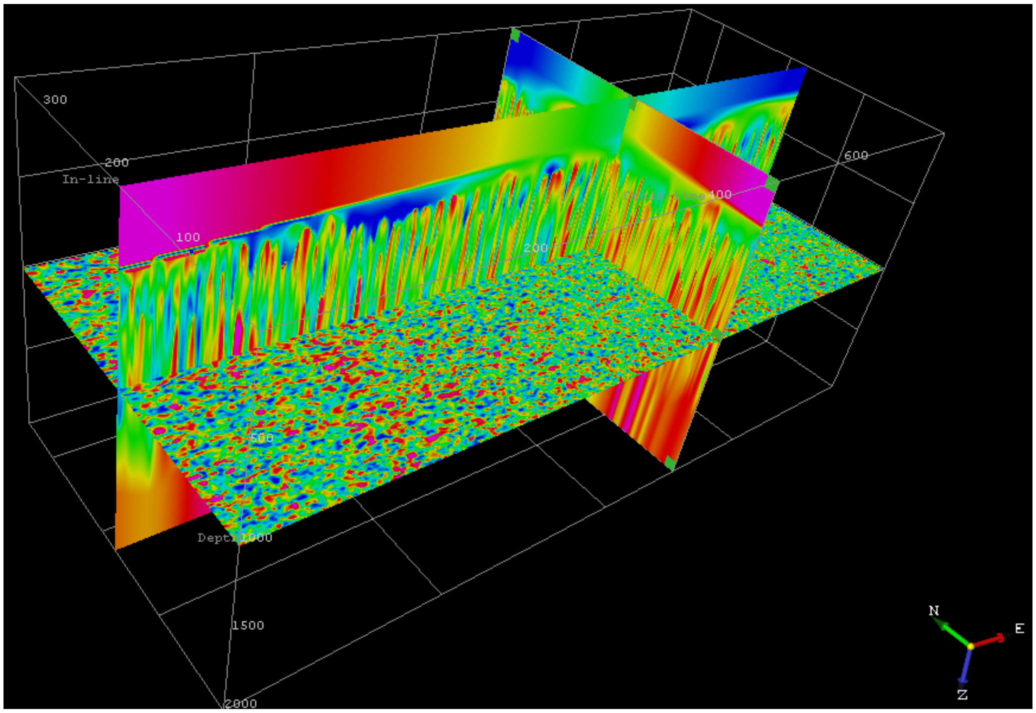
78. If we can calculate resistivity versus depth anywhere, we can calculate 3D volumes of resistivity, and put them into a form usable by seismic interpretation systems. Note that there is a minimum depth of useful information: this corresponds to the lowest energy lightning strokes; and a maximum depth of useful information, corresponding to the strongest lightning strokes.



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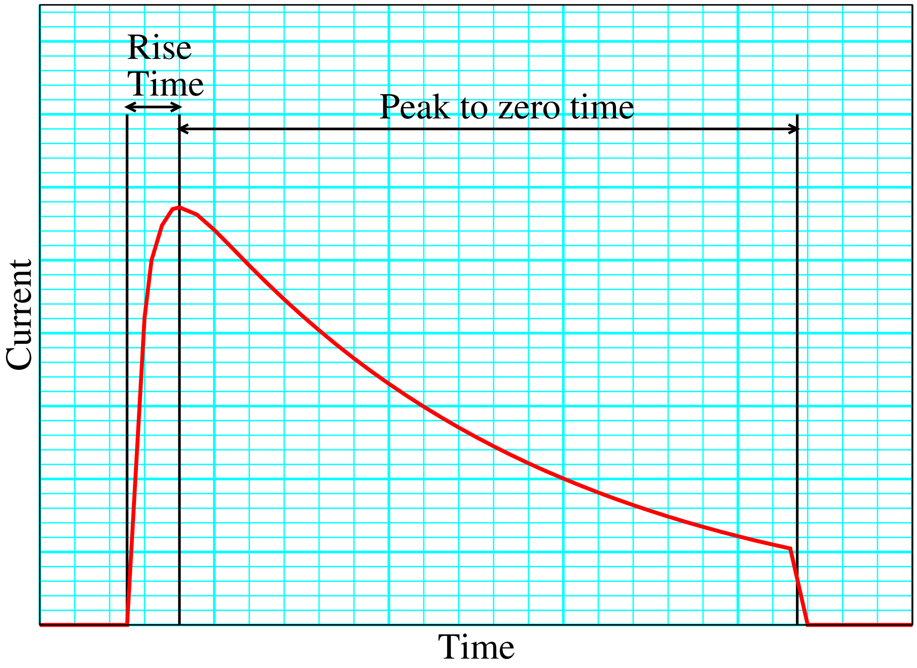
79. Now go back to our notional picture of lightning current as a function of time. That rise time is also an exponential function.



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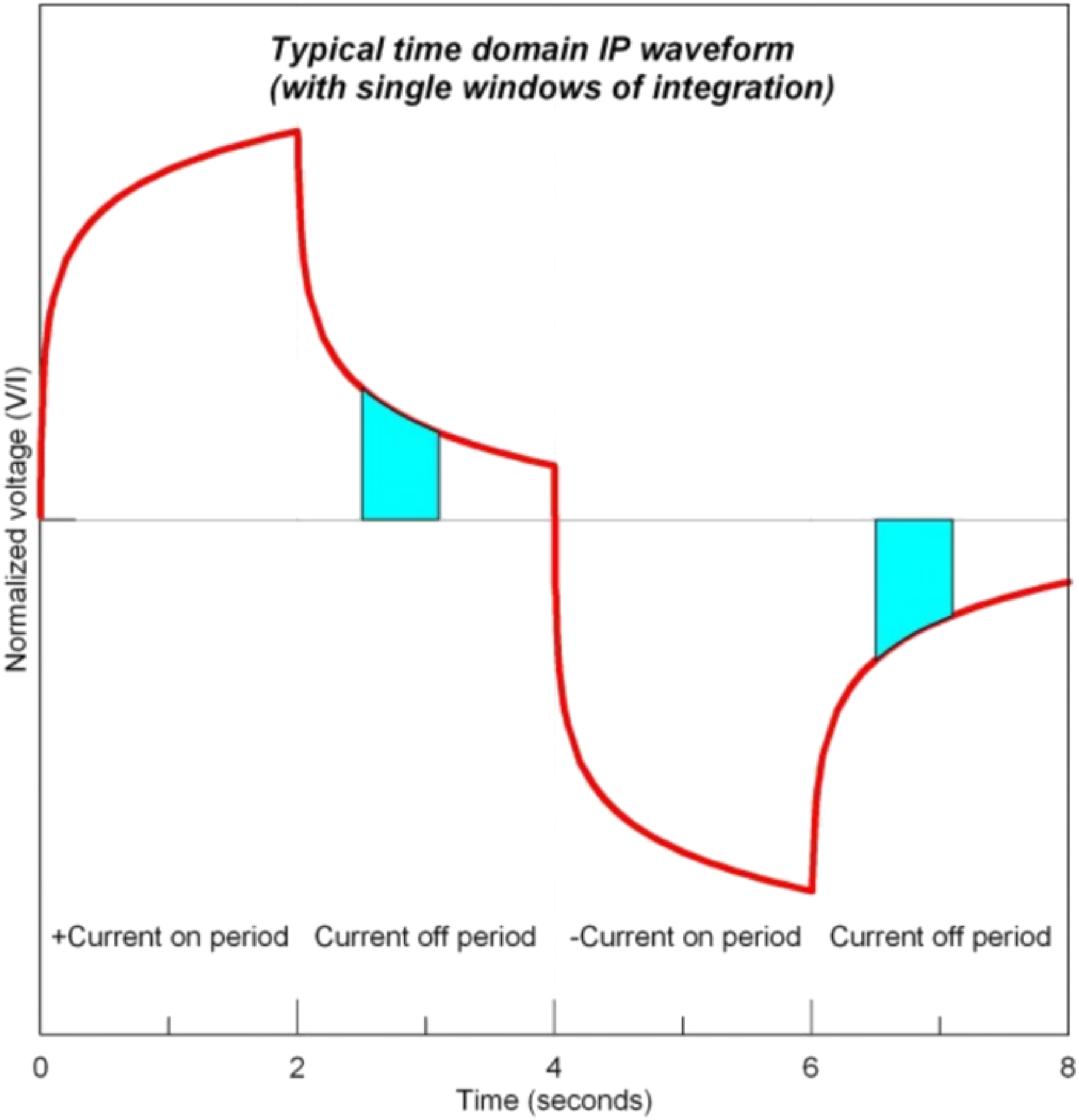
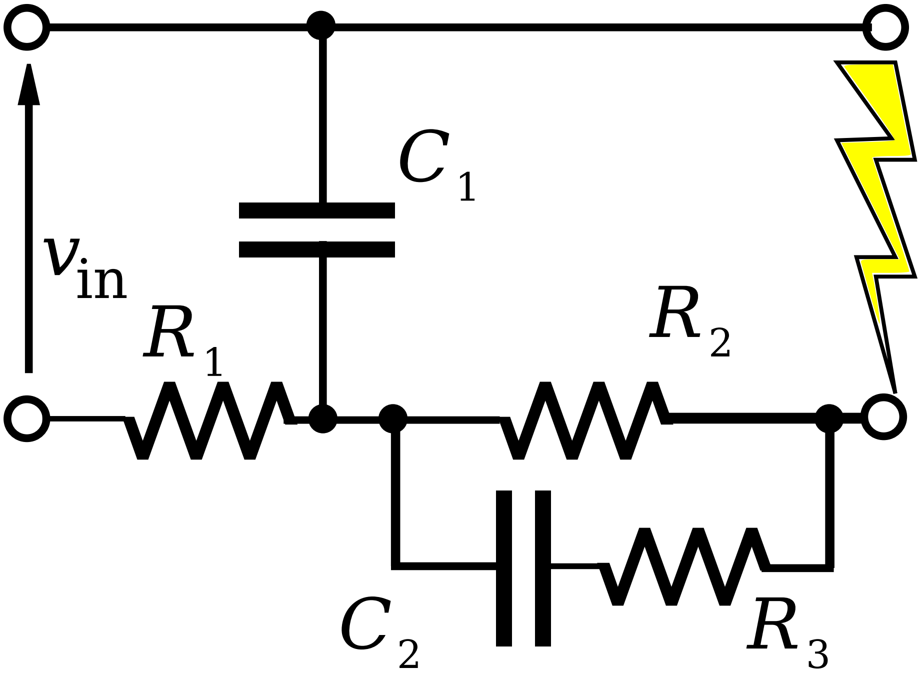
80. Look at this plot, courtesy of the U.S.. It is the typical time domain IP waveform. A very similar shape. Apparent permittivity can be calculated from either the rising curve or the falling curve. We cannot use the falling curve, because our input is not a square wave. But we do have a nearly vertical onset, so we can calculate something which we can call apparent permittivity from the rise time.


Typical time domain IP waveform
(with single windows of integration)
Normalized voltage (V/I)
+Current on period
Current off period
-Current on period
Current off period
0
2
4
6
8
Time (seconds)

81. The equivalent circuit is something like this, where the capacitor C_2 represents the capacitative effect which gives a non-zero rise time.



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82. The mathematics of this are similar to the mathematics for the resistivity calculations, and they can give us values for permittivity. This is one of our latest developments: it is approximately thirty days old.

If we consider C_2 as a distributed capacitance, we can compute apparent permittivity

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83. As with resistivity, these calculations can produce data volumes, and they can be produced anywhere we have access to lightning data archives.

Anywhere

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84. Now I will show some examples of recent projects.

Some examples

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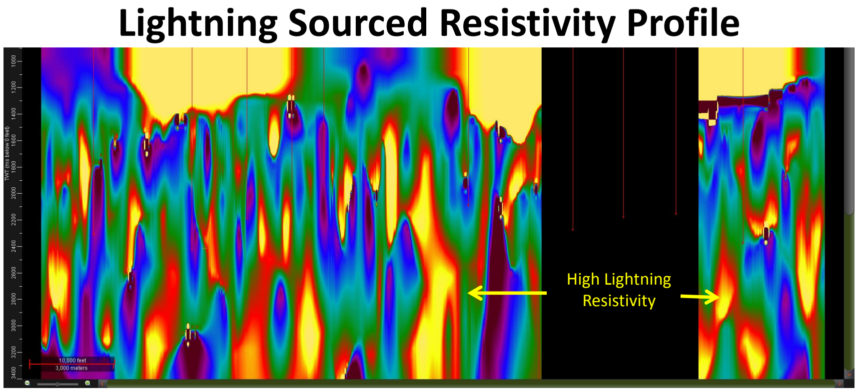
85. Here is an arbitrary line in a resistivity volume, through a series of wells in Colorado County, Texas



Lightning Sourced Resistivity Profile

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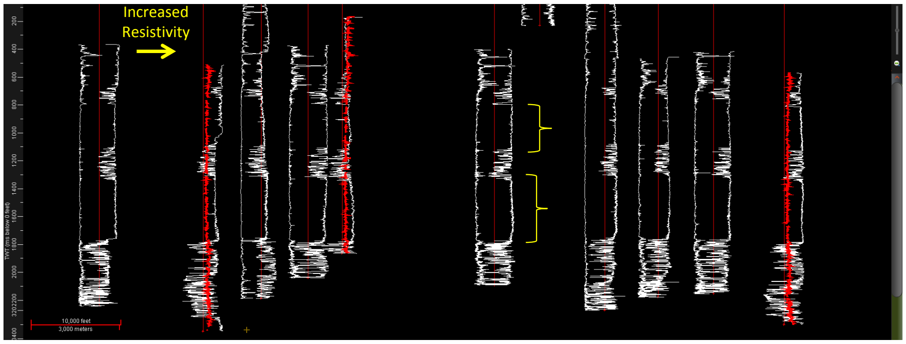
86. Here are resistivity logs at the wells.

Resistivity Logs



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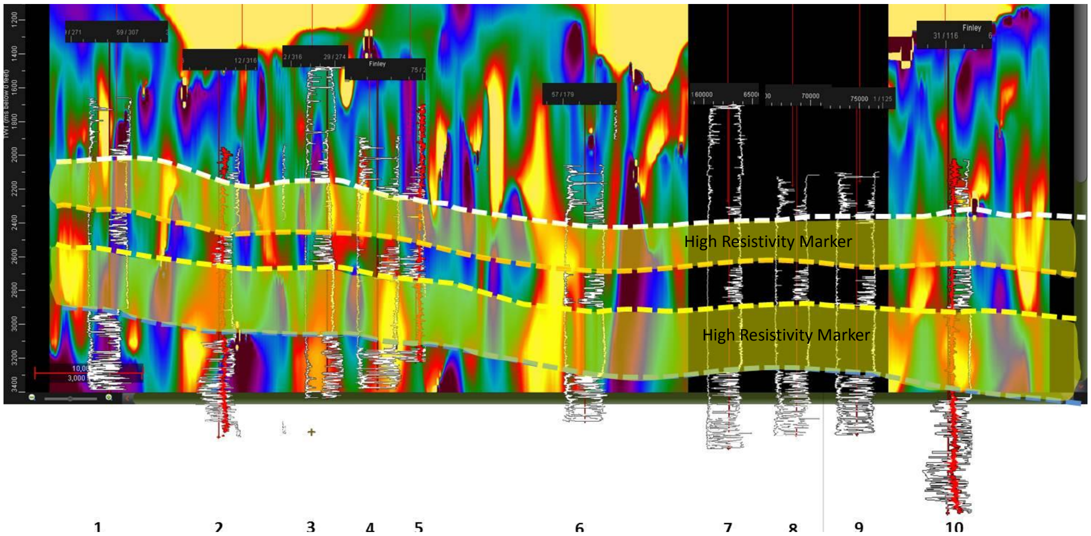
87. Here is the same arbitrary line combined with the well logs.



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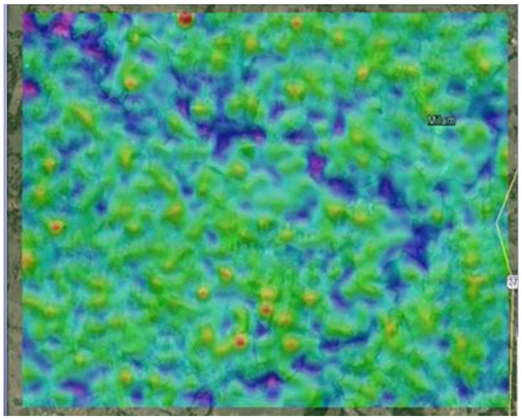
88. This is an example from Milam County, Texas. The map shows rise time rate. There are two rivers in the area, the Little River, flowing east-southeast from the northwest corner, and the San Gabriel river, flowing east then northeast from the southwest corner to join it. Both rivers marked by a series of low rise rate (magenta to dark blue) patches.



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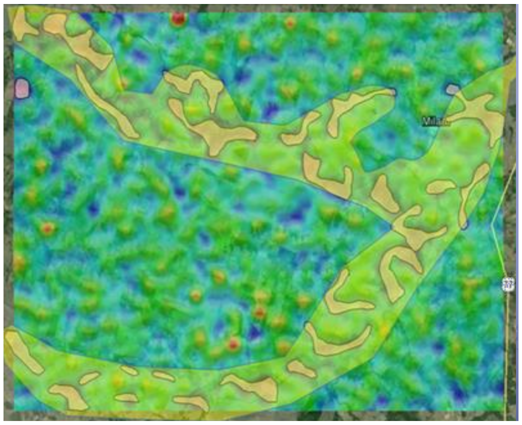
89. Here these rise rate anomalies have been interpreted as point bar sands in the near surface, filled with fresh water. The applications for anyone wishing to drill a water well are obvious. We would expect similar anomalies where there are very shallow oil reservoirs. Most oil production in Milam County is from shallow, discontinuous sands.



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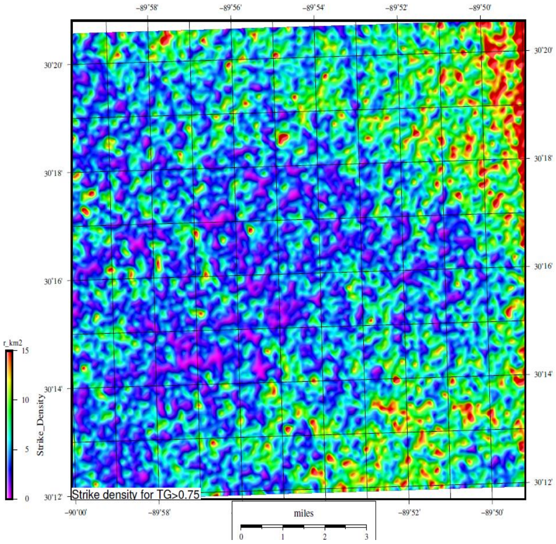
90. This example is from the north shore of Lake Pontchartrain in Louisiana. The interpretation of the strike density map is not at all obvious, but a geologist familiar

with the area made an attempt. The map shows the density of lightning strikes occuring in the top 25% of rate of change of tide.



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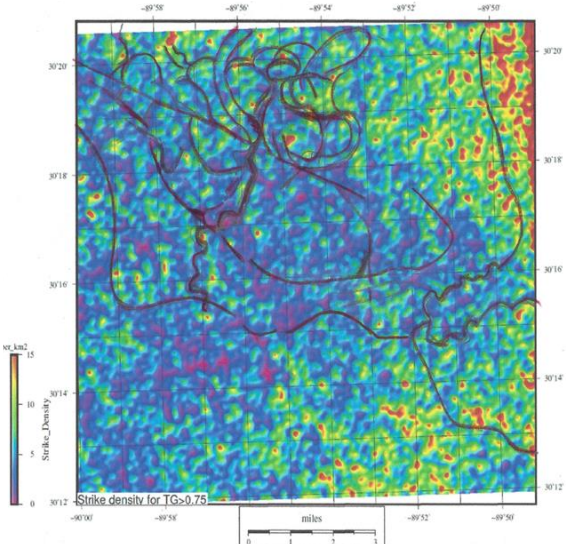
91. Here are the results.



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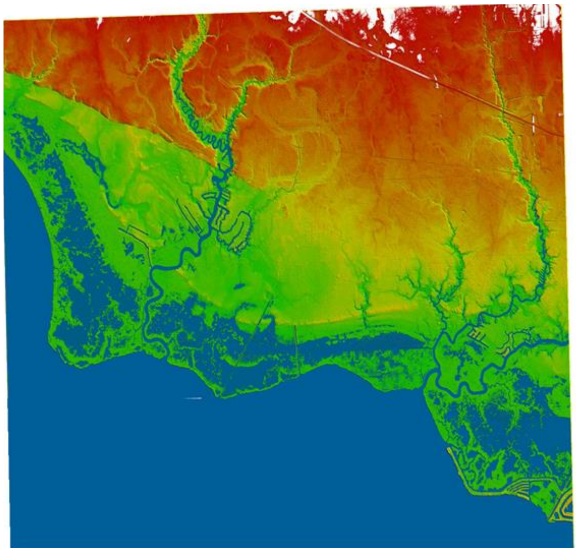
92. For comparison, here is a Lidar map of the same area.



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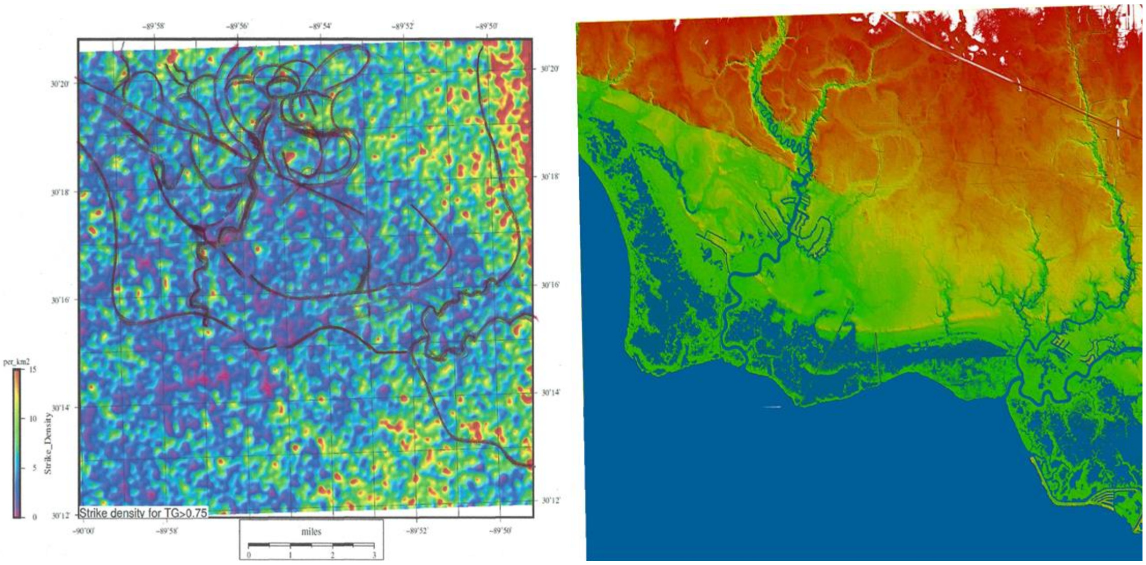
93. This is a side-by-side comparison of the last two maps.



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94. Now we will move west to look at a project in Arizona.

Moving west…

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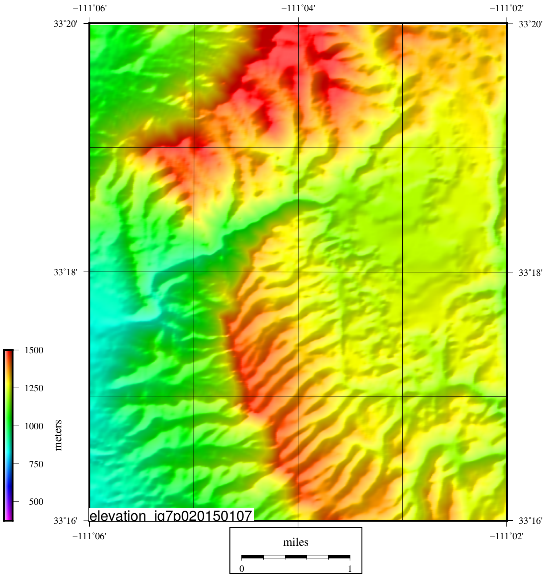
95. So far, everything I have shown is in almost flat areas on the Gulf Coast. This project is in an area with elevation changes over 1100 meters, shown here.



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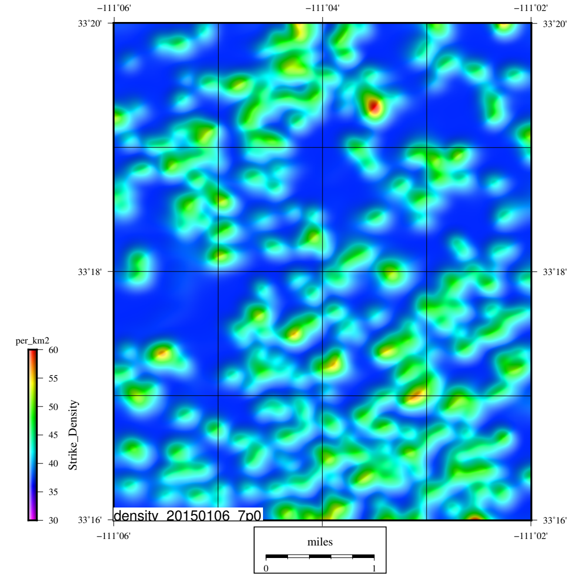
96. This is the strike density. Strikes definitely appear to have preferred locations to hit. But these preferred locations are not where the highest mountain peaks occur.



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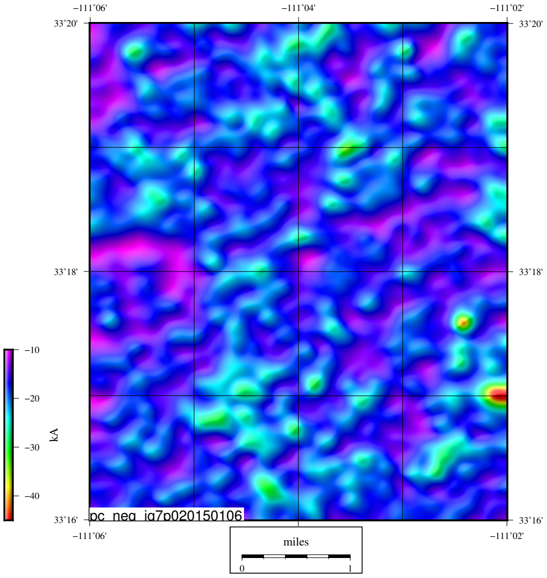
97. This map shows the average variation in peak current of negative strikes.



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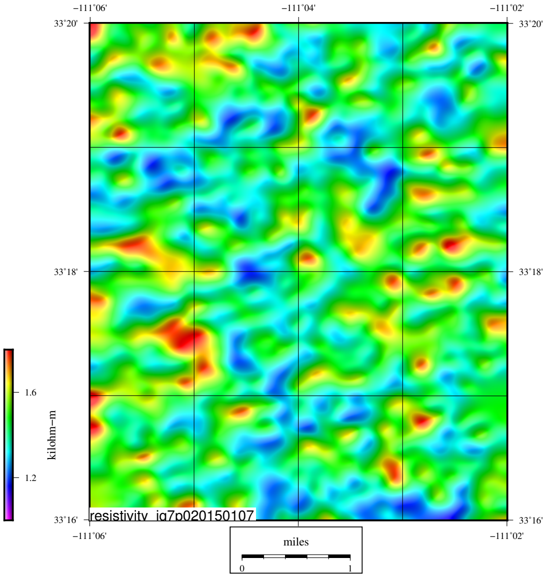
98. Here is the apparent resistivity. The variation is not great.



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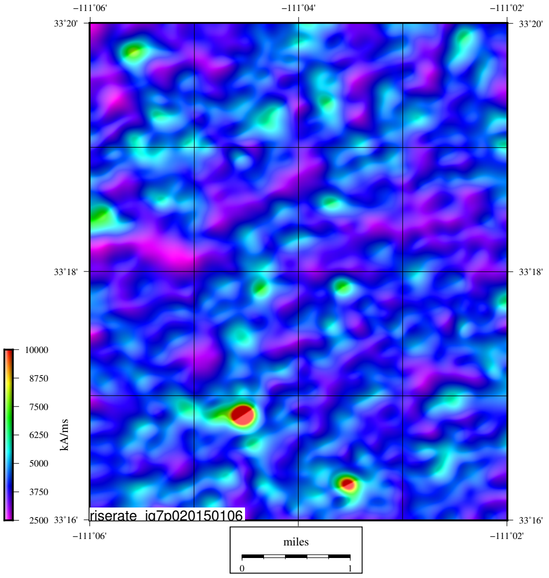
99. Here is the rise rate. The two exceptionally high values need investigation.



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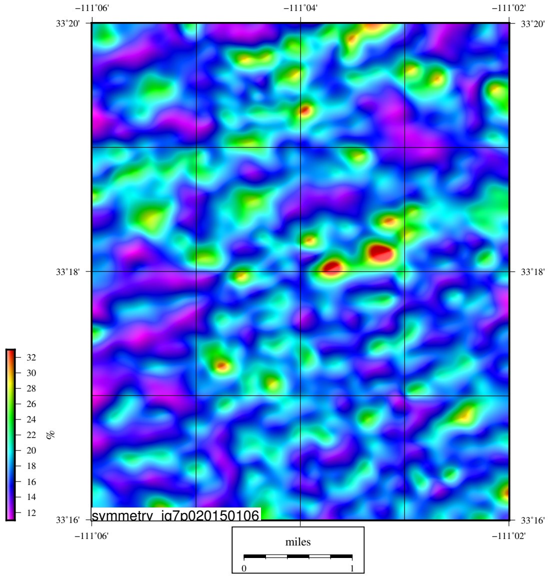
100. This is a computed attribute we call *symmetry*. It is the ratio of rise time to peak-to-zero time, expressed as a percentage. In this map there are two unusually high points near the center of the map, which will need investigation.



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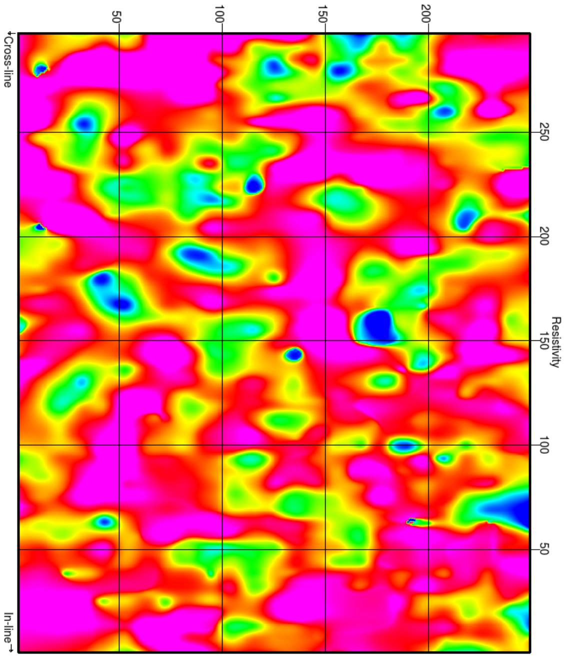
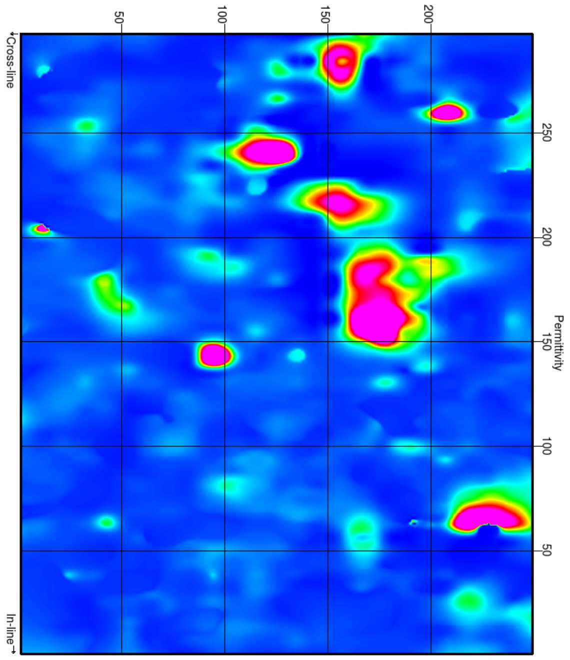
101. This is a depth slice of apparent resistivity at a depth of 520 m. The color scale is from 5000 to 10000 Ωm The computation of the depth is from a surface datum, so this is 520 m below the surface.



102. This is a depth slice of apparent permittivity at a depth of 520 m. The color scale is from 0 to 100 nF/m. The computation of the depth is from a surface datum, so this is 520 m below the surface.

The project started only ten days ago, and we have not had time to do much with it. It is over a large copper deposit. First reaction from the company developing the deposit is that the location of the ore body is where the large anomaly is on this slide.



98. This presentation has demonstrated that lightning has a real application in exploration and many other disciplines which involve the earth, such as hydrology, civil engineering, and infrastructure investment.

Petroleum exploration

Mineral Exploration

Flood control

Pipelines

Power lines

104. What are the advantages of this new mode of exploration? It is fast–this last series of slides were from a project where initial planning started on January 1. It is easy: no permits are required, no one has to visit or even fly over the study area, and there is no mobilization cost. It is low cost: hundreds of square miles of lightning analysis can be completed for the cost of one square mile of 3D seismic data.

Fast

Easy

Low cost

105.

Questions?