What Time Is It?

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Abstract
When a fault occurs on the power system, numerous devices capture the event. Each of these devices provide a fault time. Nearly all fault recorders have GPS time synchronization. In addition, many DFR manufacturers claim to have millisecond or better time accuracy on their devices.

This paper explores time stamps from four different devices and compares the time stamps for two events. It also evaluates time stamp performance for each event relative to the following event characteristics: actual event time, fault record header time and fault time within the recorded data.

A performance comparison of the time stamps from each manufacturer and model will be displayed when compared to other devices of the same model. Additionally, a performance comparison between manufacturer and model will be presented.

Finally, the paper will attempt to extrapolate a confidence boundary of time stamp performance for the devices evaluated.

TVA Overview
The Tennessee Valley Authority (TVA) is the largest public power company in the United States, with 33,000 megawatts of dependable generating capacity serving power to 155 locally owned distributors and to about 9 million residents of the Tennessee Valley. Developing advanced power monitoring system capabilities has been a high priority for TVA, particularly given the reliability record of the company's transmission systems. TVA has achieved 99.999 percent reliability for the last 11 years.

Background
When a fault occurs on the TVA transmission system, performing fault analysis quickly is paramount. Consequently, TVA has deployed devices throughout the power system to record disturbance information. In order to understand the sequence of events, these devices are time synchronized through the global positioning system (GPS). Not all monitoring equipment is on equal footing with regard to time stamping data. By utilizing a test methodology, it is possible to determine a confidence bound for the time stamp of a given manufacturer of device.

As the fault occurs on the power system, Digital Fault Recorders (DFR) capture the oscillography of the event. Depending on the fault type and protection scheme, there may be multiple reclose operations which potentially yield additional waveform recordings. As the waveforms are recorded, the DFR tags each recording with a time stamp for the event. The time stamp used for the event is based on the configuration of the DFR. Consider the waveform shown in Figure 1, below.

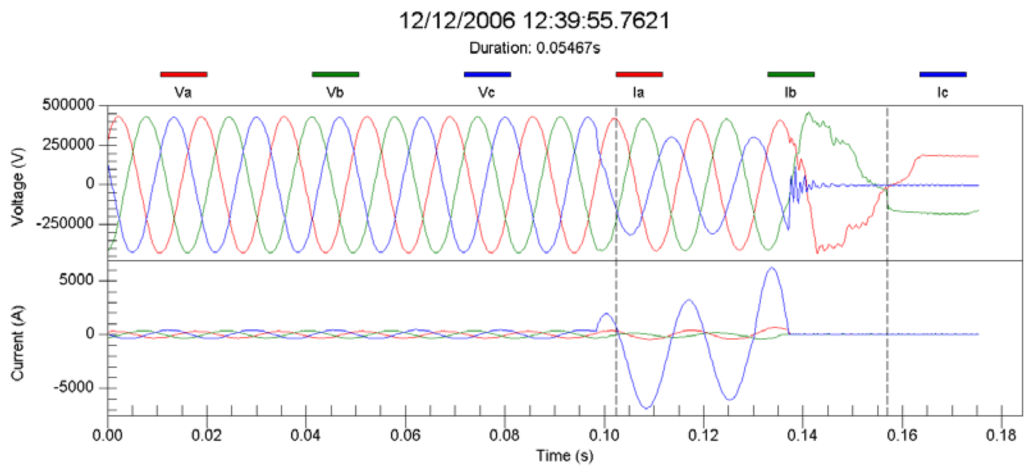

Figure 1 - Typical DFR Oscillography Record

Notice there are a number of factors which influence the time stamp: pre-trigger capture time, trigger threshold, and DFR time accuracy to name a few. In this particular case, notice the DFR is configured to capture 6 cycles of pre-trigger data. The trigger threshold is 95% of nominal voltage trigger. The manufacturer-stated DFR time accuracy is 1 millisecond.

By itself, the waveform data in the record provides meaningful information about the event. However, the difficulty comes when a DFR from another substation on the same line records the same event. As Confucius said, “A person with one clock knows the time, but a person with two is never sure!” The time stamp is very important when using computer based tools to perform fault analysis. In addition, the time stamp is important when comparing data to other systems like lightning data.

Consider Figure 2, below. Notice how the same event looks very different. The DFR is configured to capture 17 cycles of pre-trigger data. The voltage trigger threshold is still 95% of nominal. The manufacturer stated DFR time accuracy is 1 millisecond. However, notice the time stamp at the top of the record. It shows a time stamp of 12/12/206 12:39:36.000 versus the other time stamp of 12/12/2006 12:39:55.7621. Herein lies another problem. The native record format shows a different time stamp, but when the record was converted to IEEE COMTRADE the sub second quantity was dropped.

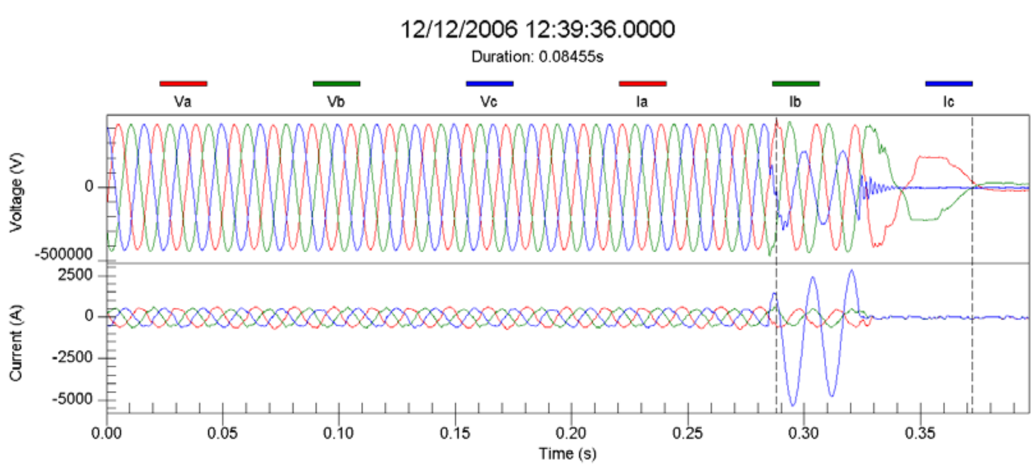

Figure 2 - Oscillography From A Different Manufacturer

With both records there is no way to be certain that the time stamp in the header represents the time the record began or the time the threshold was exceeded. Even more confusing is how the system attempted to determine the fault duration. The second graph indicated the fault is 2 cycles longer than the first. In reality, neither durations are correct because both units stopped recording before the event was over.

Without some benchmark there is reduced confidence in the time stamp of the data. Clearly, a confidence bound must be established to understand how to time-relate this information from DFRs to other DFRs and to other data sources. As a result, a test methodology was established to understand the relative performance of the time stamps from the DFRs.

Time Stamp Testing Methodology

All of the DFRs in the study utilize GPS time stamping. In fact, all of the manufacturers assert millisecond accuracy of time stamps. The methodology utilized an independent data source as the time stamp reference. After the event occurred, all of the IEDs that within a broad time window were identified. Then additional analysis was performed on the records captured by the DFR. The performance of each manufacturer and type relative to the event was measured. Finally, the comparison between manufacturers for each event was performed.

The reference events needed to be something that would effect a large number of devices. The event also had to have an independent time stamp source. Consequently, lightning was used as the data source. The NLDN data uses the GPS to time stamp data. Since all of the data used the same time reference, no additional time stamp variations were introduced. The lightning events occurred on the 500 kV system. The system acts as the backbone to the TVA transmission network. Events on the 500 system are generally recorded by many devices.

When a lightning event occurred on the 500 system, all of the DFRs were investigated and event records were identified. The initial time window to utilized to identify DFR records was 5 minutes. Utilizing a large time window allowed for identifying devices that had faulty GPS receivers.

To establish the event time, each record was opened in the native DFR analysis tool. The initial fault time was identified by scrolling to the point on the waveform where the fault began. The time was recorded in a spreadsheet for comparison to event records from other devices.

For each case study a template was used to document the research: map of the location of the meters and lightning, graph of the confidence bound for each manufacturer and a graph of the comparison of the manufacturers.

Case Study Review

Two case studies are shown below. These case studies reveal some interesting information about the time stamp accuracy for each of four instrument types. In addition, a confidence boundary for the set of devices is provided.

Case Study 1
According to the TVA Dispatch log, on May 31, 2006 at 21:12:44, weather caused the Browns Ferry-Maury 500kV line to operate due to weather. Upon closer investigation, a lightning strike was identified on the line at 21:12:42.820. Additional investigation revealed that 76 IEDs detected the disturbance. Figure 3, below shows a summary of the time stamps from all 76 devices which were manufactured by four different companies.

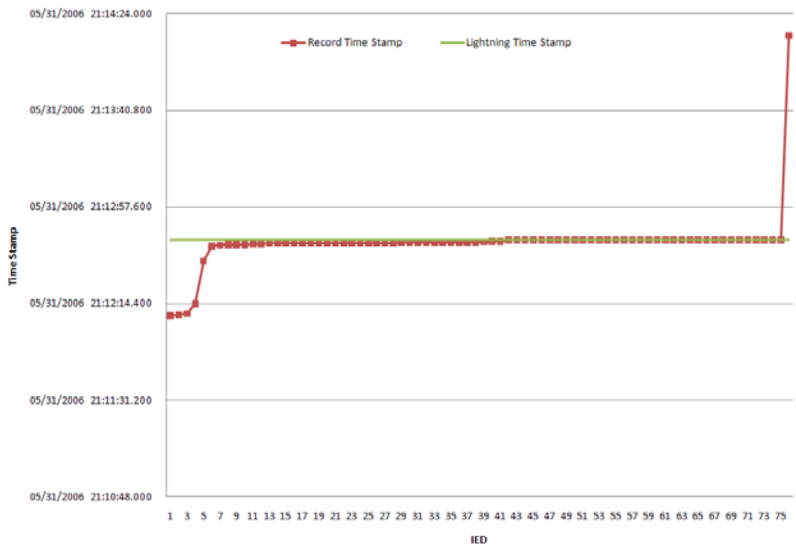

Figure 3 - Time Stamp Summary

The green line represents the time stamp of the lightning strike. Notice that several of the IEDs show a significant difference between the time stamp and the actual event time. Clearly, some of these are outliers either due to clock failure or some other technical difficulty. Naturally, these outliers should be eliminated from the actual performance analysis.

By performing a statistical summary of the data, it was clear that there were outliers. Table 1 below, shows the summary statistics of the unfiltered data set as well as the dataset with the outliers removed. The filtered data, shown in figure 4, was used for all subsequent analysis.

Table 1 - System Performance

	Unfiltered	*Refined*
Mean	3.69	0.61
Standard Error	1.43	0.08
Median	0.96	0.04
Mode	1.48	1.48
Standard Deviation	12.47	0.67
Sample Variance	155.57	0.44
Kurtosis	34.07	-1.58
Skewness	5.44	0.41
Range	91.55	1.83
Minimum	0.00	0.00
Maximum	91.56	1.83
Sum	280.46	39.95
Count	76.00	65.00

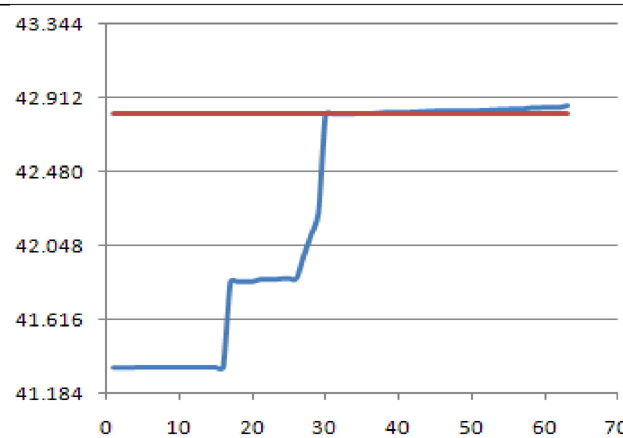

Figure 4 - Resulting Data Distribution

After filtering the data, the remaining data points were trended. Figure 5, below shows the time stamping for each brand tested. The graph reveals some interesting details in how the data compares to the lightning time stamp. Brand B, for example, has very good accuracy. On the other hand, Brand D is very consistent but always off by about 1.4 seconds. In the other devices, there was little consistency, but when it was correct it tended to be very good.

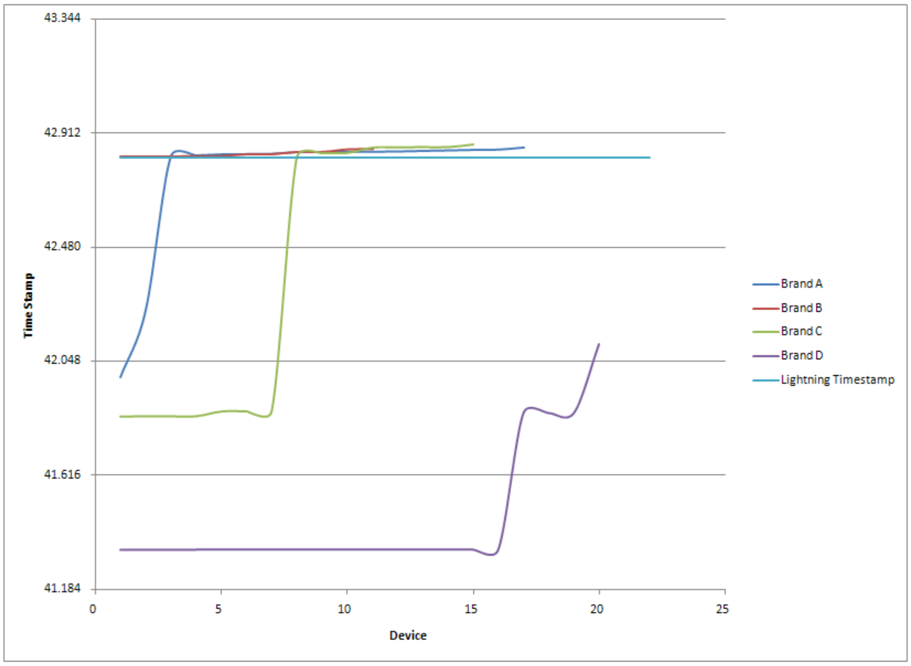

Figure 5 - Time Stamp Trending

Table 2 - Brand Lightning Timestamp Deviation

	Brand A	Brand B	Brand C	Brand D
Mean	0.101	0.013	0.471	1.368
Standard Error	0.056	0.003	0.126	0.055
Median	0.022	0.012	0.051	1.484
Mode	0.021	0.003	0.981	1.484
Standard Deviation	0.232	0.011	0.487	0.244
Sample Variance	0.054	0.000	0.237	0.060
Kurtosis	6.967	-1.003	-2.304	1.947
Skewness	2.787	0.707	0.148	-1.828
Range	0.827	0.029	0.980	0.777
Minimum	0.004	0.003	0.002	0.708
Maximum	0.831	0.032	0.982	1.485
Sum	1.719	0.148	7.063	27.359
Count	17.000	11.000	15.000	20.000

Table 2, above, shows the statistical summary of how the devices compared against the lightning time stamp. The table was developed by performing a statistical analysis of the value determined by taking the absolute value of the difference between the time stamp of the record from the IED and the lightning time stamp. Brand B had the smallest average difference from the lightning time stamp at only 13 ms. Brand B was also the most consistent with the smallest standard deviation.

What is the root cause in the time stamp variation? Could it be the location of the IED relative to the lightning event? Figure 6, below, shows how the time stamps varied for Brand A. Clearly, location is not the root cause of the variation.

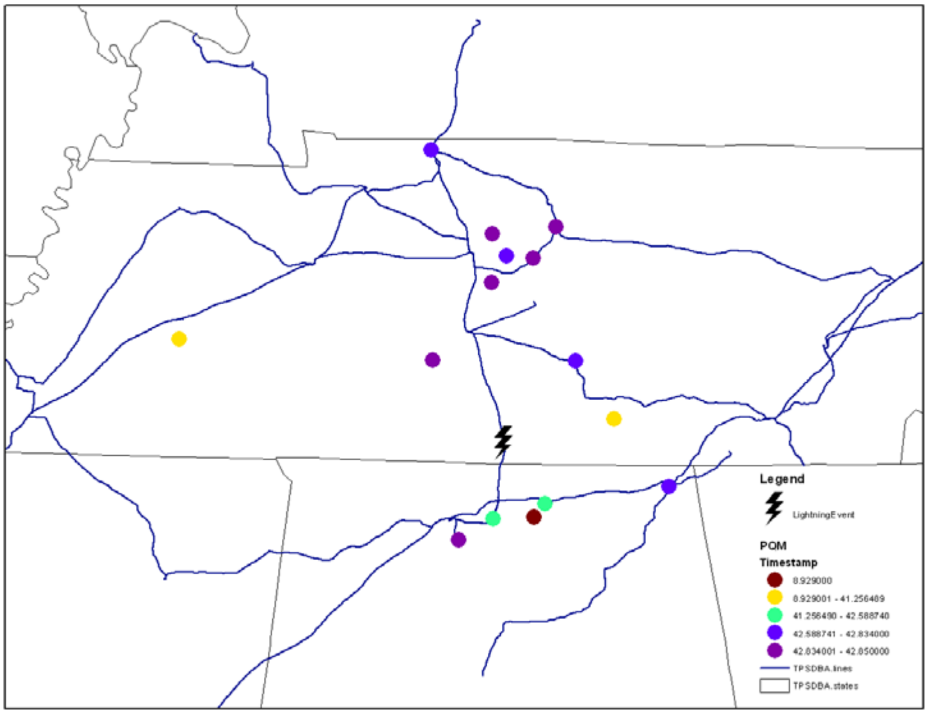

Figure 6 - Location of Measurements for Brand A

Case Study 2

According to the TVA Dispatch log, on May 2, 2006 at 22:08:34, weather caused the Sequoyah-Conasauga 500kV line to operate due to weather. Upon closer investigation, a lightning strike was identified on the line at 22:08:33.520. Additional investigation revealed that 55 IEDs detected the disturbance. Figure 7, below shows a summary of the time stamps from all 55 devices which were manufactured by four different companies.

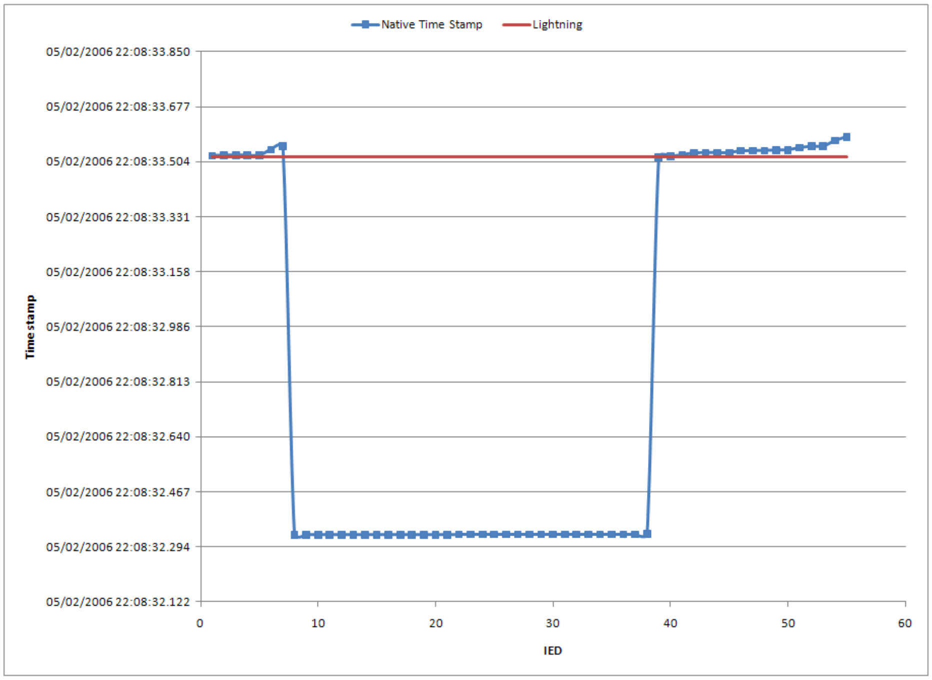

Figure 7 - Time Stamp Summary

The red line represents the time stamp of the lightning strike. As with Case 1, several of the IEDs show a significant difference between the time stamp and the actual event time. However, using a statistical outlier test revealed no data should be eliminated from the actual performance analysis. A statistical summary of the grouping is show in Table 3, below.

Table 3 -System Performance

Mean	0.677073
Standard Error	0.078942
Median	1.186999
Mode	1.186999
Standard Deviation	0.585451
Sample Variance	0.342753
Kurtosis	-2.00284
Skewness	-0.26481
Range	1.188
Minimum	0
Maximum	1.188
Sum	37.23899
Count	55

Figure 8, below shows the time stamping for each brand tested. Notice this time that Brand A, B and C show very tight correlation with the lightning time stamp. Notice again, that Brand D is very consistent but off by about 1.3 seconds.

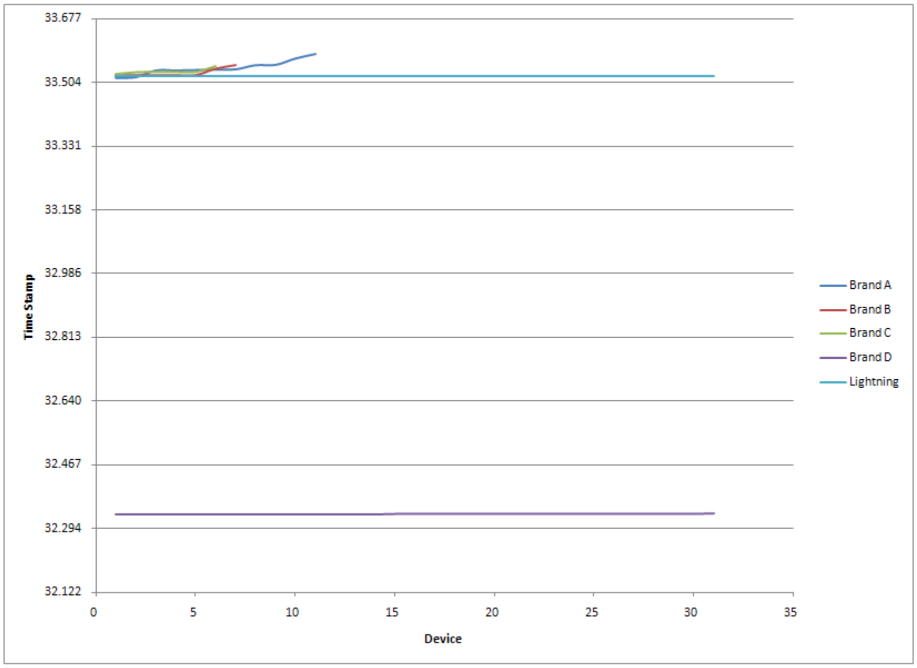

Figure 8 - Time Stamp Trending

Table 4 - Brand Lightning Timestamp Deviation

	Brand A	Brand B	Brand C	Brand D
Mean	0.025	0.010	0.014	1.187
Standard Error	0.006	0.004	0.003	0.000
Median	0.020	0.004	0.012	1.187
Mode	0.018	0.004	0.012	1.187
Standard Deviation	0.019	0.012	0.007	0.001
Sample Variance	0.000	0.000	0.000	0.000
Kurtosis	0.412	0.709	4.374	-0.857
Skewness	0.734	1.478	1.867	-0.257
Range	0.062	0.029	0.022	0.002
Minimum	0.000	0.003	0.006	1.186
Maximum	0.062	0.032	0.028	1.188
Sum	0.275	0.073	0.081	36.810
Count	11.000	7.000	6.000	31.000

Table 4, above, shows the statistical summary of how the devices compared against the lightning time stamp. The table was developed by performing a statistical analysis of the value determined by taking the absolute value of the difference between the time stamp of the record from the IED and the lightning time stamp. Brand B had the smallest average difference from the lightning time stamp at only 10 ms. However, Brand D was also the most consistent with the smallest standard deviation.

Confidence Boundary

Based on the case studies, a confidence in the time stamp for each manufacturer's device was developed. This confidence boundary is used to develop a time window for identifying lightning strikes that may have caused the phenomenon. Programmatically, software is used to identify the strikes that may have caused events on the power system. Having a confidence boundary also provides the ability to rule out lightning if the stroke happens outside the time window.

Using a summary of the statistical data in Table 5, below, it is possible to derive a confidence boundary. Using the mean and standard error with a 95% confidence margin results in a 101 ms offset plus a 110 ms confidence band for Brand A. This means that in order to ensure correlation with a lightning data source a window of over 200 ms should be used! Using a similar approach for the rest of the Bands B-D yields windows of 19 ms, 717 ms and 1475 ms respectively.

Table 5 - Study Comparison

	Study 1		Study 2	
	Avg (ms)	Conf (ms)	Avg (ms)	Conf (ms)
Brand A	101	110	25	11
Brand B	13	6	10	9
Brand C	471	246	14	6
Brand D	1368	107	1187	0

Conclusion

While manufacturers claim millisecond time resolution on time stamps, there are many factors that may result in lower performance. This is especially true when using the data from IED manufacturers with other data sets like lightning. However, it is possible to derive a confidence window using historical event data.